

This doctoral thesis investigates experimentally the feasibility of using ReBCO coated conductors as an alternative material to copper to reduce the resistive wall impedance and improve the working conditions of the future circular collider hadron-hadron design.

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Evaluation of the Surface Impedance of ReBCO Coated Conductors and Requirements for Their Use as Beam Screen Materials for the FCC-hh

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Patrick Krkotić
Doctoral Thesis



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Doctoral Thesis

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Abstract

The Future Circular Hadron Collider (FCC-hh) is a proposal for a 100-kilometre-long particle accelerator with collision energy substantially higher than previous colliders to expand the Large Hadron Collider (LHC) research.

The selection of a low surface impedance beam screen coating material for such a high-energy collider has become of fundamental importance to ensure sufficiently low beam impedance and guarantee stable accelerator operation at high beam currents. Currently, copper is the baseline coating material. In comparison to it, only high-temperature superconductors (HTSs) in the form of ReBCO coated conductors (ReBCO-CCs) have a lower surface impedance and would provide for higher margins of beam stability at the expected operating temperature (40 - 60 K). Whilst theoretical studies of HTSs under FCC-hh conditions have proved encouraging, no experimental data of ReBCO-CCs subject to FCC-hh conditions exists to confirm these predictions.

This thesis provides two main contributions: First, it presents the experimental set-ups designed and constructed to measure the surface impedance of ReBCO-CCs, on the basis of dielectric resonator structures of Hakki-Coleman and parallel plate type under AC and DC magnetic fields, photon irradiation, all at cryogenic temperatures, to mimic the environment of the beam screen in the FCC-hh. We also developed DRΩMS, an automated data acquisition software, and ARPE, a post-processing algorithm to accurately extract the parameters of the dielectric resonators -resonance frequency and quality factor- from the S-parameters of the vector network analyser.

The second contribution consists in the results from experimentally-measured surface impedance of ReBCO-CCs from six different manufacturers. We present surface impedance as a function of temperature and under strong magnetic fields in the gigahertz range. Complementary to this, we analysed the non-linear behaviour of ReBCO-CCs in the presence of a magnetic field superimposed on radio-frequency electromagnetic fields with amplitudes comparable to the ones generated by proton bunches in the FCC-hh. Finally, we studied the effect of photon irradiation on the surface resistance in-situ and ex-situ, at the ALBA Synchrotron Light Source.

Extrapolating from our data to 16 T and 1 GHz demonstrates the possibility of lowering the surface resistance of the beam screen by up to two orders of magnitude by using ReBCO-CCs instead of copper while the surface reactance is at the same order of magnitude. We conclude that ReBCO-CCs are suitable candidates to significantly reduce the resistive wall impedance in the FCC-hh.

Resumen

El Future Circular Hadron Collider (FCC-hh) es una propuesta para un acelerador de partículas de 100 kilómetros de longitud con energías de colisión significativamente superiores a los colisionadores anteriores para expandir la investigación del Large Hadron Collider (LHC).

La elección de un material de revestimiento de baja impedancia superficial para el interior del tubo de vacío se ha vuelto de fundamental importancia para garantizar una impedancia de haz suficiente baja. Esto permite un funcionamiento estable del acelerador con corrientes de haz altas. Actualmente el cobre es el material de revestimiento de referencia. En comparación con eso, solo los superconductores de alta temperatura en forma de conductores recubiertos con ReBCO (ReBCO-CCs) tienen una menor impedancia superficial. De esta manera, prometen mayores márgenes de estabilidad del haz a la temperatura esperada de funcionamiento (40 - 60 K). Mientras los estudios teóricos de superconductores de alta temperatura en condiciones FCC-hh han sido prometedores, no existen datos experimentales de conductores recubiertos con ReBCO sujetos a condiciones FCC-hh para confirmar estas predicciones.

Esta tesis aporta dos contribuciones principales. Primero, presenta las condiciones experimentales diseñadas y construidas para medir la impedancia superficial de ReBCO-CCs en base a estructuras de resonadores dieléctricos de tipo Hakki-Coleman y placa paralela bajo campos magnéticos AC y DC, irradiación de fotones, todo ello a condiciones criogénicas temperaturas, para imitar el entorno del tubo de vacío en el FCC-hh. También desarrollamos DRΩMS, un software de adquisición de datos automatizado, y ARPE, un algoritmo de posprocesamiento para extraer con precisión los parámetros del resonador dieléctrico -frecuencia de resonancia y factor de calidad- de los parámetros S del analizador de redes vectoriales.

La segunda contribución consiste en los resultados de las mediciones experimentales de impedancia de superficie de ReBCO-CC de seis fabricantes distintos. Presentamos la impedancia superficial en función de la temperatura bajo fuertes campos magnéticos en el rango de los gigahercios. Complementariamente, analizamos el comportamiento no lineal de ReBCO-CCs en presencia de un campo magnético superpuesto a campos electromagnéticos de radiofrecuencia con amplitudes comparables a las generadas por haces de protones en el FCC-hh. Finalmente, estudiamos el efecto de la irradiación de fotones sobre la resistencia de la superficie in-situ y ex-situ, en la fuente del luz del sincrotrón ALBA.

La extrapolación de nuestros datos a 16 T y 1 GHz demuestra la posibilidad de reducir la resistencia superficial del tubo de vacío de hasta dos órdenes de magnitud mediante el uso de ReBCO-CC en lugar de cobre, mientras que la reactancia superficial está en el mismo orden de magnitud. Concluimos que los ReBCO-CCs son candidatos adecuados para reducir significativamente la impedancia de la pared resistiva en el FCC-hh.

Acknowledgement

This doctoral thesis has been a long journey that would not have been possible without the unique people who pushed, encouraged, and supported me during the entire process. Many people have crossed my path throughout time, and I want to thank them for their contributions and efforts, some of which I would like to dedicate a few more words.

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ich tief im Inneren wirklich gesegnet bin euch in meinem Leben zu haben und so viele Erinnerungen mit euch zu teilen.

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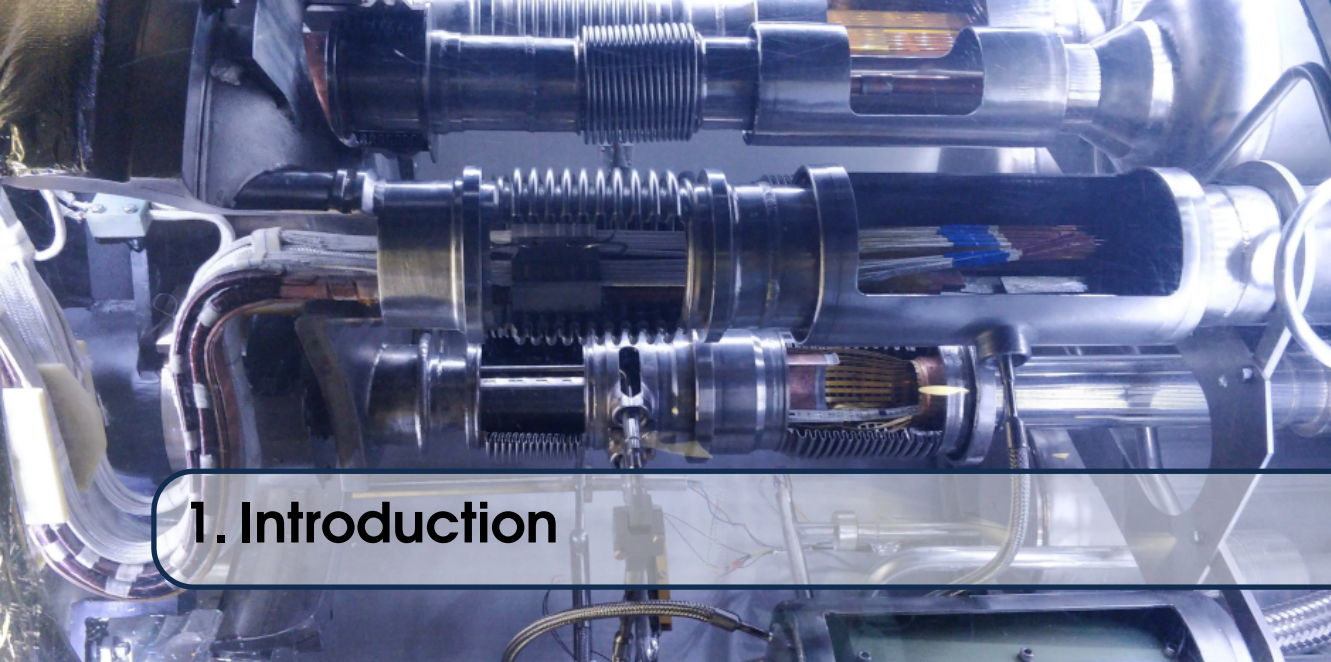
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- The Motivation -

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1. Introduction

The beginning is perhaps more difficult than anything else, but keep heart, it will turn out all right.

-Vincent Van Gogh-

This thesis presents the design, implementation and exploitation of measurement techniques for ReBCO coated conductors (CC) at the Future Circular Collider hadron-hadron baseline conditions. The work deals with the evaluation of the surface impedance of ReBCO-CCs and their requirements for the use as possible alternative beam screen materials for future particle accelerators. In this chapter, a brief introduction is given to fundamental particles and particle accelerators, providing an overview of arising beam screen issues and the features of ReBCO-CCs. In addition, the chapters and their structural relationship, as well as a statement of the problem and strategy to solve it, are outlined.

1.1 Fundamental Constituents of Matter

For centuries, it was controversial among philosophers as well as scientists whether matter was a continuum that could be divided infinitely finely or was made up of elementary particles that could not be further divided into smaller pieces. The periodic table's evolution and the discovery of over 100 elements with periodically recurring properties was the first indication that atoms themselves have an internal structure. The contemporary concept of an atom emerged as late as at the beginning of the 20th

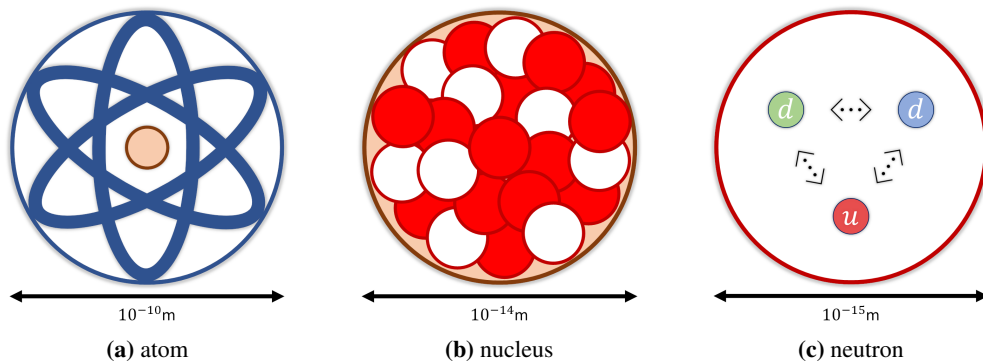


Figure 1.1: Dimensions and hierarchy in the atomic structure, starting from the classical picture of an atom, its nucleus (orange) being surrounded by an electron cloud (blue) containing neutrons (white) and protons (red) until the quark structure of the neutron. The colour assignment of individual quarks is arbitrary, but all three colours must be present. Forces between quarks are mediated by gluons ($\langle \cdot \cdot \rangle$). Adapted from [Pov+15].

century [Sch12]. In particular, Einstein and subsequently Rutherford and co-workers achieved a breakthrough in theory and experiment, respectively, proving that atoms exist and that they were composed of a dense nucleus surrounded by an electron nebula, as illustrated in Fig.1.1(a). With the discovery of the neutron in 1932, there was no longer any doubt that the building blocks of nuclei are protons and neutrons, as presented in Fig.1.1(b) [Pov+15].

This field of study closely followed the paradigm of the existence of fundamental building blocks of matter. The following 20 years it became the main focus in physics, leading to the gradually broadening of predicted and discovered particles [Shi12]. This search brought, especially with the construction of the first particle colliders in 1960 [Wie07], to the observation of hundreds of different new types of short-lived particles. Such a confusing abundance of particles has been semi-officially named ‘The Particle Zoo’, and these particles were organised in a hierarchy scheme depending on their physical properties. This has shaped the physics of elementary particles to such an extent that, again, there were widespread doubts as to whether all those particles found could be elementary or could be composed of even smaller particles. Based on this bewildering variety of particles in the Particle Zoo, the quark model was proposed by Gell-Mann and Zweig in 1964 as a possible ordering scheme [Wie07]. The particles being seen in the accelerators were, according to the theory, nothing more than combinations of these quarks. The evidence of the existence of three generations of quarks was proven through experiments provided by particle accelerators between 1970 and 1995 [Pov+15]. Suddenly, neutrons and protons were not any more fundamental and consisted of three quarks, as shown in the example for a neutron in Fig.1.1(c).

The Standard Model (SM), the current theory describing elementary particles and their interactions by categorising them into related groups, substantially simplified the overall world of particle physics showing that most matter observed are combinations of the particles shown in Fig.1.2. Developed in stages starting in the early 1970s, this

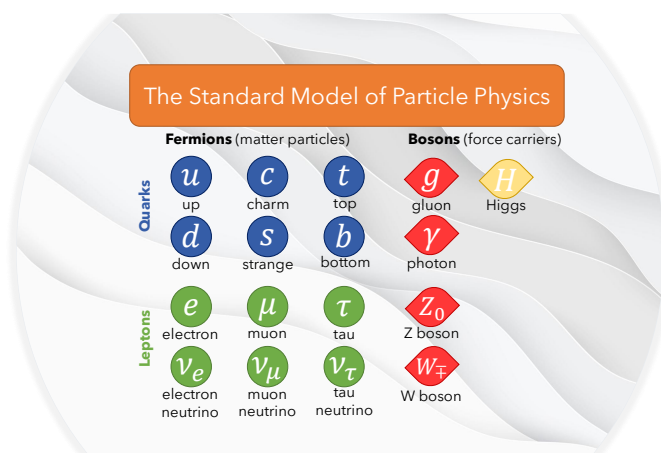


Figure 1.2: Elementary particles of the Standard Model. The model contains twelve fermions, four vector bosons mediating three elementary forces: strong, weak, and electromagnetic, and one scalar boson as the origin of mass.

model combined what was known about particles and forces at the time, to develop an entirely consistent quantum theory on matter [Pov+15].

1.2 Particle Colliders and Synchrotrons

A particle accelerator is a machine that uses electromagnetic (EM) fields to accelerate charged particles to extremely high speeds -almost the speed of light- and high energy while keeping them contained in well-defined beams. The necessary alternating EM fields are provided by a series of radio-frequency (RF) cavities, in which the field exerts a driving force on the particles bundled together in bunches. In order to redirect and guide the charged particles on their trajectory, by means of the Lorentz force, strong dipole magnetic fields are essential.

A particular type of particle accelerator is a collider. There are two main types of particle colliders; linear colliders accelerate particles in a straight path with a specified target of interest at the end. Differently, in circular colliders, two adjacent beams of particles circulate in opposite directions until they reach sufficient energy to intersect at particular crossing points of the accelerator, so-called interaction points. Detectors surrounding the interaction points track the trajectories of the created particles, which scientists use to search for new fundamental particles with unknown properties. At the time of this writing, the world's highest energy particle accelerator is the Large Hadron Collider (LHC) at CERN, as sketched in Fig.1.3, operating at a centre-of-mass (cms) collision energy of 14 TeV with a circumference of about 27 km used as a proton-proton collider [Brü+04].

Even though in the past several decades, particle accelerators have played an essential role in fundamental physics and the discovery of the constituents of the universe, they evolved in many ways and are found in a wide variety of applications: Medical applications, ranging from relatively low energy accelerators as X-ray sources,

or accelerators at the hundred MeV-GeV scale to provide particle beams for cancer radiation therapy, e.g., as the Heidelberg Ionenstrahl-Therapiezentrum (HIT) [Hei09]. Accelerators are also used as synchrotron light sources for the study of condensed matter physics. The ALBA Synchrotron Light Source (ALBA) [CEL12] with an energy of 3 GeV employs the energy lost by the electrons due to emission of photons via synchrotron radiation (SR). This light is of significant usage in the study of material science, chemistry and biology.

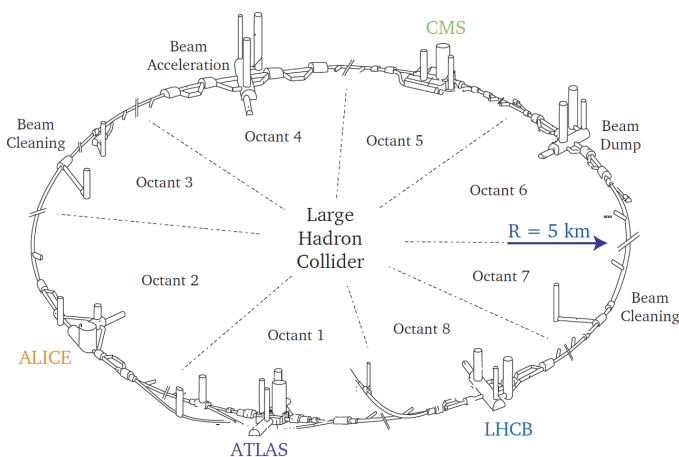


Figure 1.3: Illustration of the Large Hadron Collider at CERN. Taken from [Van16]

1.3 Physics Potential of Future Generations of Circular Colliders

The Standard Model is believed to be theoretically self-consistent and has demonstrated tremendous and continued successes in proving theoretical predictions experimentally. Not only did it describe and map what was known, but it also presented energy gaps where no particles existed and predicted the existence of yet-to-be-discovered particles, such as the Higgs boson [Hig64] at that time. With its discovery, with a mass of 125 GeV, by two consecutive experiments in 2012 in two different detectors of the LHC [Aad+12; Cha+12], the last unresolved part of the SM that explained the origin of mass within the theory was resolved. Following the answer to the question ‘Where is the Higgs?’, particle physics is confronted with an even more demanding enquiry: ‘What else is there, how, and where to discover it?’.

Indeed, there is evidence for the assumption that despite the success, the SM is only an aspect of an even more comprehensive theory, as sketched in Fig.1.4. While we can explain the constituents of matter (nuclei, atoms, molecules, etc.), there are other fundamental physical phenomena that the Standard Model cannot adequately explain, such as the nature of dark matter and dark energy or the incorporation of general relativity’s description of gravity [Ben+19b]. In order to achieve the ‘Theory of Everything’, the extension to additional unknown particles and unknown interactions are required.

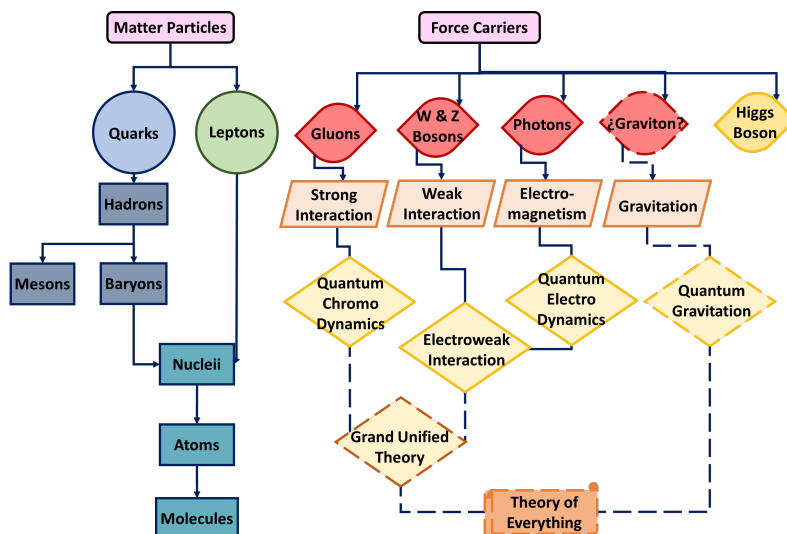


Figure 1.4: An overview of the Standard Model particles, resulting in composite particles, and the (possible) theories describing their interactions. Solid connections represent proven theories. Dashed connections and contours of boxes show not yet proven theories. Adapted from [Wik21a].

Most of the theories proposed over the most recent few decades predicted new physics to be visible at the TeV scale, even at the reachable energy level of the LHC. However, none of those predictions has been confirmed, nor any indication of their validity has been seen so far. The reasons for that can be very varied; starting from the assumption of strongly elusive phenomena, based on having low rates of appearance during collisions (low probability to appear), going over the lack of technology to trigger these new particles (lack of detectors), or in the end, by the simple idea that the energy scale of new physics is higher than expected.

Pushing the energy of colliders to new limits could therefore open a window to reach out to unknown territories of particle physics. The Future Circular Collider (FCC) project [CER20], hosted by CERN and set up in the form of an extensive worldwide collaboration, aims to address the uncertainties mentioned above by expanding the mass range through higher precision measurements with a lepton-collider (FCC-ee) and higher collision energy for direct observations using a hadron-collider (FCC-hh). The LHC limit of its discovery contingency is reached around the mid-2030s. Until then, during the further operation of the LHC and its upgrade to High-Luminosity Large Hadron Collider (HL-LHC) with higher collision rates [Abe+20], the collected future data might provide evidence of phenomena at a feasible energy level, possibly within the energy range of a High-Energy Large Hadron Collider (HE-LHC). A four-volume conceptual design report (CDR) that identifies the physics opportunities and demonstrates the technical feasibility provided by these four mentioned future generation of circular colliders was published in 2019 [Ben+19a; Ben+19b; Man+19; Zim+19].

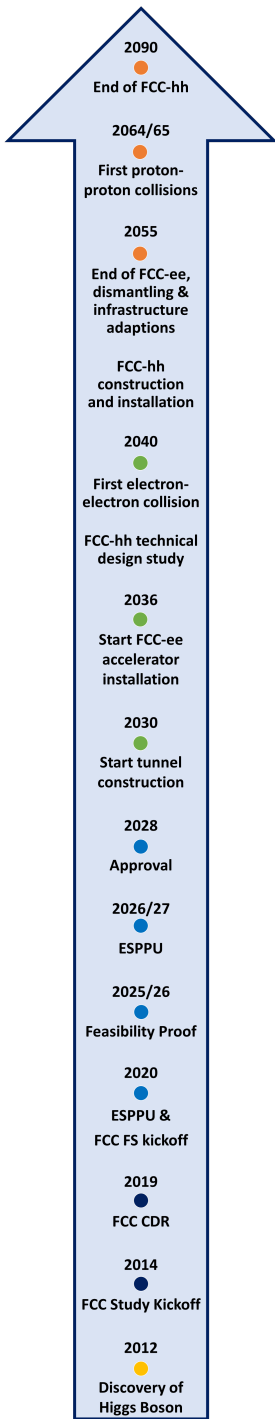


Figure 1.5: Future Circular Collider roadmap. Data taken from [Ben21a]. Colour coding indicates project dependencies.

As a direct response to the FCC design study (2013-2019), which concluded with the aforementioned CDR, presented to the European Strategy for Particle Physics, the FCC Feasibility Study (2021-2025) has become the next step as a crucial milestone to keep Europe at the forefront of particle physics during the 21st century [Gia21]. This study explores in depth the conceptual design and its suitability, also addressing the aspects of the societal and environmental impact as well as the sustainability in a long-term two-stage project, visible in the timeline in Fig.1.5, maximising the physics opportunities [Ben21b]. In stage one, the FCC-ee as a Higgs, electroweak and top-quark factory shall be constructed and implemented into the CERN facility with the earliest electron-electron collisions around 2040. In stage two, after 15 years of operation of the FCC-ee, the more ambitious scenario of the FCC-hh should be constructed as a natural continuation at the energy frontier, replacing the FCC-ee. The first proton-proton collisions would happen in 2065, and the machine would operate until the end of its contingency in 2090.

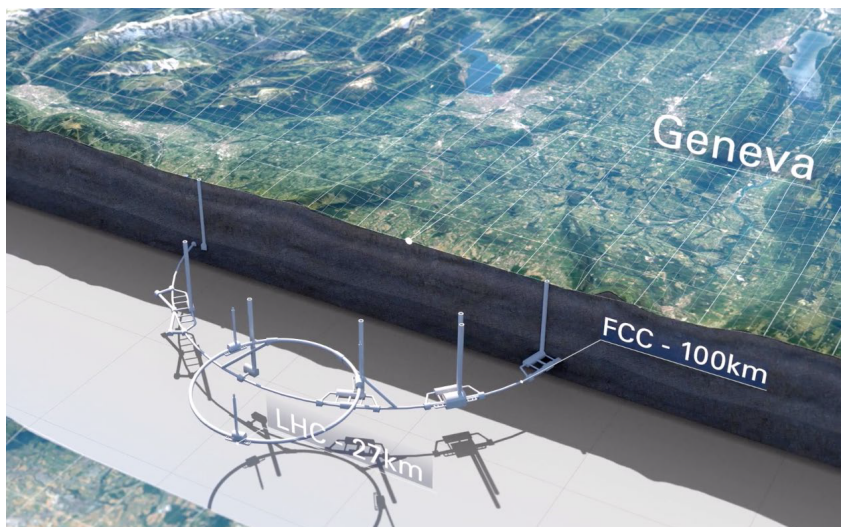
1.4 Future Circular Collider Hadron-Hadron Design

The FCC-hh aims to provide particle collisions with an unprecedented cms energy of 100 TeV operating two counter-rotating 50 TeV proton beams to provide access to an uncharted territory of physics where new (fundamental) particles might exist. The collider, with some of the key parameters given in Tab.1.1, would make use of the existing CERN accelerator complex as injector facility, starting from a linear collider called Linac4, over the accelerator storage rings Proton Synchrotron Booster (PSB), Proton Synchrotron (PS), Super Proton Synchrotron (SPS), to the LHC as baseline to inject beam with an energy of 3.3 TeV into the FCC-hh [Ben+19b]. The concept of the FCC-hh and the 100 km tunnel passing through France and Switzerland at an average depth of 300 m underground is visible in Fig.1.6.

The proposed large circumference of the FCC-hh is a direct consequence of the technological limitation on the maximum attainable magnetic field. Expecting that a 16 T dipole magnetic field will be achievable, the total

Table 1.1: Key parameters of the FCC-hh baseline compared to the HL-LHC and LHC taken from [Ben+19b].

Parameter	LHC	HL-LHC	FCC-hh
Peak luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	1.0	5.0	<30.0
Number of bunches	2808	2760	10400
Energy [TeV]	7	7	50
Current [mA]	584	1120	500
Circumference [km]	26.7	26.7	97.75
Dipole magnetic field [T]	8.33	8.33	15.96
Photon flux [ph/ m s]	$1 \cdot 10^{17}$	$1.92 \cdot 10^{17}$	$1.7 \cdot 10^{17}$
Synchrotron radiation power [W/m arc BM]	0.22	0.42	35.45
Synchrotron rad. power /ring [kW]	3.6	7.3	2400
Synchrotron critical energy [eV]	43.8	43.8	4286.3
Beam screen temperature [K]	5-20	5-20	40-60
Cold bore aperture [mm]	50	50	44
Bunch spacing [ns]	25	25	25
Bunch population $N \cdot 10^{11}$	1.15	2.2	1.0
Events per bunch crossing	27	132	<1000
Stored energy per beam [GJ]	0.36	0.7	8.4

**Figure 1.6:** Schematic of the Future Circular Collider hadron-hadron linked to the already existing accelerators, including the LHC as a possible injector. Figure taken from [BZ19].

length of the arcs result in 83.75 km leading to a total circumference of the machine of 97.75 km, almost four times larger than the LHC. The FCC-hh requires a minimum of 4668 superconducting bending magnets BM of 16 T strength to keep the two nominal beams in their circular orbit. The FCC-hh lattice is based on FODO cells, 213 m long, consisting of alternating focusing and defocusing quadrupoles. Each FODO cell contains 12 dipoles with a magnetic length of 14 m. In between these magnet elements, other accelerator elements such as orbit corrector dipoles, multipole correction coils, chromaticity sextupoles, and diagnostic elements are installed. In comparison, the LHC design cms energy is 14 TeV, achieved in a 27 km ring with 9 T NbTi magnets. Increasing the field strength involves changing the magnet material, e.g., to Nb₃Sn. The development of such new magnets, which are a key cost driver for the FCC-hh project, being capable of providing twice as much field strength of accelerator quality in a 50 mm coil aperture where a vacuum chamber for the particles must be implemented is one of the key technological challenges of the FCC-hh [Tom+17].

Indeed, the high collision energy leads further to a comparable extension of the possible discovery reach, even though there is no clear upper limit of how high the energy should be for new physics [Ben+19b]. Nevertheless, there is evidence that the strived 100 TeV is necessary and sufficient to accomplish significant measurements leading to unequivocal yes or no answers of some of the most critical questions in fundamental physics, e.g., how does the Higgs boson couple to itself [Man+19]. The answer to this question is preserved for the FCC-hh and cannot be answered by the FCC-ee or any LHC version. Besides, the FCC-hh would play a crucial role in the ongoing search for dark matter. It will be uniquely capable of producing weakly-interacting particles with masses up to a few TeV and heavier, more strongly-interacting dark sector states.

1.5 Beam Screen Requirements

The heart of any accelerator is the part which is the closest to the particle beam; the vacuum¹ chamber. To preserve a beam of particles circulating, it is essential to ensure they do not interfere with residual gas molecules on their path through the accelerator. Hence, maintaining the lowest pressure possible is a critical element for the design of an accelerator.

The vacuum chamber consists conventionally of a metallic pipe -sometimes at cryogenic temperatures- usually coated with a low resistivity material referred to as the beam screen (BS), where the charged particles perform the periodic motion around the circumference of the ring. Besides maintaining the low pressure, the BS must fulfil additional requirements related to thermal, mechanical and electromagnetic issues, which are summarised in Fig.1.7. Among others, it also has to minimise heat load arriving at the magnet cold bore, and in the event of a magnet quench, it has to withstand Lorentz's forces without permanent deformation of the BS. Important for

¹A vacuum, per definition, is a space devoid of any matter. Even though the perfect vacuum is not realisable by dint of any vacuum system.

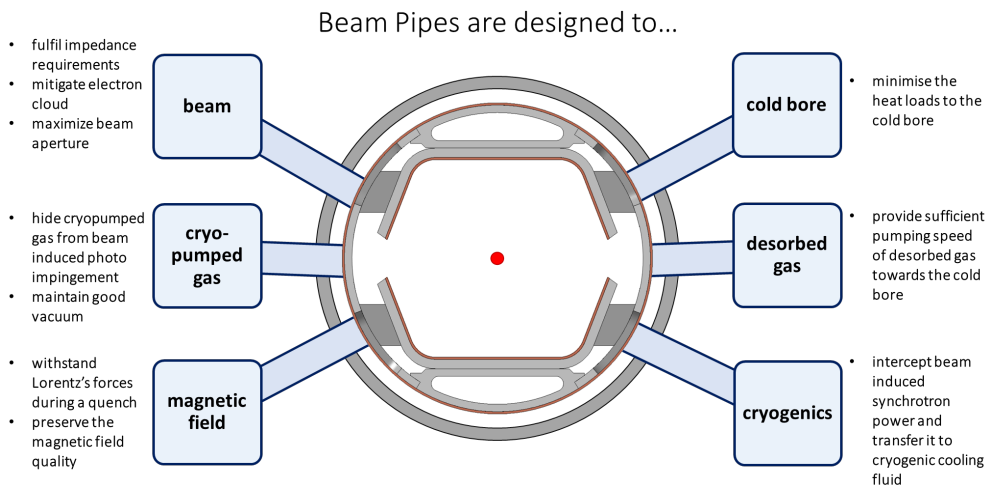


Figure 1.7: A general functional design map for a beam screen, including the FCC-hh design. The information to create the map is taken from [Bag+12] and the BS design is adapted from [Bel20].

the work presented in this thesis is that the design of the BS has to minimise the beam impedance, a concept that we are describing in the next paragraphs.

Each particle is surrounded by its own electromagnetic field. By moving through a structure such as a beam screen or another accelerator component, the electromagnetic fields are reflected on the structure and act back on the particles, perturbing its motion as depicted in Fig.1.8. These electromagnetic fields are known as *wakefields*. Under unfavourable conditions, the resulting perturbation on the beam further enhances the wakefield. The beam surroundings interaction then leads to instability and a subsequent beam loss.

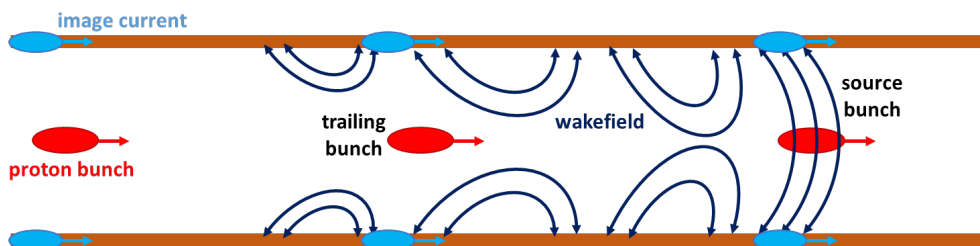


Figure 1.8: Longitudinal cut through an accelerator beam screen. The leading bunch is usually referred to as source charge, and the following bunch is referred to as trailing charge. The arrows indicate the electromagnetic field produced by the source charge and wakefield left behind, influencing the trailing charge. Wakefields are generated as the image current is running through the resistive conductor beam screen wall.

The two main types of wakefields are *geometrical wakefields* that depend on the smoothness of the beam screen and *resistive wakefields* depending on the conductivity of the BS. The latter being of most interest in this thesis. The positively charged protons induce *image currents* in the wall of the beam screen, as illustrated in Fig.1.8. The image currents follow the source through the accelerator in the walls of the beam screen and thus, give rise to ohmic dissipation. This *resistive wall impedance* (RW-impedance), which we will cover in more detail in Ch.5, is inverse proportional to the beam screen radius and directly proportional to the *surface impedance* of the beam screen material; thus, the RW-impedance is as well frequency dependent. This is the main reason why it is desirable to coat the inner part of the BS with highly conducting material such as copper; so as to provide a good flow of image currents and create less heat load, and energy losses [ZK98].

1.6 FCC-hh Beam Screen

All of the design features explained in Sec.1.5 have been incorporated into the baseline design of the FCC-hh beam screen presented in Fig.1.9. As can be seen, the FCC-hh BS consists of a double chamber design: The secondary chamber (ante-chamber) is composed of two lateral baffles, symmetrically assembled, 1 mm thick P506-stainless steel (SS) combined with an 80 μm copper (Cu) layer with sawtooth surface finishing for maximum photon absorption [Gon+19] acting as heat carrier for the induced synchrotron radiation (SR) [Bel+20]. In this way, it can shield the cold bore of the superconducting magnets operating at 1.9 K. The SR linear power generation in the bending magnets of the FCC-hh is resulting in 35.4 W/m, and is roughly 160 times higher than in the LHC due to the increased beam energy [Bel+20]. Given such high SR, and with that significantly larger required cooling power to refrigerate the whole BS, the most appropriate operating temperature range is $T_{\text{BS}} = 50 \pm 10 \text{ K}$ [Ben+19b].

The primary chamber (inner chamber) has a hexagonal shape with two slots, 7.5 mm high, symmetrically placed. SR will pass through one the slots and be absorbed in the ante-chamber. It is constructed by two 1 mm thick P506 SS sheets [Bel+20] colaminated with 0.3 mm of high-purity (at least RRR=100) OFE Cu to keep the resistive wall impedance as low as possible. Nevertheless, it has been observed that the RW-impedance represents a significant impedance source for the FCC-hh, making its contribution to the beam dynamics very critical for the machine design. Figure 1.10 summarises the impedance budget of the FCC-hh beam screen in Fig.1.9,

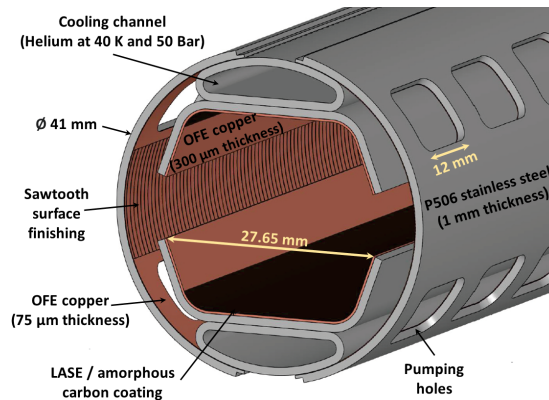


Figure 1.9: Baseline design of the FCC-hh beam screen. Figure adapted from [BMK19].

revealing that the RW impedance is predicted to be significant at both, injection and top energy (collision), due to the low revolution frequency, small horizontal and vertical dimensions, the resistivity at the operating temperature, and high magnetic fields (magneto-resistive effects). In addition, due to the high beam energy, the produced synchrotron photons lead to electron emission from the beam screen surface.

The electron multipacting phenomenon, which is the primary reason for an electron cloud (e-cloud) build-up, is crucially dependent on the surface morphology of the beam screen. As a consequence, the beam screen's internal surface at the positions closest to the beam is considered to be treated using Laser-Ablated Surface Engineering (LASE) [see Fig.1.9], modifying the morphology by creating a micrometres deep groove pattern on top and bottom copper-colaminated surfaces. This treatment, on the one hand, limits the secondary-electron yield (SEY) value below the necessary threshold to mitigate e-cloud build up [Han+21; Val+14; Val+17]. On the other hand, it has unfavourable consequences such as a rise in surface impedance and copper loose particulates. The second option to cope with e-cloud build-up is the use of thin amorphous carbon (aC) coating on top of the untreated Cu [Cal+09].

In summary, even though in the foreseen baseline design, the copper colaminated beam screen ensures that the beam impedance is within the impedance budget and low enough for beam stability, a higher stability margin by reducing the resistive wall impedance is highly desirable and advantageous from an operational point of view.

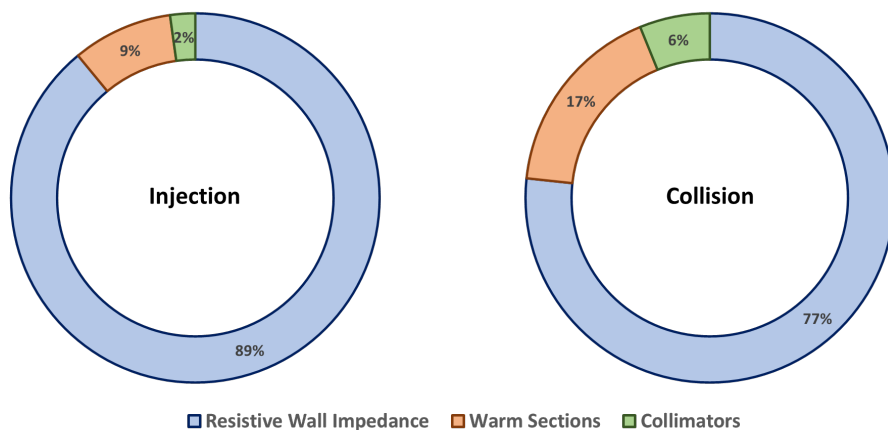


Figure 1.10: FCC-hh impedance budget based on data taken from [Ars19].

1.7 High-Temperature Superconductors as the Alternative

The reduction of the resistive wall impedance can be accomplished by either reducing the surface resistance of the material used as a beam screen or by increasing its radius. Though, increasing the radius of the beam screen is not an option due to the costs associated with increasing the aperture of the magnet. Therefore, the only possibility is to research materials that could substitute copper. An alternative is the use of

high-temperature superconductors (HTS). With the discovery of high-temperature superconductivity, a new class of superconducting material was introduced with a critical temperature higher than the boiling point of liquid nitrogen (77 K). Further, the first measurements in the microwave regime of polycrystalline and epitaxial thin HTS-films by Klein *et al.* [Kle+95] have shown that the surface impedances can be orders of magnitudes smaller than those of normal conductors such as copper. In addition, the substantial difference in the surface resistance dependency on frequency f -for metals $\sqrt{f}$ and for superconductors f^2 - make HTS materials particularly interesting for this project.

The field of study of HTS as a coating material for the FCC-hh has grown since the first idea by [Ros] and the first theoretical case studies in [Cal+17; Cal16] to validate the approach of using HTS within a beam screen and to identify the most advantageous material under in the FCC-hh operating conditions. Based on the requirements of induced currents by wakefields (high critical current density), external magnetic field (large upper critical field) and behaviour of surface impedance, two cuprate candidates raised the attention; $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) as well as $\text{Tl}_m\text{Ba}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+m+2}$ (TBCCO) [Cal+17]. Both materials present properties that make them attractive as coating materials for the beam screen. Even though thallium-based compounds are believed to be better suited for the FCC-hh project, there are issues with the production of long samples. On the contrary, rare-earth barium copper oxide (ReBCO) based long-length epitaxial coated conductors (CC) are already widely available and manufactured by several providers. Manufacturers produce coated conductors in km length, especially for building strong magnets.

Figure 1.11 shows the complex layered architecture of such ReBCO-CCs and their flat suitable geometrical shape. The main idea is to use the ReBCO-CCs in selected places in the BS in combination with the existing copper to reduce the resistive wall impedance. Hereby, the HTS-layer is facing the beam directly without being encased by a copper stabiliser or silver protective overlayer. To protect the HTS and to counteract at the same time the phenomena of the e-cloud, additional nanometres thin amorphous carbon coating of the BS surface is expected to reduce the creation

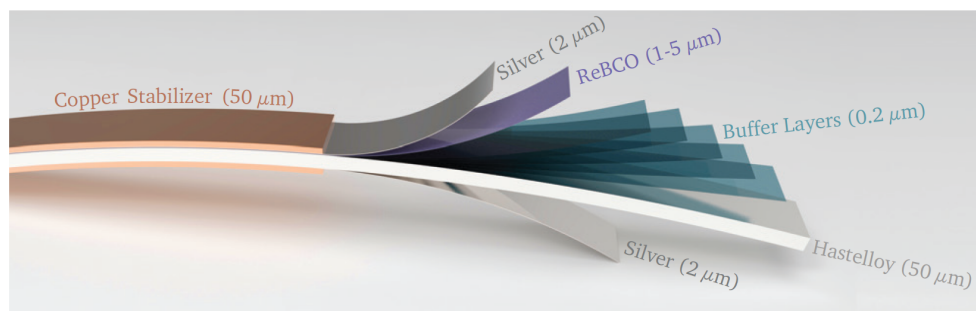


Figure 1.11: Cross sectional view of deposited ReBCO on a flexible metal tape with buffering metal oxides, known as second generation coated conductor. In fact, the copper and the silver layers fully surround the layered structure. Figure taken from [Van16].

of electron clouds without drastically affecting the surface impedance. Theoretical estimations of the radio-frequency surface resistance of HTS under the influence of external magnetic fields were performed, and numerical simulations of resistive wall impedances for the FCC-hh beam screen design (at that time) indicated the potential of impedance reduction having a coating of alternating HTS and Cu stripes along the beam screen axis [KNB18]. An example configuration is sketched in Fig 1.12.

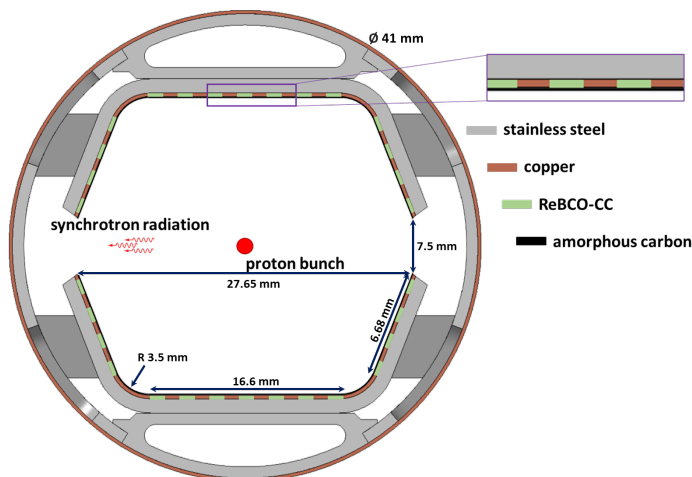


Figure 1.12: Example for a hybrid beam screen with alternating ReBCO (green) and Cu (orange) stripes covered with aC (black) for the baseline design beam screen. Figure adapted from [Bel20].

1.8 Microwaves

The precise knowledge of the surface impedance of ReBCO-CCs at FCC-hh requirements is fundamental in order to make a sound decision about its feasibility as a beam screen material. The studies mentioned in Sec.1.7 are based on theoretical values estimated over measured parameters of single crystal HTS material. Thus, a primary concern of the theoretical surface impedance values and resulting resistive wall impedances is the validity of those approaches compared to the usage of ReBCO-CCs. Small single crystal epitaxial grown HTS might perform differently than metres long coated conductors grown on flexible metallic substrates. Hence, for a meaningful statement, experimental microwave material characterisation techniques must be considered which prove that the microwave surface impedance of ReBCO-CCs indeed is much better than copper.

For the RF characterisation of the complex microwave surface impedance $Z_S = R_S + iX_S$, which can be understood as the frequency response for different materials, it is important to make the sample part of the resonant structure. The sample could be preferably placed into the cavities' inner surface by using some form of cavity end-wall replacement method [Ono+98]. The resonator is excited in a specific mode with a detectable resonance frequency f_0 and quality factor Q (Q-factor) which should allow

a straightforward calculation of the surface impedance based on average losses and differential measurements with calibrated samples. The two measurable quantities; surface resistance R_s and surface reactance X_s , result in different constraints on the possible measurement technique: R_s of a test surface is calculated from the changes in Q-factor that it produces in a microwave cavity and accounts for the dissipation inside the material. X_s of a test surface is determined from the changes in resonance frequency when that surface is used to replace another whose X_s is known and accounts for the energy stored within the material.

A measurement technique for microwave testing of materials should, by definition, have minimal uncertainty, good reproducibility and sensitivity, and be simple to use. The measurement technique should not change the properties of the materials being tested and be non-destructive. As a result, the observed characteristics should allow for highly accurate and repeatable calculations of unique microwave parameters. Based on this and the constraints discussed further in the next section, we decided to focus for the measurements on two RF techniques; the closed Hakki-Coleman dielectric resonator (CHCDR) and the parallel plate resonator (PPR), both illustrated in Figs.1.13(a) and 1.13(b), respectively.

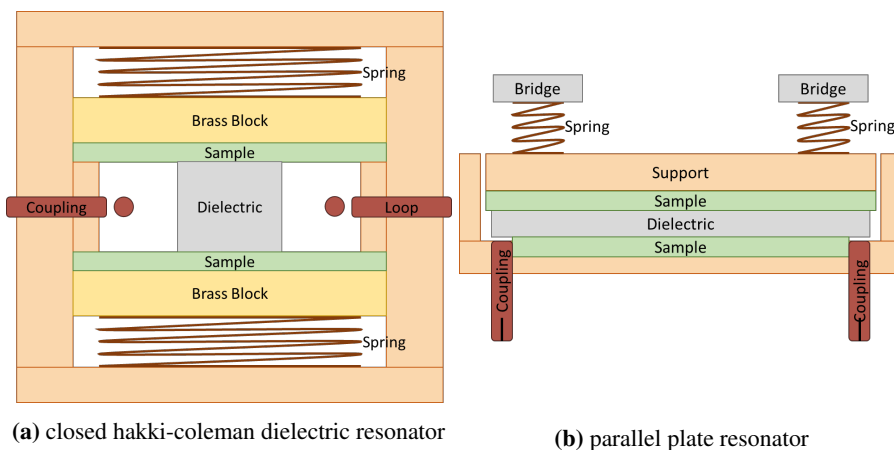


Figure 1.13: Sketch of two dielectric resonators.

1.9 Statement of the Problem

Are ReBCO coated conductors capable of outperforming copper when it comes to the foreseen requirements of the FCC-hh?

The operating conditions of the FCC-hh beam screen are extremely demanding, and with that, ReBCO-CCs would face exceptionally difficult operating circumstances, summarised in Fig.1.14. The beam screen will work at a temperature of 40 K to 60 K with 50 K as the reference temperature. The coated conductor must remain superconducting within the 66 km of 16 T dipole magnets. The average beam current

in the FCC-hh is about 500 mA and will be distributed in 10400 proton bunches with a root-mean-square bunch length of 8 cm. This results in a peak current of 24 A per bunch and peak radio-frequency azimuthal magnetic field strength of 230 A/m at the closest direct positions to the beam, which is explained detail in Sec.10.2. Assuming that the ReBCO film is about $1\text{ }\mu\text{m}$ thick; the critical current density will have to be higher than 23 kA/cm^2 at 50 K and 16 T.

Radio-frequency currents in a frequency range between 2 kHz to 3 GHz on high-temperature superconductors can display intrinsic non-linear behaviour as a function of surface current intensity which is a phenomenon that has been extensively addressed in the literature [CV21; Hei99; Pow+99]. Extrinsic effects, all of which are connected to the quality of the ReBCO film, can be considered a source of non-linearities. In addition, in the presence of a strong magnetic field, a non-linear behaviour of the surface impedance due to individual and collective vortex motion can be expected at the FCC-hh.

The two counter-rotating proton beams will achieve an energy of 50 TeV, which will result in a tremendous increase of the emitted synchrotron radiation, attaining linear power density levels of 35.4 W/m [Bel+20]. Not much is known about the behaviour of HTS under the influence of synchrotron radiation, though certainly, this power can either influence the HTS through heating or Cooper pair (CP) breaking, which both lead to a suppressing of superconductivity.

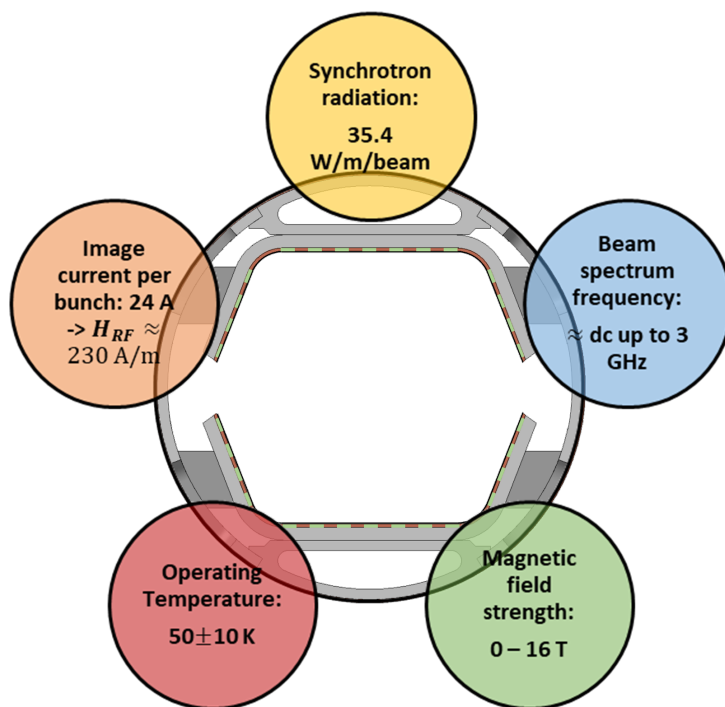


Figure 1.14: Summary of FCC-hh beam screen requirements relevant for the beam coupling impedance.

1.10 Objectives and Outline of the Thesis

The behaviour of ReBCO-CCs as a beam screen material is unknown; therefore, there is a need for obtaining information relevant to this application. A specific special technology project on this topic with the goal of constructing a proof-of-concept model device was initiated by CERN in 2017 with the participation of the following in Barcelona located institutions: ALBA, ICMAB, IFAE and UPC. The work has been divided depending on the expertise of the different institutes, as summarised in Fig.1.15. This collaboration will not only generate knowledge on the surface impedance of ReBCO-CCs, but will also find an adequate ensemble of the coated conductors to the beam screen in a hybrid version, calculate the dipole magnetic field disturbances and beam coupling impedances, generate general knowledge about the microstructure and properties of ReBCO, and experimentally determine the best way to mechanically assemble the coated conductors in the beam screen.

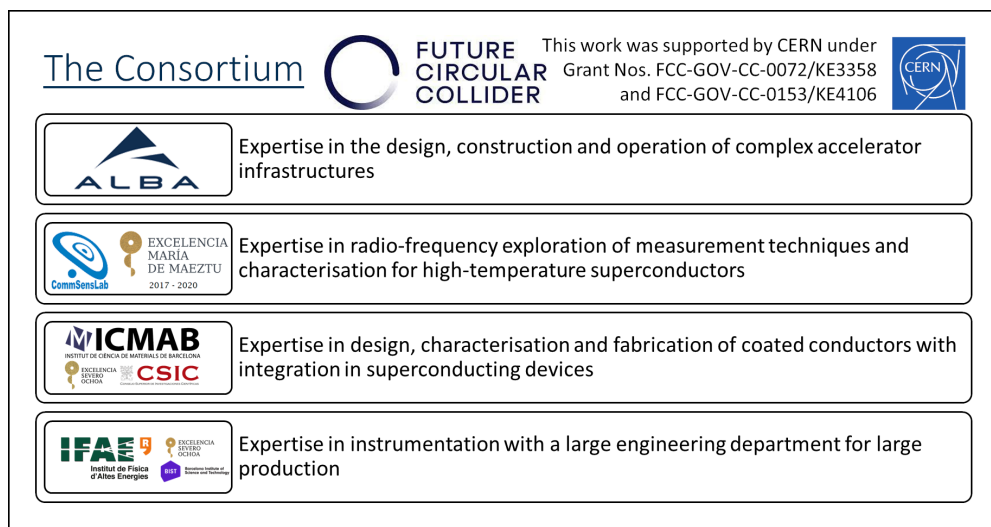


Figure 1.15: This work is part of a consortium project association between the ALBA Synchrotron Light Source (ALBA), Universitat Politècnica de Catalunya (UPC) - CommSensLab, Institut de Ciència de Materials de Barcelona (ICMAB-CSIC), Institut de Física d'Altes Energies (IFAE) and Conseil européen pour la recherche nucléaire (CERN), within the Future Circular Collider (FCC) framework.

The work presented in this thesis is part of the largest work produced by the consortium project association. The central part of my contribution to the consortium concerns the planning and implementation of the impedance study of ReBCO coated conductors within the research of the FCC-hh study, as well as its evaluation. This thesis consists of the following main parts foreseen to achieve this goal:

-Part I-

In Part I, which consists of Chapter 1, the context of the study has been introduced. The study objectives and research questions have been established, as well as the strategy to solve them is outlined.

-Part II-

In Part II, the existing literature will be reviewed to summarise the key references of the different fields of studies necessary for the development approaches and strategies within the context of this thesis.

Chapter 2 is dedicated to the fundamental concepts of (high-temperature) superconductivity and summarises the state-of-the-art of second-generation ReBCO coated conductors provided by different manufacturers for this work.

In Chapter 3, the principles of electromagnetic fields are summarised and the nomenclature is specified. In addition, the concept of surface impedance is described with the main focus on the differences between metals and superconductors.

Chapter 4 is devoted to familiarising the reader with the concepts of moving particles in beam screens. The main focus is on synchrotron radiation created by electrons passing through a bending magnet.

Chapter 5 is dedicated to becoming acquainted with the concepts of beam impedances and introduces the technical requirements for a hybrid FCC-hh beam screen in more detail.

-Part III-

Part III will discuss the design and construction of three experimental set-ups. Extensive characterisations of ReBCO-CCs as potential coatings for the FCC-hh beam screen are required under various external factors such as temperature, magnetic fields, and synchrotron radiation. Different set-ups were created to allow partial characterisation because it was impossible to include all properties in a single experimental set-up at this point of the project.

In Chapter 6, we discuss the basic parameters measurable using resonators and how to extract them accurately using vector network analysers. Further, we present how these concepts are implemented into an open source python code, available under a freeware license, under the acronym ARPE.

Chapter 7 begins by laying out the theoretical dimensions of the design of possible non-destructive microwave measurements of radio-frequency losses that can be linked to surface impedance to examine the ReBCO-CCs taking into account the following constraints:

- Prior to testing, the samples provided by the manufacturers should undergo minimum manipulation.
- The substrates of the ReBCO-CCs cannot be exposed to the RF-fields.
- Measurements of long samples with the restriction that ReBCO coated conductors have a width of 12 mm.
- Measurements of the ReBCO-CCs performance should be possible in different

environments: temperature, magnetic field, irradiation from synchrotron radiation and as close as possible to the frequency range of the FCC-hh (2 kHz to 3 GHz) .

The shielded dielectric resonator and parallel plate resonator techniques are thoroughly explained and numerical and analytical resonator parameter calculations are presented.

In Chapter 8, the design, installation, and development of the three different radio-frequency measurement methodologies and systems for investigating surface impedance as close as possible to FCC-hh conditions are presented:

- RF-measuring equipment was installed at ICMAB's current 9 T bore magnet with 2.6 cm aperture and variable temperature, which operates at 8 GHz. We created a CHCDR that solves the problem of the narrow bore opening while still delivering the necessary data with high sensitivity and signal-to-noise ratio. In addition, an automatised data acquisition tool (based on python) called DRΩMS has been implemented.
- An RF-measuring cryogenic temperature test system at the UPC working at different frequency ranges. As a result, a design study involving the construction of a CHCDR and PPR is being proposed. This latter type of resonator has the advantage of being able to attain much lower frequencies than the CHCDR. The prototype is a first prototype iteration of a future resonator to be implemented in a future 16 T magnet with a 5 cm bore at ICMAB. In addition, a goal is to see the feasibility of using both characterisation techniques for purposes other than ReBCO-materials.
- An RF-measuring system at variable temperature for larger samples (few cm) to be installed at the ALBA storage ring, where the coated-conductor tapes are irradiated in-situ with synchrotron light. The complete experimental set-up has been planned, constructed and installed at the ALBA X-ray pinhole. The study starts with a 5 cm long parallel plate resonator design using sapphire which allows the synchrotron radiation to enter the resonating structure at around 1 GHz.

-Part IV-

Part IV consists of the surface impedance evaluation and feasibility study. In order to evaluate the possibility to use ReBCO coated conductors as a low surface impedance material in the Future Circular Collider hadron-hadron beam screen, we pursued the following strategy:

In Chapter 9, the superconducting and properties of ReBCO coated conductors are investigated as a function of temperature and under the influence of up to 9 T perpendicularly applied DC magnetic fields to ascertain if:

1. ReBCO-CCs can provide a lower surface impedance than copper already at 8 GHz up to 9 T between 40 K to 60 K.
2. ReBCO-CCs follow the typical two fluid model theory.
3. ReBCO-CC's impedance is influenced strongly by an amorphous carbon coating.

Chapter 10 explores the behaviour of ReBCO-CCs in the presence of a DC magnetic field superimposed with a radio-frequency magnetic field strength of varying amplitude similar and higher to that of the FCC-hh to verify if:

4. ReBCO-CCs can provide a lower surface impedance than copper at higher RF power at 1 GHz up to 16 T at 50 K.
5. non-linear effects will be an issue in the beam screen.
6. ReBCO-CCs can be demagnetised with radio-frequency electromagnetic fields.
7. the timing of circulating proton bunches influences the surface resistance.

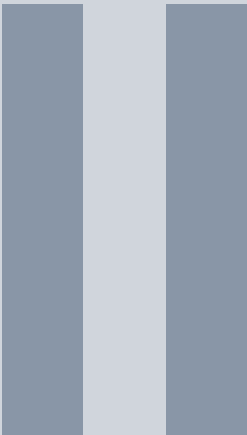
Chapter 11 deals with one of the key hurdles for the FCC-hh or any future circular collider; synchrotron radiation. This chapter concerns the understudied subject by examining the behaviour of ReBCO-CCs when exposed to ex-situ and in-situ photons from the ALBA Synchrotron Light Source to answer the following questions:

8. Can ReBCO-CCs be damaged by exposure to high-energy synchrotron light?
9. Does the ReBCO-CC's performance reduces during or after SR irradiation?
10. What are the possible mechanisms within the light-superconductor interaction?

Chapter 12 provides an understanding of the impact of the experimental determined surface impedance measurements for the resistive wall impedance by a case study for a round beam pipe.

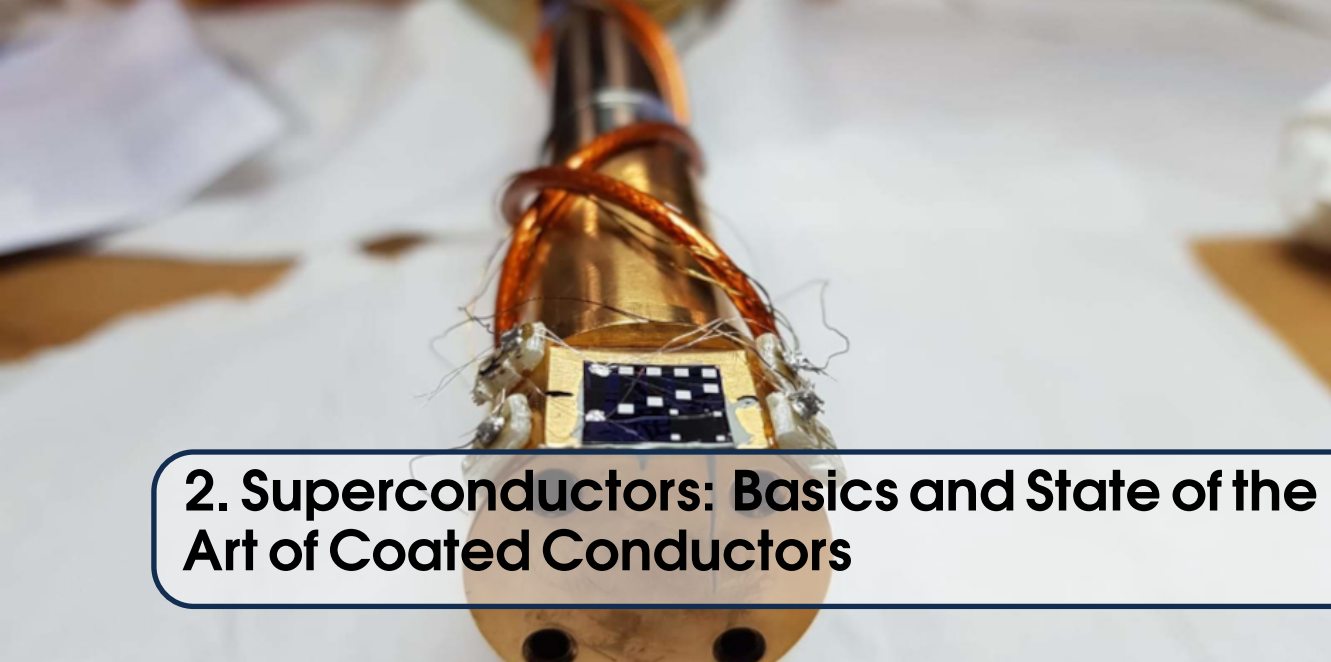
-Part V-

All concepts and analyses come together in the final Part V where we conclude if ReBCO-CC can provide the expected beam impedance minimisation under the severe conditions in the FCC-hh beam screen.



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2. Superconductors: Basics and State of the Art of Coated Conductors

Mercury had passed into a new state, which on account of its extraordinary electrical properties may be called the superconducting state

-Heike Kammerlingh Onnes-

This chapter introduces the fundamental concepts of superconductivity to provide a foundation for the remaining chapter on high-temperature superconducting coated conductors and their expected behaviour inside the FCC-hh beam screen. The discussion focuses further on second-generation ReBCO coated conductors provided by different companies. A comparison among them is given.

2.1 The Phenomenon Superconductivity

2.1.1 The Discovery

The degree to which a material resists an electrical current passing through it, is measured by its electrical resistance. Discovered by Ohm in 1827 [Ohm27], electrical resistance has some conceptual similarities to mechanical friction. According to Drude's hypothesis [Dru00], released at the beginning of the 20th century, in the case of metals, conduction electrons scatter randomly in the background of positively charged ions rigidly fixed to their ordered lattice position. In the presence of an electric potential, the 'sea' of electrons will still get scattered by the ions but promptly drift in a particular direction opposite the applied potential. As a result of the electron-phonon

interaction, a net current will flow through the metal with a particular resistance that the electrons face in their free mobility. When electrons are scattered by ions, they lose energy, which is absorbed by the lattice and dissipated as heat.

Over the years, the question arose what might happen to the electron-phonon interaction at low temperatures close to the absolute zero point. The predictions of the electrical resistance ranged from a linear decrease towards zero since at absolute zero, the phonon scattering should die down (James Dewar), or a decrease to a minimum and rise again at even lower temperatures because the electron motion will freeze as well (William Thomson Kelvin), or levelling out at some residual resistance value (Augustus Matthiessen) [RM15; Sha15]. According to Matthiessen, resistance is composed of two principles. One of them is the temperature dependent electron-phonon interaction, as described by Drude. The other is temperature independent and caused by electron scattering on impurities and imperfections in the material. The theories predicted very different outcomes close to zero; Due to this, it was even more surprising when Kamerlingh-Onnes, who achieved to liquefy helium in 1908, discovered that below the temperature of 4.2 K -the boiling point of helium- the electrical resistance of pure mercury dropped abruptly to zero as depicted in Fig.2.1.

Kamerlingh-Onnes continued inter alia studying the mechanism of electrical conductivity in other pure metals and soon was able to include lead and tin to the list of what he referred to as this enigmatic phenomenon of *superconductivity* [Kam11]. The temperature at which the material changes from normal conducting into the superconducting state is defined as the *transition temperature* or *critical temperature* T_C . It was the first discovered characteristic parameter of a superconductor and is an intrinsic material property which depends on the purity, chemical composition and crystal structure of the material. Scientists discovered that many more metallic elements exhibit

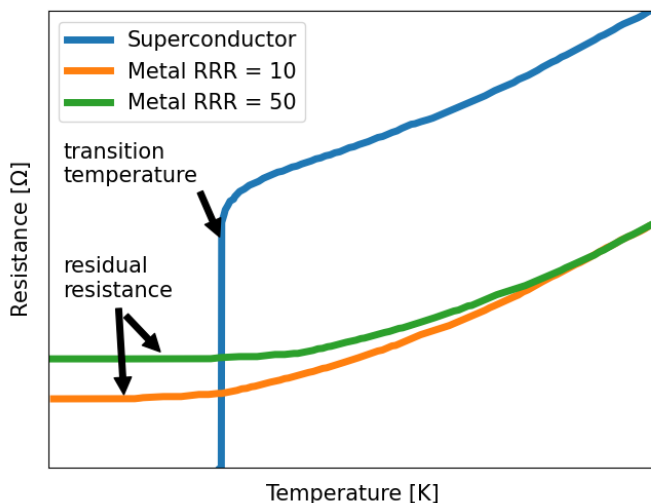


Figure 2.1: Sketch of the temperature dependence behaviour difference between superconductors and metals.

superconductivity at very low temperatures in the years to follow. Remarkably, one striking effect is that some of the elements, actually the best-known conductors such as copper, silver and gold, show a finite residual resistance [see Fig.2.1], without entering into a superconducting state, although they were measured at temperatures less than one Kelvin [Mat79], which proved that Matthiessen was not entirely wrong with his prediction.

2.1.2 Conventional Superconductivity

The vanishing of the electrical resistance below T_C is not the only unusual property of a superconductor (SC). The second defining characteristic is named after its discoverers, Meißner and Ochsenfeld, which extensively studied the magnetic properties of superconductors. In 1933 they discovered that a SC is a perfect diamagnet below a specific *critical magnetic field* B_C where applied magnetic fields beyond this value destroy superconductivity. This means that when a magnetic field is applied to a material in the superconducting state, the flux lines will be expelled from the interior of the SC keeping the magnetic field inside the material zero [MO33]. The distinctive property of superconducting material is that the exclusion of magnetic fields in the interior happens regardless of whether the SC is kept first in a magnetic field and then cooled down below T_C or if it is already in the superconducting state when the magnetic field is applied. As illustrated in Fig.2.2, the first scenario is referred to as a *field-cooled* (FC) experiment, while the latter one is called a *zero-field-cooled* (ZFC) experiment.

The aforementioned expulsion of magnetic fields follows by induced screening

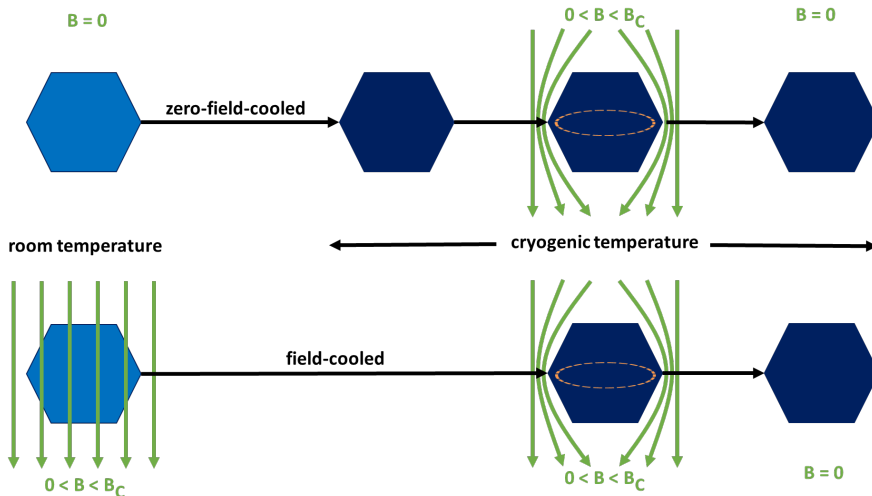


Figure 2.2: Depiction of a conventional superconductor (above T_C light blue and below T_C dark blue) in an applied magnetic field B (green lines) in the field-cooled (FC) and zero-field-cooled (ZFC) cases. In both cases, the magnetic flux is expelled from the interior of the SC by supercurrents (orange dashed line) flowing within a thin layer known as Meißner and Ochsenfeld effect.

currents (also called persistent or shielding currents) in a thin layer on the superconductor's surface that precisely cancels the external magnetic field in the interior of the superconducting bulk by opposing magnetic fields. The magnetic self-field produced by a current has the same impact as an external applied magnetic field. Accordingly, if the self-field produced by the transport current exceeds B_C , the superconducting state will reversibly be destroyed, called the Silsbee effect [Sil16]. Thus, if the applied magnetic field is increased, the screening current will also increase. In consequence, if a specific external magnetic field causes a superconducting breakdown, then there is a corresponding limit for a screening current called the *critical current density* J_C . When the vector sum of the current densities, e.g., at the surface due to an applied transport current in the SC and due to the screening current exceeds J_C , or, equivalently, when the magnitude of the vector sum of the magnetic fields that are present at the surface of the superconductor exceeds B_C , a transition to the normal conducting state occurs [Uni22].

The three interdependent critical parameters T_C , B_C , and J_C , define a conventional superconductor. In this manner, superconductivity can only occur below the so-called critical surface phase-space, which is unique for each material. The critical parameters B_C and J_C are maximal at temperature $T = 0$, and continuously decrease with the increase of temperature to zero at T_C . General expressions are given as [RM15]:

$$B_C(T) = B_C(0) \left[1 - \left(\frac{T}{T_C} \right)^2 \right] \quad J_C(T) = J_C(0) \left[1 - \left(\frac{T}{T_C} \right)^1 \right] \quad (2.1)$$

2.1.3 Zero Resistance?

The question arises, is the resistance really zero? Until today the answer is yes, as long as the applied current is a direct current (DC). Gorter and Casimir developed a hypothesis called the two-fluid model (2F-model) about the coexistence of two kinds of electrons in the superconducting state. Below T_C , a part of the total charge carriers are normal electrons with density n_n that would take into account the presence of a normal current. The other part of charge carriers are superelectrons with the density n_s that would take into account the lossless supercurrent [GC34]. This assumption implies that the two kinds of charge carriers act independently and that the relative electron density in the two fluids depends strongly on the temperature in the form:

$$n_s(T) \approx n_t \left[1 - \left(\frac{T}{T_C} \right)^4 \right] \quad \text{and} \quad n_n(T) \approx n_t \left[\left(\frac{T}{T_C} \right)^4 \right], \quad (2.2)$$

where the total carrier density is defined as $n_t = n_n + n_s$. At absolute zero temperature, all conduction electrons behave like superelectrons. However, if the temperature is raised, a fraction of normal electrons exist, whose proportion will increase until the transition temperature, at which finally all superelectrons disappear entirely.

In the particular case of a constant direct current, all the charge is carried only by the superelectrons. In fact, experiments proved that a persistent current has run for

several years in a closed superconducting ring without any measurable decay, proving that the superelectrons carry all the charge [Sha15].

Differently, in an alternating field, due to the fact that there are electrons in the normal conducting state, they are excited by the radio-frequency fields [Zho99]. Hence, a current of normal conducting electrons will flow resulting in a resistance, causing a power loss even in a superconductor. Nevertheless, the radio-frequency losses are moderate in a SC compared to a normal conductor (NC) at low frequencies. Because of the superconducting state's low Ohmic losses, microwave applications at low temperatures are exceptionally efficient. For example, resonating structures as niobium cavities in accelerators have been known to achieve high Q-factor values between $Q = 10^{10} - 10^{11}$ and are used in the LHC [Bou+99].

2.1.4 BCS-Theory

In 1957, Bardeen, Cooper and Schrieffer (BCS) proposed the quantum mechanical theory that explained the microscopic origins of superconductivity usually referred to as the *BCS-theory*. They recognised that free conduction electrons start to couple into bosonic pairs at the transition to the superconducting state, named Cooper pairs (CPs) [BCS57].

A Cooper pair is formed by two electrons -which are fermions [see Fig.1.2]- with equal but opposite spin and momenta ($\vec{k}_{F1} \uparrow = -\vec{k}_{F2} \downarrow$) as not to violate the Pauli exclusion principle², uniting to a zero-spin particle (boson) overcoming the electrostatic repulsion. The net attractive interaction is mediated by lattice vibrations travelling through the lattice over virtual phonons [BCS57]. As in the principle of exchange interactions shown in the Feynman diagram in Fig.2.3, these mediators are called virtual because they appear only during the very short correlation time between both electrons. They do not exist as a lasting vibration stimulation of the ions of the crystal lattice.

As a collection of non-interacting indistinguishable particles, the statistical coupling of electrons always transforms a part of their kinetic energy into binding energy. They are then together in a lower energy state and can occupy together one single quantum state below the Fermi level forming a single collective quantum wave of

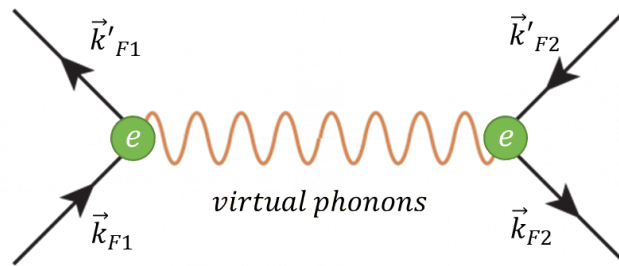


Figure 2.3: Feynman diagram of a Cooper pair.

²According to the Pauli exclusion principle, two or more identical particles with half-integer spin, i.e., fermions cannot share the same quantum state in a quantum system simultaneously.

defined phase, similar to a Bose-Einstein condensate [BK13]. This ground state being separated from excited states is also referred to as the energy gap ΔU_{CP} , usually some meV [Kit04], surrounding the Fermi edge. It can be seen as well as the minimum energy needed to break a CP and excite an electron again above the Fermi level. The main statement is that a single coherent motion of superelectrons can flow through the material without being subject to any resistance.

2.1.5 High-Temperature Superconductors

For a long time, it was believed that superconductivity could not occur above $T = 30$ K since the BCS-theory predicted this temperature to be the theoretical maximum of T_C [Sha15]. Above this temperature, the Coulomb repulsion gets stronger than the binding force through the phonon interaction. This theoretical limit has been experimentally confirmed as in most of the elements in the periodic table superconductivity occurs below 10 K with the highest critical temperature of all pure metals for niobium, $T_C = 9.2$ K [BK13]. It still serves as a reference in low-temperature applications as magnets. Above this critical temperature, only inter-metallic compounds and alloys have T_C up to 23 K, still within the predicted temperature range of the BCS-theory.

The first material that did not obey the BCS-theory was found by Bednorz and Müller when they studied the conductivity of $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$ with a $T_C = 35$ K [BM86], for which they promptly were awarded the Nobel Prize. This result divided the landscape of materials into *low-temperature superconductor* (LTS) and *high-temperature superconductor* (HTS). It triggered a worldwide revolutionary interest in the development of new superconductors pushing for room temperature applications [Sha15]. The rapid speed of development of superconducting materials over the past years since their discovery is summarised in Fig.2.4.

Worth mentioning is the work of Wu and his research group that reached in the same year as Bednorz and Müller a $T_C = 93$ K with $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_x$ well above the boiling point of liquid nitrogen (77 K) [Wu+87]. A breakthrough, that suddenly made applications of superconductivity much more realistic. Today, decades later, thousands of scientists have published an impressively large number of research papers on the subject, exploring new compounds to push T_C higher and trying to understand high-temperature superconductivity. Besides, some elements are only superconducting under high-pressure [BK13]. A superconducting transition temperature as high as 138 K was observed for $\text{Hg}_{1-x}\text{Tl}_x\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{8+\delta}$ in 1994, [Dai+95]. Further, $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{8+\delta}$ is still holding the official record for cuprates to this day with $T_c = 164$ K under pressure [Sch+93]. Noteworthy is also hydrogen sulfide H_2S exhibiting conventional superconductivity (obeys BCS-theory [see Sec.2.1.4]) and reaching the critical temperature of 203 K at extremely high pressure in 2005 [Dro+15].

Despite all of the discoveries, high-temperature superconductivity remains a fundamental difficulty in condensed matter physics since no consistent and widely accepted microscopic theory exists. It seems though, that the superconductivity is as well connected to Cooper pairing, but the mechanism that keeps them together seems to be of a different nature than that described in the BCS-theory [Ray15].

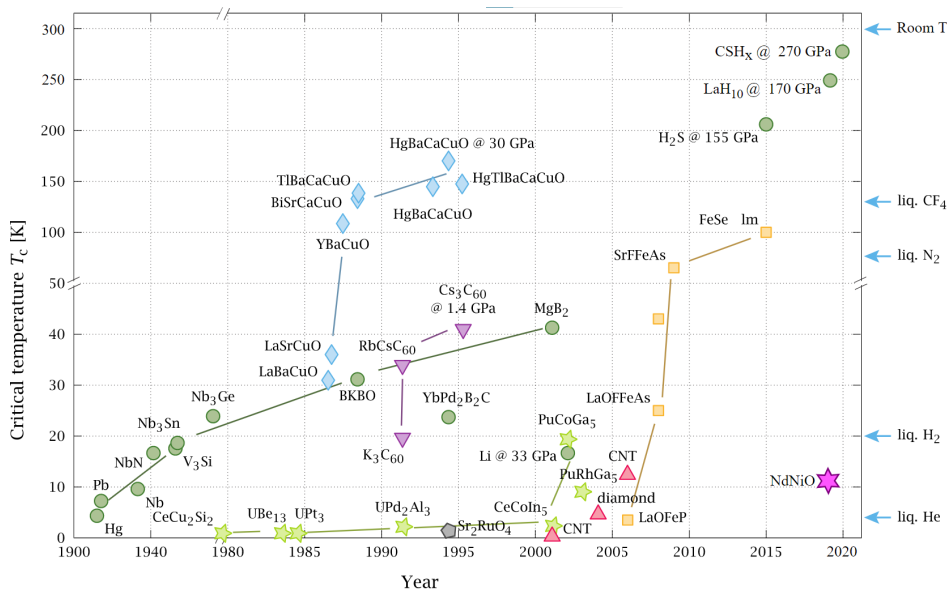


Figure 2.4: The history of some superconductors since their discovery. Note the elemental metals, alloy materials and compounds that obey the BCS theory (green circles) and the cuprates (blue diamonds), iron-pnictogen-based SCs (orange squares), buckminsterfullerene-based SCs (purple inverted triangle), carbon-allotrope (red triangle), strontium-ruthenate (grey pentagon), and nickel-based (pink star). Original figure from [Ray15]. Figure taken from [Wik21b] including community adaptations.

2.2 Superconductors in Magnetic Fields

2.2.1 Type-I and Type-II Superconductors

For a long time, it was assumed that superconductivity was all of the same type. Although a large variety of materials showed the phenomenon of superconductivity, there had been experimental observations of anomalies in the magnetic behaviour of impure metals and alloys [RM15; SR35].

Abrikosov could explain these anomalies with the aid of the Ginzburg-Landau (GL) theory, which is a macroscopic theory developed to explain superconductivity using the concept of free energies [GL50], timely before the BCS theory. The GL-theory specifies two characteristic lengths named *coherence length* ξ_{GL} and *penetration depth* λ_{GL} . The former length determines the extension where the variation of density of electrons in the superconducting state can be excited and recovered again without breaking superconductivity. The latter parameter controls how far an external magnetic field is able to enter into the superconductor or how far into the superconductor the screening currents occur, as mentioned in Sec.2.1.2. The ratio between these two lengths is the so-called *Ginzburg-Landau parameter* κ_{GL} :

$$\kappa_{\text{GL}} = \frac{\lambda_{\text{GL}}}{\xi_{\text{GL}}} \quad (2.3)$$

and turned out to play an important role to explain aforementioned anomalies. Abrikosov

considered for the first time that there are two types of superconductors depending on the value of the Ginzburg-Landau parameter [Abr57]. *Type-I* superconductors are characterised by $\kappa_{GL} < 1/\sqrt{2}$. This group, typically contains pure elements, such as lead and mercury. *Type-II* superconductors are characterised by $\kappa_{GL} > 1/\sqrt{2}$ and contains mostly alloys, compounds and high-temperature superconductors.

The two groups of SCs differ mainly in their behaviour in an applied magnetic field. A type-I superconductor always obeys the Meissner-Ochsenfeld effect until superconductivity breaks down. A type-II superconductor, however, experiences an intermediate step before the superconductivity breakdown. Below its so-called *first critical magnetic field* B_{C1} , a type-II SC behaves identically to a type-I SC. Above B_{C1} it is energetically more favourable for the SC to split the material into a large amount of normal conducting and superconducting regions whose boundaries are parallel to the applied magnetic field [RM15]. The SC is partially penetrated by the magnetic field through the normal conducting regions referred to as *vortices*. They can be seen as normal conducting cylinders embedded in the superconducting material with a radius of ξ_{GL} as depicted in Fig.2.5. The magnetic flux contained in the normal core has the same direction as the applied magnetic field and is generated by a swirling electrically shielding supercurrent of radius of λ_{GL} of rotation opposite to the surface screening currents as described in the London limit [RM15]. The magnetic flux entering into the SC is quantised in discrete units. Each vortex contains a single flux quantum or *fluxon* $\Phi_0 = h/2e = 2.067833 \cdot 10^{-15} \text{ Tm}^2$ [BK13]. As normal conducting and superconducting state coexist the superconductor is referred to be in the *mixed state*.

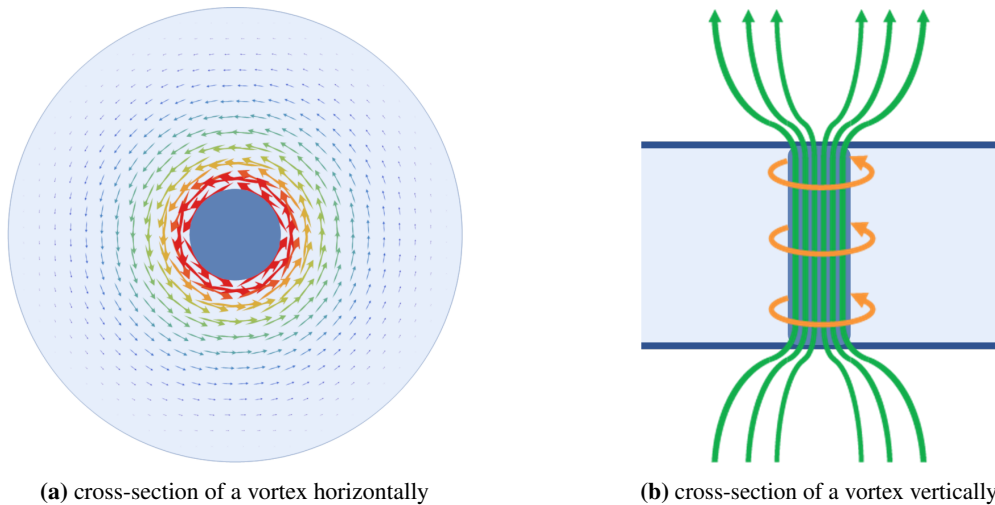


Figure 2.5: Sketch of an individual vortex in a type-II superconductor. (a) Current density of the cross-section of the superconductor. The arrows indicate the current flow direction and decay in magnitude the further away from the vortex core. At the border between the normal and superconducting state, the magnitude of the current density is J_C . (b) Flux density bending into a single vortex parallel to the applied magnetic field (green). The shielding currents are indicated with orange arrows.

2.2.2 The Mixed State

The penetration of vortices into the superconducting material allows type-II SCs to maintain the superconducting state up to much higher applied magnetic fields compared to type-I SCs. This magnetic behaviour can be illustrated briefly by the following example of a long rectangular superconducting tape with a width much larger than its thickness. The applied magnetic field $B = \mu_0 H$ -where μ_0 refers to the permeability of vacuum and H refers to the magnetic field strength- is perpendicular to its surface and slightly larger than $B_{C1} = \mu_0 H_{C1}$. By continuity of the surface field, the flux line density at the tape surface must be equal to the applied magnetic field. The first vortices form at the edges of the tape as sketched in Fig.2.6. By gradually increasing the applied magnetic field, new vortices start entering into the superconductor from each edge forcing the existing vortices to migrate further inwards the tape. The circulating current around each individual vortex interacts with the magnetic field produced by its neighbouring vortices [RM15]. By inspecting neighbouring local current loops in Fig.2.6, we can see that the currents do not cancel out [RM15]. Accordingly, vortices repel each other when they approach each other. The penetration of flux lines into the material creates a flux gradient [RM15], and therefore, thanks to Ampere's law, a corresponding current must flow perpendicular to the flux lines. In addition, as vortices enter from all sides, the current flow forms a loop such that its flow-direction creates a magnetic moment opposing the applied magnetic field, effectively trying to shield the sample interior [RM15] as indicated by the orange line in Fig.2.6. The magnetic properties are then dominated by the tape width.

When the applied field increases further, more flux lines must penetrate the material, causing the flux front to progress until it stabilises a little further in the tape. A higher magnetic field leads to a higher vortex density per area. At a particular magnetic field value, the whole area of the tape will be covered by vortices at which the vortex-vortex

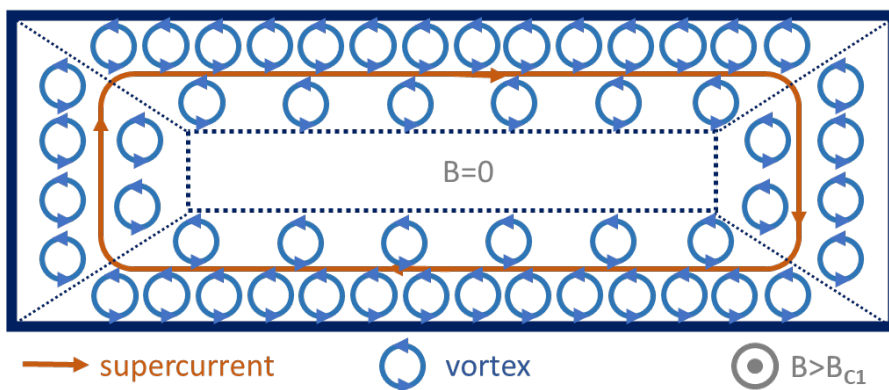


Figure 2.6: Rectangular type-II superconductor tape in an applied magnetic field according to the Bean model. The quantised flux lines and vortex current loops enter into the tape, but with a density gradient that corresponds to a current at the critical current density. In the case that the applied magnetic field is not too high the center region remains screened. Adapted from [RM15] and [BM07].

interaction forms a *vortex lattice* in a fine periodic array with the highest packing fraction and minimal enthalpy for the arrangement possible [Hue19]. In a very pure superconductor such lattice can be of hexagonal type, called Abrikosov lattice shown in Fig.2.7(a). On the one hand, there is a correlation between the vortex lattice and the crystal lattice. On the other hand, the grid structure depends on the direction of the applied magnetic field with respect to the surface of the superconductor [BP10; Poo07]. Crystal defects, such as vacancies, impurities or dislocations in a material act as traps for vortices as they already are normal conducting regions. It turns out that it is energetically more favourable for the vortices to stay at places in the material where the superconducting state is suppressed. In other words, a defect or impurity is, from the point of view of a vortex, energetically seen as a potential well. The Lorentz force of the current pulls vortices to a certain distance x out of the material's pinning wells as long as the average slope dB/dx of the flux front exceeds $\mu_0 J_C$, causing the flux front to advance and the flux gradient to decrease. The process comes to a halt when the flux gradient dB/dx equals $\mu_0 J_C$, at which point the Lorentz force is balanced by the pinning potential wells [RM15]. The vortices penetrate the tape entirely when the condition $H = 0.5J_C d$ is given, where d refers to the thickness of the SC. This physical process, with the fundamental insight that the flux gradient always stabilises at the critical current, and with any modifications to the flux configuration initiated only by applied field changes at the surface [RM15], is the base of the Bean model [Bea64].

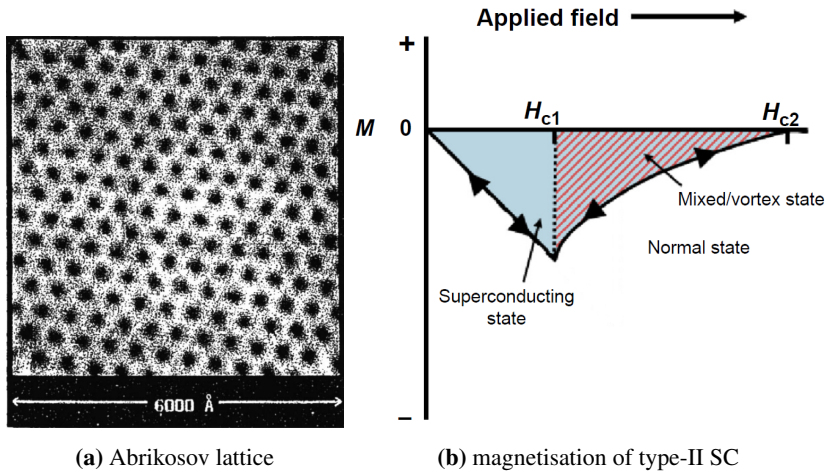


Figure 2.7: Type-II superconductor magnetisation and vortex lattice. (a) The high fraction triangular vortex lattice in a pure superconductor defined by scanning tunnelling microscopy. Figure taken from [Abr04]. (b) Magnetic field dependence of the magnetisation in a type-II superconductor. Figure taken from [RM15]

At a magnetic field value of the *second critical magnetic field* B_{C2} the vortices approach each other to a distance about their diameter. In this case, the individual circulating currents overlap to such an extent that differentiation of the single vortices can no longer occur; hence, the superconductor turns into the normal conducting state.

In summary, the mixed state is a stable superconducting state occurring at applied magnetic fields between the first B_{C1} and B_{C2} and allowing type-II SCs to maintain the superconducting state up to much higher applied magnetic fields compared to type-I SCs as shown in the magnetisation curve in Fig.2.7(b). However, HTS materials have the unique property of allowing large thermally induced magnetic fluctuations in this mixed state, which is an effect that does not occur in conventional superconductors. Wandering flux lines display a complex equilibrium behaviour reflecting liquid, crystalline and glassy phases which lead to very specific properties of high-temperature superconductors depending on the temperature and applied magnetic field of operation [Hue19]. Restrictions in the ability of vortex motion can be achieved with normal conducting regions which affect the magnetisation of the material as well as its properties discussed further in the following section.

2.2.3 Current Flow in the Mixed State

Type-II superconductors are known to carry substantial currents even in the presence of high magnetic fields, which is why most technically relevant applications use type-II superconductors, including HTS. The vortex lattice consists of tiny volumes of normal conducting cores, and one can assume that an applied transport current will always find a superconducting path through the material without hindrance. This could lead to the expectation that the electrical resistance must be zero, as in the Meissner state. Indeed, this is the case in an applied longitudinal magnetic field along with a transport current density J_{tp} . However, it does not apply to samples where the applied magnetic field is perpendicular to the transport current. The J_{tp} is carried by the type-II superconductor by reshaping the vortex distribution and adding up to the swirling supercurrents of the vortices. This gives the material the possibility to keep an external applied transport current density as long as the total current density does not locally exceed the critical current density J_C [Völ02]. The reason is that an already small amount of applied current density is sufficient to make the vortex experience a Lorentz force $\vec{F}_L$ [Hue19]:

$$\vec{F}_L = \vec{J}_{tp} \times \Phi_0 \cdot \hat{n}, \quad (2.4)$$

where $\hat{n}$ is the normal unit vector. The force is perpendicular to the transport current and applied magnetic field, and with that, moves vortices in a direction perpendicular to the direction of both; the transport current and the applied magnetic field [AK64], as indicated in Fig.2.8. This phenomenon is referred to as *flux-flow*.

The concept of a vortex lattice consisting of interacting individual vortices has tremendous consequences for practical type-II superconductors. The reason is that a varying magnetic flux causes an electric field; hence, dissipation in the SC. The first theory of flux-flow resistivity was made by Bardeen and Stephen who assumed in their model that the vortex core has a radius of $R \approx \xi_{GL}$ and an effective area of $\Gamma \approx 2\pi\xi_{GL}^2$. They determined the flux-flow resistivity ρ_{ff} from the fractional area occupied by these cores [Tin96]. In the Bardeen-Stephen model [BS65], this leads to a velocity dependent force $\vec{F}_v = -\eta \vec{v}_{\Phi_0}$, where η is a viscosity coefficient and $\vec{v}_{\Phi_0}$ is the vortex velocity.

The vortices that try to move, due to a DC transport current, are held back by the defects and impurities [see Sec.2.2.2] which exert a pinning force $\vec{F}_p$ on the vortex

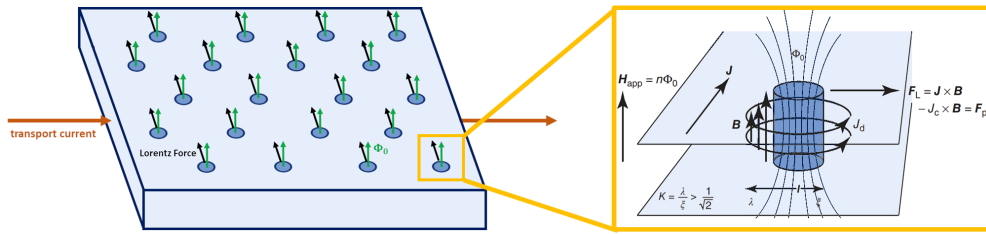


Figure 2.8: Mixed state in the presence of a transport-current density. The vortices experience a Lorentz force driving them perpendicularly to the transport current direction. The magnetic field distribution through the vortices is indicated by dark blue circles embedded into the superconductor (light blue brick). Enlarged image of a quantised line of magnetic flux penetrating the SC subjected to an applied magnetic field above the first critical field. Figure adapted from [Sei15].

lattice. Vortices do not move until the Lorentz force equals the pinning force. This leads to the equation of force balance $\vec{F}_v = \vec{F}_P - \vec{F}_L$ [Sax10]. Thus, a vortex cannot move until the Lorentz force becomes stronger than the pinning force. This occurs at a specific current density value, which is the critical current density J_C [Sha15]. Once $\vec{F}_P < \vec{F}_L$, the transport current is higher than the critical current density, a normal conducting core of a vortex moves through the superconducting material dissipating energy. As a consequence, this continuous motion or flux-flow induces a voltage along the material, i.e., a moving fluxon produces an electric field $\vec{E} = -\vec{v}_{\Phi_0} \times \vec{B}$, where $\vec{B}$ is the average magnetic field perpendicular to the direction of the current [Hue19]. The superconductor loses its ability to sustain dissipation-free current flow, thus behaving as if it would have an ohmic resistance, given by the specific flux-flow resistivity and depending on the speed of movement of the vortices [Bea64].

Applying an RF current density $J_{RF} = J_{RF,0}e^{i\omega t}$, where i is the imaginary number, ω the angular frequency and t refers to time, will lead to an oscillating motion of the individual vortex in its potential well as shown in Fig.2.9. Driven by the current, the vortex moves in this parabolic potential with a viscous flow motion, similar to a

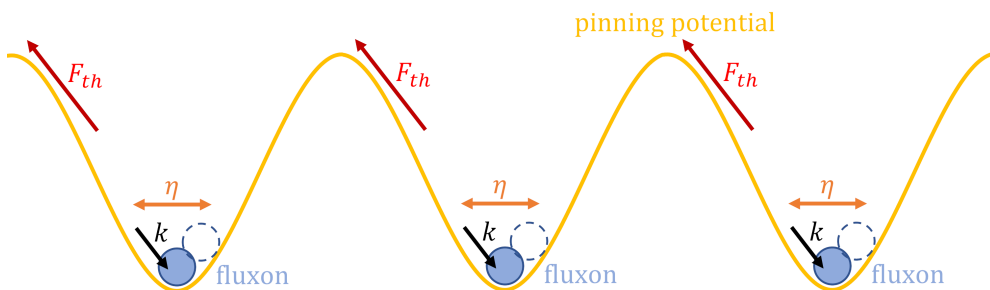


Figure 2.9: Illustration of pinning potential and the effect of the different forces acting on a vortex based on the forces in Eq.(2.5). An applied RF transport current below J_C will lead to vortex motion within its potential well. Thermal effects can lead to vortices leaving its potential well. Figure adapted from [Pom+21].

harmonic oscillator. The exact shape of the potential is not known but approximated as a harmonic potential [GR68] or sinusoidal potential [CC91]. Nevertheless, the motion of the individual vortex can be expressed over the force balance equation given by [Bra91; CC91; GR66; GR68; PS08]:

$$m_{\Phi_0}\ddot{x} + \eta\dot{x} + k_P x = J_{\text{RF}} \cdot \Phi_0 + F_{\text{th}}. \quad (2.5)$$

Here, m_{Φ_0} is the effective mass of the vortex, $\ddot{x}$ the acceleration, $\eta = \Phi_0 B_{C2} \kappa_{nc}$ is the flux-flow viscosity including the normal state conductivity κ_{nc} [KHS65], further, $k_P x = F_P$ is the depinning force with the depinning constant k_P , and F_{th} includes thermal fluctuations for HTS as mentioned in Sec.2.2.2.

Equation (2.5) can be solved under the following assumptions; First, the vortex lattice behaves as a rigid array, which is valid at high magnetic fields due to stronger vortex-vortex repulsion forces [GR66]. In this case, all the vortices have the same displacement from their equilibrium position. Second, the effective mass of the vortex can be neglected for small RF currents [GR68]. Third, at the temperature range of the FCC-hh thermally induced movement is not expected and can be neglected [CV17]. In principle, we are left with a linear force on the vortex with a maximum velocity value v_{max} [CV17]:

$$v_{\text{max}} = \frac{J_{\text{RF,max}} \Phi_0}{\eta} \left(\frac{f^2}{f^2 + f_{\text{dep}}^2} + i \frac{f f_{\text{dep}}}{f^2 + f_{\text{dep}}^2} \right), \quad (2.6)$$

where f is the frequency of the RF transport current and we introduce the *depinning frequency* f_{dep} [GR68]. It is defined as the ratio of the pinning force to the viscous drag coefficients in the equivalent harmonic oscillator. Above the depinning frequency, the viscous forces dominate (flux-flow regime) and the *vortex oscillation* is strongly dissipative, while at frequencies below the depinning frequency the vortex oscillation is almost non-dissipative [Gol+94].

In this context of vortex motion we shall introduce as well the concept of *vortex shaking* [Bra91; BM02; BM07; MB03] which in contrast to vortex oscillation, as described above, can actually lead to a movement (drift) of vortices from their initial positions. First investigations by [Wil+98] concluded that by applying a minor oscillating RF magnetic field perpendicular to a DC magnetic field causes a quick decrease of the currents circulating in the critical state of several type-II superconductors. This relaxation is demonstrated to be generated by the RF magnetic field on the surface of the SC producing a DC electric field in the inside of the SC [BM02]. The direction of the RF magnetic field with respect to the currents in the superconductor affects the DC electric field in general. The following is a breakdown of the most basic scenario as depicted in Fig.2.10 based on the quantitative explanation given in [BM02]: An infinitely long ReBCO film (y-direction) is within a DC magnetic field B_{DC} (directed along z-direction), while an RF magnetic field strength $H_{\text{RF}} = H_0 \cos(\omega t)$ is applied (x-direction) perpendicular to the currents in the sample J and the DC magnetic field.

The current flow in the critical state (assumption Bean model) of the film generates a non-uniform distribution of the magnetic field B_{DC} along the x-direction. In this

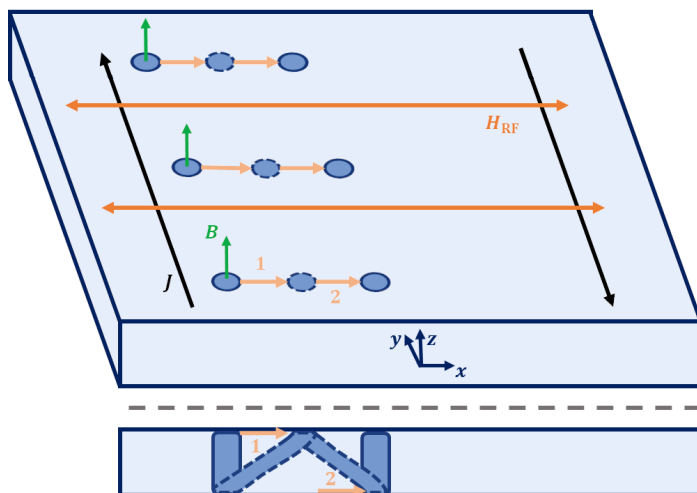


Figure 2.10: Visualisation of vortex shaking effect in an infinitely long SC film. The upper figure shows the film and fields geometry. The lower figure shows a front view of a flux line ‘walk’ from left to the center of the film. Figure based on the illustration in [BM02].

situation, H_{RF} tilts the vortices periodically. However, this tilt is not symmetric in respect to the central plane of the film ($z=0$) at each location x where a non-zero sheet³ current exists. In this case, during each cycle, the resulting DC electric field leads to a temporal sheet current whose self-field adds to H_{RF} on the upper (or lower) plane of the film and subtracts at the same time from it on the opposite plane of the film [MB03]. Consequently, the RF magnetic field strength tilts the vortices asymmetrically with respect to the SC film central plane ($x=0$), driving them to ‘walk’ towards the centre of the film [BM02], as sketched in the front view perspective of Fig.2.10. Two conditions must be fulfilled for the vortex shaking: the thickness of the SC film must be much thinner than the width and $H_0/J_C < 0.5$ [BM02]. This finding was determined using a quasistatic technique based on the standard critical state concept (Bean model), and thus holds true, even when thermally triggered flux creep is negligible [BM07].

Multiple sophisticated mechanisms outside of the scope of this thesis are involved in critical currents and irreversible magnetic characteristics of type-II superconductors⁴. Though, unlike the critical temperature and magnetic fields, which are intrinsic superconducting qualities, the critical current density is an extrinsic attribute governed by defects resulting in *pinning centres* [RM15]. This is fortunate because pinning-controlled materials can reach much higher J_C , and current can flow through the entire bulk of the material when overlaid with a magnetic field, not just on the surface as in type-I materials [RM15].

The reversibility of the magnetisation, as previously shown in Fig.2.7(b), just remains valid for ideal superconductors. Pinned type-II SCs show irreversibility in

³Current density integrated over the film thickness.

⁴The microscopic view of ReBCO-CCs and determination of intrinsic properties are discussed and presented in the doctoral thesis of Artur Romanov [Rom22].

magnetisation behaviour. The moment the magnetic flux enters the material, it will get captured at the pinning centres. Raising the field further will lead to the effects mentioned before, but reducing the field again, will show magnetic hysteresis. When the field is lowered the flux lines will be left trapped permanently leading to an imperfect Meissner flux expulsion as can be seen in Fig.2.11. Magnetisation is kept frozen-in even for vanishing external fields [Sch21].

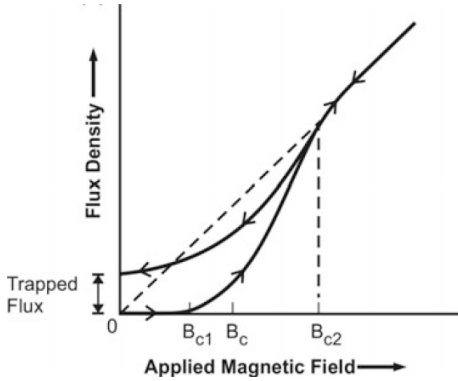


Figure 2.11: Magnetic field dependence of a type-II superconductor including imperfections that shows magnetic irreversibility in flux density and in magnetisation. Figure taken from [Sha15].

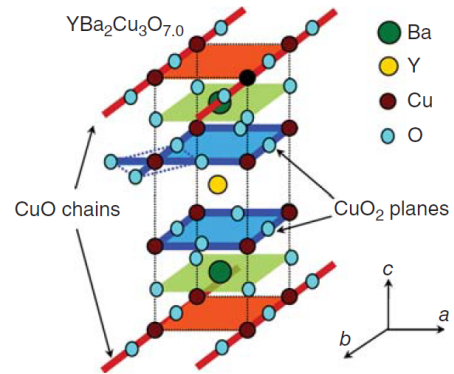


Figure 2.12: Crystal structure of YBCO. Figure taken from [Sei15].

2.3 ReBCO - Coated Conductors

2.3.1 Cuprates

Cuprates can be considered as a sequence of alternating superconducting layers and insulating charge carrier reservoirs along the crystallographic c -direction as visualised in Fig.2.12. Cuprates are typically compounds of four to five chemical elements and are, in fact, not traditional metals but doped ceramics containing parallel weakly coupled copper oxide (CuO_2) layers [BP10], separated by other layers of insulating rare-earth elements of other oxides like yttrium [MX04], which exhibit very high critical parameters compared to LTS. A comparison of the critical surface phase space for most commonly used LTS and HTS technical superconductors is given in Fig.2.13. From what is known, the superconducting state is primarily present in the CuO_2 planes inside the cuprate, which strongly influences the material's behaviour when exposed to a magnetic field. In addition, one key characteristic is the anisotropy between a - b and c -plane noticeable in every fundamental property, e.g., including the critical current density J_C given in Fig.2.14(a) which is strongly dependent on the external magnetic field angle with respect to the face normal to the CuO_2 planes [BP10]. Due to their anisotropy, the penetrated vortices are no longer well-defined if the separation layer is greater than the c -axis coherence length due to the low carrier density. Figure 2.14(b) presents the anisotropy and effect of a cuprate entering into the mixed state with an

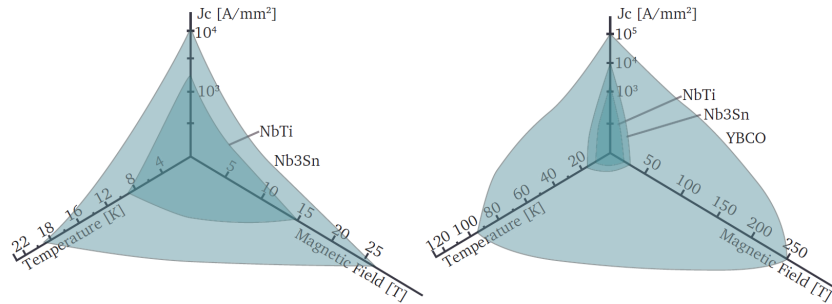
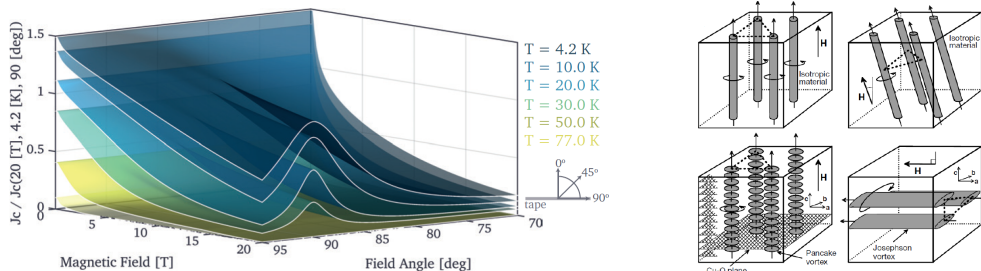


Figure 2.13: Comparison of the critical surface of LTS and HTS. Figure taken from [Van16].

applied magnetic field at different angles. It leads to a tendency for the vortices to be cut within the blocking layers, leading to short flux line segments, as first described by Clem and named pancake vortices [Cle04]. These are more flexible structures than the uninterrupted quasi-rigid flux tubes in LTS. Moveable pancakes in one layer can slip past pinned pancakes in adjacent layers. Applying a magnetic field parallel to the a-b-direction of the material; the crystalline anisotropy in the coherence length as well as in the penetration depth affects the geometrical structure of the vortex. It leads to the formation of elliptical Josephson vortices, displayed in the spaces between the CuO_2 planes [KD13]. Hence, the field can penetrate between the layers without destroying the superconducting state [KD13]. This implies that the superconductor is almost unaffected by an external magnetic field applied in this direction.



(a) change in critical current density versus temperature and angle

(b) vortex structure angle dependence

Figure 2.14: (a) The normalised critical current density as function of magnetic field, temperature, and angle of applied magnetic field. (b) Sketches of vortex structures in isotropic and anisotropic superconductor. Figures taken from (a) [Van16] and (b) [Gri+01].

2.3.2 2G Coated Conductor

The reduction in cooling requirements for HTSs promised to reduce the cost of superconducting technology and expand the potential fields of application. One of the most promising methods developed to utilise ReBCO material is on flexible metal

tapes and coated with buffering metal oxides, which is known as *second generation coated conductor* [Inf10], depicted in Fig.2.15. These second generation tapes promise high current densities, being more suitable for magnetic field applications due to the different material classes of HTS and making low-cost mass production possible. The manufacture of flexible and long-length tapes utilising these materials is limited due to a number of issues. Superconducting ceramics, unlike metals, are brittle and delicate, making them more difficult to deal with. They must have sufficient strength to withstand the fabrication process, device winding, cool-down and electromagnetic stresses. Furthermore, they must be able to be produced or cabled to sufficient size to carry operational currents ranging from hundreds to thousands of amperes at costs comparable to Cu [Lar+01]. In other words, ReBCO conductors must be reliable, robust and low cost with low RF-losses [MX04].

As mentioned previously, due to the fragility of these materials, the required flexibility necessary for the production of long tapes can just be achieved in combination with a metallic matrix or substrate, typically Hastelloy or Steel, which has high mechanical strength and stability, is heat resistant, and is polished to a mirror finish to permit the growth of thin films on its surface [Van16]. One of the main obstacles of deposition of ReBCO-films on a large scale and good quality is the crystal structure's orientation. It affects the current conductivity and limits the critical currents that can be reached.

In polycrystalline materials, the so-called *grain boundaries* contribute significantly to a reduction of the current density [GC01]. The material crystallises in randomly distributed small panels touching at their edges, including, in the worst case, a hollow space as shown in Fig.2.16. The grain boundaries are strong barriers to current flow across their boundaries, and behave as a tunnel junctions, often referred to as *weak links* [GC01]. Thus, if the coherence length ξ_{GL} is smaller than the grain boundary, the flowing supercurrent will be interrupted. As a consequence, a good conducting material as silver is needed to bypass the grain boundary. Several methods were developed to obtain biaxially textured templates suitable for fabricating high-

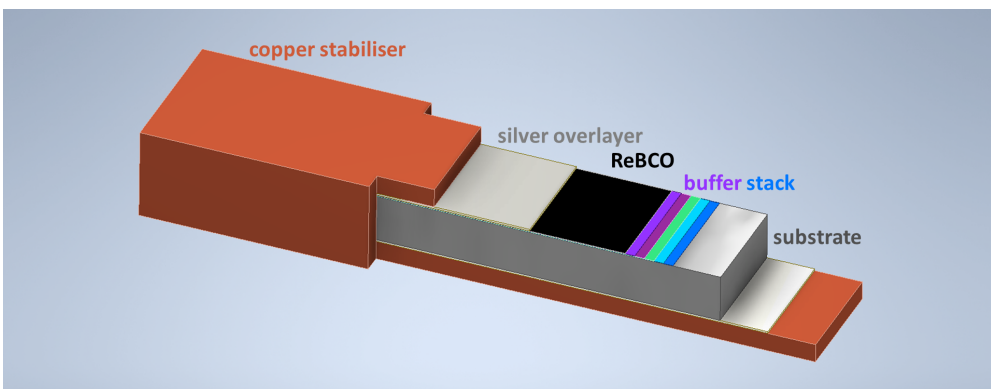


Figure 2.15: Cross-section of a ReBCO coated conductor layered structure material composition.

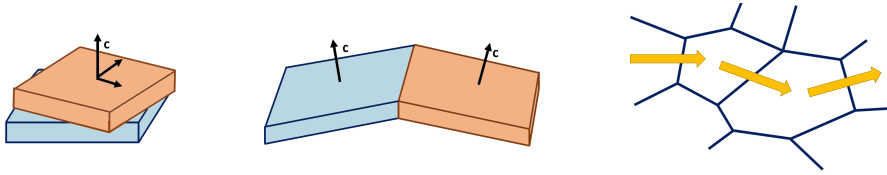


Figure 2.16: Schematic representation of grain boundary models and resulting current flow in ReBCO material. The current flow is tied to the a-b planes indicated with yellow arrows. Figure adapted from [GC01].

performance REBCO coated conductors, as Ion-Beam Assisted Deposition (IBAD), Rolling-Assisted Biaxially Textured Substrates (RABiTS), and Inclined - Substrate Deposition (ISD), leading to high critical current densities of $J_C > 10^6 \text{ A/cm}^2$ [BP10].

A central issue in the above techniques is the need to use a series of buffer layers, whose purpose is mainly to prevent the diffusion of metal elements into the superconductor during high-temperature processing and to pass the biaxial texture of the metal substrate to the deposited ReBCO-film [MX04]. Depending on the technique, those buffer layers can be arbitrary mixtures of compounds as, e.g., a $\text{CeO}_2/\text{YSZ}/\text{CeO}_2$ [Gur22]. A copper jacket finally wraps up the entire complex layered structure, as shown in Fig.2.15.

The optimisation of the present second generation coated conductors concerning their superconducting properties seems to match the initiatives to strengthen their stability in technical environments. Practical applications of HTSs have mainly focused on electric power systems and devices, such as power transmission lines and magnets [RM15]. Coated conductors are produced depending on their main application leading to a commercial variety of tapes. The length scales manufacturable at the moment are up to kilometres with a width of 4 mm to 12 mm [Bru].

ReBCO-CCs contain a high concentration of natural pinning sites, such as oxygen vacancies, stacking faults and non-superconducting phases, naturally reducing possible flux flow [see Sec.2.2.2] [BP10]. These pinning centres can be crystallographic defects in the lattice, grain boundaries, vacancies, as well as foreign atoms or dislocations [Sef+01]. Likewise, areas with a lower transition temperature can serve as pinning centres [DHK99]. Note that not each vortex must be individually pinned down for the development of a vortex lattice and an effective raise in performance of the ReBCO. Many manufacturers of superconducting wires or coated conductors use artificial defects or introduce (non-)magnetic inclusions [Ion+04; Sto+02], so-called nanodots or nanorods, that act as artificially produced pinning centres. Another very effective possibility of creating defects in a controlled manner is irradiation with particles such as ions, nucleons or electrons, which produce very precise micro-holes [Lin+96]. Hence, many CCs have specifically designed pinning centres, optimised in size, shape and arrangement [BP10]. This leads to strong flux pinning, which is necessary to increase the critical parameters. In addition, transport properties depend on the thickness of the ReBCO layer.

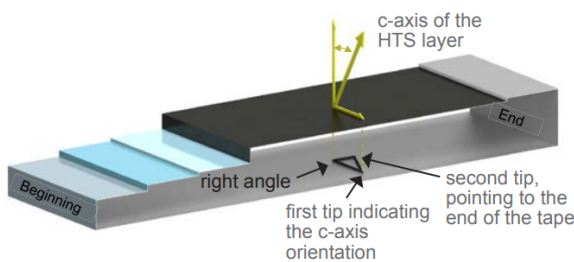
2.3.3 The Providers

We have used samples from six different manufacturers of ReBCO-CC each with individual growing techniques and surface treatments depending on their usual customer requirements. The coated conductors are provided by *Bruker HTS GmbH*, *Fujikura Ltd.*, *SuNAM Co. Ltd.*, *SuperOx*, *SuperPower Inc.*, and *Theva Dünnschicht-technik GmbH*. To demonstrate the variety of the coated conductors architecture; hence differences in the microstructure, we summarised the properties significant for this thesis in Tab.2.1.

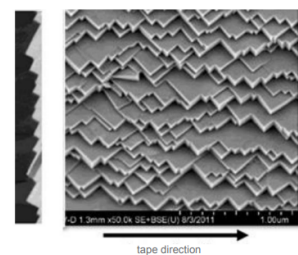
The exchange of yttrium (Y) with rare-earth materials leads to the first difference between the manufacturers. Further, there are differences in the technology and the growth mechanisms leading to different buffer stacks summarised in Tab.B.1 in the appendix. As mentioned in the previous section, the thickness of the ReBCO film varies depending on the exact purpose.

SuNAM, SuperOx and Theva are manufacturers of CCs whose microstructure relies on an as-grown pinning landscape with twin boundaries, stacking faults and point defects [RKT20]. Throughout the thesis, they will be referred to as *pristine* coated conductors. Theva deserves a specific discussion as their growth technology includes an approximately 30 degrees tilt of the ReBCO c-axis with respect to the substrate normal, transversely to the tape length [The21], as sketched in Fig.2.17. ReBCO-CCs provided by Bruker, Fujikura and SuperPower have *nano-engineered* microstructures, meaning that secondary phases are deliberately incorporated into the ReBCO matrix to enhance the pinning strength, as explained in Sec.2.3.2. This can be realised by embedding nanosized oxides, e.g., BaHfO_3 , which are incorporated into the ReBCO matrix to enhance the pinning strength for effective vortex pinning in magnetic field applications [see Sec.2.2.3] [RKT20]. We shall refer to those CCs as containing *artificial pinning centres* (APC). It is worth mentioning that Bruker's YBCO presents a double-disordered matrix very effective at pinning vortices at low temperatures [Pui+19], which is their main field of application.

Figure 2.18 shows a characterisation of the critical temperature T_C and the critical current per centimetre width I_C that has been carried out for all the providers. In these



(a) Cross section of Theva's ReBCO tape



(b) Scanning electron microscope image of MgO surface

Figure 2.17: Sketch of the corresponding c-axis tilt of the ReBCO film corresponding to the normal axis of the tape due to the MgO inclined substrate. Both figures are taken from [The21]

measurements the difference between pristine and APC CCs is observed. Also the different behaviour of Theva due to the inclined growth technology. The characterisation of the I_C was performed by means of vibrating sample magnetometry, while T_C and the (normal state) resistivity ρ of the ReBCO layer were carried out by electrical transport measurements in the Van der Pauw geometry [Pui+19].

All RF characterisations in this thesis, as mentioned in Sec.1.8, were performed directly on ReBCO-CCs whose Cu and Ag protective layers were stripped off. Some manufacturers provided the coated conductors directly without the usual silver/copper stabiliser jacket. In order to avoid degradation of the ReBCO layer, the ReBCO-CCs provided already stripped were stored in a low humidity environment. The ReBCO coated conductors provided with a protective silver layer on top usually were chemically etched right before measurements. The removal process was done using a solution of 1:1:5 of $\text{NH}_3:\text{H}_2\text{O}_2:\text{CH}_3\text{OH}$.

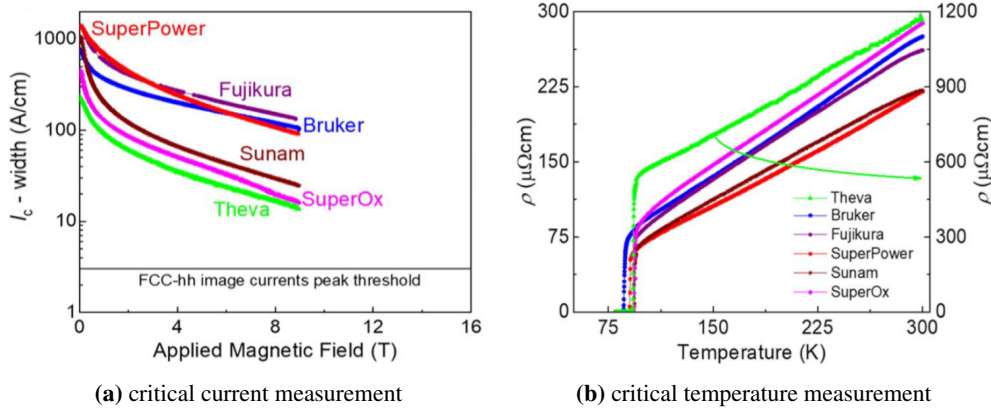
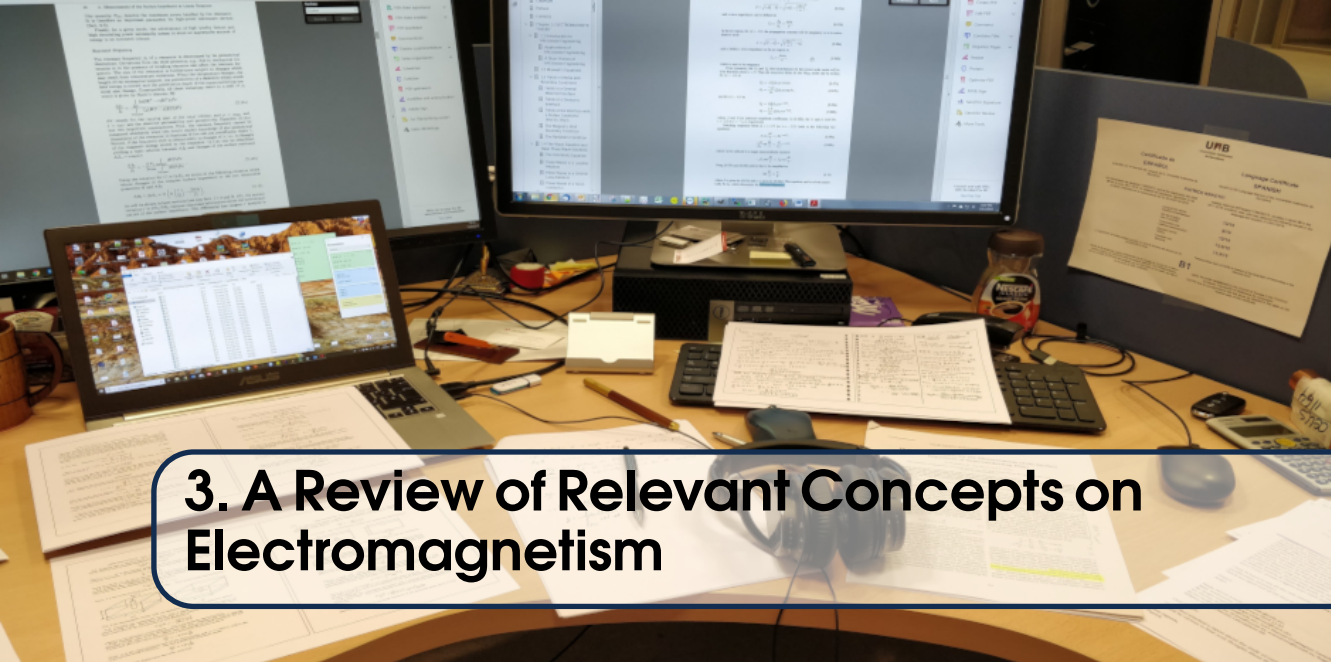


Figure 2.18: (a) Magnetic field dependence of the critical current per centimetre width I_C . (b) Temperature dependence measurement of resistivity ρ at zero applied magnetic field. Both figures are taken from [Pui+19].

Table 2.1: Comparison of the different coated conductors provided by the different ReBCO manufacturers. Data has been put together from [Pui+19; Rom22; Van16]. e.p. = electroplated, lam. = laminated

						
$ReBa_2Cu_3O_7$	Y	Gd Eu	Gd	Gd Y	{ Y,Gd }	Gd
Thickness [μm]	1.6	1.8 2.5	1.6	0.9 3.0	1.5	3.0
Nano-inclusion	BaZrO ₃	none BaHfO ₃	none	none Y ₂ O ₃	BaZrO ₃	none
Technology	PLD	PLD	RCE	PLD	MOVCD	EB-PVD
Substrate	Stainless Steel	Hastelloy C276	Hastelloy C276	Hastelloy C276	Hastelloy C276	Hastelloy C276
Thickness [μm]	100	75 50	100	60 40	50	100
Stabilizer [μm]	e.p. 25	lam. 75	e.p 20	e.p. 10	e.p 20	e.p. 20
T_C [K]	85	94 92	94	94	91	92



3. A Review of Relevant Concepts on Electromagnetism

It is during our darkest moments that
we must focus to see the light.

-Aristotle-

In this chapter, the fundamentals of electromagnetic fields applied to conductors and superconductors are summarised, and the nomenclature used throughout the thesis is presented. In addition, the concept of surface impedance is described as well as its use in a recursive multi-layer theory.

3.1 Maxwell's Equation: Dimensions, Domains and Units

Maxwell's equations derived by James Clerk Maxwell in 1865 [Max65] are comprised of four fundamental laws, i.e., Gauss's law for electric fields, Gauss's law for magnetic fields, Faraday's law and the Ampere-Maxwell law. These equations can be written in various mathematical formalisms to characterise the physical relationship between the electric field $\vec{E}$ and magnetic field $\vec{B}$ and electric displacement $\vec{D}$ and magnetic field strength $\vec{H}$. In addition, they can be written in the macroscopic (large scale behaviour in matter), or microscopic scale (atomic scale, e.g., charges in vacuum), in frequency or in the time domain, in differential or integral form, and SI or CGS system of units.

The variety of these equations facilitate often the mathematical analysis depending on the topic and problem to solve. For our purpose of considering electromagnetic (EM) fields, we are often interested in looking at a system from the point of view of a particular frequency. To give an intuitive understanding of the qualitative behaviour

of the beam screen system, we have to take into account the frequency response of all materials used in our resonating structures. In addition, the concept of beam coupling impedance describes the electromagnetic interaction of a particle beam with the surrounding equipment in the frequency domain [Glu00; Wei15]. Oppositely, for example, for the understanding of synchrotron radiation, the time domain description is beneficial.

Throughout the thesis, we present the Maxwell equations and the constitute relationships between fields and fluxes as follows in Def.3.1.1 [Bal89]. Furthermore, in this domain, we shall commonly express electromagnetic oscillations with a complex variable which are understood to be proportional to $\exp(i\omega t)$, following the nomenclature of [Bal89]⁵.

Definition 3.1.1 — Maxwell Equations.

$$\text{Gauss for E-field: } \nabla \cdot \vec{D}(\vec{r}, \omega) = \rho_{\text{source}}(\vec{r}, \omega) \quad (3.1)$$

$$\text{Gauss for B-field: } \nabla \cdot \vec{B}(\vec{r}, \omega) = 0 \quad (3.2)$$

$$\text{Faraday: } \nabla \times \vec{E}(\vec{r}, \omega) = -i\omega \vec{B}(\vec{r}, \omega) \quad (3.3)$$

$$\text{Ampere-Maxwell: } \nabla \times \vec{H}(\vec{r}, \omega) = \vec{J}_{\text{source}}(\vec{r}, \omega) + \vec{J}(\vec{r}, \omega) + i\omega \vec{D}(\vec{r}, \omega) \quad (3.4)$$

Macroscopic differential equations given in frequency domain and SI units.

Definition 3.1.2 — Field Relations.

$$\vec{D}(\vec{r}, \omega) = \epsilon(\vec{r}, \omega) \vec{E}(\vec{r}, \omega) \quad (3.5)$$

$$\vec{B}(\vec{r}, \omega) = \mu(\vec{r}, \omega) \vec{H}(\vec{r}, \omega) \quad (3.6)$$

$$\vec{J}(\vec{r}, \omega) = \kappa(\vec{r}, \omega) \vec{E}(\vec{r}, \omega) \quad (3.7)$$

Frequency dependent complex material relations including dispersive materials.

Here, ρ_{source} is the source charge density, $\vec{J}_{\text{source}}$ is the source electric current density, $\vec{J}$ is the free current density, and ϵ , μ , and κ determine the permittivity, permeability, and conductivity, respectively, that have the above material relations. The real and imaginary parts of the material parameters can be written as:

$$\epsilon = \epsilon_0(\epsilon_r' - i\epsilon_r'') - i\frac{\kappa}{\omega} \quad \mu = \mu_0(\mu_r' - i\mu_r'') \quad \kappa = \frac{\kappa_0}{1 - i\omega\tau}. \quad (3.8)$$

Here, ϵ_0 , μ_0 and ϵ_r , μ_r refer to as the permittivity, permeability of free space and relative permittivity, permeability, respectively. The real part describes the capacity and the imaginary part describes the losses [Kit04]. In addition, κ_0 is the DC-conductivity, and τ is the electron's average time between subsequent collisions or relaxation time. The dissipation of electromagnetic energy can be parametrised over the *loss tangent* $\tan(\delta)$

⁵The chosen convention the time harmonic oscillation is arbitrary. Another representation is $\exp(i\omega t)$ or $\exp(-j\omega t)$, $\exp(j\omega t)$, where $i = j = \sqrt{-1}$ [Bal89]

which is defined over the ratio of the complex quantities [Kit04]:

$$\tan(\delta_E) = \frac{\epsilon_r''}{\epsilon_r'} + \frac{\kappa}{\epsilon_0 \omega \epsilon_r'} \quad \tan(\delta_M) = \frac{\mu_r''}{\mu_r'} \quad (3.9)$$

where $\tan(\delta_E)$ and $\tan(\delta_M)$ refer to the electric and magnetic loss tangents, respectively.

3.2 Boundary Conditions

A boundary condition (BC) explains the behaviour of electromagnetic fields at boundaries between two media having different properties. It depends on the properties of the materials used and the orientation of the electromagnetic field. In this thesis, we are going to make extensive use of boundary conditions, which in the most general form are given as [Bal89]:

Definition 3.2.1 — General EM Boundary Conditions.

<i>Vector form</i>	<i>Scalar form</i>	
$\hat{n} \times (\vec{E}_\Omega - \vec{E}_{\Omega'}) = \vec{0}$	$E_{\Omega,t} - E_{\Omega',t} = 0$	(3.10)
$\hat{n} \times (\vec{H}_\Omega - \vec{H}_{\Omega'}) = \vec{J}_\Gamma$	$H_{\Omega,t} - H_{\Omega',t} = J_\Gamma$	(3.11)
$\hat{n} \cdot (\vec{D}_\Omega - \vec{D}_{\Omega'}) = \rho_\Gamma$	$D_{\Omega,n} - D_{\Omega',n} = \rho_\Gamma$	(3.12)
$\hat{n} \cdot (\vec{B}_\Omega - \vec{B}_{\Omega'}) = 0$	$B_{\Omega,n} - B_{\Omega',n} = 0$	(3.13)

A summary of the interface conditions on electric and magnetic fields at the surface boundary Γ between two materials passing from one media filling region Ω to another media filling another region Ω' . Equations (3.10) and (3.13) assure the continuity of the fields passing from one media to another media. Equations (3.11) and (3.12) state that the tangential or normal component of the field across an interface, together with an existing surface source, is discontinuous by an amount matching the surface source. In the case that no surface sources are existent, continuity must be given.

These general EM-BCs state that the tangential component of the electric field strength $\vec{E}$ has to be continuous at the interface between two regions; so it has to be the normal component of the magnetic field $\vec{B}$. In addition, the discontinuity of the tangential component of the magnetic field strength $\vec{H}$ equals the surface current density $\vec{J}_\Gamma$, while the discontinuity of the normal component of the electric displacement $\vec{D}$ equals the surface charge density ρ_Γ .

3.3 Electromagnetic Waves in Medium

3.3.1 Penetration Depth

In the following discussions, we will drop the convention $(\vec{r}, \omega)$. Further, the propagation of an electromagnetic wave in an infinitely extended homogeneous and neutral ($\rho_{\text{source}} = 0, J_{\text{source}} = 0$) and isotropic -material parameters are considered scalar- media is characterised by its permittivity ϵ , permeability μ , and conductivity κ .

Over Maxwell's equations defined in Def.3.1.1 the EM-fields $\vec{E}$ and $\vec{B}$ can be separated from this system of equations by taking the curl of the Eq.(3.3):

$$\nabla \times (\nabla \times \vec{E}) = -i\omega \nabla \times \vec{B}, \quad (3.14)$$

and take into account the relations given in Eqs.(3.4) and (3.1)

$$\nabla \times (\nabla \times \vec{E}) = -i\omega \mu \vec{J} + \omega^2 \mu \vec{D}. \quad (3.15)$$

The constitutive relationships given in Def.3.1.2 are used to replace fields and we obtain⁶

$$\Delta \vec{E} + (\omega^2 \epsilon \mu - i\omega \mu \kappa) \vec{E} = 0. \quad (3.16)$$

Correspondingly, the same result is derived for the magnetic field strength:

$$\Delta \vec{H} + (\omega^2 \epsilon \mu - i\omega \mu \kappa) \vec{H} = 0. \quad (3.17)$$

So, both vectors $\vec{E}$ and $\vec{H}$ fulfil the same wave equation, which are generally expressed in the following form:

$$\Delta \vec{E} + \tilde{\gamma}^2 \vec{E} = 0, \quad (3.18)$$

$$\Delta \vec{H} + \tilde{\gamma}^2 \vec{H} = 0, \quad (3.19)$$

where we define according to [Bal89; Wei15] $\tilde{\gamma}^2 = \sqrt{\omega^2 \epsilon \mu - i\omega \mu \kappa} = ik$ as the complex propagation constant and k known as the wavenumber.

According to [Bal89; Gri17] and from Maxwell's equations, we can determine for a time-harmonic and uniform plane wave travelling in one arbitrary direction, e.g. z-direction, that the electric and magnetic fields are oscillating in phase, in-plane transverse to the direction of propagation. Hence, the electric and magnetic fields lie in the xy-plane as sketched in Fig.3.1. A general solution based on the aforementioned directions satisfying the homogeneous differential Eqs.(3.18) and (3.19) can be written as:

$$\vec{E} = \vec{E}_0^+ e^{(-\tilde{\gamma}z + \omega t)} + \vec{E}_0^- e^{(\tilde{\gamma}z - \omega t)}, \quad (3.20)$$

$$\vec{H} = \frac{k}{\mu \omega} \vec{H}_0^+ e^{(-\tilde{\gamma}z + \omega t)} + \frac{k}{\mu \omega} \vec{H}_0^- e^{(\tilde{\gamma}z - \omega t)}. \quad (3.21)$$

⁶using the vector identity $\nabla \times (\nabla \times \vec{A}) = \nabla(\nabla \cdot \vec{A}) - \Delta \cdot \vec{A}$ [Jac75]

⁷The tilde has no mathematical function and is only used to distinguish between other variables with the same letter.

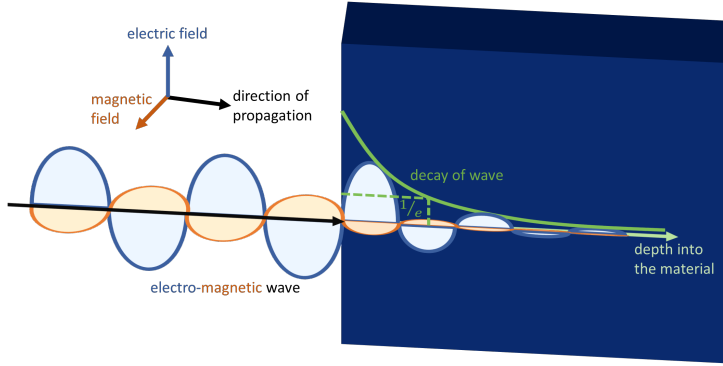


Figure 3.1: Sketch of penetration depth of electromagnetic fields in an arbitrary medium.

Here, $\vec{E}_0^+, \vec{H}_0^+$ and $\vec{E}_0^-, \vec{H}_0^-$ are the vector amplitudes of positive z-direction and negative z-direction going waves. The term $e^{\pm i\omega t}$ in both equations controls the temporal phase.

The propagation of time-harmonic plane waves in a lossy medium is implicitly contained in Eq.(3.18) by the complex propagation constant. The wavenumber consists of both components, real and imaginary. Thus, in order to derive k , we decompose it into its real $\tilde{\alpha}$ and imaginary $\tilde{\beta}$ components:

$$k = \tilde{\beta} - i\tilde{\alpha} = \sqrt{\omega^2 \epsilon \mu - i\omega \mu \kappa}, \quad (3.22)$$

where $\tilde{\alpha}$ and $\tilde{\beta}$ are always positive values and depend on frequency and properties of the medium [Gri17]. On account of $k^2 = -\tilde{\alpha}^2 - 2i\tilde{\alpha}\tilde{\beta} + \tilde{\beta}^2$ and complex comparison of both sides of the equation, it leads to:

$$\tilde{\beta}^2 - \tilde{\alpha}^2 = \omega^2 \mu \epsilon \quad 2\tilde{\alpha}\tilde{\beta} = \omega \mu \kappa. \quad (3.23)$$

From these equations we determine the two parameters $\tilde{\alpha}$ and $\tilde{\beta}$ by rewriting the left equation and applying it to the right equation. This leads to a bi-quadratic equation with four possible solutions where the only physically logical one is given by [Bal89; WH88]:

$$\tilde{\beta} = \omega \sqrt{\frac{\epsilon \mu}{2}} \sqrt{\sqrt{1 + \frac{\kappa^2}{\omega^2 \epsilon^2}} + 1} \geq 0, \quad (3.24)$$

$$\tilde{\alpha} = \omega \sqrt{\frac{\epsilon \mu}{2}} \sqrt{\sqrt{1 + \frac{\kappa^2}{\omega^2 \epsilon^2}} - 1} \geq 0. \quad (3.25)$$

Substituting these complex components, e.g., into the forward propagating part of Eq.(3.20) the general solution for EM plane waves in the vertical direction becomes:

$$\vec{E} = \vec{E}_0^+ e^{-\tilde{\alpha} z} e^{-i(\tilde{\beta} z - \omega t)}. \quad (3.26)$$

Here, we obtain a wave that decays exponentially in a medium with an envelope given by $e^{-\tilde{\alpha} z}$. The energy that the waves lose through damping is converted into

Joule heat. Thus, $\tilde{\alpha}$ is named the attenuation constant with the dimensions [Np/m] and $\tilde{\beta}$ is referred to as the phase constant [rad/m] which determines as well the wavelength [WH88]. With this, we can introduce the definition of the penetration depth δ [Bal89], namely;

Definition 3.3.1 — Penetration Depth.

$$\delta = \left| \frac{1}{\tilde{\alpha}} \right| \quad (3.27)$$

The distance the wave must travel in a lossy medium to reduce its value to e^{-1} .

3.3.2 Normal Conductor

In the case of a metal, with a finite conductivity, e.g. copper $\kappa_{Cu} \approx 58$ [MS/m] at room temperature (RT), the effective length over which the electromagnetic field penetrates inside the metal is of the order of the penetration depth in Eq.(3.27). The phenomenological model of electrical conductivity by Drude, as discussed in Sec.2.1.1, explains that free conduction electrons in a metal are scattered by defects and phonons. The force from the applied electric field is balanced after a few collisions by the scattering force so that the electrons move at a constant speed through the conductor, defining the conductivity of the material. If a harmonic and rapidly fluctuating electric field is applied to a conductor it is justifiable to assume that the current density of free electrons follow the same harmonic oscillations. At low frequencies; hence, large wavelengths electromagnetic phenomena appear in relatively long time scales [Gre08]. The propagation of an EM wave over a characteristic length of the system can be seen as quasi static. In this *Quasi-Static Regime* $\omega\tau \ll 1$ the conductivity dominates the properties of the electromagnetic wave inside the material and any frequency dependence of the conductivity in Eq.(3.8) vanishes. The conductivity is considered purely real and the same as in DC. Further, in a good conductor usually the conduction current density $\vec{J}$ is larger than the displacement current $-i\omega\vec{D}$ stated in the Ampere-Maxwell relation Eq.(3.4), i.e. $\kappa \gg \epsilon\omega \rightarrow \kappa/\epsilon\omega \gg 1$, as long as Ohm's law Eq.(3.7) remains valid. By this means, the wavenumber complex components can be approximated by:

$$\tilde{\alpha} = \omega \sqrt{\frac{\epsilon\mu}{2}} \sqrt{\sqrt{1 + \frac{\kappa^2}{\omega^2\epsilon^2}} - 1} \approx \omega \sqrt{\frac{\epsilon\mu}{2}} \sqrt{\frac{\kappa^2}{\omega^2\epsilon^2}} = \sqrt{\frac{\omega\mu\kappa}{2}}, \quad (3.28)$$

$$\tilde{\beta} = \omega \sqrt{\frac{\epsilon\mu}{2}} \sqrt{\sqrt{1 + \frac{\kappa^2}{\omega^2\epsilon^2}} + 1} \approx \omega \sqrt{\frac{\epsilon\mu}{2}} \sqrt{\frac{\kappa^2}{\omega^2\epsilon^2}} = \sqrt{\frac{\omega\mu\kappa}{2}}. \quad (3.29)$$

Accordingly, in the Quasi-Static Regime the real and imaginary part of the wavenumber are the same, and Eq.(3.27) for the *skin depth* can be rewritten as:

$$\delta_s = \sqrt{\frac{2}{\mu\omega\kappa}}. \quad (3.30)$$

Table 3.1: Summary of electrical DC parameters of various materials a room temperature and resulting skin depth at 1 GHz taken from [Ohr95].

Material	Resistivity [Ω m]	Conductivity [S/m]	Skin Depth [μ m]
Silver	$1.59 \cdot 10^{-8}$	$6.30 \cdot 10^7$	2.00
Copper	$1.72 \cdot 10^{-8}$	$5.80 \cdot 10^7$	2.09
Aluminium	$2.65 \cdot 10^{-8}$	$3.77 \cdot 10^7$	2.59
Brass	$6.9 \cdot 10^{-8}$	$1.11 - 1.66 \cdot 10^7$	3.90 - 4.77
Amorph. Carbon	$5 - 8 \cdot 10^{-4}$	$1.25 - 2.00 \cdot 10^3$	356 - 450

From this equation, we can see that the skin depth, i.e. the sheet in which the total current flows, decreases as the conductivity, permeability, and frequency increase. Table 3.1 presents the values of some commonly used metals and resulting skin depth.

3.3.3 Superconductor

In the analysis of normal conductors we discussed the resistivity over Drude's model and the scattering of electrons on the crystal-lattice. In a superconductor, however, there is no such scattering force with DC currents [see Sec.2.1.3]. The phenomenological approaches first introduced by the London brothers do not attempt to explain this in detail as the BCS theory in Sec.2.1.4, but rather take it as an axiom in order to investigate the consequences when they defined [LL35]:

Definition 3.3.2 — London Equations.

$$\vec{E} = \frac{m}{n_s q^2} \frac{\partial \vec{J}_{sc}}{\partial t} \quad (3.31)$$

$$\nabla \times \vec{J}_{sc} = -\frac{n_s q^2}{m} \vec{B} \quad (3.32)$$

Here, n_s remains the number density of superconducting carriers [see Sec.2.1.3], q^2 is the charge ($2e$), $m = 2m_e$ is the effective electron mass m_e , and $\vec{J}_{sc}$ is the superconducting current density.

The first London equation (3.31) describes the property to transport current without any loss. Thus, it can be assumed that there is no electric field in the superconductor unless the current changes with time.

The second London equation (3.32) relates the supercurrent density to the magnetic field. The magnetic field within a superconductor in an external applied magnetic field can be investigated by taking the curl of Eq.(3.31) and applying Faraday's law Eq.(3.3):

$$\frac{d}{dt} \left[\nabla \times \vec{J}_{sc} + \frac{n_s q^2}{m} \vec{B} \right] = 0. \quad (3.33)$$

In order to explain the Meissner effect [see Sec.2.1.2] the London brothers required

that not only the derivation of the parentheses vanishes, but the expression inside the parenthesis as well. Indeed, it further states that the magnetic field is not expelled entirely from the superconductor. Manipulating the second London equation by including the Maxwell-Ampere relation Eq.(3.4) (neglecting the displacement current), it can be seen that the magnetic field is screened exponentially from the interior, as we obtain:

$$\nabla \vec{J}_{sc} = \frac{\mu_0 n_s q^2}{m} \vec{J}_{sc}. \quad (3.34)$$

In other words, we search for a function that is twice differentiable and after differentiating twice, results in the same function except for a constant. Therefore, the solution is an exponential function, including an attenuation constant. As we know from Eq.(3.27), the reciprocal of the damping defines the penetration depth, which leads to the *London penetration depth*:

$$\lambda_L = \sqrt{\frac{m}{\mu_0 n_s q^2}}. \quad (3.35)$$

Even though phenomenological, the resulting penetration depth is equal to the GL penetration depth λ_{GL} mentioned in Sec.2.2.1. Unlike the skin depth of metals, which depends on the frequency as indicated in Eq.(3.30), the London penetration depth, is independent of the frequency [Lan06]. The shielding currents flow in a very thin layer in the order of magnitude of $\lambda_L \approx 100$ nm, much less than in normal conductors. Though, there are differences between LTS and HTS; some example values are given in Tab.3.2. In addition, the stoichiometry of the HTS influences the penetration depth [Pla10].

Table 3.2: London penetration depth of some superconductors at 0 K. Values are taken from [BP10; Pla10; Sha15].

Material	$\lambda_{L,ab}$ [nm]	$\lambda_{L,c}$ [nm]
Lead	39	39
Aluminium	50	50
YB ₂ Cu ₃ O ₇	150	800
YB ₂ Cu ₃ O _{6.7}	210	453
Tl ₂ Ba ₂ Ca ₂ Cu ₃ O ₁₀	200	> 2000

3.4 Surface Impedance

3.4.1 Surface Impedance and its Physical Meaning

Surface impedance Z_S can be seen as an electromagnetic response parameter of a material that characterises its radio-frequency impedance regardless of its specific

geometry. The theory of surface impedance describes electrodynamics at the interface between any two media and is intertwined with the concept of penetration depth. The *surface impedance boundary condition* (SIBC) is often used when solving electromagnetic problems combined with complicated geometries of the medium, reducing it to a single interface. The benefit lies within the possibility to identify a solution to a certain problem only with the knowledge of the surface impedance, while the geometry beyond this interface does not necessarily have to be known. A well known SIBC is given by Leontovich, who defines the impedance as the wave impedance in the conductor [ILH11; Leo48].

Definition 3.4.1 — Leontovich SIBC.

$$\vec{E}_t = \sqrt{\frac{\mu}{\epsilon}} \vec{H}_t \times \hat{n} \quad \text{on } \Gamma \quad (3.36)$$

It is obtained under the assumption that the approximation of half-space is given, i.e., the penetration depth is much smaller than the material thickness, and when the curvature of the conducting surface is large with respect to the skin depth in the plane wave approximation [Gug09]. The unit normal vector $\hat{n}$ is pointing into the conducting material.

The Leontovich SIBC is useful in a variety of scattering problems because it establishes a correlation between the electric and magnetic fields at the conductor's surface without knowing the field distribution within.

Combining the Leontovich SIBC with the general boundary conditions given in Def.3.2.1 makes obtaining the total fields much easier, as it will be stated in Sec.3.5. Equation (3.36) yields the surface impedance, which is defined as the ratio of the tangential components of the electric and magnetic fields at the surface of the material. The determination of the total fields is considerably simplified by combining the Leontovich SIBC with the general boundary conditions given in Def.3.2.1, as will be discussed in more detail in Sec.3.5. The surface impedance is then defined as the ratio of the tangential components of the electric field and the magnetic field at the surface of material resulting from Eq.(3.36) [Lan06; Leo00; Poz11].

Definition 3.4.2 — Surface Impedance.

$$Z_S = \frac{\vec{E}_t}{\vec{H}_t} \Big|_{\text{surface}} = \frac{\omega\mu}{k} = R_S + iX_S \quad (3.37)$$

The real part is referred to as *surface resistance* R_S while the imaginary part is referred to as *surface reactance* X_S . In this case, we took the harmonic electric wave solutions in Eqs.(3.20) and (3.21) propagating in z-direction from vacuum towards a medium extending from $z = 0$ to infinity, the same as in Fig.3.1. At the interface at $z = 0$, the sum of the incident and reflected waves must be equal to the transmitted wave as we know from the BCs in Def.3.2.1. Knowing from Eq.(3.22)

that the wave number k is a complex parameter, the surface impedance consists of a real part R_S and the imaginary part X_S .

The propagation of the electromagnetic field impinging on a lossy medium entering within δ_S will induce a current density; hence, there will be an ohmic power dissipated in the lossy material. In addition, the electrons of the surface current density induced by the magnetic field need a certain amount of energy for the kinetic motion. The direction of the energy transport of a propagating electromagnetic wave is given by the Poynting vector $\vec{S}$, as defined in Def.3.4.3, and, in the case of time-harmonic plane waves, it is perpendicular to the vectors of the electric and magnetic field strengths.

Definition 3.4.3 — Poynting Vector.

$$\vec{S} = \frac{1}{2} \left(\vec{E} \times \vec{H}^* \right) \quad (3.38)$$

It represents the directional energy flux of an electromagnetic field through a unit area in direction $\vec{S}$, per unit time t .

From the time averaged real and imaginary part of the Poynting vector we can relate the real part of the surface impedance to the power dissipated P_{diss} and the imaginary part of the surface impedance to the energy stored U_{st} [Lan06]:

$$P_{\text{diss}} = \frac{1}{2} R_S \iint \left| \vec{H}_t \right|^2 dA, \quad (3.39)$$

$$U_{\text{st}} = \frac{1}{2} \frac{1}{\omega} X_S \iint \left| \vec{H}_t \right|^2 dA. \quad (3.40)$$

Therefore, the surface resistance is a parameter that is proportional to the RF losses and determines the application potential of materials, e.g. used in passive microwave components. Likewise, the physical meaning of the surface reactance is connected to the electromagnetic energy stored in the material Eq.(3.40). The total energy stored in the magnetic field has to be the same as the electrical energy attributed to the current flowing within the penetration depth. In this case, we can determine that the surface reactance determines the energy stored in the material during one frequency cycle ω [Lan06].

3.4.2 Impedance of Normal Conductors

The surface impedance for normal conductors Z_{Snc} can be obtained by substituting the wavenumber k with its complex components given in Eqs.(3.28) and (3.29) into Def.(3.4.2), assuming $\mu \approx \mu_0$ -true for many metals- resulting in:

$$Z_{Snc} \approx \sqrt{\frac{i\mu_0\omega}{\kappa_0}} = \frac{(1+i)}{\delta_S\kappa_0}. \quad (3.41)$$

This reveals that in the Quasi-Static Regime of the regular skin effect, both quantities, the real and imaginary part are equal and proportional to the square root of the frequency.

With decreasing temperature, the average thermal velocity of the electrons decreases, but the distance a charge carrier travels on average without being scattered, the mean free path l , becomes larger because less lattice vibrations are thermally excited. Thus, both effects lead to an in good approximation linear increase in the metal conductivity κ or vice versa linear decrease in resistivity ρ as a function of temperature. However, every solid contains impurities which are not coupled to each other as the regular lattice of the material and, therefore, can absorb energy and momentum from scattered electrons without exciting lattice vibrations [Dem04]. Due to this, at very low temperatures, the resistivity tends to a constant value based on the purity of the sample, usually defined over the residual-resistance ratio (RRR):

$$\text{RRR} = \frac{\rho(300\text{ K})}{\rho(4.2\text{ K})}. \quad (3.42)$$

The skin depth δ_S , as stated in Eq.(3.30), decreases with decreasing resistivity; hence, with temperature. In addition, δ_S decreases with increasing frequency while the electron free mean path l does not. Thus, there are specific scenarios where these two arguments are of comparable size, or the mean free path gets even longer than the skin depth. In this instance, the current density and the electric field are no longer linked by a local relation as stated in Ohm's law Eq.(3.7) and, $\vec{J} \neq \kappa \vec{E}$. This scenario is defined as the *anomalous skin effect* (ASE) $\delta_S/l < 1$, and the complete theory has been developed by Reuter and Sondheimer [RS48] with an integral solution for the limiting cases, including specular reflection and diffuse scattering of charge carriers at the surface of the conductor. The *normal skin effect* (NSE) means $\delta_S/l > 1$. Figure 3.2 presents the differences between ASE and NSE in the example of the surface resistance of copper at 8 GHz and zero magnetic field displayed as a function of temperature for different values of the RRR. It can be seen that the higher the RRR value, the more significant the differences in R_S values at lower temperatures. In addition, the discrepancy between ASE and NSE begins to arise at higher temperatures for higher RRR.

The presence of a magnetic field influences metals' resistivity due to the material's electron mobility, similarly to the Hall effect. Due to the Lorentz force, the electrons in the material are deflected by moving through a magnetic field, leading to an asymmetric distribution and additional electric field [Koh50]. Thus an applied magnetic field on metals leads to an increased, field-dependent resistivity referred to as *magnetoresistance*. This tendency of a material to change the value of its electrical resistance in an externally applied magnetic field is given by Kohler's empirically determined law -valid only in the range between $10 < \text{RRR} \cdot B[\text{T}] < 10000$ [Cal20]- and can be implemented into the surface impedances given above [Cas+99; Koh50; Mét11]:

$$\frac{\rho(T, B) - \rho(T, 0)}{\rho(T, 0)} = 10^{-2.69} (\text{RRR} \cdot B)^{1.055}. \quad (3.43)$$

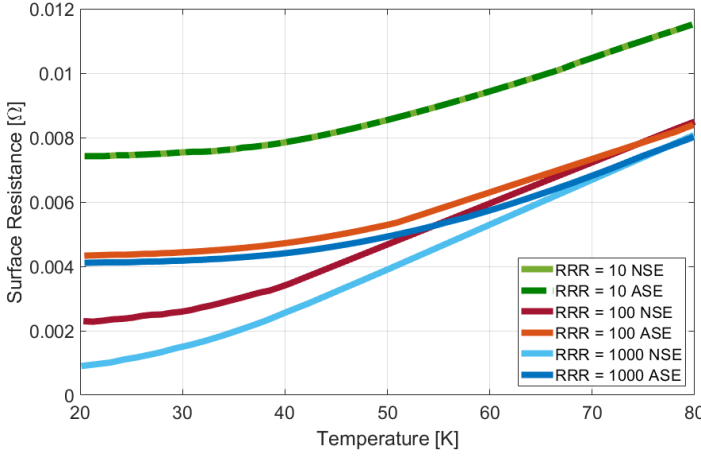


Figure 3.2: Example of the surface resistance differences between ASE and NSE for Cu at 8 GHz. Data taken from [Cal20].

3.4.3 Impedance of Superconductors

Due to the coexistence of normal and superconducting charge carriers in a superconductor, the total current density can be expressed over the sum of the superconducting and normal conducting current density $\vec{J}_{sc} = \vec{J}_n + \vec{J}_s$. Figure 3.3(a) shows the density of superconducting electrons as a function of temperature as given by Eq.(2.2). Ohm's law Eq.(3.7), in conjunction with the London theory [see Sec.3.3.3] and the 2F-model reveals the microwave absorption of superconductors. Over the first London equation Eq.(3.31), we can find the relation between the superconducting current density and the electric field, which assuming a time-harmonic field, results in [Lan06]:

$$\vec{J} = \kappa_{sc} \vec{E} = (\kappa_n - i\kappa_s) \vec{E} = \left[\kappa_n + i \frac{1}{\mu_0 \lambda_L^2 \omega} \right] \vec{E}, \quad (3.44)$$

where κ_{sc} is the complex superconductors' conductivity, κ_n is the normal conducting and κ_s is the superconducting conductivity, respectively, and λ_L is the temperature dependent London penetration depth. With this, taking the surface impedance from Eq.(3.41), we can substitute the skin depth by the London penetration depth and the conductivity by the superconductor complex conductivity leading to [Lan06]:

$$Z_{Sc}(T, f) = \frac{(1+i)}{\lambda_L \kappa_{sc}} \xrightarrow{\kappa_n \ll \kappa_s} \underbrace{\frac{1}{2} \omega^2 \mu_0^2 \kappa_n \lambda_L^3}_{R_{Sc}} + i \underbrace{\omega \mu_0 \lambda_L}_{X_{Sc}}. \quad (3.45)$$

As indicated, the approximation implemented in the derivation is that the normal conductivity of the superconductor is much smaller than the superconducting conductivity. In this case, at low temperatures, the surface resistance results to be much smaller than the surface reactance [Lan06]. If $\kappa_s \ll \omega \mu$, then the values of both real and imaginary surface impedance can be very low $Z_{Sc} \ll 1 \Omega$ [Lan06]. Furthermore, R_{Sc} depends

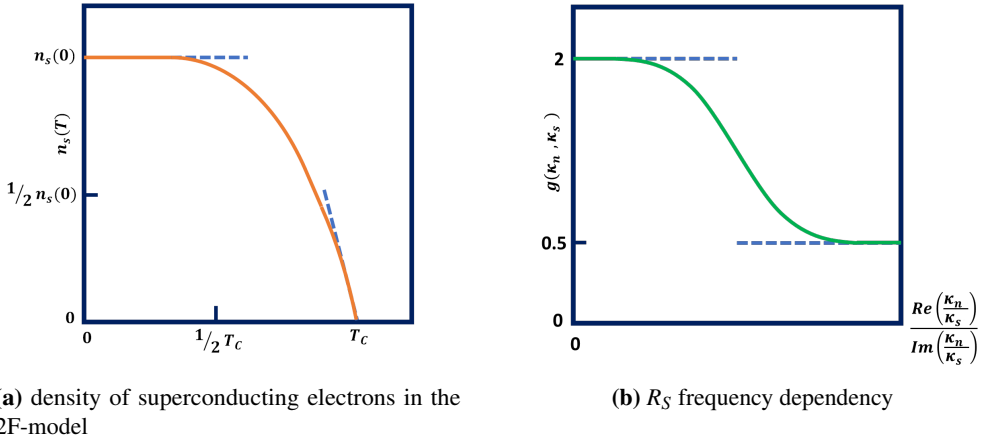


Figure 3.3: Sketch of superconducting parameters affecting the surface resistance based on the 2F-model: (a) density of cooper pairs versus temperature and (b) surface resistance frequency dependency parameter g versus ratio of normal to superconducting conductivity. Adapted from [Lan06] and [Hei99], respectively.

quadratically with the frequency, while $X_{S_{sc}}$ presents a linear dependence. Nevertheless, for HTS deviations to these power laws have been reported to depend on $\omega\kappa_n$ [Hei99]. The extension of the frequency dependence for the 2F-model for high-temperature superconductors has been given in [Hei99] as:

$$g(\kappa_n, \kappa_s) = \frac{1}{2} + \frac{\sqrt{1 + \left(\frac{\kappa_n}{\kappa_s}\right)^2} \pm \left(1 - \left(\frac{\kappa_n}{\kappa_s}\right)^2\right)}{2 \left(1 + \left(\frac{\kappa_n}{\kappa_s}\right)^2\right) \left(\sqrt{1 + \left(\frac{\kappa_n}{\kappa_s}\right)^2} \pm 1\right)}, \quad (3.46)$$

where g refers to the frequency exponent f^g and the lower and upper signs are dedicated to the surface resistance and reactance, respectively.

Once $R_{S_{sc}}$ and $X_{S_{sc}}$ are experimentally obtained, it is possible to determine the complex values of κ_{sc} by rearranging Eq.(3.45) and obtaining [Hei99]:

$$\kappa_n - i\kappa_s = \frac{2\mu_0 R_{S_{sc}} X_{S_{sc}} \omega}{(R_{S_{sc}}^2 + X_{S_{sc}}^2)^2} + i \left(\frac{\mu_0 R_{S_{sc}}^2 \omega}{(R_{S_{sc}}^2 + X_{S_{sc}}^2)^2} - \frac{\mu_0 X_{S_{sc}}^2 \omega}{(R_{S_{sc}}^2 + X_{S_{sc}}^2)^2} \right). \quad (3.47)$$

The application of temperature effects can be included over the 2F-model as well as the theory given by Ginzburg and Landau. On this basis, restricting to the phenomenological models, we can generalise the London penetration depth expression Eq.(3.35), given by [Che+06] based on the works of [And+97; Anl+96; Hen+97]:

$$\lambda_L(T) = \lambda_L(0K) \left[1 - \left(\frac{T}{T_C} \right)^a \right]^{-b}. \quad (3.48)$$

Table 3.3: Fitting parameters for three models of $\lambda_L(T)$ [Che+06].

Model	b	a
Critical Regime	$1/3$	1
Ginzburg-Landau	$1/2$	1
(Reduced) Two-fluid model	$1/2$	$(2) / 4$

where a and b are fitting parameters summarised in Tab.3.3.

In the presence of an applied magnetic field we can expand the definition for the current flowing in the superconductor from Eq.(3.44) [Hei99]:

$$\vec{J} = \kappa_{sc} \vec{E} = (\kappa_n - i\kappa_s) (\vec{E} - \vec{v} \times \vec{B}), \quad (3.49)$$

where $\vec{E}$ is referred to the electric field associated with the intrinsic current flow and $\vec{B}$ is the external applied magnetic field. We know from Sec.2.2.2 that at applied magnetic field above B_{C1} vortices will penetrate the superconductor experiencing a Lorentz force perpendicular to the applied current. Within this rigid-vortex lattice hypothesis [CV17] -we underline that all individual vortices are considered rigid and are subject to the same force- the general expression of the surface impedance including the influence of magnetic fields can be expressed by defining an effective conductivity over Eqs.(3.49) and (2.6) substituting the conductivity in Eq.(3.45) leading to [CV17]:

$$Z_{Sc}(T, f, B) = (1 + i) \sqrt{\mu_0 \pi f}. \quad (3.50)$$

$$\sqrt{\frac{\kappa_n(T)}{\kappa_s^2(T)} + \frac{i}{\kappa_s(T)} + \frac{B}{\kappa_{nc}(T)B_{C2}} \left(\frac{f^2}{f^2 + f_{dep}(T)} + i \frac{f f_{dep}(T)}{f^2 + f_{dep}(T)} \right)}.$$

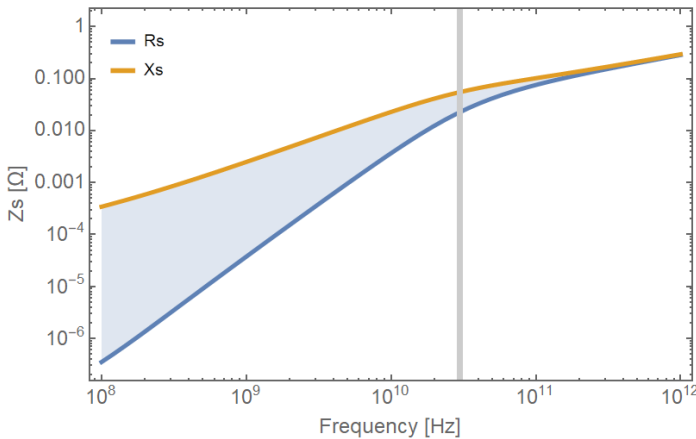


Figure 3.4: Plot of surface impedance $Z_{Sc}(50, f, 16)$ from Eq.(3.50). The values used are $\kappa_n = \kappa_{nc} = 3.6$ MS, $\kappa_s = 4.1$ GS, $B_{C2} = 60$ T [Cal+17] and $f_{dep} = 30$ GHz [RKT20] (grey vertical line)

Figure 3.4 shows this surface impedance as a function of frequency. As mentioned above, below the depinning frequency [see Sec.2.2.3] the surface resistance is smaller than the surface reactance.

3.5 Recursive Model of Thin Film Surface Impedance

In this section, we describe the method for determining surface impedance in a multi-layer arrangement such as the one in Fig.3.5. This problem has been addressed for several optics and microwave engineering applications, such as non-reflecting optical surfaces and broadband microwave matching networks. In Sec.3.4, the propagation of electromagnetic waves in conductive media was discussed, in a material with a flat surface at $z = 0$ filling the entire half-space ($z > 0$), the electromagnetic field decays entirely in the material as illustrated in Fig.3.1.

Materials are often covered with one or more layers (e.g. the steel BS co-laminated with copper from Sec.1.6). The number of conductive layers, their intrinsic properties, and their thickness determines the field distribution in the multi-layer arrangement. Suppose the thickness of a given layer is in the order of magnitude of its penetration depth. In that case, there will be an overlap of the transmitted and reflected electromagnetic wave, and the field strength will no longer decrease exponentially with depth. The penetration depth Def.3.3.1 defines the distance a wave must travel before its amplitude has decayed by a factor of $1/e$ which is about 37% of the amplitude. Hence, a rule of thumb is that the thickness of the medium should be at least three times the penetration depth thickness in order not to be influenced by the material below. As mentioned in Sec.1.5, thin layers of amorphous carbon on copper or ReBCO shall be used to reduce the electron cloud. Thus, with this recursive multilayer method, we can estimate surface impedances of ReBCO-CCs with a layer of aC based on surface impedance measurements of ReBCO-CCs.

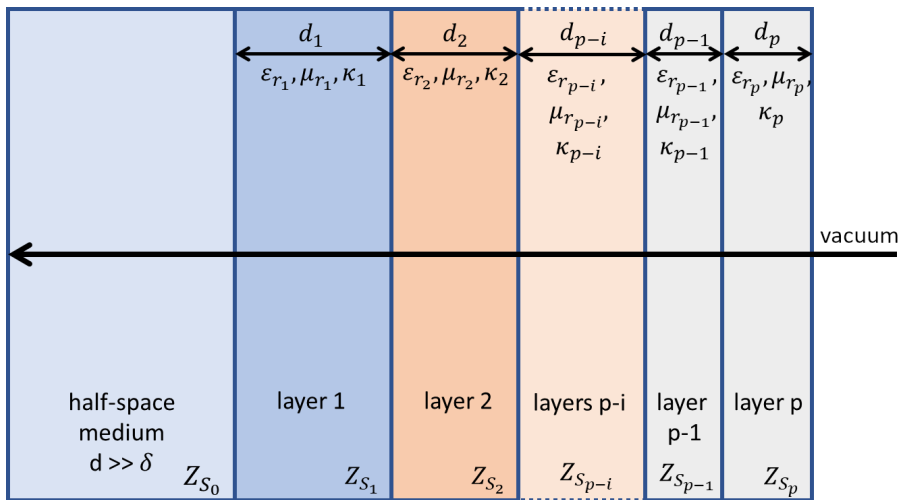


Figure 3.5: Ansatz of an electromagnetic wave propagating through a multi-layer system

We approach the solution to this analytical problem by starting with a plane electromagnetic wave as derived in the previous sections Eqs.(3.20) and (3.21), reaching a two-layer material, which consists of one material that fulfils the half-space approximation, one additional material and vacuum. As indicated in Fig.3.5 we count materials starting from the half-space medium. Thus, the first material transition (first layer) is from vacuum to the first material with a thickness d_1 , permeability μ_1 and conductivity κ_1 perpendicular to the boundary in x-y-plane. The complete set of equations needed to describe the wave propagating in such multi-layer is:

$$\vec{E}_2(z) = \vec{E}_{2a} \cdot \exp[-ik_2z] + \vec{E}_{2r} \cdot \exp[+ik_2z], \quad (3.51)$$

$$\vec{E}_1(z) = \vec{E}_{1a} \cdot \exp[-ik_1z] + \vec{E}_{1r} \cdot \exp[+ik_1z], \quad (3.52)$$

$$\vec{E}_0(z) = \vec{E}_{0a} \cdot \exp[-ik_0z], \quad (3.53)$$

$$\vec{H}_2(z) = \frac{k_2}{\omega\mu_2} \left[\vec{E}_{2a} \cdot \exp[-ik_2z] - \vec{E}_{2r} \cdot \exp[+ik_2z] \right], \quad (3.54)$$

$$\vec{H}_1(z) = \frac{k_1}{\omega\mu_1} \left[\vec{E}_{1a} \cdot \exp[-ik_1z] - \vec{E}_{1r} \cdot \exp[+ik_1z] \right], \quad (3.55)$$

$$\vec{H}_0(z) = \frac{k_0}{\omega\mu_0} \left[\vec{E}_{0a} \cdot \exp[-ik_0z] \right]. \quad (3.56)$$

Here, the index a stands for the forward-propagating and r backward-propagating wave⁸. On each transition plane between two materials, continuity conditions have to be considered for the electric and magnetic fields, that can be derived through Maxwell's equations. The two relevant boundary conditions are given from Def.3.2.1:

$$\begin{aligned} \vec{n} \times (\vec{E}_{p+1} - \vec{E}_p) &= 0 \rightarrow \vec{E}_{t,p+1} = \vec{E}_{t,p}, \\ \vec{n} \times (\vec{H}_{p+1} - \vec{H}_p) &= 0 \rightarrow \vec{H}_{t,p+1} = \vec{H}_{t,p}, \end{aligned} \quad (3.57)$$

whereas p describes the index number and t the tangential component. These boundary conditions have to be applied in our example for $z = 0$ and $z = d_1$.

Due to Eq.(3.57), the surface impedance at the transition between the vacuum and the layer (where $z = 0$) will be given by:

$$Z_{S,1} = \frac{\vec{E}_2(0)}{\vec{H}_2(0)} = \frac{\vec{E}_1(0)}{\vec{H}_1(0)} = \frac{\vec{E}_{1a} + \vec{E}_{1r}}{\frac{k_1}{\omega\mu_1} [\vec{E}_{1a} - \vec{E}_{1r}]} = \zeta_1 \cdot \frac{1 + \Lambda_1}{1 - \Lambda_1}, \quad (3.58)$$

$$\text{defining: } \zeta_1 = \left(\frac{\omega\mu_1}{k_1} \right), \quad \Lambda_1 = \left(\frac{\vec{E}_{1r}}{\vec{E}_{1a}} \right), \quad (3.59)$$

where ζ_p usually is referred to as the *intrinsic impedance* of the medium. The surface impedance at the transition between the first layer and the zeroth layer (or base layer) can be calculated in the same way:

$$Z_{S,0} = \frac{\vec{E}_0(d_1)}{\vec{H}_0(d_1)} = \frac{\vec{E}_1(d_1)}{\vec{H}_1(d_1)} = \zeta_1 \cdot \frac{\exp[-ik_1d_1] + \Lambda_1 \exp[+ik_1d_1]}{\exp[-ik_1d_1] - \Lambda_1 \exp[+ik_1d_1]}. \quad (3.60)$$

⁸Note that the harmonic term $e^{(-\omega t)}$ is being omitted.

This equation can be used to define a equation for the variable Λ_1 :

$$\Lambda_1 = \frac{[Z_{S0} - \zeta_1] \cdot \exp[-ik_1 d_1]}{[Z_{S0} + \zeta_1] \cdot \exp[+ik_1 d_1]}. \quad (3.61)$$

In addition, from Maxwell's equations derived the expression for the wave number k including Eqs.(3.24) and (3.25):

$$ik_1 = \underbrace{\omega \sqrt{\frac{\epsilon_1 \mu_1}{2}} \sqrt{\sqrt{1 + \frac{\kappa_1^2}{\omega^2 \epsilon_1^2}} - 1}}_{\alpha} + i \underbrace{\omega \sqrt{\frac{\epsilon_1 \mu_1}{2}} \sqrt{\sqrt{1 + \frac{\kappa_1^2}{\omega^2 \epsilon_1^2}} + 1}}_{\beta}, \quad (3.62)$$

such that we can rewrite our parameter Λ_1 now dependent on the new exponent K_1 :

$$\Lambda_1 = \frac{[Z_{S0} - \zeta_1] \cdot \exp[-K_1]}{[Z_{S0} + \zeta_1] \cdot \exp[+K_1]} \quad \text{with} \quad K_1 = ik_1 d_1. \quad (3.63)$$

This two-layer-problem derived, is a very classical result, widely used in microwave engineering. For example, it is described in [Poz11], in the context of lossless transmission lines and Smith Chart. The formulation is identical by replacing voltages by electric fields and currents by magnetic fields⁹

The results can be easily generalised by including more layers, because always the same recursive two-layer expressions will occur through the boundary conditions shown in Eq.(3.57). Furthermore, the surface impedance of the previous $Z_{S,p-1}$ layer system is already known up to the point where $Z_{S,0}$ is needed. The generalised multi-layer surface impedance set of equations is summarised as:

Definition 3.5.1 — General Multilayer Surface Impedance.

$$\begin{aligned} Z_{S,p}(Z_{S,p-1}) &= \frac{1 + \Lambda_p}{1 - \Lambda_p} \cdot \zeta_p \\ \Lambda_p &= \frac{[Z_{S,p-1} - \zeta_p] \cdot \exp[-K_p]}{[Z_{S,p-1} + \zeta_p] \cdot \exp[+K_p]} \\ \zeta_p &= \frac{\omega \mu_p}{k_p} \quad K_p = ik_p d_p \end{aligned} \quad (3.64)$$

⁹In fact, the impedance can be calculated with [Poz11] Eq.(2.61). If the line has losses, the tangent functions are replaced by hyperbolic tangents.



4. A Review on Synchrotron Radiation

Phantasie ist wichtiger als Wissen,
denn Wissen ist begrenzt.

-Albert Einstein-

This chapter is devoted to introduce the concepts related to particle accelerators as interactions between particle bunches and the beam screen and the emission of synchrotron radiation. The main focus is on the creation of photons by electrons passing through a bending magnet, as it has a considerable relevance for the thesis. Further, light-matter interactions are discussed, and the toolkit XOP is introduced.

4.1 EM-Field of a Moving Charge in a Beam Screen

In a particle accelerator, charged particles are constantly accelerated and kept moving close to the speed of light. Each electrically charged particle is surrounded by an electric field. However, as the particles circulate in relativistic motions, the electric field lines differ strongly from those known in classical electrodynamics. The electric field of an arbitrarily moving charged particle at relativistic speed cannot be described by classical electrodynamics and Coulomb's field any more. Two relevant movements of the particles are of interest in this thesis; uniform acceleration providing the emission of synchrotron radiation and uniform motion to describe the effect of induced image charges. Before going into the detail of the two phenomena, a better understanding of the effects of motion on the charged particle shall be discussed.

The electromagnetic field distribution of a moving charged particle is defined by Liénard-Wiechert, who generalised the Coulomb field.

Definition 4.1.1 — Liénard-Wiechert Fields. From the Liénard-Wiechert potentials [Lié98; Wie01] one can derive the electric field of a moving point charge on an arbitrary trajectory [Jac75]:

$$\vec{E}(\vec{r}, t) = \frac{e}{4\pi\epsilon_0} \left[\underbrace{\frac{\hat{n} - \vec{\beta}}{\gamma^2(1 - \hat{n} \cdot \vec{\beta})^3 R^2}}_{\text{velocity field}} + \underbrace{\frac{\hat{n} \times \{(\hat{n} - \vec{\beta}) \times \dot{\vec{\beta}}\}}{(1 - \vec{\beta} \cdot \hat{n})^3 c R}}_{\text{acceleration field}} \right]_{\text{ret}} \quad (4.1)$$

$$\vec{B}(\vec{r}, t) = \frac{\hat{n} \times \vec{E}}{c} \quad (4.2)$$

where $\gamma = \sqrt{(1 - \beta^2)^{-1}}$ correspond to the universal Lorentz factor, $\beta = v/c$ defines the velocity in units of the speed of light, $\hat{n}$ is the unit vector in the direction of $\vec{r} - \vec{r}_0(t_{\text{ret}})$, where the absolute value of $|\vec{r} - \vec{r}_0(t_{\text{ret}})| = R = (t - t_{\text{ret}})c$. The right hand side of the equation has to be evaluated at the time t_{ret} as the fields observed at the time t are generated by the particle at a previous time t_{ret} (retarded). The difference $\Delta t = t - t_{\text{ret}}$ is equal to the transit time from the particle to the observer which happens at the speed of light.

Figures 4.1 and 4.2 show the electric field of a moving charge in two different cases of motion. In Fig.4.1 an electron is accelerated in a short period of time and then continues moving with a uniform velocity. In Fig.4.2 the electron is always moving uniformly at different velocities.

Figure 4.1(a) shows a stationary charge at the time $t = 0$, where there is only a radial electric field with respect to the charged particle position. In this case $\beta = \dot{\beta} = 0$ and Eq.(4.1) reduces to the classical isotropic Coulomb field. In the following, the particle shall be accelerated along the horizontal axis within one unit of time $t = 1$ s to $v = 0.7c$ and afterwards prolonged with this constant velocity for $t = 2, 4, 6$ s. As

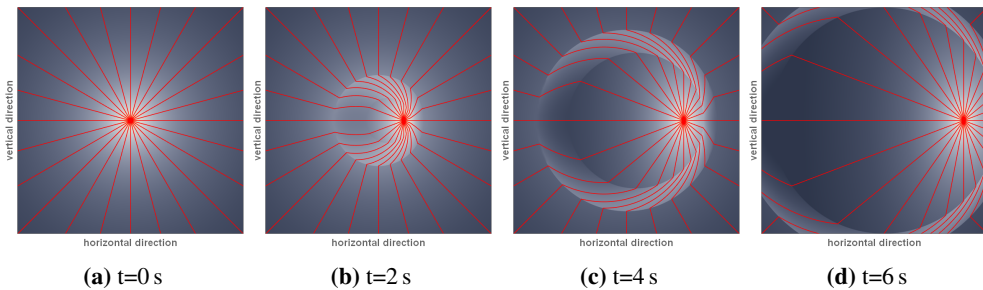


Figure 4.1: Electric field of an electron accelerated for 1 s up to $\beta = 0.7$ and that continues moving with uniform velocity afterwards. The Mathematica [Inc21] script with the implementation of Liénard-Wiechert Fields is taken from [RME20] and slightly adapted to our purposes.

can be seen in Fig.4.1(b), after the particle is accelerated, the information about this movement will take time to reach the observer. The information about the change of motion cannot be transmitted faster than the speed of light but at the speed of light. The field at any corner of the frame of the figure at the time t originated from the same charge when it was at its retarded position in the centre at the retarded time t_{ret} . The information of the change of electric field is given in a shock wave in which, within this shell, the EM-field is not only radial anymore but azimuthal. This shock wave can be seen as *electromagnetic radiation*, and hence, it is always and only emitted as long as a charged particle is accelerated. In particular, accelerated charges are producers of electromagnetic radiation, such as that emitted by oscillating electric dipoles and synchrotron radiation.

In Fig.4.2 we continue the discussion from above, but this time only having a uniform motion of the charged particle; hence, no EM-radiation. Figure 4.2(a) shows the distribution of electric field lines of a charged particle with velocity $\beta = 0.7$, $\dot{\beta} = 0$. In this case, the electrical field seen in the observer frame, now being parallel to the centre of the frame, is given only by the velocity term in Eq.(4.1). This expression describes an isotropic electric field which is ‘squeezed’ by the inverse of the Lorentz factor $1/\gamma$ [RME20] which can be seen in the progressive increase of speed in Fig.4.2(a) to Fig.4.1(d). Additionally, it can be seen in Fig.4.2(d) that the faster the velocity of the charged particle is, the smaller are the components of the field lines along the direction of motion compared to the perpendicular component. If we relate the strength of the electric field to the density of the field lines in a conventional way, we see a stronger field at the sides and a weaker field ahead and behind [FLS11].

The two different motions of charged particles have essential meanings for a beam screen in an accelerator. The acceleration produces synchrotron light which will lead to photon-induced effects and power dissipation. The uniform motion at almost the speed of light leads to the sharp concentrated electric field lines [see Fig.4.2(d)], which are truncated by the beam screen and image charges are induced into the beam screen coating. In fact, there will always be imaging currents in the BS, but if the particles

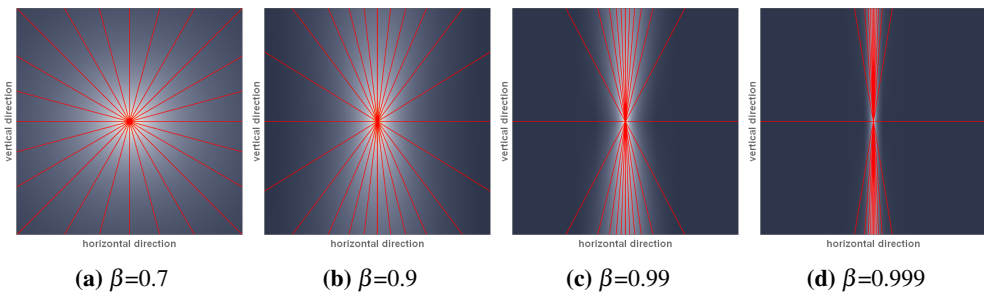


Figure 4.2: Electric field lines of a uniformly moving charged particle at different velocities. When a charged particle moves at high speeds, field lines contract in the direction of motion due to relativistic effects. The contraction is larger the faster the charged particle moves. The Mathematica script with the implementation of Liénard-Wiechert Fields is taken from [RME20] and adapted by implementing the uniform motion.

move at the speed of light, we can safely assume that the image currents in the beam screen coating have the same charge as the beam travelling in the accelerator.

4.2 Image Currents in a Beam Screen

We now can consider the scenario in which a bunch of protons moves with an ultra-relativistic uniform velocity along the axis of an axially symmetric beam screen. The individual electromagnetic fields generated by the protons within one bunch will be linearly added and result in a field distribution contracted into a thin disc-like electric field aligned to the bunch trajectory as discussed in the previous Sec.4.1. From Maxwell Def.(3.1.1), we know that a time-varying electric field is always accompanied by a perpendicular magnetic field. Hence, the bunch is accompanied by a radial E-field and an azimuthal B-field parallel to the beam screen wall. Using the Biot-Savart law the azimuthal RF magnetic field strength $H_{\text{RF,BS}}$ in a round beam screen with radius R_{BS} generated by a bunch current I_{bunch} can be approximated quite well as:

$$H_{\text{RF,BS}} = \frac{I_{\text{bunch}}}{2\pi R_{\text{BS}}}. \quad (4.3)$$

The value for the current can be obtained, e.g. from the operating parameters of the FCC-hh summarised in Table 1.1. Each bunch has a root-mean-square (RMS) bunch length of $\sigma = 8$ cm and consists of 10^{11} protons. Assuming a Gaussian bunch distribution, the peak current can be calculated as [Cala]:

$$I_{\text{bunch}}(x) = \frac{ec}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(x - \tilde{\eta})^2}{2\sigma^2}\right], \quad (4.4)$$

where σ and $\tilde{\eta} = 0$ m are the standard deviation (bunch length) and mean of the distribution (position), respectively. The current distribution along the bunch and its corresponding frequency spectrum is shown in Fig.4.3. The peak bunch current

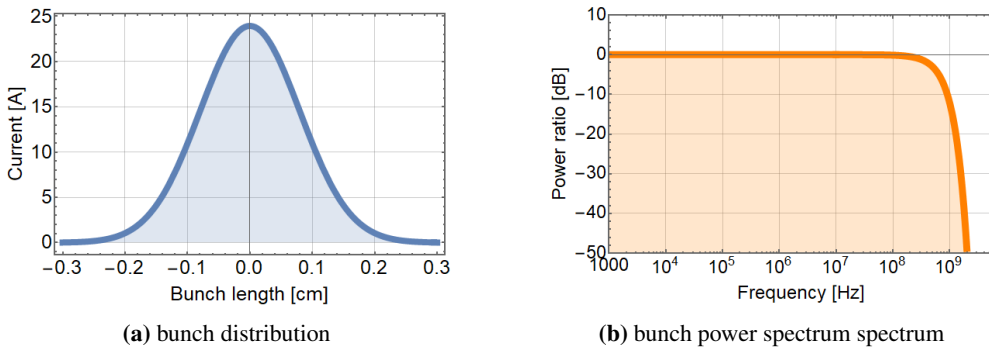


Figure 4.3: (a) Bunch distribution for a Gaussian shaped bunch with 10^{11} protons within 8 cm RMS length. The peak bunch current is about 25 A. (b) Frequency spectrum of the bunch distribution in (a). The higher frequency end is at about 1 GHz for the first order estimation.

turns out to be $I_{\text{bunch}}(0) = I_{\text{bunch, peak}} = 24 \text{ A}$. Considering a beam screen radius of $R_{\text{BS}} = 15 \text{ mm}$ we get $H_{\text{RF,BS,peak}} = 254.7 \text{ A/m}$ or equivalently $B_{\text{RF,BS,peak}} = 0.3 \text{ mT}$.

This approximation works appropriately for a round pipe, but finding an analytical solution gets complicated for real geometries of beam screens as in the FCC-hh. Therefore, we have used a finite-element-method (FEM) solver implemented in Mathematica, which we demonstrate here that provides the same results as the use of the Biot-Savart Law in Eq.(4.3). Starting with Maxwell's equations and replacing the magnetic field $\vec{B}$ in the stationary Maxwell-Ampere law by the vector potential $\vec{A}$ in the magneto-static approach, the Poisson equation in the Coulomb gauge can be written as:

$$-\nabla^2 \vec{A} = -\mu_0 J, \quad (4.5)$$

where $J = I_{\text{bunch,peak}}/(\Omega_{\text{BS}})$ refers to the peak current density and Ω_{BS} is the area of the meshed BS vacuum region. To solve this equation, it is assumed that a perfect electrical conductor (PEC)¹⁰ surrounds the region Ω_{BS} with the imposed boundary conditions:

$$\Gamma_N : \partial A = 0 \quad \text{for } (x,y) \in \partial\Omega_{\text{BS}}, \quad (4.6)$$

$$\Gamma_D : A = 0 \quad \text{for } (x,y) \in \partial\Omega_{\text{BS}}, \quad (4.7)$$

where the subscripts N and D refer to a Neumann and Dirichlet boundary condition, respectively. The solution for the vector potential $\vec{A}$ is found by numerically solving Eq.(4.5) for a fine mesh and using $\vec{A}$ to find the azimuthal magnetic field strength $\mu_0 \vec{H}_{\text{RF,BS}} = \nabla \times \vec{A}$ as presented together in Fig. 4.4(a). The result demonstrates that for a round pipe with a radius of $R_{\text{BS}} = 15 \text{ mm}$ we obtain an azimuthal magnetic field strength of $H_{\text{RF,BS,peak}}^{\text{num}} = 254.7 \text{ A/m}$ in agreement with the analytically calculated

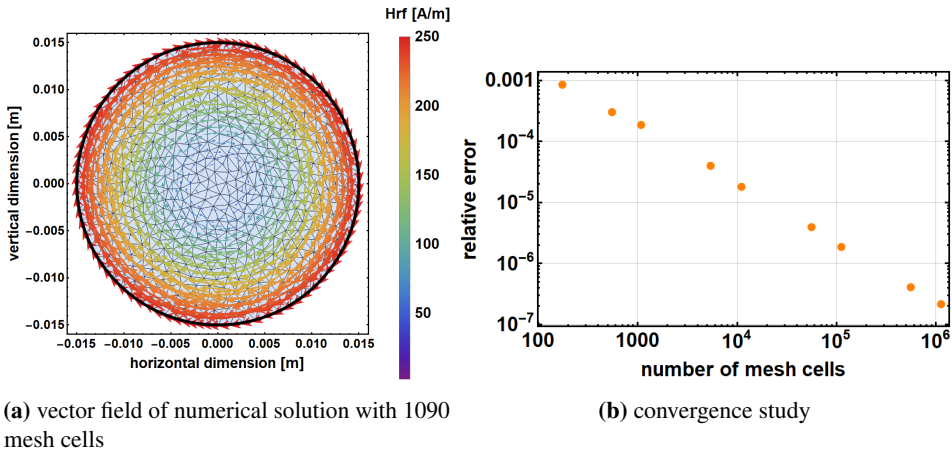


Figure 4.4: (a) Vector field plot including mesh of the azimuthal magnetic field strength distribution produced in the inner part of a round beam screen. (b) Convergence study for magnetic field strength deviation compared to analytical solution in Eq.(4.3).

¹⁰A PEC is an idealised non-existing material with infinite conductivity or, equivalently, zero resistivity.

value. Figure 4.4(b) shows how the calculated magnetic field strength changes with the amount of mesh cells used for the numerical calculations. It provides information about the relative error, as a measure of uncertainty, defined here as:

$$\frac{H_{\text{RF,BS,peak}}^{\text{num}} - H_{\text{RF,BS,peak}}^{\text{ana}}}{H_{\text{RF,BS,peak}}^{\text{ana}}} - 1. \quad (4.8)$$

where, $H_{\text{RF,BS,peak}}^{\text{ana}}$ is the value given by using Eq.(4.3). It shows a relative fast convergence of the numerical solution towards the analytical solution, i.e., by using about 100000 mesh cells, the deviation is about 0.001%.

4.3 Radiation Power and Distribution

The Poynting vector as defined in Def.3.4.3 determines the radiation pattern and the direction in which a single particle radiates:

$$\vec{S} = \frac{1}{\mu_0} (\vec{E} \times \vec{B}) \Rightarrow \frac{1}{\mu_0 c} |\vec{E}|^2 \cdot \hat{n}. \quad (4.9)$$

$\vec{S}$ represents the directional energy flux of an electromagnetic field through a unit area in direction of $\hat{n}$, per unit time t (observer time). In the far field, $\vec{E} \cdot \hat{n} = 0$ and the electric and magnetic field are perpendicular to each other. Hence, the energy radiated must be perpendicular to both. Looking at the particle at a distance x under the solid angle $d\hat{\Omega}$ the power received at our position can be described as [Jac75]:

$$dP = (\vec{S} \cdot \hat{n}) x^2 d\hat{\Omega}. \quad (4.10)$$

To express the power radiated from the emitter per unit time we must include the relativistic factor $\frac{dP}{d\hat{\Omega}}(t_{\text{ret}}) = \frac{dP}{d\hat{\Omega}} \frac{dt}{dt_{\text{ret}}} = \frac{dP}{d\hat{\Omega}} (1 - \hat{n} \cdot \vec{\beta})$. Substituting Eq.(4.1) into Eq.(4.9) and then into Eq.(4.10) we get a general expression for the power radiated per particle [Wie07]:

$$\frac{dP}{d\hat{\Omega}} = \frac{e^2}{(4\pi)^2 \epsilon_0 c} \frac{(\hat{n} \times \{(\hat{n} - \vec{\beta}) \times \dot{\vec{\beta}}\})^2}{(1 - \vec{\beta} \cdot \hat{n})^5}, \quad (4.11)$$

where we used the definition of the speed of light as $c^2 = (\mu_0 \epsilon_0)^{-1}$.

In the non-relativistic case, $\beta \ll 1$, if a charge is accelerated and observed from a frame of reference far away, then the emitted energy in a solid angle per second can be described as [Wal94]:

$$\frac{dP}{d\hat{\Omega}} = \frac{e^2}{(4\pi)^2 \epsilon_0 c} |\hat{n} \times \hat{n} \times \dot{\vec{\beta}}|^2 = \frac{e^2}{(4\pi)^2 \epsilon_0 c^3} |\vec{a}|^2 \sin^2(\Theta), \quad (4.12)$$

where we used the vector identity for a double cross-product, and choose Θ as the angle between the vector of acceleration $\vec{a}$ and unit normal vector $\hat{n}$ as depicted in Fig.4.5.

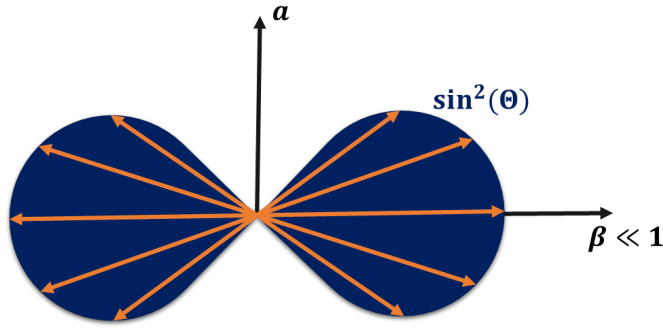


Figure 4.5: Radiation lobe of a non-relativistic particle, equivalent to its rest frame. Figure inspired from [Wal94].

This derived power per unit solid angle $d\hat{\Omega} = \sin(\Theta)d\Theta d\phi$ (unit sphere) reveals significant spatial dependence of the power distribution. It is concentrated perpendicular to the direction of acceleration, proportional to $\sin^2(\Theta)$, and is rotationally symmetric about the axis of acceleration. It corresponds to the power distribution of a Hertzian dipole as shown in Fig.4.5 [Gri17]. In order to calculate the total power radiated, we need to integrate over all angles:

$$P = \frac{e^2}{(4\pi)^2 \epsilon_0 c^3} |\vec{a}|^2 \int_0^{2\pi} \int_0^\pi \sin^3(\Theta) d\Theta d\phi, \quad (4.13)$$

where ϕ is the azimuthal angle with respect to the direction of the acceleration. The result of the integrals is 4/3 and the total power is [Wal94]:

Definition 4.3.1 — Larmor Formula.

$$P = \frac{2}{3} \frac{e^2}{4\pi \epsilon_0 c^3} |\vec{a}|^2 \quad (4.14)$$

This formula describes the total emitted radiation of a non-relativistic particle.

It can directly be seen that, in agreement with the previous discussion in Sec.4.1, the radiation only occurs while the charged particle is accelerated.

In the relativistic case, the total power radiated can be found either by following the same steps as above but without the assumption of $\beta \ll 1$ or by making a Lorentz transformation of the already derived Larmor formula [Wil13]:

Definition 4.3.2 — Liénard Formula.

$$P = \frac{2}{3} \frac{e^2}{4\pi \epsilon_0 c^3} \gamma^6 [\vec{a}^2 - (\vec{v} \times \vec{a})^2] \quad (4.15)$$

This formula describes the total emitted radiation of a relativistic particle.

This equation can be analysed in two particular cases: one in which the velocity is parallel to the direction of acceleration -linear motion- and with that $\vec{v} \times \vec{a} = 0$ and

another in which the velocity is perpendicular to the direction of acceleration -circular motion- and $\vec{a}^2 - (\vec{v} \times \vec{a})^2 = |\vec{a}|^2/\gamma^2$:

$$P_{\parallel} = \frac{2}{3} \frac{e^2}{4\pi\epsilon_0 c^3} \gamma^6 \vec{a}_{\parallel}^2 \Rightarrow \frac{2}{3} \frac{e^2}{4\pi\epsilon_0 m_0^2 c^3} \left(\frac{d\vec{p}}{dt} \right)^2, \quad (4.16)$$

$$P_{\perp} = \frac{2}{3} \frac{e^2}{4\pi\epsilon_0 c^3} \vec{a}_{\perp}^2 \gamma^4 \Rightarrow \frac{2}{3} \frac{e^2}{4\pi\epsilon_0 m_0^2 c^3} \gamma^2 \left(\frac{d\vec{p}}{dt} \right)^2, \quad (4.17)$$

taking into consideration that $\gamma m \vec{a} = d\vec{p}/dt$, where $\vec{p}$ refers to the momentum. From these expressions, it is clear that for a given applied force, the power radiated is a factor γ^2 larger if this force is applied perpendicular to the direction of motion than in the same direction. This is the case, e.g., when a relativistic particle travels under the influence of a magnetic field. The resulting electromagnetic radiation is then called *synchrotron radiation* (SR). In this case, a transformation of the $\sin^2(\Theta)$ distribution in Fig.4.5 into the observer frame changes the angular distribution of the radiation pattern into a strongly focused narrow cone with a vertical half opening angle of $1/\gamma$ [Wal94], as shown in Fig.4.6.



Figure 4.6: Radiation lobe of a relativistic particle in the observer frame. Figure inspired from [Wal94].

4.4 Synchrotron Radiation from a Bending Magnet

In most accelerators, the particle trajectories are bent by magnetic fields; particle energy loss due to SR causes technological restrictions for circular accelerators like the FCC-hh. As the particle energy is driven higher and higher, more and more RF power must be supplied to the beam to replace the energy losses due to SR [Wie07]. The limit is reached when the radiation power grows high enough to either exceed cooling capabilities, RF-capabilities, or beam-induced vacuum effects.

We continue the following discussion based on one single electron moving with relativistic velocity through a bending magnet (BM) as shown in Fig.4.7. The electron travels in this BM through a uniform magnetic field and describes the arc of a circle of radius R_{BM} dependent on the strength of the magnetic field B_{DC} . Hence, including

$\frac{d\vec{p}}{dt} = \frac{\gamma mc^2 \beta^2}{R_{BM}}$ into Eq.(4.17) and $B_{DC} = \frac{U_e}{ecR_{BM}}$ we get the power radiated by a single electron with energy U_e :

$$P_{\perp} = \frac{2}{3} \frac{e^4 \gamma^2}{4\pi\epsilon_0 m_0^2 c} B_{DC}^2. \quad (4.18)$$

The total energy U_{tot} received per unit solid angle passing once through the BM is given by:

$$\frac{dU_{tot}}{d\hat{\Omega}} = \int \frac{dP}{d\hat{\Omega}} dt. \quad (4.19)$$

In order to calculate the frequency spectrum of the electromagnetic wave it is more convenient to perform the calculations in Frequency Domain by Fourier transforming Eq.(4.19) and the Liénard electric fields. The total energy received per unit solid angle per unit frequency interval during one passage of a single electron past the observer is given by [Wal94]:

$$\frac{d^2 U_{tot}}{d\hat{\Omega} d\omega} = \frac{e^2}{16\pi^3 \epsilon_0 c} \gamma^2 \left(\frac{\omega}{\omega_c} \right)^2 (1 + \gamma^2 \Psi^2)^2 \Xi, \quad (4.20)$$

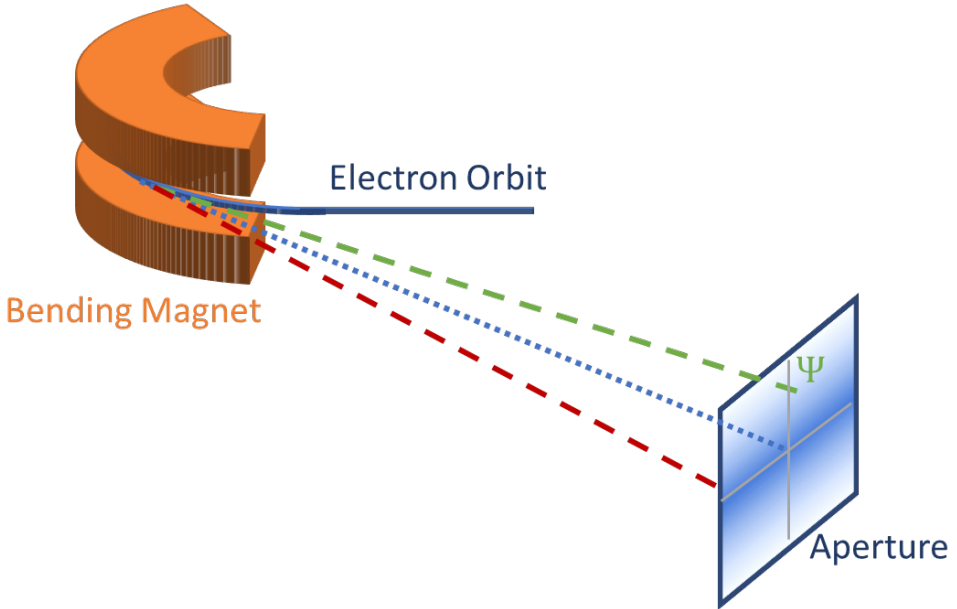


Figure 4.7: This figure shows how an observer would see an electron passing through a bending magnet, and thus, radiating synchrotron light. The angular radiation constraint has significant consequences for the spectrum of the radiation. The emitted photons from the electron will jet along a straight line (blue dotted) with the speed of light in a cone with a vertical opening angle Ψ (green dashed line). The radiation received in a given direction corresponds to only a small arc of the particle trajectory (red dashed line) which is constant in the horizontal plane as the intensity extends equally over the trajectory indicated in blue.

with,

$$\Xi = \left[K_{2/3}^2(\xi) + \frac{\gamma^2 \Psi^2}{1 + \gamma^2 \Psi^2} K_{1/3}^2(\xi) \right] \quad \xi = \frac{\omega}{\omega_c} \frac{(1 + \gamma^2 \Psi^2)^{3/2}}{2} \quad \omega_c = \frac{3\gamma^3 c}{2R_{BM}}, \quad (4.21)$$

where we introduce the modified Bessel functions K_x of the fractional order x . The two terms in Ξ correspond to radiation polarised in the horizontal and vertical planes, respectively. Note that the intensity changes are dependent only in the vertical plane Ψ . The critical frequency ω_c is defined as the frequency that divides the spectrum into two parts of the same radiation power [Wil13].

Equation (4.20) provides the energy radiated per unit solid angle per unit frequency interval during the passage of one single electron. In the case of an electron beam with current I_{beam} passing through a BM, the total energy per second received per unit solid angle per unit frequency interval is proportional to the number of electrons given as [Wal94]:

$$\frac{d^2 U_{\text{tot}}}{d\hat{\Omega} d\omega} \frac{I_{\text{beam}}}{e}. \quad (4.22)$$

The critical energy is defined as $U_{\gamma,c} = \hbar\omega_c$, which in practical units becomes [Wal94]:

$$U_{\gamma,c}[\text{keV}] = 665[\text{GeV}] U_{\text{beam}}^2[\text{GeV}] B_{\text{DC}}[\text{T}]. \quad (4.23)$$

Synchrotron radiation intensities are also commonly expressed in terms of photons per second, which in practical units is given by [Wal94]:

$$\frac{d^2 P}{d\hat{\Omega} d\omega} \frac{1}{\hbar} = \frac{d^2 F}{d\hat{\Omega} d\frac{\omega}{\omega_c}} = 1.325 \cdot 10^{13} U_{\text{beam}}^2 I_{\text{beam}} \left(\frac{U_{\gamma}}{\hbar\omega_c} \right)^2 (1 + \gamma^2 \Psi^2)^2 \Xi \left[\frac{\text{photons/s}}{\text{mrad} \cdot (0.1\% \text{BW})} \right]. \quad (4.24)$$

Figure 4.8 shows the change in the radiated frequency spectrum in the equivalent photon energy depending on the electron energy and beam current. The higher the electron energy, the broader the spectrum reaching higher photon energies visible in Fig.4.8(a). The critical photon energies also increase (dashed lines in Fig.4.8) which are calculated with Eq.(4.23) and are tabulated in Tab.4.1. When more electrons are injected into the machine -the beam current is increased- the frequency spectrum stays the same while the amount of photons increases as visible in Fig.4.8(b). This implies the same critical energy but a higher total power as well seen in Tab.4.1.

Bear in mind, the formulae above are valid only for electrons. For protons the results have to be scaled a mass-ratio-factor of electron to proton $a_{e-p} = 1/1823$ to the appropriate power [Wal94].

Table 4.1: Bending magnet ($B_{DC}=1.41$ T) synchrotron radiation comparison using different parameters of beam current and electron energy. The flux spectrum is plotted in Fig.4.8.

I_{beam} [mA]	U_{beam} [GeV]	$U_{\gamma,c}$ [eV]	$P_{\perp}$ [kW]	$U_{\gamma,c}/h$ [PHz]
100	1	937.68	3.74	226.73
100	3	8439.17	101.10	2040.57
100	5	23442.15	468.07	5668.74
300	5	23442.15	1404.21	5668.74
500	5	23442.15	2340.35	5668.74

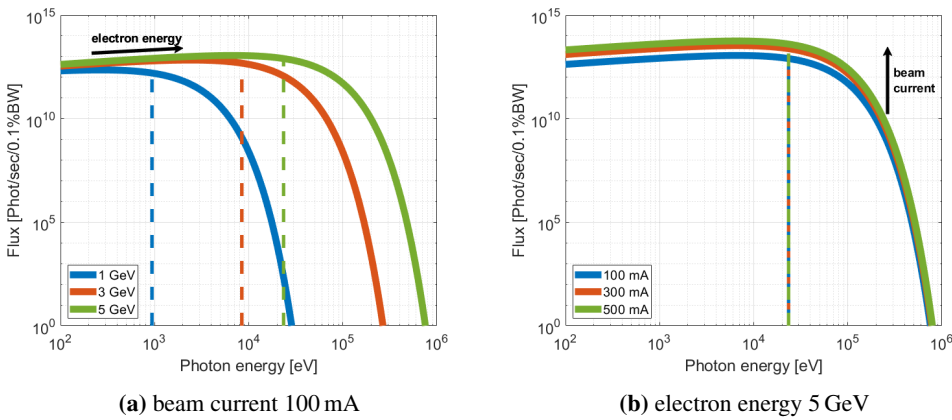


Figure 4.8: Bending magnet ($B_{DC}=1.41$ T) synchrotron radiation spectrum - flux versus photon energy - showing the dependency of the resulting photon energy on (a) the electron energy and (b) beam current. The dashed lines in both figures indicate the position of the critical energy. Idea of this figure taken from [Wil13].

4.5 Effects of Synchrotron Radiation on Materials

After its first observation in 1947, SR was quickly recognised as a powerful research instrument for material sciences, surface physics, and various other fields. Many methods take advantage of the high intensity, polarisation, and collimation of the photon light to investigate the structure of matter. Over the years, all over the world, more than 50 accelerator structures have been constructed that are dedicated to the production of synchrotron light [Lig21].

Light-matter interactions are diverse, and the interaction depends strongly on the photon energy. Nevertheless, photons incident on a material surface will be either reflected, transmitted through the material or absorbed. The absorption is a process by which photons interact with electrons of molecules and atoms, exciting them into a higher energy state leading to ionisation and fluorescence. There will also be power deposited onto the sample under examination.

The absorption coefficient can specify the selective light-matter interaction by a

particular material. It is a parameter that determines how far photons of a particular energy or wavelength can penetrate a specific material before it is absorbed. Generally, the higher the density of a material, the larger the atomic number where there are many electron shells for the incoming photon to interact with, and to match in energy [HB21] and, in addition, the thicker the material is, the higher the absorption rate. Vice versa, light is only poorly absorbed in a material with a low absorption coefficient, and if the material is thin enough, it will appear transparent to that photon energy. The absorption coefficient is determined by the substance as well as the wavelength of light absorbed.

When the full flux spectrum of synchrotron radiation hits the surface of BS material it mainly deposits power on it. Heat load refers to release of energy in terms of heat in an accelerator structure which can be equated to the energy loss of the particle. Therefore, a high amount of SR leads to a high deposition of heat load onto the beam screen wall. The second common process is the emission of electrons due to the photoelectric effect, which in beam screen chambers as the FCC-hh leads to strong electron cloud (e-cloud) instabilities [Ohm+15]. Desorption of molecules on the surface of the materials especially at cryogenic temperatures occurs as well and can lead to unwanted interactions [BMK19].

For the determination of synchrotron radiation and absorption due to different materials, the software *XOP* provided by the European Synchrotron Radiation Facility [ESR21], is used throughout this thesis. *XOP* is a software package with a graphical user interface (GUI) to determine basic quantities for synchrotron beamline designers and experimentalists [RD11]. The main calculations include simulation of source characteristics, e.g., bending magnets shown in Fig.4.8, and modelling of optical elements, including a tool called *Xpower* for the attenuation and reflectivity in media.

Figure 4.9(a) illustrates the absorption and counterpart transmission coefficient as a function of the photon energy of a 200 μm thick sheet of copper produced with *XOP*.

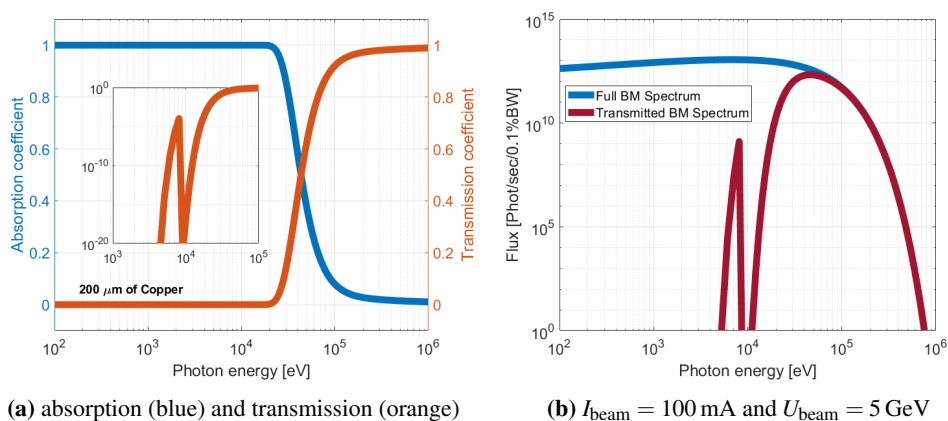


Figure 4.9: Synchrotron radiation spectrum from a bending magnet transmitted through a 200 μm thick copper sheet. (a) shows the absorption and transmission coefficient with the inset zooming into the Cu K-edge. (b) shows the comparison between the total SR and the one after traversing a 200 μm thick Cu sheet.

In a metal, the light will interact with the electrons in the conduction band and the valance electrons of the metal lattice. The interaction is favoured at low photon energy as can be seen in the absorption (blue line) in the same figure. In Fig.4.9(b) we applied the absorption coefficient from Fig.4.9(a) to the SR flux spectrum from Fig.4.8(a). The low energy photons are all absorbed by the 200 μm thick sheet of copper and only photons with energies above 10 keV are transmitted through the copper sheet. The sudden edge in the spectrum is explained over the so-called K-edge¹¹ [Kau+87].

The interaction of photons with superconductors is, in principle, similar to metals. LTSs do not change their density when entering into the superconducting state, i.e, a density based absorption coefficient does not change. However, it is known that in a LTS, Cooper pairs are formed between two electrons with a certain binding energy [see Sec.2.1.4]. Unlike metals, the light-superconductor interaction includes thus the effect of possible breaking or hindering of Cooper pairing, as illustrated in Fig.4.10(a), which is experimentally verified in certain experiments [Tak91; Tes71; Xi+12]. However, for example, the energy gap in Nb is $\Delta U_{\text{CP}} = 2.372 \text{ meV}$ [Sur88], and hence, a relatively low energy is needed to break a CP. Even though it is not yet known how exactly the Cooper pairing mechanism works in HTS and which partners are involved, the binding energy has been measured and is stated to be $\Delta U_{\text{CP}} = 3.3 \text{ meV}$ for YBCO [Sur88], and with that not much higher than in the LTS. Contrary to the K-edge in metals, it is stated

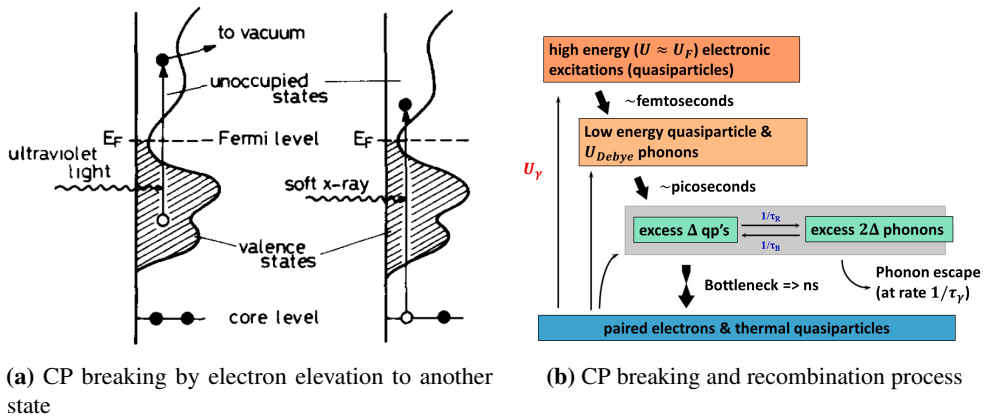


Figure 4.10: (a) Schematic diagram of Cooper pair breaking by photons close to the binding energy of CPs. Figure taken from [Tak91] (b) Sketch of Cooper pair breaking with highly energetic photons compared to the binding energy. The impacting photon produces a pair of high-energetic quasiparticles, that relax rapidly due to interactions with other charged particles and by emission of high-energy phonons. During this period, these phonons can break Cooper pairs. Afterwards, within picoseconds, the quasiparticles relax to the gap edge. This time, each quasiparticle must locate a Cooper pair companion with the opposite spin. The pair binding energy is released in the form of a $2\Delta U_{\text{CP}}$ phonon during recombination. This phonon, on the other hand, can break another Cooper pair. Figure adapted from [Xi+12]

¹¹It means that the energy of the photon interacting with the atom is just above the binding energy of the innermost electron shell the K-shell [Kau+87], which is taken into account in XOP.

in [Xi+12] that as well high-energy photons can break CPs indirectly over quasiparticle dynamics in a cascade procedure as sketched in Fig.4.10(b). The formation of CPs is a statistical event with a very fast pairing timing $\tau_{\text{CP}} \approx 10^{-3} - 10^{-6}$ s [Day+03], the photon-electron interaction rate must be faster than the recombination time after Cooper pair breaking in order to suppress the superconducting state constantly.



5. Beam versus Beam Screen

I would rather have questions that
can't be answered than answers that
can't be questioned

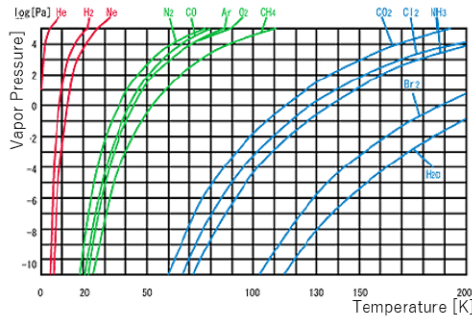
-Richard P. Feynman -

This chapter deals with the interactions of a particle beam and its environment circulating in the vacuum chamber. This chapter will briefly explain how certain requirements for the FCC-hh beam screen are implied. In addition, the overall technical requirement for a ReBCO-CC shall be discussed to understand the broad picture of the consortium project.

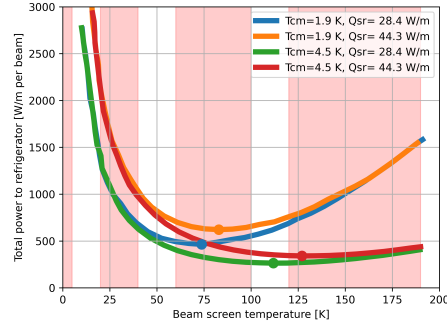
5.1 Interaction of Beams with the Environment

Electromagnetic fields in particle accelerators store and accelerate beams of charged particles. These beams must move in a high vacuum in order to avoid particle loss by scattering on the residual gas molecules [ZK98]. The vacuum chamber generally consists of solid materials like metals to maintain the large difference in pressure to the atmosphere. Most common gas species found are H_2 , H_2O , CH_4 , CO , and CO_2 [LT14].

In static mode -no beam present- the only gas source is the thermal outgassing of the vacuum chamber wall material. At cryogenic temperatures, some of the remaining molecules can condense on the vacuum chamber wall acting as cryo-pumps and helping to lower the pressure of the system as shown in Fig.5.1(a) [Bel20]. In dynamic mode -when the beam is present- beam-induced vacuum effects, such as photon stimulated



(a) vapour pressure vs temperature



(b) power needed for stable cooling

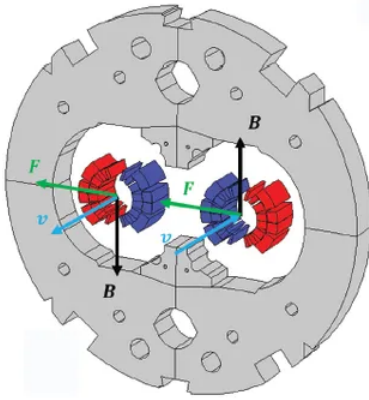
Figure 5.1: (a) Vapour pressure of different gases taken from [ULV21]. (b) Total cryogenic power needed as a function of beam screen temperature, for two different temperatures of the magnet cold bore (T_{mc}) and two different synchrotron radiation heat loads (Q_{sr}). The power consumption minima are indicated with circles. Regions excluded by vacuum issues are shaded in red. Adapted from [LT14].

desorption, electron stimulated desorption, and ion stimulated desorption, can arise.

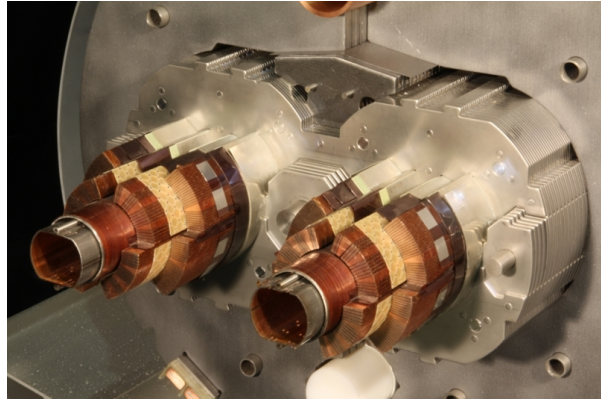
In order to keep a long beam-vacuum lifetime, it has been shown [Bag+12] that there are certain temperature ranges where these static and dynamic vacuum issues can be dealt with by rapid elimination of the physisorbed layers. Based on these considerations the allowed beam screen temperatures are: 5-20 K, 40-60 K, 100-120 K and above 190 K [Bag04], as depicted in Fig.5.1(b) where regions excluded by vacuum issues are shaded in red.

Figure 5.2 shows, the beam screen cross-section of the LHC two-in-one configuration of the BMs in which two vacuum chambers are incorporated into one big iron yoke inside the same cryostat [Brü+04]. The whole iron yoke is cooled down with superfluid helium at 1.9 K to assure high current densities in the NbTi magnet coils operating at $B_{DC} = 8.33$ T. In the previous Ch.4, we have discussed the electromagnetic field distribution of a circulating particle bunch as well as the resulting synchrotron radiation in the dipole bending magnets. Due to the general movement of the operation of accelerators towards high-energy and high-intensity beams, the heat load induced in the surrounding structures has to be minimised to keep the intended operating temperature. Consequently, combined as part of the ultra-high vacuum system, a BS is implemented inside the vacuum chamber as an interception between beam-induced heat loads and the cryogenic environment to preserve the superconducting magnet cold bores operating at 1.9 K as shown in the LHC design for the magnets in Fig.5.2. Here, the cold bore is protected by the beam screen that operates at the higher temperature range of 5-20 K to avoid the synchrotron radiation to reach the cold bore.

However, not only does SR impinge on the beam screen wall, as well particles are absorbed by the BS, generating heat and producing photoelectrons that trigger the gas desorption. Scattered photons and lost particles can extract electrons from the BS wall, which can be resonantly accelerated between opposite walls, extracting additional



(a) 3D slice of the LHC dipole magnet



(b) 2-in-1 dipole configuration

Figure 5.2: (a) A cross section of the LHC dipole 2-in-1 configuration. Blue and red domains represent the superconducting coils keeping the particles in a circular trajectory. The gray domain represents the iron yoke which are needed to keep the superconducting coils in place to counteract the electromagnetic forces. Figure taken from [COM17]. (b) Actual picture of the dipole aperture including the LHC beam screens. Picture is courtesy of CERN.

secondary electrons. This electron multipacting phenomenon triggers a build-up of an electron-cloud (e-cloud) inside the beam screen chamber, leading to instabilities and deposition of energy to the cold wall of the beam screen [Grö01; Ohm+15]. To avoid build-up of an electron cloud, it is necessary to reduce the secondary electron yield (SEY) to a value of $\delta_{\text{SEY}}=1.0$. Thus, selecting the material for the beam screen depends strongly on various material properties at the specific operating temperature.

5.2 Beam Coupling Impedance

The electromagnetic aspect of the beam-environment interaction which we have briefly introduced in Sec.1.5 is one of the main limiting factors for the maximum beam intensity in an accelerator. The charged particles interact over their surrounding electromagnetic field as discussed in Sec.4.2 with elements of the accelerator, mostly the beam screen, but as well other vacuum components as cavities, and directly in between particles as depicted in Fig.5.3(a).

Let us consider two ultra-relativistic charged bunches travelling approximately at the speed of light with a certain distance between them in a round beam screen. The leading charge (red) will be the source bunch and the following charge (green) the trailing bunch. When the source bunch encounters a discontinuity, e.g. a cavity shaped deformation as sketched in Fig.5.3(a), the source self-field produced will change during the passage of the discontinuity and trail behind, referred to as a *wakefield*. In this process, the source bunch loses energy, while the trailing bunch is subject to a net force all along an effective length of the discontinuity, structure or device that caused the wake [Rum13]. Those fields may be trapped in resonant electromagnetic field modes in such deformations or even propagate inside the beam screen, but in any case,

these fields can then effectively reach the trailing particle, as its arrival time at this arbitrary location is delayed and react back on the charge affecting its path through the accelerator [ZK98].

The frequency content of the wakefield (time-domain) can typically be examined by conducting a Fourier transformation on it [FMP13]. This leads to the concept of *beam impedance*¹² (frequency-domain) which indicates the strength of interaction throughout the length of an accelerator component from the source to the trailing charges, normalised by their charges [Mét13]. The beam impedance (or wakefield) results in a ‘kick’ that disturbs the beam pushing it out of the perfect trajectory. As a result, the beam impedance forces will make the beam oscillate, similar to a harmonic oscillator [Ber19] depicted in Fig.5.3(b). The impedance can influence the motion of the trailing particles in the longitudinal $Z_{\parallel}$ and or both transverse $Z_{\perp}$ directions. Either individually, ‘incoherent motion’, or as an ensemble, ‘coherent motion’. In any case, the energy lost by the beam is dissipated in the surrounding equipment producing undesirable secondary effects such as excessive heating of sensitive components at or close to the vacuum chamber wall -known as beam-induced RF heating- [Mét13].

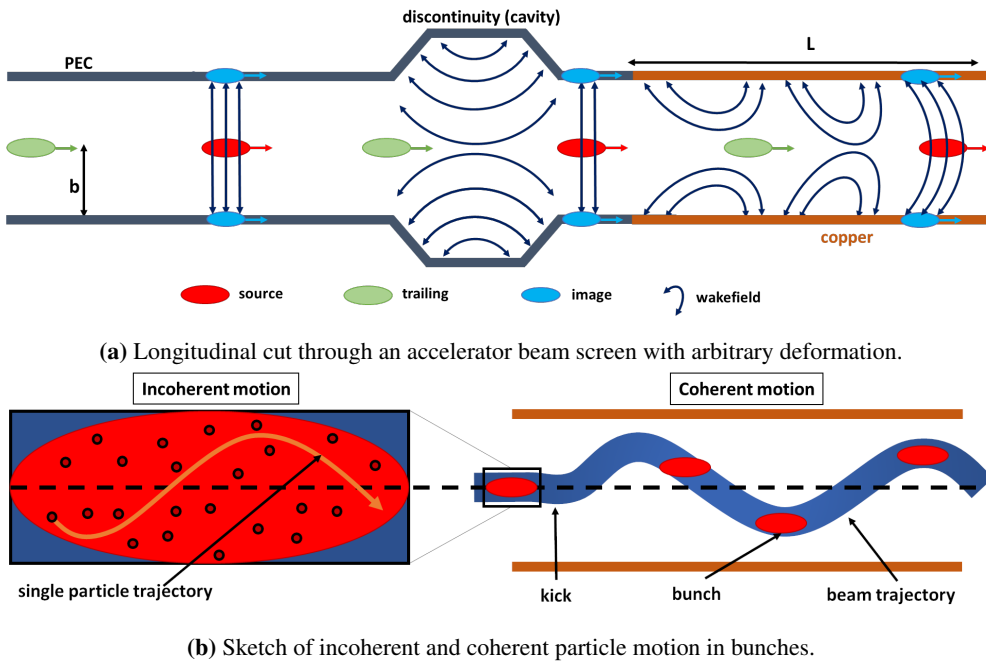


Figure 5.3: The leading particle is the source charge and the following bunch is the trailing charge. The arrows indicate the electromagnetic fields produced by the source charge and wakefields left behind which influences the trailing charge resulting in a coherent or incoherent particle motion. L refers to the Length of the round beam screen and b is the radius. Figures inspired by [Sch09].

¹²It is common to separate the study of self-fields between direct particle-particle interactions (space charge impedance) and indirect particle-particle interactions (beam coupling impedance) [FMP13].

Under unfavourable conditions, as the beam is circulating, the beam impedance forces can act on the beam in a closed-loop (resonant kicks on the particles); thus, the perturbation on the beam further enhances leading to instability and in the worst-case subsequent beam loss and blow-up of the particle beam [Ber19]. A short-lived wake, decaying over the length of one bunch, can only cause intra-bunch (head-tail) coupling; thus, single bunch instabilities may be caused by it [Rum13]. A long-lived wake field that decays over the length of a bunch train or even more than a turn, causes bunch-to-bunch or multi-turn coupling; hence, it could be the cause of multi-bunch or multi-turn instabilities [Rum13].

5.3 Resistive Wall Impedance

The previously mentioned geometric discontinuities are not the only possible origin of wakefields. Beam screens are usually made out of metal and can be seen similar to a Faraday cage [Ber19]. Hence, the travelling positive charges in the center of the beam screen will be accompanied by a ring of induced *image charges* of the same total magnitude formed on the surface of the beam screen walls where the electric field of the self-field ends, as seen in Fig.5.3(a). As long as source and trailing charges move in a smooth, constant cross-section, and PEC beam screen, the induced charged (blue) move in synchronism with the bunch on axis, therefore called *image currents* [MS20]. Thus, no forces will act on the trailing charge because no wakefields are produced. However, the situation is somehow different, if the material in the beam screen walls has a finite conductivity, e.g. copper, as shown in Fig.5.3(a). The image currents are hindered by the resistivity, which will give rise to ohmic dissipation, consequently heating, and a wakefield perturbing the trailing bunch. The resulting *resistive wall impedance* (RW-impedance) can be approximated in the ultra-relativistic regime and low frequencies in a round BS through [Cha93]:

$$Z_{\parallel}^{\text{RW}}(f) = \frac{Z_s(f)L}{2\pi b} \quad Z_{\perp}^{\text{RW}}(f) = \frac{cZ_s(f)L}{2\pi f b^3}, \quad (5.1)$$

where f refers to the frequency, b the beam screen radius, Z_s the surface impedance of the BS material, c the speed of light, and L the length of the BS. It can be noticed from Eq.(5.1) that the impedance depends strongly on the BS radius as well as on surface impedance.

As discussed in Sec.1.6, the resistive wall impedance is one of the most important sources of beam impedance in large high-energy accelerators and it is responsible for low intensity thresholds [Mig+19]. The transverse effects due to the RW-impedance are usually more severe than longitudinal ones [Mét11]. Transverse RW-impedance is responsible for coupled bunch instabilities, especially in machines with small beam screens, i.e., small radius.

5.4 Technical Requirements for a ReBCO-CC Beam Screen

The requirements of a technologically advanced collider as the FCC-hh demands a novel design of a beam screen that is able to cope with the challenging operating

conditions. Even though the baseline design with a Cu beam screen ensures that the impedance is low enough for beam stability, a higher stability margin is desirable from an operational point of view and this search has led to the present investigations of using HTS as coating material for the beam screen as discussed in Sec.1.7.

In order to determine if ReBCO-CCs provide the desired solution for the extreme conditions in the beam screen as described in Sec.1.9, we must investigate the ReBCO-CC's superconducting properties under the FCC-hh conditions and assess their compatibility with the needs of a high-energy circular collider. Despite the high critical temperature of ReBCO-CCs for practical uses in terms of relative low cooling requirements, other properties must as well fulfil the FCC-hh requirements. The critical current density, magnetic sustainability, mechanical nature, and vacuum stability are as relevant for the concrete application in the beam screen as the high T_C .

In Sec.5.3, we discussed that the resistive wall impedance is directly dependent on the surface impedance, which, as explained in Sec.3.4, is frequency dependent.

The lowest frequency important for the beam impedance to expect in the FCC-hh is close to the revolution frequency $f_{min}^{inj} \approx 2$ kHz at injection. On the other side of the frequency spectrum, the highest frequency is dependent on the bunch length, as shown in Fig.4.3(b). According to the 8 cm bunch length for the FCC-hh we can estimate $f_{max} \approx 3$ GHz. Having discussed the two limits of the frequency range of interest we shall resume -for completeness- how the beam spectrum in between these two frequencies looks like and what it could mean for the superconductors and the measurements within this thesis. An actual measurement of a beam power spectrum is shown in Fig.5.4 for the LHC taken in 2011 for a stable beam. The figure shows the power amplitude measured as a function of frequency. To understand this figure, as a recapitulation, we start with the spectral information contained

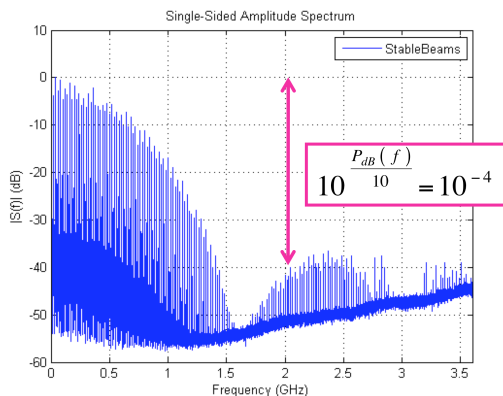


Figure 5.4: Power spectra measurement for LHC beam 1 taken from [Mét13].

in a single bunch passing along the axis of the beam screen at a certain position. As discussed in Sec.4.2, we assume a Gaussian longitudinal particle distribution in time and accordingly, we expect a Gaussian distribution in frequency¹³. As depicted in Fig.4.3(b), a continuous frequency spectrum is seen, which means that the single bunch spectrum contains all frequencies within. If we now assume a continuous sequence of single bunches passing periodically with defined bunch spac-

¹³We are only taking the positive half of the distribution into account as negative frequencies have no significance for the description of physical phenomena.

ing, then the continuous frequency spectrum of a single bunch at single passage becomes a line spectrum with equidistant discrete frequencies at multi passage [Sch20]. The reason lies within the fact that since the several bunches are passing with a time delay of the bunch spacing, all the existing frequency components will constructively or destructively interfere resulting in the discrete residual frequency spectrum [Sch20]. In Fig.5.4, a large number of peaks -with the highest amplitudes- are spaced apart by about 20 MHz, which is expected for the used 50 ns bunch spacing. These peaks represent the fundamental bunch frequency, which corresponds to the inverse bunch spacing, and its series of frequency harmonics below an envelope -corresponding to the expected bunch length and distribution- that is reducing in amplitude as a function of frequency up to a specific value before revealing a side lobe with a height of about -35 to -40 dB [Mét13]. A continuous series of bunches is not entirely a suitable representation of a circular accelerator. Due to bunch injection and extraction, gaps exist at positions where a bunch could be circulating; hence, resulting in a greater bunch spacing between two groups of bunches. As soon as the continuous bunch pattern is modified by aforementioned gaps, the revolution harmonics, which exist at every multiple of the revolution frequency, appear surrounding each bunch frequency line [Sch20]. In addition, the bunches oscillate in both transverse planes (betatron oscillations) which leads to a series of revolution harmonics with side-bands around them [Sch20].

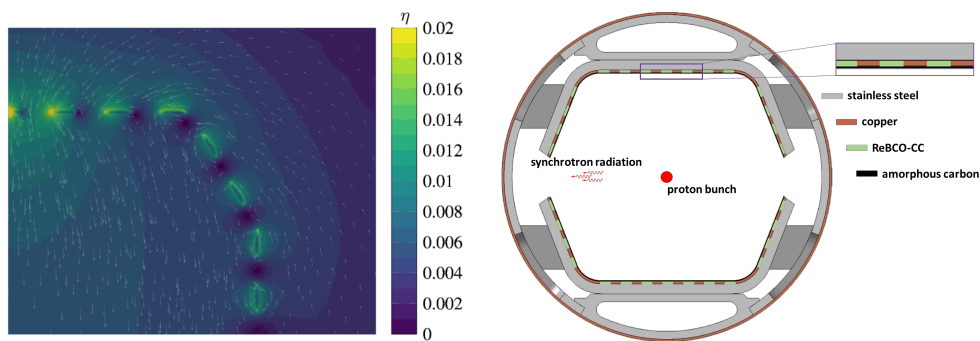
As a consequence of the aforementioned, the ReBCO-CCs in the FCC-hh BS will experience EM fields which are not simple harmonic in time. Thus, the conditions faced by the ReBCO coated conductors in the accelerator are not precisely replicated by the comparison with surface impedance measurements at a fixed frequency. Regardless of the fact that the spectrum is discrete, surface impedance of ReBCO-CC will have broadband features, meaning that it will not change much in the short frequency intervals between spectral lines. In other words, the linear behaviour of ReBCO-CC can be tested by making measurements at a few frequencies chosen according to the spectrum envelope and ignoring the fact that the spectrum is discrete. Accordingly, a lengthy discussion on the reasons that make the spectrum discrete is probably not very relevant. In the linear regime one should measure at multiple frequencies within the beam screen spectrum. In the non-linear regime, how strong the influence of the different multiple harmonics in the beam frequency spectrum with arbitrary different magnitudes on ReBCO can be, is out of scope of this doctoral thesis. Nevertheless, within the FCC-hh frequency region, the stronger frequency dependency of ReBCO-CC's surface impedance compared to copper can be beneficial, as explained in Sec.3.4.

In addition, the surface impedance of coated conductors can be drastically changed when a magnetic field is applied. At the injection energy of 3.3 TeV, a dipolar magnetic field of $B_{DC} = 1$ T is present. As discussed in Ch.2, an applied magnetic field on HTSs induces vortices in the materials, which interact with each other forming a vortex lattice. The proton bunches induce a high radio-frequency current with which the vortex lattice will interact. It is therefore necessary to investigate the image current (or RF field) induced flux motion and flux shaking [see Sec.2.2.3], taking into account the timing and field strength of the circulating proton bunches. In addition, the magnetic field will

be ramped from injection to collision from $B_{DC} = 1$ T to 16 T within approximately 30 min [Ben+19b]. During this time, more vortices will penetrate the ReBCO-CCs. The previously discussed discrete frequency components will influence the vortex motion which is addressed in [CV21].

Not only is the surface impedance responsible for the beam stability, but the magnetic field quality has to be considered. As aforementioned, the number of vortices per ReBCO-CC will change as a function of time until 16 T is reached. The superconducting layer of the CC disturbs due to the shielding effect and vortices -this depends strongly on the geometry- the homogeneity of the magnetic dipole fields in the bending sections. The question is as to what degree a ReBCO-CC microscopically (magnetic flux density bending through a vortex, vortex displacement, and vortex shaking) and macroscopically (magnetization due to persistent currents and vortex lattice shaking) manipulates the dipole magnetic field quality. The relative deviation from the ideal homogeneous field in the aperture of a magnet should not exceed a few parts in units of 10^{-4} to be able to store the high-intensity particle beam [Völ02]. Work conclusion in [NBC17; Pat+19] based on the Bean critical model [Bea64] [see Sec.2.2.2] affirmed that a ReBCO-coating in the form of stripes is practical as the magnetisation in striated ReBCO [Cob+02] impairs the magnetic field quality strongly for a complete coating as shown in Fig.5.5(a). Thus, a compromise between field quality and impedance reduction has to be found. For this reason, one idea would be to place ReBCO-CCs stripes on several chosen positions in the beam screen to satisfy the impedance requirements as well as the magnetic properties needed for a stable beam. This leads to the idea of having a *hybrid beam screen* coating [KNB18]. One example configuration is shown in Fig.5.5(b). However, the final configuration of the positions and width of the ReBCO-CCs will depend on the compromise between beam impedance, magnetic field study and the possibility to attach the material inside the BS.

During a magnetic quench, the beam screen has to withstand Lorentz's forces



(a) relative magnetic field disturbance for a hybrid beam screen

(b) example hybrid Cu-ReBCO beam screen

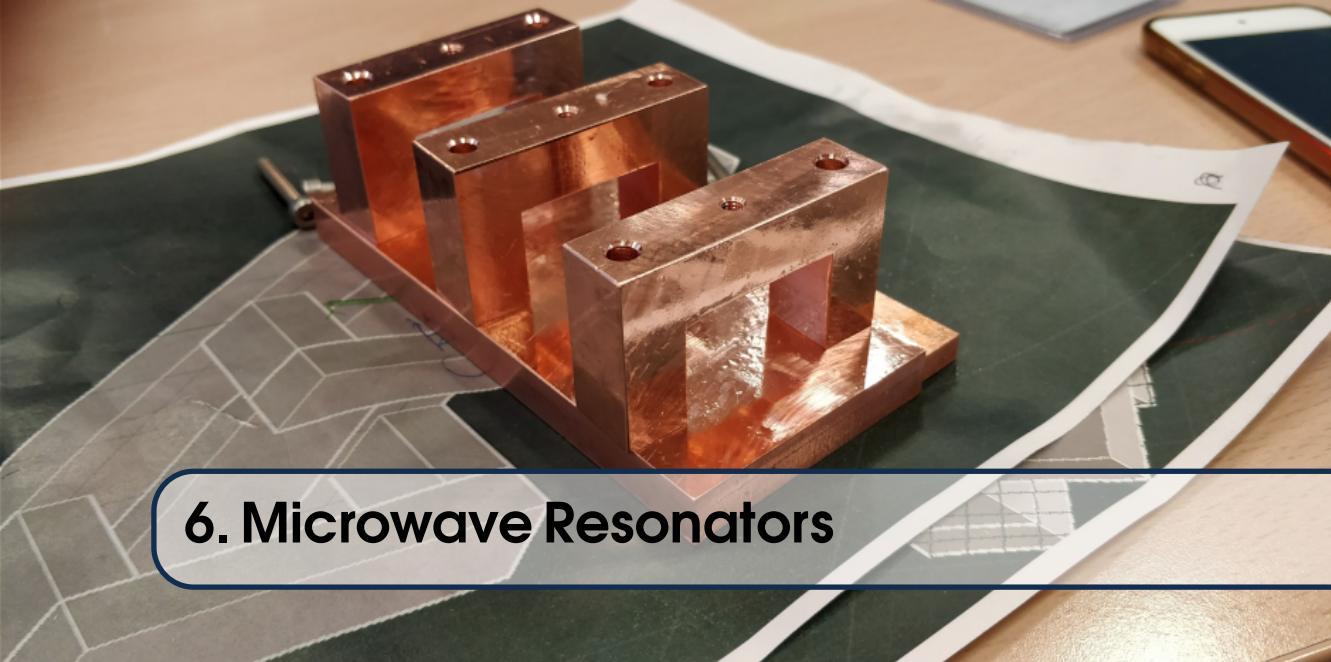
Figure 5.5: (a) Relative disturbance of magnetic field η as contour and absolute difference for quarter of the beam screen. Taken from [Pat+19]. (b) Example for a hybrid beam screen with alternating ReBCO (green) and Cu (orange) stripes covered with aC (black) for the baseline design beam screen. Figure adapted from [Bel20].

without plastic deformation. The mechanical forces that arise depend strongly on the material's conductivity, forcing the beam screen to be stretched outwards on the horizontal axis. Hence, the ReBCO-CCs must have a mechanically stable attachment. Besides this worst-case scenario of a magnetic quench, already during the ramping the mechanical forces on the ReBCO-CC will be trying to pull the coating towards the inside centre of the beam screen. How to implement coated conductors into the beam screen is a major challenge in this investigation. Especially, because not every glue or solder is vacuum compatible and fulfils the vacuum requirements as discussed in Sec.5.1.

Besides possible out-gassing effects of the ReBCO material in the vacuum, the e-cloud has to be suppressed. The emission of electrons is crucially dependent on the surface properties of the material and can be reduced by thin-film coatings, or surface treatments by laser ablation [Cal+09]. These e-cloud effects are considered a serious issue for the FCC-hh as they cause coherent instabilities [see Sec.5.2]. Laser treatment of the ReBCO layer is infeasible as it would destroy the material. Consequently, a hybrid beam screen must be combined with a very thin surface layer of amorphous carbon coating. This treatment, on the one hand, might limit the secondary-electron yield (SEY) value below the necessary threshold to mitigate e-cloud build up [Han+21; Val+14; Val+17]. On the other hand, it might produce simultaneously undesirable effects such as an increase in the surface impedance and loose carbon particulates.

- Devices and Methods for ReBCO testing -

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The image shows three rectangular copper components, likely microwave resonators, arranged in a row on a dark green circuit board. Each component has a central rectangular cutout and four small holes on its top surface. The components are resting on a light-colored wooden surface, with a smartphone visible in the top right corner.

6. Microwave Resonators

Do not settle for average. Bring your best to the moment. Then, whether it fails or succeeds, at least you know you gave all you had. We need to live the best that is in us.

Angela Bassett

The experimental techniques used in this thesis are based on non-destructive measurements of radio-frequency losses, which can be associated with the surface impedance of the materials under examination. A well-established technique, which is extensively used, is based on resonating structures and the precise determination of resonance frequency and quality factor, which are then related to surface impedance. Therefore, we introduce the basic parameters measurable with resonators in this chapter and further explain their relationship to the physical parameters discussed in the previous chapters. Further, we present how to extract the quality factor and resonance frequency accurately when using the vector network analyser's scattering parameters and introduce its implementation into an open-source Python code, which we have made available under a freeware license. The routine to extract the resonator parameters has been published ©[2022] IEEE, and parts of the publication are reprinted in this chapter, with permission, from [Krk+21a].

6.1 Microwave Resonator

A microwave resonator is any structure that can confine an oscillating electromagnetic field. Either the structure is hollow, or dielectric material is used to fill it. In principle, it accommodates a number of *resonant modes*, each one having a different EM-field configuration that can only be held at a specific *resonance frequency* f_0 . Considering the requirements for the measurements of surface impedance mentioned in Sec.1.10, we decided to use cavities partially filled with dielectrics, which are usually referred to as *dielectric resonators* (DR). These resonators are capable of concentrating most of the electromagnetic fields within the dielectric and generate large RF current densities on the samples being measured. In addition, the size of a DR is considerably smaller than the size of an empty resonant cavity operating at the same frequency, provided the relative dielectric constant of the material is a number substantially larger than unity. If the cavity of the resonator is completely filled, the resonance frequencies decrease by a factor $\sqrt{\epsilon_r}$, with respect to those of an air-filled cavity. Nowadays, materials having a dielectric constant between 10 and 100, relatively independent of temperature and/or low dielectric losses, have become available, e.g., sapphire and titanium dioxide. As in all resonators used to determine material properties, relating resonator parameters (Q_0 and f_0) with those characterising the material (Z_S and/or $\tan(\delta)$) requires knowing the spatial distribution of the electromagnetic fields at the resonant mode(s) used, either by using mathematical equations or numerical simulations.

6.2 Characteristic Parameters of Resonators

The *unloaded quality factor* Q_0 is used to characterise RF loss in a resonator. It is defined as the ratio of the stored electromagnetic field energy U_{st} to the power dissipated P_{diss} in the resonator, in one oscillation period [Jac75]:

Definition 6.2.1 — Unloaded Quality Factor.

$$Q_0 = 2\pi f_0 \frac{\text{energy stored in the cavity}}{\text{power dissipated}} = \frac{\omega U_{st}}{P_{diss}}. \quad (6.1)$$

For cavity resonators, the power dissipation by ohmic loss P_κ , dielectric loss P_d , and radiation P_r contribute to the unloaded quality factor. These different loss mechanisms can be individually accounted for, and the total power dissipated is the sum of the individual components:

$$P_{diss} = P_\kappa + P_d + P_r. \quad (6.2)$$

Substituting Eq.(6.2) into Eq.(6.1), the unloaded quality factor becomes:

$$\frac{1}{Q_0} = \frac{1}{Q_\kappa} + \frac{1}{Q_d} + \frac{1}{Q_r}, \quad (6.3)$$

where Q_κ refers to the conductor Q-factor, Q_d the dielectric Q-factor, and Q_r the radiation Q-factor. This equation reveals that the higher the losses are, the lower the

value of the quality factor is. Furthermore, the lowest Q_i of the three Q-factors in the right-hand side of Eq.(6.3) will tend to dominate, and if it does, it will approximately be equal to Q_0 [Kaj11].

The conductor losses are those associated with the conduction currents relating thereto ohmic dissipation in the resonator walls. They can be expressed over Eq.(6.1) leading to the following relation [Lan06]:

$$Q_\kappa = \frac{\omega \iiint_{\text{res}} \mu |\vec{H}|^2 dV}{\kappa \iiint_{\text{con}} |\vec{E}|^2 dV} = \frac{\omega \mu \iiint_{\text{res}} |\vec{H}|^2 dV}{R_s \iint_{\text{con}} |\vec{H}|^2 dA} = \frac{G}{R_s}. \quad (6.4)$$

The integral with the subscript ‘res’ in the numerator represents the total energy stored U_{st} within the resonating structure and, therefore, is an integration over the whole volume of the resonator. The integral in the denominator with subscript ‘con’ represents the average power dissipated over the conducting volume. This can be expressed as the integral into the conductor, normal to its surface, resulting in a surface integral including the expression of the surface resistance [Lan06]. In addition, we define the *geometry factor* G . This parameter depends only on the dimensions of the resonating structure and the magnetic field distribution of the resonant mode. In some simple resonator geometries, its value can be determined analytically, whereas in complicated structures, it has to be numerically calculated with the aid of electromagnetic simulation software. The integral in the denominator can be split as the sum of several integrals, one for each cavity surface, which can be convenient, e.g., if the resonator is constructed of different materials which contribute differently to the unloaded Q-factor.

If the whole resonator or parts of the resonator are filled with a dielectric material, then there will be a loss of energy by dissipation in the dielectric expressed over the dielectric quality factor Q_d [Lan06]:

$$Q_d = \frac{\omega \iiint_{\text{res}} \mu |\vec{H}|^2 dV}{\kappa \iiint_{\text{die}} \epsilon |\vec{E}|^2 dV} = \frac{1}{\tan(\delta)} \frac{\iiint_{\text{res}} \epsilon |\vec{E}|^2 dV}{\iiint_{\text{die}} \epsilon |\vec{E}|^2 dV} = \frac{1}{p \cdot \tan(\delta)}, \quad (6.5)$$

where we define the dimensionless *filling factor* p that indicates the ratio between the energy of the electric field stored within the dielectric volume and the total energy stored in the resonator. If the whole resonating structure is filled with one dielectric the two integrals, numerator -integral over the whole resonator volume- and denominator -integral over the whole dielectric volume- cancel each other out, resulting in a filling factor equal to one.

In the scenario where the resonator is not fully closed, parts of the electromagnetic fields will escape the structure and lead to radiation losses. It is of interest to analyse how much this radiation affects the resonator operation. Again over Eq.(6.1) we can define the radiation quality factor as [Lan06]:

$$Q_r = \omega \frac{\iiint_{\text{res}} \mu |\vec{H}|^2 dV}{\iint_{\text{sphere}} \frac{1}{2} \text{Re}\{\vec{E} \times \vec{H}\} \cdot d\vec{A}} \xrightarrow{\text{free space}} 2\omega \sqrt{\mu \epsilon} \frac{\iiint_{\text{res}} |\vec{H}|^2 dV}{\iint_{\text{sphere}} |\vec{H}^*|^2 dA}, \quad (6.6)$$

where the average power dissipated is given by the Poynting vector as given in Def.3.4.3 integrated over a sphere surrounding the resonating structure. If the integral can be

solved in free space in a far away approximation, then the integral of the denominator can be reduced to the magnetic field distribution only.

Suppose any further losses are present that are not discussed in this section, e.g. adding a second dielectric to the resonator. In that case, the losses can be added similarly as described in the three cases above.

6.3 Coupling to the Microwave Field

In order to use the cavity, it is necessary to excite the desired modes via probes, coupling loops, or other coupling structures. Inductive coupling via loops or capacitive coupling via probes are both used in this thesis and are common coupling elements between resonators and coaxial lines. However, any connection to the cavity to couple the electromagnetic fields into it, e.g., transmission lines, will absorb power and has to be considered in the correct estimation of the unloaded quality factor.

Analogously to the previous section, the power loss due to the presence of any external coupling device can be described through the external quality factor:

$$Q_{\text{ext}} = \frac{\omega U_{\text{st}}}{P_{\text{ext}}}. \quad (6.7)$$

Here, the stored energy U_{st} is the stored energy in the resonator as in Eq.(6.1), and P_{ext} rises is the dissipated power due to external losses, as the resonator has to be attached to an external circuit for power supply.

The loaded Q-factor Q_L is the total quality factor that includes the total losses, external and internal. For a two-port configuration, as indicated in Fig. 6.1, the loaded Q-factor can be written as [Hei99]:

$$\frac{1}{Q_L} = \frac{P_{\text{total}}}{\omega U} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}_1}} + \frac{1}{Q_{\text{ext}_2}} + \frac{1}{Q_{\text{paras}}}, \quad (6.8)$$

where the index in the external Q-factor refers to the designated port. Often, in optimised measurement systems, the parasitic quality factor Q_{paras} can be accommodated to very high values much above Q_{ext_i} , and thus, its inverse can be neglected [Hei99].

In practice, Q_L is the only experimentally measurable Q-value and Q_0 is estimated from Q_L and other resonator parameters (coupling factors), all of which are determined by the analysis of the measured response in the frequency domain over a narrow frequency range close to resonance. This is generally done by measuring the complex scattering parameters (*S-parameters*) with vector network analysers (VNAs). Complex scattering parameters characterise networks by means of complex ratios between normalised voltages of the incoming and outgoing waves. The term scattering applies to the way in which the travelling waves in a transmission line are affected when they encounter a discontinuity, e.g., impedance mismatch caused by the insertion of a network into the transmission line. When the travelling waves reach the input of the device under test, part of the signal can be reflected back towards the signal origin at one port, while the rest of the signal is transmitted through the device to the other port.

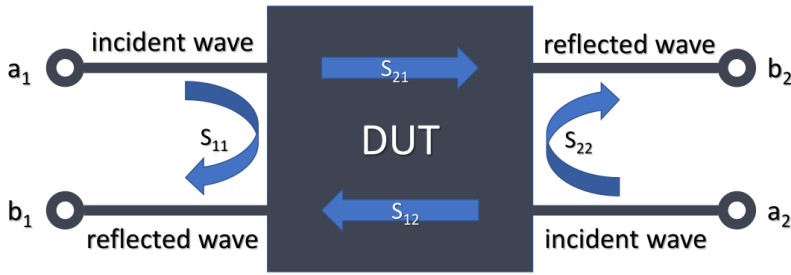


Figure 6.1: Schematic representation of the scattering parameters of a 2-port resonator.

Figure 6.1 shows the case of a two-port network and the relationship between reflected, incident and transmitted waves a_i and b_i [Poz11]:

$$\text{reflection : } S_{ii} = \left. \frac{b_i}{a_i} \right|_{a_j=0} \quad \text{and} \quad \text{transmission : } S_{ij} = \left. \frac{b_i}{a_j} \right|_{a_i=0}, \quad (6.9)$$

where the indices i, j are: $i = 1, 2; j = 1, 2; i \neq j$. As indicated, in Eq.(6.9), we assume that only one port is excited at a time, so the incident wave is zero for the other ports, which are terminated with the system's characteristic impedance [Poz11]. For a two-port device, four ratios can be formed that are traditionally denoted as S_{ii} - S_{11} and S_{22} correspond to the complex reflection coefficients at ports 1 and 2, respectively- and S_{ij} - S_{21} corresponding to the transmission coefficients having port 1 as input and port 2 as output, vice versa for S_{12} .

At present, VNAs store the S-parameters in the so-called *Touchstone* format (.snp) [For09], which has become the de facto industry-standard file format for the measurement equipment. Touchstone files represent the S-parameters in linear magnitude and angle, logarithmic magnitude and angle, or real and imaginary part, though in all three cases versus frequency.

The link between the magnitude of S-parameters at the resonance frequency and the unloaded Q-factor is given by the coupling factors β_i [Kaj11]:

$$\beta_1 = \frac{1 - |S_{11}|}{|S_{11}| + |S_{22}|} \quad \beta_2 = \frac{1 - |S_{22}|}{|S_{11}| + |S_{22}|} \quad |S_{21}| = |S_{12}| = \frac{2\sqrt{\beta_1\beta_2}}{1 + \beta_1 + \beta_2}, \quad (6.10)$$

that, in addition, describe the ratio of power dissipated in the external circuit to the power dissipated in the resonator [Kaj11]:

$$\beta_i = \frac{Q_0}{Q_{\text{ext}_i}}. \quad (6.11)$$

By substituting Q_{ext_i} from Eq. (6.8) into Eq. (6.11), one obtains the relationship between the unloaded and the loaded quality factor as follows:

$$Q_0 = Q_L(1 + \beta_1 + \beta_2). \quad (6.12)$$

For identical input and output coupling ($\beta_1 = \beta_2 \ll 1$), Q_0 can be determined approximately by [Kaj11]:

$$Q_0 = \frac{Q_L}{1 - |S_{21}|} \Big|_{\beta_1 = \beta_2}. \quad (6.13)$$

If, in addition, weak coupling is established and the peak in S_{21} is below -40 dB, the external load then can be neglected, leading to:

$$Q_0 = \frac{Q_L}{1 - 10^{-40/20}} = \frac{Q_L}{0.99} \approx Q_L. \quad (6.14)$$

Theoretically, Q_L can be roughly determined from the shape of the resonance peak over three frequency points, also known as the 3 dB method. As shown in Fig.6.2, the three points are the S_{21} maximum (f_0), the lower (f_1) and upper (f_2) -3 dB bandwidth frequency points defined as the width of the peak at half its maximum amplitude. The loaded quality factor of the system is inversely proportional to the difference between the 3 dB frequencies f_1 and f_2 at the left and right side of the resonance frequency f_0 [Kaj11]:

$$Q_L = \frac{f_0}{f_2 - f_1}. \quad (6.15)$$

In summary, the loaded quality factor Q_L characterises the internal losses of the resonator. The losses due to external networks are characterised by the coupling coefficients described in Eq.(6.10).

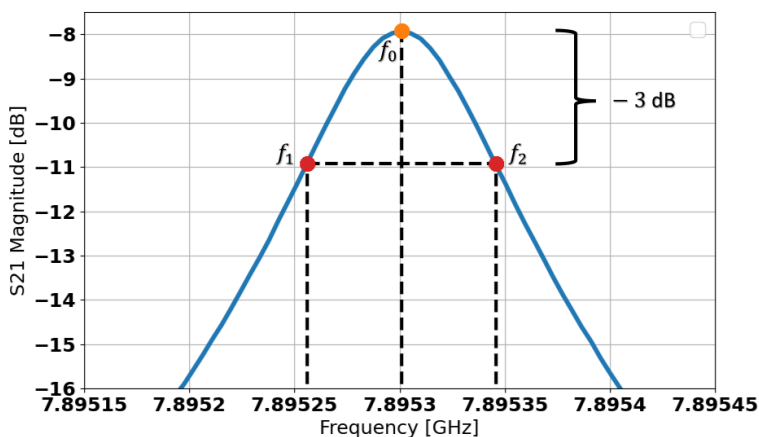


Figure 6.2: Example of a Lorentzian line shaped S_{21} -Parameter. The marked points (resonance f_0 in orange, f_1 and f_2 at -3 dB from the maximum value in red) represent how the loaded quality factor can be estimated within the 3 dB method.

6.4 Resonator Perturbations

The resonance frequency of a resonator is determined by its geometrical dimensions and permittivity of the dielectric used [see Sec.6.1]. Hence, it is sensitive to changes in the dielectric properties, the change in the effective size of the resonator, mechanical tolerances, and coupling elements. Some of these changes may be due to temperature changes. In this section we will use Slater's theorem [Hei99; Sla50] to calculate the frequency shift $\Delta\omega = 2\pi\Delta f$ due to these perturbations.

Definition 6.4.1 — Slater's Perturbation Theorem.

$$\frac{\omega - \omega_0}{\omega_0} \approx \frac{\iiint_{\Delta V} \epsilon |E_0|^2 - \mu |H_0|^2 dV}{\iiint_V \epsilon |E_0|^2 + \mu |H_0|^2 dV} = \frac{\Delta U_E - \Delta U_M}{U_{tot}} \quad (6.16)$$

Figure 6.3 (left) represents a resonator formed by a PEC covering the surface Γ and enclosing the volume Ω , while Fig. 6.3 (right) depicts a deformation of the original resonator (left) such that the conductor covers $\Gamma' = \Gamma - \Delta\Gamma$ and encloses $\Omega' = \Omega - \Delta\Omega$. The EM fields and resonance frequency are known in the unperturbed resonator. According to Slater's theorem, the frequency shift due to the perturbation can be calculated with Eq.(6.16), where the fields in the integrals are those of the unperturbed resonator, the integrand in the numerator extends over the perturbation volume, and that of the denominator extends over the entire, unperturbed resonator volume.

In the case of lossy walls, we can consider the surface impedance boundary condition from Def.3.4.1 giving [Har01; Lan06]:

$$\frac{\omega - \omega_0}{\omega_0} = \frac{-i \iint_A Z_S H \cdot H_0^* \cdot \hat{n} dA}{\omega_0 \iiint_V \epsilon E \cdot E_0^* + \mu H_0^* \cdot H dV} = \frac{-i \iint_A Z_S H \cdot H_0^* \cdot \hat{n} dA}{2\omega_0 \iiint_V \mu H_0^* \cdot H dV}, \quad (6.17)$$

where we assume that the electric U_E and magnetic U_M energy are equal. Bear in mind, that in this case the tangential component of the electric field over the surface will not vanish $\hat{n} \times \vec{E} \neq 0$ and we get [Har01]:

$$\frac{\omega - \omega_0}{\omega_0} = \frac{-X_S \iint_A |H_0|^2 dA}{2\omega_0 \iiint_V \mu |H_0|^2 dV} = -\frac{X_S}{2G}. \quad (6.18)$$

In the case that a shift in resonance frequency results from the inclusion of materials

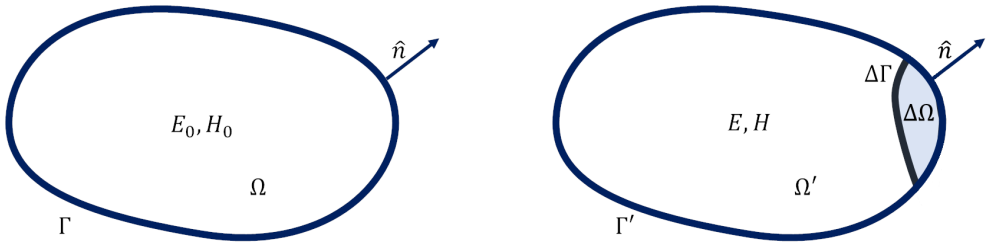


Figure 6.3: An arbitrary resonating structure in two different scenarios: unperturbed (left) and perturbed (right). Figure inspired by [Har01].

with permittivity changes $\varepsilon = \varepsilon + \Delta\varepsilon$, Eq.(6.16) leads to [Har01]:

$$\frac{\omega - \omega_0}{\omega_0} = -\frac{\iiint_V \Delta\varepsilon |E_0|^2 + \mu |H_0|^2 dV}{\iiint_V \varepsilon |E_0|^2 + \mu |H_0|^2 dV} = -p \frac{\Delta\varepsilon}{2\varepsilon}. \quad (6.19)$$

6.5 Algorithm for Resonator Parameter Extraction

6.5.1 ARPE

The importance in the accurate determination of the main resonator parameters, namely loaded quality factor Q_L , resonance frequency f_0 , coupling coefficients β_i and resulting unloaded quality factor Q_0 , is key for this thesis. The determination of surface impedance relies strongly on these parameters as seen in Eqs.(6.4) and (6.18). The drawback of the 3 dB bandwidth explained in Sec.6.2 is that it relies solely on the discrete data given by the number of frequency points used in the VNA measurement. Furthermore, it requires weak coupling on the input and output ports. Since, according to Eq.(6.10) weak coupling results in low $|S_{21}|$ at resonance, this method provides less accurate results when the signal-to-noise ratio decreases and/or the shape of resonance curve deviates from a Lorentzian such as the one shown in Fig.6.4. Many different parasitic phenomena, such as noise, frequency-dependent delay, transmission line and connector losses, crosstalk, etc., can distort the shape of the reflection and transmission response [PA98], see for example, the off-resonance slope in S_{11} and S_{22} in Fig.6.4. Due to this, an algorithm based on Python has been developed. It uses techniques that are less sensitive to experimental errors than the 3 dB bandwidth as described in the paragraphs below.

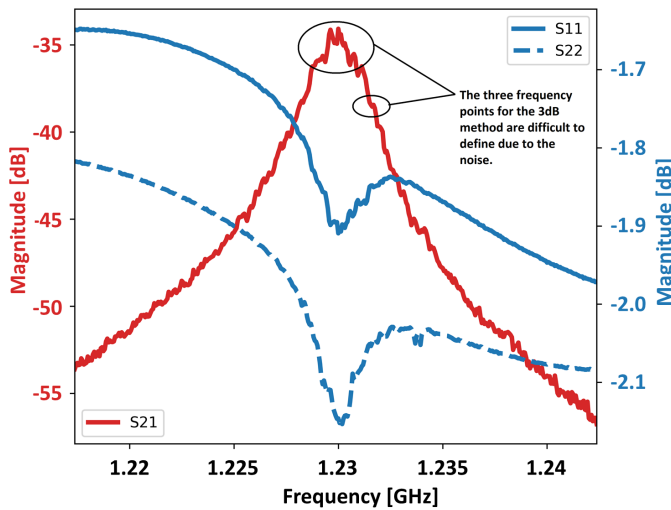


Figure 6.4: The Magnitude of the measured S-parameter in a two port configuration. A noisy trace introduces uncertainties defining the three frequency points for the 3 dB bandwidth method.

The *algorithm for resonator parameter extraction* (ARPE) is capable of extracting Q_0 and the f_0 of microwave resonators from vector S-parameters. Both symmetrical (Lorentzian) and asymmetrical (Fano) transmission responses are supported. The algorithm performs an adaptive outlier removal to discard measurement points affected by noise or distortion. In addition, it has then been further developed into a web-executable Python application with open-source access to the source code to promote the use of microwave resonators outside the engineering community [Gal20; Krk+21a; Krk+21b; Krk+21d].

6.5.2 Transmission Response in the Complex Plane

To eliminate uncertainties in the determination of the resonator parameters, it is preferable to make use of more than only three frequency points by including a fitting procedure. To be able to fit not only symmetrical Lorentz shaped transmission responses [see Fig.6.5 (left red curve)], but also asymmetrical responses, including those following a Fano profile [see Fig.6.5 (left blue curve)], it is preferable to take a look at the S-parameters in the complex plane. Regardless of the transmission response shape in the magnitude versus frequency plot, the same data plotted in the complex plane follows a circular pattern as presented in Fig.6.5 (right). The important properties of this *Q-circle* are that, in the ideal case, the circle starts and ends at the origin, whereas the resonance frequency is located straight on the opposite side of the Q-circle. However, non-idealities in real measurements have certain effects on the smoothness and shape of the Q-circle:

- Noise is always present in any VNA measurement and produces random variations in the amplitude and phase of the complex S-parameters. In the complex plane, this leads to a deviation of each individual data point position away from the ideal Q-circle which is shown in Fig.6.6(a).
- Often, especially in cryogenic experiments, the calibration possibilities of the transmission lines connecting the VNA and device under test are limited. Uncal-

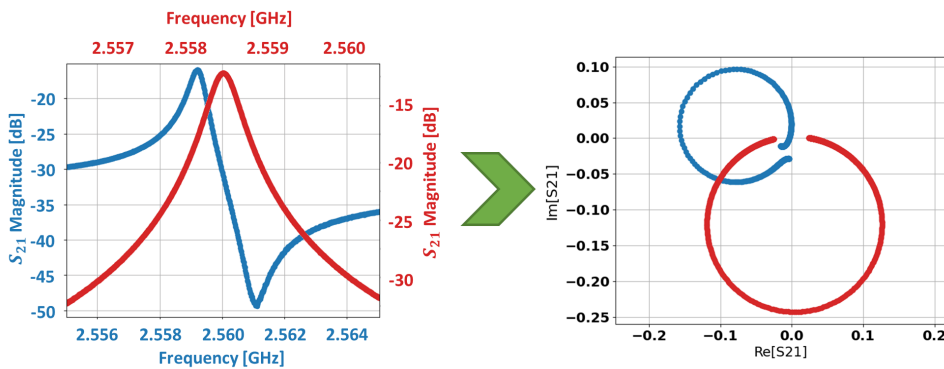


Figure 6.5: Symmetrical and asymmetrical transmission response and each individual mapping in the complex plane. The frequency increases clockwise starting from the left-handed origin. Adapted from [Krk+21a]

ibrated transmission lines can introduce frequency-dependent electrical delay, equivalent to a frequency-dependent phase shift [Kaj11]. The frequency dependence of the phase shift rotates the data points on the Q-circle around the origin as indicated in Fig.6.6(b) but its effect on points at higher frequencies is larger than that at lower frequencies. Hence, distortion of the circular shape occurs, re-shaping the Q-circles to a 'balloon' shape [Pro+15].

- Stray coupling between the two coupling ports of a resonator can lead to so-called cross-talk commonly present in Fano responses. The cross-talk can often be assumed to be frequency-independent, and thus, it does not distort the shape of the Q-circle; rather it results in an offset of the position of the whole circle with respect to the origin of the complex plane as indicated in Fig.6.6(c).

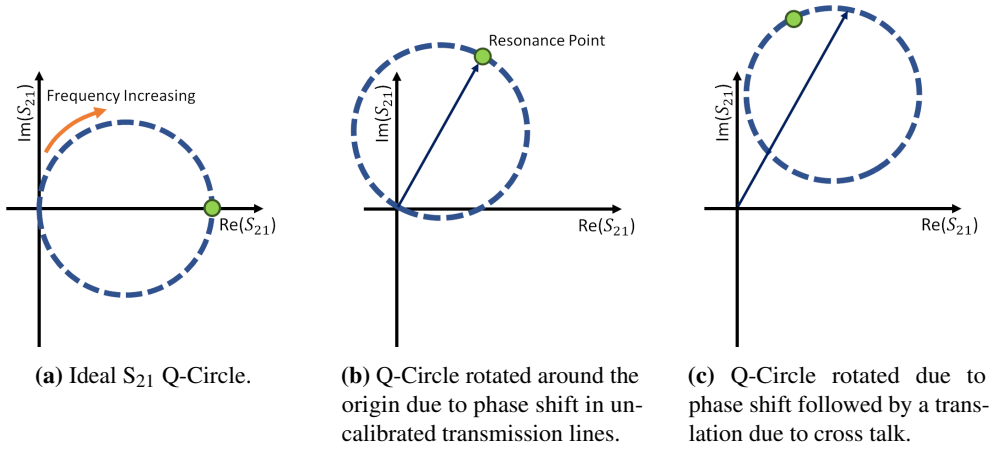


Figure 6.6: Q-Circles including different parasitic effects. Adapted from [Tor+89].

6.5.3 Algorithm Fitting Procedure

To define an algorithm being capable of coping with these parasitic effects introduced on the resonator response, we start with the relation between the resonator transmission response and some characteristic resonator parameters given by [SMZ19] as:

$$S_{21_k}(f_k) = \frac{S_{21\text{res}}}{1 - 2iQ_L \left(\frac{f_k - f_0}{f_0} \right)}. \quad (6.20)$$

Here, $S_{21}(f_k)$ are the values of S_{21} measured at discrete frequencies f_k , $S_{21\text{res}}$ is the maximum value given at the resonance frequency f_0 , and the subindex $k = 1 \dots n$ refers to each data point with the total amount of n points. An initial guess of the resonance frequency can be made by assuming the frequency at which the magnitude of S_{21} is maximum. However, due to the discrete data, this is not very accurate, and we redefine Eq.(6.20) into:

$$S_{21_k}(f) = \frac{K}{1 - 2iQ_L (\delta_k - \delta_e)}, \quad (6.21)$$

where $\delta_k = \frac{1}{2} \left(\frac{f_k}{f_0} - \frac{f_o}{f_k} \right)$. Note that substituting f_0 by $f_0 + \Delta f$ with $\Delta f \ll f_0$ for infinitesimal changes in the resonance frequency decreases δ_k by a term $\delta_e = \Delta f / f_0$; thus, δ_e is a fitting parameter that is associated to the tolerances in the estimated resonance frequency. Furthermore, K is a fitting parameter to get the proper value of $S_{21\text{res}}$ in absence of cross-talk. To recover the transmission response de-location in the complex plane caused by cross-talk back to its theoretical position [LM02], we re-position the Q-circle first roughly by shifting the values of S_{21_k} with the midpoint between the two ends of the Q-circle as:

$$S'_{21_k} = S_{21_k} - \frac{S_{21_1} + S_{21_n}}{2}. \quad (6.22)$$

Besides, a small residual cross-talk effect might be left over, which we can correct for by including the corresponding repositioned values S'_{21_k} into Eq. (6.21) and include another fitting parameter G that takes into account any residual cross-talk, leading to:

$$S'_{21_k} = \frac{K}{1 - 2iQ_L(\delta_k - \delta_e)} + G. \quad (6.23)$$

This equation can be rewritten as:

$$S'_{21_k} = F + 2iQ_L G \delta_k - 2iQ_L S'_{21_k} (\delta_k - \delta_e), \quad (6.24)$$

where $F = K + G - 2iQ_L G \delta_e$ is a new complex fitting parameter. Dividing this equation into its real and imaginary components leaves us with a overdetermined system of equations in matrix form $A\bar{x} = \bar{b}$ as [Gal20]:

$$\underbrace{\begin{bmatrix} 1 & 0 & -2\delta_1 & 0 & -2\text{Im}\{S'_1\} & 2\text{Im}\{S'_1\}\delta_1 \\ 1 & 0 & -2\delta_2 & 0 & -2\text{Im}\{S'_2\} & 2\text{Im}\{S'_2\}\delta_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & -2\delta_n & 0 & -2\text{Im}\{S'_n\} & 2\text{Im}\{S'_n\}\delta_n \\ \\ 0 & 1 & 0 & 2\delta_1 & 2\text{Re}\{S'_1\} & -2\text{Re}\{S'_1\}\delta_1 \\ 0 & 1 & 0 & 2\delta_2 & 2\text{Re}\{S'_2\} & -2\text{Re}\{S'_2\}\delta_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & 0 & 2\delta_n & -2\text{Re}\{S'_n\} & -2\text{Re}\{S'_n\}\delta_n \end{bmatrix}}_A \underbrace{\begin{bmatrix} \text{Re}\{F\} \\ \text{Im}\{F\} \\ Q_L \text{Im}\{G\} \\ Q_L \text{Re}\{G\} \\ Q_L \delta_e \\ Q_L \end{bmatrix}}_{\bar{x}} = \underbrace{\begin{bmatrix} \text{Re}\{S'_1\} \\ \text{Re}\{S'_2\} \\ \vdots \\ \text{Re}\{S'_n\} \\ \text{Im}\{S'_1\} \\ \text{Im}\{S'_2\} \\ \vdots \\ \text{Im}\{S'_n\} \end{bmatrix}}_{\bar{b}}. \quad (6.25)$$

To find the values of the six unknowns in $\bar{x}$, we can solve this equation by transforming it into an overdetermined system of equations having six unknowns and twice as many equations as frequency points in the measurement set:

$$(A^T A)^{-1} A^T \bar{b} = \bar{x}, \quad (6.26)$$

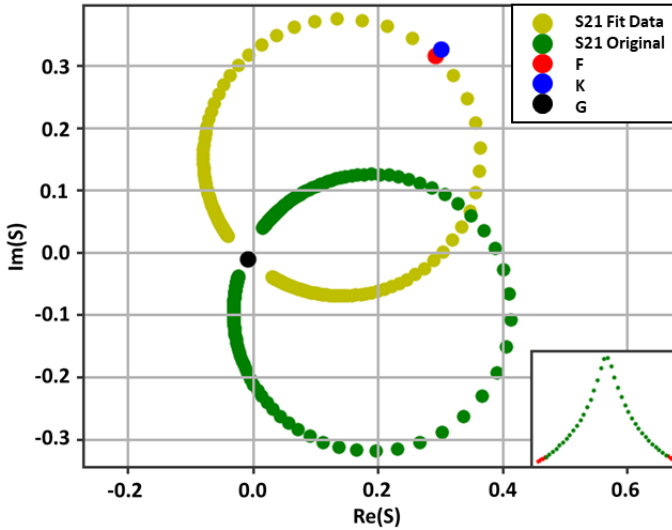


Figure 6.7: Q-Circle of the original data (green) as well as the corrected data for the weighted complex circle fit (light green). The rotation of the circle is the result of phase correction and phase unwrapping. The red, black and blue dots are the parameters F, G and K respectively, as defined in Eqs.(6.23) and (6.24).

where $(A^T A)^{-1} A^T = A^+$ corresponds to a so-called ‘pseudo-inverse’. Particularly, in linear algebra, the *Moore-Penrose inverse* A^+ [Pen55] of a matrix A is the most prominent generalisation of the inverse matrix [Ste73]. A convenient use of A^+ is for the computation of a good fit that minimises the least-squares error in a system of linear equations that may lack a unique solution¹⁴, especially if the initial matrix is not an n -by- n invertible matrix as in our case. Hence, we use Moore–Penrose inverse routines by using A^+ to find the solution of $\bar{x}$ that minimises the least-square error between the left- and right-hand sides of Eq.(6.25). Before the least-squares fit is performed, estimate the resonance frequency f_0 as the frequency value for which S_{21} -magnitude is maximum. Once the least-squares fit is performed, we obtain the loaded Q-factor Q_L and an update of the resonance frequency estimation renamed here as f'_0 over the fitting parameter δ_e given as:

$$f'_0 = f_0 (1 + \delta_e). \quad (6.27)$$

The result of the fit procedure is shown in Fig.6.7 where we include the original data Q-circle in green with the linear phase corrected Q-circle in yellow as well as the significant fitting parameters from Eqs.(6.23) and (6.25).

6.5.4 Weights and Outlier Removal

The previous figures show a typical distribution of S_{21} measurement points along a resonance circle in the complex plane. The linear frequency sweep produced by

¹⁴The least-squares solution is unique if A is a full-ranked matrix (rank = number of linearly independent columns)

most network analysers results in a distribution of points in the complex plane whose density is minimum at resonance and maximum at the edges of the trace, close to the origin. However, cryocoolers and vacuum pumps can lead to vibrations of the set-up, leading to arbitrarily positioned disturbances in the S_{21} transmission magnitude. These effects are illustrated in examples of an experimentally determined S_{21} trace showing the distortion at the tails of the trace in Fig.6.8(a) and close to the resonance peak in Fig.6.8(b).

In general, due to the non-uniform distribution of points in the Q-circle, any least-squares algorithm will tend to prioritise the edges close to the origin which, in turn, are the parts of the trace with the worst signal to noise ratio and which are most vulnerable to be distorted because of imperfections in the device and measurement set-up and the parasitic effects mentioned earlier. The long distorted tails in Fig.6.8(a) combined with the inhomogeneous distribution of measurement points will lead to erroneous results in a least-squares fitting software. An effective solution to overcome this problem is by applying weights to Eq.(6.25) in coordination with removing the most distorted points from the fitting procedure.

A weight can be assigned to each row in the system of equations in Eq.(6.25) by multiplying the first n equations by $Re\{S'_{21}\}$ and the following ones by $Im\{S'_{21}\}$. Since weights set the influence of a given equation on the final parameters, the data points closer to the resonance frequency acquire a heavier weight than those further away. This gives good results with S_{21} traces having little or no distortion.

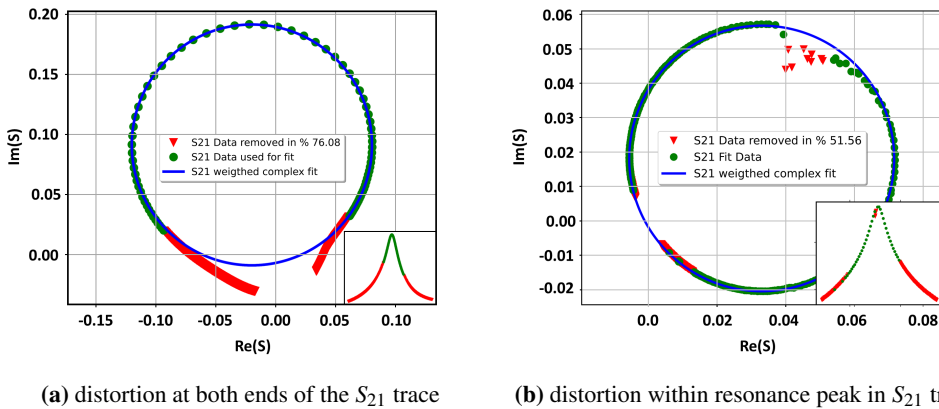


Figure 6.8: S_{21} distribution in the complex plane obtained from an (a) uncalibrated measurement of a 27 GHz dielectric resonator (published in [Krk+21a]) and (b) 8 GHz dielectric resonator distorted by cryocooler vibrations, both processed with the automatic outlier removal procedure. The threshold condition is set $Th = 10$. Red triangles: points rejected; green circles: points used in the fit; and blue trace: fitted response. For a better view, only every fifth point is displayed in (a). The inset at the bottom right corner of both figures corresponds to $|S_{21}|$. If no points are removed, the resulting Q_0 diverges by 19% in (a) and 1% in (b) because the least-squares algorithm is affected by the distorted portion of the trace.

However, for traces with significant distortion, such as the ones in Fig.6.8, weighting the trace is not sufficient, and removal of the worst data points, the outlier points, is needed. Especially in Fig.6.8(b), the distortion of data close to resonance can affect the weighted fit if the data is not removed. Thus, the algorithm performs an adaptive outlier removal once the weighted least-squares fit on $S'_{21,i}$ is performed and computes the fitting error below:

$$\epsilon_i = \left| \frac{1}{(S'_{21,i} - G)} - \left(\frac{K}{1 + 2jQ_L(\delta_i - \delta_e)} \right)^{-1} \right|, \quad (6.28)$$

which tends to enlarge the error at frequency data points further away from resonance and thus, the points more likely to be affected by parasitic effects. The point with the highest error ϵ_{max} is identified and its error is compared to a threshold:

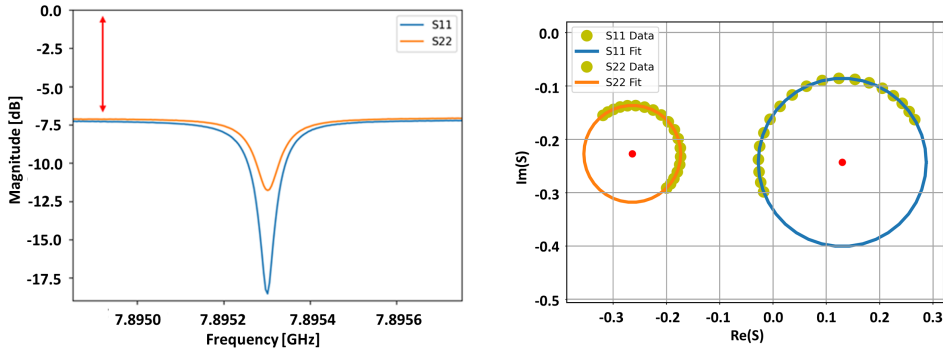
$$\epsilon_{max} < \frac{1}{Th} \cdot \frac{1}{|K|}, \quad (6.29)$$

where K is the fitting parameter appearing in Eq.(6.21) and in the inset of Fig.6.7, and $Th = 10$ is a threshold scaling parameter whose value was defined after an extensive case study [Krk+21a]. It is a compromise between the amount of data removed -fitting will be unaffected by large distortion in the trace tails- and being left with a small amount of data points -least-squares fit results will be more sensitive to noise in S_{21} -. If the condition posed in Eq.(6.29) is not satisfied, the corresponding data point with the highest fitting error is removed from the data set and the least-squares fit is re-evaluated. This is repeated recursively until Eq.(6.29) is satisfied. Note that, Q_L and f'_0 are updated in every iteration using Eqs.(6.25) and (6.27).

6.5.5 Determination of Coupling Factors

After finding the loaded quality factor, the reflection response needs to be used to calculate the unloaded quality factor as given in Eq.(6.12). This is done by determining the coupling factors from the magnitudes of S_{ii} at resonance using Eq.(6.10). To accurately calculate $|S_{11}|$ and $|S_{22}|$ in Eq.(6.10) we have to take into account the loss between the calibration plane and the device under test as indicated in Fig.6.9(a). If the set-up cannot be calibrated, the off-resonance frequency points in the magnitude will not be at the ideal 0 dB line. This gap indicates the losses in the transmission lines and other structures placed between the calibration plane and the resonator. In the case of Fig.6.9(a), the correction of the off-resonance loss can be acquired relatively easily due to the off-resonance flatness of the traces. In contrast, in Fig.6.4 the situation looks very different due to the high and non-linear slope.

Similarly to the transmission response, the ideal reflection traces form a circle in the complex plane, named in this thesis *C-circle*. Hence, it is more convenient to treat this data again in the complex plane by performing a geometric least-squares circle fit



(a) example of asymmetric coupling with off-resonance loss (b) C-Circle of coupling coefficients shown in (a)

Figure 6.9: (a) Measured $|S_{ij}|$ of a strongly-coupled resonator with uneven coupling at ports 1 and 2. Adapted from [Gal20] (b) Distribution of input and output reflection coefficient in the complex plane. Green points: measured data within 3-dB bandwidth. Solid lines: least-squares circle fits. Red points: fitted circle centres. Published in [Krk+21a]

of $S_{11}(f)$ and $S_{22}(f)$ close to resonance [OCa+97]:

$$\underbrace{\begin{bmatrix} \text{Re}[S_{mm}]_1 & \text{Im}[S_{mm}]_1 & 1 \\ \text{Re}[S_{mm}]_2 & \text{Im}[S_{mm}]_2 & 1 \\ \vdots & \vdots & \vdots \\ \text{Re}[S_{mm}]_n & \text{Im}[S_{mm}]_n & 1 \end{bmatrix}}_M \underbrace{\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_3 \end{bmatrix}}_a \approx \underbrace{\begin{bmatrix} -|S_{mm}|_1^2 \\ -|S_{mm}|_2^2 \\ \vdots \\ -|S_{mm}|_n^2 \end{bmatrix}}_P, \quad (6.30)$$

$$C_{mm} = \left(-\frac{a_1}{2}, -\frac{a_2}{2} \right), \quad r_{mm} = \sqrt{\frac{1}{4} (a_1^2 + a_2^2) - a_3}, \quad (6.31)$$

where the index is either $m = 1$ or 2 , and a_1, a_2 and a_3 are the fitting parameters to be found using the Moore-Penrose inverse technique Eq.(6.30) and, once they are determined, the complex centres C_{11} , C_{22} and radii r_{11} , r_{22} can be calculated using Eq.(6.31).

In the absence of loss, the C-circles should be tangent to the unit circle [Alt47; Kaj94]. As discussed in [Krk+21a], the values of $|S_{11}|$ and $|S_{22}|$ at resonance to be used in Eq.(6.10) are the points of the C-circles closest to the origin of the complex plane. When taking into account a scale factor that would make the C-circles tangent to the unit circle [Alt47], $|S_{11}|$ and $|S_{22}|$ can be written as:

$$|S_{11}| = \left| \frac{C_{11} - r_{11} \cdot C_{11}/|C_{11}|}{C_{11} + r_{11} \cdot C_{11}/|C_{11}|} \right| = \frac{|C_{11}| - r_{11}}{|C_{11}| + r_{11}}, \quad (6.32)$$

$$|S_{22}| = \frac{|C_{22}| - r_{22}}{|C_{22}| + r_{22}}. \quad (6.33)$$

Figure 6.9(b) shows an example of the geometric C-circle fit performed on the measured S_{11} and S_{22} using Eq.(6.30). Note that only the points for which $|Q_L \delta_i| \leq 1/2$ are used for this fit. This condition reduces the number of frequency points to only those covering half the perimeter of the C-circle and, at the same time, avoids using off-resonance measurement points in the geometric circle fit. Due to this, the transmission line loss is evaluated at the resonance frequency and the algorithm removes the effect of any frequency-dependent loss between the calibration planes and the resonator ports, such as the one in Fig.6.4.

6.5.6 Algorithm Summary

The ARPE algorithm is capable of extracting the unloaded quality factor and resonance frequency of microwave resonators from vector S-parameters. Both symmetrical (Lorentzian) as well as asymmetrical (Fano) transmission responses are supported.

The algorithm begins with performing a phase unwrapping procedure [Gal20] to remove discontinuities in the S-parameter's phases. In the same procedure, the linear phase dependence [LM02; Pom+17] is taken out by carrying out a linear regression on two frequency segments; 10 % of the first and last frequency data points of the total span. In the next step, the coarse cross-talk is removed by shifting the Q-circle closer to the origin, and the first resonance frequency guess is taken. A weight is then included on the modified S-parameters to begin the Moore-Penrose complex circle fit with outlier removal. This recursive process, where both Q_L and f_0 are recursively updated and corrected in the outlier removal process, is iteratively repeated until Eq.(6.29) is satisfied. In the further step, the geometric Moore-Penrose inverse C-Circle fit returns the coupling factors. However, at very low coupling ($|S_{21}|_{max} < -50\text{dB}$) the resonance circles in $S_{11}(f)$ and $S_{22}(f)$ are very small and the circle fit does not work properly any more. In this case, the accuracy in the determination of coupling factors has no practical effect; anyway, instead of neglecting the coupling coefficients completely, Eq.(6.10) is applied. The magnitudes of S_{ii} are taken from its values corresponding to the frequency at which $|S'_{21}|$ is maximum after coarse cross-talk correction compensated for losses which are estimated from the off-resonance values of $|S_{11}|$ and $|S_{22}|$. In the final step, the calculation of the unloaded quality factor Q_0 is performed with Eq.(6.12). The procedure as mentioned above is graphically outlined in Fig.6.10.

The algorithm and its source code are then implemented in a Dash app [Inc15] flask based environment to be available under a freeware license running on a web-accessible Ubuntu server on the UPC-TSC-CommSensLab. Fig.B.1 [in the appendix] shows the web interface with an example experimental Touchstone file. Having the source code openly available, and at the same time, the underlying algorithm appropriately explained in [Krk+21a], the first step to contributing to the international research community with an open-access collaboration to avoid duplications and the vast amount of publications on this topic and expand the algorithm's capability in a global environment.

Of course, the algorithm has limits which lead to a recommendation for the most accurate results. In the symmetrical Lorentzian shaped trace, the VNA frequency sweep should be centred at the position of the maximum of $|S_{21}(f)|$ and the total

frequency span should cover a span of 10 times the 3 dB bandwidth with at least 201 frequency points. If the frequency span is very broad and thus the peak contains only a few points not being centred, the algorithm fails. Furthermore, if multiple resonances

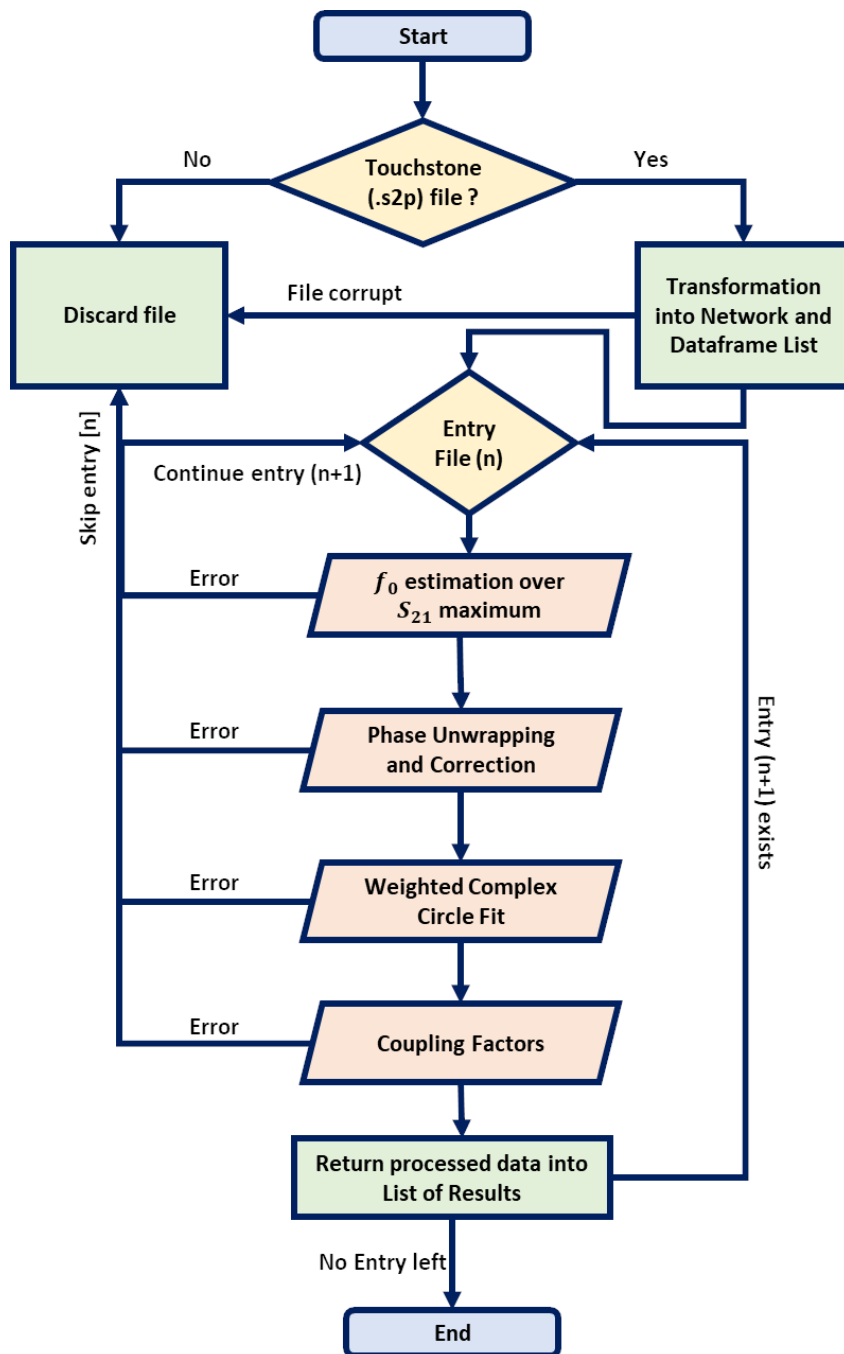
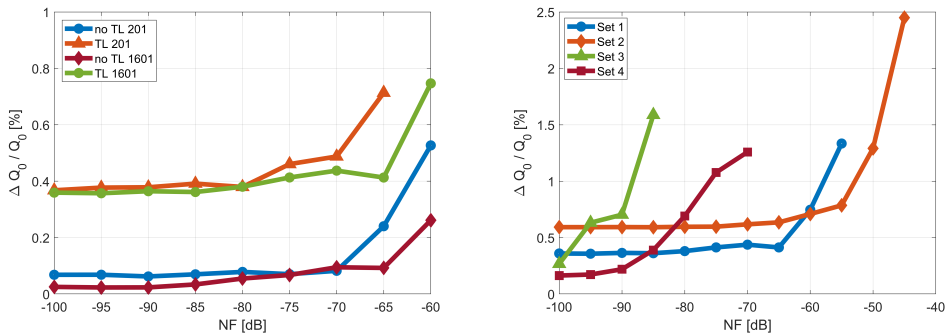


Figure 6.10: Outline of the algorithm for parameter extraction from symmetrical and asymmetrical transmission responses.

are included in the frequency span, the algorithm will choose the peak with the highest $|S_{21}(f)|_{\max}$ value.

In the asymmetrical Fano case, the trace should be identical but shifted with respect to the origin of the complex plane [LM02]. The vector network analyser parameters have to be adjusted according to the polar plot setting the centre frequency at the point of the trace with a minimum density of points. At least 20 points should be covering a 180° arc about the centre frequency and setting a sweep with a frequency span ten times the bandwidth required to cover the 180° arc above. The number of points in the frequency sweep should be at least 201.

The algorithm's performance assessment, including statistical studies, is reported and explained in detail in [Krk+21a]. It results that the uncertainties seem to be dominated by parasitic effects of cabling, connectors, calibration, and frequency dependence in coupling networks dominate over those produced by noise in current VNAs using standard IF bandwidths in the range of kHz. Hence, error bounds are hard to generalise since they depend on the specifics of the resonator and experimental set-up. We found that below a certain noise threshold, the uncertainty remains constant and independent of VNA noise, as shown in Fig. 6.11. This residual uncertainty increases when transmission lines are included between the calibration plane and the resonator, as seen in the same figure. Below this visible noise threshold, the relative uncertainty on the resonance frequency is close to $1/(10Q_L)$ for f_0 . In addition, disabling a calibration or substituting the VNA and/or cabling provokes relative differences in Q_0 close to 1% in most cases (max 2.7%).



(a) relative uncertainty vs simulated VNA noise floor (b) relative uncertainty vs simulated VNA noise floor

Figure 6.11: Relative uncertainty as a function of simulated VNA noise floor for (a) in a data set including 1.5 m long transmission lines in an equivalent circuit used to produce the S-parameter files. The values 201 and 1601 indicate the number of points in the frequency span. (b) with 1601 points per trace as a function of simulated VNA noise floor for four different sets of data with different noise floor ratios and parasitic effects. The vertical scale has been chosen to show only uncertainties below 2.5%. Further details are explained in [Krk+21a] where the figures are taken from.



7. Resonators for Materials Testing

Great minds rarely think alike with how they thought just yesterday. They are wrestlers grappling with the truth, trying to pin it down, letting the best idea win - only tomorrow to challenge it again.

-justbelmont-

The link between surface impedance and resonator parameters described in the previous chapter is applied here to study the design of possible microwave resonating structures to examine the ReBCO coated conductors. The closed Hakki-Coleman dielectric resonator and parallel plate resonator technique are discussed in-depth, and the first calculations of the expected resonator parameters are presented.

7.1 Measuring ReBCO Coated Conductors for FCC-hh

Surface impedance can be determined with the help of the resonator parameters described in the previous chapter. The specific design of any resonator to evaluate the surface impedance of ReBCO has to take into account the following constraints:

- The samples as provided by the manufacturers should undergo minimum manipulation prior to testing.
- The substrates of the ReBCO-CCs, Hastelloy and stainless steel, should not be exposed to the RF fields.

- Measurements should be performed as close as possible to the frequency range of the FCC-hh, expected to be between 2 kHz to 3 GHz.
- Measurement of long-length samples.
- The ReBCO coated conductor tapes have a width of 12 mm. The tapes are available in lengths much longer than those required for characterisation (up to 100 m).
- Measurements of the ReBCO-CCs performance should be possible in different environments: temperature, magnetic field, irradiation from synchrotron radiation [see Sec.1.9].

The techniques that use the samples as part of the resonant structure, e.g., as cavity end-plates, are very well suited to test the samples in a non-destructive way. However, the fixed 12 mm tape width becomes one of the resonator's design restrictions as the general condition for resonance states that the length of the resonating structure L must be equal to an integer number N of half of the wavelength; hence, the resonance is given by, $f = Nc/2L$. Accordingly, the 12 mm width of the ReBCO-CC leads to a frequency of 12.5 GHz, which does not fulfil the requirement of measuring close to the beam frequency spectrum. We know that the larger the cavity, the lower the resonance frequency. In order to reach 1 GHz, we would need a resonating structure of $L = 15$ cm. However, typical systems for cryogenic measurements in high magnetic fields have small opening bores. In our case, the bore has 25 mm in diameter (9 T PPMS system by Quantum Design). Due to this, we decided to take advantage of resonant techniques including dielectrics with high permittivity and low loss-tangent, because both, geometric dimensions and resonance frequency can be lowered at the same time, as explained in Sec.6.1.

Based on this, the two following resonators are the most adequate to accomplish the surface impedance measurements within the requirements. The Hakki-Coleman resonator [HC60] achieves low frequencies due to a very high dielectric permittivity, whereas the parallel plate resonator uses a moderate permittivity and propagation along a 'long' strip of a coated conductor.

7.2 Modelling of Dielectric Resonators

7.2.1 Numerical Modelling of Resonators

Resonators can be designed with any arbitrary shape, and for some designs, a closed solution for the electromagnetic field distribution cannot be analytically obtained. The same applies to the determination of the resonance frequency. Kajfez and Guillon have developed various semi-analytical methods by solving the partial differential equation (PDE) system for calculating the field distribution in shielded dielectric resonators of symmetrical shape [KG98]. In addition, an approximation of PDEs can be constructed and solved numerically based upon different types of discretisation. The finite-element-method (FEM) is one of these tools to compute such approximate solutions for various real-world scientific problems which include complex domains (regions) subjected to general boundary conditions as defined in Def.3.2.1. Nowadays, FEM based solvers are becoming an essential tool in the design or modelling of physical phenomena

helping to reduce the experimental trial and error analysis by means of simulations performed before constructing the desired device.

As part of this thesis, the field distributions, overall design of the resonating structures, resonance frequencies, geometry and filling factors [see Sec.6.2] were determined with the support of the FEM based numerical simulation tool Computer Science Technology (CST) [CST21]. The program package CST Microwave Studios, a software package for electromagnetic analysis and design based on solving Maxwell's equations on a finite amount of mesh cells, has become a standard tool in cavity development. It contains a graphical solid modelling front end and a fully automatic meshing procedure that can be adapted to a particular problem. Furthermore, it contains a variety of solvers in the time domain or frequency domain and internally defined boundary conditions to be adapted to the specific problem. Mainly two simulation techniques have been utilised in this thesis that deserve a short discussion:

- **Eigenmode Solver:** This particular solver is dedicated to the simulations of closed resonant structures. It solves Maxwell's equations in the frequency domain directly in each mesh cell and finds the electromagnetic field distribution of all resonant modes and their resonance frequencies. It also uses perturbation theory [see Sec.6.4] to extract other material-dependent parameters such as the quality factor. In this work, this solver has been useful to identify all possible resonant modes and their resonance frequencies depending on the dielectric parameters used. It has helped to design the proper dimensions of the resonator to separate desired modes from parasitic ones.
- **Frequency Domain Solver:** This solver, as the name indicates, solves the PDEs in the frequency domain for a specific frequency range of interest in equidistant discrete frequencies, including specifically a source for the fields that must be defined, determining the propagation through an arbitrary structure. It delivers the electromagnetic near and far-fields including multi-port S-parameters. In this thesis, this solver has been helpful for determining the correct coupling method to excite the wanted mode only. In addition, it is useful to calculate resonator S-parameters which -together with ARPE introduced in Sec.6.5- have been key to predicting coupling factors and quality factors.

In general, CST discretises the volume within a cuboid boundary box, solves Maxwell's equations, and applies boundary conditions (set by the user) at the faces of the boundary box. The boundary conditions can be defined separately at each face of the boundary box. The BCs that can be imposed and are used in this thesis are: *Electric* $\hat{n} \times \vec{E} = 0$, i.e., perfect electric conductor and all tangential electric fields and normal magnetic fluxes are set to zero. *Magnetic* $\hat{n} \times \vec{H} = 0$, i.e., perfect magnetic conductor -the counterpart to PEC- and all tangential magnetic fields and normal electric fluxes are set to zero. *Conducting Wall*, means that the boundary behaves like a wall of lossy metal material with properties that can be defined by the user. *Open* operates as if there is free space at the border and beyond. This means that waves can pass this boundary with minimal reflections. *Open (add space)* is similar to the 'Open' boundary, though with an enhanced distance between the device under test and the boundary box. This extra volume gives the possibility for far-field calculations, primarily used for antenna

designs, where the electromagnetic fields are visualised outside the device under test.

7.2.2 Analytical Modelling of Cylindrical Resonators

In this section, we analytically solve a simple cylindrical structure to illustrate the method used to analyse the dielectric resonator used along with this thesis. CST simulations and experimental results have been benchmarked against the analytical results. The electromagnetic analysis of a cavity can be done with Maxwell's equations Def.3.1.1 in the frequency domain for a linear, homogeneous and source free medium, and assuming a perfect electrical conductor shielding wall as the boundary condition. As opposed to SCs, in PECs the magnetic field within the material has to be constant with time, and the interior magnetic field remains fixed. This means that PEC does not exhibit quantum effects such as the Meißner-Ochsenfeld effect discussed in Sec.2.1.2. On that account, a PEC-BC implies the special case that no EM-field enters into the material, i.e., from Def.3.2.1 results that $\hat{n} \times \vec{E} = 0$ and $\hat{n} \cdot \vec{B} = 0$. It imposes that the tangential component of the electric field is zero and the normal component of the magnetic field also.

As explained in Sec.3.3.1 this leads directly to the Helmholtz equations (3.16) and (3.17) that can be decomposed into the three cylindrical coordinates (r, φ, z) leading to four scalar Helmholtz equations [KG98]:

$$\left(\frac{\partial^2}{\partial z^2} + k^2\right) H_r = i\omega\epsilon \frac{1}{r} \frac{\partial}{\partial \varphi} E_z + \frac{\partial^2}{\partial z \partial r} H_z \quad (7.1)$$

$$\left(\frac{\partial^2}{\partial z^2} + k^2\right) H_\varphi = -i\omega\epsilon \frac{\partial}{\partial r} E_z + \frac{1}{r} \frac{\partial^2}{\partial z \partial \varphi} H_z \quad (7.2)$$

$$\left(\frac{\partial^2}{\partial z^2} + k^2\right) E_\varphi = \frac{1}{r} \frac{\partial^2}{\partial z \partial \varphi} E_z + i\omega\mu \frac{\partial}{\partial r} H_z \quad (7.3)$$

$$\left(\frac{\partial^2}{\partial z^2} + k^2\right) E_r = \frac{\partial^2}{\partial z \partial r} E_z - i\omega\mu \frac{\partial}{\partial \varphi} H_z, \quad (7.4)$$

This proves that all transverse field components can be obtained once the longitudinal components E_z and H_z are determined.

Helmholtz equations in cylindrical coordinates are solved by the method of separation of variables. In essence, the method of separation of variables seeks a solution in cylindrical coordinates of the form $F(r, \varphi, z) = R(r)P(\varphi)Z(z)$. Substituting this solution into the Helmholtz equation leads to three independent differential equations [Gri17]:

$$\frac{1}{Z} \frac{d^2 Z}{dz^2} + k_z^2 = 0 \quad \frac{1}{P} \frac{d^2 P}{d\varphi^2} + m^2 = 0 \quad r \frac{d}{dr} \left(r \frac{dR}{dr} \right) + (k_r^2 r^2 - m^2)P = 0 \quad (7.5)$$

where m is a constant, and relates the radial wave number k_r , the medium wave number k , and the waveguide propagation constant k_z . Note, that we have converted the partial differential Helmholtz equation into three ordinary differential equations of the general

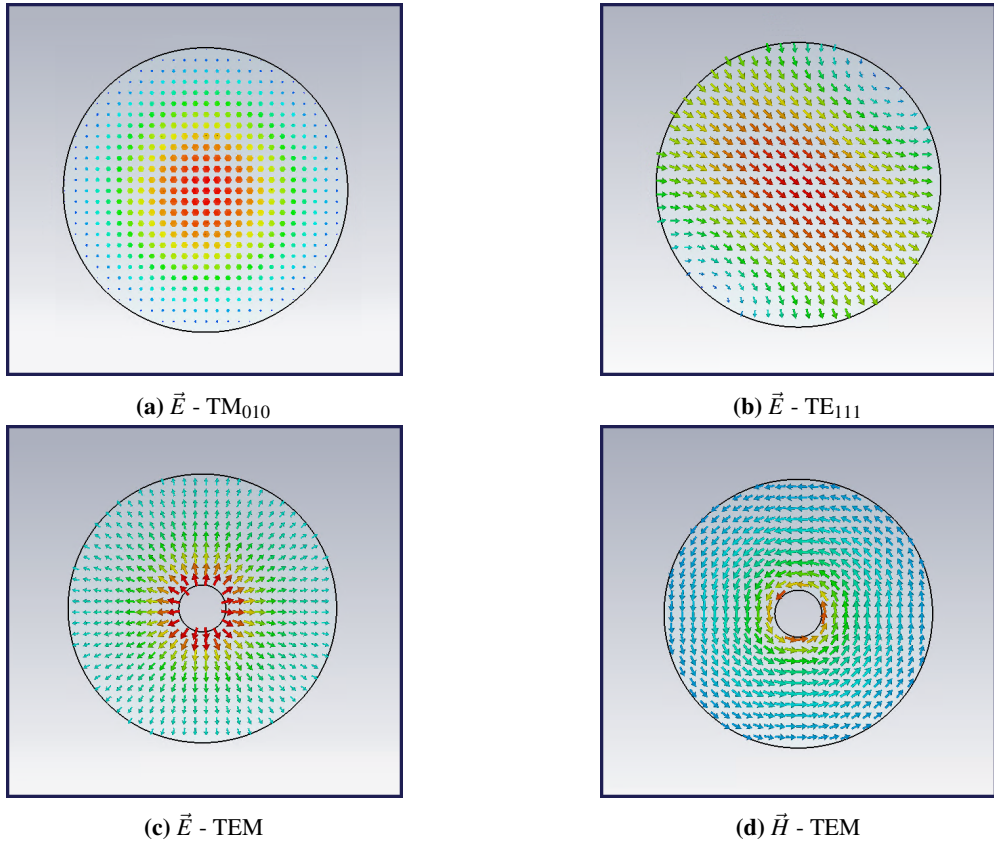


Figure 7.1: Transverse cross-section at the mid-height of the resonating structure. (a) and (b) are representations of different modes existing in a cylindrical resonating structure with a PEC boundary. (c) and (d) are representations of coaxial structures with inner and outer PEC boundaries.

solution. The azimuthal differential equation $P(\varphi)$ and the axial differential equation $Z(z)$ are harmonics and due to that, their solution have to be of trigonometric nature. The last differential equation in Eq.(7.5) represents a Bessel differential equation of order m whose solutions are naturally Bessel-functions of any kind [Bro+01]. For example, the Bessel function of the second kind $Y_m(r)$ as well as the modified Bessel function of the second kind $K_m(r)$ diverge when $r \rightarrow 0$. For this reason these solutions can be excluded from problems where the region of interest includes $r = 0$. Then again, the Bessel function of the first kind $J_m(r)$ and the modified Bessel function of the first kind $I_m(r)$ diverge at $r \rightarrow \infty$; thus, they will be excluded from solution which is not limited in extent. In general, one has to investigate all possibilities of solutions leading to the linear combination of all possible solutions [EMT21]:

$$\Psi = \sum_m \sum_{k_z} C_{m,k_z} R(k_r r) P(m\varphi) Z(k_z z) \quad (7.6)$$

The indexes m, n, p are always integers whose minimum value is 0 or 1, depending

on the specific case. Only a limited number of different modes can occur within a resonator depending on the dimensions, format and coupling conditions. Resonating modes that propagate in the axial direction can be categorised as [see Fig 7.1]:

- **Transverse electromagnetic (TEM)**, where both the electric and magnetic fields are perpendicular to the direction of propagation.
- **Transverse electric (TE)**, where only the electric field is perpendicular to the direction of propagation.
- **Transverse magnetic (TM)**, where only the magnetic field is perpendicular to the direction of propagation.
- **Hybrid modes (HE/HM)**, where neither the electric nor the magnetic fields are fully perpendicular to the direction of propagation and the designation hybrid electric (HE) or hybrid magnetic (HM) depends on which field is dominant in direction of propagation.

An ideal hollow structure as in Figs.7.1(a) and 7.1(b) has boundary conditions that force the propagation of the EM-fields to be either TE or TM. To support a TEM mode as in Figs.7.1(c) and 7.1(d) at least two conductors have to exist, as can be seen in the change of the hollow resonating structure by placing a PEC cylinder in the centre. Symmetries facilitates the degree of the problem to solve. In the case of azimuthal symmetric problems it means that $m = 0$ -with the direct consequence that only Bessel function of the zeroth order are involved instead of the sum of Bessel functions- and with that, many terms of the general solution in Eq.(7.6) can be discarded.

7.3 Closed Hakki-Coleman Resonator

7.3.1 Resonator Structure

The dielectric resonator (DR) based on the Hakki-Coleman (HC) design is typically formed by a metallic body housing a small dielectric cylinder in its centre axially shielded by the two samples to be measured, as shown schematically in Fig.7.2. Accordingly, the two samples to be measured form part of the resonator structure and close the cavity as end-walls. The electromagnetic energy in the dielectric resonator is mostly stored within the dielectric cylinder due to its relative permittivity being much higher than that of vacuum. This concentrates the losses of the resonant device in the samples. One condition for a suitable mode for surface impedance measurements is that the surface currents flow primarily azimuthally in the resonator's upper and lower end-plate surfaces, and radial currents over the edges to the lateral wall are avoided. Since no radial currents exist, the cavity performance does not depend on the contact between the samples under test and the metal housing of the resonator. This can be achieved with TE-modes. In order to measure at the lowest possible frequencies, the fundamental TE mode, namely TE_{011} ¹⁵, is commonly used for measurements of surface impedance of metals and superconductors [Kle+95; MG98; Wos+17].

¹⁵ TE_{nm0} does not exist as it would violate the short-circuit boundary conditions at both ends of the resonator [KT80]. The subscript 0 means no field variation along the z-direction.

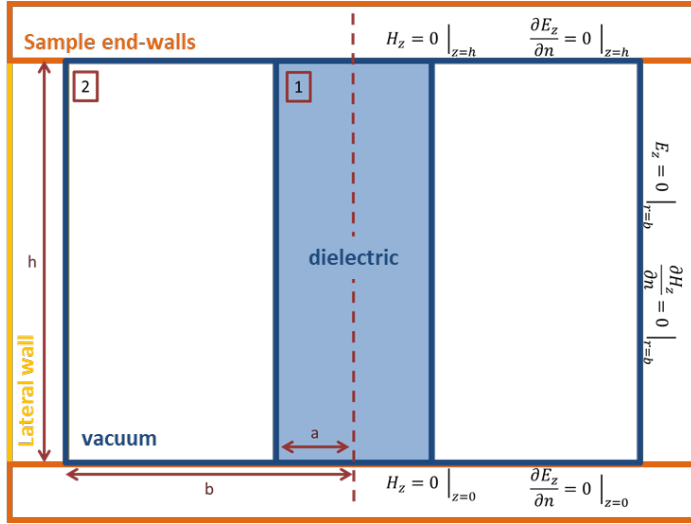


Figure 7.2: The cross-sectional area of the geometry of a cylindrical dielectric resonator (blue area with radius (a) placed between two parallel conducting plates (orange with distance h among them) and closed with a conducting lateral wall (yellow with radius (b)). In addition, the Neumann and Dirichlet boundary conditions that apply to the blue surfaces are indicated.

7.3.2 The TE_{011} Mode

As we have already derived the general solutions for the different TE and TM-modes, we can now determine [see App.B.3.1] the electromagnetic fields and resonance frequency for the TE_{011} mode for the closed Hakki-Coleman dielectric resonator (CHCDR) shown in Fig.7.2 [MG98]:

$$H_{r1}(r, z) = -A \frac{k_z}{k_{r1}} J_1(k_{r1} r) \cos(k_z z), \quad (7.7)$$

$$H_{z1}(r, z) = A J_0(k_{r1} r) \sin(k_z z), \quad (7.8)$$

$$E_{\phi1}(r, z) = -iA \frac{\omega \mu}{k_{r1}} J_1(k_{r1} r) \sin(k_z z), \quad (7.9)$$

$$H_{r2}(r, z) = T \frac{k_z}{k_{r2}} [-\Omega' K_1(k_{r2} r) - I_1(k_{r2} r)] \cos(k_z z), \quad (7.10)$$

$$H_{z2}(r, z) = T [-\Omega' K_0(k_{r2} r) + I_0(k_{r2} r)] \sin(k_z z), \quad (7.11)$$

$$E_{\phi2}(r, z) = iT \frac{\omega \mu}{k_{r2}} [-\Omega' K_1(k_{r2} r) - I_1(k_{r2} r)] \sin(k_z z) \Omega' = -\frac{I_1(k_{r2} b)}{K_1(k_{r2} b)}, \quad (7.12)$$

$$T = A \frac{J_0(k_{r1} a)}{[-\Omega' K_0(k_{r2} a) + I_0(k_{r2} a)]}, \quad (7.13)$$

$$k_{r1}^2 = k_0^2 \epsilon_r - k_z^2, \quad k_{r2}^2 = k_z^2 - k_0^2, \quad (7.14)$$

$$k_z = \frac{\pi}{h}, \quad k_0 = \frac{\omega}{c}. \quad (7.15)$$

The resonance frequency is determined by matching the electric and the magnetic field strength at the boundary between the vacuum region and that filled with the dielectric,

i.e. $H_1 = H_2|_{r=a}$ and $E_1 = E_2|_{r=a}$, leading to two equations with two unknown variables to be solved:

$$\underbrace{A J_0(k_{r_1}a)}_{w(f)} - T \underbrace{[-\Omega' K_0(k_{r_2}a) + I_0(k_{r_2}a)]}_{x(f)} = 0$$

$$\underbrace{A \frac{1}{k_{r_1}} J_1(k_{r_1}a)}_{y(f)} + T \underbrace{\frac{1}{k_{r_2}} [-\Omega' K_1(k_{r_2}a) - I_1(k_{r_2}a)]}_{z(f)} = 0.$$

We can rearrange this into a matrix equation:

$$\underbrace{\begin{bmatrix} w(f) & x(f) \\ y(f) & z(f) \end{bmatrix}}_M (f) \underbrace{\begin{bmatrix} A \\ T \end{bmatrix}}_C = \underbrace{\begin{bmatrix} 0 \\ 0 \end{bmatrix}}_0 \quad (7.16)$$

According to this, for A,T, having non-trivial solutions, the determinant of M must be equal to zero:

$$k_{r_1} J_0(k_{r_1}a) [-\Omega' K_1(k_{r_2}a) - I_1(k_{r_2}a)] + k_{r_2} J_1(k_{r_1}a) [-\Omega' K_0(k_{r_2}a) + I_0(k_{r_2}a)] = 0. \quad (7.17)$$

which is only valid at the resonance frequency. Thus, we determine f_0 analytically from Eq.(7.17) and can compare the accuracy of the numerical FEM based solvers.

7.3.3 Eigenmode Analysis

In order to design a CHCDR to be used for specific ReBCO-CCs samples, we have to take several conditions into account. First, the tape width of 12 mm restricts the maximum diameter of the cavity to 11 mm, to have a minimum of 1 mm clearance to mechanically close the cavity with the ReBCO-CC. Second, the lateral wall must be placed away from the dielectric cylinder in order to minimise the contribution of the losses due to the induced fields in the lateral walls. Rutile (TiO_2) is used as a dielectric material due to its large permittivity ($\epsilon_r \approx 87$ @ RT). As a rule of thumb, a minimum ratio of 2.5 of the radius of the resonator over the dielectric radius b/a should be given as explained in [Mou95]. Third, the resonance frequency of the TE_{011} mode has to be sufficiently separated from the other modes existing in the resonating structure. In order to find a compromise between the effect of lateral walls and the separation of modes, a study was performed to determine the suitable size of the resonator. The study was performed based on having an 11 mm diameter cavity in the CST Eigenmode solver where we specify a certain frequency range and the tool identifies all the resonant modes that exist within this frequency range for a permittivity of $\epsilon_r = 100$ (TiO_2 at 77 K). Figures 7.3(a) and 7.3(b) show the electric field and magnetic field strength distribution of the TE_{011} mode, respectively. It can be seen that the maximum of the H_z field component occurs at the centre of the dielectric. Additionally, a maximum of the H_r field occurs on the surfaces of the samples to be measured. This magnetic field

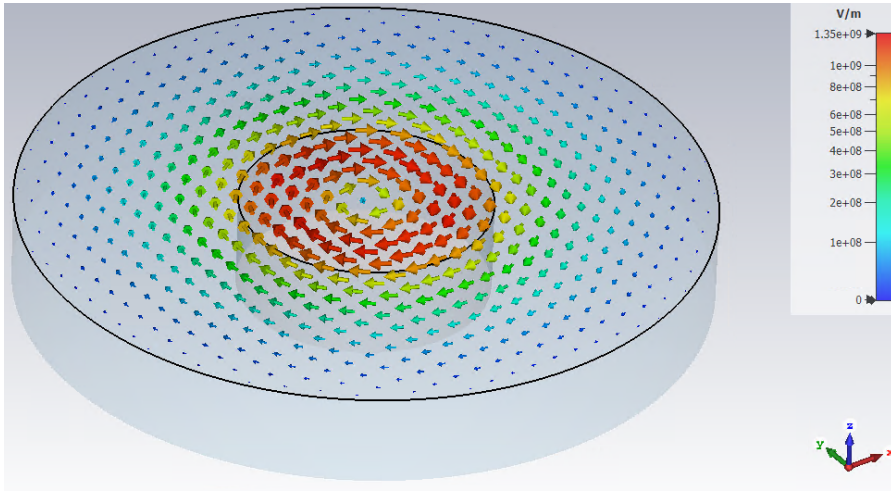
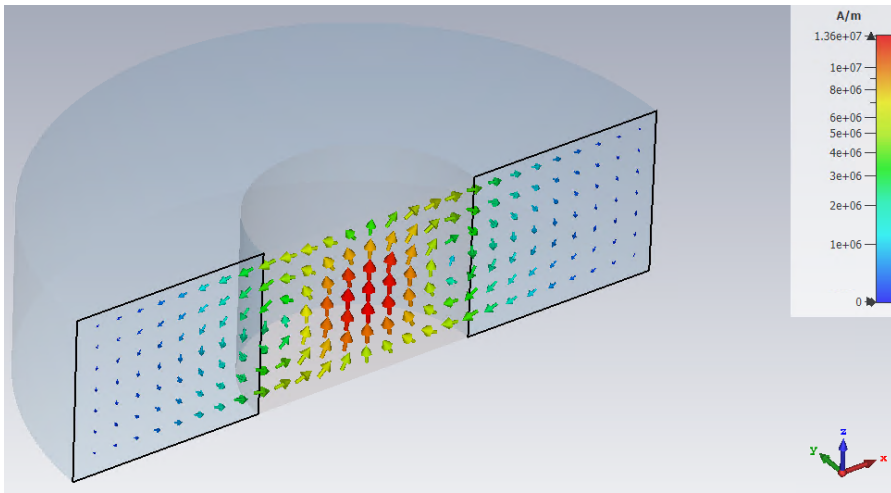
(a) TE_{011} electric field(b) TE_{011} magnetic field strength

Figure 7.3: Results of the Eigenmode simulations for a CHCDR using a rutile dielectric. (a) and (b) show the electric field and magnetic field strength distribution for the TE_{011} mode, respectively.

strength induces circular currents on the sample. The electric field component E_ϕ has its maximum at the mid-height of the dielectric rod. The exponential decrease of the electromagnetic field towards the lateral walls is visible though not always negligible as shown in Fig.7.4(a). In these simulations, the lateral walls have been chosen to be made of copper at 77 K and a material simulating a SC with a factor 10 higher conductivity has been chosen as the samples. As can be seen in this figure, not only the ratio of diameters have to be taken into account but the height of the dielectric has a significant impact. Taking into consideration the mechanical stability of the crystal and the way it has to be mounted, we decided that a height of $h = 3$ mm with

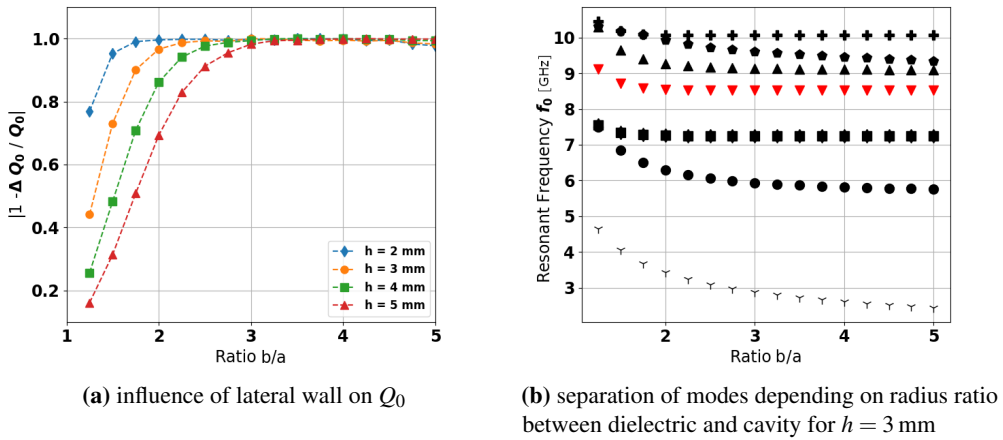


Figure 7.4: Results of the Eigenmode simulations for a CHCDR using a rutile dielectric. (a) presents the deviation in the unloaded quality factor depending on the ratio of radii between dielectric and cavity for different heights of the resonator. (b) a summary of the resonance frequencies for the first seven modes appearing in a CHCDR with a height of $h = 3$ mm.

a ratio $b/a = 2.75$ is a good choice. Thus, the dimensions of the cavity were chosen to be 11 mm in diameter and 4 mm in diameter for the dielectric. Fig.7.4(b) shows the resonance frequency of the TE₀₁₁ mode (red) and different spurious modes around this mode (black). It can be seen, that for the chosen dimensions the TE₀₁₁ mode is still well separated from any other mode (black). Even though some of the spurious modes resonate at lower frequencies, they are not the best option for the determination of the surface impedance Z_S due to their electromagnetic field distribution and related induced surface currents which either are strongly induced at undesired positions in the cavity and/or depend strongly on the electrical contact between the sample and lateral wall.

7.3.4 S-Parameter Analysis

After setting the dimensions of the cavity to $h = 3$ mm and $b/a = 2.75$, the CST Frequency Domain Solver is used to simulate how to couple energy into the resonator, derive the S-Parameters, design the coupling structures to obtain the right coupling. The azimuthal position of the excitation loops is irrelevant since the TE₀₁₁ mode has rotational symmetry. They are placed at diametrically opposed positions to maximise the separation among them and minimise the cross-coupling. As the TE₀₁₁ mode has an axial magnetic field strength component, we decided to couple inductively through the lateral walls. Figure 7.5(a) shows the same resonator as in Fig.7.3 fed by a pair of semi-rigid coaxial cables with a loop at the end. The source, or input and output port for each coaxial cable, for the fields are defined in two ports at the beginning of each coaxial cable (red squares) and determines the propagation through the resonating structure. The coupling strength can be adjusted by changing the insertion depth of

the cables. The accuracy of the two-port analysis can deteriorate when the input and output coupling is strong and induce parasitic effects, as discussed in Sec.6.5. The transmission coefficient S_{21} versus frequency seen in Fig.7.5(b) confirms that we can loosely couple at -40 dB to the wanted mode and reflects the separation of modes as indicated in Fig.7.4(b). The coupling position zero is defined as the end of the coaxial cable facing the dielectric being aligned with the lateral wall of the cavity so as the whole loop is inside the cavity. Each value is given in millimetres and the coupling loop itself has an inner diameter of 1 mm. For example, the position shown in 7.5(a) is at a coupling position of -1.5 mm.

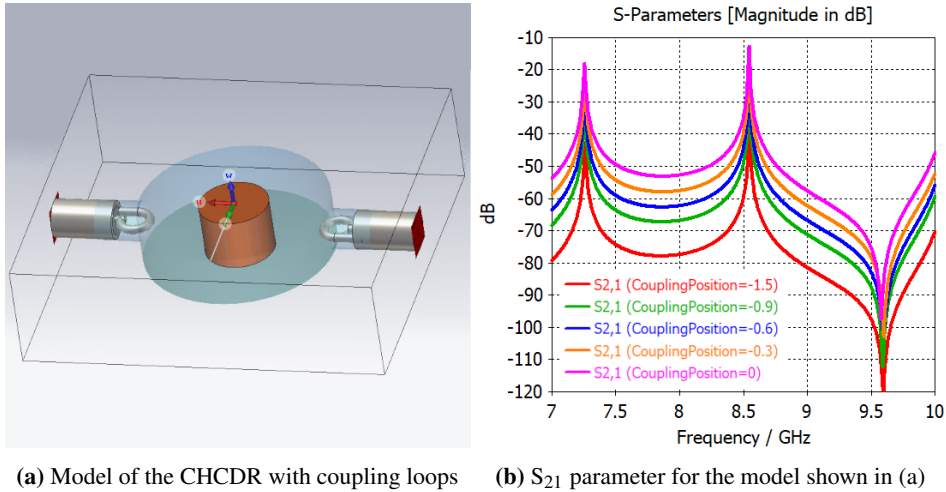


Figure 7.5: (a) Extension of the model of the CHCDR shown in Fig.7.3 to simulate S-Parameters in Frequency Domain. (b) S_{21} parameter for different coupling positions.

7.3.5 Characteristics of the Resonator

Surface resistance is determined from the Q-factor according to Eq.(6.3):

Definition 7.3.1 — Loss Equation CHCDR.

$$\frac{1}{Q_0} = \frac{R_{S,Up}}{G_{S,Up}} + \frac{R_{S,Down}}{G_{Down}} + \frac{R_{S,Lat}}{G_{Lat}} + p \cdot \tan \delta, \quad (7.18)$$

where R_{S_i} are the surface resistances of the upper, lower and lateral walls, and G_i their corresponding geometry factors. Due to the cavity symmetry, the geometry factors of the upper and lower walls are identical.

The geometry factors and filling factor for the cavity can be determined in three different ways; numerically, analytically and experimentally as described in [KA018] and presented below.

For the comparison between the three methods, the DC resistivity ρ at RT of two sample pairs of pure copper (Cu) and an alloy of copper with beryllium (CuBe) have been obtained using a four-point-probe measurement technique, resulting in

$\rho_{\text{Cu}} = 1.772 \mu\Omega\text{cm}$ and $\rho_{\text{CuBe}} = 9.729 \mu\Omega\text{cm}$. From [BB40; Bre16] a relative permittivity value of $\epsilon_{r,\text{TiO}_2} = 87$ and loss tangent value of $\tan(\delta)_{\text{TiO}_2} = 1.5 \cdot 10^{-4}$ should be expected. The dimensions of the dielectric cylinder are $a = 2.01 \text{ mm}$ and $h = 3.02 \text{ mm}$.

The first method includes the experimental determination of the geometry factor of the top and bottom cover as well as the loss tangent of the dielectric. It can be performed by measuring Q_0 of different materials with known surface resistances R_S using a round-robin methodology in which all the possible combinations of the Cu and CuBe pairs are measured. Neglecting the contribution of the lateral walls [see Sec.7.3.3], Eq.(7.18) can be rewritten into a matrix form considering the round robin approach as:

$$\underbrace{\begin{bmatrix} 2R_{S,\text{Cu}} & 1 \\ 2R_{S,\text{CuBe}} & 1 \\ R_{S,\text{Cu}} + R_{S,\text{CuBe}} & 1 \end{bmatrix}}_K \underbrace{\begin{bmatrix} G^{-1} \\ p \cdot \tan(\delta) \end{bmatrix}}_x = \underbrace{\begin{bmatrix} Q_{0,\text{Cu}}^{-1} \\ Q_{0,\text{CuBe}}^{-1} \\ Q_{0,\text{Cu}+\text{CuBe}}^{-1} \end{bmatrix}}_b \quad (7.19)$$

Solving this overdetermined system of equations with $x = (K^T K)^{-1} K^T b$ we obtain the measured geometry factor G and loss tangent times the filling factor $p \cdot \tan(\delta)$ as these two parameters cannot be divided in this approach. Note that this experimental procedure takes into account the effects of small imperfections (such as scratches and cracks in the dielectric) on the geometry factor.

The second method is based upon using the CST Eigenmode Solver by closing the cavity with aforementioned copper as end plates and by defining the rest of the resonating structure being lossless. Accordingly, Eq.(7.18) reduces to the simple form:

$$\frac{1}{Q_0} = 2 \frac{R_{S,\text{Up}}}{G_{S,\text{Up}}}. \quad (7.20)$$

where the factor two arises because $R_{S,\text{Up}} = R_{S,\text{Down}}$ and $G_{S,\text{Up}} = G_{S,\text{Down}}$. In addition, taking the experimental measurement with copper end plates as reference and assuming an ideal experimental set-up, we can determine the permittivity of the rutile by comparing numerical and experimental f_0 , resulting in $\epsilon_{r,\text{TiO}_2} = 86.2$.

The third method includes the analytical calculations of the field relations given in Sec.7.3.2. The geometry factor and filling factor can be estimated by substituting Eqs.(7.7)-(7.12) into Eqs.(6.4) and (6.5) and solving the integrals with the relative permittivity estimated with CST simulations. Note that both quantities G and p depend entirely on the geometry of the resonator and the excited field mode, and not on the materials used.

The results of the three different methods are summarised in Tab.7.1. The slight differences in the geometry factor can be explained by the imperfections in the dimensions of the DR due to mechanical tolerances. Secondly, CST simulations depend strongly on the discretisation of the numerical model. More mesh cells lead to more accurate results, e.g., the same model gives a $G = 247.95$ using about 2500 mesh cells, $G = 250.45$ using about 20000 mesh cells while the result in Tab.7.1 was produced with

Table 7.1: Estimation of the geometry factor with three different methods; analytically, numerically and experimentally. In the experiment we cannot separate between the filling factor and loss tangent; hence the result is the joint value.

Method	f_0 [GHz]	G [Ω]	G_{Lat} [Ω]	p	$p \cdot \tan(\delta)_{\text{TiO}_2}$
Experimental	9.12	251.72	-	-	$1.24 \cdot 10^{-4}$
Numerical	9.12	250.71	139876	0.998	-
Analytical	9.12	251.89	138697	0.997	-

almost 100000 mesh cells. Nevertheless, it can be stated that the three geometry factors coincide well. The product of the loss tangent and the filling factor is comparable to the expected values mentioned previously. Furthermore, the filling factor obtained in the analytical solution is very close to one ($p = 0.997$) which supports the assumption that most of the EM-energy is stored in the dielectric and that the field decays outside the dielectric rapidly.

Having determined the geometry factors and the loss tangent, it is now possible to use the rutile loaded CHCDR to measure R_S of other samples at room temperature and compare the results with literature. Even though the specific samples used may be different from the samples employed in literature, it is still a valid experiment to check the accuracy of the method used to determine the characteristics of the experiment. Results of this testing is given in Tab.7.2.

To measure with the rutile loaded closed Hakki-Coleman dielectric resonator as a function of temperature it is necessary to determine the temperature dependence of the properties of the dielectric cylinder used. Figure 7.6 shows the temperature dependence of the permittivity and of the geometry factor between 30 and 100 K. The temperature dependence was found by tracking the resonance frequency of the CHCDR as a function of temperature with brass endplates and neglecting minor effects such as the change of any dimension due to thermal contraction. As brass has a relatively low conductivity compared to copper, the ASE could be neglected. Comparing the

Table 7.2: Summary of the measured surface resistance R_S and resulting resistivity obtained ρ_M compared to theoretical values ρ_T of common metals obtained from [Ohr95]. Data published in [Arc+19]. The copper measured here is not the same as used in the previous round robin method and is less pure.

Material	f_0 [GHz]	Q_0	R_S	ρ_M [$\mu\Omega\text{cm}$]	ρ_T [$\mu\Omega\text{cm}$]
Copper (99.95%)	9.01	2864	27.19	2.08	1.72
Molybdenum	9.01	2100	42.59	5.10	5.35
Titanium	9.01	905	118.8	39.70	42.00
Brass	9.03	1742	54.46	8.32	$\approx 6-9$

resonance frequency to CST simulations, the permittivity of the dielectric Fig.7.6(a) could be extracted. The permittivity was compared to published data by [Bre16] and good agreement was obtained. We used the analytical solution for the calculation of the geometry factor for the several temperatures and extrapolate the values in between them Fig.7.6(b).

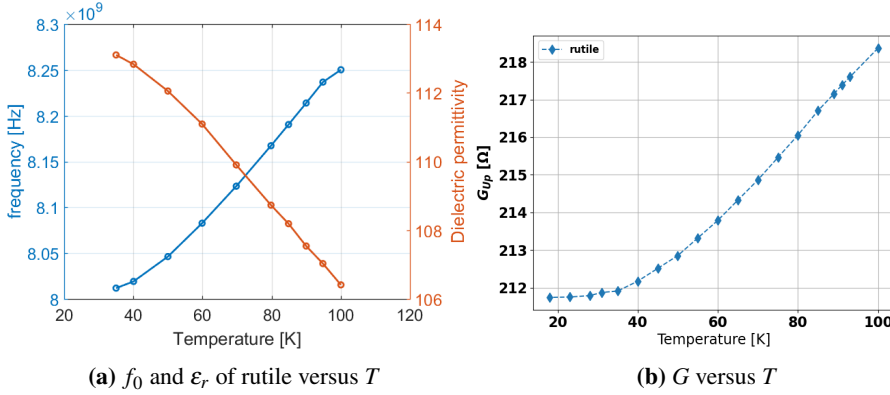


Figure 7.6: The characteristic parameters: resonance frequency, dielectric permittivity and geometry factor as a function of temperature for the rutile loaded CHCDR operating in the TE_{011} mode.

7.3.6 Determination of Power Dependency

With regards to the technical use of ReBCO coated conductors in the beam screen, it is not sufficient to characterise the samples at low power levels as those provided by the standard Vector Network Analyzer (VNA) ($\approx 1 \mu W$), as at higher power levels non-linearities might occur. To investigate the RF surface magnetic field B_{RF} it is necessary to specify the relationship between the electromagnetic fields of the TE_{011} mode Eqs.(7.7)-(7.12) and the VNA output power P_{out} . This can be done by relating the stored energy U_{st} , the unloaded quality factor Q_0 , the dissipated power P_{diss} and the electromagnetic fields inside the resonator, which gives the peak surface RF magnetic field strength H_0 :

Definition 7.3.2 — Surface Magnetic Field in CHCDR.

$$H_0 = H_r(r_{max}, h) = m_B(r_{max}, h) \sqrt{2\pi f_0 U} \quad (7.21)$$

$$= m_B(r_{max}, h) \sqrt{Q_0 P_{diss}} \quad (7.22)$$

Here r_{max} refers to the radius where the azimuthal surface RF magnetic field strength is maximum, and h is the height of the dielectric cylinder. This formula expresses the maximum RF magnetic field value on the surface of the samples to be examined.

The complete expression of the field factor m_B is determined by solving the volume integral for U_{st} in Eq.(6.1) for the azimuthal electric fields of the TE_{011} and using the relation between the amplitudes given by the continuity condition. This leads to an

expression that relates the constant A to the quality factor Q_0 and the dissipated power P_{diss} . Substituting into H_r gives :

$$m_B(r) = \sqrt{\frac{1}{\left[\Xi_1 \int_0^a J_1^2(\xi_1 r) r dr + \Xi_2 \int_a^b F_1^2(\xi_2 r) r dr \right]}} \frac{\beta}{\xi_1} J_1(\xi_1 r) \cos(\beta h), \quad (7.23)$$

$$\Xi_1 = \frac{\epsilon_r \epsilon_0}{2} \left(\frac{2\pi f_0 \mu_0}{\xi_1} \right)^2 \pi h \quad \Xi_2 = \left(\frac{J_0(\xi_1 a)}{F_0(\xi_2 a)} \right) \frac{\epsilon_0}{2} \left(\frac{2\pi f_0 \mu_0}{\xi_2} \right)^2 \pi h.$$

As explained in Sec.7.3.2, the electromagnetic fields for the TE_{011} are mostly concentrated within the dielectric. We can assume that the maximum of the radial magnetic field strength will be within the dielectric region which leads to the equation to be solved:

$$\frac{\partial H_{r1}}{\partial r} = -A \frac{\beta}{2} \cos(\beta h) [J_0(\xi_1 r) - J_2(\xi_1 r)] = 0, \quad (7.24)$$

$$\iff J_0(\xi_1 r) - J_2(\xi_1 r) = 0. \quad (7.25)$$

Knowing this, we can calculate the radial RF-magnetic field distribution on the samples. Fig.7.7(a) shows a normalised density plot of the results where we can find the maximum of H_r . The maximum magnitude given by Eq.(7.24) is the radial position of the maximum $r_{\text{max}} = 1.30$ mm (radius of the dielectric is 2 mm). The value is compared to CST simulations in Fig.7.7(b) and in good agreement. The spatial variation of the field distribution of the TE_{011} mode generates an azimuthal surface current that is mainly focused in the centre of the samples close to the edge of the dielectric rod.

To perform the complex S-parameter measurements at high microwave power, a P5002A Keysight Streamline USB-VNA that provides output power from $P_{\text{out}} =$

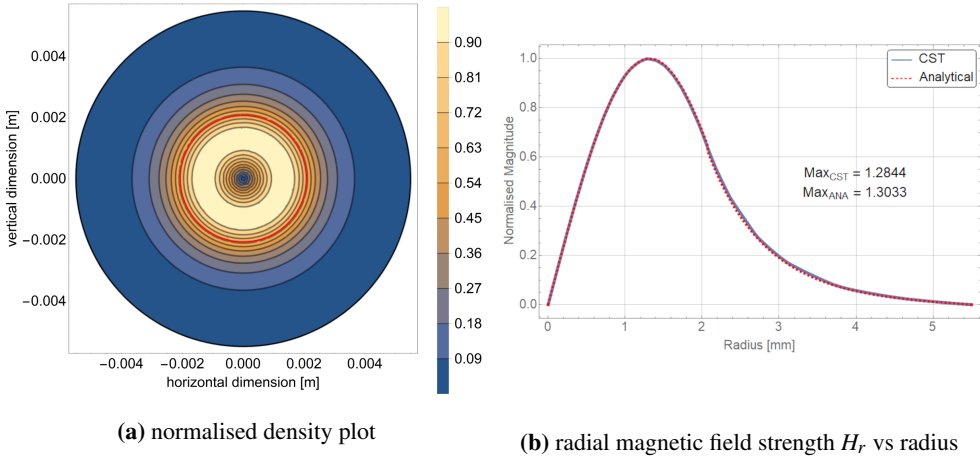


Figure 7.7: Surface magnetic field distribution of the TE_{011} at the samples: (a) Density plot of the normalised RF-surface magnetic field distribution. The field strength is normalised to the maximum value. The red circle indicates the edge of the dielectric. (b) Comparison of the radial RF surface magnetic field strength distribution along the radius.

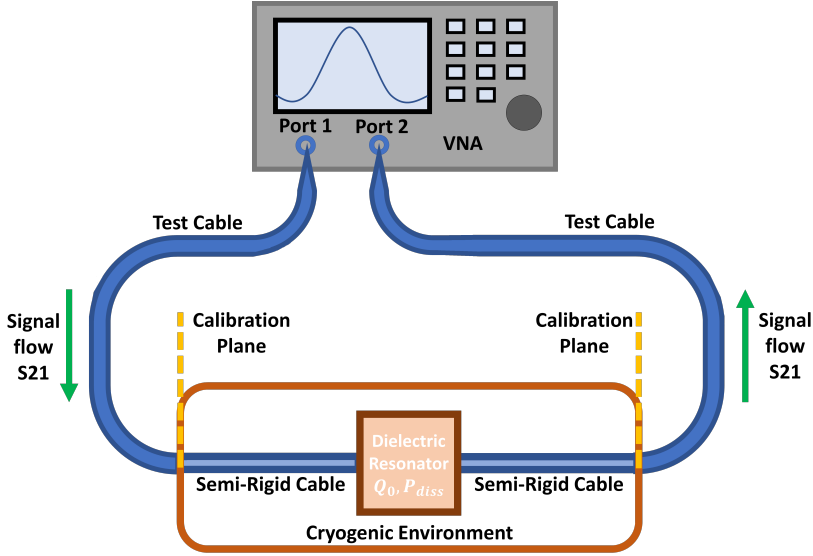


Figure 7.8: Layout of the connections between a VNA and CHCDR in a cryogenic experimental set-up. Published in [Krk+21c].

−60 dBm to +13 dBm (equivalent 1 pW to 20 mW) at about 8 GHz is available. To establish the relation between the RF surface magnetic field strength on the samples and the output power from the VNA, we need to be able to compute the available power at the cavity input P_{in} . This power depends on the insertion loss L_{off} of the cables inside the cryostat, as depicted in Fig.7.8. Determining the insertion loss of the test cable outside the cryostat L_{const} is a measurement that can be performed with a power meter. On the other hand, the semi-rigid cable inside the cryostat is not accessible. Its insertion loss varies with temperature and is estimated to be half the off-resonance return loss in dB as indicated with a red arrow in Fig.6.9(a). Consequently, we can estimate the available power at the resonator input P_{in} in dBm as:

$$P_{in} = P_{out} - L_{const} - 0.5L_{off}, \quad (7.26)$$

where P_{out} [dBm] is the power available at the VNA output, L_{const} [dB] is the loss of the cable between the VNA and the cryostat and L_{off} [dB], the off-resonance return loss. Note that the equation above only holds if the S-parameters calibration includes the cable between the VNA and cryostat [see Fig.7.8].

The power dissipated P_{diss} in the DR can be related to P_{in} through the coupling factors β_1, β_2 [Gin57]:

$$P_{diss} = P_{in} \frac{4\beta_1}{(1 + \beta_1 + \beta_2)^2}. \quad (7.27)$$

7.4 Parallel Plate Resonator

7.4.1 Resonator Structure

The parallel plate resonator (PPR) pioneered by Taber [Tab90] can be considered as another type of dielectric resonator which uses a dielectric with a very high aspect ratio. The PPR is typically formed by two small flat conducting parallel aligned plates of the materials to be measured, separated by a thin dielectric layer, usually made out of PTFE of 12.5 μm thickness [MG98; RW91]. Samples as large as 2.5 x 5 cm [RW91] have been measured with this resonator. A diagram of the PPR is shown in Fig.7.9. The peculiarity of this resonating structure is that the lateral walls are not directly shielded by metal. As no electrical contact is made to the edges of the plates, the edges represent open-circuit boundary conditions. Due to this, radiation losses occur and they need to be minimised by the combination of a very thin dielectric material and housing the PPR in a high conducting cavity, e.g., gold as used in [Tab90]. On the other hand, in theory, thicker dielectric materials can be used the higher the relative permittivity is, as higher permittivity leads to stronger confinement of the electromagnetic fields, which we will explore by numerical simulations in the following sections.

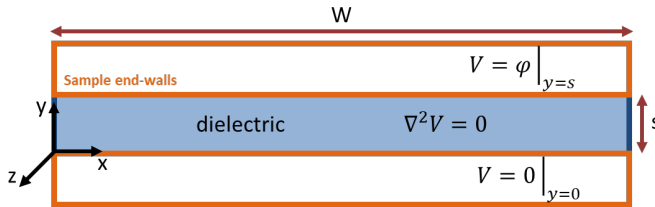


Figure 7.9: The cross-sectional area of the geometry of two parallel conducting plates (orange of width W) separated by a thin dielectric spacer (light blue) of height s , forming the PPR. In addition, the boundary problem is given based on a perfect electric conducting material surrounding the resonating structure (dark blue). The reference coordinate system for the derivation of the EM fields is given.

7.4.2 TEM

The electromagnetic analysis for the PPR is much simpler than that in the closed Hakki-Coleman dielectric resonator, as we can use a Cartesian coordinate system for one completely dielectric filled region Ω . The two separated conducting plates support a TEM wave that can be excited as explained in Sec.7.2.2. To find the general solutions for Maxwell's equations for the specific case of a TEM-wave propagation in a parallel plate configuration, we define the geometry of the PPR and boundary conditions as seen in Fig.7.9. The main assumption to be taken within this approach is, that the width W is expected to be much greater than the separation s of the conducting layers so that fringing fields can be ignored; hence, we will completely neglect the effects of radiation in this derivation. A material with permittivity ϵ and permeability μ is assumed to fill the region between the two plates. TEM waves are characterised by the longitudinal component of the electromagnetic field being non-existent. This reduces the problem

from a three-dimensional Helmholtz equation to a two dimensional Laplace equation, which means that the transverse fields are the same as the static fields that can exist between two conductors [Gri17].

In the electrostatic case we can express the electric field as the gradient of a scalar potential $V(x, y)$:

$$E_y(x, y) = -\nabla V(x, y). \quad (7.28)$$

In a PPR the bottom plate is at ground potential $V = 0$ while the top plate is at the potential $V = \varphi$, where φ can have an arbitrary value. To find the electrostatic potential between the two plates we solve the Laplace equation satisfying following boundary conditions:

$$\nabla^2 V(x, y) = 0 \quad \text{for} \quad 0 \leq x \leq W \quad 0 \leq y \leq s, \quad (7.29)$$

$$V(0, y) = 0 \quad V(x, s) = \varphi. \quad (7.30)$$

As we know that there is no variation in x-direction, the general solution for Eq.(7.29) can be described as

$$V(x, y) = A + By, \quad (7.31)$$

where A and B refer to constants. Including the BCs it results that $A = 0$ and $B = \varphi/s$, leading to the total solution:

$$\vec{E}(x, y) = -\frac{\varphi}{s}\hat{y}. \quad (7.32)$$

This is the solution for a static homogeneous distributed field. Nevertheless, for a resonating structure we need to include a resonance condition. We can generally assume a time-harmonic field with an exponential dependence $\exp[i\omega t]$ as described in Eqs.(3.20) and (3.21) and add the the boundary condition that the electric field has a minimum at $z = L/2$, which is the analogous of having half a wavelength resonating in the structure. Knowing that $\exp[-ikz] = \cos(kz) - i\sin(kz)$ and applying $\vec{E}(x, y, L/2) = 0$ we get the final solution:

$$\vec{E}(x, y, z) = -\frac{\varphi}{d}\cos(kz)\hat{y}, \quad (7.33)$$

$$\vec{H}(x, y, z) = i\frac{\varphi k}{\omega\mu d}\sin(kz)\hat{x}, \quad (7.34)$$

plotted in Fig.7.10, where resonance is given if:

$$\begin{aligned} k_0^2 \cdot \epsilon_r &= k^2, \\ f &= \frac{1}{\sqrt{\epsilon_r}} \frac{c}{2L}. \end{aligned} \quad (7.35)$$

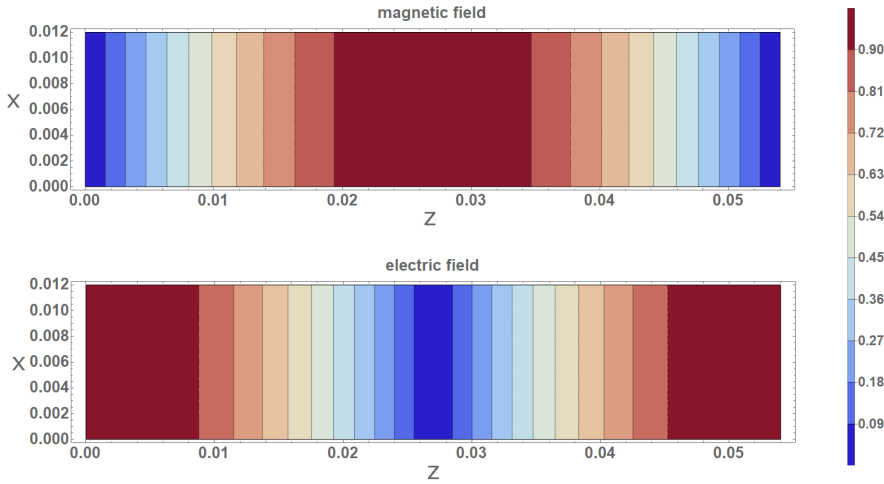


Figure 7.10: Contour plot of the normalised absolute magnitude values of the electromagnetic field distribution.

7.4.3 Eigenmode Analysis

In this section we will present a CST Eigenmode analysis to assess the performance and design of a parallel plate resonator. Unlike the CHCDR, which is shielded by metal walls, the basic PPR has no shielding and it is necessary to assess its radiation losses and the possibility of high-order modes. We have studied three different PPR configurations: First, the ideal parallel plate resonator which follows the theory given in Sec.7.4.2, and which serves as performance reference in this study for the two following PPRs. Thus, its length is always the same as the PPR to compare to. The second PPR with a length of about $L = 5$ cm is intended to be used for the study of ReBCO-CC under the influence of synchrotron radiation and will be referred to as *SR-PPR*. The third PPR in the study includes a $L = 10$ cm long PPR which is enclosed by a copper housing to reduce possible radiation losses and measure surface impedance of ReBCO-CCs. Therefore, we will refer to this version as the *shielded-PPR*. The simulations for all three configurations were performed based on having a sapphire ($\epsilon_r = 9.9$) loaded parallel plate resonator with a width of $W = 12$ mm which is the ReBCO width.

Ideal Parallel Plate Resonator (Ideal-PPR)

The propagating TEM wave in this parallel plate resonator can be seen in Fig.7.11. The ideal-PPR consists of two conducting plates with the same length and width as the dielectric, as visible in the inset of Fig.7.11(a). As can be seen in Fig.7.11(a) the electric field component E_y has two maxima at the edges of the dielectric, having equal magnitude and opposed direction. Figure 7.11(b) shows the maximum of the H_x field component which occurs at the mid-length of the resonator in the same way as in Fig.7.10. The resonance frequency is determined analytically over Eq.(7.35) as

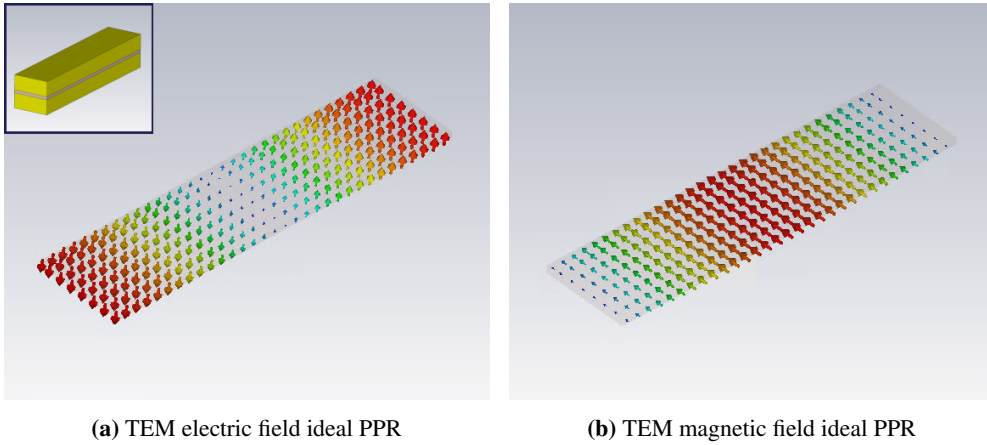


Figure 7.11: Electromagnetic field distribution of the TEM wave in the ideal-PPR.

$f_{0,5cm} = 882.22$ MHz and $f_{0,10cm} = 441.11$ MHz which is the same as given by the simulations independently of the dielectric spacer thickness¹⁶.

Synchrotron Radiation Parallel Plate Resonator (SR-PPR)

In the specific case of in-situ SR irradiation measurements of the surface resistance, the PPR should not be shielded and had to be developed to suit the experimental set-up, which will be discussed in detail in Sec.8.4. Accordingly, the design had to be made in such way, that the PPR is open, with a mechanism that will press the two parallel plates together and hold them in place. As depicted in Fig.7.12(a) the design of the SR-PPR includes a large metallic fixture base with the width $W = 60$ mm and length $L = 70$ mm and a smaller upper metal carrier having the same dimensions as the sapphire dielectric $W = 12$ mm and $L = 54$ mm. Figures 7.12(c) and 7.12(d) show the TEM mode for this version of the parallel plate resonator. Note that the electric and magnetic field distribution extend outside the dielectric, indicating radiation losses. In addition, in Fig.7.12(d) magnetic swirls appear at the edges of the dielectric. Care has to be taken as the electromagnetic field simulation is restricted to a rectangular cuboid boundary box in CST. Nevertheless, due to the higher permittivity of sapphire compared to vacuum the numerical estimation of the resonance frequency is a fast valid approach. The red curve in Fig.7.12(b) represents the simulated resonance frequency versus dielectric thickness for the SR-PPR configuration with the same BC as for the ideal-PPR. As can be seen, the resonance frequency starts to deviate strongly from the analytical solution towards higher f_0 for larger dielectric thickness. Besides affecting the resonance frequency, the metallic fixture base may also affect the resonator losses if made of normal conductor which due to the boundary box, we cannot simulate appropriately in the Eigenmode Solver but in the Frequency Domain Solver explained in the next section 7.4.5.

¹⁶In the Eigenmode Solver an open boundary condition cannot be set. Therefore, the boundary conditions imposed on the four lateral sides of the dielectric are magnetic BCs [see Sec.7.2.1]. Accordingly, no radiation losses are simulated.

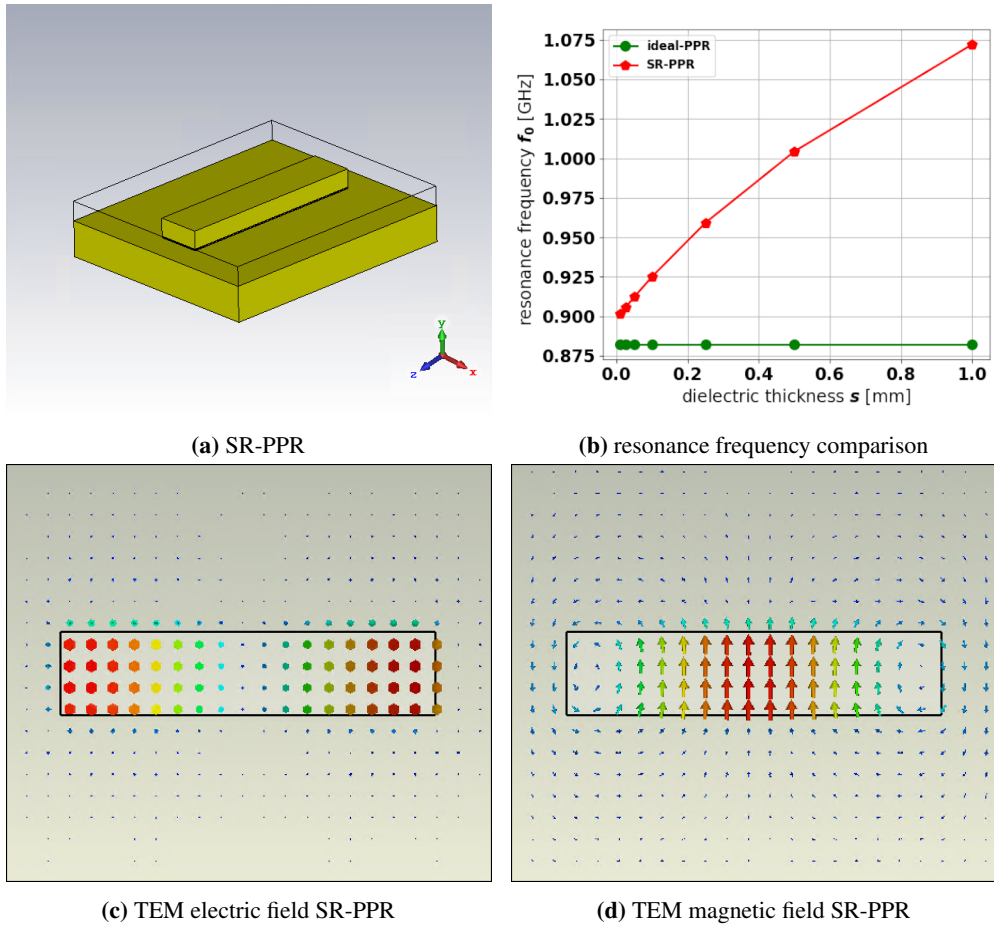


Figure 7.12: (a) design of the SR-PPR in CST. (b) resonance frequency comparison between the SR-PPR and ideal case as a function of dielectric thickness. (c) and (d) Electromagnetic field distribution of the TEM wave in the SR-PPR at the cross section of the mid height of the dielectric.

Shielded Parallel Plate Resonator (shielded-PPR)

The third case study investigates the possibility of measuring the surface impedance of long-length samples, including estimating the London penetration depth. The numerical model is shown in Fig.7.13(a). The dielectric is positioned in the centre of the resonating structure in order to minimise the losses induced by the metallic fixture base. We used the conducting wall boundary condition defined in CST [explained in Sec.7.2.1]. The boundary box is assigned with a designated conductivity of copper for the numerical calculations, and thus, the housing does not have to be 3D-modelled, though the influence on the resonance frequency is taken into account. The electromagnetic field distribution is similar to the SR-PPR. The results of the resonance frequency study are given in Fig.7.13(b). The higher the thickness of the dielectric, the higher the deviation from the ideal case.

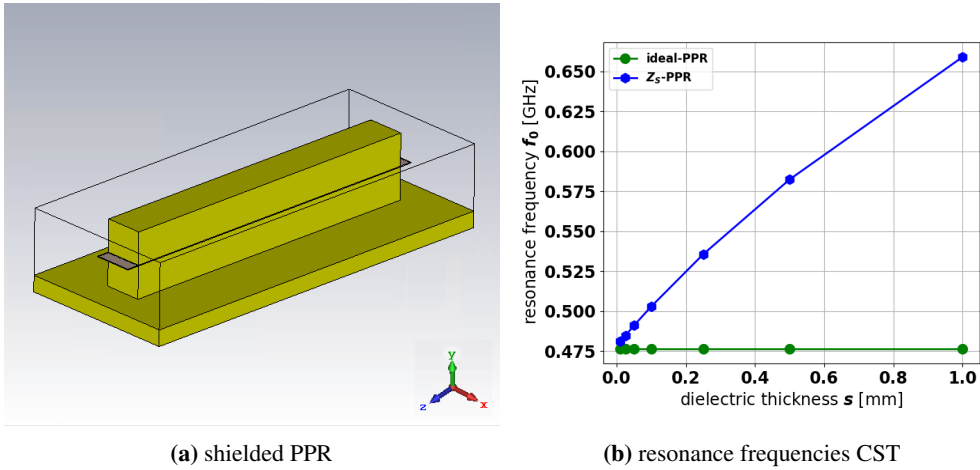


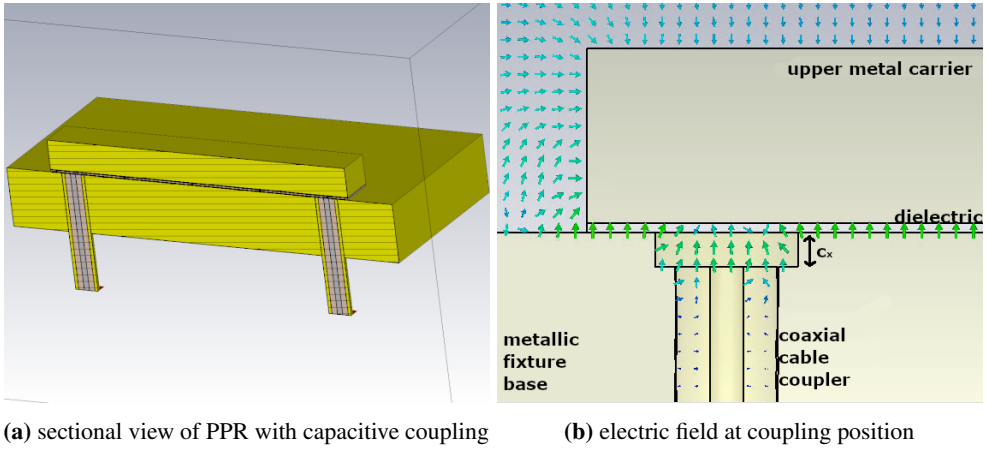
Figure 7.13: Design and simulation results for the shielded PPR.

7.4.4 S-Parameter Analysis

In this section, the CST Frequency Domain Solver is used to simulate how to couple energy into the resonator. For the S-Parameter analysis we will neglect the ideal case and focus on the following discussion on the configuration of the SR-PPR, though the numerical results are valid as well for the shielded-PPR as we use the same coupling mechanisms for both versions. In contrast to the CST Eigenmode solver, the Frequency Domain solver does not necessarily need closed boundary conditions because electromagnetic ports are given as a source. Hence, the boundary box can be set with open boundary conditions [see Sec.7.2.1] applied in combination with expanding the boundary box to add some space to the device under test.

Unlike the CHCDR, the positioning of the coupling is of higher relevance in the PPR. Capacitive coupling to the resonator can be obtained by positioning a pair of semi-rigid coaxial cables with a planar cut close to the edges of the sapphire, where the electric field has maximum values. Figure 7.14(a) shows the same resonator as in Fig.7.12(a) fed by a pair of semi-rigid coaxial cables including an input and output port at each coaxial cable beginning. The semi-rigid cables are implemented into the metallic fixture base and positioned such that the end of the upper metal carrier and dielectric covers them slightly. The endings of the coaxial cables are oriented to be coplanar with the dielectric spacer but do not touch the dielectric surface, as can be seen in Fig.7.14(b). In addition, we can see the electric field coupling to the resonator and the electric field outside the desired dielectric volume. The coupling is done by adjusting the position/depth at which the semi-rigid ends indicated as c_x in Fig.7.14(b).

We performed a parametric sweep of the coupling strength where the plane end of the semi-rigid tips are within a range of $c_x = 1$ to $c_x = 0$ mm away from the dielectric for the dielectric thickness of $s = 0.25$ mm, to try to obtain an adequate coupling with the S_{21} maximum magnitude close to -40 dB. The transmission coefficient S_{21} versus frequency seen in Fig.7.14(c) shows that we can couple at -40 dB if the distance



(a) sectional view of PPR with capacitive coupling

(b) electric field at coupling position

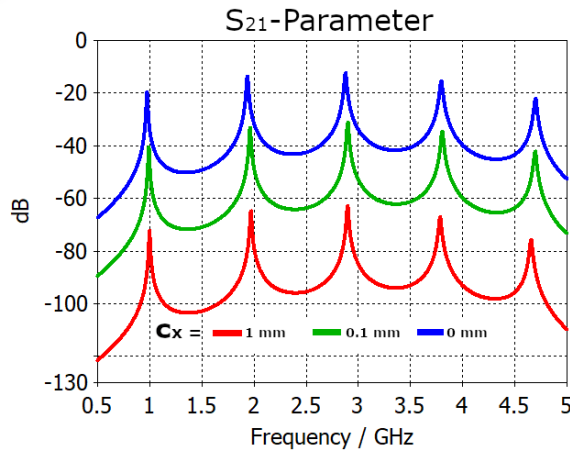
(c) Results for the simulated S_{21} parameter plotted for weak coupling of for the SR-PPR.

Figure 7.14: Cross-section of the SR-PPR with capacitive coupling, enhanced view of the capacitive coupling to the electric field into the resonating structure, and Frequency Domain Solver simulation results.

between the end of the semi-rigid line and the dielectric is about $100\ \mu\text{m}$ for a resonator having copper samples at room temperature. The same figure shows as well the first five harmonics that we can excite at the same time. Comparing the first resonance with the resonance value given in the Eigenmode Solver in Fig. 7.12(b) at the same dielectric thickness, we can see a higher resonance for the open SR-PPR simulations.

In the case of the shielded-PPR, the copper housing might reduce the radiation losses but might introduce unwanted modes with resonances close to the TEM mode or any of the harmonics that have to be identified. The simulations for the shielded-PPR showed that a mode appears at very low frequencies, below the expected TEM, and with that, the necessary separation between the harmonics and other modes within the closed cavity is given.

7.4.5 Characteristics of the Resonator

So far, only a parallel plate resonator with two copper plates has been discussed. Let us now discuss what happens when the samples to be tested are sandwiched between the metallic fixture base and the upper metal carrier, as shown in Fig.7.15. The upper sample can have the same length as the upper metal carrier, but the lower sample has to be as short as the distance between the two semi-rigid cables in order not to disturb the coupling. The effect of having one sample shorter than the dielectric can be seen in the simulation results of the electric field magnitude at the mid height of the dielectric in Fig.7.16. The maximum electric field should be at the left and right ends of the dielectric (indicated by the black rectangle), as previously shown in the contour plot of the ideal-PPR in Fig.7.10. However, the maximum of the electric field (red) is located at the edges of the lower sample. This means, that the sample attached to the metallic fixture base, effectively shortens the PPR length, and with that, a higher resonance frequency results than expected.

The unloaded Q-factor for the PPR is determined from the loss equation in Eq.(6.3) including all three loss contributions: the resistive loss due to the surface impedance of the samples to measure, the dielectric loss, and the radiation loss at the edges arising from the fringing fields which extend outside the PPR. The overall Q-factor is then

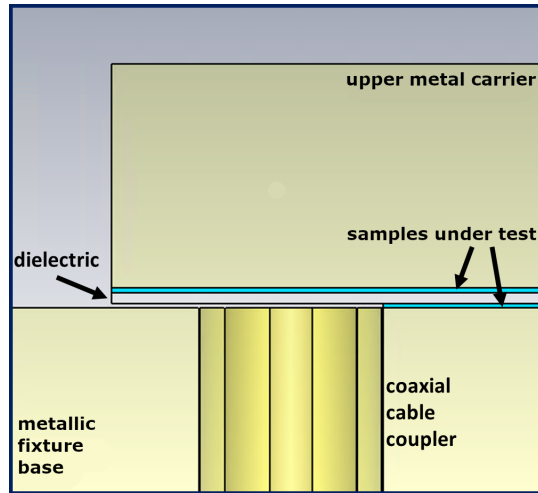


Figure 7.15: Cross-section of a PPR with capacitive coupling including samples.

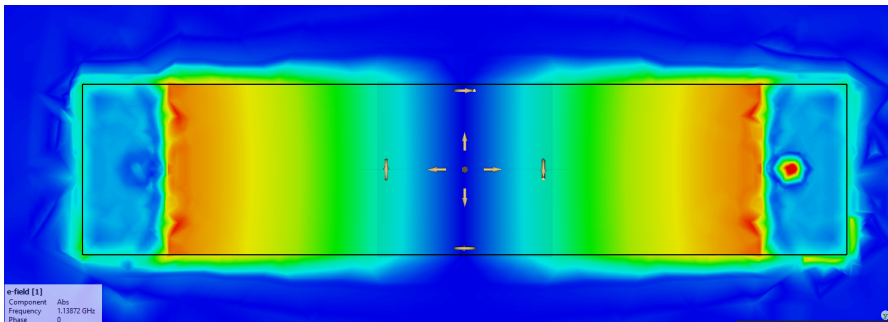


Figure 7.16: Countour plot of the PPR with capacitive coupling including samples and resulting electric field magnitude.

given by [FKB88; Tab90]:

Definition 7.4.1 — Loss Equation PPR.

$$\frac{1}{Q_0} = \frac{R_S}{\pi\mu_0fs} + \alpha + \tan(\delta), \quad (7.36)$$

where, s is the separation between the conducting plates and α is the radiation coefficient which depends on the frequency and the precise details of the surroundings of the resonating structure.

Only in the case that the radiation and dielectric losses are negligible, one obtains a direct relation between Q_0 and R_S :

$$\frac{1}{Q_0} = \frac{R_S}{\pi\mu_0fs} \quad (7.37)$$

To establish under which condition this formula is adequate for the two PPR designs -SR-PPR and shielded-PPR- we extracted Q_0 from simulations performed in the Frequency Domain Solver for samples with different theoretical surface resistances. In the simulations, we have used a dielectric thickness of $s = 250\mu\text{m}$ and a $\tan(\delta) = 10^{-6}$. From the exported Touchstone files, we used ARPE [see Sec.6.5] to extract the unloaded Q-factor. Figure 7.17(a) compares Q_0 for the SR-PPR (orange) and shielded-PPR (green) as a function of surface resistance compared to the approximation in Eq.(7.37). As can be seen in the same figure, if the $R_S < 10^{-3}\Omega$, we cannot extract R_S with Eq.(7.37) any more for the SR-PPR. Hence, the influence of the radiation leads to a strong deviation from the ideal PPR. Figure 7.17(b) shows the radiation loss α which can be calculated from Eq.(7.36) as we can define R_S , s and $\tan(\delta)$ in the simulations. It can be seen, that the value for α in the open SR-PPR is

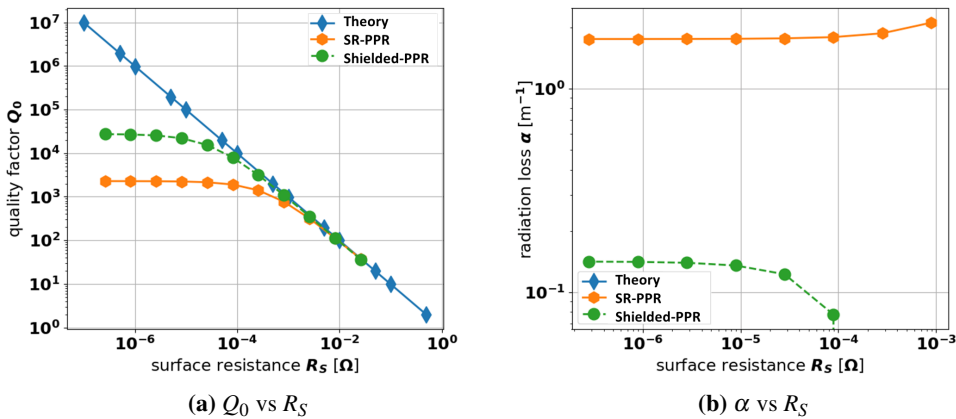


Figure 7.17: (a) unloaded Q-factor versus sample surface resistance. (b) estimated radiation losses over Eq. (7.36) for simulation results in (a).

an order of magnitude higher than that in the closed shielded-PPR. The influence of the shielding for the PPR leads to the possibility to measure the surface resistance up to $R_S \approx 10^{-5} \Omega$. In both PPR designs, for lower surface resistances, the contribution of the surface resistance of the metallic fixture base and upper metal carrier prevails over the surface resistance of the samples to be measured and the value for α can get unsuitably large to measure R_S accurately.



8. Experimental Set-ups

El arquitecto es el hombre sintético,
el que es capaz de ver las cosas en
conjunto antes de que estén hechas.

Antoni Gaudí

This chapter describes the design, implementation, and exploration of radio-frequency measurement techniques and systems to investigate the surface impedance at FCC-hh conditions. The study of ReBCO-CCs as possible coatings for the FCC-hh beam screen requires extensive characterisations under different external agents like temperature, magnetic fields and synchrotron radiation. It has not been possible in the present stage of the project to combine all requirements in a single experimental set-up; therefore, different set-ups have been produced to allow for partial characterisation. The diagram in chapter 1 in Fig.1.14 shows the different external conditions to which the ReBCO-CCs will be subjected to when implemented on the beam screen. Along with this chapter and the next ones, this diagram will be adapted to each of the set-ups presented. In addition, a summary of collaborative projects established during the thesis is given.

8.1 CHCDR - Closed Cycle Cryostat

A closed Hakki Coleman dielectric resonator has been adapted to measure the surface impedance as a function of temperature. The response of the resonator to the microwave electromagnetic fields and the calculation of the surface resistance from its parameters

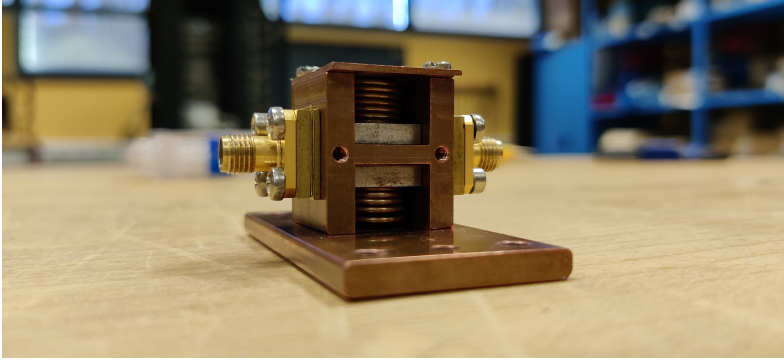


Figure 8.1: Side view of the CHCDR with stainless steel samples.

have been described in Sec.7.3. The manufactured CHCDR is shown in Fig.8.1. The housing is made of oxygen-free electronic (OFE) copper and houses a dielectric cylinder (diameter: 4 mm, height: 3 mm), and a pair of equal ReBCO-CC samples under test. Due to the width of the coated conductors, the sample size is chosen to be 12 x 12 mm. The resonator is designed to operate in the TE_{011} mode; either using a rutile single crystal with a resonance frequency of about 9 GHz at room temperature (RT) and about 8 GHz at cryogenic temperatures or using a sapphire crystal of the same dimensions leading to a resonance frequency around 27 GHz at room and cryogenic temperatures. The samples are pressed against each other with two copper-beryllium springs that close the cavity and fix the dielectric crystal to its designated position in the cavity axis, despite housing expansion or contraction due to temperature changes. ReBCO-CCs are very thin, and therefore, have to be supported to prevent the bending of the samples under pressure from the springs. We used brass blocks where the samples are glued with adhesive, e.g., GE-Varnish. Using a brass support prevents damage to the ReBCO-CC's surface and increases the reproducibility of the measurement. On the contrary, fixing the dielectric with adhesive material is not possible as it would introduce high losses in the cavity and might change the surface morphology of the CC samples.

The magnetic coupling is achieved through the lateral walls by a pair of semi-rigid coaxial cables with a loop at the end, visible in Fig.8.2 where the CHCDR is attached to the cold head of a Janis CCS-250L closed-cycle cryocooler. The coupling loops are made by directly connecting the inner conductor of a semi-rigid cable with its outer conductor mounted to a standard SMA connector. The coupling strength can be adjusted ex-situ by changing the insertion depth of the loops into the cavity with the aid of in-house made brass spacers of different thicknesses to adjust to a suitable coupling level as simulated in CST in Sec.7.3.4. Since the RF coupling cannot be adjusted during a measurement, test measurements were performed at a temperature of 77 K by immersing the cavity into liquid nitrogen. In this way, a coupling was preselected that neither caused a strong nor too weak coupling to provide a sufficient signal-to-noise ratio because ARPE [see Sec.6.5] was not developed yet at the time of the construction and calibration. We decided that the maximum S_{21} magnitude shall be around -40 dB

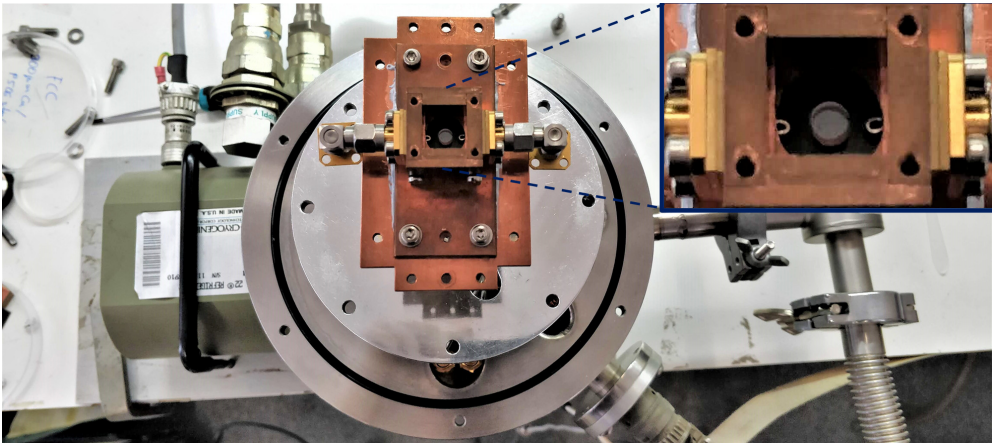


Figure 8.2: Mounting of the CHCDR on the Janis System.

as a good reference as explained in Sec.6.3.

Semi-rigid cables for the EM-coupling are wrapped around the cold head column to a SMA terminated feedthrough in the base, to which a Keysight P5002A USB VNA can be connected, as sketched in Fig.8.3. It has been used to perform the complex S-parameter measurements at high microwave power as it provides power up to +13 dBm at 8 GHz. The calibration of the test cables used to connect the resonator to the VNA is described in Sec.7.3.4. Thermal paste -visible in Fig.8.2 on the sides of the CHCDR- is used to anchor the resonator to the cold finger ensuring good thermal contact. The cold finger temperature is monitored with a calibrated DT-470 silicon diode temperature sensor (T -sensor) and regulated with a heater connected to a LakeShore 310 Temperature Controller. The entire CHCDR assembly is integrated into a double vacuum chamber system. An internal radiation shield is placed around the cold head, followed by an external vacuum cavity with a buna O-ring gasket to ensure a good vacuum. The vacuum chamber was evacuated using an Agilent Technologies TwisTorr 74 FS AG Vacuum pumping system to an absolute pressure below 10^{-4} mbar to provide thermal isolation and avoid ice formation inside the resonator and ReBCO-CC samples. The closed-cycle CTI-Cryogenics helium compressor 8200 is utilised for the cool-down, once the final pressure was achieved.

The set-up as shown in Fig.8.3 allows the temperature-dependent surface resistance to be measured in a temperature interval from 10 K to 300 K. The temperature controller and VNA are connected via USB to a computer. A Python code has been developed to automatise the process of tracking the TE_{011} mode over the whole temperature range. Once the system achieves the base temperature and stabilises, the code instructs the VNA to find the correct mode and sets the frequency span to 10 times the 3 dB bandwidth, as discussed in Sec.6.5. Next, the code instructs the temperature controller to take the system to the first temperature point to be measured, using its built-in proportional-integrator-differentiator (PID) algorithm to keep the temperature stable. The Python code monitors the shift in the resonance frequency until the desired

temperature is achieved and further interrogates the VNA to acquire f_0 , Q_L , and S_{21} maximum magnitude of the resonance, as well as store the Touchstone files including all four S-parameters within the desired frequency span. This procedure is iterated for predefined increments of temperature ΔT .

The surface resistance has been measured between 30 and 100 K, slightly above T_C and it includes the temperature range of interest for FCC-hh as described in Sec.1.5. In addition to the temperature sensor placed on the cold finger, we make use of the strong temperature dependence of rutile's permittivity to determine the temperature of the resonator and temperature stability. A constant frequency indicates a constant

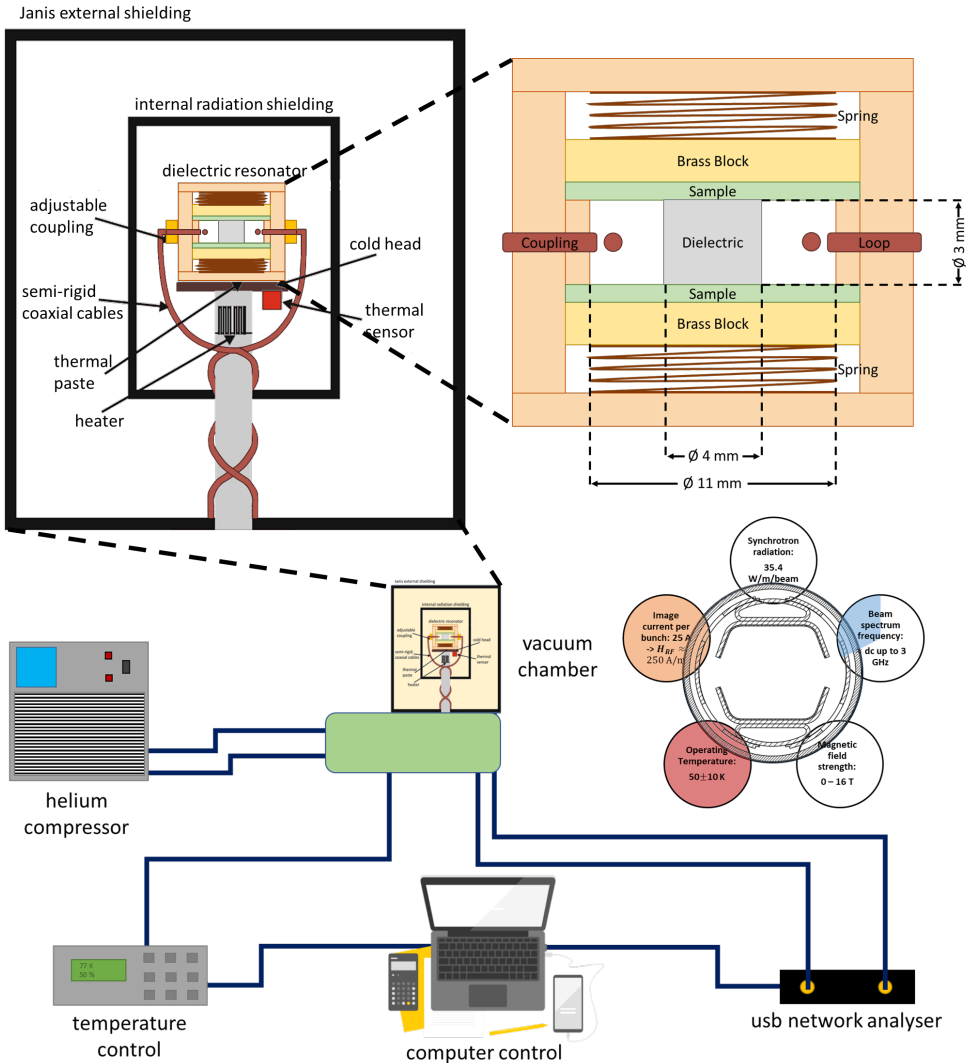


Figure 8.3: Experimental set-up of the closed cycle refrigerator, including the closed Hakki-Coleman dielectric resonator. Parts of the sketch adapted from Breeze [Bre16].

temperature; hence equilibrium. In this case, the average temperature-dependent surface resistance $R_S(T)$ of both samples under test is calculated using formula as defined in Eq.(7.18), neglecting the contribution of the lateral walls, i.e.:

$$R_S(T, H_0) = \frac{G(T)}{2} \left(\frac{1}{Q_0(T, H_0)} - p \cdot \tan(\delta(T)) \right), \quad (8.1)$$

where H_0 refers to the surface magnetic field strength from Def.7.3.2.

This set-up has not only been used to measure surface resistance of ReBCO-CCs but also of other materials as summarised here:

- Metal coatings are deposited on plastic substrates in additive manufacturing, such as copper on polyvinylchloride. The samples were obtained by electrolytic deposition of copper onto the plastic surface, which had previously been coated with a silver conductive primer. Besides measuring R_S at RT, we showed a procedure to study the homogeneity of the metallisation in a large surface by dicing it into smaller pieces. By taking pieces from different places of the original plate and setting up a round-robin in which all the combination pairs are measured, we can compare all determined values to the average value. The complete description is given in [KAO18].
- Characterisation of 2D materials like graphene. Herein, the aim was to show that the CHCDR can be used to measure the electrical surface resistance of conducting coatings deposited on different substrates. It is known that the substrate exerts a strong influence capable of intrinsically modifying the properties of 2D materials, as found in graphene. The CHCDR method was used for different samples such as carbon nanotubes (bucky paper), a film of compacted graphene flakes, a film of compacted graphene oxide flakes, and graphene obtained by chemical vapour deposition (CVD) on different substrates (SiO₂/Si, quartz, and polyethylene terephthalate (PET)). The results published in [Arc+19] show that reasonable values can be obtained for thin conducting materials with a thickness of not less than a few micrometres. In the case of graphene grown on a substrate, the presence of graphene can be detected, but the resistivity value cannot be accurately extracted.
- LASE modification of Cu samples. In the past few years, it has been established that Laser Ablation Surface Engineering is a very effective way of producing surfaces that have Secondary Electron Yields (SEY) $\delta_{SEY} < 1$. The technique involved in achieving such low SEY requires rapid surface micro- and nano-restructuring at room temperature using very short high-power laser pulses (from nano to picoseconds) at various wavelengths for the processing of aluminium, stainless steel and copper surfaces. The influence of micro- and nanostructures induced by the laser surface treatment of copper samples as a function of various laser irradiation parameters has been discussed at length in [Val+17]. However, the treatment leaves moderately deep grooves and nano-particulates that, on the one hand, help to reduce the SEY, but on the other hand, can produce undesirable effects such as an increase in the surface resistance. In [Han+21] we use the dielectric resonator technique to quantify the surface resistance of laser-treated

copper and stainless steel samples from ambient to cryogenic temperatures. We could demonstrate that the LASE surface can be produced with $\delta_{\text{SEY}} < 1$ and an RF surface resistance of only $\approx 6\%$ higher than that on untreated surfaces.

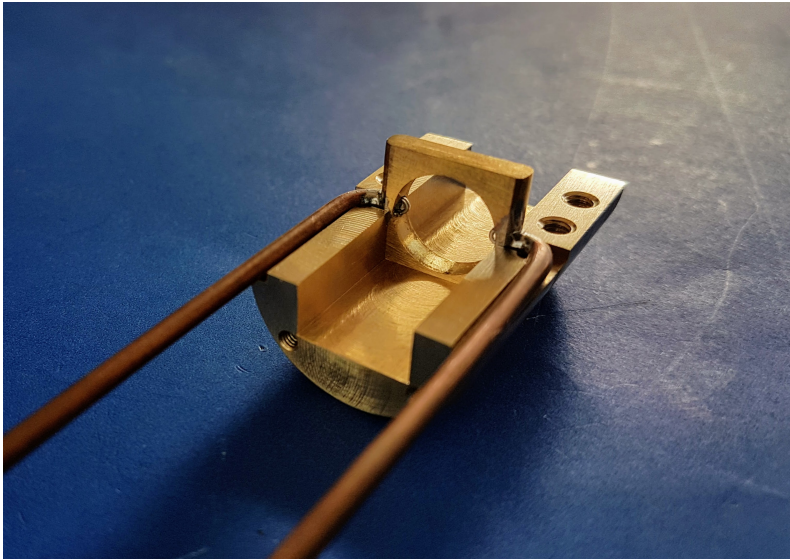
8.2 CHCDR - Magnetic Field System

In order to characterise the surface impedance $Z_S(T, H_0, B_{DC})$ of ReBCO coated conductors as a function of temperature, surface magnetic field strength, and applied DC magnetic dipole field B_{DC} , we used a Quantum Design's PPMS[®] cryostat operating in a temperature range between 1 and 400 K and equipped with a 9 T superconducting coil magnet embedded in liquid helium. This system is mainly designed for the measurement of small samples at low-temperature and magnetic field and for extracting their properties like specific heat, magnetic AC and DC susceptibility, and both, electrical and thermal DC transport properties. Accordingly, the closed dielectric resonator had to be adapted and made compatible with the 25 mm bore of the PPMS cryostat.

It was of interest to keep the inner dimensions of the resonating structure as used in the set-up discussed in the previous section, i.e., the same dielectric and cavity diameter and height as shown in Sec.8.1. The main reason is that it was already fully characterised and well functioning as well as results could be compared between different systems and measurements. Nevertheless, the aforementioned dimensional restrictions, externally from the cryostat bore and internally from the cavity diameter, forced the design to be very compact. Figure 8.4(a) shows the inner part of the CHCDR, which is made out of brass due to easier mechanical manufacturing compared to copper, and thus, higher precision in the tolerances. It can be seen in the same figure that the cavity is separated from the outer two walls and with that is exchangeable in case of a problem with the inner cavity.

The coupling loops are made directly at the end of two 97 cm long semi-rigid cables and had to be soldered to the cavity for mechanical stability as the usage of SMA transitions, as in the design in Sec.8.1, is impossible in this system. The drawback is that once the coupling is set, it cannot be adjusted any more. In addition, the semi-rigid cables are embedded into the housing to keep the total diameter of the device at 24 mm. Due to this, the coupling had to be experimentally iteratively tested at $T = 77$ K with experiments with liquid nitrogen taking a ReBCO-CC with intermediate surface resistance as reference.

For the precise temperature monitoring, a LakeShore Cernox CX-1050-SD-HT sensor is installed into the housing as illustrated in Fig.8.4(b). The sensor is directly connected to the PPMS control unit and serves as the reference for the measurements. The reason for a second external temperature sensor is to closely monitor the cavity temperature, which may be affected by the heat load produced by the connection of the semi-rigid cables to the KF-40 SMA flange at the outer wall of the vacuum system. Furthermore, in Fig.8.4(b) an elongation of the CHCDR can be seen. The brass piece of the same length as the DR is designed to contact the bottom cold plate of the PPMS so that cooling can be achieved through convection and conduction to reach faster temperature stability. It includes a mechanism including a spring always



(a) Opened dielectric resonator exposing the exchangeable cavity center piece.



(b) Closed dielectric resonator with the positioning of the Cernox T -sensor at the top of the assembly and elongation piece at the bottom for conduction cooling.



(c) The PPMS system mounted.

Figure 8.4: The three figures show the closed Hakki-Coleman dielectric resonator and the PPMS system used to perform the measurements. The GPS antenna is not included in this figure.

to have maximum thermal contact with the cold ground of the PPMS over the whole temperature range.

The network analyser used is a FieldFox N9918A handheld VNA as it is portable and includes the option of enhanced frequency stability of 0.01 ppm by connecting a GPS antenna to it. The whole set-up can be seen in Fig.8.4(c) and is sketched again in Fig.8.5.

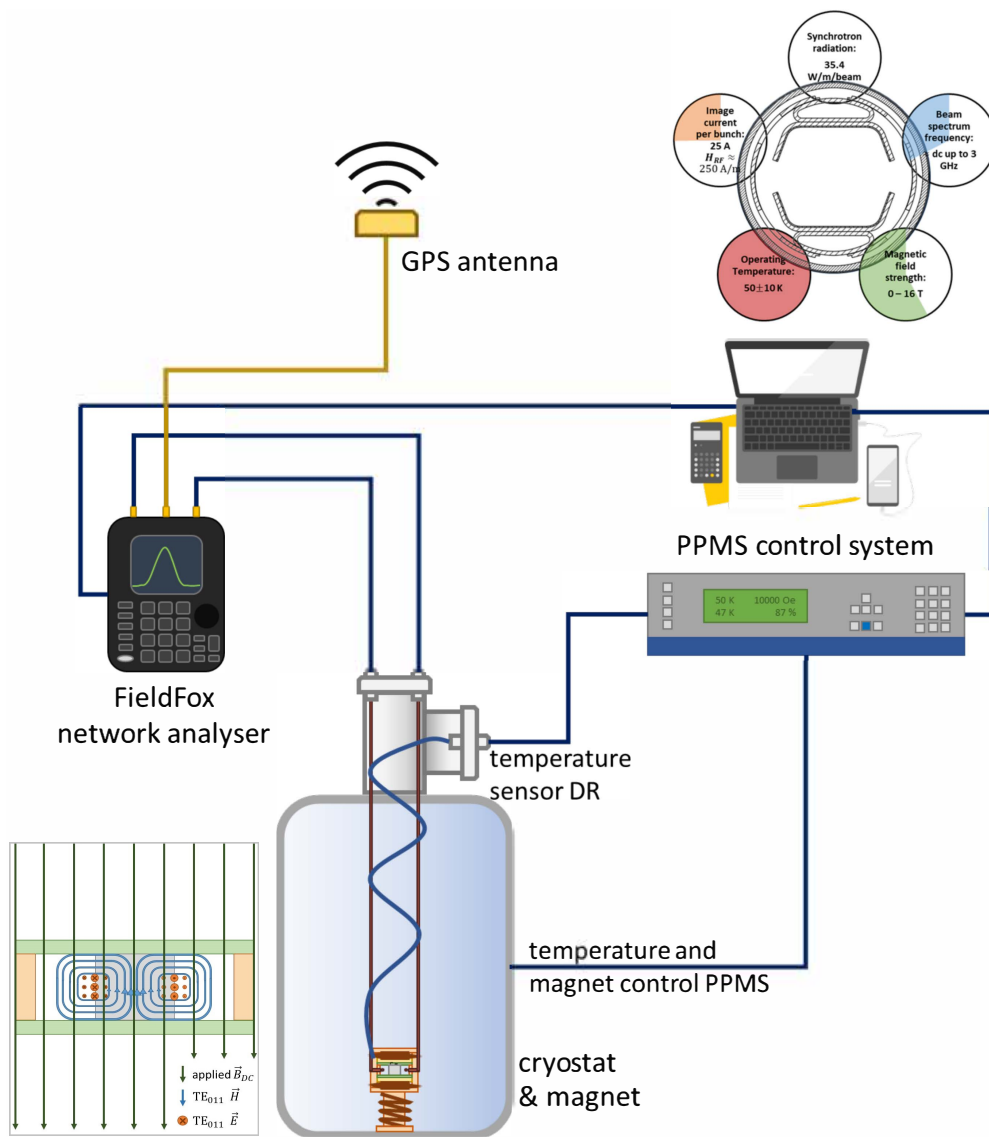
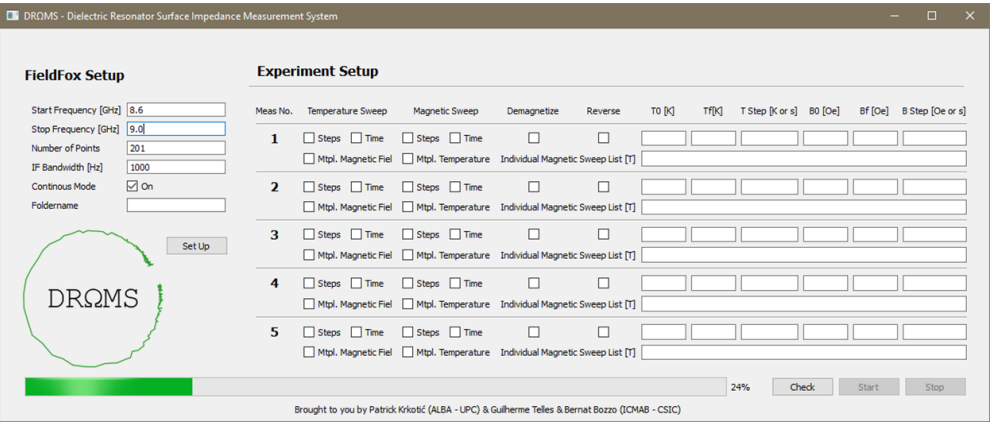
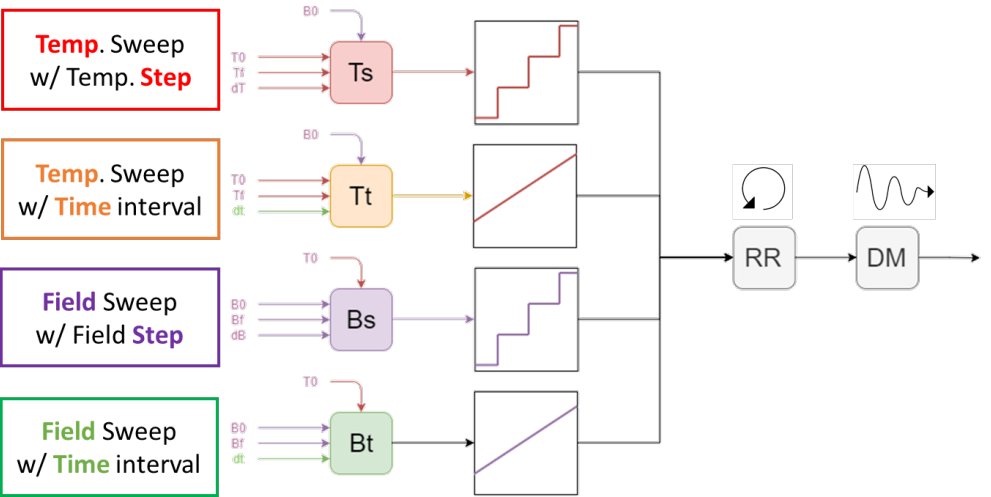


Figure 8.5: Design of the set-up for measuring the temperature and magnetic field surface impedance. The inset shows the magnetic field orientation on the resonator in the TE₀₁₁ mode.

A Dielectric Resonator Surface Impedance Measurement System software called DRΩMS was developed in collaboration [Tela] based on Python and implemented into a graphical user interface (GUI) as shown in Fig.8.6(a), in order to automatise several measurement procedures possible with the PPMS system and facilitate the usage of the dielectric resonator system by any user. The main functions programmed are the possibilities to do temperature and magnetic field sweeps in terms of either equidistant temperature ΔT and/or magnetic field ΔB steps with stabilisation at each measurement point, or using a constant temperature 1 K/min and/or magnetic field ramping rate 10 mT/sec without the need of stabilisation and continuous data storage. Hence, each combination of magnetic field and temperature can be selected and each



(a) PyQT based graphical user interface of DRΩMS



(b) DRΩMS experiments outline. T = temperature, B = magnetic field, t = time, s = step, RR = reverse ramp, DM = demagnetisation

Figure 8.6: Graphical user interface and experimental outline of DRΩMS [Tela].

measurement individualised as visualised in Fig.8.6(b). Further information is given in the appendix B.4.1.

The complete system set-up provides a broad range of measurement opportunities, including studies out of the scope of the FCC-hh requirements, e.g. studies connected to the micro-structure of the ReBCO films in temperature ranges down to $T = 2$ K. Nevertheless, in this section, we will focus on the measurements connected to the FCC-hh requirements. The main focus of this experimental set-up is the study of the surface impedance and material compatibility for the six different providers from Sec.2.3. The data points of in-field measurements were acquired primarily in ZFC mode [see Sec.2.1.2], which means that the magnetic field was turned on after entering the superconducting state. In addition, as can be seen in the inset of Fig.8.5, in this set-up, the magnetic field (represented by green arrows) can only be applied perpendicularly to the sample surface.

The measured Q-factors can be directly related to the overall surface resistance in the same way as described in Sec.8.1 as :

$$R_S(T, H_0, B_{DC}) = \frac{G(T)}{2} \cdot \left[\frac{1}{Q_0(T, H_0, B_{DC})} - p \tan(\delta(T)) \right]. \quad (8.2)$$

Following the discussion in Sec.6.4 about resonator perturbations we can assume that a perturbation in temperature and/or magnetic field in the TE_{011} mode produces a relative change in the resonance frequency according to the equation [PTS14]:

$$-2 \frac{\Delta f_0(T, H_0, B_{DC})}{f_0(T, H_0, B_{DC})} = \frac{\Delta X_S(T, H_0, B_{DC})}{G(T)} + \frac{\Delta X_M(T)}{G_M(T)} + p \frac{\Delta \epsilon_r(T)}{\epsilon_r(T)}, \quad (8.3)$$

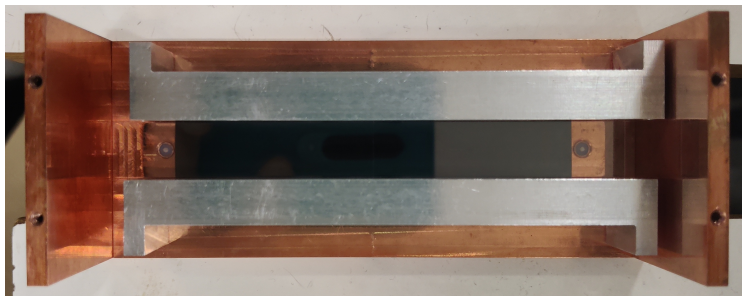
where ΔX_S is the change in surface reactance in the top and bottom plates of the resonator, ΔX_M refers to the change in surface reactance of the metal lateral walls, p is the dielectric filling factor and $\Delta \epsilon_r$ is the change in the relative permittivity. The terms G and G_M are the sample-independent geometry factors obtained from the calculations presented in Sec.7.3.5. Determining the change in surface reactance ΔX_S when the temperature changes from a given reference T_{ref} requires measuring the relative frequency change and knowing the two rightmost terms at the right hand side of Eq.(8.3). However, as the permittivity of rutile is strongly temperature dependent, the influence of the changes in permittivity prevails over that of the rest of the terms. A possible alternative is to use sapphire, but as at the time of this writing this was not possible, because the resulting high resonance frequency is above the frequency range of the available VNA. However, we were able to do resonator measurements while performing DC magnetic field sweeps at constant temperature and low VNA output power. In these conditions, and taking into consideration that only ΔX_S depends on the applied magnetic field, we can determine the changes in frequency and calculate the changes in the surface reactance. Therefore, Eq.(8.3) reduces to:

$$-2 \frac{\Delta f_0(T, B_{DC})}{f_0(T, B_{DC})} = \frac{\Delta X_S(T, B_{DC})}{G(T)}. \quad (8.4)$$

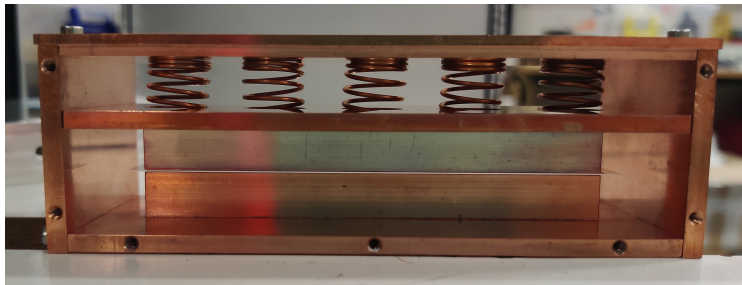
8.3 PPR - Closed Cycle Cryostat

The system for measuring the surface impedance as a function of temperature at frequencies within the expected FCC-hh range consists of the same experimental set-up as previously discussed in Sec.8.1, except for the use of a parallel-plate resonator. Several designs of the PPR have been tested [see pictures in App.B.4.2]. This section will focus on the shielded parallel plate resonator, as characterised and designed based on the simulations in Sec.7.4 to operate with a fundamental TEM mode around 600 MHz and its subsequent four higher order modes, and describe how it is implemented into the Janis Cryogenic system.

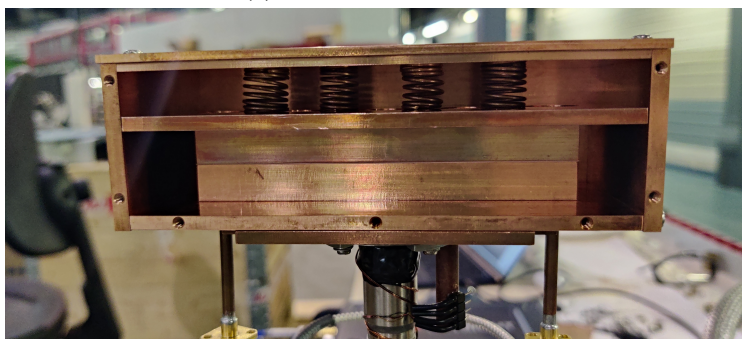
The manufactured shielded-PPR is shown in Fig.8.7 to explain the mechanical structure. In this set of figures, it can be seen that the complete structure consists of



(a) Shielded-PPR top view with aluminium alignment aid



(b) Shielded-PPR side view



(c) Shielded-PPR side view with one side wall on cold head

Figure 8.7: Shielded parallel plate resonator for the Janis Cryostat.

copper, using ReBCO-CC samples of the same provider with different lengths - 12 x 100 mm top sample and 12 x 80 mm bottom sample. Figure 8.7(a) shows the mounting procedure of the device. The U-shaped aluminium blocks are adapted to perfectly surround the metallic fixture base and used to align the different layers (ReBCO-sapphire-ReBCO) as well as hold the upper metal carrier in place until the springs are applied and the structure holds itself in place, as can be seen in Fig.8.7(b). The samples are pressed against each other with five CuBe springs to hold the different layers in place over the entire temperature range in the case of thermally induced contraction and expansion. After mounting the springs, the aluminium blocks can be removed. In this particular case in Fig.8.7 we used two sapphire plates (54 x 12 x 0.25 mm) which in sum are longer than the metallic fixture base, and hence, the aluminium blocks face outwards not to break the overhanging sapphire on each side. The mounting can be facilitated by applying GE-varnish or thermal paste to the copper surfaces to prevent bending of the samples and support the thermal conduction.

The capacitive coupling is achieved through the ground plate by a pair of semi-rigid coaxial cables with a stab at the end which can be seen in Figs.8.7(a) (top-view) and 8.7(c) (side-view). The adjustment of the coupling has been performed in the same way as explained in Sec.8.1 for the CHCDR, with simulations in CST in Sec.7.4.5 and test measurements at 77 K with liquid nitrogen.

The PPR is mounted on the cold head of the Janis CCS-250L closed-cycle cryocooler as depicted in Fig.8.7 with one side wall closed. The whole set-up is illustrated in Fig.8.8, already discussed in Sec.8.1.

The system is designed with the intention to determine two parameters. Firstly, the average temperature-dependent surface resistance $R_s(T, H_0)$ of both samples under test. It is calculated using the formula in Def.7.4.1:

$$R_s(T, H_0) = \pi \mu_0 f_0 s \left(\frac{1}{Q_0(T, H_0)} - \alpha(T, H_0)s \right). \quad (8.5)$$

Here, we include the simulated radiation losses α presented in Fig.7.17(b) but neglect the dielectric losses of sapphire.

Secondly, the shielded-PPR can also be used to estimate the London penetration depth $\lambda_L(T)$, and with that, the absolute surface reactance $X_s(T)$, as both parameters are related over Eq.(3.45) as $X_{s_{sc}}(T) = \omega \mu_0 \lambda_L(T)$. Therefore, by measuring increments $\Delta X_s(T)$ at low VNA output power with respect to a reference temperature of interest T_{ref} by means of changes in resonance frequency Eq.(8.4)¹⁷, we can find the changes in the London penetration depth $\Delta \lambda_L(T)$ relative to a reference temperature:

$$\Delta X_{s_{sc}}(T) = 2\pi f_0 \mu_0 \Delta \lambda_L(T) \quad (8.6)$$

Using above Eq.(8.6), we can convert surface reactance increments to increments in penetration depth. We can determine $\lambda_L(0)$ and T_C by using the measured values of $\Delta \lambda(T)$ at various temperatures, and an appropriate numerical procedure for data fitting

¹⁷Due to this, a dielectric as sapphire is necessary because of its temperature stability of the permittivity, which makes its contribution to the frequency shift negligible versus that of the superconductor.

of Eq.(3.48) to the specific model of the London penetration depth with parameters a and b given in Tab.3.3 described in Sec.3.4.3. The fitting can be performed to find the values of T_C and $\lambda_L(0)$ that minimise the error function below:

$$\text{Err} = \sum_{i=1}^n \left[\Delta\lambda_L(T_i) - \lambda_L(0) \left(\left[1 - \left(\frac{T_i}{T_C} \right)^a \right]^{-b} - \left[1 - \left(\frac{T_{\text{ref}}}{T_C} \right)^a \right]^{-b} \right) \right], \quad (8.7)$$

where T_{ref} is a arbitrary chosen reference temperature below T_C .

Once $\lambda_L(0)$ is known, the absolute London penetration depth $\lambda_L(T)$ can be determined for any temperature below T_C and with that, we can determine the absolute

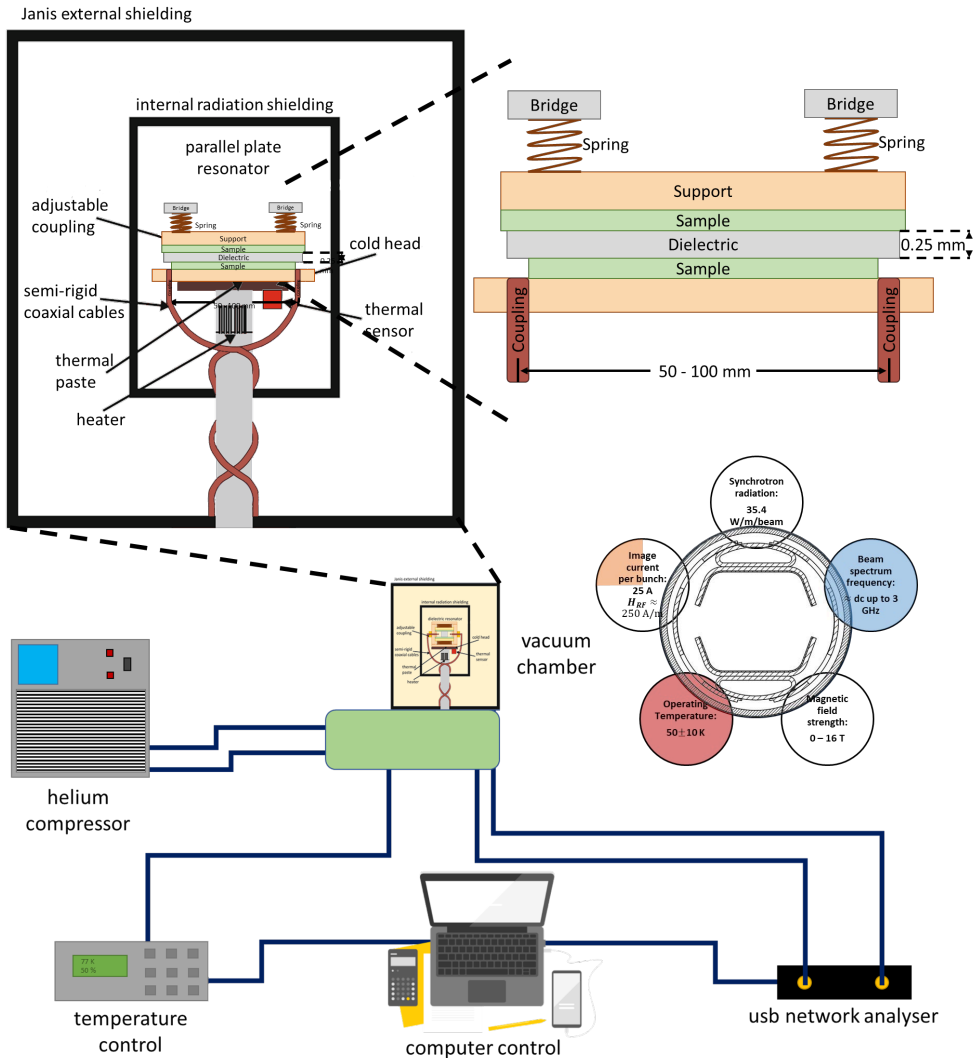


Figure 8.8: Closed-cycle cryocooler set-up including the parallel-plate resonator. Parts of the sketch adapted from Breeze [Bre16].

reactance through the imaginary part of Eq.(3.45). In any case, by fitting to the London penetration depth we will be able to determine the zero-field absolute reactance at a given temperature of interest.

8.4 PPR - Synchrotron Radiation System

8.4.1 ALBA Light Source

The synchrotron radiation at the ALBA Synchrotron is produced by a circulating electron beam with an intensity of 250 mA and an electron energy of 3.0 GeV. With this current and energy, 254 kW of synchrotron radiation power is emitted by the beam. Figure 8.9 compares the spectral photon flux of LHC, FCC-hh and the ALBA synchrotron as calculated using Eq.(4.24). The synchrotron radiation power and flux in the FCC-hh are much higher than in the LHC, but relatively comparable to the ALBA synchrotron. From Eq.(4.23) we can estimate the critical energy for each accelerator tabulated in Tab.8.1. While the linear SR power per beam for the FCC-hh is a factor of 150 times larger than that of the LHC, it is only a factor ten smaller compared to ALBA. However, the power per beam differs only by a factor of ≈ 2 between FCC-hh and ALBA. In order to investigate the effect of synchrotron irradiation on ReBCO coated conductors, experiments have been performed with *ex-situ* and *in-situ* irradiation.

Table 8.1: Comparison of synchrotron radiation between ALBA (electron accelerator), LHC (proton accelerator), and FCC-hh (proton accelerator).

Accelerator	$U_{\gamma,c}$ [eV]	P_{bunch} [W]	B_{DC} BM [T]
ALBA	8499.00	3444.55	1.42
LHC	43.80	2.09	8.33
FCC-hh	4269.00	342.20	15.96

8.4.2 Ex-Situ Testing

In ex-situ measurements, samples are irradiated during a certain amount of time while the effect of SR on the samples is measured before and after irradiation. For ex-situ synchrotron radiation testing of the ReBCO-CCs, ReBCO-CC samples were mounted behind the ALBA crotch absorbers, as shown in Fig.8.10, getting irradiated by the high energy residual X-rays. This was done to acquire knowledge about any surface resistance degradation of ReBCO-CC after long-term irradiation in air. The samples were placed in such a way, that the photons hit the centre of the sample as can be seen in Fig.8.10 (inset right corner) indicated as the dark line appearing on the green photosensitive dosimetry-film [Ash19] to assure correct irradiation. After four weeks of irradiation, the samples were taken out of the synchrotron and tested externally.

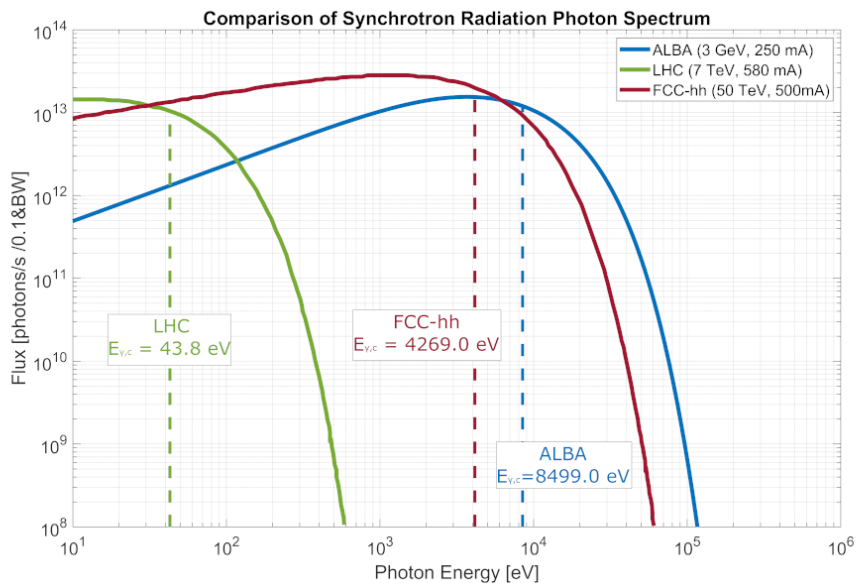


Figure 8.9: Synchrotron radiation flux spectra comparison between LHC, FCC-hh, and ALBA. The data has been calculated by using XOP.

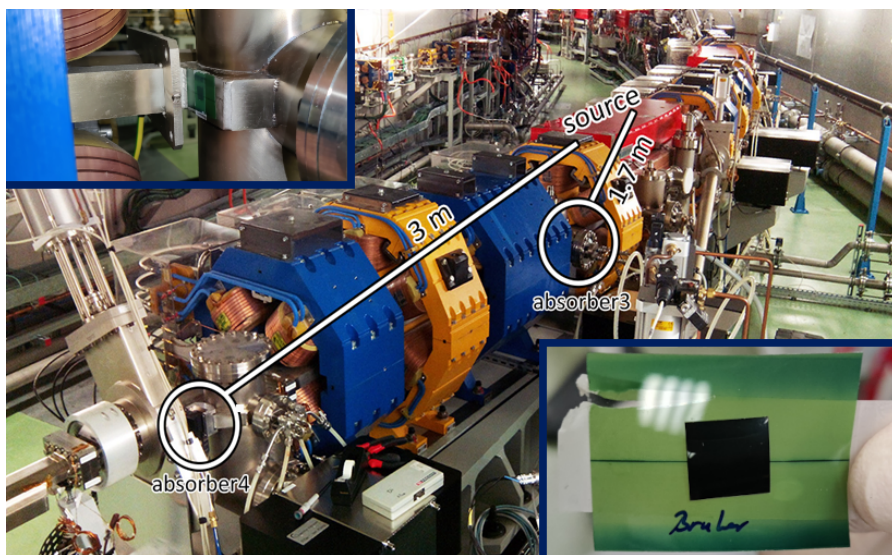


Figure 8.10: Picture of the magnets in the ALBA synchrotron - bending magnet (red), quadrupole magnet (blue) and sextupole magnet (yellow) - showing the position of crotch absorbers (white circles). The left upper inset shows how the ReBCO-CC to be irradiated is positioned at a crotch absorber. The right lower inset shows a sample from Bruker glued on a dosimetry-film after irradiation.

A crotch absorbers' role is, in principle, to protect the ultra-high vacuum chamber at positions where high amount of synchrotron radiation is produced and not used for experiments. This is done to guarantee that no radiation will hit the vacuum chamber walls, hence, the synchrotron radiation behind a crotch absorber is strongly reduced. In this case, the synchrotron radiation has to traverse 35 mm of the copper absorber and 2 mm of steel anti-chamber wall. This results in photon flux of high energy and low intensity as depicted in Fig.8.11.

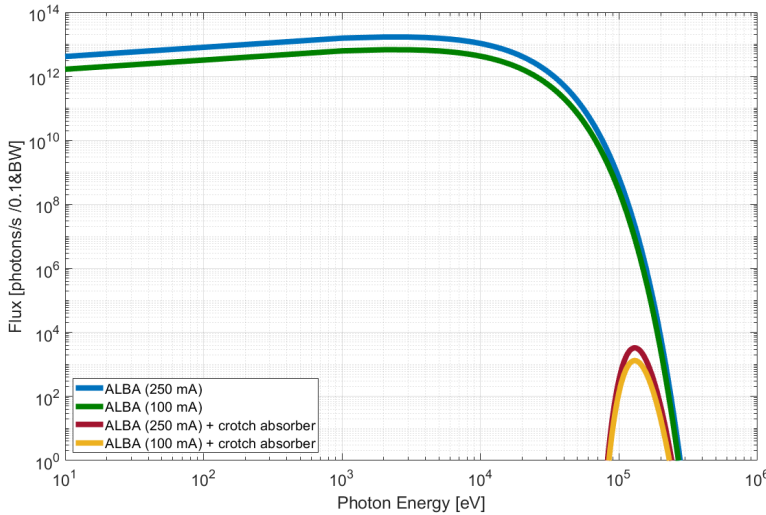


Figure 8.11: Synchrotron radiation flux spectra comparison showing the resulting energy spectrum at the location of the ReBCO-CCs behind the crotch absorbers visible in Fig.8.10.

8.4.3 In-Situ Testing

In order to determine the effect of synchrotron irradiation on ReBCO-CCs in-situ, we had to implement a cryogenic measurement set-up into the ALBA particle accelerator infrastructure without disturbing its regular operation for the users of the beamlines. The suitable position found was at the X-ray pinhole beamline that continuously monitors the transverse beam size during normal operation. Figure 8.12 depicts the location of the pinhole. During the experiments, the pinhole and the filter were removed from the synchrotron light path, as indicated by the black arrows in the same figure. However, the aluminium (Al) window of 1 mm thickness separating vacuum from the air and a Kodial (80% silica (SiO_2), 13% boric oxide (B_2O_3), 4% sodium oxide (Na_2O) and 2-3% aluminium oxide (Al_2O_3), with a density of 2.65 gr/cm^3) window of 3 mm thickness separating RT from cryogenic temperatures at the cryostat cannot be removed. Thus, the synchrotron radiation produced in the bending magnet with a total horizontal opening of almost 1 mrad that reaches the ReBCO-CC samples mounted perpendicular to the beamline installed -about 13.0 m away from the source- receives photons with energies starting at 10 keV as shown in the flux spectrum in Fig.8.13.

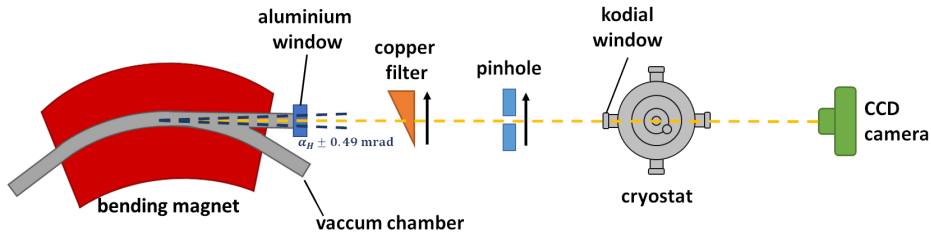


Figure 8.12: Sketch of the ALBA Light Source x-ray pinhole set-up.

The experiments have been carried out with a continuous liquid helium flow cryostat Janis Research Model ST-400 UHV Supertran System that can operate between $T = 4$ and 350 K [Cry21a]. The whole experimental set-up is shown schematically in Fig.8.14(a). The system contains a Cryofinger [better visible in Fig.8.15(a)] where samples can be mounted on a gold-plated copper base, including an internal heater and T -sensor (GaAs diode) for the temperature control of the system. The heater and temperature sensor are connected to a LakeShore 331 temperature controller [Cry21b] for temperature regulation. The controller has an additional temperature sensor input to which we connect a LakeShore Cernox CX-1050-SD-HT sensor positioned on the test fixture, close to the samples, for accurate temperature monitoring. The liquid helium is connected via a 3.2 m transferline from the dewar to the Cryofinger. Prior to the cool down procedure, the cryostat is evacuated in two stages with a Pfeiffer Vacuum ACP roots pump in combination with a HighPace[®] 300 turbopump to achieve a pressure of 10^{-5} mbar.

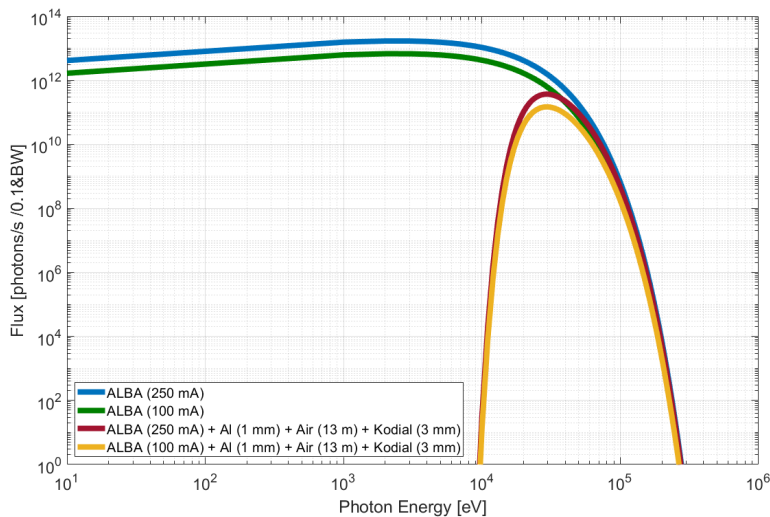
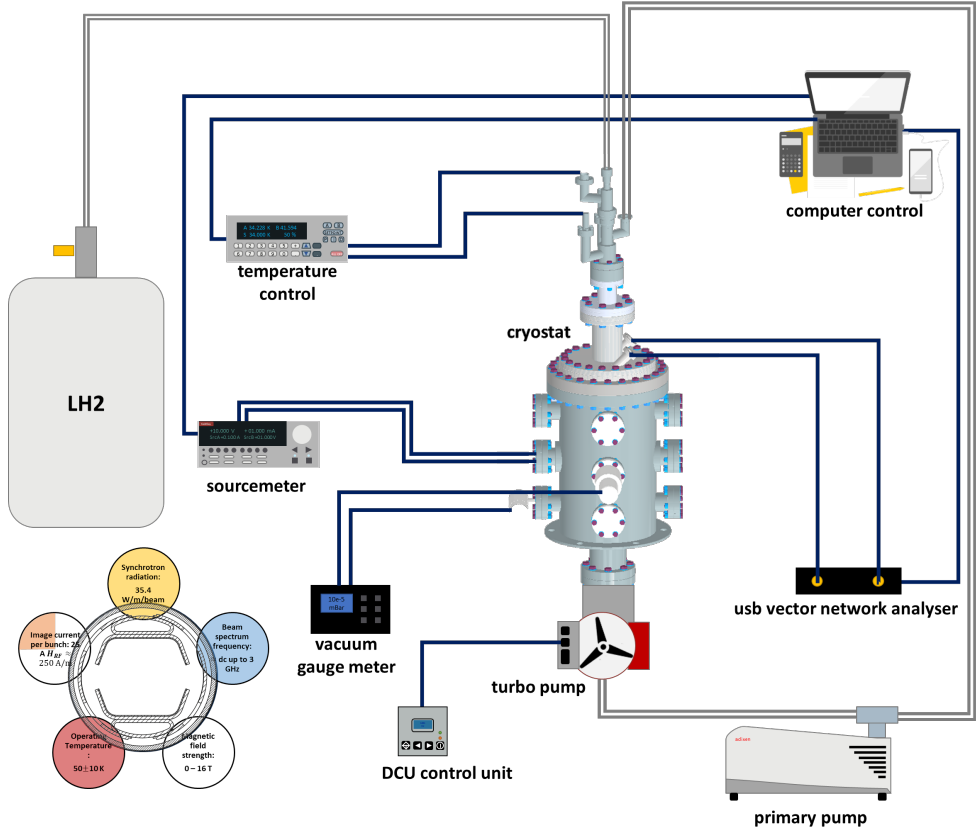
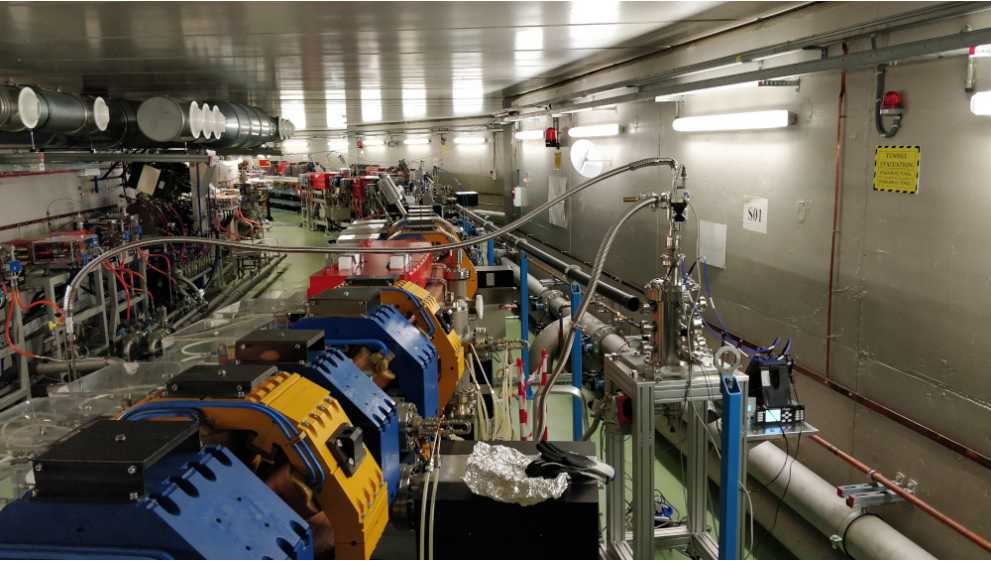


Figure 8.13: Photon flux that reaches the ReBCO-CC sample in the configuration shown in Fig.8.12 as a function of energy. Note that the low energy part of the spectrum is absorbed mainly by the Al window.



(a) Sketch of the measurement system for synchrotron irradiation

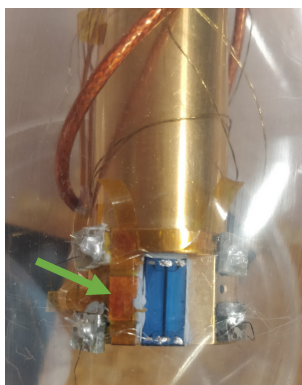


(b) Picture of the cryogenic system at the pinhole.

Figure 8.14: Experimental set-up for measuring critical temperature and surface resistance under synchrotron irradiation at the ALBA synchrotron.

The sample base of the Cryofinger measures 14 x 13 mm on which the ReBCO-CCs can be mounted and wired. The pre-installed four gold wires of the Supertran System were utilised to measure resistances connected to a Keithley 2604B Sourcemeter, which can measure two channels simultaneously. In addition, two semi-rigid cables are connected to two SMA feedthroughs to which a Keysight P5002A USB VNA is connected, the same as mentioned in Sec.8.1, in the KF 125 flange to mount and dismount the Cryofinger from the cryostat. In addition, the VNA has been connected to the Synchrotron's GPS clock to achieve higher frequency stability. It is not possible to be inside the tunnel during the operation of the accelerator. Due to this, the communication to the different devices was performed remotely from the control room.

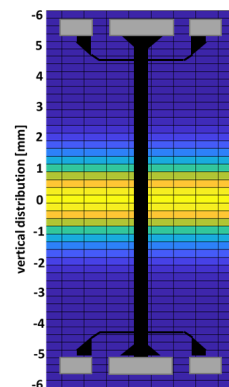
The set-up shown in Fig.8.14 was utilised for two main experiments: The first experiment consisted in measuring the critical temperature T_C during irradiation. Figure 8.15(a) shows a mounted -thermal paste is used to hold the sample and assure good thermal contact- and modified ReBCO-CC on the sample base of the Cryofinger. The coated conductor, visible in the same figure, has been patterned by photolithography [WDR97] leading to the exposed pattern into the material as shown in Fig.8.15(b). The superconducting strip at the centre is used to apply currents less than $I = 1$ mA to the ReBCO-film, while two side pads are utilised to measure voltage. The current and voltage pads are made of the pre-existing silver layer, which protects the ReBCO-CC samples on which we attached two 50 μ m silver wires per pad glued with silver paint and connected to the four conducting plates attached to the Cryofinger as shown in Fig.8.15(a). The geometrical pattern has been chosen such that a four-wire measurement can be performed to determine the resistance. At the same time, synchrotron radiation hits the mainline in the centre with the maximum area possible, as indicated in Fig.8.15(c) which shows the normalised magnitude of SR distribution over the coated conductor. In the ideal scenario, the photons hit the sample at the centre so that only



(a) ReBCO-CC on sample base. The green arrow indicates the Cernox T -sensor location.



(b) pattern of ReBCO-CC sample



(c) synchrotron radiation distribution on sample

Figure 8.15: Example of one sample for the testing on the effects of SR on the critical temperature T_C .

the ReBCO is affected by the SR. In order to achieve this, the sample holder is aligned with the height of the accelerator's bending magnets. The irradiation of the sample during the operation of the accelerator is indicated in two ways: by a photosensitive dosimetry-film being irradiated and by a measured temperature raise of the sample. The dosimetry-film is placed at the position of the cryostat kodial window, and the Cernox temperature sensor can be seen surrounded by its copper housing to monitor the sample's temperature in Fig.8.15(a).

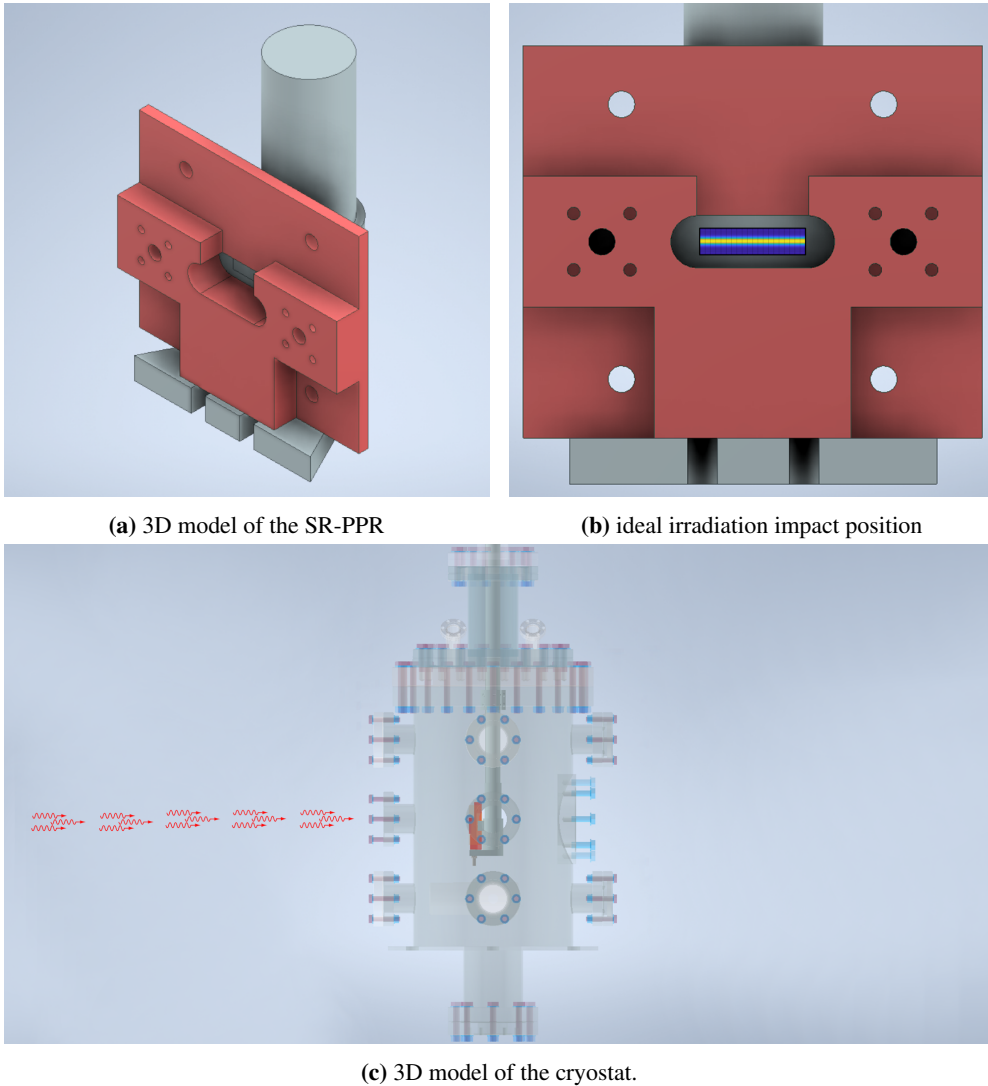


Figure 8.16: Parallel plate resonator for in-situ measurement of SR impact on R_S . (a) 3D model of the SR-PPR mounted on the Cryofinger and support. (b) SR intensity profile hitting the samples. (c) sectional view of the cryostat including the SR-PPR aligned to the kodial window where the photons arrive.

Besides the DC measurements described above, the system in Fig.8.14 is also used to make microwave surface resistance measurements under synchrotron radiation. We modified the SR-PPR from Sec.8.2 in order to be able to irradiate the ReBCO-CCs. As shown in the technical drawing in Fig.8.16 we removed as much copper as possible from the metallic fixture base for cooling purposes. In addition, a holder -made out of copper- for the SR-PPR had to be manufactured, which elongates the Cryofinger and helps to cool down the device. An elliptic cut-out going through the whole metallic fixture base of the SR-PPR assures photons hit the samples with the flux spectrum from Fig.8.13. Figure 8.16(b) shows the back view of the SR-PPR facing the synchrotron radiation intensity profile and the kodial window.

Synchrotron radiation, as discussed in Sec.4.5, interacts with materials and gets absorbed depending on the density of the material and thickness. The layered structure of the ReBCO-CCs, as shown in Fig.8.17 for the provider Fujikura, contains many layers with a thick Hastelloy substrate at the bottom. The main idea behind the design of the elliptic cut-out in the metallic fixture base is to assure that a high amount of SR irradiates the samples perpendicularly to the ReBCO surface. Thus, by covering the cut-out with the ReBCO-CC, as provided, the Hastelloy layer would absorb most of the SR. On the other hand, the Cu and Ag jacket of the ReBCO-CC [see Fig.2.15] is very thin for some providers -less than $30\text{ }\mu\text{m}$ -. Therefore, instead of using a ReBCO-CC as provided, we *de-laminate* the ReBCO-CC at the position of the buffer layer, indicated as the yellow line between CeO_2 and ReBCO in Fig.8.17. The de-lamination was done in collaboration with [Telb]¹⁸. In this way, as shown in Fig.8.18, the SR-PPR is formed by the cut-out covered by the de-laminated ReBCO-CC (Cu-Ag-ReBCO), the sapphire dielectric plate (AlO_2) and an 'ordinary' ReBCO-CC (ReBCO-buffer-Hastelloy).

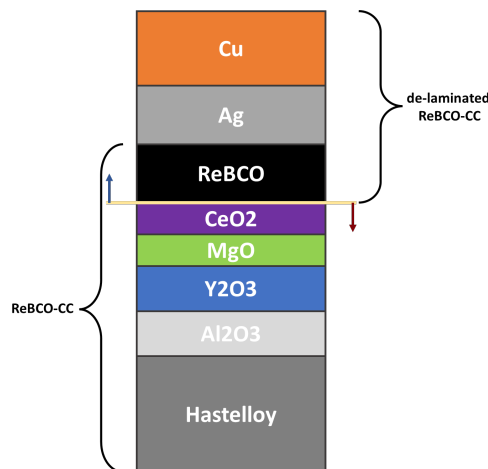


Figure 8.17: Drawing of the ReBCO-CC layered structure as provided and de-laminated. The yellow line indicates where the ideal de-lamination takes place.

¹⁸The de-lamination procedure is part of the PhD project of Guilherme Telles, and henceforth, is not discussed in detail in this thesis.

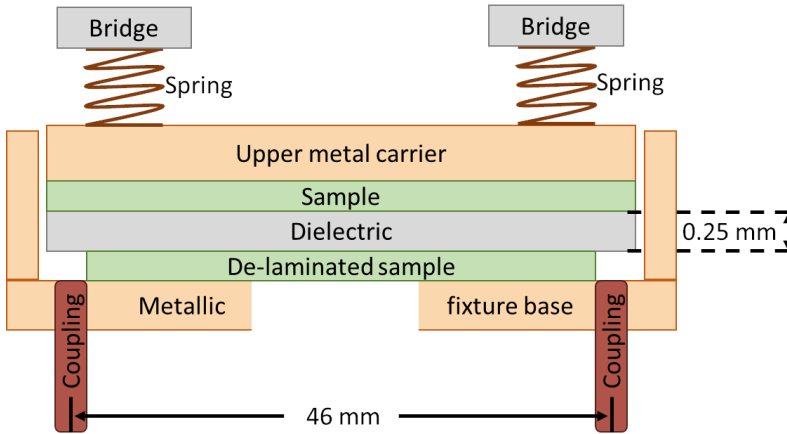
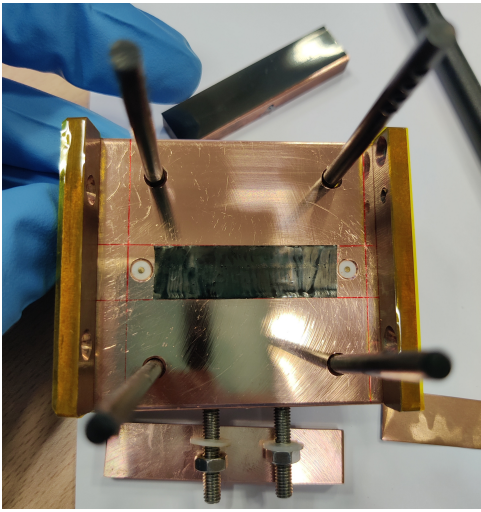
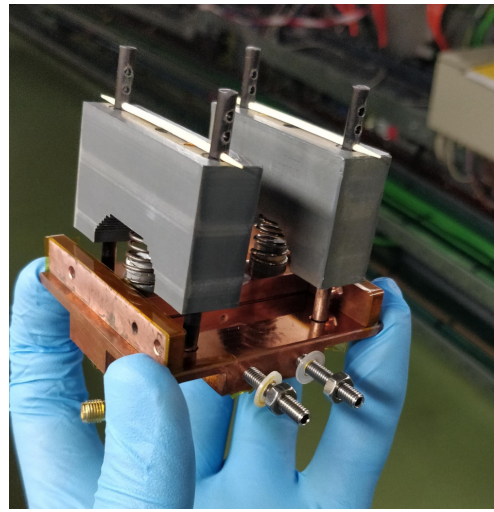


Figure 8.18: Sketch of the SR-PPR.

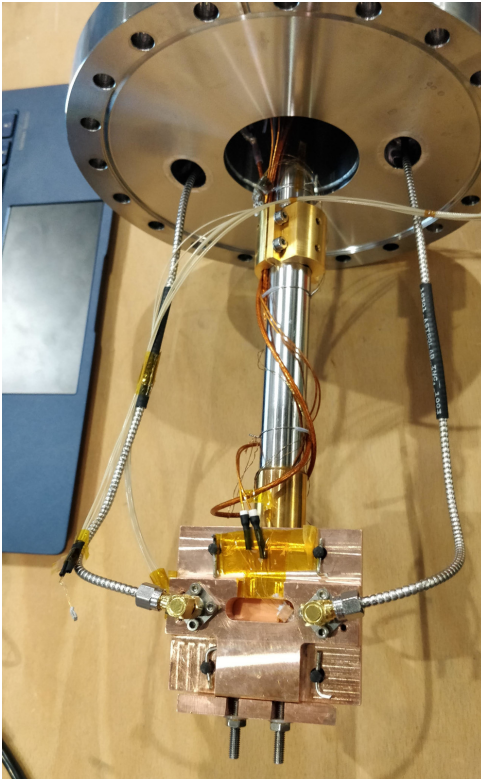
The manufactured SR-PPR and the complete assembly of the SR-PPR on the Cryofinger can be seen in the set of figures in Fig.8.19. Figure 8.19(a) shows a de-laminated ReBCO-CC (12 x 42 mm) attached to the metallic fixture base in between the coaxial coupling. In addition, in the background of the same figure, a ReBCO-CC as provided (12 x 54 mm) can be seen attached to the upper metal carrier. Due to the flexibility of the thin ReBCO-CC samples, we glue them with GE-varnish to each metal carrier. The capacitive coupling is achieved through the metallic fixture base by a pair of semi-rigid coaxial cables with a stab at the end, which can be seen as well in Fig.8.19(a). The adjustment of the coupling has been performed with simulations in CST in Sec.7.4 and test measurements at 77 K with liquid nitrogen. In Fig.8.19(b) we can see the assembled SR-PPR. The steel springs are attached to two PVC bridges because, in different trials of the PPR, we noticed that metallic bridges lead to strong distortions of the modes. The resonator is designed to operate with a TEM close to $f = 1$ GHz sandwiching a sapphire plate (54 x 12 x 0.25 mm). Figures 8.19(c) and 8.19(d) show the mounted SR-PPR on the Cryofinger - front and back view -.



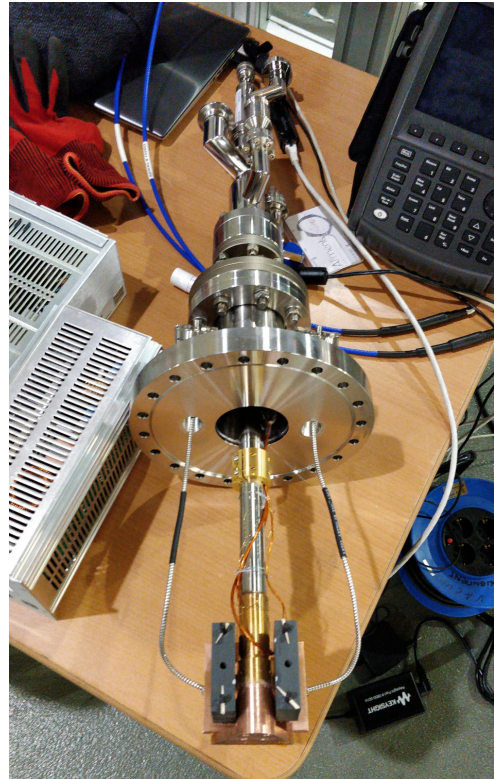
(a) metallic fixture base preparation



(b) assembled SR-PPR



(c) mounted SR-PPR on Cryofinger - front

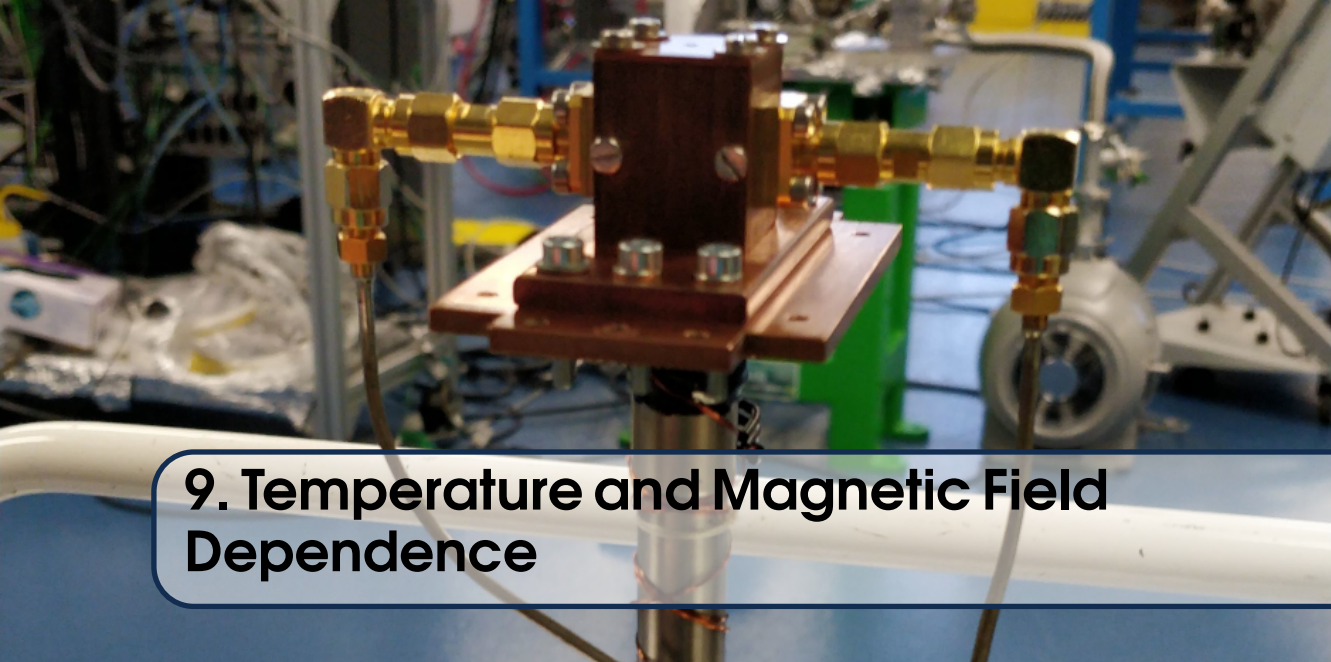


(d) mounted SR-PPR on Cryofinger - back

Figure 8.19: Pictures of the SR-PPR assembly: (a) metallic fixture base preparation. The shorter ReBCO coated conductor between the coupling probes covers the cut-out in the metallic fixture base. The two copper side walls are attached to reduce the radiation losses. (b) shows the complete SR-PPR put together. (c) and (d) show how the SR-PPR is mounted on the Cryofinger of the Janis Supertran System. The screws visible in (a) and (b) are used to hold the device in place and are fixed to the copper support. The semi-rigid coaxial cables for the measurement of the Q-factor with the aid of the VNA are visible. In addition, a second temperature sensor is placed inside the cut-out.

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9. Temperature and Magnetic Field Dependence

Only through experiment and observation, irrelevant if positive or negative outcome, we can help to understand the great everything we are living in.

-Kricx-

In order to assess if ReBCO coated conductors can provide the desired minimisation of beam impedance for the demanding conditions in the FCC-hh beam screen, the following chapter studies their superconducting and complex layered mechanical properties as a function of temperature and under the influence of up to 9 T perpendicularly applied DC magnetic fields. Parts of this chapter have been published in [Pui+19] and the original content from that work may be used under the terms of the Creative Commons Attribution 3.0 license.

9.1 Temperature Dependence of the Surface Resistance

For this study, the surface resistance of ReBCO-CCs from six different manufacturers was measured in a temperature sweep between 30 and 100 K without DC magnetic field applied, beginning from the lowest temperature. The purpose of this measurement is to establish if the different compositions of the samples [see Tab.2.1] influence their surface resistance. The data presented below is obtained with the CHCDR and a rutile dielectric as explained in Ch.8 by the excitation of the TE_{011} mode at about

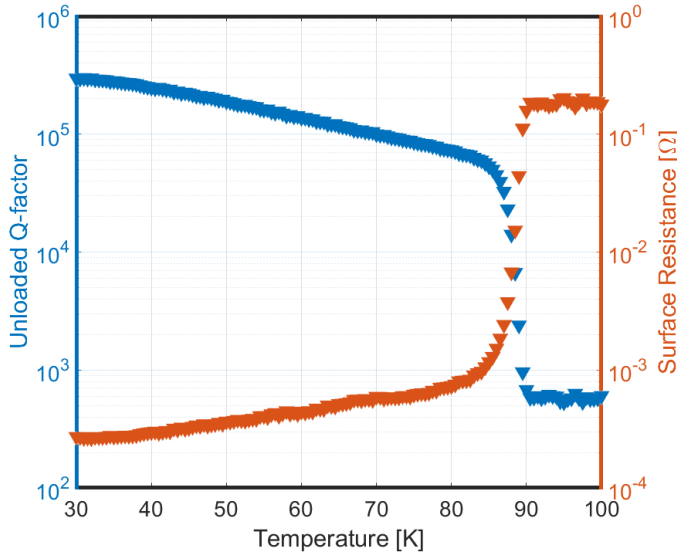


Figure 9.1: Temperature dependence of the unloaded Q-factor and resulting surface resistance measured at $f = 8$ GHz.

8 GHz [see Sec.7.3]. Accordingly, the samples are measured in pairs, and the average surface resistance is determined. The unloaded quality factors obtained measuring different CCs ranged from about 500 above T_C to 300000 at 30 K for SuperPower, as shown in Fig.9.1. From Eq.(8.1), the surface resistance R_S values are determined from the unloaded quality factor Q_0 . The detailed change in resonance frequency over the temperature for rutile can be seen in Fig.7.6 in Sec.7.3. To accurately post-process the stored Touchstone files and extract the unloaded quality factor we used the ARPE algorithm as explained in Sec.6.5.

Figure 9.2 shows the temperature dependence of the surface resistance of 12x12 mm pairs of ReBCO coated conductors. For the comparison with the FCC beam screen, a measurement of a copper co-laminated stainless steel sample pair, which was cut out from a BS prototype, is also presented (FCC-hh BS). The transition from the normal conducting to the superconducting state was not investigated in detail with the measuring system but is nevertheless recognisable. The differences in the composition of the ReBCO-CCs can be identified in the results obtained. The ReBCO-CC samples show the expected sharp drop in R_S when undergoing the transition from the normal conducting to the superconducting state at the given T_C values summarised in Tab.2.1. Bruker shows a much lower T_C compared to the other ReBCO-CCs due to its double disordered ReBCO layer mentioned in Sec.2.3.3, which is optimised to perform at 4.2 K and high magnetic fields; though, sacrifices in performance at high temperatures [Pui+19]. One has to mention that the results for the measurements above the critical temperature have to be considered with caution. In the normal conducting state of the superconductor, the ReBCO-film thickness of micrometres can become comparable to or smaller than the penetration depth at the normal state skin depth. In

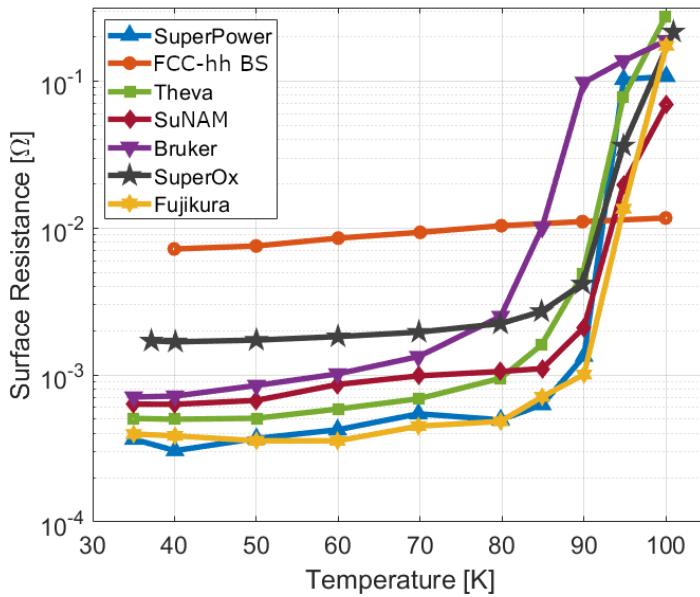


Figure 9.2: Surface resistance as a function of temperature without an applied magnetic field for all providers measured at $f = 8$ GHz. In addition, for comparison, a sample of the FCC-hh beam screen prototype (stainless steel with 300 micrometre co-laminated copper) is included.

such a case, electromagnetic fields penetrate through the ReBCO and buffer layers and the substrates influence the measured R_S , as discussed in Sec.3.5.

The relative performance of the various ReBCO samples in terms of R_S does not correspond to that obtained from the I_C -width measurements at 50 K and zero applied DC magnetic field in Fig.2.18(a). These findings appear due to the difference in current flow in these two separate experiments. This is because I_C -width is measured with a DC current, while R_S is measured with an RF current. Therefore, DC measurements are not as affected by limitations in current distribution as RF ones, since in the latter, the current distribution is imposed by the resonant mode and the London penetration depth (λ_L). In contrast, in DC measurements, the current can follow a variable path through the samples and avoid possible normal material regions.

Further, it can be seen in Fig.9.2 that ReBCO-CC samples show a monotonic, smooth temperature profile of the surface resistance from the critical temperature down to about 80 K. Between 80 K and 30 K, the surface resistance does no longer decrease so much and a tendency to form a plateau is observed, which is as expected from the 2F-model discussed in Sec.3.4.3. In this range, the temperature dependence is primarily determined by the unpaired charge carriers, the quasiparticles [Bon+93; Har+93; Zuc97]. The residual surface resistance R_S^{res} at $T \rightarrow 0$ can be obtained by linearly extrapolating the temperature-dependent curves down to the absolute zero point, as illustrated in Fig.9.3(a). The figure shows how the extrapolation is performed for samples of some providers as in Fig.9.2, though different sample pairs -from

Table 9.1: Summary of the extrapolated residual resistances at 0 K.

Sample	R_S^{res} [m Ω]
FCC-hh Copper	4.801
Bruker	0.635
Fujikura	0.091
SuNAM	0.389
SuperPower	0.220
SuperOx	1.004
Theva	0.640

the same tape but different locations of the tape-. The residual surface resistance is highly dependent on the individual samples and can be seen in Tab.9.1. However, care must be taken for samples based on Gd as rare-earth component. Figure 9.3(b) presents measurements performed down to 5.9 K. Unlike Bruker (YBCO) or the Thallium pellet¹⁹, the $R_S(T)$ behaviour shows an upturn below 40 K. This has solely and repeatable been seen in measurements performed with providers including Gd which can be attributed to the antiferromagnetic behaviour Gd-ions at low temperatures [Lee+18]. However, this will not effect the FCC-hh beam screen, as its operating temperatures are between 40 to 60 K.

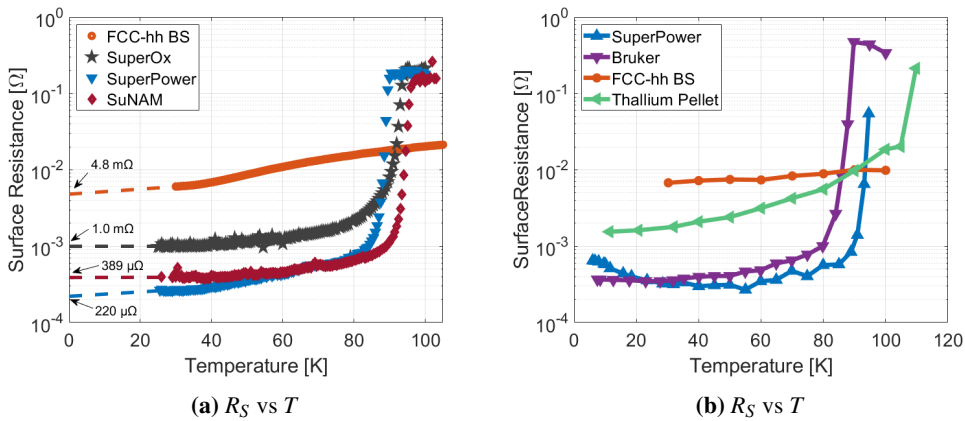


Figure 9.3: Temperature dependence of the surface resistance at $f = 8$ GHz for ReBCO-CC samples (a) extrapolated to 0 K, and (b) measured down to 5.9 K to compare different rare-earth composition (Bruker = YBCO, SuperPower [Y,Gd]BCO)

¹⁹The thallium based superconducting samples were provided by Allesandro Leveratto and Aisha Saba from CNR-SPIN.

9.2 Frequency Dependence of the Surface Resistance

An important consequence for the FCC-hh study is to know if the results obtained can be scaled down to the frequency range of interest (2 kHz to 3 GHz). For numerical beam impedance estimations in the frequency domain, the knowledge of the surface impedance as a function of frequency is one of the most important values.

At temperatures close to 50 K, surface resistance and surface reactance should follow Eq.(3.46), which depends on the ratio of normal to superconductive conductivity. For the specific case of SuNAM, the normal state conductivity can be found from Fig.2.18(b) $\kappa_n(50\text{ K}) = 3.6\text{ MS/m}$ and the superconductive conductivity at 1 GHz from Eq.(3.44) with $\lambda_L(0)=150\text{ nm}$ [BP10] (the standard value for YBCO) is $\kappa_s(50\text{ K}) = 4.1\text{ GS/m}$. In these conditions, Eq.(3.46) leads to a square power-law dependence ($g = 2$) for R_S versus frequency and a linear dependence ($g = 1$) for X_S , confirming Eq.(3.45). The same dependencies were found for the rest of the providers.

To experimentally verify this prediction, we performed measurements with a rutile dielectric as well as a sapphire dielectric of the same dimensions in the same CHCDR with the same samples. In this way, we obtain the surface resistance at 8 GHz and 27 GHz. Comparing the two resulting R_S -values, we would expect a surface resistance at 27 GHz, around a factor eleven times higher than that at 8 GHz. With the analytical solution of the TE_{011} mode in Sec.7.3, we can obtain the characteristic parameters for the sapphire loaded CHCDR, summarised in Tab.9.2. In addition, it is well-known in literature that a c-axis oriented sapphire has a very low $\tan(\delta) \approx 10^{-8}$ at cryogenic temperatures [Bre16]. Since there are no other significant contributions to resonator loss, Eq.(8.1) reduces to:

$$R_S = 2 \frac{G}{Q_0}. \quad (9.1)$$

Figure 9.4 represents the results obtained for a SuNAM ReBCO-CC. The orange diamonds represent the measured values of the sapphire loaded CHCDR, while the blue circles refer to the measured data with rutile. To investigate the frequency dependence, we scaled the measured surface resistance at 27 GHz down to 8 GHz (represented as green triangles in Fig.9.4) with a frequency square dependency $R_S \propto f^2$ as predicted by the theory discussed above. In contrast to the expectation, the scaled values (green) do not overlap with the measured rutile values (blue). The accuracy of the measurements with rutile in contrast to sapphire depends strongly on the knowledge of the loss tangent values. Thus, we believe this disagreement is due to an incorrect estimate of the loss tangent of rutile, as will be explained in the paragraph below.

The initial loss tangent values chosen at the beginning of the measurements for

Table 9.2: Analytical estimated parameters for a sapphire loaded dielectric resonator at RT.

f_0 [GHz]	ϵ_r	$G_{\text{up,down}}$ [Ω]	G_{lat} [Ω]	p
27.2	9.4	726.648	190939	0.967

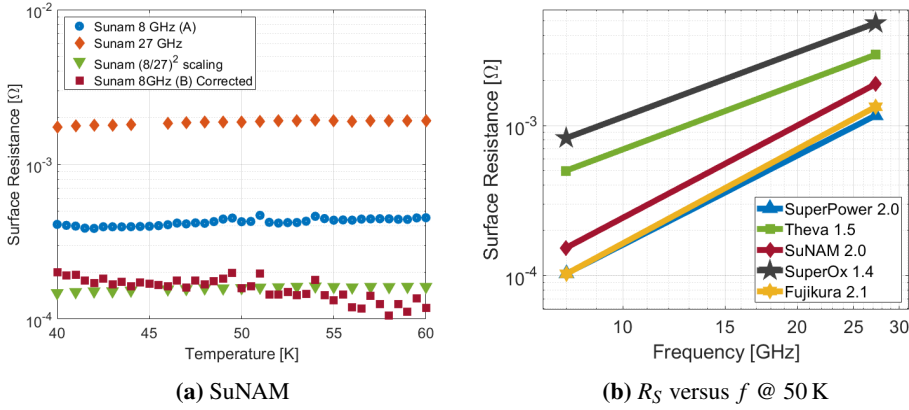


Figure 9.4: (a) Surface resistance as a function of temperature at two different frequencies for SuNAM. Orange diamonds represent the data measured at 27 GHz. Green triangles show the aforementioned data scaled down to 8 GHz. The blue circles represent the data measured at 8 GHz and post-processed using $\tan(\delta)$ values of rutile from literature. Red squares show the same measured data as the blue circles, however, post-processed with measured $\tan(\delta)$ values. (b) Surface resistance as a function of frequency measured for several providers.

this thesis were taken from [Kle+95], and are lower than those by other authors, e.g., [Bre16]. The reason to choose precisely those values lies within the fact that the lower the loss tangent value, the higher the resulting surface resistance [see Eq.(8.1)], giving us a rather ‘worst case’ scenario for the FCC-hh. During the thesis we have performed a measurement of the loss tangent of the rutile crystal available which was done by [Die20] in form of a Bachelor Thesis with the results and technique presented in the appendix B.5.1. Re-evaluating the surface resistance for SuNAM in Fig.9.4 (red squares) shows now results which are in very good agreement with the frequency squared theory at 50 K.

We have extended the analysis in Fig.9.4 to more providers. Figure 9.4(b) and Tab.9.3 show the measured surface resistance as a function of frequency for different providers at 8 GHz and 27 GHz. From the slope of the line, we can extract the frequency dependence for each provider. We have found that a single common value of rutile’s loss tangent ($\tan(\delta) = 3.90 \cdot 10^{-6}$) at 50 K and 8 GHz yields a square frequency dependence for Fujikura, SuperPower, and SuNAM. On the contrary, shown in Fig.9.4(b), SuperOx shows only a $R_S \propto f^{1.4}$ dependence. It is the thinnest film of all providers (900 nm) and the layers underneath the film might influence its R_S . Thus, a

Table 9.3: Measured surface resistance frequency dependence $R_S \propto f^g$ at 50 K with a loss tangent value of $\tan(\delta) = 3.90 \cdot 10^{-6}$.

Provider	Fujikura	SuNAM	SuperPower	SuperOx	Theva
g_{meas}	2.1	2.0	2.0	1.4	1.5

thicker ReBCO-film grown might result in the expected frequency dependency again. In addition, Theva indicates a similar $R_S \propto f^{1.5}$ dependence which might be resulting due to the tilted growth techniques of the ReBCO-layer as discussed in Sec.2.3.3. Data for Bruker has not been obtained. However, due to its similarities in thickness and structure to SuNAM and SuperPower, a frequency square dependency could and shall be assumed.

Comparing the values from Fig.9.4 with those presented in Fig.9.2 at 50 K the actual surface resistance values might be even better than initially expected. For example, determining again $R_S(50\text{ K})$ by applying the previously mentioned loss tangent value to FCC-hh copper reduces the surface resistance by about 3%. Oppositely, applying the $\tan(\delta)$ to SuNAM leads to a reduced R_S value of 60%.

9.3 Determination of the London Penetration Depth

The London penetration depth $\lambda_L(0)$ can, in general, be measured from the change in resonance frequency Δf of a resonator close to the transition from superconducting to normal conducting state. The ReBCO surface reactance at T close to T_C is high and strongly temperature-dependent. This can be used to determine the London penetration depth if changes in resonator frequency are mainly due to changes in X_S in a small temperature range, as elaborated in detail in Sec.8.3. In this section we present for the first time attempts to measure λ_L of 10 cm long commercial ReBCO coated conductors.

In principle both resonators, CHCDR and the shielded-PPR, fulfil the above-mentioned requirement when the chosen dielectric is sapphire. However, even though $\lambda_L(0)$ is frequency independent, we actually measure the changes in frequency resulting from changes in the surface reactance, whose absolute value has a linear frequency dependence [see Sec.3.4.3]. Therefore, the transition slope between normal conducting and superconducting state will be more significant at 1 GHz than at 27 GHz. Accordingly, the shielded-PPR is more advantageous than the CHCDR. The utilisation of rutile in the CHCDR is not suitable because of the strong temperature dependence of rutile's permittivity.

For the measurements of $\lambda_L(0)$, we use only one ReBCO-CC mounted on the upper metal carrier and leave the metallic fixture base plane with copper on the other side of the shielded-PPR. In this way we can avoid a broadening of the T_C due to two transitions of two ReBCO-CC separated by the sapphire dielectric. Figure 9.5(a) shows the resonance frequency as a function of temperature and the resulting London penetration depth $\lambda(T)$. The changes in resonance are in the MHz range confirmed in [Che+06]. Combining Eqs.(8.3) and (8.6) leads to the fit function:

$$-2 \frac{\Delta f_0(T)}{f_0(T)} \frac{G(T)}{2\pi f_0 \mu_0} = \lambda_L(0) \left(\left[1 - \left(\frac{T_i}{T_C} \right)^a \right]^{-0.5} - \left[1 - \left(\frac{T_{\text{ref}}}{T_C} \right)^a \right]^{-0.5} \right),$$

$$\text{2F-model : } a = 4 \quad \text{reduced 2F-model : } a = 2 \quad \text{GL : } a = 1, \quad (9.2)$$

where $\lambda_L(0)$ is the fitting factor, the geometrical factor is defined as $G = \pi \mu_0 f_0 s$ and a depends on the fitting theory as described in Tab.3.3. For the fitting procedure only

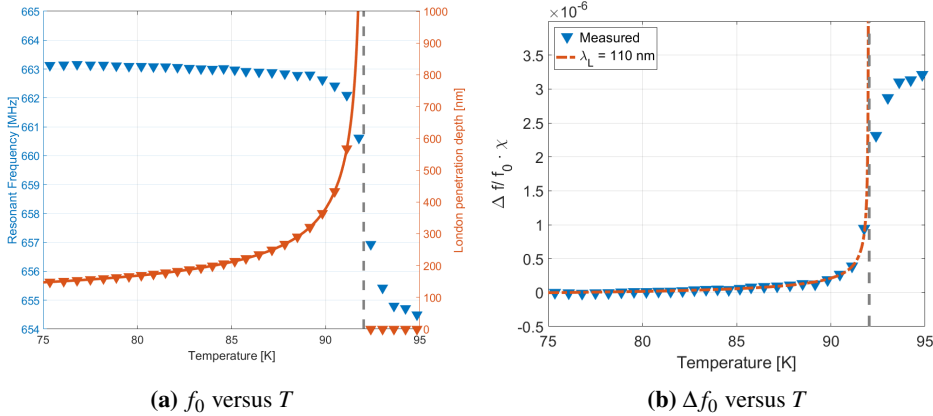


Figure 9.5: Temperature dependence of the resonance frequency and London penetration depth for SuperPower measured with the shielded-PPR.

the data between 70 and $\approx T_C$ has been used. Figure 9.5(b) provides an example fit for SuperPower - χ summarises everything else on the left hand side of Eq.(9.2)-.

The results for four providers are tabulated in Tab.9.4. It is apparent from the table that the results in the penetration depth differ depending on which method was utilised. Further, there are significant differences between the providers which follows the ranking (besides Fujikura) of the surface resistance in Fig.9.2. In theory, the higher the surface resistance at low temperature the larger the London penetration depth. SuNAM, SuperPower and Bruker show penetration depth values (depending on the model) within the typical range reported for $\text{YBa}_2\text{Cu}_3\text{O}_7$ between 100 to 200 nm [Far+98; Pla10; Pro+00; Sax10]. Previous works show some controversy about the temperature dependence of λ_L ; while for the 2F-model $a = 4$ and $a = 2$ have been both reported in [Hei99; Por+93; Wu+87], there have been further studies that claim $a = 4/3$ [Pro+00] close to T_C ²⁰.

Surprisingly, Fujikura's fitting leads to a high penetration depth. The expected

Table 9.4: Penetration depth from resonance frequency versus temperature for each of the three models considered.

Method	SuperPower	Bruker	Fujikura	SuNAM
2F-model [nm]	110	356	541	254
reduced 2F-model [nm]	69	244	378	173
GL [nm]	48	170	264	120
λ_{ave} [nm]	76	256	394	182

²⁰The different T^a dependencies result from the different theories explaining superconductivity over BCS theory, 2F-model, and s-wave and d-wave pairing state of quasiparticles.

values should be close to or lower than SuperPower, because we know from Tab.2.1 that T_C of YBCO and GdBCO are almost similar. In a defect-free ReBCO both the superconducting coherence length and penetration depth depend strongly on the hole content in the CuO₂ planes [Pla10]. It has been suggested that if the CuO planes are disordered the penetration length will be larger [Phi95].

We cannot state which fitting is best suited nor which is the absolute value of the penetration depth as many of the values given in Tab.9.4 are by up to a factor 2 away from what would be expected from ReBCO grown on single crystals. However, this combination of findings -being in the same order of magnitude- provides some support for the conceptual premise that the London penetration depth can be measured with the shielded-PPR and that most of the ReBCO-CCs follow the general measured values given in the literature. Thus, the usage of the standard value of $\lambda(0) = 150$ nm is a valid approximation for the following studies in Sec.9.4 of surface reactance measurements. The influence of the resulting uncertainty by this assumption will be discussed in detail in Sec.9.6. In addition, the results confirm the ReBCO coated conductors penetration depth ratio to the film thickness is high enough for accurate surface resistance measurements for the four measured providers. A limitation factor that has to be taken into account for further measurements is the relatively high dielectric thickness (influence of radiation) as well as the possible influence of the buffer layers of the ReBCO-CC which will be discussed in more detail in Sec.11.5.

9.4 Surface Impedance versus DC Magnetic Field

9.4.1 Surface Resistance versus Magnetic Field

In the first section of this chapter, we discussed and presented the surface resistance as a function of temperature without applied DC magnetic field for the six different providers of ReBCO-CCs. However, at the injection energy of the FCC-hh, particles are accumulated in the accelerator until it is completely filled before accelerating them to the desired collision energy. Already at injection, a magnetic field $B_{DC} = 1$ T is present before it gets ramped up to 16 T. Accordingly, ReBCO-CCs surface impedance has to be favourably compared to that of FCC-hh BS Cu in the presence of DC magnetic fields.

We used the rutile CHCDR ($f_0 = 8$ GHz) for measurements of R_S up to $B_{DC} = 9$ T - the highest available magnetic field as explained in Sec.8.2- at stabilised temperatures in the ZFC case [see Sec.2.1.2] perpendicular to the samples, and with that, parallel to the c-axis of the ReBCO for all providers but Theva due to the inclined growth technique as explained in Sec.2.3.3. The main results of the measurements are presented in Fig.9.6.

Figure 9.6(a) shows the measured $R_S(9\text{ T})$ as a function of temperature T . It can be seen that, unlike the FCC-hh BS copper, the ReBCO-CCs have a significant raise in R_S compared to the results given in Fig.9.2 at $B_{DC} = 0$ T. Furthermore, in Fig.9.6(a) the sharp transition from superconducting to normal conducting state at T_C is not as severe as in Fig.9.2. As we know from Sec.2.1.2, the three interdependent critical parameters - T_C, B_C, J_C ,- span a critical surface [see Fig.2.13]. Due to B_{DC} , the critical temperature T_C drops to a lower value compared to zero applied fields which can be still slightly

seen for Fujikura and Bruker in Fig.9.6(a).

Figures 9.6(b) to 9.6(d) provide detailed information about the R_S dependence on DC magnetic field at the particular temperatures $T = 40, 50$ and 60 K. The results show a steady increase of the surface resistance with increasing applied DC magnetic field for all providers. The magneto-resistive effects on the FCC-hh beam screen copper sample are almost negligible as shown in Fig.9.6(c). It is apparent by comparing the results from Fig.9.6(b) to Fig.9.6(d) that the in-field performance changes with temperature and some provider's R_S is higher than FCC-hh BS Cu at 60 K but not at 50 K. Thus, the different in-field behaviour in resulting surface resistance, suggests that the R_S depends strongly on the ReBCO-CCs microstructure. As described in Sec.2.3.3, different providers follow different strategies depending on the main target of usage of the coated conductor. In the measurements in Fig.9.6, the difference between pristine CCs and APC CCs, as defined in Sec.2.3.3, is strongly visible.

The pristine ReBCO-CCs by SuperOx and SuNAM show a very steep B_{DC} dependence resulting at $B_{DC} = 9$ T to be close to (or above) the surface resistance of

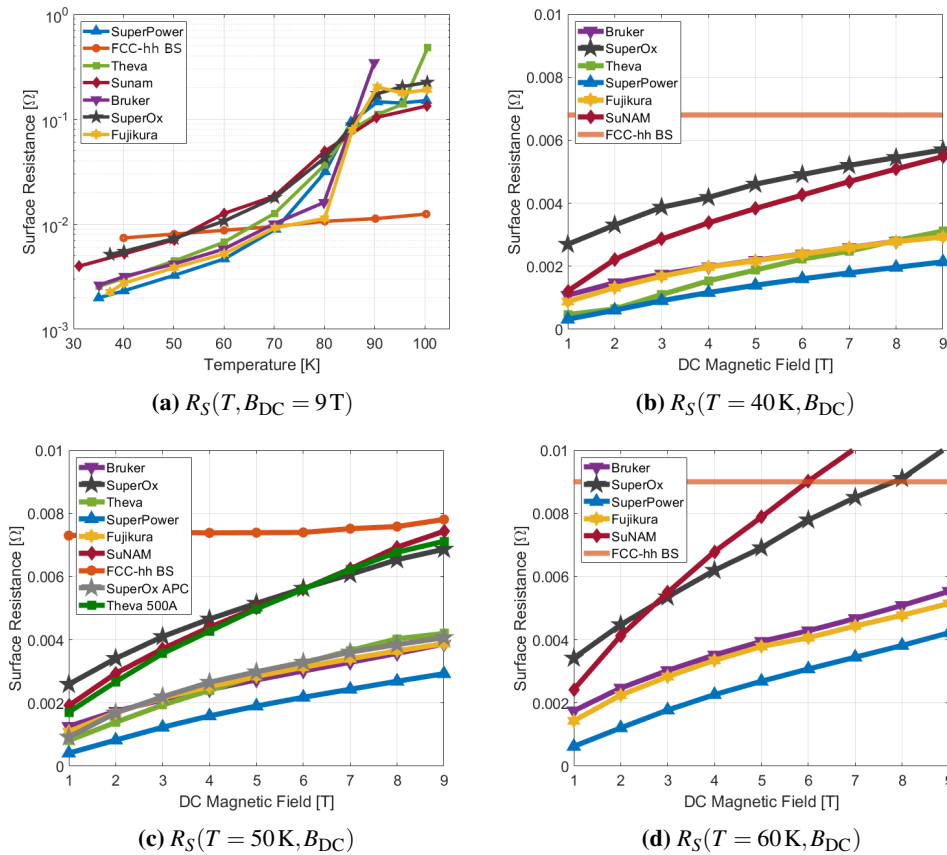


Figure 9.6: (a) Surface resistance at $f = 8$ GHz as a function of temperature with 9 T applied DC magnetic field. (b) - (d) Magnetic field dependence of the surface resistance at FCC-hh relevant temperatures. In (d) the data for Theva at 60 K is missing and has not been obtained.

FCC-hh BS Cu, and with that, much higher than the ReBCO-CCs that include artificial pinning centres. The materials belonging to this group are ReBCO-CCs whose I_C -width in Fig.2.18(a) is observed to have also a steeper magnetic field dependence -especially at low magnetic fields-. Theva, however, due to its inclined substrate technology has two main implications regarding the surface resistance. On the one hand, the applied magnetic field during the experiments is not directed along the c-axis of the ReBCO. It is tilted by almost 30 degrees away from it, as discussed in Sec.2.3.3, and illustrated in Fig.2.17. Accordingly, due to the anisotropic nature of the materials [see Sec.2.3.2], this translates into the superconductor being exposed to an effective DC magnetic field along the c-axis which is 10% lower compared to the actual value [Pui+19]. On the other hand, while in the I_C -width measurements at $T = 50$ K versus applied B_{DC} showed a similar behaviour as the other pristine samples, during the R_S measurements it proves an effective pinning of vortices without the usage of nano-inclusions; hence, performs closer to a ReBCO-CC with APCs. Fujikura's ReBCO-CC as a result of an intrinsic disorder is as well very efficient at pinning vortices. Additionally, in Fig.9.6(c) we show the measurements results of a second Theva sample which performs closer to a pristine ReBCO-CC and a SuperOx APC.

ReBCO-CCs grown by SuperPower and Bruker include nano-rods in the HTS matrix which prove to be very effective vortex pinning centres; thus weak magnetic field dependence. Due to this, these samples show in Fig.9.6 a decent magnetic field dependence and outperform FCC-hh BS Cu in the whole range up to 9 T at 8 GHz. The higher in-field performance of APC-based superconductors is encountered as well from critical current measurements presented in Fig.2.18(a).

9.4.2 Magnetisation of ReBCO-CCs

In the FCC-hh, after a certain amount of collisions at the desired interaction points, the remaining protons in the beam are dumped and the magnetic field is brought back down to 1 T in order to refill the accelerator. Therefore, we continued the study discussed in the previous section by measuring R_S as a function of B_{DC} , though ramping the magnetic field from 0 T to 9 T and then back from 9 T to 0 T at $T = 50$ K. In addition, we measured the possible magnetisation for both cases, FC and ZFC.

Figure 9.7 shows the surface resistance as a function of magnetic field for a Fujikura sample for $B_{DC} = 0$ T to $B_{DC} = 9$ T (blue line) and $B_{DC} = 9$ T to $B_{DC} = 0$ T (orange line). After being exposed to a high magnetic field, the coated conductor exhibits a slightly higher surface resistance than before. This hysteretic behaviour below 2 T [see Fig.9.7 inset] may be associated with the induced vortices that remain inside the material even when the applied DC magnetic field is turned off. The magnitude of magnetisation is different for the different providers and can be associated over the relative changes in measured Q-factor before and after being exposed to a magnetic field.

The hysteresis in the Q-factor in the ZFC case is given in the first column of Tab.9.5 and can go up to 25 per cent. The hysteric behaviour changes depending on the cool down procedure. The differences between field-cooled (FC) and zero-field-cooled (ZFC) ranges between 4 to 44 per cent in the relative changes of the Q-factor visible

Table 9.5: Q-reduction after exposure to a 9 T magnetic field, where $Q_0^{ZFC}(B=0T)$ refers to the unloaded Q-factor before magnetisation zero-field-cooled. The additional subscript M refers to the unloaded Q-factor after being exposed to the 9 T field. $Q_{0M}^{FC}(B=0T)$ refers to the unloaded Q-factor after being exposed to the 9 T field when being field-cooled. The FC versus ZFC data is taken from [RKT20].

REBCO-CC	$\frac{Q_0^{ZFC}(B=0T) - Q_{0M}^{ZFC}(B=0T)}{Q_{0M}^{ZFC}(B=0T)}$ [%]	$\frac{Q_{0M}^{FC}(B=0T) - Q_{0M}^{ZFC}(B=0T)}{Q_{0M}^{ZFC}(B=0T)}$ [%]
Bruker	10	44
Fujikura APC	18	15
SuperPower	5	4
Fujikura	14	31
SuNAM	18	35
SuperOx	6	27
Theva	10	10

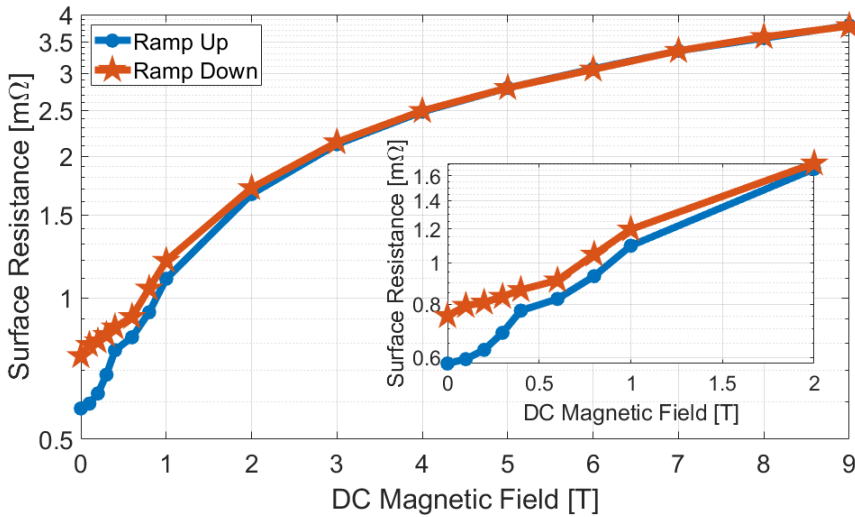


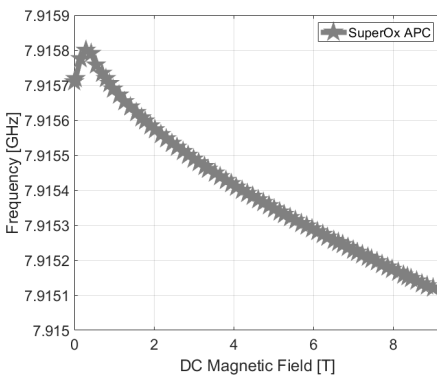
Figure 9.7: R_S of Fujikura APC measured at $T = 50$ K and $f_0 = 8$ GHz. The blue line guides the results when ramping the magnetic field from 0 T to 9 T in the FC case and the orange lines guide ramping the magnetic field down again from 9 T to 0 T.

in the second column of Tab.9.5. The difference can be explained by the way the mixed-state occurs, and with that, the way vortices are formed inside ReBCO film area. As discussed in Sec.2.2.2 the penetration of vortices into the superconducting material, when ZFC, starts from the edges of the ReBCO-CC and the vortices move towards the center when a higher magnetic field is applied. Oppositely, when a magnetic field is already applied the magnetic field penetrates already the whole material homogeneously over the whole tape area.

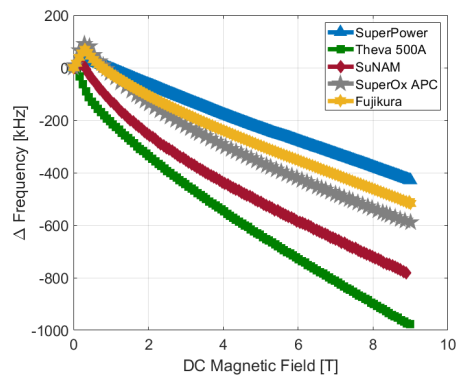
9.4.3 Surface Reactance versus Magnetic Field

In Sec.5.2 we discussed that not only R_S is of importance for the stable operation of the accelerator, but X_S as well. Certainly, the measurement of surface reactance is much more difficult to achieve than surface resistance. Following Eq.(8.3), temperature stability and low temperature dependent dielectric values are significant for accurate measurements. Thus, to avoid the effect of the temperature dependence of the dielectric permittivity of rutile on the measurement, the cooldown procedure for the samples was done overnight to stabilise the temperature to a temperature window of $50\text{ K} \pm 5\text{ mK}$. Data acquisition was programmed within DRΩMS [see Sec.8.2]. As the Cernox temperature sensor implemented into the CHCDR had magnetoresistive effects during ramping which changed the reference temperature and with that equilibrium, we used the PPMS T -sensor as reference while monitoring with the Cernox T -sensor. Small magnetic ramps ΔB_{DC} had to be performed which made the whole measurement very time consuming and hence, led to few measurement sets acquired.

Following Eq.(8.4) a perturbation due to an applied DC magnetic field on the ReBCO-CCs within the rutile-loaded CHCDR produces a relative change in surface reactance ΔX_S of the samples which is reflected in the changes in resonance frequency Δf_0 as presented for SuperOx APC in Fig.9.8(a). The sharp peak at $B_{DC} = 300\text{ mT}$ refers to B_{C1} and the entrance into the mixed state, where below this magnetic field the ReBCO film completely expels the applied DC magnetic field. This is in accordance with the theory of change of surface energy on the sample given by the Ginzburg-Landau theory [GL50]. The changes of resonance frequency Δf_0 , taking the zero-field resonance frequency for each provider individually as reference, is shown in Fig.9.8(b). The frequency shifts are within hundreds of kHz compared to a resonance of about 8 GHz and result into surface reactance increments ΔX_S visible in Fig.9.8(c). Based on Eq.(3.45) and Eq.(3.48) the absolute value of $X_S(T = 50\text{ K}, 0\text{ T})$ can be estimated using the standard value of $\lambda_L(0) = 150\text{ nm}$ for all providers. The measured $\Delta X_S(T = 50\text{ K}, B_{DC})$ can be added to the base value $X_S(T = 50\text{ K}, 0\text{ T})$ leading to the results given in Fig.9.8(d) of the absolute values of the surface reactance in comparison with FCC-hh copper. As can be seen, the influence of B_{DC} on X_S is much higher than



(a) $f_0(T = 50\text{ K}, B_{DC})$



(b) $f_0(T = 50\text{ K}, B_{DC}) - f_0(T = 50\text{ K}, 0\text{ T})$

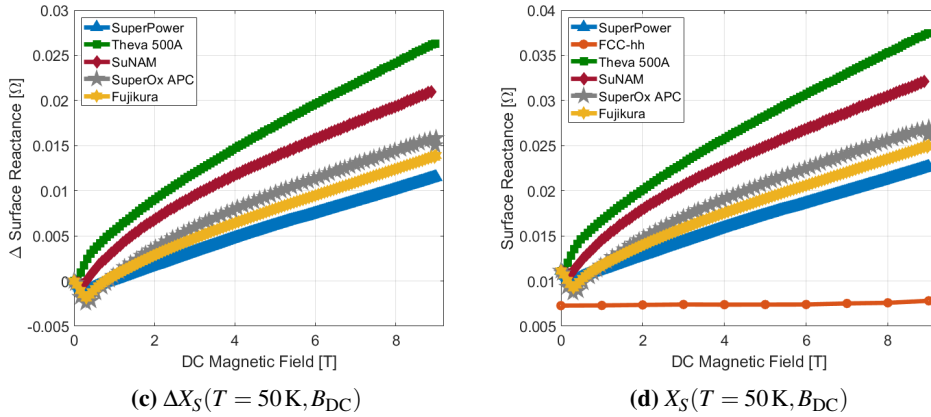


Figure 9.8: (a) Resonance frequency, (b) Changes of the resonance frequency, (c) Changes in the surface reactance, and (d) Absolute values of the surface reactance as a function of an applied DC magnetic field.

on R_S in Fig.9.6(c). This is in accordance to the discussion in Sec.3.4.3 where we aforementioned that the expected surface reactance would be much higher than the surface resistance.

Being a Type-II superconductor and in contrast to metals within the normal skin depth regime where $R_S \approx X_S$ is valid, the ReBCO material differs strongly in its behaviour. In contrast to the surface resistance, the surface reactance is higher than FCC-hh copper for all magnetic fields at 50 K and 8 GHz. Thus, the exact value of the London penetration depth within the expected range of 100 to 200 nm (factor 2 difference in $X_S(T = 50 \text{ K}, 0 \text{ T})$ estimation) will not strongly influence the outcome of the results that the reactance is higher than FCC-hh BS copper at 50 K and 8 GHz.

9.4.4 Rigid Fluxon Model and Depinning Frequency

Figure 9.9(a) summarises the results from this chapter for the six providers at $T = 50$ K, $f = 8$ GHz and low VNA output power $P_{\text{out}} = -15$ dBm. The figure shows the absolute surface impedance as a function of perpendicularly applied DC magnetic field up to $B_{DC} = 9$ T, whereas the real and imaginary parts are separated; bold lines refer to the measured surface resistance and dashed lines refer to measured surface reactance. As can be seen, R_S of all providers at $B_{DC} = 1$ T, which is important at the injection of particles into the accelerator, is about 4 to 20 times less than the FCC-hh BS copper. This surface resistance ratio reduces as a function of B_{DC} down to 1 to 2.5 at $B_{DC} = 9$ T. Oppositely, X_S is slightly higher for all providers at the same conditions. Note that these absolute surface reactance values are based on the assumption, that the London penetration depth is $\lambda_L(0) = 150$ nm for all providers [see Sec.9.3]. In addition, the more pessimistic reduced 2F-model approach is used to calculate $\lambda_L(50 \text{ K}) = 178$ nm.

In Ch.4.2 we discussed that the mid beam frequency spectrum is about 1 GHz. The frequency dependency of metals and ReBCO-CCs has been explained in Sec.3.4 and partially confirmed in Sec.9.2, so as we are able to extrapolate the results in Fig.9.9(a)

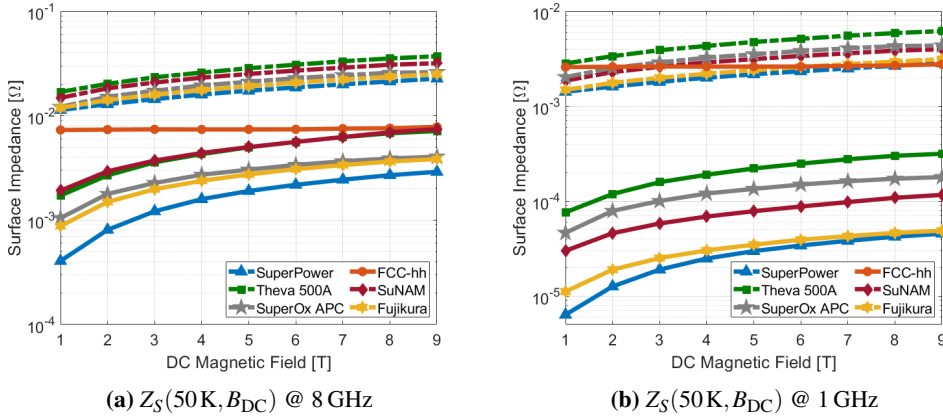


Figure 9.9: Surface Impedance of ReBCO-CCs.

based on Tab.9.3 down to $f = 1$ GHz. The extrapolated data as a function of B_{DC} is shown in Fig.9.9(b). At this specific frequency and $B_{DC} = 1$ T the R_S of all providers outperforms the FCC-hh BS Cu by a factor of 30 to 330 times and it is visible that even up to $B_{DC} = 16$ T the surface resistance would be lower than FCC-hh BS copper by an order of magnitude. On the other hand, X_S , depending on the provider, has a point of intersection between 2 to 8 T, meaning that all providers would have a higher surface reactance than FCC-hh BS Cu at 16 T. However, the higher X_S values of ReBCO are in the same order of magnitude as copper, and thus not of great concern for the overall beam resistive wall impedance. The impact of the measurements on the resistive wall impedance will be discussed in further detail in Ch.12.

Taken all the previous results together, it points substantially towards an influence of APC and vortex dynamics on surface resistance. Additional in-field measurements outside the temperature range of interest are given as a surface plot for all providers in Fig.B.11 in App.B.5.2. The measurements performed in the different temperature ranges lead to the possibility of extracting several microscopic parameters, e.g., vortex viscosity factor [see Sec.2.2.3], which are helpful to estimate the surface impedance over more microstructure related theories as given in Eq.(3.50). However, the necessary parameters are partially out of scope of this thesis, though the results of both approaches have been compared, combined and published together in [Pui+19] and [RKT20] and shall be briefly discussed in the following paragraphs.

The ReBCO-CC microstructures control the magnetic field behaviour of the surface resistance. The corresponding Z_S increases due to the motion of trapped fluxons and under the effect of RF-surface currents, as discussed in Sec.2.2.3. Theoretically, we could expect a Z_S following Eq.(3.50). Nonetheless, there are a number of possible reasons for the discrepancy between theory and experiment. The rigid-fluxon model appears to rely on two strong hypotheses [Cala; Vag]:

1. Each individual vortex behaves as a rigid flux line which does not bend or break.
2. The entire vortex lattice cannot deform and moves as a whole unit.

These two statements may be true for some LTS and very thin films, but they do not

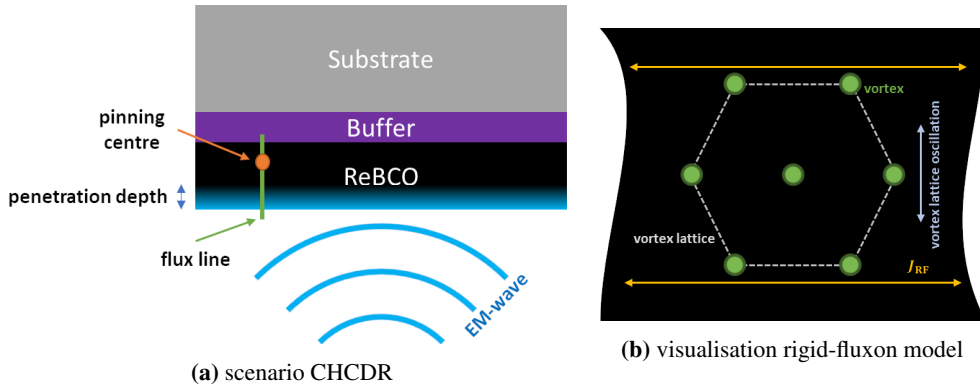


Figure 9.10: Sketch of EM-field induced forces on vortices in ReBCO-CCs.

adequately represent the complex vortex physics of high-temperature superconductors [see Sec.2.2.3], particularly at temperatures above 50 K and in the case of ReBCO-CCs with strong artificial pinning centres.

The first hypothesis implies that a vortex is a rigid tube whose motion is restricted within its potential and does not bend under the force of an applied RF current. In addition, when depinned it will move as a whole entity. However, the thickness of the ReBCO-CCs that we analyse range from about one to three micrometres [see Tab.2.1], whereas the currents induced by H_0 in the CHCDR [see Def.7.3.2] circulate mostly within $\lambda_L \approx 200$ nm. This translates into a force acting on the vortex that is not uniform along its length as depicted in Fig.9.10(a). The electromagnetic field (blue) penetrates the ReBCO film within the penetration depth while the particular flux line (green) is pinned (orange) deep in the ReBCO film, far away from the induced surface current. Due to this, it is expected that under this scenario, a firmly pinned vortex will depin inhomogeneously along its length; thus, bending and twisting of the vortex, in reality, also plays a substantial role in the accurate theoretical predictions.

The second hypothesis implies that if one of the vortices moves, then the entire lattice moves with it. For ReBCO-CCs, especially those with intentionally created APC landscapes, this scenario seems unlikely [Pui+19]. The reasoning lies within the fact that the pinning landscape of ReBCO-CCs with artificial pinning centres is complex, with both, weak and strong pinning centres [Gut+07]. Hence, different vortices will be affected by varying pinning force intensities at a local scale, above magnetic fields not too great (0.1 T at 50 K), as nanorods will strongly pin some vortices, multiple weak pinning centres may partially pin others, and others will be interstitially pinned [Pui+19].

As a result, under the conditions of our measurement set-up, the rigid fluxon model overestimates the actual value of the surface impedance. Though, it does describe the magnetic field dependence qualitatively very well when scaled down to our results [Pui+19]. Therefore, we use this model to cross-check the results as well as to determine other superconducting parameters as the depinning frequency f_{dep} that we introduced in Sec.2.2.3.

Knowing the incremental changes in the surface impedance values gives the option to determine f_{dep} within the rigid-fluxon model by [CV17]. Measuring directly the ratio $\Delta X_S / \Delta R_S$ for small changes in ΔB_{DC} around a definite, large value of DC magnetic field, gives a function for the depinning frequency depending on the applied DC magnetic field $f_{\text{dep}}(B_{\text{DC}})$ [Vag]. From the general expression of the surface impedance Eq.(3.50) the following formula can be determined in the large field and high frequency regime [Vag]:

$$f_{\text{dep}} \approx \frac{X_S^2 f_0 - R_S^2 f_0}{2R_S X_S} \quad (9.3)$$

Figure 9.11 shows the depinning frequency calculated with Eq.(9.3). At low magnetic fields the approximation is not valid and reveals unrealistically large values. At high magnetic fields the curves reach an asymptotic value which is tabulated in Tab.9.6 as the depinning frequency. The results are in good agreement with the values calculated from the Gittleman-Rosenblum theoretical model calculated from the micro-structure parameters in [RKT20].

The findings reveal that we are always measuring below the depinning frequency where the vortex oscillation motion is almost non-dissipative as explained in Sec.2.2.3. This, in turn, means that at high magnetic fields the influence of the surface of normal conducting areas on the surface impedance due to the existence of fluxons is higher than the fluxon motion itself. We investigated these parameters with a relatively small VNA output power of $P_{\text{out}} = -15$ dBm in which the net motion of the vortices is restricted to their pinning potential well. In Ch.10 we will discuss further possible vortex motions which depend on the applied radio-frequency magnetic field strength.

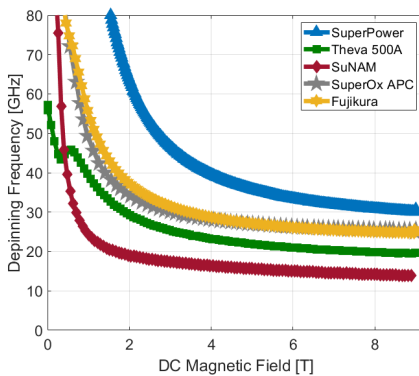


Figure 9.11: Estimation of the depinning frequency of different providers.

Table 9.6: Summary of the extrapolated depinning frequency.

Sample	f_{dep} [GHz]
Fujikura	25
SuNAM	14
SuperPower	31
SuperOx APC	25
Theva 500A	19

9.5 Surface Resistance of aC-coated ReBCO-CC

As discussed in Sec.1.5 the e-cloud build up is a common barrier to overcome in designing high-energy particle accelerators and assure a stable beam. ReBCO-material

is known to be a material with high SEY number that had to be characterised in detail. In the untreated form it is not suitable for the usage in a particle accelerator. Reportedly, amorphous carbon (aC) deposition has proven to be an effective treatment due to its convenient and non-damaging deposition and it is considered as baseline for HL-LHC [Abe+20]. Hence, as CERN developed extensive know-how in SEY reduction by several surface treatments, we had the chance to collaborate with the TE-VSC group which provided us with three samples of differently coated CCs of the same provider. A titanium layer is used as a sublayer sandwiched between ReBCO and aC to increase the adhesion between the two mentioned layers and further acts as a getter for conceivable aC contaminants [Vol]. In [Pui+19] there is an extensive discussion on how the samples were deposited and their resulting SEY values.

The deposited film layer thickness is a compromise between low SEY and low R_S . Each layer has a certain conductivity which according to the theory discussed in Ch.3 will partially shield the ReBCO layer by reducing the electromagnetic field amplitude impinging on it. However, due to its low conductivity $\kappa_{aC} \approx 10^4$ S/m at

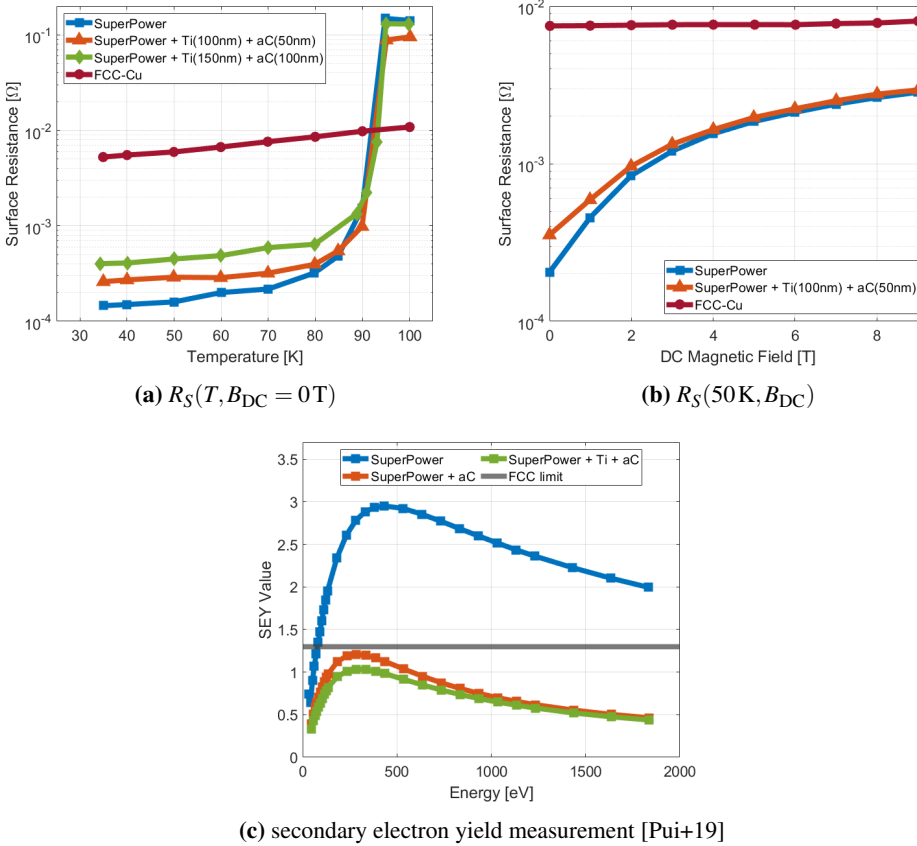


Figure 9.12: Effect of thin film amorphous carbon on ReBCO-CCs surface resistance exemplary for SuperPower.

room temperature (RT) [Gut], very thin aC top layers should not affect the overall surface resistance but might have a larger effect on the surface reactance. Using titanium as a sub-layer with $\kappa_{\text{Ti}} = 10^6 \text{ S/m}$ [Gut] might have a strong impact on the surface impedance. In Fig.9.12(a) we present that this multi-layer coating on a CC has a two- to three-fold increase in $R_S(T)$ depending on the total multi-layer thickness. However, the resulting $R_S(T)$ is still one order of magnitude lower than that of FCC-hh copper in the same conditions. The slight increase in $R_S(T)$ is consistent with the thickness of the multi-layer. The thicker the titanium and amorphous carbon layers are, the higher the surface resistance. At 8 GHz and 50 K the skin depth of aC $\delta_{\text{aC}} \approx 23 \mu\text{m}$ [Pui+19] is relatively large compared to the thickness of the layers $d = 50 \text{ nm}$ and $d = 100 \text{ nm}$. Therefore, the surface resistance increase could be due to the titanium layer having a skin depth $\delta_{\text{Ti}} \approx 1 \mu\text{m}$ [Pui+19] close to the layer's thickness, which is between $d = 100 \text{ nm}$ and $d = 150 \text{ nm}$. In Sec.3.5 we introduced a recursive method to determine the individual surface resistances of multi-layer systems. Thus, by using this method Eq.(3.5.1) and substituting as well $\epsilon_{r,\text{aC}} = 10$ [Calb], we can extract a maximum value for the conductivity of the sputtered amorphous carbon in order not to influence the surface resistance resulting in $\kappa < 10 \text{ kS/m}$. Further, we can extract as well a value for the conductivity of titanium resulting in $\kappa_{\text{Ti}} \approx 11 \text{ MS/m}$. This would be equivalent to a measured skin depth calculated with Def.(3.3.1) of $\delta_{\text{Ti,meas}} = 1.7 \mu\text{m}$; hence, comparable with the previously given value.

Figure 9.12(b) compares the same CC as in Fig. 9.12 as a function of magnetic field at 50 K. We do not observe a degradation of the R_S values before and after coating it with aC or Ti-aC similar to the temperature dependence. The slight increase in the surface resistance appreciated for the samples ascribed to the loss introduced by the 100 nm thick metallic Ti layer while magneto-resistive effects are negligible for such thin layers. Hence, an aC-coating seems a feasible possibility in combination with ReBCO to reduce the SEY value below the threshold without influencing the surface resistance strongly, as presented in Fig.9.12(c).

9.6 Error Analysis

The purpose of this section is to look into probable errors due to random and systematic uncertainty in our experimental procedures used to determine the surface impedance.

In Sec.7.3.5 we introduced the CHCDR technique in which the top and bottom plates of the cavity consist of ReBCO-CCs and the lateral wall is made of metal. In our example, a low-loss rutile cylinder with a diameter of 4 mm and a height of 3 mm was used, taken into account into the design that the distance between dielectric and lateral wall ensured that the losses in the ReBCO-CCs was quite substantial in comparison to other fixture losses. The average surface resistance is determined from the Q-factor according to the loss equation:

$$\frac{1}{Q_0} = \frac{R_{S,\text{Up}}}{G_{S,\text{Up}}} + \frac{R_{S,\text{Down}}}{G_{\text{Down}}} + \frac{R_{S,\text{Lat}}}{G_{\text{Lat}}} + p \cdot \tan \delta, \quad (9.4)$$

where R_{S_i} are the surface resistances of the upper, lower and lateral walls, and G_i their

corresponding geometry factors. The geometry factors of the top and lower walls are identical due to cavity symmetry.

The relative error $\Delta R_S/R_S$ depends on many uncertainties as measured loaded Q-factor and post-processed unloaded Q-factor, the loss tangent of the dielectric, conductivity of the lateral walls, and estimation of geometry factors and filling factor. $\Delta R_S/R_S$ can be determined according to [CKK95; MJ06] as:

$$\frac{\Delta R_S}{R_S} = \left[\left(1 + \frac{R_{S,Lat} G_{Up}}{R_{S,Up} G_{Lat}} + \frac{G_{Up}}{R_{S,Up}} p \tan \delta \right)^2 \left| \frac{\Delta Q_0}{Q_0} \right|^2 + \left| \frac{\Delta G_{Up}}{G_{Up}} \right|^2 + \left(\frac{R_{S,Lat} G_{Up}}{R_{S,Up} G_{Lat}} \right)^2 \cdot \left(\left| \frac{\Delta R_{S,Lat}}{R_{S,Lat}} \right|^2 + \left| \frac{\Delta G_{Lat}}{G_{Lat}} \right|^2 \right) + \left(\frac{G_{Up}}{R_{S,Up}} p \tan \delta \right)^2 \left(\left| \frac{\Delta p}{p} \right|^2 + \left| \frac{\Delta \tan \delta}{\tan \delta} \right|^2 \right) \right]^{0.5} \quad (9.5)$$

The analysis of G_i and p discussed in Sec.7.3.5 showed that the discrepancy between analytical, experimental, and FEM calculations are about $\Delta G_i/G_i, \Delta p/p < 0.5\%$; thus, the influence is negligible.

The main advantage of the CHCDR characterisation system is that, for the suitable design of the cavity, the losses concentrate in the ReBCO-CCs. Thus, given the values of the uncertainties involved the correction term arising, e.g., at 50 K is $R_{S,Lat}/G_{Lat} \approx 5 \cdot 10^{-8}$. The measured highest inverse quality factor and loss tangent for rutile values are of two orders of magnitude higher; hence, the correction term arising from the lateral wall is insignificantly small.

With the development of ARPE the uncertainty in the estimation of unloaded quality factor could be minimised to about 1% for a low noise floor and high quality factor [Krk+21a]. However, the uncertainty in reproducibility of Q_0 measurements by de-assembling and re-assembling the entire CHCDR needs to be taken into account. Thus, in order to discard that the spread in R_S values does not come from a lack of repeatability in the measurements, we performed a series of 10 consecutive measurements on the same pairs of samples for metals at room temperature as well as superconductors immersing them in liquid nitrogen (77 K). The resonator was fully re-assembled before each measurement. In our measurements the resulting spread in the unloaded Q-factor for repeated measurements of the same sample is about 5%. Note that this error includes the non-homogeneity of the sample, because the quality factor is dominated by the loss of the fraction of the sample in contact with the dielectric cylinder and includes as well the error arising from the limited accuracy in placing the dielectric cylinder exactly into the center of the resonator. Thus, we can measure with precision of 5%. In addition, a study of the spread in R_S values for coated conductor samples along the same provided tape was performed. A series of five sample pairs have been utilised for this study and resulted in a spread in the results of about 10% within each provider. Hence, for the relative error estimation we will include $\Delta Q_0/Q_0 = 10\%$.

A major source of uncertainty lies within the value for the rutile loss tangent used

to calculated the surface resistance. The effect of the loss tangent value depends on two factors. On the one hand the material examined and on the other hand the temperature range. At 50 K, the loss tangent uncertainty has little effect in the experimental determination of copper surface resistance, since the dielectric loss is about 3% of the overall resonator loss. However, for superconducting samples, dielectric loss can dominate the overall loss and its uncertainty impacts that of the R_S of the samples being measured. In our case, we were able to measure each set of samples in each experimental set-up with the same dielectric rod. Comparing the estimated surface resistances using the two different loss tangent values from [Kle+95] -where temperature and frequency ranges are similar to those of our set-up- and [Die20] at 50 K for FCC-hh BS copper, SuperOx, and SuNAM, we get an absolute deviation of R_S of about 5%, 30% and 60%, respectively and resulting without doubts in the highest source of inaccuracy of the experimental set-up. Thus in the relative error calculation we will take into account a $\Delta \tan(\delta)/\tan(\delta)$ which is determined by the measured deviation between the results as a function of temperature from [Die20] and [Kle+95] as presented in Fig.B.10(a).

Figure 9.13 shows the determined total relative error in the surface resistance determined by Eq.(9.5) for two providers and FCC-hh beam screen copper for comparison. The results include the analysis of Sec.9.2 where we determined that the loss tangent of the rutile crystal used for the measurements is worse than we expected. The fact that the estimated loss tangent gives consistent results in the frequency square dependency presented in Fig.9.4(b) for several providers hints that it is worse than the published one. Thus, further data collection is required to determine the exact $\tan(\delta)$ for each rutile crystal used. Nevertheless, it is important to state that the aforementioned is a systematic error common to all measurements. Therefore it will not influence the ranking among the various samples used in this thesis. In addition, the results published

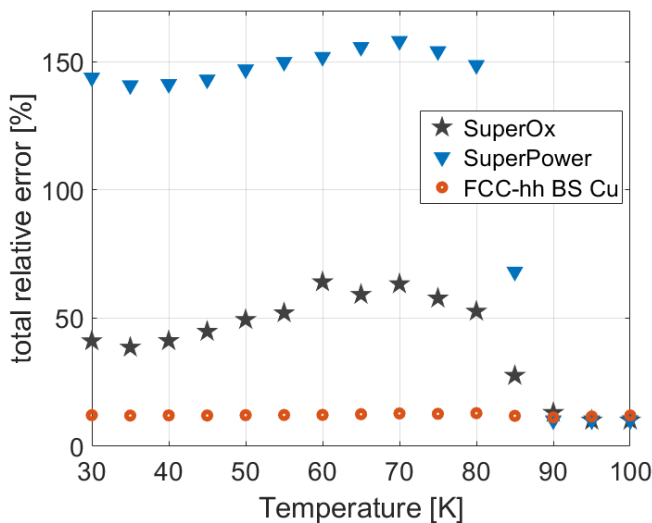


Figure 9.13: Relative error of R_S as a function of temperature.

in [Krk+21c; Pui+19; RKT20] as well as this thesis give a pessimistic estimation of the surface resistance for FCC-hh.

Having defined what is meant by the uncertainties in R_S , we will now move on to discuss the uncertainties in the surface reactance X_S . We determined the average surface reactance at 50 K as a function of magnetic field over

$$X_S = X_{S,\lambda_L} + G_{Up} \left(\frac{\Delta f_0}{f_0} - \frac{\Delta X_{Lat}}{G_{Lat}} - p \frac{\Delta \epsilon_r}{\epsilon_r} \right), \quad (9.6)$$

where X_{S,λ_L} is the absolute value of the surface reactance at zero magnetic field estimated over Eq.(3.45), ΔX_{Lat} refers to the change in surface reactance of the metal lateral walls and $\Delta \epsilon_r$ is the change in the relative permittivity. The relative error $\Delta X_S/X_S$ is thus given as:

$$\begin{aligned} \frac{\Delta X_S}{X_S} = & \left[\left| \frac{\Delta X_{S,\lambda_L}}{X_{S,\lambda_L}} \right|^2 + \left(\frac{2\Delta f_0}{f_0} - \frac{\Delta \epsilon_r}{\epsilon_r} - \frac{\Delta X_{Lat}}{G_{Lat}} \right)^2 \left| \frac{\Delta(G_{Up})}{G_{Up}} \right|^2 + \left(\frac{2\Delta f_0 G_{Up}}{f_0^2} \right)^2 \right. \\ & \cdot \left| \frac{\Delta(\Delta f_0)}{f_0} \right|^2 + \left(\frac{G_{Up}}{G_{Lat}} \right)^2 \left| \frac{\Delta(\Delta X_{Lat})}{X_{Lat}} \right|^2 + \left(\frac{G_{Up} \Delta X_{Lat}}{G_{Lat}^2} \right)^2 \left| \frac{\Delta G_{Lat}}{G_{Lat}} \right|^2 \\ & \left. + \left(\frac{\Delta \epsilon_r G_{Lat}}{\epsilon_r^2} \right)^2 \left| \frac{\Delta(\Delta \epsilon)}{\epsilon_r} \right|^2 + \left(\frac{\Delta \epsilon_r G_{Lat} p}{\epsilon_r} \right)^2 \left| \frac{\Delta p}{p} \right|^2 \right]^{0.5} \quad (9.7) \end{aligned}$$

The reference absolute value without magnetic field is estimated over the theoretical value of the London penetration depth of $\lambda_L(0) = 150$ nm but as described in Sec.9.3 can vary between 100 to 200 nm. Thus we assume for $\Delta X_{S,\lambda_L}/X_{S,\lambda_L} = 33$ %.

Determining the change in frequency when the temperature changes from a given reference T_{ref} requires measuring the relative frequency change and knowing the two rightmost terms at the right hand side of Eq.(9.6). However, as the permittivity of rutile is strongly temperature dependent, the influence of the changes in permittivity prevails over that of the rest of the terms. The exact position of the dielectric influences as well the resulting resonance frequency of the particular measurement. However, as long as the determination of f_0 is accurate, there is no issue in having small differences within measurements of the same samples or providers. The relative uncertainty $\Delta f_0/f_0$ on the resonance frequency is close to $(10Q_L)^{-1}$ when processing the data with ARPE. This results in a relative variation of 6.7 ppm when measuring copper and up to 0.25 ppm for a superconductor. At 8 GHz, the uncertainties vary in the range of 53 kHz to 6 kHz which is low enough to determine surface reactance of ReBCO-CCs accurately. In addition, the frequency stability of the instrument used to measure resonance frequency (FieldFox VNA) was upgraded to include a GPS frequency reference whose frequency stability is specified at 0.01 ppm.

The dielectric permittivity of rutile and its strong temperature dependence may be powerful enough to dominate the measurement of surface reactance. Small relative errors in determining $\Delta \epsilon_r/\epsilon_r$ may be large compared to $\Delta X_S/G_S$, making it impossible to have an accurate determination of ΔX_S , despite any calibration procedure and post-processing tool. In such a case, two mitigating measures might be taken: Reduce the

temperature range to a minimum with good temperature stability which we achieved to be 50 ± 0.005 K. This translates into $\Delta\epsilon_r \approx \pm 0.00045$ which analytically calculated results in a resonance frequency change of almost ± 14 kHz and with that the biggest uncertainty for the surface reactance measurement. Instead of rutile, the use of the resonator with a more temperature-stable dielectric, such as sapphire or the materials used in filters for telecommunications and broadcasting would be recommended to reduce the possible error. On the other hand, measuring at lower temperatures, e.g., 20 K can counteract the error source as the permittivity of rutile does not change significantly below 30 K.

Figure 9.14 shows the determined relative error in the surface reactance as a function of magnetic field. As can be seen, the error is prevailed by the correct determination of the London penetration depth rather than exact temperature stability and frequency stability of the given system.

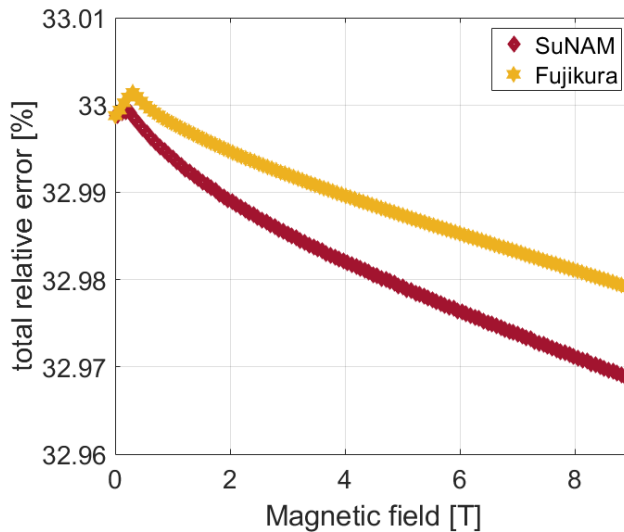


Figure 9.14: Relative error of X_S as a function of magnetic field.

It shall be noticed that the design leads to a high sensitivity with the possibility to measure samples over five orders of magnitude in surface resistance or even more once the $\tan(\delta)$ of rutile is determined. When the losses in the ReBCO-CCs are dominant -for example, as a result of an external magnetic field-, there can be a low uncertainty in the R_S values as the relative error in the surface resistance is then equal to the relative error in the unloaded quality factor and in the geometry factor.

In summary, it has been shown from this review that:

- the loss tangent is a major uncertainty in the R_S determination
- we have used published loss tangent values
- we have evidence that the loss tangent in our crystal is larger than the published one
- the loss tangent is a deterministic unknown affecting all R_S measured, since the

same crystal has been used in all published data

- despite the loss tangent uncertainty, comparing the surface resistance values, ReBCO-CCs outperform copper already at 8 GHz, 50 K and up to 9 T
- the R_S ranking is not affected by loss tangent uncertainty
- the determined surface resistance values are pessimistic
- the London penetration depth $\lambda_L(0)$ is a major uncertainty in the X_S determination
- despite the London penetration depth uncertainty, comparing the surface reactance values, ReBCO-CCs do not outperform copper at 8 GHz, 50 K and up to 9 T
- the accuracy in the knowledge of the $\lambda_L(0)$ does not significantly change the outcome of the results as the magnetic field influence ΔX_S is stronger than $X_S(0T)$
- the measurement of ΔX_S as a function of magnetic field has a higher accuracy than the estimation of the penetration depth
- the significance of this thesis lies within the task to prove or disprove that ReBCO-CCs perform better than copper at FCC-hh conditions. Again, at 8 GHz, ReBCO-CCs outperform Cu in terms of R_S but underperform in terms of X_S . As 8 GHz is out of the FCC-hh band of interest, extrapolation of the experimental results to this band is crucial to show the advantages of ReBCO versus Cu. This extrapolation is done later in this thesis.



10. Thermal and RF Power Dependence

Mis ideas son de una lógica indiscutible; lo único que me hace dudar es que no hayan sido aplicadas anteriormente.

Antoni Gaudí

This chapter aims to experimentally evaluate the non-linear behaviour of ReBCO coated conductors in the presence of a DC magnetic field superimposed on a radio-frequency magnetic field strength of varying amplitude -comparable with that of the FCC-hh- and relate the observed behaviour to the FCC-hh BS performance. A significant part of this chapter has been published in [Krk+21c], and the original content from that work may be used under the terms of the Creative Commons Attribution 4.0 license.

10.1 ReBCO-CC Non-Linear Effects at the FCC-hh

The previous chapter on ReBCO-CCs surface impedance has shown that their small-signal surface resistance can be close to or below that of Cu in the measurements between $T = 40$ to 60 K and $f_0 = 8$ GHz up to $B_{DC} = 9$ T. In the FCC-hh beam screen, the ReBCO-CC would be exposed to the RF wakefields generated by the particle bunches superimposed with a strong DC magnetic field of the dipole magnets. An illustration of the electromagnetic configuration in the particle accelerators is given in Fig.10.1. Hence, there are other non-linear aspects related to the ReBCO-CC's surface

impedance that may compromise their use in the FCC-hh beam screen, which have to be investigated further, specifically: its dependence on radio-frequency electromagnetic field strength under large applied DC magnetic fields, its resulting vortex oscillation and the appearance of temperature effects, including self-heating, resulting from the application of large RF fields.

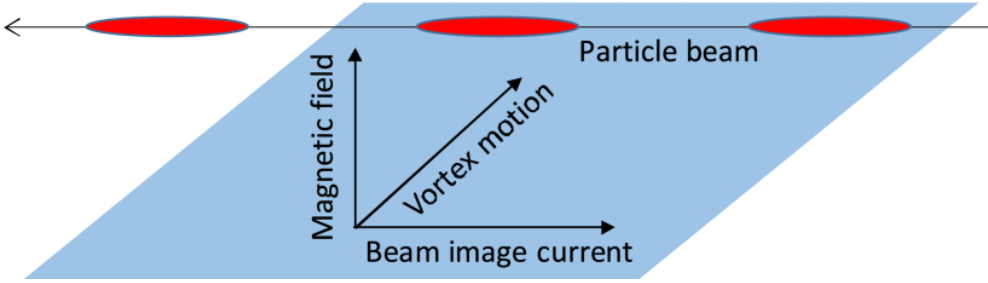


Figure 10.1: Beam screen electromagnetic layout. The circulating particle beam (bunches) induces image currents (RF magnetic field strength) leading to a motion of the vortices created by the DC magnetic dipole field, perpendicular to both, the beam image current and the DC magnetic field. Figure taken from [CV21].

ReBCO superconductors have an intrinsic non-linear behaviour in RF as a function of the intensity of surface currents; hence, RF magnetic field strength at the surface H_{RF} . Many different possible loss mechanisms have been reported for the non-linear microwave response of high-temperature superconductors. Generally, three terms describe the total surface resistance [Ben+99; Cal16]:

$$R_S(H_{\text{RF}}, T, B_{\text{DC}}) = R_{\text{BCS}}(H_{\text{RF}}, T) + R_{\text{res}}(H_{\text{RF}}) + R_{\text{fl}}(H_{\text{RF}}, T, B_{\text{DC}}). \quad (10.1)$$

First, a contribution is resulting from the BCS-theory R_{BCS} that depends on the energy gap parameter of the superconductor. Second, lattice defects, grain boundaries, or impurities are summarised as the residual resistance R_{res} . Both these two terms depend on the strength of the radio-frequency field applied on the samples but do not depend on the applied DC magnetic field and are the dominating terms at $B_{\text{DC}} = 0$. Only the term R_{fl} , which is dependent on the applied DC magnetic field, accounts for the creation of vortices in the superconductor and their dissipative oscillating movement around their pinning centres when driven by an RF current [CV21].

The sources of non-linear power dependence leading to the raise of R_S can be divided into magnetic and/or thermal effects, depending on the prevailing mechanism of the excitation energy. The first mechanism is connected to the possibility of having either a $\mu_0 H_{\text{RF}} \gtrsim B_{\text{C1}}$ or in the presence of a strong DC magnetic field $B_{\text{DC}} \gtrsim B_{\text{C1}}$. Below the lower critical field the superconductor will be in the Meißner state expelling the magnetic field entirely by inducing shielding currents over the surface [see Sec:2.1.2]. Among the possible causes of applied DC magnetic fields lies the non-linearity of the vortex lattice pinning potential. The second mechanism is connected to the possibility that the non-linear effects are caused by the dissipation of microwave power.

To identify the aforementioned possible limitations of ReBCO-CCs, the strategy that was used was as follows: Prior to commencing the study, we numerically determined the expected azimuthal radio-frequency magnetic field strengths $H_{\text{RF,FCC}}$ at the surface of the coating for the baseline FCC-hh beam screen design [see Sec.1.5]. The determined values will be used as reference for the experiments in the following sections. We used the CHCDR and the set-up discussed in Sec.8.2 to experimentally evaluate the non-linear behaviour of ReBCO-CC's surface resistance R_s in the presence of a DC magnetic field B_{DC} superimposed on a radio-frequency magnetic field strength H_0 ²¹ of varying amplitude, reproducing the FCC-hh beam screen requirements, and relate the observed behaviour to the FCC-hh BS performance.

We conducted the first experiments of R_s versus RF power without applied DC magnetic field, and afterwards, we performed measurements including DC magnetic fields up to 9 T. The measured data is then extrapolated from 8 GHz and 9 T to 1 GHz and 16 T. Following these measurements, we discuss the correlation between the electromagnetic fields provided by the vector network analyser and the timing of the circulating proton bunches and how this might induce (transient) thermal effects in the beam screen. Finally, we investigate possible net flux displacement or vortices and demagnetisation of ReBCO-CCs caused by the RF magnetic field strength.

10.2 FCC-hh Beam Screen RF Magnetic Field Strength

In this section, we calculate the expected azimuthal radio-frequency magnetic field strength $H_{\text{RF,FCC}}$ on the surface of the actual inner FCC-hh beam screen with the same approach as explained in Sec.4.2 for a round pipe. The actual shape and dimensions of the BS have been taken from [Bel20]. In this case, we found the solution for the vector potential A in Eq.(4.5) by discretising the inner part of the beam screen Ω_{BS} in a fine mesh of $\approx 140\,000$ triangular elements, as can be seen in Fig.10.2. In the next step, we used A to find the azimuthal magnetic field strength $\mu_0 H_{\text{RF,FCC}} = \nabla \times A$ shown in Fig.10.3.

The result demonstrates that the inner coating of the beam screen, marked in black in Fig.10.3, facing the protons directly, would be exposed to an RF azimuthal magnetic field strength between $H_{\text{RF,FCC}} = 130 - 230$ A/m -equivalent to $B_{\text{RF,FCC}} = 0.16 - 0.29$ mT- depending on the positioning of the coating, which is much smaller than the first critical magnetic field of ReBCO-CCs. Close to the openings of the mid-horizontal plane to let the synchrotron radiation pass, the magnetic field strength

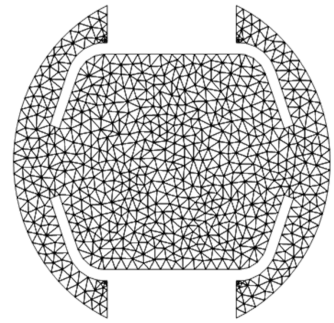


Figure 10.2: Example of a coarse FCC-hh beam screen mesh in Mathematica.

²¹ H_0 is the maximum RF magnetic field strength value $H_{\text{RF,max}}$ in the CHCDR set-up as defined in Def.7.3.2.

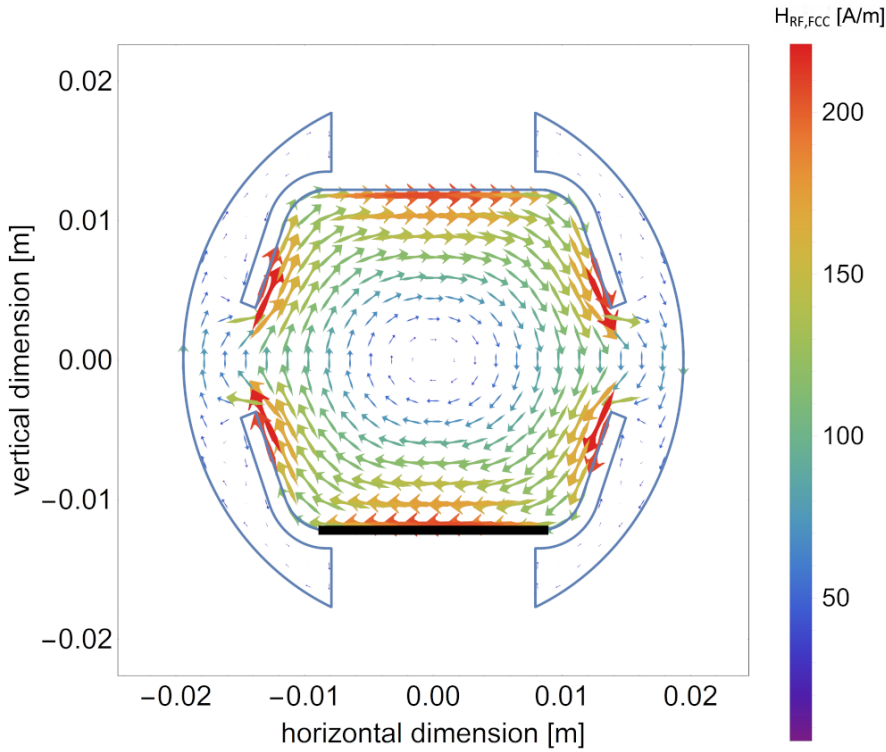


Figure 10.3: Vector field plot of the azimuthal magnetic field strength distribution produced in the inner part of the FCC-hh beam screen (baseline design).

is also significant, although in this numerical calculations the values might be exaggerated and connected to the sharp edge in the models used and a numerical artefact of the FEM solver.

10.3 Surface Resistance versus RF Power

The purpose of the investigation of this study is to explore the relationship between RF surface magnetic field strength H_0 on the sample and the influence on the surface resistance. In Sec.10.1 the three main contributors to the surface resistance have been discussed which all depend on H_0 . In this section, therefore, we set out to assess the effect of enhanced RF surface magnetic field strength on the first two terms of Eq.(10.1) only, in order to facilitate the determination whether thermal (surface heating) or magnetic (vortices) aspects influence the possible non-linear behaviour of ReBCO-CCs in the FCC-hh.

First measurements were performed with the rutile CHCDR closed cycle cryostat set-up described in Sec.8.1. The investigations were performed at the fixed temperature of $T = 50$ K, hence $f = 8$ GHz, monitoring the unloaded Q-factor Q_0 as a function of the available RF-field input power P_{in} [see Eq.(7.26)]. In order to investigate the resulting RF surface magnetic field strength $\mu_0 H_0 = B_0$ dependency [see Def.7.3.2]

of the surface resistance, it is necessary to specify the relationship between the electromagnetic fields in the CHCDR and the VNA output power P_{out} as described in Sec.7.3.6. To establish the relation between P_{out} and the dissipated power P_{diss} in the cavity, the insertion loss L_{const} of the cables between the VNA and the resonator has to be quantified as prescribed in Eq.(7.26). For the test cable outside the cryostat as sketched in Fig.7.8, this is a simple measurement that can be performed with a power meter. Accordingly, the available input power P_{in} at the resonator is 2.65 dB below the VNA output power P_{out} . However, the semi-rigid cable inside the cryostat is not accessible. Its insertion loss is estimated to be half the off-resonance return loss L_{off} . Once the power dissipated in the sample and the Q-factor are known, we can determine the amplitude of the fields in the cavity through Eq.(7.23).

The VNA output power was programmed at 8 GHz to change from $P_{\text{out}} = -60$ dBm to +10 dBm in 10 dB steps, including one measurement at +13 dBm. The measurements of the provided ReBCO-CCs given in Tab.2.1 (besides Bruker) were performed in this particular set of measurements presented in this section with a VNA intermediate frequency bandwidth (IFBW) set to 1 kHz and 401 points in the frequency sweep. The data has been taken in the continuous wave (CW) mode, though we have taken care that we remain in the sinusoidal-steady-state in which the transient decay time Q/ω_0 is smaller than the reciprocal of the IFBW.

Figure 10.4 illustrates the effect of non-linear microwave losses on the transmission coefficient S_{21} measured with a frequency sweep across the resonance Δf_{span} for two different sweep times. The figure shows two measurements performed on the same SuperPower ReBCO-CC sample pairs at the maximum power output of the VNA. The difference lies in the amount of points used for the frequency sweep. A lower

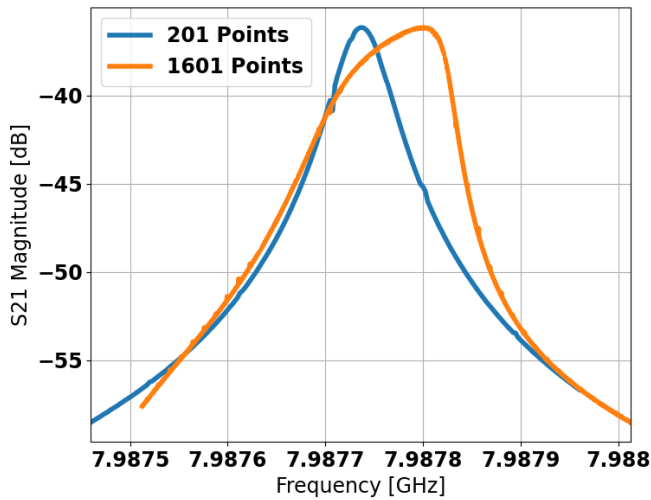


Figure 10.4: Measured transmission coefficient S_{21} for a single resonant mode for two different sweep times. Data is shown for SuperPower.

number of frequency points leads to a faster sweep time. Otherwise, the measurement conditions in both frequency sweeps were the same. The resonance curve deviates from the expected Lorentzian shape indicating a non-linear behaviour of ReBCO superconductors. As a result, the determination of Q_0 , R_S and B_0 , can have additional uncertainties depending on the chosen sweep velocity $\Delta f_{\text{span}}/t_{\text{sweep}}$. We elaborate further on this effect in Sec.10.6.

Figure 10.5 shows the power-dependent surface resistance of the several providers as a function of the resulting surface magnetic field. On the one hand, within the results, SuperPower and Fujikura CCs show a slight linear increase in the surface resistance with respect to the RF surface magnetic field B_0 . On the other hand, SuperOx and SuNAM indicate an exponential increase which is predominantly visible in Theva above a RF surface magnetic field of $B_0 = 0.1$ mT.

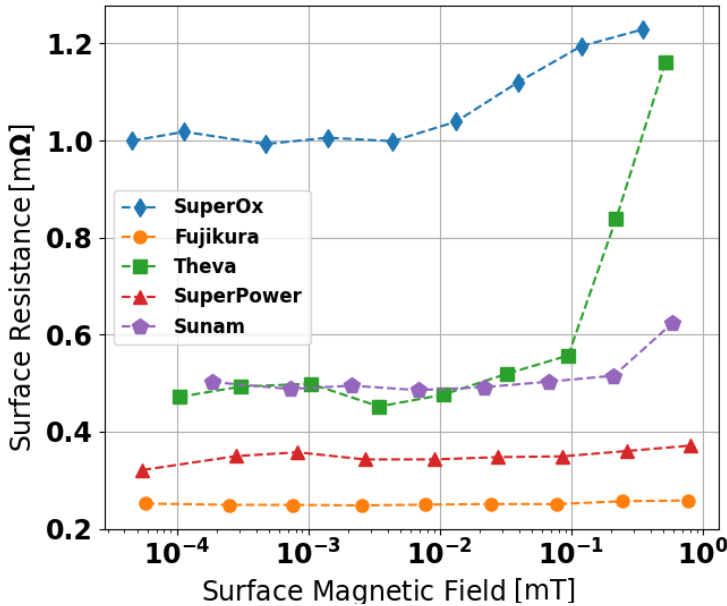


Figure 10.5: Surface resistance R_S at 8 GHz versus maximum surface magnetic field B_0 for different providers at $T = 50$ K.

Opposed to the zero resistivity of SCs with respect to DC currents, RF currents or fields cause microwave losses in the ReBCO layer, that are converted into Joule heat and increase the temperature either locally in the position of the maximum field amplitude or globally over the whole ReBCO layer. A global quench occurs when the dissipated power is sufficient to induce a thermal superconducting to normal conducting transition across the entire ReBCO layer. The treatment of the dissipation of heat is dependent on several factors as, operating frequency, film thickness, temperature dependence of the surface resistance, defects and weak links, thermal properties of the CC substrates and the overall cooling conditions [Pow+99]. These mechanisms,

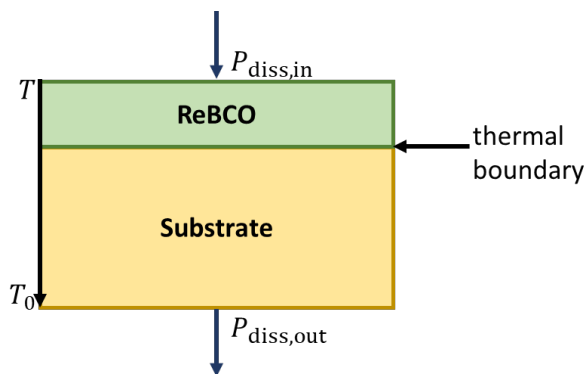


Figure 10.6: Schematic of a ReBCO layer on its substrate with a thermal boundary. The substrate is kept at a constant temperature T_0 while the ReBCO layer is exposed to the electromagnetic fields in the CHCDR. The resulting heat due to the dissipated power $P_{\text{diss,in}}$ has to be conducted through a thermal barrier, which consequently, might lead to a temperature change of the ReBCO layer. Figure adapted from [Hei99].

especially weak links, reportedly can cause an increase in the surface resistance even at lower RF surface magnetic fields [Oat+92]. A very simplified sketch is shown in Fig.10.6. The electromagnetic field penetrates the ReBCO-film within λ_L leading to ohmic dissipation. Between the substrate and the ReBCO layer lies a thermal boundary. Assuming that the substrate has a constant temperature T_0 , an increase in B_0 might be equivalent to raising the temperature of the ReBCO layer, reflecting a thermally induced $R_S(B_0)$ versus $R_S(T)$. Numerical models in order to evaluate the effect of heating on the microwave response of YBCO films on substrates described in [Hei99], show a linear RF surface magnetic field dependence of the surface resistance at low RF amplitudes similarly as visible in Fujikura and SuperPower.

If thermal heating was the only mechanism, then the R_S behaviour of SuNAM, SuperOx and Theva could be caused by a local thermal heating or even local quench. A local warm spot, limited at a defect location, with a temperature that is higher than the rest of the sample or the cold sink could explain the steep increase in surface resistance. Comparing the values from Fig.10.5 with the values in Fig.9.2, it indicates that the local temperature of the sample at maximum B_0 would correspond to 80 K, 75 K and 83 K for SuperOx, SuNAM and Theva, respectively. The fact that the most significant increase in R_S is seen in Theva is most likely due to the special inclined growth technology explained in Sec.2.3.3. The c-axis of this ReBCO tape is tilted by approximately 30 degrees with respect to the substrate normal, transversely to the tape length [The21]. Accordingly, the circulating currents induced into the sample have to flow partially in the growth direction but also perpendicularly to it.

In the scenario that the provided energy density in the vicinity of any defect becomes so high that the local temperature rises above T_C , the energy stored in the ReBCO film can be released like an avalanche and superconductivity in the entire film changes into the normal conducting state [Hei99; Irg02]. Though, this phenomenon is only observed on very high quality samples at higher surface magnetic fields above B_{C1} .

The lower critical magnetic field values for YBCO samples on different substrates with different oxygen doping are reported to be between 1-800 mT at absolute zero temperature with a narrower average between 10 to 300 mT for the stoichiometry $\text{YBa}_2\text{Cu}_3\text{O}_7$ [Hei99; Irg02; Lia+05; Pla10]. However, in our configuration we do not reach magnetic fields higher than 1 mT, and therefore, it seems unlikely that the increase in $R_S(B_0)$ is caused by flux tubes penetrating any of the ReBCO coated conductors.

Many other different possible magnetic mechanisms which evoke a non-linear response of superconductors have been investigated and are summarised in [Hei99], nonetheless, these effects are described to be at magnetic fields $B_0 > 100$ mT which is far away from what our set-up can deliver, and in addition, no external applied magnetic field is present. In order to obtain higher power field strengths than the presented $B_0 = 0.9$ mT in Fig.10.5 in the rutile loaded CHCDR, the RF coupling has to be set to critical $\beta_1 = 1$ and the RF decoupling to weak $\beta_2 \approx 0$. As these measurements were combined with temperature dependence measurements the coupling was set to be symmetrical and weak in both ports $\beta_1 \approx \beta_2 < 0.01$. Assuming that Fujikura would continuously be only slightly affected at enhanced surface magnetic field levels we can estimate the maximum B_0 we could achieve with this system utilizing the values given at maximum output power though changing the values of the coupling factors to $\beta_1 = 1$ and $\beta_2 = 0.001$ leading to $B_0 = 4.37$ mT.

10.4 Surface Resistance versus RF Power and DC Field

The FCC-hh most probable cool down procedure will be to first cool down the accelerator and then turn on the magnets. Any superconducting material in the beam screen would then be zero-field cooled. Accordingly, for the measurements presented in this section, the ReBCO-CCs were ZFC-down to $T = 50$ K where the temperature was stabilised before applying the DC magnetic field B_{DC} . Microwave measurements were carried out by applying the VNA output power P_{out} from -40 dBm up to +10 dBm in 5 dB steps, and in addition, one measurement at the maximum output power of +13 dBm. The power sweep was performed for a DC magnetic field from 0 T to 9 T in 1 T steps without changing the temperature in between the magnetic sweep measurements.

The surface resistance R_S as a function of VNA output power P_{out} superimposed with a DC magnetic field B_{DC} for one of the providers (Theva) can be seen in Fig.10.7. Similar to Fig.10.5 where $B_{\text{DC}} = 0$, Fig.10.7(a) shows a non-linear behaviour of the surface resistance as it increases with a power-law dependence for VNA output power levels above -10 dBm²². Figure 10.7(b) shows the magnetic field dependence of R_S at different VNA output powers. Two main features are observed: R_S increases with the DC magnetic field starting from non-zero values at zero magnetic field, and the higher the VNA output power, the higher the surface resistance. The last term in Eq.(10.1) is the only applied DC magnetic field dependent term which accounts for the creation of

²²Both measurements on Theva samples (previous section and here) have been performed for two different tapes provided and two different resonators with different coupling strength.

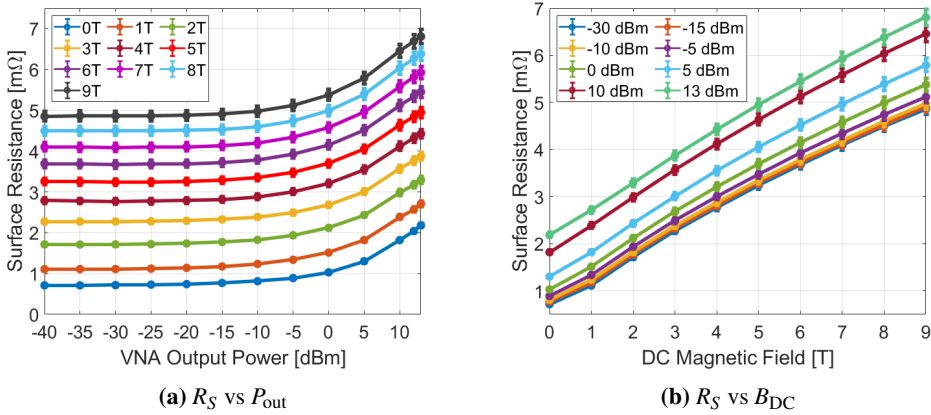


Figure 10.7: Surface resistance at 8 GHz and 50 K as a function of VNA output power for several DC magnetic fields. Data is shown for Theva.

vortices in the superconductor and their dissipative oscillating movement around their pinning centres when driven by an RF current [CV21] and is the dominating one at high magnetic fields and in the work presented here. Additionally, other mechanisms may also partially contribute to the non-linear surface resistance observed in Fig.10.7: radio-frequency flux line dynamics -including nucleation-, self-heating and intrinsic pair breaking [Hei99; Pow+99; Rab70]. We rule out any significant contribution to R_S from the substrate under the superconducting layer. While this may happen in some thin films, the findings in Ch.9 showed that this contribution is generally negligible in most ReBCO coated conductors.

Figure 10.8 illustrates how a surface impedance dependent on RF power affects the S_{21} parameter for the specific case of a SuperOx sample. The higher the VNA power,

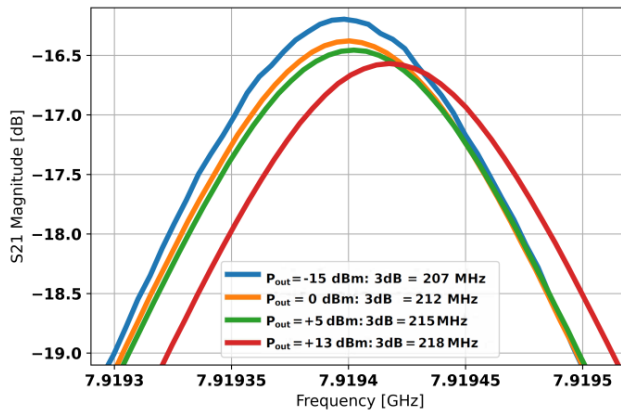


Figure 10.8: Measured transmission coefficient S_{21} within 3 dB bandwidth for a single resonant mode without DC magnetic field and different VNA output power. Data is shown for SuperOx.

Table 10.1: RF peak surface magnetic field strength ratios for the studied providers. The ratios are defined as follows: First column: RF surface magnetic field strength at maximum output power +13 dBm over RF surface magnetic field strength at -15 dBm at 9 T and second column: RF surface magnetic field strength at maximum output power +13 dBm over the lower and upper RF azimuthal magnetic field strength values for FCC-hh also at 9 T.

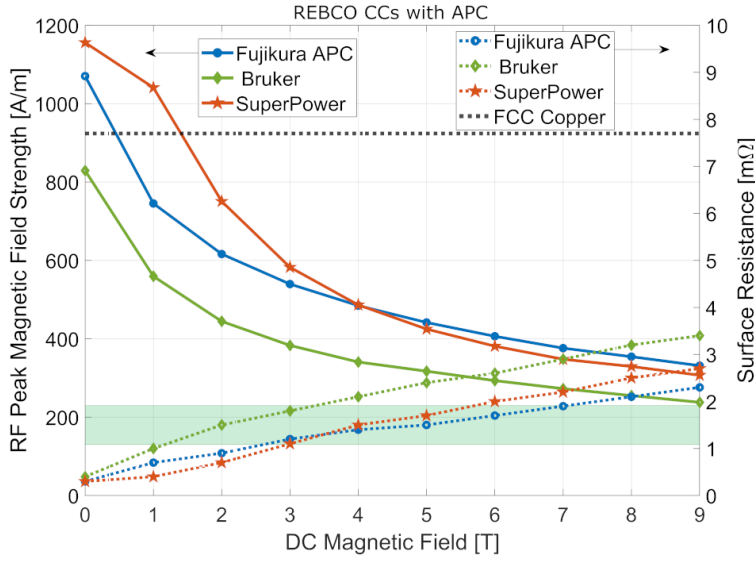
ReBCO-CC	$\frac{H_S(+13\text{dBm})}{H_S(-15\text{dBm})}$	$\frac{H_S(+13\text{dBm})}{H_{RF,FCC}}$
Bruker	25.2	1.8 - 1.0
Fujikura APC	24.9	2.5 - 1.4
SuperPower	25.1	2.4 - 1.3
Fujikura	25.7	1.7 - 0.9
SuNAM	25.8	0.8 - 0.5
SuperOx	25.0	1.2 - 0.7
Theva	18.5	1.1 - 0.6

the broader the resonant peak, which is indicated in the legend of Fig.10.8 by the 3 dB bandwidth value. The higher the bandwidth the lower the resulting quality factor due to a higher R_S , though, within a power level without deformation of the Lorentzian shape as previously visible in Fig.10.4. As shown in Fig.10.8, the VNA power also causes a shift of the resonance frequency caused by the dependence of surface reactance on RF field amplitude. Similar results have been obtained for the other samples used in this thesis.

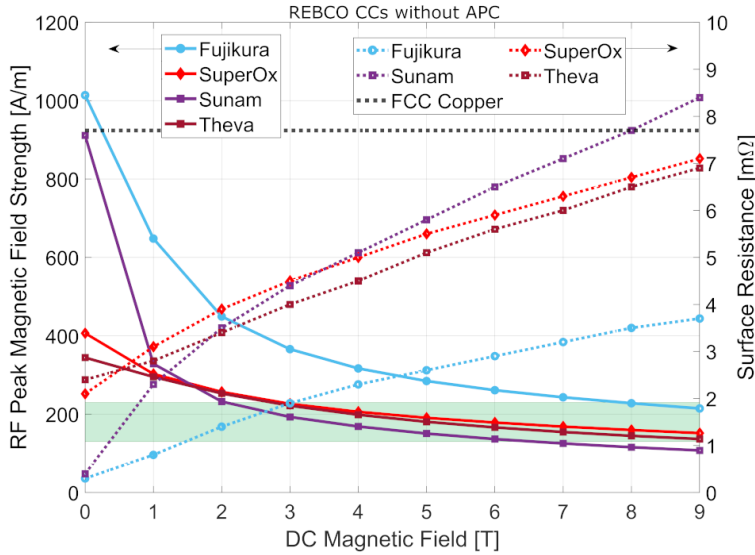
Figure 10.9 shows the RF peak surface magnetic field strength $H_0 = B_0/\mu_0$ and surface resistance R_S as a function of B_{DC} for $P_{in} = +13$ dBm. The green area marks the expected RF azimuthal magnetic field strength $H_{RF,FCC}$ at the surface of the FCC-hh beam screen following the calculations shown in Fig.10.3. The results shown in Fig.10.9(a) are for ReBCO-CCs that contain artificial pinning centres (APC), as indicated in Tab.2.1. The lower R_S in ReBCO-CCs with APC generates RF field strengths on the samples (H_0) larger than those in samples without APC, as presented in Fig.10.9(b). When compared to the RF field estimated for the FCC-hh ($H_{RF,FCC}$), all samples with APC are within or above the $H_{RF,FCC}$ estimation, and most of the samples without APC were within this estimate as well.

Table 10.1 lists the peak RF magnetic field strength applied on each sample compared to the RF azimuthal magnetic field in the FCC-hh and compared to the RF field in Ch.9. Note that peak RF fields in all samples are comparable or larger than the RF azimuthal field in the FCC-hh.

Due to experimental limitations, our measurements have been performed at higher frequencies (8 GHz) and lower DC magnetic field (9 T) than those specified for the FCC-hh (up to 1 GHz and 16 T, respectively). It shall be mentioned that in the present experiments, B_{DC} is always perpendicular to the ReBCO-CC surface -the worst case in terms of surface resistance [CC92]- while in the FCC-hh beam screen, coated



(a) H_0 vs B_{DC} and R_S vs B_{DC} for samples including APC at 8 GHz



(b) H_0 vs B_{DC} and R_S vs B_{DC} for pristine samples at 8 GHz

Figure 10.9: RF peak surface magnetic field H_S and surface resistance vs. DC magnetic field at 8 GHz and 50 K for ReBCO-CCs with and without artificial pinning centers for the maximum input power of +13 dBm we have studied. Solid lines show the RF surface peak magnetic field strength (left axes) on the samples while the dashed lines show their surface resistance (right axes). The green area indicates the azimuthal RF magnetic field strength $H_{RF,FCC}$, to be found in the FCC-hh beam screen as calculated in section 2. The horizontal arrows indicate the vertical axis to which each legend belongs.

conductors will have different orientations with respect to the magnetic field. In the paragraphs below, we extend the results to $f = 1$ GHz and $B_{DC} = 16$ T to match the worst-case FCC-hh conditions.

As shown in Fig.10.9, above $B_{DC} = 2$ T all samples show a nearly linear increase of R_S with the applied DC magnetic field, indicating that RF losses are proportional to the areal density of vortices, which is consistent with the theory discussed in Sec.2.2.3 and many theoretical calculations [CV17]. Accordingly, we have fitted our surface resistance versus DC field dependence with a linear dependence, including an independent term $R_S = mB_{DC} + n$. In this equation, the proportional term m takes into account the flux-flow contribution to the surface resistance [CV17], while the independent term n accounts for the field-independent residual surface resistance due to lattice defects, grain boundaries, or impurities, and to the BCS contribution described earlier in Eq.(10.1). Using this equation, we extrapolate the value of R_S at 16 T and 8 GHz. Figure 10.10 shows the fitting and extrapolation for Fujikura APC, which results in $R_S(B_{DC} = 16 \text{ T}; f = 8 \text{ GHz}) = 3.56 \text{ m}\Omega$, less than half that of FCC-hh copper at the same frequency.

Combining Eqs.(7.23) and (8.1), we can relate the changes in R_S to the changes in H_0 . This allows us to estimate the value of H_0 at 16 T:

$$H_0 = m_B \sqrt{\frac{P_{\text{diss}}(R_S)}{\frac{2R_S}{G} + p \tan(\delta)}} \quad (10.2)$$

In the equation above, we have made explicit the dependence of the power dissipated

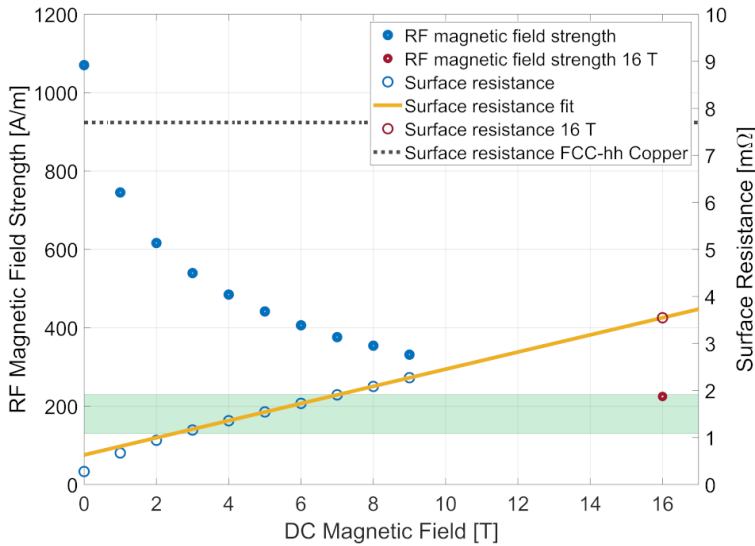


Figure 10.10: Applied DC magnetic field dependence of the surface resistance R_S at 8 GHz and peak RF magnetic field on the Fujikura APC sample (H_0). Circles show measured points at B_{DC} from 0 to 9 T. Red circles show extrapolated values for $B_{DC} = 16$ T. The yellow line shows a straight-line fitting following the flux-flow model in [CV17].

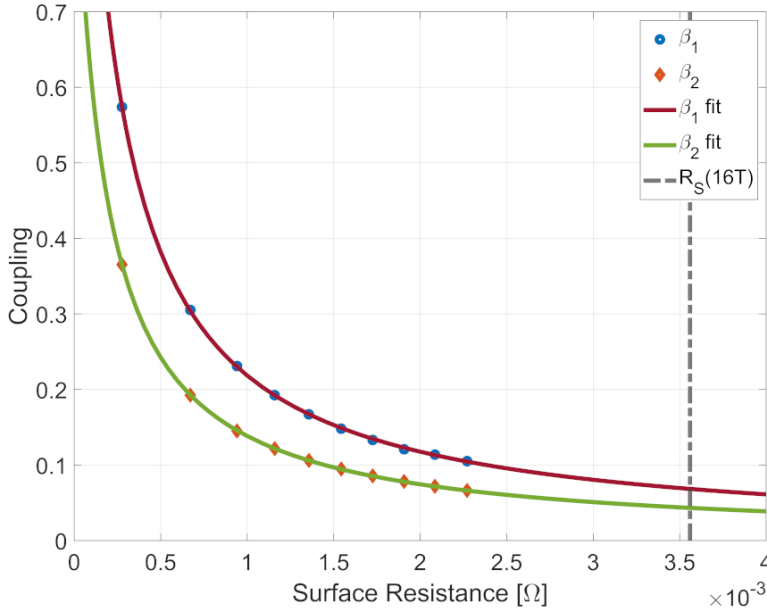


Figure 10.11: Coupling factors vs. surface resistance in the dielectric resonator with the Fujikura APC sample. Dots are values measured for B_{DC} from 0 to 9 T. Lines are the results of a fitting to $\beta = a/(R_S + b)$, where a and b are the fitting parameters. The vertical line represents the value of R_S for $B_{DC} = 16$ T.

in the resonator with surface resistance $P_{diss}(R_S)$ which, in turn, is due to a dependence of the resonator couplings β_i on R_S . As shown in Fig.10.11, coupling factors vary upon changes in R_S . This dependence can be fitted with a rational function:

$$\beta_i = a/(R_S + b), \quad (10.3)$$

where a and b are the fitting parameters [see appendix B.6.1]. Using this function, we can find the values of β_1 and β_2 corresponding to the foreseen value for R_S at $B_{DC} = 16$ T. Using Eqs.(7.27) and (10.2), and the extrapolated values of β_1 and β_2 , we can derive the prediction for H_0 at 16 T and 8 GHz as indicated already in Fig.10.10 (red dot). Table 10.2 summarises the results for all samples used in this study. Assuming a frequency square dependence as determined in Sec.9.2 of the surface resistance as given by the two-fluid model [Pro+00] an extrapolation to 1 GHz has been performed and is also shown in Tab.10.2.

Note that, unlike the surface resistance, the peak RF magnetic field strength cannot be extrapolated down to 1 GHz from the 8 GHz measurements. This is because the dependence of the coupling factors on R_S (Fig.10.11) is specific of our 8 GHz resonator. Still, the values foreseen for $R_S(16 \text{ T}, 1 \text{ GHz})$ are similar to those we reported previously [RKT20] under much weaker RF strength. Accordingly, our results show that under the working conditions of the FCC-hh, the impact of the H_{RF} power in the $R_S(H_{RF})$ is small and therefore, an RF loss significantly smaller than that attainable with copper is

Table 10.2: Extrapolated surface resistance for all providers at +13 dBm, and their corresponding maximum RF field amplitude. As reference, the values for FCC-hh BS Cu are $R_S(16 \text{ T}, 8 \text{ GHz}) = 7.8 \text{ m}\Omega$ and $R_S(16 \text{ T}, 1 \text{ GHz}) = 2.8 \text{ m}\Omega$. R_S values at 1 GHz are scaled-down from those at 8 GHz assuming a square dependence of the surface resistance on frequency. The values in brackets are given based on the analysis of the frequency dependency in Sec.9.2.

ReBCO-CC	H_0 [A/m]	$R_S(16 \text{ T}, 8 \text{ GHz})$ [m Ω]	$R_S(16 \text{ T}, 1 \text{ GHz})$ [$\mu\Omega$]
Bruker	162	5.3	84.9
Fujikura APC	228	3.7	59.3
SuperPower	207	4.4	70.5
Fujikura	156	4.9	78.5
SuNAM	79	13.0	208.3
SuperOx	109	10.0	160.2 (553.8)
Theva	91	10.3	165.0 (450.4)

expected with ReBCO-CCs even in the presence of the DC and RF fields foreseen in the FCC-hh beam screen.

10.5 Thermal RF Power Dependence

The thermal runaway discussed in this section has been developed and discussed by [VC19]. We are verifying experimentally with our measurements of surface resistance as a function of temperature at 9 T using the CHCDR the theoretical predictions given in [VC19].

In the FCC-hh, two counter-rotating proton beams will be circulating and inducing about $P_{\text{RF,Cu}} = 1 \text{ W/m}^2$ of power into the beam screen copper coating. ReBCO-CCs, due to their layered structure as shown in Fig.10.12(a), are considered to have a high transverse thermal resistivity R_T that can generate a non-negligible increase in the surface temperature due to the constantly passing by proton bunches. An increase in surface temperature due to the RF power increases the ReBCO-CC surface resistance that produces an increase in the dissipated power and then further increases the surface temperature, as visualised in Fig.10.12(b). Due to the transverse thermal resistivity of ReBCO coated conductors, this process can either lead to a surface equilibrium temperature or it can lead to the so called thermal runaway. A thermal runaway scenario would relate to an uncontrolled increase in the surface temperature of the coated conductor, by each particle bunch passing by, until superconductivity is suppressed due to a temperature increase above T_C .

ReBCO-CCs are considered as part of a multi-layered heat transfer system and therefore it is theoretically difficult to estimate the thermal resistance. Instead, a model has been developed by [VC19] where R_T is considered as a free parameter given in an equation relating the surface resistance of the coated conductor with the transverse

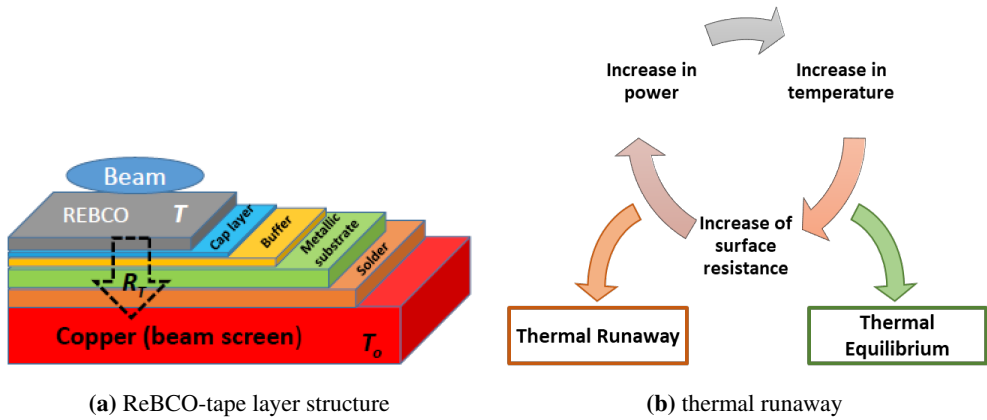


Figure 10.12: (a) ReBCO-tape complex layer structure shown on top of the copper beam screen layer taken from [VC19]. (b) Diagram of the thermal runaway problem.

thermal resistivity:

$$R_S(f, T) = \frac{T - T_{BS}}{R_T} \frac{R_{S,Cu}}{P_{RF,Cu}}, \quad (10.4)$$

where $T_{BS} = 50$ K is the steady beam screen temperature, T is the temperature on the ReBCO coating, $R_{S,Cu}$ the surface resistance of copper given by the direct measure-

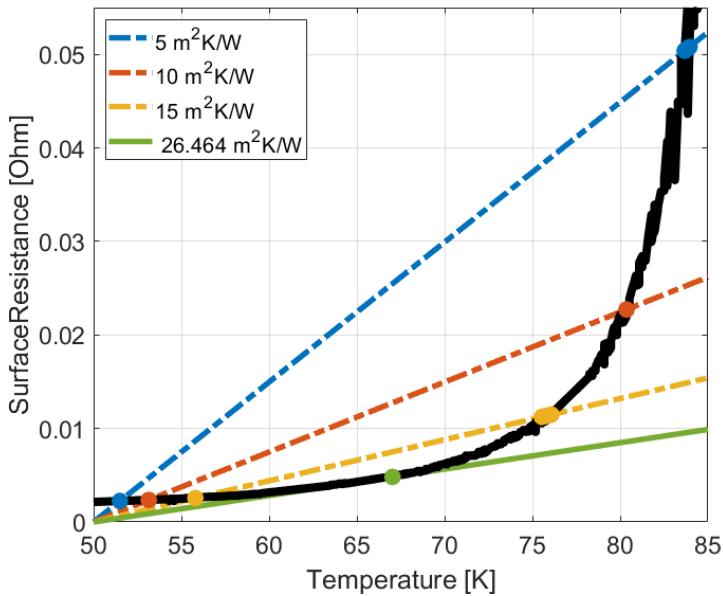


Figure 10.13: Temperature dependence of the surface resistance at $f = 7.9$ GHz and $B_{DC} = 9$ T represented as black curve. Dashed lines result from Eq.10.4 by varying the values of the transverse thermal resistance.

Table 10.3: Summary of the resulting thermal resistances and ergo highest equilibrium temperature determined according to the thermal runaway problem.

Coated conductor	Thermal resistance [Km ² /W]	Equilibrium temperature [K]
Bruker	15.0	64.7
Fujikura	16.7	66.2
Fujikura APC	26.5	67.3
SuNAM	8.0	70.0
SuperPower	16.1	65.1
SuperOx	8.4	66.4
Theva	11.8	62.3

ments at 9 T, 8 GHz, and 50 K. The equation is based on the general proportionality of temperature and dissipated power $T = T_{BS} + R_T P_{RF}$. Note that the ReBCO-CC in Eq.(10.4) shall not be seen as dependent on the surface resistance of Cu, rather that the ratio of $R_{S,Cu}/P_{RF,Cu} = R_{S,ReBCO}/P_{RF,ReBCO}$ is defined as constant for copper as the power dissipated by the ReBCO film is not constant.

An upper limit to the thermal resistance can be obtained graphically in the following way [VC19]: Equation (10.4) indicates a linear relation between R_S and T whose slope is determined by the value of the thermal resistance R_T . Consequently, we can plot R_S versus T for different R_T and the measured surface resistance as a function of temperature, the point of tangency indicates the upper limit for the thermal resistance. Below that value of R_T there will be no thermal runaway. This procedure is shown in Fig.10.13 for Fujikura APC. The black curve shows experimentally measured surface resistance versus temperature, while the dashed lines show Eq.(10.4) for different values of the transverse thermal resistivity. The point of tangency is found at $R_T = 26.5 \text{ Km}^2/\text{W}$ at a equilibrium temperature between 65 - 70 K. For transverse thermal resistivity numbers above this value there will be no thermal equilibrium on the ReBCO. In the case of an $R_T = 15 \text{ Km}^2/\text{W}$ the coated conductor would heat up from 50 K to 56 K and stay in equilibrium. It is shown that depending on the provider summarised in Tab.10.3, the critical R_T value varies between 8 to 27 Km^2/W . All samples show a relatively high critical thermal runaway resistance value, which most

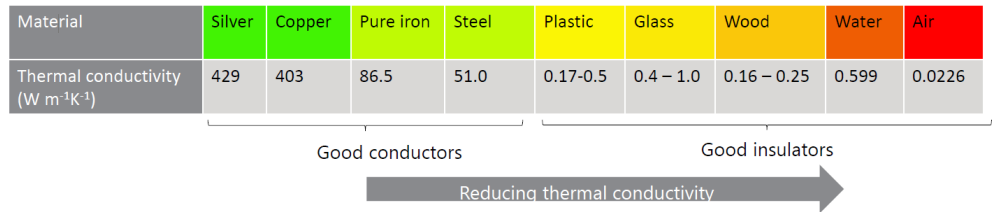


Figure 10.14: Thermal conductivity of various materials taken from [Cou21].

probably is significantly above the real value for coated conductors. If we assume an average thickness of around $50\text{ }\mu\text{m}$ for a ReBCO-CC without the copper and silver layers, then the thermal conductivity range would be between 6.25 to $1.85\text{ }\mu\text{W/Km}$, respectively. Figure 10.14 shows the thermal conductivity of different materials at room temperature to compare these values. It can be seen, that these values are above the range of good insulators and with that most certainly much lower than the real thermal conductivity of the ReBCO-CCs. The higher the equilibrium thermal resistance value is, the better for the application.

10.6 Transient Thermal Effects

The previous discussion refers to the worst case scenario of an uncontrolled heating of the ReBCO-CCs due to the RF fields produced by the circulating bunches. We have seen that the thermal runaway is not a concern for FCC-hh. Nevertheless, we have seen in Secs. 10.3 and 10.4 that a higher VNA output power leads to a higher surface resistance, and higher heat dissipated in the sample. Measurements of the surface resistance for different VNA output powers as a function of VNA sweep time at a stable temperature of 50 K is a possibility to study possible transient thermal effects, as discussed in [Pro+00; Rab70]. Thus, measurements were performed as a function of the VNA sweep time t_{sweep} to study possible transient thermal effects at $B_{\text{DC}} = 1\text{ T}$ and $B_{\text{DC}} = 9\text{ T}$ for three different output power P_{out} (-15 dBm , 0 dBm , and $+13\text{ dBm}$). The sweep time is defined as the time the VNA needs to acquire one measurement, i.e. sends and receives the signal at each frequency point in a certain frequency span and can be varied by either changing the number of points and/or the IFBW. The sweep time has been changed by varying only the IFBW without changing the amount of sweep points.

Results for SuperPower are presented in Fig. 10.15. As can be seen, the surface resistance asymptotically tends to a constant value for short VNA sweep times. Hence, for fast sweep times there is strong dependence of the surface resistance on the applied DC magnetic field and a minor one on the applied power. VNA power only has a measurable effect for long sweep times. Nevertheless, the onset of sweep time at which the R_s starts increasing and the amplitude of the change depends on the applied DC magnetic field: at 1 T , the sweep time onset is lower than at 9 T , and R_s has a steeper increase at 1 T than at 9 T .

Figure 10.15 provides indirect information on the thermal time constants in our set-up. At frequencies close to resonance, RF fields seem to heat the samples under measurement. Heat generation is strongest at resonance -at the mid-point of the frequency span- and decays as the VNA frequency departs from resonance. The asymptotic behaviour in Fig. 10.15 can be explained in terms of VNA sweep time versus thermal time constant: when the VNA sweep time is much shorter than the thermal time constant, no heat can build up in the samples under measurement. Conversely, when R_s depends on sweep time, we can infer heating effects with time constants comparable to VNA sweep time.

The discussion above can be translated to the FCC-hh by considering that there

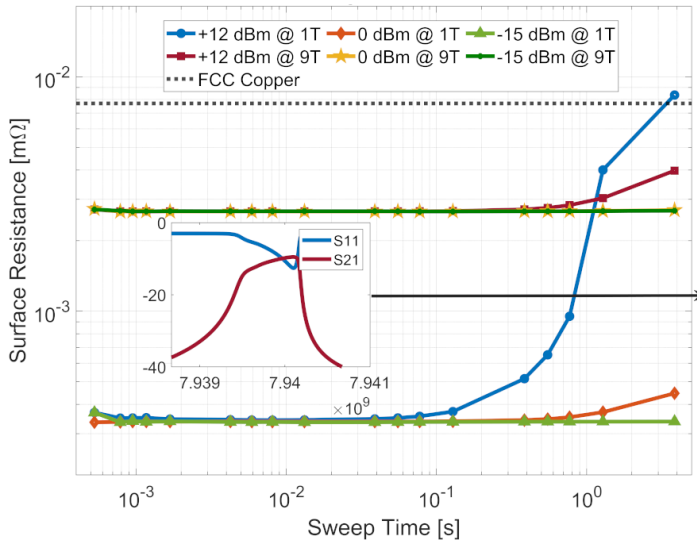


Figure 10.15: The surface resistance for three different VNA output power at two different applied DC magnetic fields as a function of the sweep time. The only parameter chosen to control the sweep time is the IF bandwidth. The inset figure shows two S-parameters, one reflection and one transmission coefficient, as a function of frequency at resonance. The disturbed resonance curve results for very slow measurements with a sweep time of 15 s. Data is shown for Superpower.

will be 10400 circulating bunches in the FCC-hh, each carrying 10^{11} protons with a revolution time of ≈ 0.3 ms. The bunches, separated by 25 ns are assumed to be Gaussian and have an RMS length ($\sigma_t = \sigma/c$) of 270 ps [Ben+19b]. These times are much shorter than the threshold sweep times that affect R_S in Fig.10.15 and suggest that there should not be any transient thermal effects due to the timing structure of the proton beams provided that, as in our set-up, the thermal relaxation time constants in the FCC-hh beam screen are much longer than the length of the proton bunches and the separation between bunches. This is in accordance with the predictions in [VC19] and the results in Sec.10.5 which as well confirm that in the FCC-hh no thermal issues due to the complex layer of the ReBCO-CCs shall develop.

10.7 Flux Shaking

Vortex motion including displacement normally is referred to as vortex shaking effect [BM02] and explains the generation of a DC electric field due to vortex displacement, which tends to homogenise the overall distribution of the magnetic induction in the critical state [see Sec.2.2.3]. A similar situation occurs in the ReBCO-CCs in the FCC-hh beam screen where the vortices will be subjected to a DC magnetic field perpendicular to the RF image currents induced by the beam, as shown in Fig.10.1. This scenario can give rise to a vortex oscillating motion [CV21] which might include

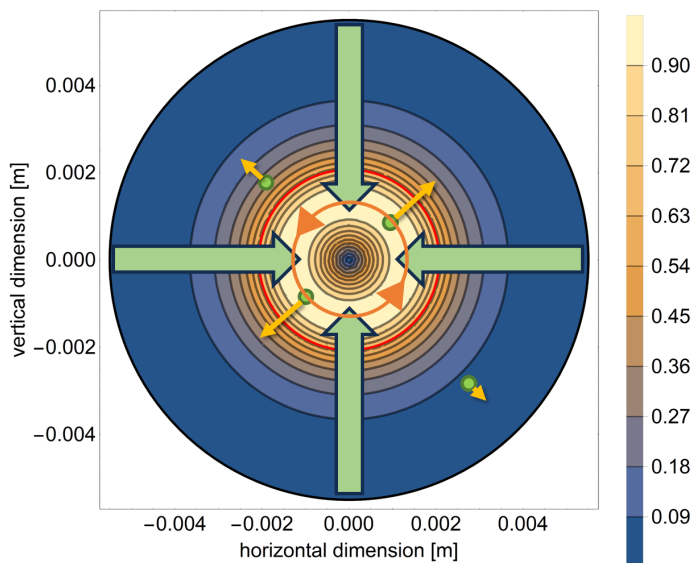


Figure 10.16: RF surface magnetic field strength distribution H_r on a sample ($12 \times 12 \text{ mm}^2$) inside the DR structure. The field strength is normalised to the maximum value. The red line indicates the border of the rutile crystal. The green arrows show the radial $H_r(r; L)$ distribution, the orange triangles are the resulting azimuthal surface currents at maximum position, the green circles represent vortices at different positions and the overall position-dependent force on them (yellow arrows).

as well a net displacement. As a result, it is essential for the FCC-hh to determine whether the induced RF azimuthal magnetic field strength will be sufficient to fluctuate and/or displace the trapped vortices away from their static position.

These effects can be examined with our closed Hakki-Coleman dielectric resonator, where vortices are trapped after applying a magnetic field ramp aligned in the axial direction, and they are subject to a single-sided and position-dependent RF-induced radial force following the spatial distribution of H_r in Fig. 10.16 [see details in Sec. 7.3.6]. If the RF surface magnetic field strengths are sufficiently strong, the net vortex displacement will move vortices across the sample towards the resonator's axis or the outer rim. In both cases, RF fields are minimal in these areas, so the net displacement of vortices should decrease the radio-frequency losses and should result in an increase in quality factor. Therefore, to confirm if the RF magnetic field strength used in this study is sufficient to move vortices after the samples have been magnetised, the following measurement was performed for each provider: First, the REBCO-CC's quality factor was measured at 50 K in a zero-field cooled configuration as a function of the VNA output power. Then, the magnetic field is ramped up to 9 T and back to 0 T, leaving the REBCO-CC in a remnant critical state configuration and finally, the quality factor was re-measured as a function of the VNA output power waiting for 10 seconds per 1 dB. The VNA output power was ramped up and down. The VNA was set with 401 frequency points and an IFBW of 10 kHz leading to a sweep time of $t_{\text{sweep}} = 3.9 \text{ ms}$.

The frequency sweep was set to be centred at the resonance frequency with a span factor ten times the 3 dB bandwidth [see Sec.6.5].

Figure 10.17 shows the quality factor for two samples (one from Bruker containing APS and a pristine sample from SuNAM) in the remnant critical state relative to their zero-field cooled one. Similar results were obtained for the other samples. The results in Fig 10.17 show the normalised loaded quality factor as a function of the VNA output power. The coloured arrows explain the ramping direction, e.g., green arrow means that the VNA power was ramped from low to high P_{out} .

From the data we can see that the REBCO-CCs remain in the same critical state after a 9 T ramp, i.e., the quality factor does not recover after ramping the VNA output power. A flux shaking mechanism could therefore not be observed on the measurements presented. Only a minor raise -within the sensitivity of the experimental set-up- in the Q-factor is observed for all pristine samples after ramping up and down the RF power, which could indicate a partial vortex displacement of individually weakly pinned vortices but not a complete demagnetisation. That no demagnetisation was observed is in accordance with [BM02] which states that a net vortex displacement requires RF magnetic field amplitudes $H_0 > 0.5J_C$, where J_C is the critical current per cm-width. If this condition is fulfilled, then the magnetisation decreases exponentially. In [Pui+19] the measured critical current per cm-width on an equivalent REBCO tape is $J_C \approx 110000$ A/m, which is two orders of magnitude larger than the $H_0 \approx 1200$ A/m induced on the samples at the maximum VNA output power. This suggests that the

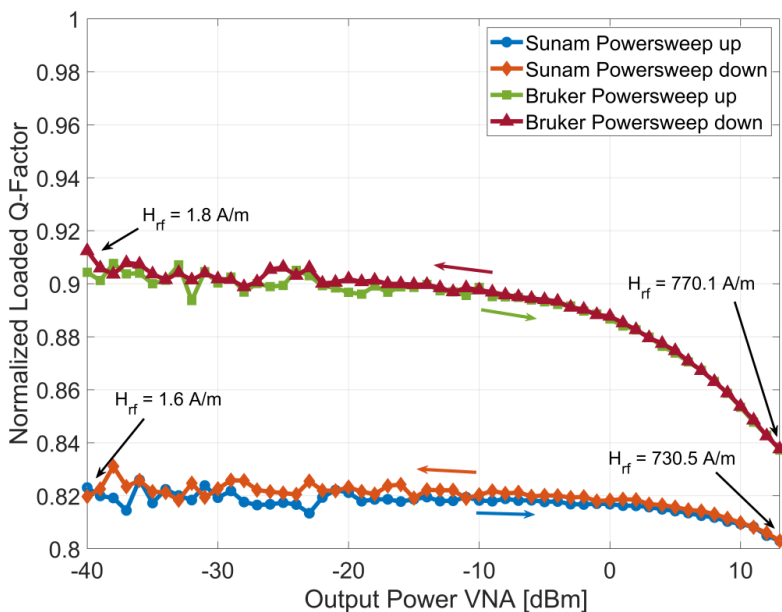
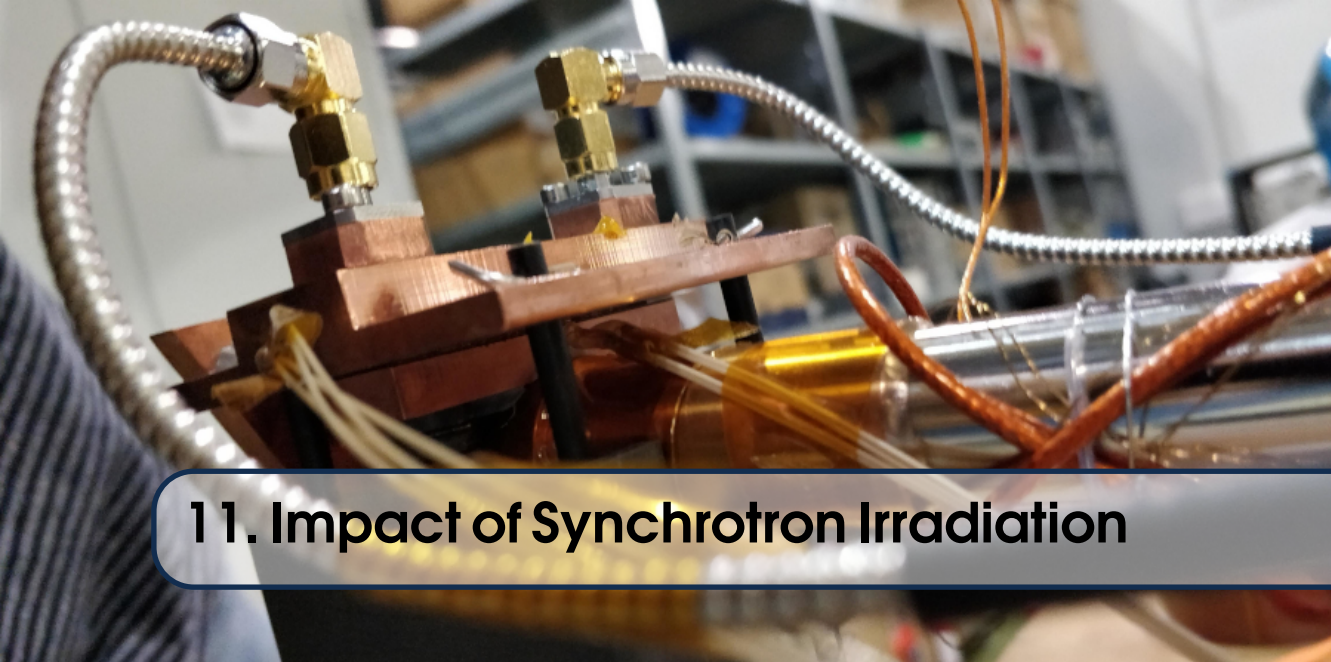


Figure 10.17: Measured normalised loaded quality factor as a function of the VNA output power for two REBCO-CCs with (Bruker) and without APC (SuNAM). The quality factors are normalised to the 0 T values before the magnetic ramp.

vortices fluctuate around their trapped position but have no net displacement, including no influence onto the behaviour of the ReBCO-CC, and there is no net increase in quality factor detectable with the dielectric resonator.



11. Impact of Synchrotron Irradiation

La única diferencia entre un loco y yo, es que el loco cree que no lo está, mientras yo sé que lo estoy.

Salvador Dalí

Synchrotron radiation is one of the major challenges for the FCC-hh or any other future circular collider. Sufficient understanding of the behaviour of the ReBCO-CCs under the influence of synchrotron radiation is fundamental to achieving a sound decision. This chapter aims to illuminate this uncharted field of study by experimentally evaluating the behaviour of ReBCO-CCs being irradiated ex-situ and in-situ with photons provided by the ALBA Synchrotron Light Source.

11.1 Synchrotron Radiation in the FCC-hh Beam Screen

The beam screen of the FCC-hh will have to cope with unprecedented levels of synchrotron radiation, while simultaneously dealing with a tighter magnet aperture. This has significant implications for the vacuum system design which have been discussed in detail in Ch.5. Figure 11.1(a) shows the SR power density deposited on the FCC-hh beam screen at the nominal operational parameters. The particle beam trajectory is depicted in the same figure by the yellow curved line in the centre, which is due to the 16 T dipole magnetic field (not depicted in the figure). We know from Ch.4 when charged particles travel in curved paths due to a bending magnet they emit photons in the forward direction, tangential to the particle beam trajectory as

represented by the green lines in Fig.11.1(a). A portion of the SR reaches directly or indirectly (scattering) the inner chamber, where coated conductors are considered to be positioned. It can be seen on the left ante-chamber, that the region exposed on the same height as the particle beam is directly irradiated and receives the highest SR power density. A peak linear power density of 40 W/m has been calculated at this particular region. Furthermore, as discussed in Sec.4.4, the Gaussian-like power distribution can also be observed.

The impact of the deposited SR power density can be seen in Fig.11.1(b). It shows the beam screen temperature when the cooling channels are kept at 40 K. The SR leads to a heat up of the main impact region up to 58 K. That a significantly smaller flux per area is reaching the inner chamber; hence, a smaller power per area, is visible in the smaller temperature increase. However a total power of 0.6 W in the primary chamber is expected [Bel20].

[Bel20] claims that with the current beam screen design of the FCC-hh the photon flux expected on the ReBCO-CCs is very low. Nevertheless, in this chapter we aim to assess the behaviour of ReBCO-CCs under the influence of synchrotron radiation in different scenarios to get a sense of how the coated conductors would perform in the particle accelerator. To our knowledge, no study addressed the SR effects on surface resistance of ReBCO.

We investigated possible long-term irradiation damages on ReBCO-CCs from different providers by high-energy photons. Furthermore, we measured in-situ the photon impact on the transition temperature of ReBCO-CCs. Finally, we explored in-situ the effect of photons on the surface resistance.

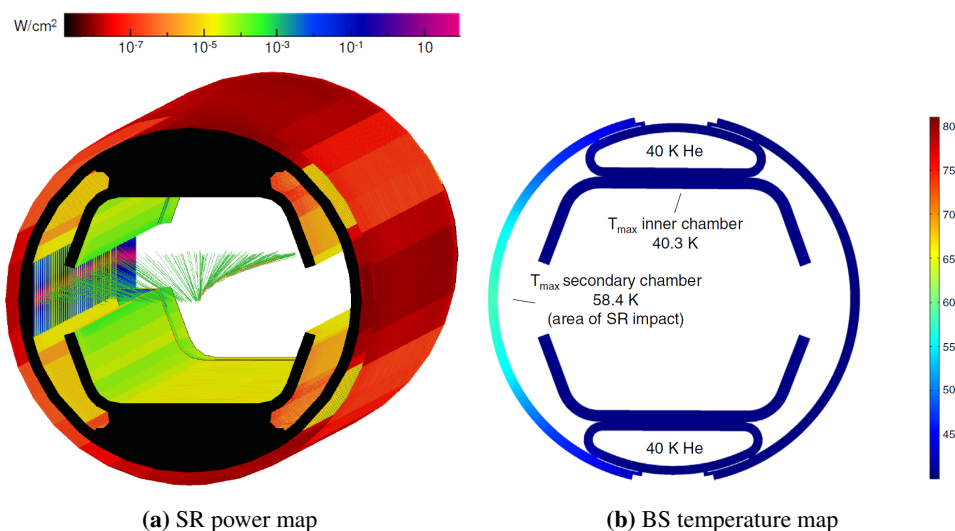


Figure 11.1: Synchrotron radiation in the FCC-hh emitted by the 16 T bending magnet at nominal parameters (a) Deposited power density in the FCC-hh BS. (b) Resulting beam screen temperature due to the SR. Both figures are taken from [Bel20].

11.2 Long-Term Irradiation

To determine whether ReBCO-CCs are permanently damaged after the long-term exposure to high-energy synchrotron light, we performed an experiment in which sample-pairs of five different ReBCO-CC providers (12 x 12 mm) were mounted behind the ALBA crotch absorbers, as detailed in Sec.8.4.2. The ReBCO-CCs were left during normal operation of the Light Source, once at 150 mA (Experiment 1) and once at 250 mA (Experiment 2) beam current for four weeks, equivalently about 552 h of irradiation. In addition, in order to compare if the impact of possible degradation is due to SR or being exposed to air, we stored control samples for the same amount of time in the storage ring tunnel without being irradiated. For each individual experiment new samples were prepared.

The ReBCO-CCs were exposed to the synchrotron radiation which has to traverse 35 mm of the copper absorber and 2 mm of steel anti-chamber wall, as sketched in Fig.11.2. This results in a photon flux of high energy $U_\gamma > 100$ keV but low intensity compared to FCC-hh as depicted in Fig. 8.11. The ReBCO-CCs were placed in such a manner, that the photons collide in the full width in the center. Due to differences in the thickness of the different coated conductors, the total flux, energy and power absorbed differs from samples to sample and is summarised in Tab.11.1. We assume here a density of about $\rho_{density} = 6.3$ g/cm³ [Dev] for all ReBCO films and exclude buffer layers and stabilisers.

A comparison of the surface resistance measured before and after irradiation is the physical quantity experimentally accessible to determine a probable degradation of the ReBCO-CC. Figure 11.3(a) shows the current density distribution as determined in Sec.7.3.6 overlapped with the synchrotron radiation impact region (light green line). If degradation has taken place, the surface currents would flow over a higher resistive region leading to a decreased Q-factor measured with the CHCDR.

Figure 11.3(b) shows the measured absolute changes in surface resistance $|\Delta R_S|$ of each sample pair of different manufacturers before and after being irradiated. Each data point is based on the individual sample pair and is not compared to another pair of samples of the same provider. In addition, we included the 5% deviation line indicating the precision we can measure with the CHCDR as explained in Sec.9.6. In the first

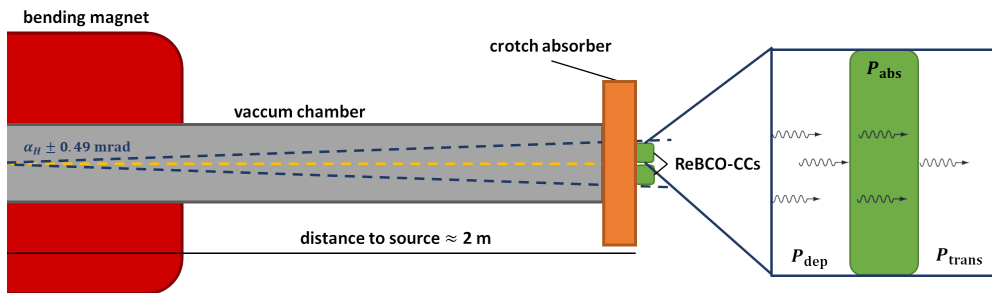
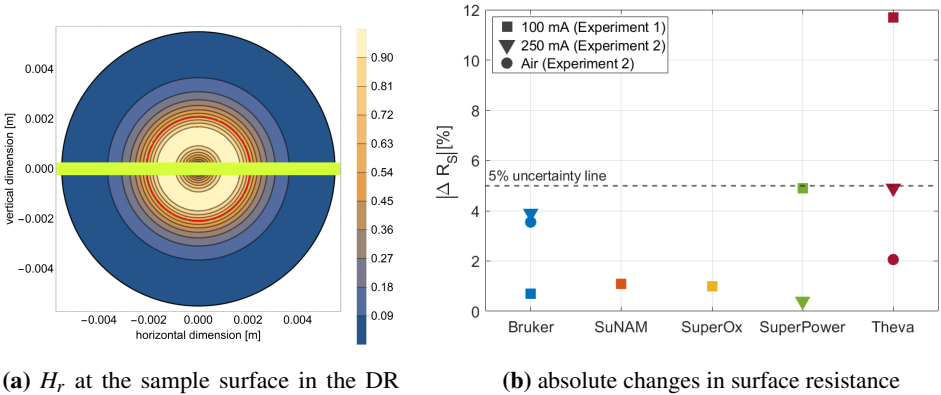


Figure 11.2: Sketch of the experimental set-up for the long term irradiation of ReBCO coated conductors.

Table 11.1: Radiation key parameters of the ALBA Synchrotron crotch absorbers experiment. The incoming flux at the samples surface after the absorbers is for all samples the same and equals $F_{\text{dep}} = 5.28 \cdot 10^7$ ph/sec/mradH at a beam current of $I_{\text{beam}} = 150$ mA. The total irradiation time was 552h which leads to a total amount of $F_{\text{dep}} = 6.30 \cdot 10^{14}$ photons. This translates into an arriving power of $P = 50.82$ nW. The parameters at a beam current of $I_{\text{beam}} = 250$ mA can be determined by multiplying all given values by a factor of 1.7.

	Bruker	SuNAM	SuperOx	SuperPower	Theva
$F_{\text{abs}} \cdot 10^{11} [\text{ph}]$	3.06	3.06	1.72	2.87	5.73
$P_{\text{abs}} [\text{nW}]$	247	247	139	231	461
$U_{\text{abs}} [\mu\text{J}]$	49.08	49.08	27.62	45.90	91.61
Dose [Gy]	393.27	393.27	393.45	392.31	391.50



(a) H_r at the sample surface in the DR structure

(b) absolute changes in surface resistance

Figure 11.3: (a) Surface current density distribution on the surface of the samples inside the dielectric resonator. The green line indicates the spatial position of synchrotron irradiation. (b) Absolute changes in surface resistance at 77 K, after irradiation.

experiment the accelerator was operating with 150 mA beam current (squares). No significant changes in R_s outside the range of measurement sensitivity and accuracy could be measured besides in Theva. Further trials should asses the impact of synchrotron radiation in a second experiment at higher beam current of 250 mA (triangles) to confirm the previous data. Again, no significant changes in the surface resistance have been detected, not even in Theva’s samples this time, contradicting the previous result. We would expect a higher change in the surface resistance with increased beam current rather than reduced. The control samples of Bruker and Theva without being irradiated (circles) are as well within the uncertainty.

Taken together, the findings suggest that there is no damage on superconductors and SR for the specific amount of time irradiated. Except for one data point, no changes within the uncertainty of the measurements have been detected. A possible explanation for the deviation is a possible degradation due to mechanically scratching the surface of

the CC during mounting and/or dismounting on the crotch absorbers. Sliding a ReBCO layer over another material has been proven to damage the CC [Tela]. In addition, being exposed to air in the tunnel (low humidity) for four weeks does not impact the coated conductor either.

11.3 Critical Temperature

In-situ experiments, were first conducted with the experimental set-up discussed in Sec.8.4 to measure the critical temperature T_C , and with that, investigate the influence of high-energy photons on ReBCO's superconducting state and properties. To measure T_C , we monitored the resistance as a function of temperature in a four-wire-configuration. The temperature was stabilised around 85 K close to the expected critical temperature given in Tab.2.1. A slow temperature ramp of 0.5 K per minute was set to increase the temperature and data points were taken approximately every 10 seconds. A new sample was always prepared for each of the experiments conducted. Experiments were performed with SuperPower containing APC or SuperOx pristine samples. Two temperature sensors have been used for this experiment as sketched in Fig.11.4(a). The first temperature sensor is the reference temperature sensor from the set-up system (Temperature Cryofinger) which is installed inside the Cryofinger tube and is located outside the radiation region. The second temperature sensor (Temperature Cernox) installed next to the sample, monitors its temperature during irradiation. How the sample is mounted on the Cryofinger is visible in Fig.11.4(b).

Figure 11.5 shows how we determine the transition width ΔT_C between normal- and superconducting state based on the Cernox T -sensor. It is defined by the temperature range in which the measurement signal drops from 90% to 10% of the step height. The critical temperature T_C is then determined by the position of 50% of the transition width.

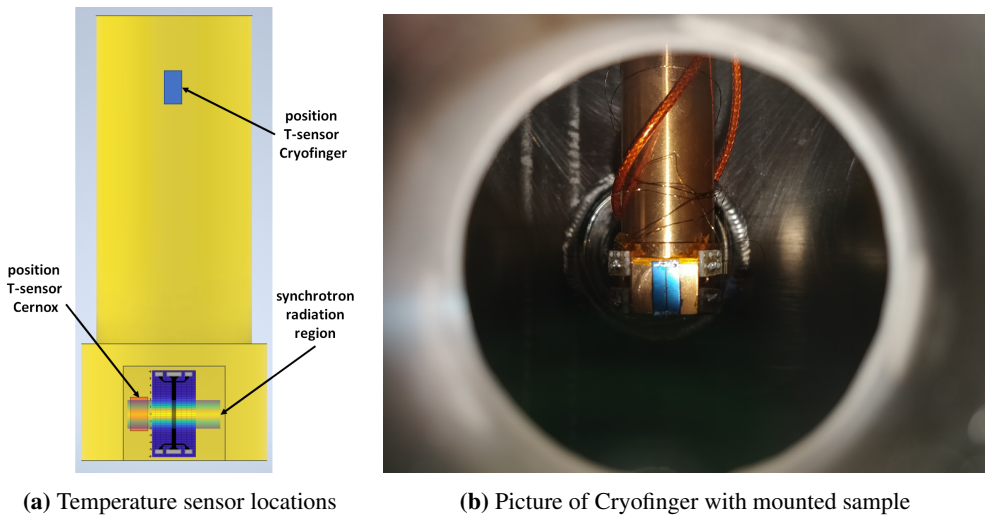


Figure 11.4: Sketch and picture of the Cryofinger's sample holder with mounted sample for T_C -measurements under synchrotron radiation.

In this particular example for SuperPower the critical temperature value measured is around $T_C \approx 90$ K, which is close to the typical value of $T_C = 91$ K given in Tab.2.1 with a $\Delta T_C = 0.75$ K. Such transition width value lies within the expected value < 5 K for good quality high-temperature superconductors [RM15].

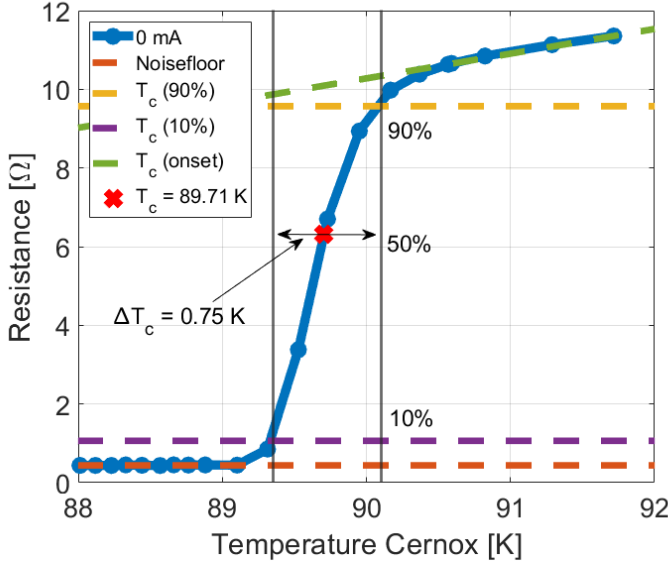


Figure 11.5: Example plot for the determination of T_C with SuperPower.

Prior to commencing the study, we tested the accuracy of the set-up by repeating measurements of T_C of the same sample without irradiation. Figure 11.6(a) shows four measurements of the same sample by repeating the same temperature cycle (sequence). In Fig.11.6(b) we compare the same data as in Fig.11.6(a) though plotted as a function of the temperature normalised to the T_C estimated for the first cycle Seq.1. From this figure the mean uncertainty in the critical temperature between measurements can be obtained as $\Delta T = \pm 0.0002 \cdot T_C \approx \pm 20$ mK which is higher than the accuracy of the Cernox temperature sensor $\approx \pm 5$ mK.

Two different measurements including SR were performed:

1. samples were irradiated with a fixed flux resulting from an injected beam current of either beam current $I_{\text{beam}} = 100$ mA or $I_{\text{beam}} = 200$ mA and the temperature of the sample was increased until the critical temperature was reached. Measurements of T_C without irradiation ($I_{\text{beam}} = 0$ mA) were taken before any irradiation and after irradiation to be used as reference.
2. samples were kept at a fixed temperature and the photon flux on the sample was increased by ramping the beam current from $I_{\text{beam}} = 0$ mA to 100 mA or $I_{\text{beam}} = 0$ mA to 200 mA.

Note that in this experiment, the source, the distance, and geometry of the samples are different compared to the long-term experiment discussed in the previous Sec.11.2. In this experiment, the photon energy spectrum begins at $U_\gamma > 10$ keV and the photon

Table 11.2: Radiation key parameters of the ALBA Synchrotron T_C measurement experiment. The incoming flux at the samples surface after the absorbers is for all samples the same and equals $F_{\text{dep}} = 5.61 \cdot 10^{15}$ ph/sec/mradH at a beam current of $I_{\text{beam}} = 100$ mA. The irradiation time per experiment is in average about 2 h and results in a total amount of photons of $F_{\text{dep,total}} = 3.92 \cdot 10^{18}$ and a accumulated power of $P = 87$ mW impinging on the ReBCO surface. Assumed density for ReBCO is $\rho_{\text{density}} = 6.3$ g/cm³. The parameters at a beam current of $I_{\text{beam}} = 200$ mA can be determined by multiplying all given values by a factor of 2.

	SuperOx	SuperPower
$F_{\text{abs}} \cdot 10^{16}[\text{ph}]$	5.84	9.74
$P_{\text{abs}} [\text{mW}]$	1.31	2.18
$U_{\text{abs}} [\text{J}]$	9.43	15.72
Dose [MGy]	290.21	483.69

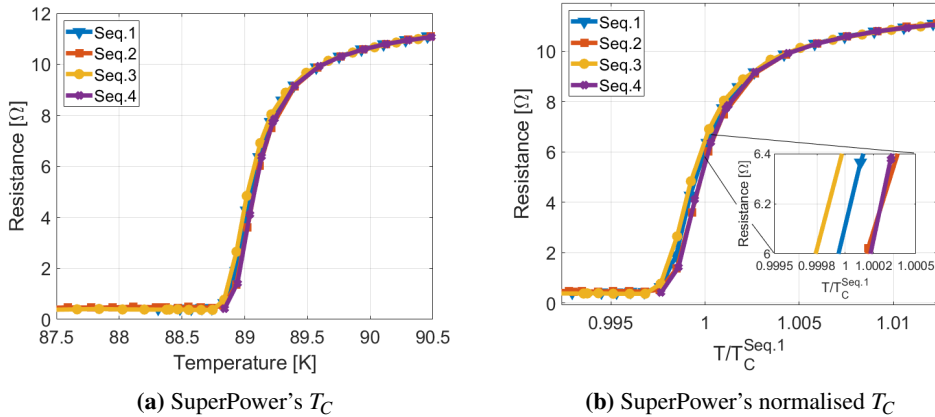


Figure 11.6: Four thermal cycling critical temperature measurements for SuperPower without synchrotron radiation.

flux is higher. The irradiation time per experiment is in average about 2 h and results in a accumulated power of $P = 87$ mW impinging on the ReBCO surface, which is a factor of a million higher in power than in the experiment in Sec.11.2. Table 11.2 summarises the estimated flux, power and energy deposited on the sample.

Figure 11.7 presents the results of an experiment with a SuperOx sample. It shows the resistance as a function of temperature given for both T -sensors. The dashed lines show the measured resistance plotting as a function of the Cryofinger sensor temperature, while the bold lines present the data versus the Cernox sensor temperature. In the first sequence (Seq.1) both T -sensors show consistent results with a negligible difference in temperature. Sequence 3 shows the results of the measurement after irradiation which coincides again with the results before irradiation. A permanent damage on the superconductor, e.g., due to a change in the stoichiometry of oxygen

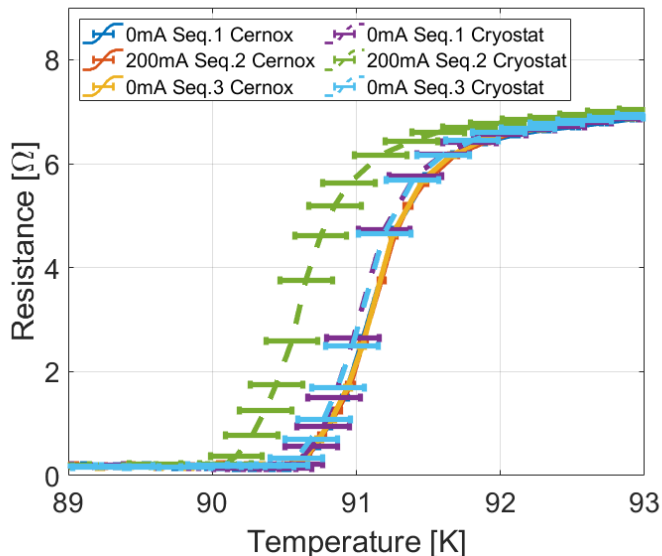


Figure 11.7: Comparison of T_C results in measured temperatures between the two T -sensor including SR.

would be detectable in a non-reversible shift in T_C which is not the case²³. The main difference between the results with reference to one sensor or the other is in Seq.2 during SR irradiation. It can be seen that during irradiation, T_C appears at a lower temperature with reference to the Cryofinger sensor, which would indicate a property change of the ReBCO. However, these data must be interpreted with caution, because the temperature of the sample might be higher than measured by the Cryofinger temperature sensor as it is out of reach of the SR. Looking at the same data as a function of the Cernox temperature sensor (bold lines), the results of the three sequences overlap without any shift in T_C . This proves, that the sample indeed has a higher temperature than what is measured by the Cryofinger T -sensor.

The findings of Fig.11.7 suggest that there is no damage on the sample during the irradiation and that the effect of a shift in T_C seen, is based on the positioning of the Cryofinger T -sensor out of the synchrotron radiation fan. In addition, what happens is that the Cryofinger has not enough cooling power to counteract the increase of temperature due to the SR absorbed by the sample holder. Another possibility, rather than a permanent damage of the sample, is that the superconducting state is suppressed during irradiation due to CP breaking by high energy photons [see BCS-Theory in Sec.2.1.4 and CP breaking in Sec.4.5]. In this case, we could expect a broadening of the critical temperature compared to the measurements without irradiation²⁴

²³Superconductivity in YBCO depends strongly on the stoichiometry and thus as well the critical temperature [BK13]

²⁴Considering the 2F-Model discussed in Sec.2.1.3, the lowest amount of Cooper pairs should be available close to the critical temperature.

Figure 11.8 presents the measured resistances as a function of the normalised temperature T/T_C for SuperPower in Fig.11.8(a) and for SuperOx in Fig.11.8(b). In both figures, each sequence has been normalised based on the T_C of each sequence individually estimated. The inset in both figures shows an enhanced view of the measured resistance as a function of the monitored Cernox temperature including the expected error ranges. The results for both ReBCO-CC providers indicated neither a change in the transition width, nor any significant change in the critical temperature. Additionally, as can be seen in both insets the different curves overlap within the expected thermal cycling uncertainty.

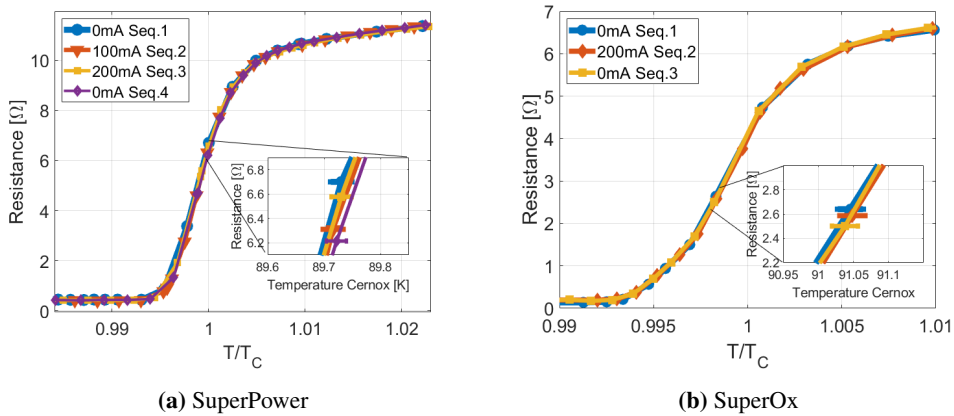


Figure 11.8: Measurement results of the influence of synchrotron irradiation on the critical temperature for SuperPower and SuperOx.

In the case that in the central part of the sample, where the irradiation has its maximum, superconductivity should be suppressed and a higher resistance would be measured. Therefore, we measured the resistance as a function of beam current injected in the accelerator while keeping the Cryofinger at a constant temperature. The results are given in Fig.11.9 for two different temperatures for SuperPower. In Fig.11.9(a) the Cryofinger temperature is stabilised at $T = 89$ K close to the 10% position of the transition to the normal conducting state as shown in Fig.11.5. The resistance is monitored as a function of the injected beam current, i.e., photon flux per second. It can be seen, that the resistance follows the beam current in the storage ring. Injection was stopped at $I_{\text{beam}} = 100$ mA and the beam current kept constant at that value. The resistance, which has increased by 30% also stabilised. This change observed in the resistance is consistent with a temperature increase of the order of 0.4 K as observed in Fig.11.5 and also consistent with the results presented in Fig.11.7. A drop back to the initial resistance value can be seen, when the samples are shielded from the radiation. The second measurement in Fig.11.9(b) shows the resistance stabilised at the FCC-hh beam screen temperature of $T_{\text{BS}} = 50$ K compared to the beam current. Again the resistance follows the beam current in the storage ring. However, the change in resistance as compared to the measurement at 89 K is much smaller, which is in agreement with the fact that we are well below transition in a region where resistance

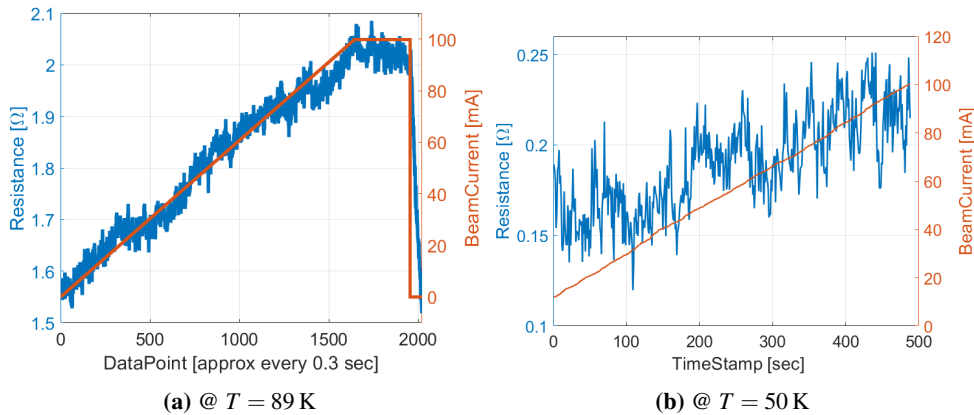


Figure 11.9: Resistance versus beam current for SuperPower.

is almost constant.

Taken together, these results suggest that the effect of synchrotron radiation, as used in this experiment, on the superconductivity is rather of thermal nature. It shall be stated that the result does not exclude entirely that Cooper pairs are broken, only that thermal effects seem to prevail in these measurements. However, since no fundamental theory can either describe the mechanisms behind HTS cooper pairing or the pairing partners involved [see Sec.2.1.5], we cannot give absolute numbers of CP breaking in this experiment. Whereas, what we can state is that taking the data from Tab.11.2 we can estimate that the total flux arriving from the bending magnet on the sample with 1 mm width in approximately 10 m distance is $F = 5.44 \cdot 10^{14}$ ph/sec at $I_{\text{beam}} = 100$ mA. The bunch spacing at the ALBA Synchrotron is 2 ns, meaning that every two nanoseconds, photons impinge on the ReBCO. Assuming that all photons arriving at the sample would break a CP, in principle, that would imply that photons of high energy arrive at a shorter repetition time at the sample (ns) than the recombination time of Cooper pairs (ms- μ s) are, as stated in Sec.4.5. As a result, Cooper pairing would be suppressed within the irradiation area, and the superconducting properties would differ. Conversely, in this particular configuration, we do not see it in our data. In the case of an indirect CP breaking over-excited quasiparticles by emission of phonons, as discussed as well in Sec.4.5, the reported time frame lies within femtoseconds in the first stage and picoseconds in the second stage, both faster than the bunch spacing. Thus, faster creation of quasiparticles which are responsible for the indirect CP breaking is not given.

11.4 Surface Resistance

As we reviewed the electrodynamics of superconductors in Sec.2.1 and Sec.3.4, a SC has zero resistance for an applied DC transport current which is carried by CPs. However, in the following we conducted in-situ experiments of the surface impedance. The main difference is that a SC has a non-zero impedance for RF currents. While

in a DC measurement the non-superconducting quasi particles do not contribute to the overall losses in the superconducting state, the normal conducting current carriers do certainly effect the surface impedance. A higher amount of normal conducting electrons leads to a higher surface impedance.

As discussed in the previous section, photons with sufficiently high energy might break apart one or more Cooper pairs which will subsequently recombine again on a time scales $\tau_{CP} \approx 10^{-3} - 10^{-6}$ s [Day+03]. The efficiency and sensibility of the detection of possible CP breaking depends on the ReBCO-CC temperature (amount normal conducting electrons in thermal equilibrium), energy of the impinging photons (ΔU_{CP} is much lower than the hard X-ray photons in this experiment), as well as speed of data acquisition with the VNA (sweep time of microseconds). Basically, we expect a fractional surface impedance variation to be comparable to the fraction of Cooper pairs that are broken [Day+03; TFM71]; hence, a reduced surface resistance during SR, represented by a reduced unloaded Q-factor, as well as a reduced surface reactance during irradiation, represented by a lower resonance frequency.

11.4.1 Experimental Arrangement

To assess whether and how the surface resistance is affected by synchrotron radiation, we measured in-situ R_S versus T and synchrotron radiation with the SR-PPR described in Sec.7.4. The position and photon source is the same as in the previous section and the details about the experimental set-up have been discussed in Sec.8.4. Figure 11.10(a) presents a sketch of the assembled SR-PPR and the layered structure. Due to the complexity of the parallel plate resonator, its larger dimensions, and resulting higher mass we implemented additional temperature sensors compared to the in-situ T_C measurements, as shown in Fig.11.10(b). In total four temperature sensors were utilised; the first sensor is inside the Cryofinger (blue rectangle), from now on referred to as Cryofinger T -sensor. The second sensor is located on the upper metal carrier (yellow rectangle) which is in direct contact with the Cryofinger supporting the coated conductor sample. The third sensor (pink rectangle) is implemented into the side wall of the metallic fixture base. The fourth sensor is positioned on the back side of the de-laminated sample (green rectangle) to monitor its temperature in the elliptical cut-out for the irradiation (Cernox temperature) as seen in Fig.11.10(c). It is the only directly irradiated T -sensor.

Similar to the critical temperature measurement in Sec.11.3, we measured in sequences:

1. samples were irradiated with a fixed flux resulting from an injected beam current of either beam current $I_{beam} = 100$ mA or $I_{beam} = 250$ mA and the temperature of the sample -monitored by the Cryofinger T -sensor- were increased until the critical temperature was reached. Measurements of Q without irradiation ($I_{beam} = 0$ mA) were taken before any irradiation and after irradiation to be used as reference.
2. samples were kept at a fixed temperature and the photon flux on the sample was increased by ramping the beam current from $I_{beam} = 0$ mA to 100 mA or $I_{beam} = 0$ mA to 250 mA.

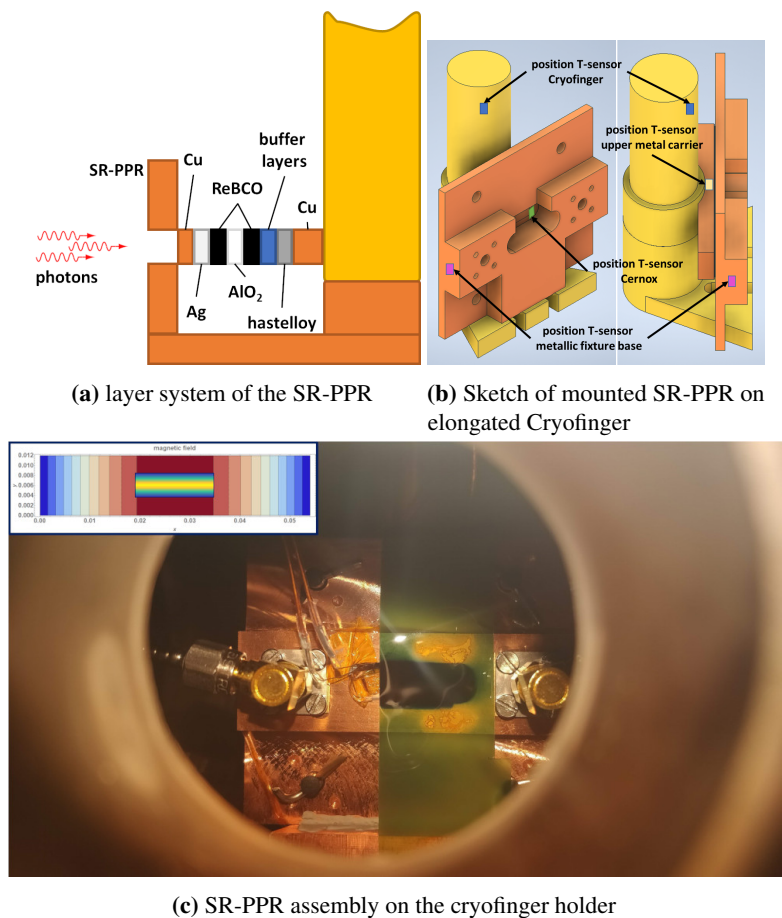


Figure 11.10: Experimental arrangement of the SR-PPR: (a) Layered structure of the SR-PPR, (b) temperature sensor locations, and (c) picture of the irradiated SR-PPR inside the Cryostat.

Table 11.3: Radiation key parameters of the ALBA Synchrotron R_S measurement experiment. The incoming flux at the samples surface after the absorbers is for all samples the same and equals $F_{\text{dep}} = 5.61 \cdot 10^{15}$ ph/sec/mradH at a beam current of $I_{\text{beam}} = 100$ mA. The irradiation time per experiment is in average about 2 h and results in a total amount of photons of $F_{\text{dep, total}} = 3.89 \cdot 10^{19}$ and a accumulated power of $P = 0.85$ W impinging on the ReBCO surface. Assumed density for ReBCO is $\rho_{\text{density}} = 6.3$ g/cm³. The parameters at a beam current of $I_{\text{beam}} = 250$ mA can be determined by multiplying all given values by a factor of 2.5.

	SuperPower	Fujikura
$F_{\text{abs}} \cdot 10^{17} [\text{ph}]$	7.31	8.77
$P_{\text{abs}} [\text{mW}]$	16.20	19.44
$U_{\text{abs}} [\text{J}]$	116.94	140.33
Dose [MGy]	22.49	67.47

The key radiation parameters are summarised in Tab.11.3. Note that in this experiment, even though the magnet, distance of the sample to the source, and irradiation time is the same as in the T_C experiments, the absorption values change significantly in this arrangement. The reason lies within the larger ReBCO-CC samples and wider impinging area, as indicated in the inset of Fig.11.10(c), which shows the mounted SR-PPR and surface current density superimposed with the synchrotron radiation impact region. As can be seen, the photons hit the region of the sample where the current density is maximum. While in the T_C experiment [see Fig.11.4] most of the synchrotron radiation was impinging on the surrounding of the ReBCO film due to the 1 mm width of the sample, the sample in this experiment is larger than the entire SR impact region; thus, maximising the interaction area. Hence, we can reach an accumulated power of $P = 0.85$ W which is above the expected 0.6 W in the primary chamber of the FCC-hh.

Figure 11.11 shows the measured quality factor as a function of temperature. It reveals a gradual decrease in the Q-factor as a function of temperature with a sharp drop at the expected T_C close to 91 K. The inset shows the transmission coefficient at 50 K (green curve) and at 94 K (orange curve).

Due to the preliminary stage of the de-lamination process when these experiments were performed, deviations in the Q-factor were observed among samples of the same provider which is discussed further in App.B.7.1. These discrepancies are much higher than the expected 10% discussed in Sec.9.6. Therefore, we normalise the Q-factor in order to compare the samples. Fig.11.11 shows on the right-hand y-axis the normalised

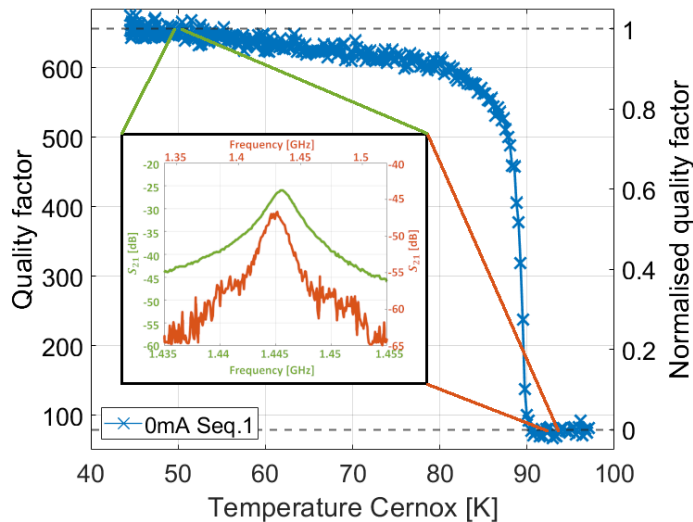


Figure 11.11: In-situ Q -factor temperature sweep at 0 mA injected beam current. The inset presents the S_{21} -parameter at 50 K (green) and 94 K (orange).

quality factor Q_{norm} defined as:

$$Q_{\text{norm}}(T) = \frac{Q(T) - Q_{\text{ave}}^{\text{NC}}}{Q_{\text{ave}}^{\text{SC}} - Q_{\text{ave}}^{\text{NC}}} \quad (11.1)$$

Here, $Q_{\text{ave}}^{\text{NC}}$ refers to the average Q-factor in the normal conducting state, i.e., the average of the data taken above T_C . Furthermore, $Q_{\text{ave}}^{\text{SC}}$ refers to the average of the first five Q-values measured at the lowest temperature in the superconducting state. In this way, $Q_{\text{ave}}^{\text{NC}}$ gives the lowest value, while $Q_{\text{ave}}^{\text{SC}}$ gives the highest value. We normalise all sequences among one set of data with reference to the first sequence at $I_{\text{beam}} = 0$ mA.

11.4.2 Temperature Sweep at Constant Beam Current

We present the results for a measurement with the particular sequence with reference to the beam current in the storage ring: $I_{\text{beam}} = 0 \text{ mA} \rightarrow 100 \text{ mA} \rightarrow 0 \text{ mA}$. In each sequence we cooled down the samples to $T = 40 \text{ K}$ Cryofinger temperature, waited 15 minutes, and then ramped the temperature up to $T = 100 \text{ K}$ (Cryofinger temperature) with a ramp rate of 2 K/min .

The results in Fig.11.12 show the normalised Q-factor (Fig.11.12(a)) and resonance frequency (Fig.11.12(b)) versus temperature for the three aforementioned sequences. A reduced Q-factor is not measured; thus it does not indicate any deviation in the behaviour of the ReBCO-CC's Q_{norm} , during and after irradiation. However, a slight temperature shift in T_C in the Cernox temperature sensor is appearing in the second sequence at $I_{\text{beam}} = 100 \text{ mA}$ beam current, as visible in the inset. Note, this data and change in T_C is plotted as a function of the Cernox T -sensor which is attached to the de-laminated samples' backside, and with that, directly exposed to the irradiation. A similar behaviour can be observed for the resonance frequency against temperature. In addition, in Fig.11.12(b) a noise pattern in the resonance frequency has been observed which we have not been able to explain neither reproduce.

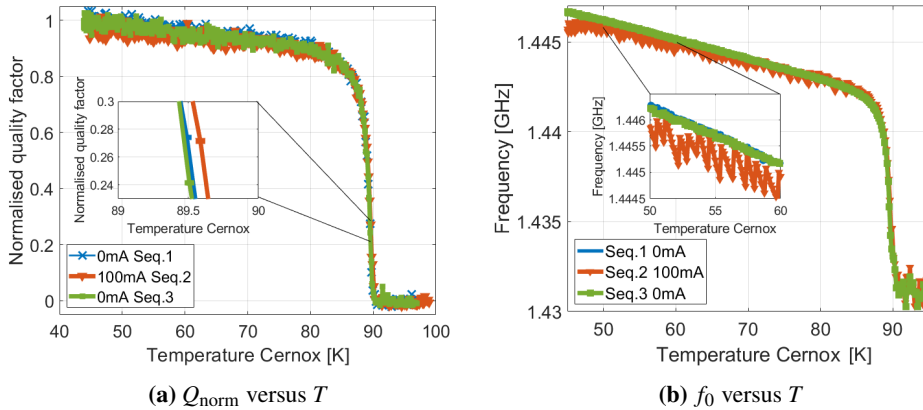


Figure 11.12: SuperPower in-situ surface resistance experiment with sequence $0 \text{ mA} \rightarrow 100 \text{ mA} \rightarrow 0 \text{ mA}$.

11.4.3 Beam Current Ramp at Constant Temperature

Similar to Sec.11.3 we have also performed measurements as a function of the injected current I_{beam} while keeping the cryofinger at a constant temperature T . For these experiments we normalised the quality factor differently than in the previous section. The normalisation is based on the first Q-factor $Q_{I_{\text{beam}}=0}$ measured at $I_{\text{beam}}=0$ mA, which is taken as the maximum value, and every other Q-factor is divided by that value $Q_{\text{norm}} = Q_i / Q_{I_{\text{beam}}=0}$.

The first test-measurement was performed at $T = 40$ K, reproducing the scenario as in Fig.11.1, and then irradiated as a function of injected beam current into the storage ring from $I_{\text{beam}} = 0$ mA to $I_{\text{beam}} = 100$ mA.

We monitored the four temperature sensors during the beam current ramp and the data is illustrated in Fig.11.13. This double y-axis plot shows on the left axis Q_{norm} and on the right axis I_{beam} . First to be noticed is the absolute difference in temperature without beam current. The Cernox temperature as well as the upper metal carrier are consistent around $T = 43$ K. It means that we can assume both ReBCO-CC samples basically at the same temperature without SR radiation and that the temperature of the samples is different than of the Cryofinger support. The metallic fixture base stabilised at $T = 45$ K, and therefore 5 K higher than the Cryofinger. This indicates a cooling of the ReBCO-CCs mainly through the upper metal carrier and sapphire plate²⁵. Taking a look on the temperature data as a function of the injected beam current we observed the following: The Cryofinger temperature (blue circles) stays unchanged during the whole irradiation time. This is in agreement with our assumption in Sec.11.3 that the Cryofinger T -sensor is unaffected by SR. Contrary, all other T -sensors attached

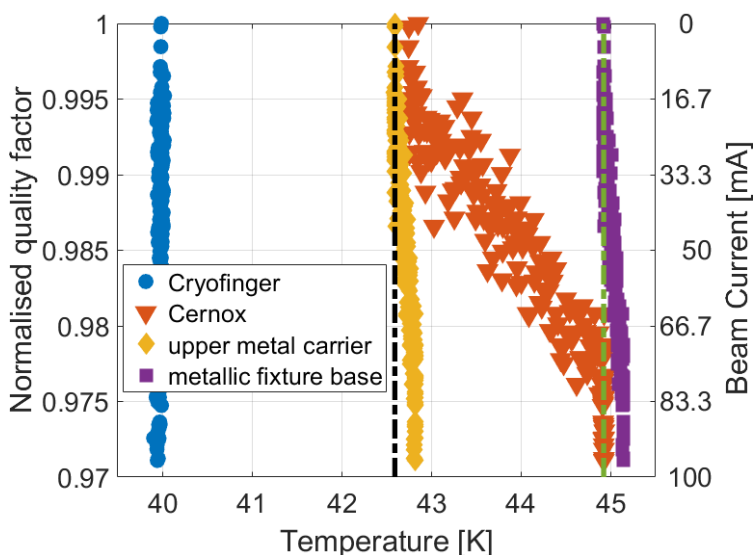


Figure 11.13: Beam current ramp $I_{\text{beam}} = 0$ to 100 mA

²⁵The SR-PPR was modified in later stage for more efficient cooling of the metal fixture base.

show a change in temperature during irradiation but to a very different extent: The upper metal carrier (yellow diamonds) which is attached directly to the sample holder varies slightly to a higher temperature $\Delta T < 1\%$. The same raise in temperature is visible for the metallic fixture base (violet squares). These findings prove a photon power deposition on the SR-PPR which shifts the thermal equilibrium to a minor higher temperature. The highest SR impact is visible in the Cernox temperature sensor directly irradiated (orange triangles) with a $\Delta T \approx 5\%$. This finding confirms that during irradiation a temperature gradient between the two ReBCO-CC samples exists as well as between the de-laminated sample at the position of the Cernox and the SR-PPR metallic fixture base edge. However, it confirms as well possible temperature gradients: a local hot-spot on the de-laminated sample, a temperature gradient between the two ReBCO-CC. Correlating these aforementioned temperature changes to the normalised Q-factor we can demonstrate that by increasing the injected beam current up to $I_{\text{beam}} = 100$ mA a reduction in Q_{norm} by 3% follows.

In the next step, we expanded the study to a beam current of $I_{\text{beam}} = 250$ mA. In this test, we stabilised the temperature of the Cryofinger at $T = 50$ K which resulted in a stabilised temperature of 56 K on the Cernox temperature and 52 K on the upper metal carrier²⁶. This is the starting point of the data presented in Fig.11.14(a) showing Q_{norm} against I_{beam} . The blue data points present the ramp of injected beam current into the accelerator from 0 mA to 250 mA, while the red data points present the I_{beam} ramp down back to zero beam current.

The figure shows that, while ramping the beam current up to around $I_{\text{beam}} \approx 120$ mA, the normalised Q-factor is unchanged. Above this beam current a gradual decrease in Q_{norm} down to the lowest value of 40% of the initial value at 250 mA was measured. At the same time, visible in the second x-axis, the temperature increase measured by the Cernox T -sensor is given. The temperature change is synchronised to the beam current, and in total a raise of around 7 K was measured.

Comparing these findings with the previous results in Fig.11.11 and in Sec.9.1 such a reduction of Q-factor suggests that the sample was entering transition into the normal conducting state at the position of the maximum current density. The possibility that the changes in Q_{norm} are related to the changes in $\tan(\delta)$ of sapphire are unlikely, because the losses in sapphire are known to be very low at cryogenic temperatures and the loss tangent values do not change over magnitudes at cryogenic temperatures either. In addition, the inset on the left of Fig.11.14(a) confirms that the temperature of the Cryofinger has been stable throughout the measurement.

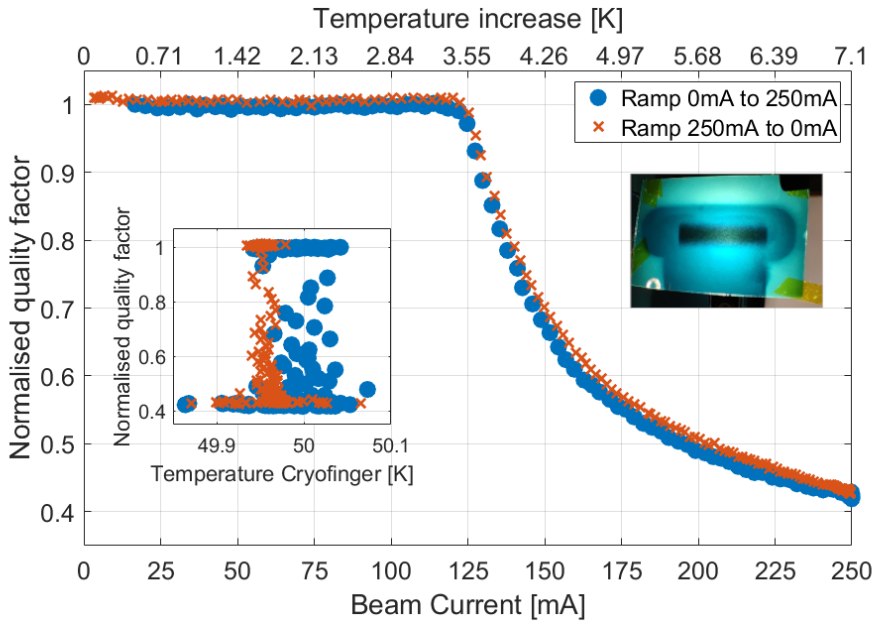
Reducing the beam current again, reveals that the process is reversible. The normalised Q-factor gets back to its initial value, which proves again as in the previous sections, that there is no permanent damage on the sample due to SR. This was additionally investigated with the aid of a Hall scan system developed by [Bar22; Bar]. Figure 11.14(b) illustrates a current density map of the de-laminated Fujikura sample after irradiation²⁷. The map indicates a low current flow in blue and a high current flow

²⁶The metallic fixture base T -sensor was removed due to noticeable interferences with the resonance peak.

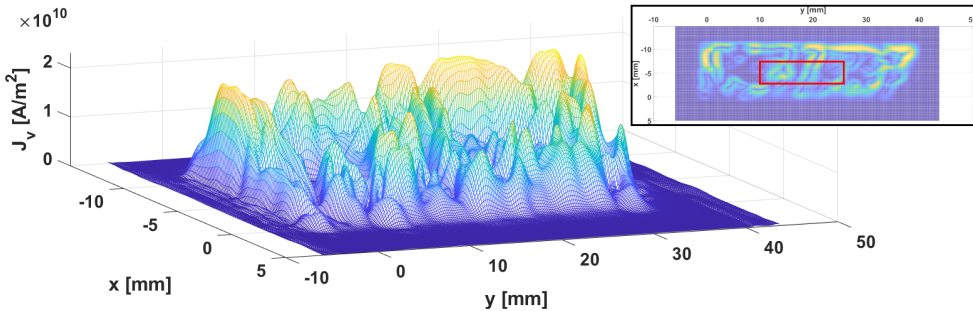
²⁷A Hall scan could not be performed before irradiation due to irreversible damage on the samples after

in yellow. As can be seen in this Fig.11.14(b), the high superconducting regions are not uniformly distributed over the entire sample as within non-de-laminated samples. Anyhow, the intention of the Hall scan is to visualise if the synchrotron radiation damages the sample within the region of irradiation -red square inset of Fig.11.14(b)-. No degradation of the sample due to photon impact could be found.

The small temperature increase measured compared to the strong quality factor decrease could indicate that due to the larger irradiation area there is a stronger cooper pair breaking affecting the ReBCO. On the other hand, a strong local heating of the sample which might not be measurable at the position of the Cernox sensor might cause the same effect. Therefore, in order to investigate further which effect prevails and with



(a) Fujikura in-situ surface resistance experiment no.1.



(b) Hall scan of an irradiated de-laminated ReBCO-CC.

Figure 11.14: In-situ R_s measurements as a function of injected beam current up to 250 mA.

the scan.

intention to confirm the measured effects in Fig.11.14(a), we repeated the experiment with another Fujikura and SuperPower sample. Though this time, we repeated the measurement with a faster termination of the beam current by once shielding the experimental set-up with the conical copper filter [see Fig.8.12] and once with a beam dump²⁸. Figure 11.15 provides the results of two measurements of the Q -factor as a function of beam current for Fujikura and SuperPower, respectively.

As visible in Fig.11.15(a), a similar behaviour was measured as in the previous Fujikura sample shown in Fig.11.14. In this measurement the Q_{norm} reduces linearly by 5% up to a injected beam current of $I_{\text{beam}} \approx 140$ mA. Above 140 mA a noticeably decrease down to 63% of the initial value is visible. In addition, it has to be stated, that the thermal anchoring in this experiment of the SR-PPR was not as good as in previous experiments which is visible in the high initial temperature of 71 K as starting point of the experiment, while the Cryofinger temperature is kept stable at 50 K. In total, a temperature increase of about 12 K was measured, again less than what would be expected by such strong reduction of quality factor.

As aforementioned instead of ramping the beam current back to 0 mA, we decided to move the filter in front of the sample and shield it entirely from any SR. Shielding, the parallel plate resonator causes in a fast recovery of the initial Q -factor. The filter though, is of conical in shape, and hence, we see a gradual shielding of SR demonstrated starting by one data point at 0 mA and $0.7Q_{\text{norm}}$ and close to the initial value.

The results for SuperPower are given in Fig.11.15(b). The first to notice is that the strong decrease of the Q_{norm} with higher I_{beam} in the storage ring begins at a

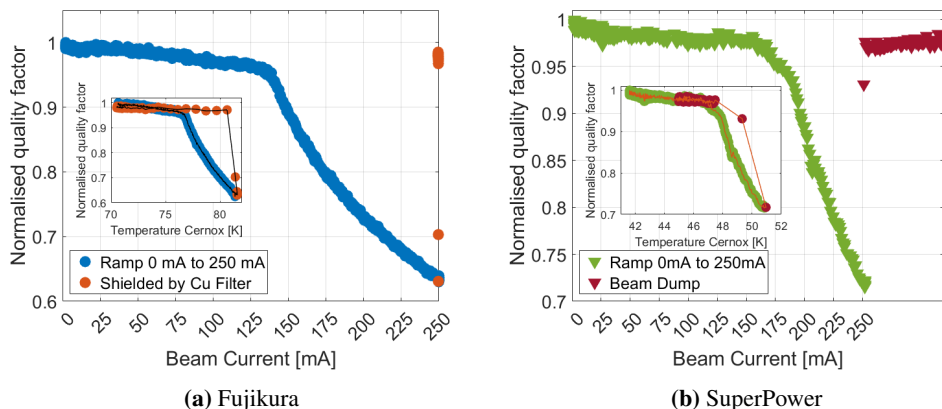


Figure 11.15: In-situ R_S measurements as a function of injected beam current up to 250 mA for two providers: (a) Fujikura in which the SR is reduced by shifting the filter in front of the experiment. The blue data shows the values before shielding and orange after shielding. (b) SuperPower in which the SR is reduced by a beam dump. The green data shows the values before the beam dump and the red data after.

²⁸A beam dump is a instantaneous loss of the particle beam in the accelerator giving us the fastest switch to ‘turn off’ the photon light.

higher beam current compared to Fujikura. Furthermore, Q_{norm} decreases by almost 30% of the initial value at 250 mA beam current. This might be linked to the fact that the thermal anchoring in this measurement was better, leading to an only 2 K deviation between the Cernox and the Cryofinger, which was kept at $T = 40$ K. The total temperature increase measured on the de-laminated sample was 8 K.

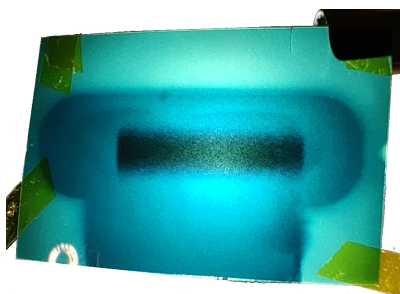
Shortly after reaching the desired beam current, the beam was dumped and a steep recovery of the normalised quality factor can be seen. A pure Cooper pair breaking affect would lead to such an effect, especially when measuring a temperature change of 8 K only. However, there is one significant data point around $\approx 0.94Q_{\text{norm}}$. This single data point was recorded five seconds after the beam dump and the VNA sweep times are in the milliseconds range. As aforementioned, any Cooper pairing recombination time is much shorter, and because of that, we would expect a recovery of the unity value to be almost instantaneous outside of our measurement possibilities. We cannot completely discard the breaking of Cooper pairs or other physical phenomena, but this data point seems to be a strong indication that thermal effects prevail in this measurement.

11.5 Difficulties, Limits and Possibilities

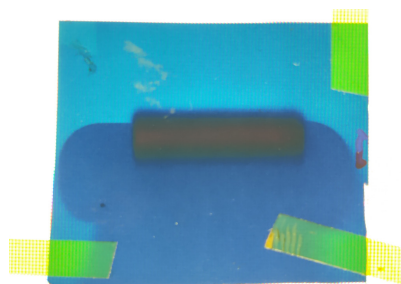
11.5.1 Synchrotron

The experimental set-up for the study in this chapter is very demanding and needs a lot of preparation time in order to be accomplished. A limitation of this study is that the experiments could only be performed in machine dedicated time, when no users were at the facility. The positioning of the set-up at the X-Ray pinhole of the synchrotron meant that the Cryofinger and the SR-PPR had to be removed after each experimental day. Furthermore, unexpected problems by restarting the accelerator complex after the maintenance time leads to a reduced measurement time or in the worst case the cancelling of the measurement.

The constant opening and closing of the Cryostat lead to unwanted movements of the experimental set-up. Hence, the height of the set-up had to be often re-aligned



(a) good alignment



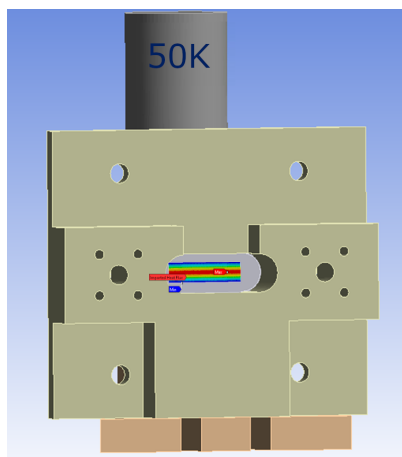
(b) bad alignment

Figure 11.16: Pictures of irradiated photosensitive dosimetry film attached on the SR-PPR cut-out. The darker the area the higher the SR impact.

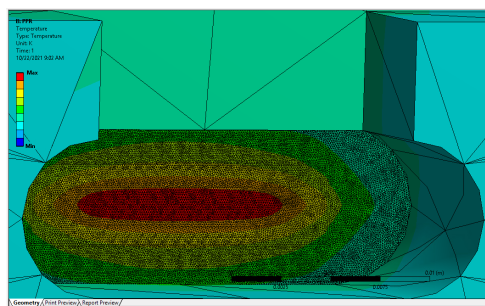
with the particle beam in the storage ring in order to hit the target properly. That the target was hit properly can only be seen after the measurements on the photosensitive dosimetry film. Figure 11.16 presents in 11.16(a) the synchrotron radiation impact when the set-up was well aligned and in 11.16(b) when it was misaligned. The massive 1 cm thick SR-PPR ground plate is at that position and absorbs all of the synchrotron radiation. This leads to less SR flux than theoretically expected and has to be taken into account when analysing the data, especially as the ground plate will be heated strongly.

11.5.2 Thermal Simulations

Very preliminary thermal studies in ANSYS shown in Fig.11.17 have been started at the end of the thesis and the outcome shall be qualitatively explained. A simplified version of the SR-PPR including the support of the Cryofinger has been implemented into ANSYS as shown in Fig.11.17(a). The boundary conditions for the numerical calculations are a constant temperature of the Cryofinger and an imported SR heat flux corresponding to the expected SR at the experimental position that we estimated beforehand, as can be seen in Fig.11.17(a). In this thermal simulation the entire SR power is assumed to be dissipated on the back of the de-laminated sample. The results of the first simulations, visible in Fig.11.17(b), have confirmed that a local hot-spot in the center of the SR impact area with a high thermal gradient can appear; thus, confirming the findings in Sec.11.4. The slope of the thermal gradient depends strongly on the imported conductivities of the several layers in the simulations as well as conductivities in between layers and SR power which is a study continued at the moment.



(a) ANSYS model of the PPR with the imported heat flux



(b) preliminary ANSYS results

Figure 11.17: Preliminary ANSYS simulation results with the Steady-State Thermal Solver.

11.5.3 The Parallel Plate Resonator

An issue that was not addressed in this study was whether we can estimate the absolute values of the surface resistance with any of the designed parallel plate resonators. Within the thesis the surface resistance of ReBCO-CC could not be directly measured which might have the following main reasons:

1. The radiation losses are much higher than expected through the simulations.
2. Based on the measured surface resistance without magnetic field in Ch.9 and frequency scaling, we would expect to measure in average $R_S \approx 10 \mu\Omega$; hence, the results might be in addition to radiation influenced by the loss tangent of sapphire.
3. Mechanical issues due to thermal contraction have been noticed in the measurements due to small tolerances in the design.
4. A possible influence due to the exposed buffer layer with relative high permittivity might lead to trapped EM-fields in between substrate and ReBCO film.
5. Each ReBCO-CC of the different providers has a different thickness, surface structure and bending which impedes a consistent assembly.

Nevertheless, with the last design of the shielded PPR as presented in Ch.8 we achieved symmetric coupling within five different modes, as shown in Fig.11.18 for SuNAM. We used two 10 cm long ReBCO-CC samples of which none was de-laminated. In this configuration we achieved to measure a surface resistance of $R_S(0.7 \text{ GHz}) = 225 \mu\Omega$ taking into account the simulated radiation losses in Sec.7.4.5. The determined value is by a factor 10 higher than the expected theoretical value of $R_S^{\text{theo}}(0.7 \text{ GHz}) = 19 \mu\Omega$. However, this measured value is about a factor 10 lower than what we measured with the CHCDR at 8 GHz, and with that, the overall lowest surface resistance that we measured.

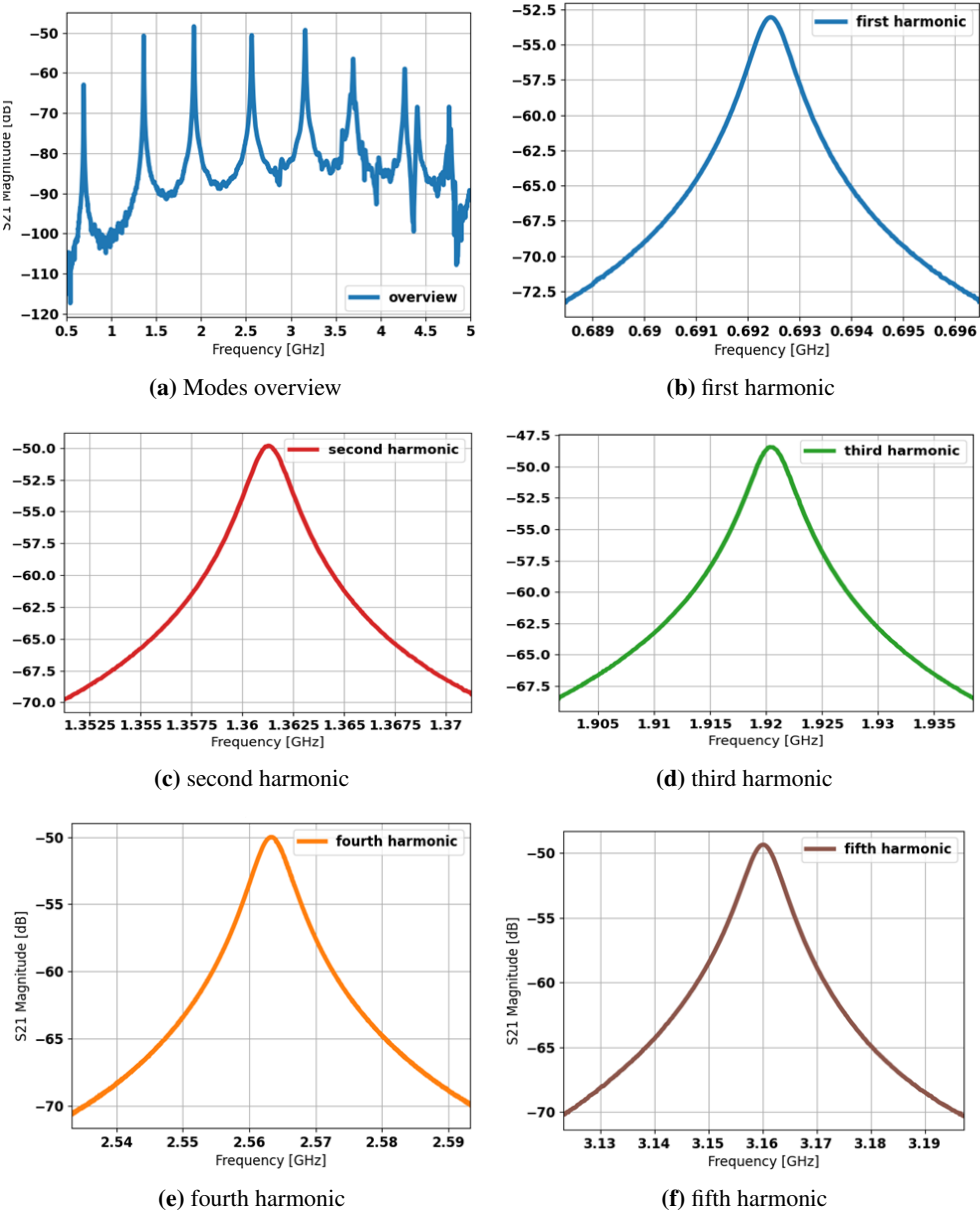
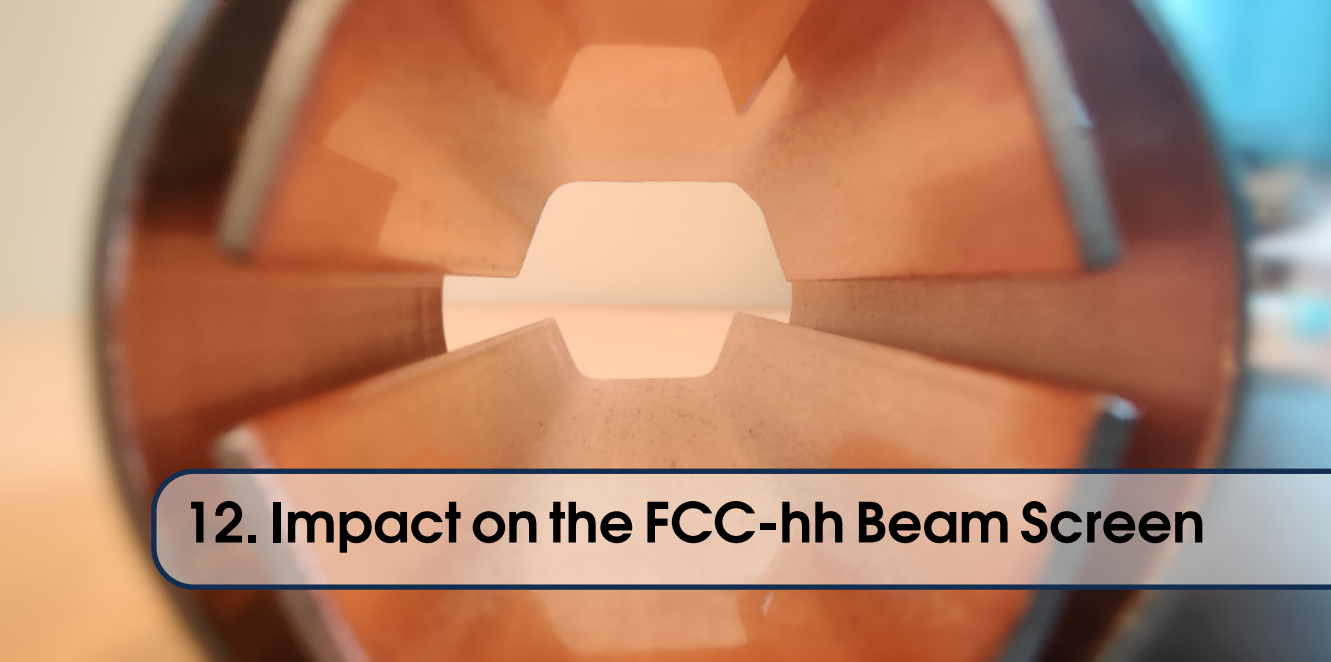


Figure 11.18: Shielded parallel plate resonator S_{21} -parameters for the first five harmonics.



12. Impact on the FCC-hh Beam Screen

Just as the constant increase of entropy is the basic law of the universe, so it is the basic law of life to be ever more highly structured and to struggle against entropy.

-Vaclav Havel-

The results in the previous chapters of this part of the thesis provide important insights into the possible impact of ReBCO-CCs on the resistive wall impedance. In this chapter we will provide an introduction to the study of beam impedances by means of a round pipe approximation. This chapter is not meant to determine the exact resistive wall impedance for the actual beam screen geometry, rather than to give the reader a broader picture and understanding of the influence and potential of ReBCO-CCs on the resistive wall impedance reduction.

In the previous chapters we measured and compared the surface impedance of the baseline FCC-hh beam screen copper coating with the provided ReBCO coated conductors as close as possible to the requirements in the foreseen future collider. This combination of findings can be used in order to answer some questions regarding the nature and extent of ReBCO-CCs impact on the resistive wall impedance. It correlates to the impact of the beam screen's surface impedance on the particle beam, as mentioned in Sec.5.2. Therefore, the outcome seen in the results of the surface impedance

measurements in the previous chapters can be transferred to the RW-impedance over Eq.(5.1) which describes a formula for a perfect cylindrical pipe in the ultra-relativistic limit in the medium frequency range:

$$Z_{\parallel}^{\text{RW}}(f) = \frac{Z_S(f)L}{2\pi b} \quad Z_{\perp}^{\text{RW}}(f) = \frac{cZ_S(f)L}{2\pi f b^3}. \quad (12.1)$$

The medium frequency range is specified as the frequency range at which the skin depth is small enough to penetrate only the first conducting layer [see multi-layer theory in Sec.3.5], e.g., in the FCC-hh the co-laminated copper thickness is 300 μm ; thus, thick enough that the formulas given are valid over almost the whole frequency range of interest at 50 K. Additionally, the penetration depth for superconductors is frequency independent, and hence, the same equations cover the whole frequency range of interest for an entire coating with ReBCO coated conductors.

As the RW-impedance approximation is valid only for a round pipe, we assume here, that the BS is closed and the mean radius of the horizontal and vertical dimensions of the FCC-hh beam screen is $b = 13.61 \text{ mm}$, as indicated as blue dashed circle in Fig.12.1. The length of the pipe that is considered in this calculation is $L = 1 \text{ m}$. In this case study, we will consider only the two scenarios of an entirely copper coated BS and an entirely ReBCO coated BS. The reason for this is because every hybrid coating system will have an impedance that is somewhere in between these two coating possibilities, regardless of the surface ratio of Cu to ReBCO or the exact location of ReBCO.

Substituting the surface impedance formulas for normal conductors and superconductors as discussed in Sec.3.4 into Eq.(12.2) determines the resistive wall impedance Z^{RW} frequency dependencies resulting in:

$$Z_{\parallel, \text{Cu}}^{\text{RW}}(f) = R_{\parallel, \text{Cu}}^{\text{RW}}(f) = X_{\parallel, \text{Cu}}^{\text{RW}}(f) \propto \sqrt{f} \quad (12.2)$$

$$Z_{\perp, \text{Cu}}^{\text{RW}}(f) = R_{\perp, \text{Cu}}^{\text{RW}}(f) = X_{\perp, \text{Cu}}^{\text{RW}}(f) \propto \frac{1}{\sqrt{f}} \quad (12.3)$$

$$R_{\parallel, \text{ReBCO}}^{\text{RW}}(f) \propto f^2 \quad X_{\parallel, \text{ReBCO}}^{\text{RW}}(f) \propto f \quad (12.4)$$

$$R_{\perp, \text{ReBCO}}^{\text{RW}}(f) \propto f \quad X_{\perp, \text{ReBCO}}^{\text{RW}}(f) = \text{const.} \quad (12.5)$$

The frequency dependency difference between Cu and ReBCO is more evident in the transverse RW-impedance due to the general reciprocal proportionality of

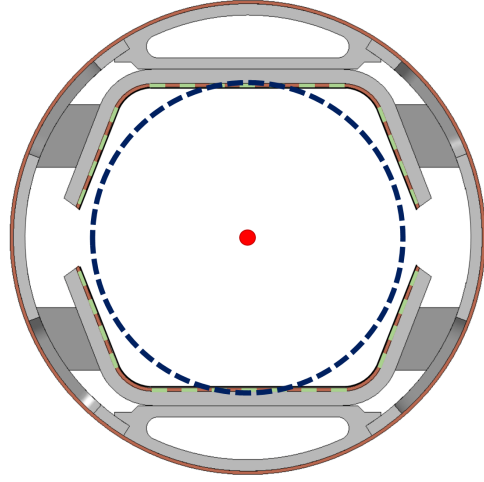
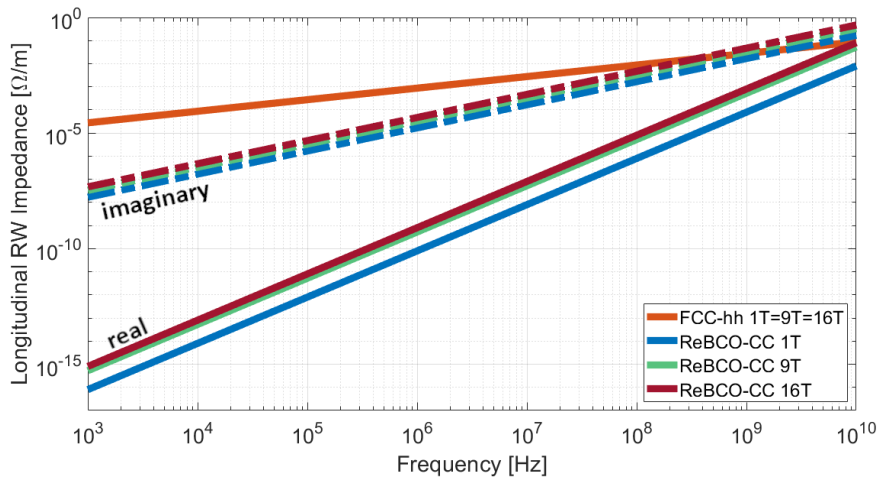


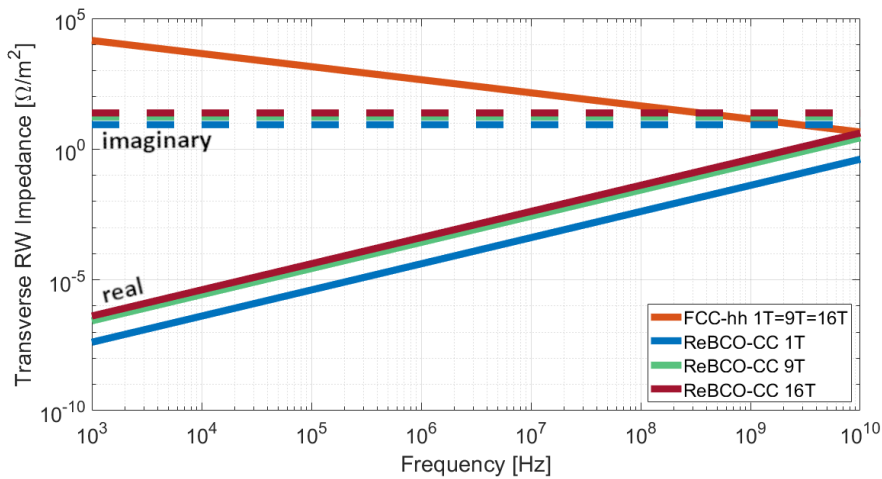
Figure 12.1: Round beam screen approximation of the FCC-hh beam screen.

$Z_{\perp}^{\text{RW}} \propto 1/f$. Due to this, the slope for $Z_{\perp}^{\text{RW}}$ changes sign for the metal coating compared to the ReBCO-CCs. Especially, due to the linear frequency proportionality of the surface reactance for ReBCO-CCs, the frequency dependency for $Z_{\perp}^{\text{RW}}$ cancels and the imaginary part of the transversal resistive wall impedance becomes a constant throughout the whole frequency spectrum.

The actual significance of our measurements, over the whole frequency range important for the FCC-hh is visible in Fig.12.2. The figure shows the estimated longitudinal Fig.12.2(a) and transverse Fig.12.2(b) RW-impedance for the entire frequency range of interest in the FCC-hh BS. In addition, the figure shows the real (solid lines) and imaginary (dashed lines) parts per meter which have been calculated by substituting



(a) $Z_{\parallel}^{\text{RW}}$ @ 50 K



(b) $Z_{\perp}^{\text{RW}}$ @ 50 K

Figure 12.2: Resistive wall impedance for a thick wall round pipe approximation.

the measured and extrapolated Z_S [see Tab.10.2] of:

- FCC-hh BS Cu ($Z_S(50\text{ K}, 16\text{ T}, 1\text{ GHz}) = 2.8 + i2.8\text{ m}\Omega$)
- SuperPower ($Z_S(50\text{ K}, 16\text{ T}, 1\text{ GHz}) = 70 + i4000\text{ }\mu\Omega$)²⁹

into Eqs.(12.2) and extrapolating the values with the frequency dependency indicated in Sec.3.4 for Cu and the measured frequency dependency presented in Sec.9.2 for ReBCO-CCs.

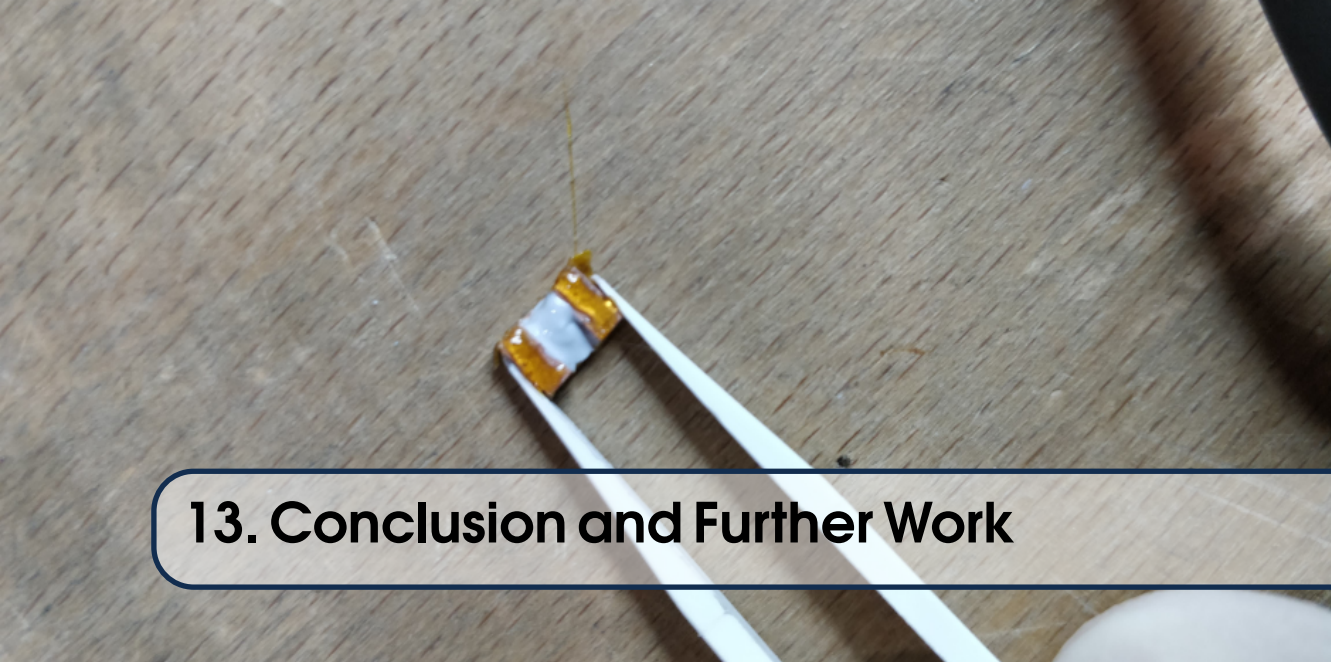
As can be seen in these figures the real part (bold lines) of the longitudinal and transverse RW- impedance is orders of magnitude lower than that of the copper coating in the whole frequency range of interest up to 16 T at 50 K. On the other hand, the imaginary part (dashed lines) of the longitudinal and transverse resistive wall impedance is comparable to that of copper at frequencies above the GHz range while orders of magnitude lower at low frequencies. This is important, especially at injection (low revolution frequency and low magnetic field) because the RW-impedance has to be as low as possible in order to be able to fill the whole particle accelerator with the desired amount of bunches before accelerating the particles afterwards to the necessary collision energy.

As promising as this data seems, it must be interpreted with caution because the above discussion covered an elementary example of the resistive wall impedance for a round pipe in which the effect of the particular normal conducting ante-chamber of the FCC-hh BS is neglected. Additionally, the direction of the applied magnetic field is not taken into account. However, the measurements presented in this thesis were done always with a perpendicular applied DC magnetic field resulting in the highest surface impedance which is beneficial for ReBCO-CCs. We are not taking into consideration other magnetic components in the accelerator complex, e.g., the second largest amount of magnets the quadrupole magnets which create a gradient magnetic field whose magnitude grows with the radial distance from its longitudinal axis. In addition, we have not included in this simple approach the possibility of a residual resistance resulting at lower frequencies due to normal conducting inclusions in the ReBCO film. The given findings may be somewhat limited as well by the effects of synchrotron radiation and the way ReBCO-CCs would perform under strong synchrotron radiation irradiation covered in Ch.11.

In total, the combination of findings as well as taken into account the aforementioned drawbacks and advantages, provides support for the conceptual premise that the usage of ReBCO-CCs is strongly recommended to reduce the main impedance of the FCC-hh impedance budget as presented in Fig.1.10.

²⁹The surface reactance value has been evaluated by a linear fit similar to the one shown in Fig.10.10 for R_S based on data presented in Fig.9.9.

V - The Conclusion -



13. Conclusion and Further Work

Study the science of art. Study the art of science. Develop your senses, especially learn how to see. Realize that everything connects to everything else.

-Leonardo da Vinci-

In this concluding chapter, we summarise the highlights of the thesis and the answers to the research questions introduced in section 1.10. In addition, we discuss further work and general observations for the development of a future hybrid beam screen.

The central part of this thesis concerns the implementation of the impedance study of ReBCO-CCs within the FCC-hh research, through non-destructive radio-frequency measurement techniques. The final aim was to evaluate if the commercially available second generation ReBCO-CCs are capable of outperforming copper at the foreseen requirements of the FCC-hh.

Design, development, and installation of experimental set-ups

To determine the surface impedance of ReBCO-CCs, we successfully designed, fabricated, and installed various dielectric resonators in three main experimental set-ups, reproducing the environment of the FCC-hh.

First, at ICMAB, an RF-measuring equipment which operates at 8 GHz was added to the current 9 T bore magnet with 2.6 cm aperture and variable temperature. Second, at the UPC, an RF-measuring cryogenic temperature test equipment was entirely renewed and now operates at several frequencies at variable temperature. Third, at the ALBA synchrotron, we developed, built, and deployed a variable temperature RF-measuring equipment for samples of 5 cm length with resonance at roughly 1 GHz, where the coated-conductor tapes are irradiated in-situ with synchrotron light.

In summary, we managed to characterise ReBCO-CCs under the influence of the following conditions: temperature $T = 2 - 300$ K, radio-frequency field strength $H_{\text{RF}} = 100 - 1200$ A/m, DC magnetic field $B_{\text{DC}} = 0 - 9$ T, and synchrotron radiation with photon energies above $U_{\gamma} > 10$ keV. This way, we almost covered the entire FCC-hh BS requirements: $T = 40 - 60$ K, $H_{\text{RF}} = 100 - 230$ A/m, $B_{\text{DC}} = 1 - 16$ T and $U_{\gamma} > 0$ keV.

Development of a software for the automated acquisition of data and an algorithm for the extraction of resonator parameters

As part of this work, we developed a software to measure the resonance frequency and Q-factor of dielectric resonators as a function of temperature and DC magnetic field. The dielectric resonator surface impedance measurement system (DR Ω MS) was collaboratively created and implemented into a graphical user interface to automate several measurement procedures mainly with the 9 T magnet system at ICMAB. The main functions programmed are the ability to perform tailored temperature and magnetic field sweeps: equidistant temperature and/or magnetic field steps with stabilisation at each measurement point, or use a constant temperature and/or magnetic field ramping rate without stabilisation and continuous data storage. The python programme instructs the VNA to locate the correct mode (TE₀₁₁) and sets the frequency span to 10 times the 3 dB bandwidth after the system reaches the base temperature and stabilises. Further, it constantly tracks the resonance frequency shift until the desired measurement point is reached. Then, it interrogates the VNA to obtain the maximum magnitude of the resonance (f_0 , Q_L , and S_{21}) and save Touchstone files with all four S-parameters within the desired frequency range. Many parts of this code were used as well for the experimental set-ups at UPC and ALBA.

To process the measurement data of the different resonators, we have also developed an algorithm (ARPE) for accurate post-processing of the two-port S-parameter files produced by VNAs. This algorithm is capable of fitting Lorentzian (symmetrical) and Fano (asymmetrical) responses. It has been implemented in an automated code suitable for remote web execution, where only the S-parameter files generated by the VNA are needed. If several files are uploaded, the algorithm returns loaded and unloaded Q-factor, resonance frequency, and coupling factors of each file. Additionally, the source code is available under a freeware license for further collaborative development. The most significant technical feature of the algorithm is the automatic process to remove outliers. Such process corrects the impacts created by an uneven distribution of measurement points along with the resonance circles in the complex plane resulting from the linear frequency sweep of the VNA. This technique is capable of fitting resonator

parameters, especially in cryogenic experiments, where the calibration possibilities of the transmission lines connecting the VNA and resonator are limited. In modern VNAs with standard IF bandwidths, the effects of cabling, connectors, calibration, and frequency dependency on coupling networks prevail over those induced by noise. As a result, error limitations are difficult to generalise since they are dependent on the peculiarities of the resonator; however, the relative variation in the unloaded quality factor determined with ARPE was maximum (2.7%, in comparison to a common value of 1%) and less than $1/(10Q_0)$ for the resonance frequency, in comparison to equivalent circuit values.

The measuring systems developed as part of this work are suitable to determine high-frequency losses. They allow fully-automated multi-hour measurements of the surface impedance, including the post processing of data when loss tangent values of dielectric crystals are given to the algorithm.

Measurement of surface impedance of ReBCO-CCs at the temperature, magnetic field, and RF magnetic field strength of high energy colliders

We studied the microwave properties of ReBCO-CCs provided by six different manufacturers in working conditions similar to those found in high energy colliders. Furthermore, we compared copper, the baseline FCC-hh beam screen coating, to the ReBCO-CCs in terms of surface impedance -both the real part surface resistance and imaginary part surface reactance-. The conditions consisted in cryogenic temperatures focused at 50 K, a perpendicularly applied DC magnetic field up to 9 T, and a frequency field of variable intensity at 8 GHz achieved with a rutile-loaded closed Hakki-Coleman dielectric resonator. In such conditions, we could prove that the best ReBCO-CCs outperform FCC-hh BS Cu in surface resistance by a factor of 20 at 1 T and by a factor of 2 at 9 T. The surface reactance of FCC-hh BS Cu's surface is lower than the one of all ReBCO-CCs by a factor of 2 at 1 T and by a factor of 4 at 9 T.

We revealed that the magnitudes of the surface impedance against magnetic field strongly correlate with the micro- (and nano-) structure of the ReBCO layer. Specifically, in our experimental settings, we established that the superior pinning capabilities of the ReBCO layer are the primary cause of low surface impedances at high magnetic fields. These findings support the relevance of micro-structures and pinning forces when ramping the magnetic field up and down. Even when the magnetic field is not applied anymore, pinning forces can cause vortices to remain in the sample for long periods of time. As a result, the ReBCO coated conductors have a slightly higher surface resistance after being exposed to the 9 T magnetic field. The hysteretic behaviour is seen below 2 T and the magnitude of magnetisation varies for the different providers with changes between 5% to 25% in the surface resistance. In addition, we investigated the difference in the magnetic behaviour between zero-field-cooled and field-cooled. Such differences range from 4% to 44%. This hysteretic behaviour must be considered in the particle collider when performing the different magnetic field ramps.

Explicit surface resistance measurements as a function of the RF surface magnetic field strength in which the samples were subjected to a perpendicular DC magnetic field of up to 9 T were performed. These measurements revealed that the surface resistance

-and most probably surface reactance- increases not only because of the applied DC magnetic field, but also because of higher surface RF magnetic field strengths. In samples above 100 A/m, we observed a gradual increase in non-linear losses with increasing surface RF magnetic field strength, depending on the VNA sweep time. This observation is attributed to the existence of defects caused by the growth methods and radio-frequency vortex dynamics. This approach proved that the performance of a ReBCO coating in a particle accelerator is not only influenced by the DC magnetic field, but also by the RF fields. The latter are created by image currents flowing in the BS because of the temporal structure of the proton beam.

As aforementioned, we observed that at the elevated VNA output power, the results are also influenced by the VNA sweep time. We discussed the relationship between the electromagnetic fields provided by the VNA and the timing of the circulating proton bunches. We proved that the onset of thermal effects starts at times much larger than the ones characteristic of the circulating proton bunches. Therefore, transient thermal effects in the BS shall not affect the surface resistance of ReBCO-CCs.

Vortex motion and depinning frequency

We determined the depinning frequency for each ReBCO-CC in the context of a rigid vortex motion, over the incremental changes in the surface impedance data. The depinning frequencies, which range from 14 to 31 GHz depending on the ReBCO-CC, greatly exceed the measurement frequency where the vortex oscillation motion is almost non-dissipative. This encourages to employ ReBCO-CCs in the beam screen chamber. However, before integrating ReBCO-CCs into a BS, it is essential to evaluate whether the strength of the induced RF azimuthal magnetic field produced by proton bunches would be sufficient to fluctuate and/or push the trapped vortices away from their static position. The investigation revealed that, in the FCC-hh regime, the net motion of the vortices is restricted to their pinning potential well, and the applied RF magnetic field strength is not sufficient to provoke flux-shaking effects. The Q-factor of samples in the remnant state did not improve after ramping the VNA power, showing that there was no net flux displacement produced by applying a strong RF magnetic field to the samples. This implies that, at high magnetic fields, the influence of the surface of normal conducting areas on the surface impedance due to the existence of vortices is higher than the vortex motion itself. This happened for samples containing APC as well as for pristine samples, providing a deeper insight into the vortex dynamics when a proton bunch passes by.

Effect of photon irradiation on surface resistance ex-situ & in-situ

To our knowledge, the synchrotron radiation study within this thesis is the only empirical investigation of the impact of synchrotron radiation on the resistance of ReBCO-CCs ex-situ and in-situ.

In the long-term ex-situ irradiation study, ReBCO-CC samples from several providers were exposed for up to 552 h to high-energy synchrotron radiation attenuated by a 35 mm thick copper crotch absorbers; thus photon energies above $U_\gamma > 100$ keV. We observed that the photons did not cause any mechanical or chemical damage on

the ReBCO layer. This is a beneficial result for the operation of the FCC-hh with ReBCO-CCs. We finally demonstrated that the surface resistance of irradiated samples remains as high as before irradiation. These results have been confirmed in the in-situ measurements, where we could lower the photon energy starting from $U_\gamma > 10$ keV.

In the in-situ measurements we first performed several critical temperature measurements with and without synchrotron radiation. We could not identify any changes in the value of T_C or the width of the transition from superconducting to normal conducting state. On the contrary, in the in-situ surface resistance measurements with the parallel plate resonator, we could see an impact of synchrotron radiation on ReBCO-CCs. The results revealed a median reduced quality factor of 40% at 50 K at a total impinging flux of $3.86 \cdot 10^{19}$ photons, which equals a power of 0.83 W; therefore, with successive increases in the intensity of the synchrotron radiation, the surface resistance increases. Reducing the synchrotron radiation revealed that the process is reversible. Regardless, such an intense change in quality factor suggests that the superconducting state is locally suppressed.

It is not of fundamental importance in this thesis whether thermal or quantum physical effects can explain the effects observed on ReBCO. Still, our findings provide some insights for light-ReBCO interactions, and we can state that thermal effects prevail Cooper pair breaking at photon energies above 10 keV for ReBCO layers of around $2 \mu\text{m}$ thickness. We cannot disprove that Cooper pairs are separated during the irradiation, although, over the acquisition time of seconds, there is strong evidence for thermal effects to prevail.

This new understanding should help to improve predictions of the impact of synchrotron radiation on ReBCO in the beam screen. According to our results, ReBCO coated conductors can lose performance because of the impact of a local strong concentrated radiation of photons in the hard X-ray region. Local heating could become an issue when the coated conductor is irradiated. The sudden change of surface resistance of orders of magnitude would substantially influence the circulating particles. Thus, the cooling capability of the system must be strong enough to compensate for the radiation heat load of the photons. Finally, we have to consider that each coated conductor has a different complex layered structure with different thickness and materials. The recommendation of placement of ReBCO-CCs in the beam screen would be in positions with low direct impact.

Extrapolation to FCC-hh conditions: 16 T and 1 GHz

At the time of writing this thesis, we did not have the relevant set-up with a magnet up to 16 T and resonator at 1 GHz to measure the surface impedances in the specified domain; therefore, we extrapolated the measured values of surface impedance based on the rigid vortex model and determined frequency dependence of surface resistance by measurements with the closed Hakki-Coleman dielectric resonator at 27 GHz. Moreover, we found a relationship between the peak RF magnetic field strength and coupling factors, to predict the peak RF magnetic field strength at 16 T in the rutile loaded dielectric resonator. Even at 16 T, we could characterise the ReBCO-CCs with the closed Hakki-Coleman dielectric resonator close or within the FCC-hh conditions,

with RF magnetic field strengths between 79 A/m to 228 A/m.

At 50 K, 1 GHz, and 16 T, ReBCO-CCs are expected to have surface resistances that are about a factor of 5 to 50 times lower than FCC-hh beam screen copper. At the same time, they would maintain a slightly higher but in the same order of magnitude surface reactance, neglecting any magnetoresistive effects for copper that would raise its surface impedance. This would finally result in significant gains in beam stability margins and losses in resistive power within the FCC-hh.

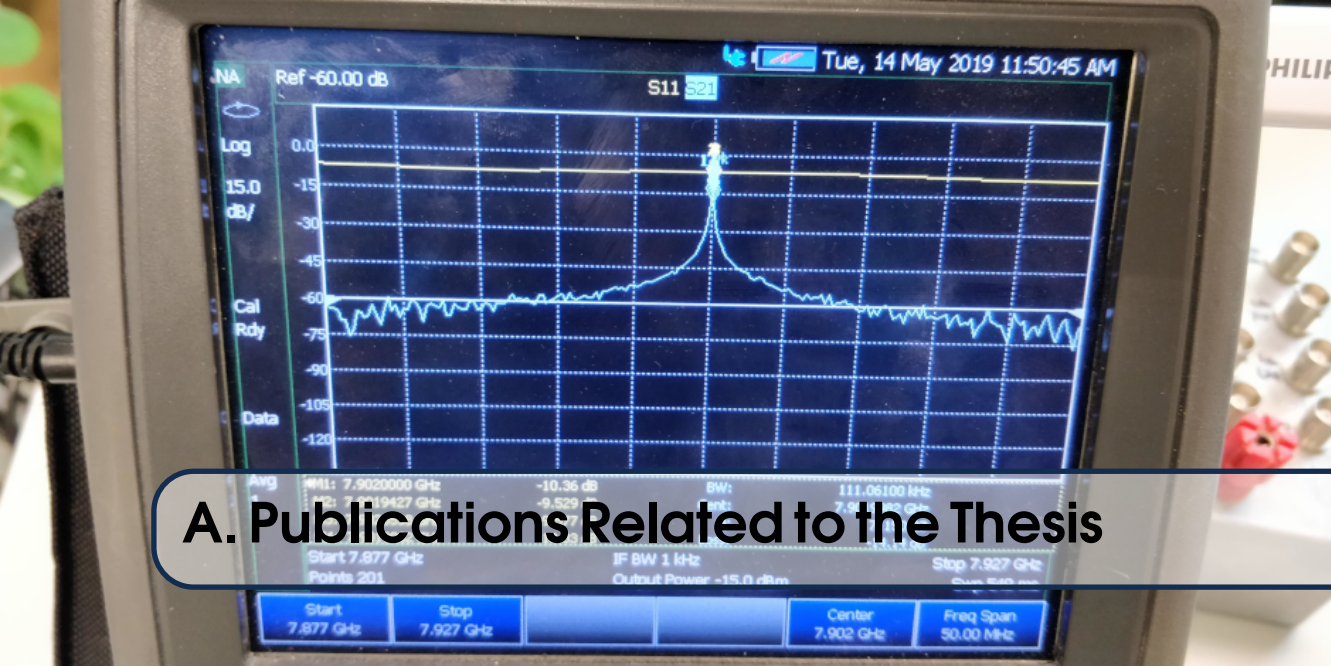
Beam impedance on a round pipe: Copper against ReBCO-CC

The main significance of our experiments reside in the resistive wall impedance. We performed a modelling with a simple case study of a round pipe approximation being either entirely coated by copper or entirely coated by one of the best performing ReBCO-CC. This way, we could draw conclusions on the true potential impact of the results on the resistive wall impedance for the accelerator.

By means of all the results, the different frequency dependency proved through our measurements and predicted magnetic field effects on the surface impedance of ReBCO-CCs and FCC-hh BS copper, employing ReBCO-CCs as a beam screen coating alternative to copper promotes a significant reduction -orders of magnitude- of the resistive wall impedance in the whole beam frequency spectrum; both longitudinal and transverse. Our study provides the first experimental evidence that ReBCO-CCs are genuine potential candidates to substitute copper as the coating for the beam screen chamber of the Future Circular Hadron Collider.

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Two peer-reviewed articles were published as the primary author during the doctoral thesis, outlining the thesis's most significant accomplishments with the third and fourth publication are in preparation. In addition, two proceeding articles were published as the primary author, outlining partial thesis's accomplishments. Within the consortium project, two additional peer-reviewed articles were published with highly relevant content for this thesis. Furthermore, two peer-reviewed articles were written with collaborators outside the consortium framework performing measurements with the experimental set-ups established during the thesis. The last publication to mention is the conceptional design report for the future circular collider hadron-hadron design.

- 2018

Small Footprint Evaluation of Metal Coatings for Additive Manufacturing - *P. Krkotić, A. Aguasca and J.M. O'Callaghan* at the 48th European Microwave Conference IEEE Xplore, DOI: 10.23919/EuMC.2018.8541442
- 2019

Coated conductor technology for the beamscreen chamber of future high energy circular colliders - *T. Puig, P. Krkotić, A. Romanov, and +11*, in Superconductor Science and Technology, DOI: 10.1088/1361-6668/ab2e66

- 
- Contactless Electrical Resistance of 2D Materials Using a Rutile Resonator** - *D. Arcos, P. Krkotić, J.M. O'Callaghan, and +3*, in *Physica Status Solidi B*, DOI: 10.1002/pssb.201900428
- FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3"** - *M. Benedikt, M. Caprignani, F. Cerutti, and +1339*, in *The European Physical Journal Special Topics*, DOI: 10.1140/epjst/e2019-900087-0
- Characterisation of copper and stainless steel surfaces treated with laser ablation surface engineering** - *A.N. Han-nah, P. Krkotić, R. Valizadeh, and +6*, in *Vacuum*, DOI: 10.1016/j.vacuum.2021.110210
- High frequency response of thick REBCO coated conductors in the framework of the FCC study** - *A. Romanov, P. Krkotić, G. Telles, and +7*, in *Nature Scientific Reports*, DOI: 10.1038/s41598-020-69004-z
- RF Characterisation of New Coatings for Future Circular Collider Beam Screens"** - *P. Krkotić, F. Perez, M. Pont, and +10*, at the *JaCoW IPAC 21 Proceedings*, DOI:10.18429/JACoW-IPAC2021-TUPAB399
- Algorithm for Resonator Parameter Extraction From Symmetrical and Asymmetrical Transmission Responses** - *P. Krkotić, Q. Gallardo, N. Tagdulang, and +2*, in *IEEE Transactions on Microwave Theory and Techniques*, DOI: 10.1109/tmtt.2021.3081730 Webpage developed: www.arpe.upc.edu
- Evaluation of the nonlinear surface resistance of REBCO coated conductors for their use in the FCC-hh beam screen** - *P. Krkotić, A. Romanov, N. Tagdulang, and +8*, in *Superconductor Science and Technology*, DOI: 10.1088/1361-6668/ac4465

B. Appendices

B.1 Appendix on Superconductors: Basics and State of the Art of Coated Conductors

B.1.1 Buffer Layer of ReBCO-CC Providers

Table B.1 provides the different buffer layers that are used by the several providers to grow ReBCO films with different techniques. The table is an extension of Tab.2.1 which compares the different coated conductors measured in our set-ups. Table B.1 is taken from and provided by [Rom22].

Table B.1: Buffer layer structure of provided ReBCO-CCs taken from [Rom22].

Manufacturer	Buffer
Bruker	Y-stabilized Zr (2 μm)/CeO ₂ (70 nm)
Fujikura	Al ₂ O ₃ /Y ₂ O ₃ /MgO/CeO ₂ (700nm)
Fujikura APC	Al ₂ O ₃ /Y ₂ O ₃ /MgO/CeO ₂ (700nm)
SuNAM	Al ₂ O ₃ (40 nm)/Y ₂ O ₃ (7 nm)/MgO (10 nm) /MgO (20 nm)/LaMnO ₃ (20 nm)
SuperOx	Al ₂ O ₃ (50 nm)/Y ₂ O ₃ (40 nm)/MgO (6 nm) /LaMnO ₃ (40 nm)/CeO ₂ (150 nm)
SuperOx APC	Al ₂ O ₃ (40 nm)/Y ₂ O ₃ (7.5 nm)/MgO (6 nm) /MgO (100nm)/LaMnO ₃ (40 nm)
SuperPower	MgO (10nm)/MgO (30 nm)/LaMnO ₃ (30 nm)
THEVA	MgO (2.5 nm)/MgO (300 nm)

B.2 Appendix on Microwave Resonators

B.2.1 Algorithm for Resonator Parameter Extraction with Outlier Removal

Figure B.1 is a screenshot of the online executable version of ARPE. As can be seen in the figure, data files can be easily uploaded and then post-processed by pressing the calculate button. Each file can be seen in the list of files individually as in the given example in the figure. A table summarises all the results which can be exported as an Excel file.

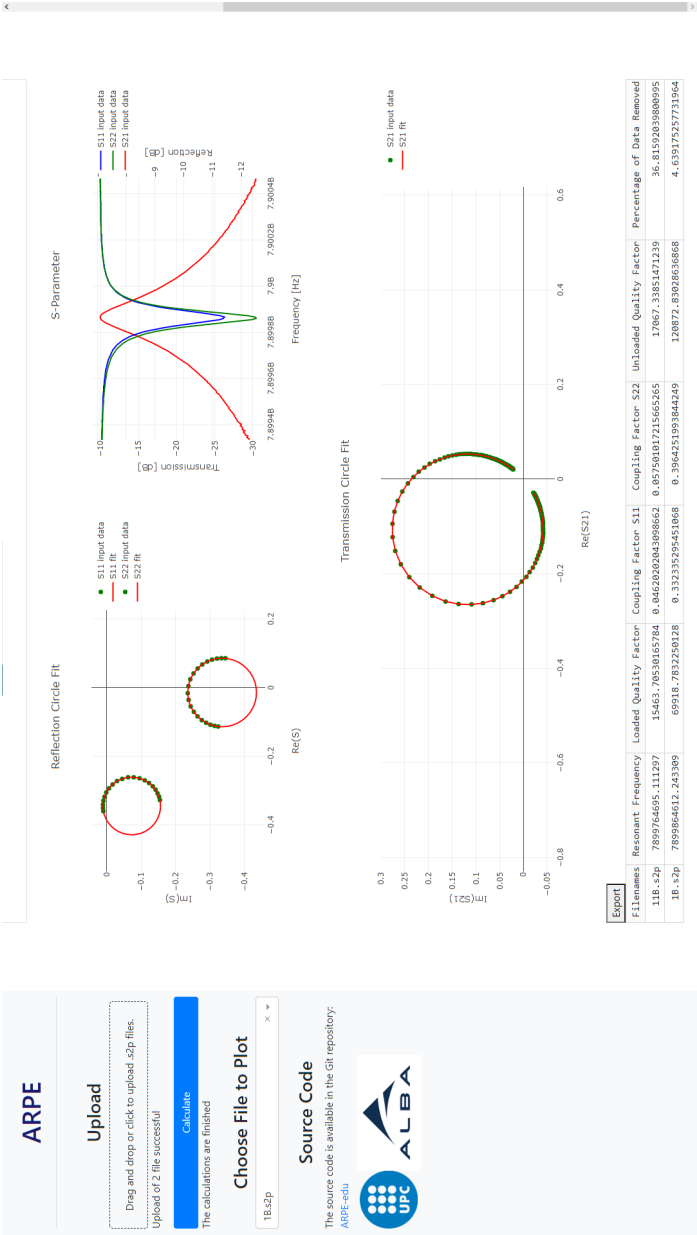


Figure B.1: This Figure is a screenshot of the online executable version of ARPE.

B.3 Appendix on Resonators for Material Testing

B.3.1 Derivation of the EM fields in the CHCDR

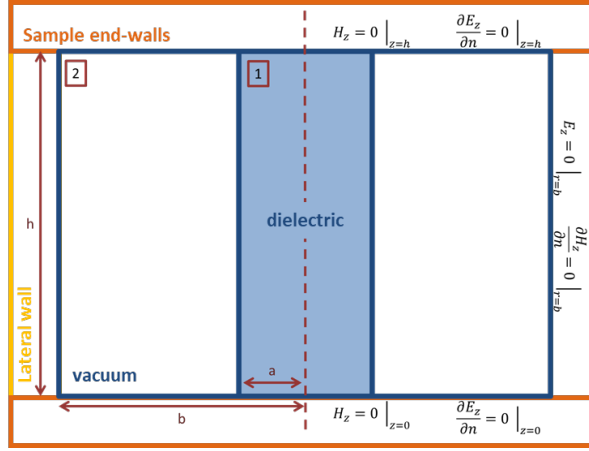


Figure B.2: The cross-sectional area of the geometry of a cylindrical dielectric resonator (blue area with radius (a) placed between two parallel conducting plates (orange with distance h among them) and closed with a conducting lateral wall (yellow with radius (b)). In addition, the Neumann and Dirichlet boundary conditions that apply to the blue surfaces are indicated.

In this section, we expand the derivation of the electromagnetic fields for a CHCDR, continuing from the general Eq.(7.6) in Sec.7.2. The general solutions depending on the region including a cylindrical dielectric (region 1) in a cylindrical cavity (region 2) based on the conditions shown in Fig.B.2 can be found as:

$$\begin{aligned} M_z(r, \phi, z) &= [A J_m(k_{r_1} r) + B Y_m(k_{r_1} r)] [C \cos(m\phi) + D \sin(m\phi)] [E \cos(\beta z) + F \sin(\beta z)] \\ N_z(r, \phi, z) &= [S K_m(k_{r_2} r) + T I_m(k_{r_2} r)] [U \cos(m\phi) + V \sin(m\phi)] [W \cos(\beta z) + X \sin(\beta z)], \end{aligned} \quad (\text{B.1})$$

where, the function M belongs to the region including the dielectric and the function N expresses the region without dielectric. $A - F$ and $S - X$ are constants, J, Y, K, I denote the Bessel- and Hankel-functions of order m . Inside the dielectric puck the electromagnetic fields have to be finite and periodic with respect to ϕ . Furthermore, we have to assume a standing wave in respect to z . Outside the dielectric, the electromagnetic fields are similarly periodic with respect to ϕ and z . However, unlike the components inside, they shall be exponentially decaying in r -direction. The radial wave numbers are defined as:

$$\begin{aligned} k^2 &= k_0^2 \epsilon_r \\ k_{r_1}^2 &= k^2 - \beta^2 \\ k_{r_2}^2 &= \beta^2 - k_0^2. \end{aligned} \quad (\text{B.2})$$

In the next step, the boundary conditions have to be applied to the general solutions in Eq.(B.1).

Radial Dependence

Region 1

The electromagnetic fields do not only have to be finite, but also finite in the origin. As $Y_m(r=0) \rightarrow \infty$ the constant $B=0$.

Region 2

Here, even though we expect an exponential decay outside the dielectric we have to keep both radial functions to assure that we can consider the effect of the lateral walls.

Azimuthal Dependence

Region 1 and 2

Only for $m=0$, the fields are split into transverse electric (TE) and transverse magnetic fields (TM) with no ϕ -variation, completely independent of each other. For all $m>0$, the fields are hybrid (HEM) having both TE and TM parts [KG98]. As we are mostly interested in the azimuthal independent modes we will consider $m = 0$ throughout the derivation.

With these two simple assumptions the general solutions already reduce to:

$$M_z(r, z) = A J_m(k_{r1} r) [E \cos(\beta z) + F \sin(\beta z)] \quad (\text{B.3})$$

$$N_z(r, z) = [S K_m(k_{r2} r) + T I_m(k_{r2} r)] [W \cos(\beta z) + X \sin(\beta z)]. \quad (\text{B.4})$$

Keep in mind, that these two general formulations are valid for both, magnetic and electric field, meaning; $M_z = H_{z1} = E_{z1}$ and $N_z = H_{z2} = E_{z2}$, where the subscript denotes the region. For the continuing derivation another subscript will be added to distinguish the constants of the electric and magnetic field.

Boundary Condition: $H_z(r, z) = 0|_{z=0} \quad \partial_n E_z(r, z) = 0|_{z=0}$

Region 1

Applying the boundary condition on the general solutions lead to:

$$H_{z1}(r, 0) = A_H J_m(k_{r1} r) [E_H \cos(\beta 0) + F_H \sin(\beta 0)] = 0 \quad (\text{B.5})$$

which is only true if $E_H = 0$. Further,

$$\partial_z E_{z1}(r, 0) = A_E J_m(k_{r1} r) [-E_E \sin(\beta 0) + F_E \cos(\beta 0)] = 0, \quad (\text{B.6})$$

which, on the opposite, is only true if $F_E = 0$.

Therefore, our electromagnetic fields in region 1 reduce to:

$$H_{z1}(r, z) = A_H J_m(k_{r1} r) \sin(\beta z) \quad (\text{B.7})$$

$$E_{z1}(r, z) = A_E J_m(k_{r1} r) \cos(\beta z) \quad (\text{B.8})$$

where we summarised all leftover constants into one.

Region 2

As the dependence in z -direction is defined in the same manner as in region 1 the calculation is basically the same, leading to the field equations:

$$H_{z2}(r, z) = [S_H K_m(k_{r2}r) + T_H I_m(k_{r2}r)] \sin(\beta z) \quad (\text{B.9})$$

$$E_{z2}(r, z) = [S_E K_m(k_{r2}r) + T_E I_m(k_{r2}r)] \cos(\beta z) \quad (\text{B.10})$$

Boundary Condition $H_z(r, z) = 0|_{z=h}$ $\partial_n E_z(r, z) = 0|_{z=h}$

Region 1

Applying the boundary conditions leads to

$$H_{z1}(r, h) = A_H J_m(k_{r1}r) \sin(\beta h) = 0 \quad (\text{B.11})$$

$$\partial_z E_{z1}(r, h) = -A_E J_m(k_{r1}r) \sin(\beta h) = 0 \quad (\text{B.12})$$

Both cases are only true if

$$\sin(\beta h) = 0 \longleftrightarrow \beta = \frac{p\pi}{h} \quad (\text{B.13})$$

Region 2

The same dependence for β results applying this boundary condition to the electromagnetic fields of region 2, which makes sense, as the two regions have to be in phase.

Boundary Condition $E_z(r, z) = 0|_{r=b}$ $\partial_n H_z(r, z) = 0|_{r=b}$

This boundary condition can only be applied for region 2:

$$\partial_r H_{z2}(b, z) = [k_{r2} S_H K'_m(k_{r2}b) + k_{r2} T_H I'_m(k_{r2}b)] \sin(\beta z) = 0 \quad (\text{B.14})$$

$$E_{z2}(b, z) = [S_E K_m(k_{r2}b) + T_E I_m(k_{r2}b)] \cos(\beta z) = 0. \quad (\text{B.15})$$

From Eq.(B.14) we get:

$$\begin{aligned} [k_{r2} S_H K'_m(k_{r2}b) + k_{r2} T_H I'_m(k_{r2}b)] &= 0 \\ S_H K'_m(k_{r2}b) + T_H I'_m(k_{r2}b) &= 0 \\ S_H &= -T_H \frac{I'_m(k_{r2}b)}{K'_m(k_{r2}b)} = -T_H \Omega', \end{aligned} \quad (\text{B.16})$$

and from Eq.(B.15) we get:

$$\begin{aligned} [S_E K_m(k_{r2}b) + T_E I_m(k_{r2}b)] &= 0 \\ S_E &= -T_E \frac{I_m(k_{r2}b)}{K_m(k_{r2}b)} = -T_E \Omega, \end{aligned}$$

Solutions

With these boundary conditions applied on the general solution we have defined our electromagnetic fields within the whole cavity as follows:

$$H_{z1}(r, z) = A_H J_m(k_{r1} r) \sin(\beta z) \quad (\text{B.17})$$

$$E_{z1}(r, z) = A_E J_m(k_{r1} r) \cos(\beta z) \quad (\text{B.18})$$

$$H_{z2}(r, z) = T_H [-\Omega' K_m(k_{r2} r) + I_m(k_{r2} r)] \sin(\beta z) \quad (\text{B.19})$$

$$E_{z2}(r, z) = T_E [-\Omega K_m(k_{r2} r) + I_m(k_{r2} r)] \cos(\beta z). \quad (\text{B.20})$$

The description of the full electromagnetic field z-component, is, as we know from Eqs.(7.1)-(7.4) enough to provide the full set of the electromagnetic fields:

TE_{0np}-Modes (B.21)

$$H_{rx} = \frac{1}{k_{rx}^2} \frac{\partial^2}{\partial z \partial r} H_z \quad (\text{B.22})$$

$$H_{\phi_x} = \frac{1}{k_{rx}^2} \frac{1}{r} \frac{\partial^2}{\partial z \partial \phi} H_z \quad (\text{B.23})$$

$$E_{\phi_x} = \frac{1}{k_{rx}^2} i\omega\mu \frac{\partial}{\partial r} H_z \quad (\text{B.24})$$

$$E_{rx} = -\frac{1}{k_{rx}^2} i\omega\mu \frac{\partial}{\partial \phi} H_z \quad (\text{B.25})$$

TM_{0np}-Modes (B.26)

$$H_{rx} = \frac{1}{k_{rx}^2} i\omega\epsilon \frac{1}{r} \frac{\partial}{\partial \phi} E_z \quad (\text{B.27})$$

$$H_{\phi_x} = -\frac{1}{k_{rx}^2} i\omega\epsilon \frac{\partial}{\partial r} E_z \quad (\text{B.28})$$

$$E_{\phi_x} = \frac{1}{k_{rx}^2} \frac{1}{r} \frac{\partial^2}{\partial z \partial \phi} E_z \quad (\text{B.29})$$

$$E_{rx} = \frac{1}{k_{rx}^2} \frac{\partial^2}{\partial z \partial r} E_z \quad (\text{B.30})$$

Here x is the index for the region considered. Take into account, that the sign of the equations will change depending on the region definition of the radial wavenumber. Furthermore, bear in mind, that $m = 0$ and the derivative of the Bessel- and Hankel-functions are:

$$J_0(\gamma x) = -\gamma J_1(\gamma x)$$

$$K_0(\gamma x) = -\gamma K_1(\gamma x)$$

$$I_0(\gamma x) = \gamma I_1(\gamma x).$$

Substituting $n=1$ and $p=1$ for the TE-mode results in the electromagnetic fields given in Sec.7.3.2.

B.4 Appendix on Experimental Set-ups

B.4.1 DRΩMS Key Features

Dielectric Resonator Surface Impedance Measurement System - DRΩMS is a joint developed software within the consortium between ALBA, ICMAB, and UPC, provided by Patrick Krkotić, Guilherme Telles, and Bernat Bozzo.

This section summarises briefly all available measurement possibilities and gives an overview of the main functions. There are four types of experiments, which are executed by four different experiment functions: *TemperatureStep*, *TemperatureTime*, *FieldStep* and *FieldTime*. In the following subsections, each of these functions is described in more detail. As a reference, Fig.B.4 illustrates the behaviour of each experiment function individually.

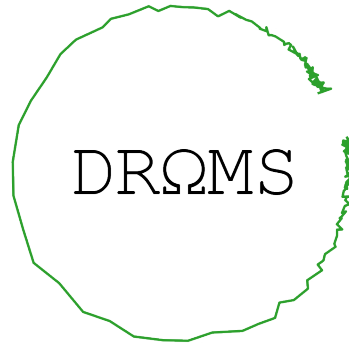


Figure B.3: Software logo

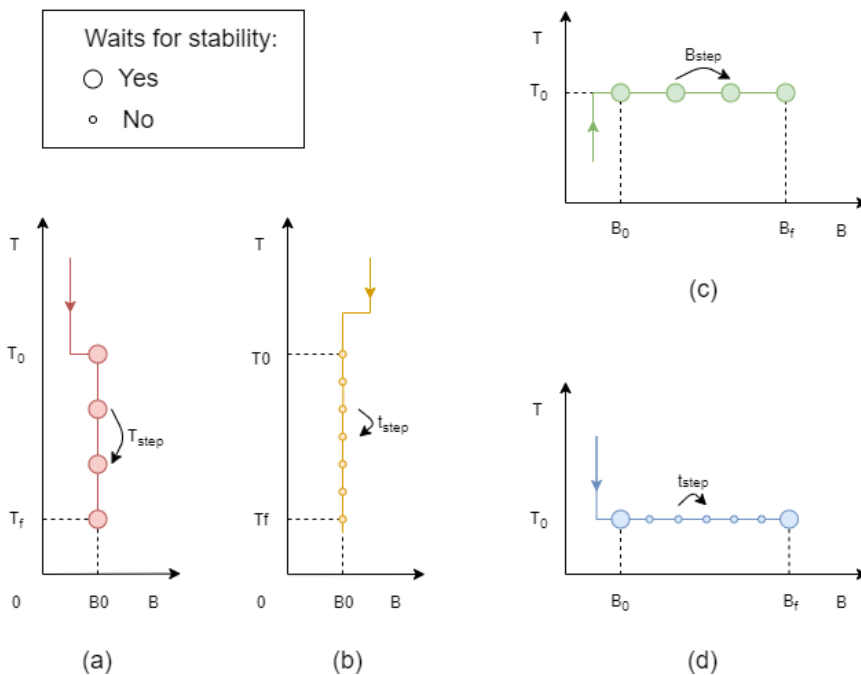


Figure B.4: General behaviour of each of the experiment functions: (a) *TemperatureStep*, (b) *TemperatureTime*, (c) *FieldStep*, and (d) *FieldTime*. Figure created by Guilherme Telles.

TemperatureStep - Temperature Sweep in Steps

TemperatureStep is a routine for making a temperature sweep with equidistant temperature steps T_{Step} at a fixed magnetic field B_0 . After receiving the parameters from the list of experiments and configuring the network analyser, the function will set the temperature to $T = T_0$, where T_0 is the user defined first cool-down temperature, then waits for stabilisation and ramps the magnetic field to $B = B_0$. Once both are signalised by the PPMS system to be stable, the measurement itself will begin. At each measurement point, the network analyser zooms in the frequency range of interest in order to increase accuracy. After storing the S-parameter data, the frequency range is zoomed out, back to its initial values predefined by the user. For the following points, the magnetic field is already set, so only the temperature needs to be changed by T_{Step} to T_i , where $T_i = T_0 \pm i \cdot T_{Step}$ is between T_0 and T_f , and $i \in \mathbb{N}$. After the PPMS signalises temperature stability, the measurement procedure is repeated, until the final temperature, T_f , is reached.

Function Summary:

- Inputs: B_0 , T_0 , T_f , T_{Step}
- Equidistant temperature points (ΔT min. 5 K)
- Multiple magnetic field sweeps 0-9 T
- Temperature range 12 - 310 K
- Temperature sensor decoupling below 40 K: Yes
- Temperature stability: Yes
- Magnetic field stability: Yes

TemperatureTime - Temperature Sweep in Time Intervals

TemperatureTime is a routine for making a temperature sweep with a constant time interval t_{Step} at a fixed magnetic field B_0 . The function configures the VNA and sets the field to $B = B_0$ and the temperature to a value $T = T_0 \pm 15 \text{ K}$ in such a way that it is outside the measurement range, $[T_0, T_f]$. Once, the temperature is stabilised, a temperature ramp rate of 1 K per minute is applied and the function constantly monitors the temperature, once a temperature within the desired the measurement range is reached, the actual begins measuring. Measurement points are taken when $T_i = T_0 \pm i \cdot \frac{1}{60} [\text{K/sec}] \cdot t_{Step}$ is between T_0 and T_f , and $i \in \mathbb{N}$. Figure B.5 shows an example of the temperature behavior for the *TemperatureTime* function with a decreasing temperature sweep. For the first measurement point, it instructs the VNA to change the frequency range to increase accuracy, then stores the data. After that, it waits for t_{Step} for the next measurement, while constantly tracking the S_{21} peak to keep the f_0 .

Function Summary:

- Inputs: B_0 , T_0 , T_f , t_{Steps}
- Equidistant temperature points (1 K/min)
- Multiple magnetic field sweeps 0-9 T
- Temperature range 12 - 310 K
- Temperature sensor decoupling below 40 K: No
- Temperature stability: No
- Magnetic field stability: Yes

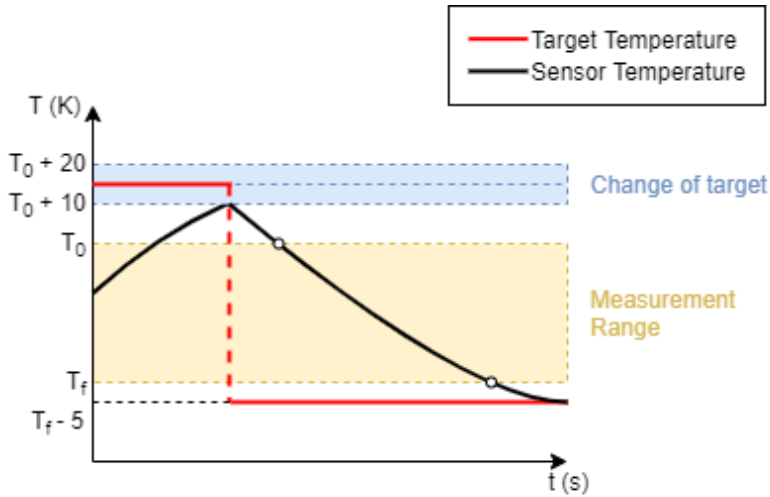


Figure B.5: Temperature behaviour for the *TemperatureTime* function. Figure created by Guilherme Telles.

FieldStep - Magnetic Field Sweep in Steps

The *FieldStep* function follows the same logic as *TemperatureStep*, except that now the Temperature is at a fixed value and the field changes at constant steps. Both functions can be viewed as basically the same with the variables swapped. Measurement points are taken where $B_i = B_0 \pm i \cdot B_{Step}$ is between B_0 and B_f , and $i \in \mathbb{N}$. It waits for stability in both temperature and field until each measurement is performed and frequency range is zoomed in and out at all measurement points. As the whole experiment happens at a single temperature value, the reference sensor will be defined in the beginning of the experiment, as opposed to at each point like with *TemperatureStep*.

Function Summary:

- Inputs: T_0 , B_0 , B_f , B_{Steps}
- Equidistant magnetic field points (ΔB min. 100 Oe)
- Multiple temperature sweeps 12-310 K
- Magnetic field range 0 - 9 T
- Temperature sensor decoupling below 40 K: Yes
- Magnetic field stability: Yes

FieldTime - Magnetic Field Sweep in Time Intervals

FieldTime is the function for field sweeps with fixed time intervals at constant temperatures. It is similar to *TemperatureTime* in many ways, but with a few notable differences. As is the case with *FieldStep*, only a single temperature value is required. Therefore, temperature is set to $T = T_0$ and it waits for stability. The magnetic response of the system is much faster than its thermal response. This means that, while it is not strictly necessary to reach stability for the magnetic field, it does not offer much advantage not to do so. Therefore, for the first measurement point, the field is also set to $B = B_0$ and the system waits for stability. Then, it sets the field to $B = B_f$ and measurement begins.

The measurement points are taken where $B_i = B_0 \pm i \cdot 100 [Oe/sec] \cdot t_{Step}$ is between B_0 and B_f , and $i \in \mathbb{N}$. From there on, it behaves similar to the *TemperatureTime* with the variables swapped: for the first point, range is zoomed in for accuracy, then it just updates the range to keep the resonance frequency at the centre. Once field is once again stable, the experiment ends.

Function Summary:

- Inputs: T_0, B_0, B_f, t_{Steps}
- Equidistant magnetic field points in time (100 Oe/sec)
- Multiple temperature sweeps 12-310 K
- Magnetic field range 0 - 9 T
- Temperature sensor decoupling below 40 K: Yes
- Magnetic field stability: Yes

Reverse

One of the options available to the user is manifested through the *Reverse* function. Selecting this option repeats the experiment in question once it is done, but with reversed parameters, i.e. add a reverse measurement to the subset: a magnetic field from B_1 to B_2 will then be repeated from B_2 to B_1 and a temperature sweep from T_1 to T_2 will then be repeated from T_2 to T_1 .

Demagnetisation

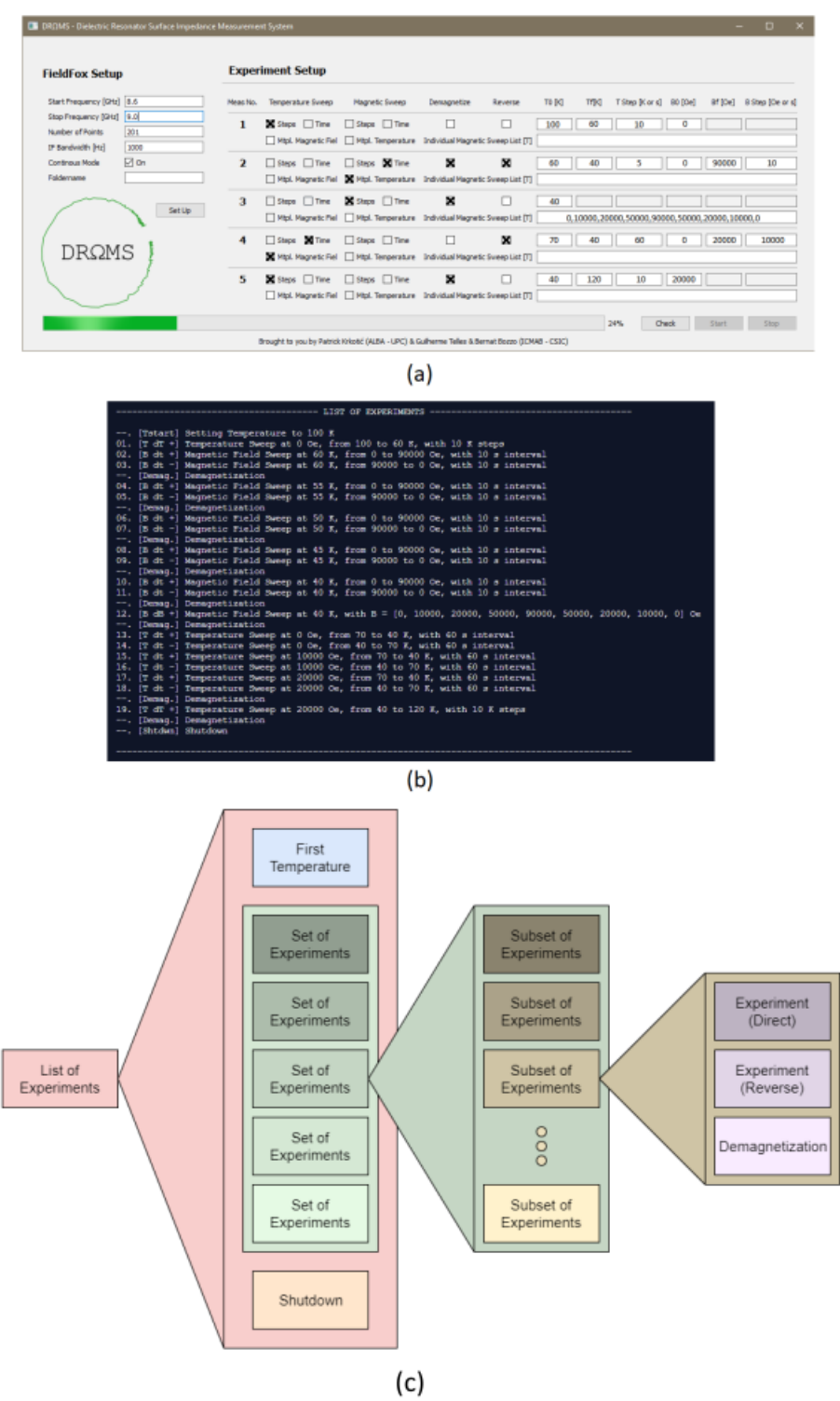
If the user selects the *Demagnetize* function, a demagnetisation procedure will be performed after the measurement in the line in question is finished before starting the next procedure. This function brings the field to negative³⁰ 10000 Oe and then sets it back to zero in an oscillating mode, which should be enough to reduce the magnetisation to a negligible value.

Sets of Experiments

An example to understand how above mentioned functions can be used for multiple experiments is shown in Figure B.6, which shows one possibility of how the GUI parameters can be chosen and the consequent list of experiments generated by it. Every time the *Check* button is pressed and no errors are found, a list of experiments is generated. This list is printed so that the user can verify that all steps are correct. If that is the case, pressing the *Start* button executes the experiments displayed in the list in the order they are listed. At this point, the user can still change the parameters in the GUI, needing only to check and confirm the list of experiments once again. The order and hierarchy of the generated list of experiments is shown in Fig.B.6.

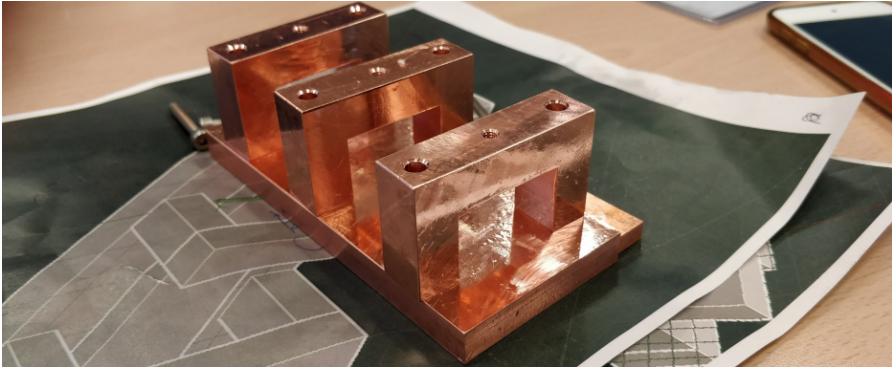
There can be up to five sets of experiments, each of which may contain several subsets depending on whether the *Multiple Fields / Temperature* was selected. On their turn, each subset always contains an experiment as configured by the user in the GUI. It may also contain a reverse experiment and the demagnetization procedure, if the *Reverse* and *Demagnetize* options were chosen.

³⁰The sign refers to the magnetic field orientation.

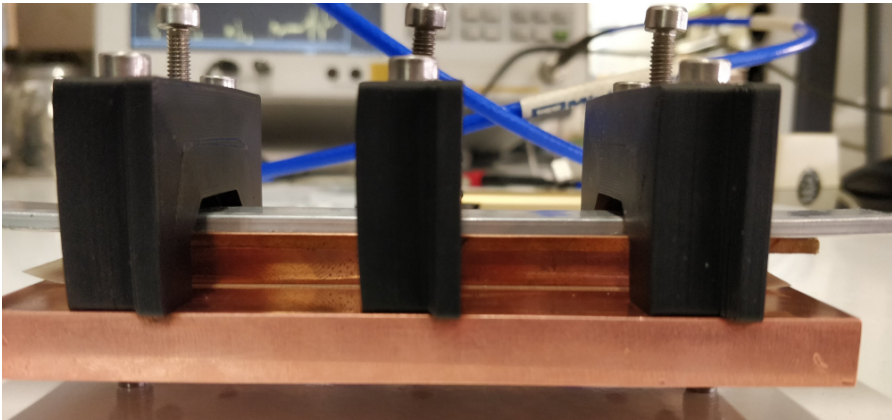


B.4.2 PPR Designs

Over the different stages of designing and testing the parallel plate resonator, several PPRs were constructed and modified which shall be illustrated in this section.



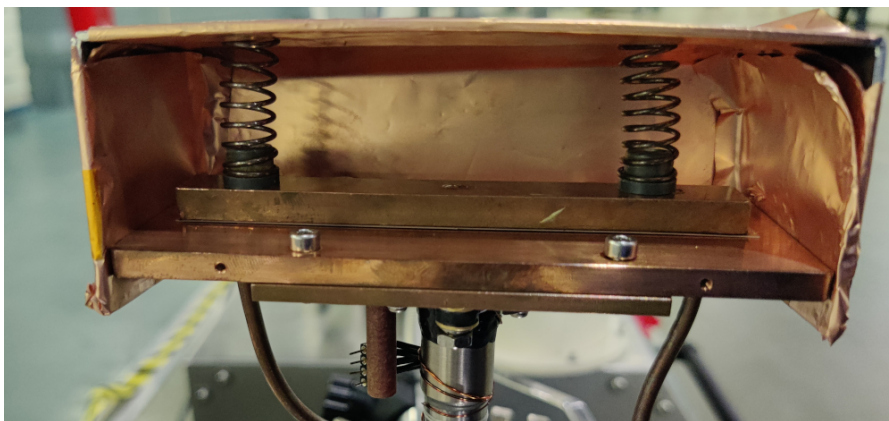
(a) 10 cm PPR with metal bridges



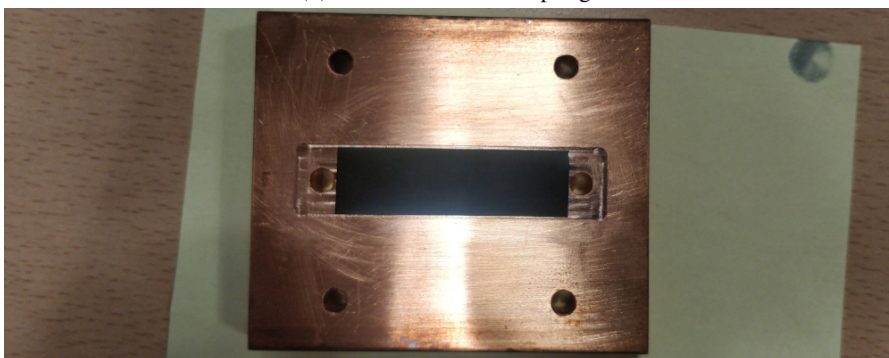
(b) 10 cm PPR with 3D printed bridges and screws



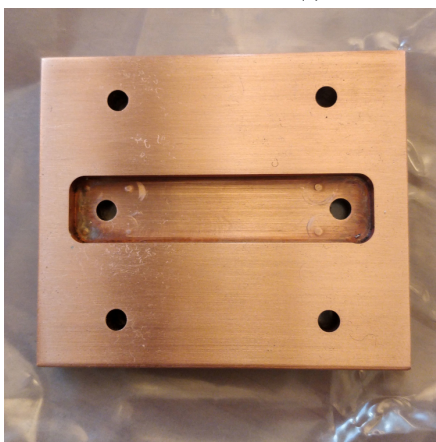
(c) 5 cm PPR with PVC bridges and screws



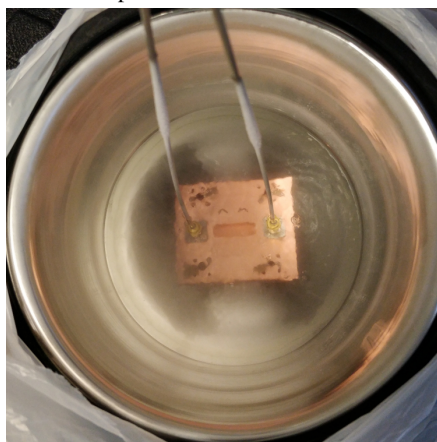
(d) 10 cm flat PPR with springs



(e) 5 cm PPR with 1 mm depth



(f) 5 cm PPR with 1 cm depth



(g) 5 cm PPR with full cut-out cool-down test

Figure B.7: Several parallel plate resonator designs.

B.5 Appendix on Temperature and Magnetic Field Dependence

B.5.1 Rutile dielectric loss measurements

The shielded dielectric resonator presented in detail by [Bre16] is very similar to the Hakki-Coleman design whereas the main goal here is to determine the properties of the dielectric cylinder instead of the metallic housing. This technique enables the most accurate measurements of very low loss dielectric materials. However, the technique is quite complex and requires large dielectric samples of specific shape. The resonating structure, sketched in Fig.B.8, consists of a metallic body housing a

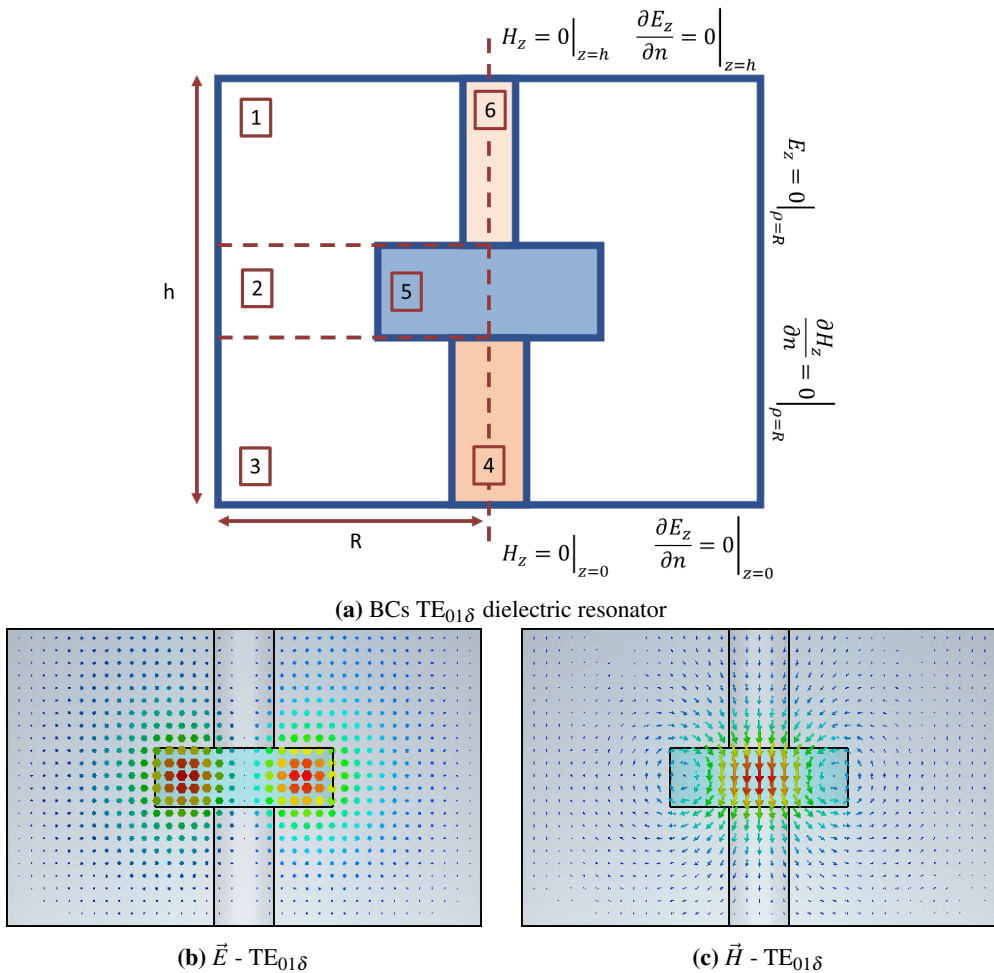


Figure B.8: (a) The cross-sectional area of the overall geometry of the boundary problem, including the corresponding Neumann and Dirichlet boundary conditions and several region needed for the $TE_{01\delta}$ DR. The geometry consists of four cylinders of different radius and material. (b) and (c) show the electric and magnetic field of the $TE_{01\delta}$ mode, respectively. It can be seen in these figures that due to the change in geometry of the cylinders and difference in permittivity the field lines are not exactly the same as in Fig.7.3.

dielectric in its center which considerably larger distance to the end-plates reduces the losses of the metal plates significantly and increases the percentage of volume losses in the dielectric, predominantly in its loss tangent $\tan(\delta)$. To hold the dielectric to be characterised in the cavity center it is supported by two other dielectric cylinders. The dielectric materials have to be chosen in such a way, that the permittivity of the dielectric of interest is the highest, so as to maintain the highest contribution of volume losses from the material to be measured. Furthermore, its permittivity dominates the overall resonance frequency. The ideal ratio of relative permittivity goes along with the loss tangent of the dielectrics. However, the electromagnetic analysis is in practise substantially more difficult to perform analytically. The ansatz is the same as in Sec.7.2 whereas here, several regions have to be matched in radial and axial directions complicating the boundary problem. In fact, the solution can be only found by quasi-analytical mode matching technique whose accuracy is governed by the number of terms in the truncated series expansion of eigenmode basis functions and is discussed extensively in [Bre16]. Nevertheless, it is a very time consuming procedure which can be overcome by using CST and has been accomplished and explained in detail in the work of [Die20].

The permittivity so far has been always considered a scalar value. In reality microwave dielectric materials as sapphire (Al_2O_3) have interesting single-crystal anisotropic properties. In the most general case, the permittivity is expressed over a tensor $\tilde{\epsilon}$ [Bre16]:

$$\tilde{\epsilon} = \underbrace{\begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz} \end{bmatrix}}_{\text{general permittivity tensor}} \longrightarrow \underbrace{\begin{bmatrix} \epsilon_{trans} & 0 & 0 \\ 0 & \epsilon_{trans} & 0 \\ 0 & 0 & \epsilon_{long} \end{bmatrix}}_{\text{uniaxial media tensor}}. \quad (\text{B.31})$$

The first tensor is the most general way of representing the effects of material polarization when the material is anisotropic. However, having a resonant or operating transversal modes, the tensor can be simplified to the values of interest, which are the transversal ϵ_{trans} and longitudinal ϵ_{long} permittivities, represented as a uniaxial media. In a uniaxial media, two of the diagonal entries of the permittivity tensor are the same and one is different which gives reason to use the two fundamental TE_{011} and TM_{010} modes for the two directions. The electric field distribution is either purely azimuthal or axially in these modes, so as the transversal component of the permittivity and loss tangent or longitudinal component can be extracted, respectively. Nevertheless, in the case of including several dielectrics, and with that, inducing an abrupt change of permittivity axially producing a disturbance in the z-direction. The field distribution changes and the modes are actually quasi- $\text{TE}_{01\delta}$ and quasi- $\text{TM}_{01\delta}$ modes. The variation is denoted by the $\delta = 2h/\lambda_g < 1$, where h is the height of the resonator and λ_g refers to the guide wavelength of the TE_{01} dielectric waveguide mode [Poz11]. The electromagnetic field distributions are shown in Fig. B.8.

The dielectric properties of a rutile cylinder were obtained by [Die20] for the temperature range 30 – 300 K. The TE-mode was tested so as to obtain the perpen-

dicular component of the permittivity and loss tangent, and the results can be seen in Fig.B.9. These values are comparable to the ones measured in [Bre16] and [Kle+95], though, the loss tangent measured is higher than in both publications. It can be partially explained by the fact that we measured at a much higher resonance frequency.

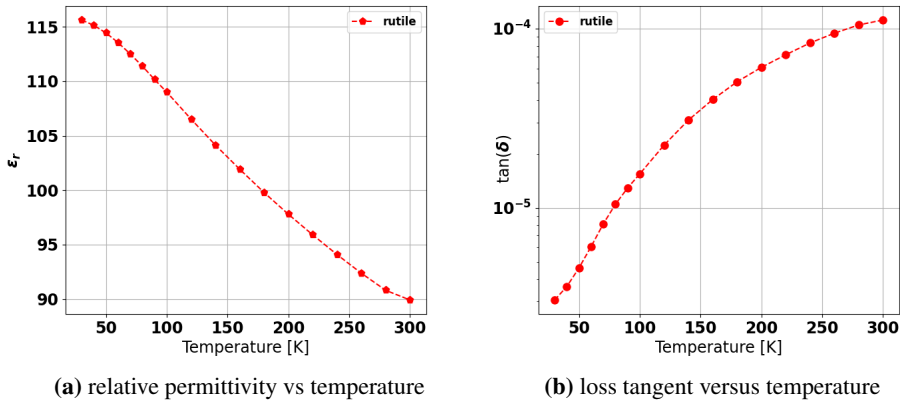


Figure B.9: Relative permittivity and loss tangent as a function of temperature. Data taken from [Die20]

Effect on ReBCO Coated Conductors

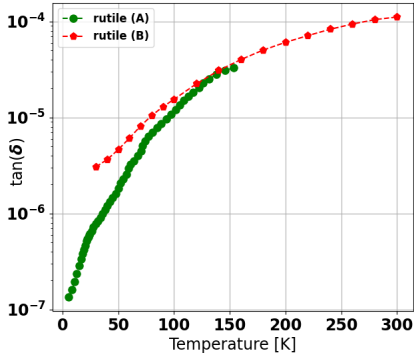
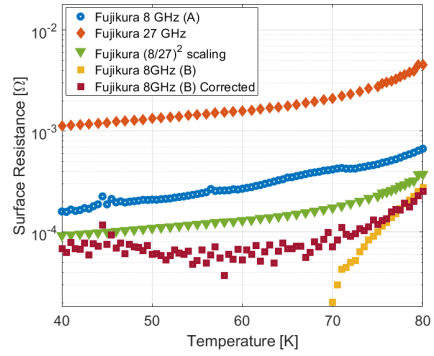
An important consequence of the aforementioned results is the possible frequency dependence of the CCs. As can be seen in Fig.B.10(a), the measured values by [Die20] refer to as rutile (B) are comparable down to cryogenic temperature to the ones measured in [Kle+95] referred to as rutile (A). However, there is a visible split between rutile (A) and (B) in the $\tan(\delta)$ values below 80 K. The re-examined R_S with the determined $\tan(\delta)$ from rutile (B) is presented for Fujikura in Fig.B.10(b) as yellow squares. The findings show that in this case the surface resistance results in a negative value below 70 K. In Fig.B.10(c) the re-examined values for Super Power are in a relatively good agreement between measurement and theory and indicate a frequency square dependency. In the measurements, the unloaded Q-factors of Fujikura and SuperPower without applied magnetic field are distinguishable but certainly very close. This leads to the following two assumptions. On the one hand, a possible unnoticed temperature issues in the measurement set-up for loss tangent measurements - and is under ongoing investigation [Tag]-. The plateau forming deviation below 50 K in rutile (B), as visible in Fig.B.10(a) supports this assumption. On the other hand, in addition, the closely measured quality factors for the two best performing providers indicate that we reached the lower limit of possible surface resistance measurements with this system and specific rutile.

A $\tan(\delta)$ correction method has been performed for rutile (B). We used the scaled values for SuperPower from the sapphire measurement and substituted them into the

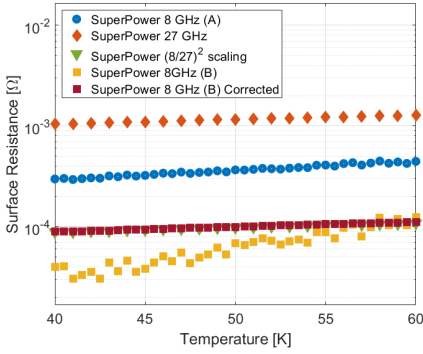
rearranged equation:

$$\tan(\delta)_{\text{rutile (B) corrected}} = \frac{1}{Q_{8\text{GHz}}} - \frac{2R_{S,27\text{GHz scaled}}}{G_{8\text{GHz}}} \quad (\text{B.32})$$

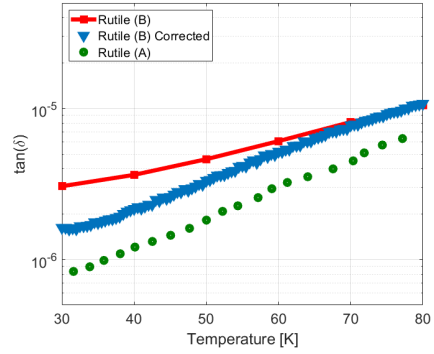
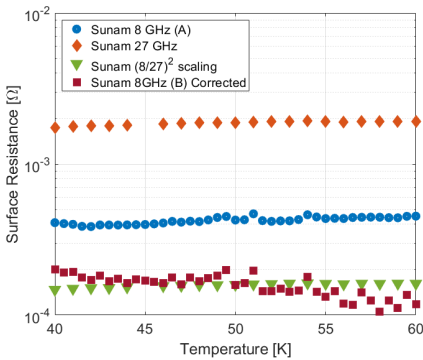
Note, that the quality factor and geometric factor are still taken from the measurements at 8 GHz. The resulting values for the loss tangent is given in Fig.B.10(d), which confirms that the measured values of rutile (B) are erroneous below 70 K due to temperature issues in the system. The deviation is about 25 per cent at 50 K. Re-evaluating the surface resistance of Fujikura (red squares Fig.B.10(b)) shows values close to the frequency squared theory. A pristine sample as SuNAM (Fig.B.10(e)) shows very good agreement with the frequency squared theory. Duet to this a general frequency squared rule is proven and can be assumed for all providers besides SuperOx. SuperOx on the contrary in Fig.B.10(c) shows only a $R_S \propto f^{1.4}$ dependence. The total film thickness of SuperOx is 900 nm, and with that the thinnest ReBCO films of all providers, which means, that the measured R_S values might be slightly influenced by the substrates as the thick film approximation might not be valid any more.


 (a) $\tan \delta$ comparison


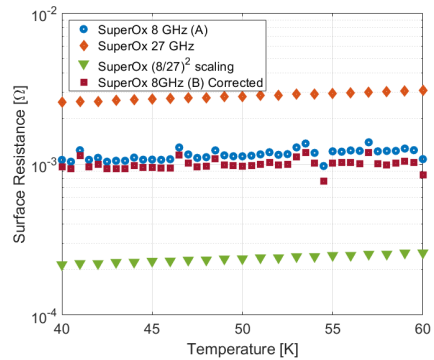
(b) Fujikura



(c) SuperPower


 (d) $\tan \delta$ correction


(e) SuNAM



(f) SuperOx

Figure B.10: Surface resistance as a function of temperature at two different frequencies including $\tan \delta$ corrections.

B.5.2 Surface Resistance Characterisation

We present here the characterisation of seven coated conductors from six different providers as a function of temperature and magnetic field.

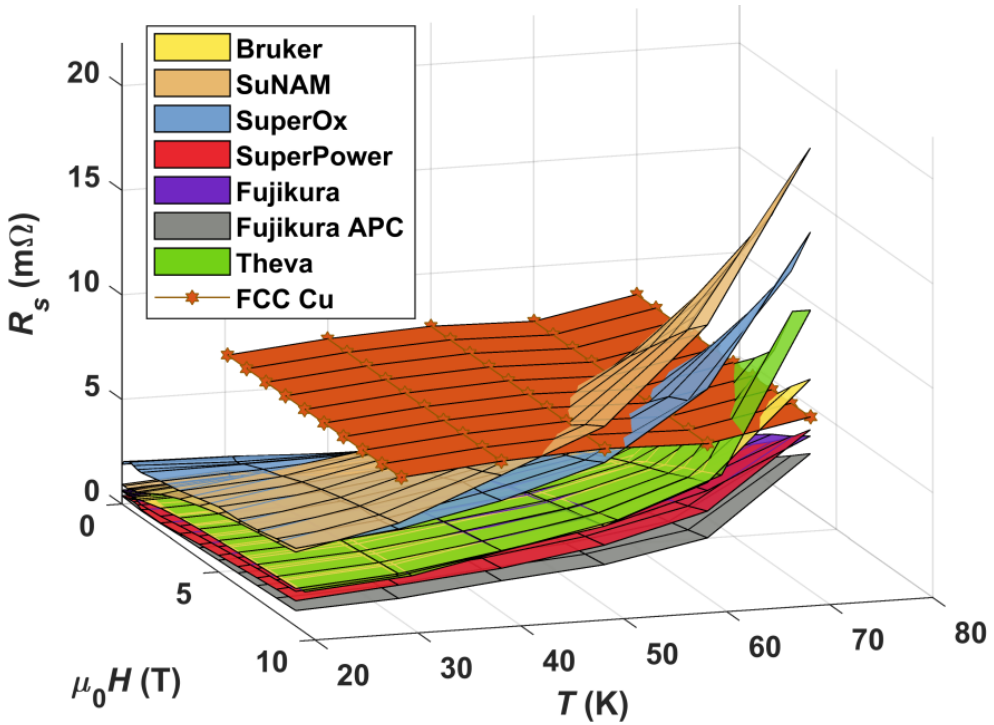


Figure B.11: Surface resistances of all providers as a function of magnetic field between 20 to 70 K. Figure taken from [RKT20]

B.6 Appendix on Thermal and RF Power Dependence

B.6.1 Supplementary Information: Why Coupling versus Surface Resistance can be Expressed as a Rational Function?

According to Sec.10.4, and to the body of the text in section III A of [Krk+21a] where an equivalent circuit of a two-port resonator is given:

$$J = \sqrt{\frac{\beta}{Z_0 R}} \longleftrightarrow \beta = J^2 Z_0 R. \quad (\text{B.33})$$

Here, J refers to the admittance transformation constant, β is the coupling factor, Z_0 is the reference impedance, and R the circuit resistance. The higher the loss in the cavity, the higher the current through the shunt resistor. Therefore, it is reasonable to assume that the conductance in the equivalent circuit is proportional to the surface resistance of the material being tested, i.e.:

$$\frac{1}{R} = cR_S + d, \quad (\text{B.34})$$

where c and d are fitting constants. The constant c sets the proportionality between surface resistance and the equivalent circuit conductance. The constant d accounts for cavity losses other than those created by the surface resistance of the materials under test. Combining the two previous equations, we obtain:

$$\beta = J^2 Z_0 \frac{1}{cR_S + d} = \frac{J^2 Z_0}{c} \frac{1}{R_S + (\frac{d}{c})}, \quad (\text{B.35})$$

which is of the form $\beta = \frac{a}{R_S + b}$ postulated in section 4 and shown in figure 10.11.

B.7 Appendix on Synchrotron Radiation

B.7.1 Delamination of Coated Conductors

An additional uncontrolled factor in the study is the de-lamination of the ReBCO-CCs which at the time of the study was under strong investigation. Due to this, the repeatability of these results is subject to certain limitations. For instance, the quality factor varied very strong among samples by the same provider. Figure B.12 shows pictures taken of de-laminated samples for the SR-PPR. Figure B.12(a) shows the example of a well de-laminated sample next to a coated conductor of the same provider as given by the provider. The exposure of the buffer layer can be taken as an indicator of the quality of the de-laminated sample. Hence in this figure, the buffer layer (violet) is visible over a large area while residuals of the ReBCO layer (black) can be seen only on the edges of the tape. Fig.B.12(b) shows another de-laminated sample in which the whole ReBCO layer has been partially removed from the sample instead of the buffer layer. Figure B.12(c) deals as a visual comparison between the two providers Fujikura and SuperPower.

The de-lamination process has a strong influence on the data and explains the differences in quality factor between the measurements. For a good reproducibility the de-lamination is under ongoing study by [Tela]. Nevertheless, the results still can be generalised to the FCC-hh beam screen requirements the ReBCO-CCs have to fulfil, though the sensitivity of the measurements is influenced.

The perfect de-lamination is not straightforward and the ReBCO film can be in local positions, partially or completely removed. In addition, the de-lamination line as indicated in Fig.8.17 as the yellow line, can happen to be as well partially between the CeO_2 and MgO leaving residuals of the buffer layer on the ReBCO film. In this way, as depicted in Fig.8.18, the SR-PPR is formed by the cut-out covered by the de-laminated ReBCO-CC (Cu-Ag-ReBCO), the sapphire dielectric plate (AlO_2) and an ‘ordinary’ ReBCO-CC (Hastelloy-buffer-ReBCO).

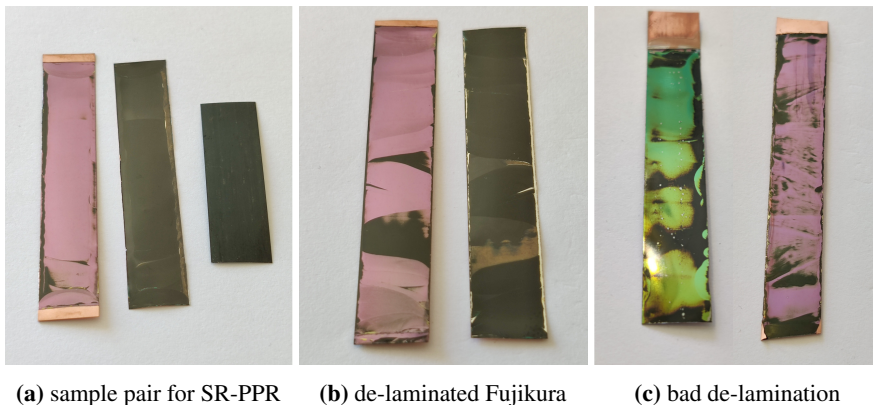


Figure B.12: Pictures of several de-laminated samples.



C. Listings

List of Acronyms

<i>T</i> -sensor	temperature sensor
2F-model	two-fluid model
AC	alternating current
aC	amorphous carbon
ALBA	ALBA Synchrotron Light Source
APC	artificial pinning centres
ARPE	algorithm for resonator parameter extraction
ASE	anomalous skin effect
BC	boundary condition
BCS	Bardeen, Cooper and Schrieffer
BM	bending magnet
BS	beam screen

CC	coated conductor
CDR	Conceptual Design Report
CERN	Conseil Européen pour la Recherche Nucléaire
CHCDR	closed Hakki-Coleman dielectric resonator
cms	centre-of-mass
CP	Cooper pair
CST	Computer Science Technology
CVD	chemical vapour deposition
CW	continuous wave
DC	direct current
DR	dielectric resonator
DRΩMS	dielectric resonator surface impedance measurement system
e-cloud	electron-cloud
EM	electromagnetic
FC	field-cooled
FCC	Future Circular Collider
FCC-ee	Future Circular Collider electron-positron
FCC-hh	Future Circular Collider hadron-hadron
FEM	finite-element-method
GL	Ginzburg-Landau
GUI	graphical user interface
HC	Hakki-Coleman
HE	hybrid electric
HE-LHC	High-Energy Large Hadron Collider
HIT	Heidelberger Ionenstrahl-Therapiezentrum
HL-LHC	High-Luminosity Large Hadron Collider
HM	hybrid magnetic
HTS	high-temperature superconductor

IFBW	intermediate frequency bandwidth
LASE	Laser-Ablated Surface Engineering
LHC	Large Hadron Collider
LTS	low-temperature superconductor
NC	normal conductor
NSE	normal skin effect
OFE	oxygen-free electronic
PDE	partial differential equation
PEC	perfect electrical conductor
PET	polyethylene terephthalate
PID	proportional-integrator-differentiator
PPR	parallel plate resonator
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
ReBCO	rare-earth barium copper oxide
RF	radio-frequency
RMS	root-mean-square
RRR	residual-resistance ratio
RT	room temperature
RW	resistive wall
SC	superconductor
SEY	secondary-electron yield
SIBC	surface impedance boundary conditions
SM	Standard Model
SPS	Super Proton Synchrotron
SR	synchrotron radiation
SS	stainless steel
TBCCO	thallium barium calcium copper oxide

TE	transverse electric
TEM	transverse electromagnetic
TM	transverse magnetic
VNA	Vector Network Analyzer
YBCO	yttrium barium copper oxide
ZFC	zero-field-cooled

List of Symbols

Fundamental Constants

NAME	DESCRIPTION	VALUE	UNIT
c	speed of light	299792458	m / s
e	elementary charge	$1.6021 \cdot 10^{-19}$	C
$\Phi_0 = h/2e$	flux quantum	$2.0678 \cdot 10^{-15}$	Tm ²
h	Planck constant	$4.1357 \cdot 10^{-15}$	eVs
$\hbar = h/2\pi$	reduced Planck constant	$0.6582 \cdot 10^{-15}$	eVs
i	imaginary unit	$\sqrt{-1}$	
μ_0	free space permeability	$1.2566 \cdot 10^{-6}$	NA ²
ϵ_0	free space permittivity	$8.8541 \cdot 10^{-12}$	F / m
π	Archimedes' constant	3.14159...	
m_e	electron mass	$9.1095 \cdot 10^{-31}$	kg

Elements

NAME	DESCRIPTION
B	boron
Ba	barium
Be	beryllium
C	carbon
Ca	calcium
Ce	cerium
Cu	copper
Eu	europium
Gd	gadolinium

Continued on next page

Table C.2 – Continued from previous page

NAME	DESCRIPTION
H	hydrogen
Hf	hafnium
Hg	mercury
La	lanthanum
N	nitrogen
Na	sodium
O	oxygen
S	sulfur
Si	silicium
Tl	thallium
Y	yttrium
Zr	zirconium

Uppercase Greek Letters

NAME	DESCRIPTION	UNIT
Γ	Arbitrary surface or area	
Δ	incremental change	
Θ	arbitrary angle	rad
Λ	arbitrary parameter	
Ξ	arbitrary parameter	
Υ	Arbitrary contour or path	
Ψ	vertical angle	rad
Ω	Arbitrary region or volume	
$\hat{\Omega}$	unit solid angle	srad

Lowercase Greek Letters

NAME	DESCRIPTION	UNIT
$\tilde{\alpha}$	attenuation constant	Np/m

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NAME	DESCRIPTION	UNIT
β	velocity factor v/c	
$\tilde{\beta}$	phase constant	rad/m
β_i	coupling factor of port i	
γ	Lorentz factor $1/\sqrt{1-\beta^2}$	
$\tilde{\gamma}$	complex propagation constant	m^{-1}
δ	penetration depth	m
δ_S	skin depth	m
δ_{SEY}	secondary electron yield	
$\tan(\delta)$	loss tangent	
ϵ	permittivity $\epsilon_0\epsilon_c$	
ϵ_c	complex permittivity $\epsilon_r(1 - i\tan(\delta_E))$	
ϵ_r	relative permittivity	
ζ	generalised permittivity	
η	viscosity coefficient	m^2/s
$\tilde{\eta}$	bunch position	m
κ	conductivity	S/m
κ_0	DC conductivity	S/m
κ_{GL}	Ginzburg-Landau parameter	
κ_n	normal conducting conductivity	S/m
κ_{nc}	normal state conductivity	S/m
κ_{sc}	complex superconducting conductivity	S/m
κ_s	superconducting conductivity	S/m
λ	wavelength	m
λ_L	London penetration depth	m
λ_{GL}	Ginzburg-Landau penetration depth	m
μ	permeability $\mu_0\mu_c$	
μ_r	relative permeability	
μ_c	permeability $\mu_r(1 - i\tan(\delta_M))$	
ξ_{GL}	coherence length	m
ρ	resistivity	$\Omega \text{ m}$
ρ_{ff}	flux-flow resistivity	$\Omega \text{ m}$
ρ_{source}	source charge density	C/m^3
ρ_{Γ}	surface charge density	C/m^2

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NAME	DESCRIPTION	UNIT
σ	root-mean-square bunch length	m
τ	relaxation time	s
τ_{CP}	CP recombination time	s
ω	angular frequency	Hz
ω_0	angular resonance frequency	Hz
ω_c	critical photon frequency	Hz

Uppercase Roman Letters

NAME	DESCRIPTION	UNIT
A	magnetic vector potential	V s/m
B	magnetic field	T
B_0	peak RF magnetic field	T
B_C	critical magnetic field	T
B_{C1}	first critical magnetic field	T
B_{C2}	second critical magnetic field	T
B_{DC}	dipole magnetic field	T
B_{RF}	RF magnetic field	T
D	electric displacement	V m
E	electric field	N/C
F_L	Lorentz force	Nm
F_P	pinning force	Nm
F_v	velocity dependent force	Nm
F_{th}	thermal force	Nm
G	geometry factor	Ω
H	magnetic field strength	A/m
H_0	peak surface RF magnetic field strength	A/m
H_C	critical magnetic field strength	A/m
H_{C1}	first critical magnetic field strength	A/m
H_{C2}	second critical magnetic field strength	A/m
H_{RF}	RF magnetic field strength	A/m
I	current	A

Continued on next page

Table C.5 – Continued from previous page

NAME	DESCRIPTION	UNIT
I_{bunch}	bunch current	A
I_{beam}	beam current	A
I_C	critical current	A / m ²
J	current density	A / m ²
J_C	critical current density	A / m ²
J_1	Bessel function of the first kind	
J_{nc}	normal conductor current density	A / m ²
J_n	normal conducting current density	A / m ²
J_{sc}	superconductor current density	A / m ²
J_s	superconducting current density	A / m ²
J_{RF}	radio-frequency current density	A / m ²
J_{source}	source current density	A / m ²
J_{tp}	transport current density	A / m ²
L	arbitrary length	m
L_{const}	off resonance return loss	dB
L_{off}	insertion loss	dB
N	arbitrary integer number	
N_γ	amount of photons	ph/s
P	power	W
P_d	power dissipated through dielectric loss	W
P_r	power dissipated through radiation loss	W
P_κ	power dissipated through ohmic loss	W
P_{diss}	power dissipated	W
P_{ext}	power dissipated through external loss	W
P_{total}	total dissipated power	W
P_{in}	cavity input power	dBm
P_{out}	VNA output power	dBm
Q	quality factor	
Q_0	unloaded quality factor	
Q_{ave}	average quality factor	
Q_L	loaded quality factor	
Q_κ	conductivity quality factor	
Q_d	dielectric quality factor	

Continued on next page

Table C.5 – *Continued from previous page*

NAME	DESCRIPTION	UNIT
Q_r	radiation quality factor	
Q_{ext}	external quality factor	
Q_{paras}	parasitic quality factor	
R	arbitrary radius	m
RRR	residual resistance ratio	
R_S	surface resistance	Ω
R_{BM}	bending magnet radius	m
R_{BS}	beam screen radius	m
$R_{S_{sc}}$	superconductor surface resistance	Ω
R_S^{res}	residual surface resistance	Ω
R_T	transverse thermal resistivity	$\text{m}^2\text{K/W}$
S	Poynting vector	W/m^2
S_{ii}	reflection S-parameter	dB
S_{ij}	transmission S-paramter	dB
T	temperature	K
T_C	critical temperature	K
T_{BS}	beam screen temperature	K
T_{ref}	reference temperature	K
U	energy	J
U_γ	photon energy	eV
U_e	electron energy	eV
$U_{\gamma,c}$	critical photon energies	eV
U_{st}	stored energy	J
U_{tot}	total energy	J
U_E	electric energy	J
U_M	magnetic energy	J
ΔU_{CP}	Cooper pair energy gap	eV
V	scalar potential	V
W	arbitrary width	m
X_S	surface reactance	Ω
$X_{S_{sc}}$	superconductor surface reactance	Ω
Z_S	surface impedance	Ω
$Z_{S_{nc}}$	normal conductor surface impedance	Ω

Continued on next page

Table C.5 – *Continued from previous page*

NAME	DESCRIPTION	UNIT
$Z_{S_{sc}}$	superconductor surface impedance	Ω
$Z_{\parallel}$	longitudinal beam coupling impedance	Ω
$Z_{\perp}$	transverse beam coupling impedance	Ω / m
$Z_{\parallel}^{RW}$	longitudinal resistive wall impedance	Ω
$Z_{\perp}^{RW}$	transverse resistive wall impedance	Ω / m

Lowercase Roman Letters

NAME	DESCRIPTION	UNIT
a	acceleration	m / s^2
b	beam screen radius	m
fd	arbitrary layer thickness	m
f	frequency	Hz
f_0	resonance frequency	Hz
f_{dep}	depinning frequency	Hz
Δf_{span}	frequency span	Hz
g	superconductor Z_S frequency dependence	
k	wavenumber	m^{-1}
k_F	spin-momentum	$\text{kg m}^2 / \text{s}$
k_p	depinning constant	m^{-1}
k_r	radial wave number	m^{-1}
k_z	waveguide propagation constant	m^{-1}
l	mean free path	m
m	mass	kg
m_B	magnetic field factor	
m_{Φ_0}	effective mass of a vortex	kg
$\hat{n}$	normal unit vector	
n_n	normal electron density	$1 / \text{m}^3$
n_s	superconducting electron density	$1 / \text{m}^3$
n_t	total charge carrier density	$1 / \text{m}^3$
p	filling factor	
q	charge	C

Continued on next page

Table C.6 – *Continued from previous page*

NAME	DESCRIPTION	UNIT
s	arbitrary thickness	m
t	time	s
t_{ret}	retarded time	s
t_{sweep}	VNA sweep time	s
v	velocity	m / s
v_{Φ_0}	vortex velocity	m / s
x	arbitrary distance	m

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