Development of a Measurement Set-up for Testing of RF-Bypasses in the LHC Injector Chain

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CERN-THESIS-2018-159
15/03/2018

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February 28, 2018

Résumé

Le CERN, Organisation européenne pour la recherche nucléaire, effectue des expériences afin de découvrir les lois de la physique fondamentale et de l'Univers. Les machines principales sont des accélérateurs à particules, connectés en chaine afin d'obtenir une énergie maximale dans le dernier maillon, le LHC, Large Hadron Collider. Dans cet accélérateur circulaire, deux faisceaux de particules circulant en sens inverse à la vitesse de la lumière et à très haute énergie entrent en collision en quatre points précis, appelés expériences. C'est à ces endroits que les interactions sont observées afin de comprendre les lois de la physique fondamentale.

Dans ce réseau d'accélérateurs, les deux premières machines circulaires, le Proton Synchrotron Booster (PSB) et Proton Synchrotron (PS) permettent d'accélérer les particules et d'augmenter leur énergie. Les particules circulent dans une chambre à vide autour desquelles se trouvent par exemple les cavités accélératrices, les unités de test ou les aimants permettant de donner un angle aux particules. Les particules étant chargées, un courant image circule dans le conduit conducteur. Dans ces deux machines, des flasques isolées électriquement, serrées par des brides, ont été ajoutées pour empêcher les courants induits par les aimants de se propager dans la structure, ce qui pourrait déstabiliser les faisceaux.

Ces isolations ont créé un circuit électronique équivalent émettant des résonances. C'est pour cela que des filtres radiofréquence (RF-Bypasses) ont été intégrés dans ces deux structures. Ceci permet de déplacer la fréquence de résonance, mais aussi d'assurer une faible impédance au domaine de fréquence utile du faisceau. Il est donc important chaque année lors de l'arrêt de la machine de vérifier le bon fonctionnement de ces éléments. Etant donné le grand nombre de filtres dans les deux anneaux, il est nécessaire de créer un moyen de mesure rapide mais aussi répétable car il est demandé qu'une base de données des mesures au fur et à mesures des années soit créée afin de permettre une maintenance préventive. Les données extraites peuvent par la suite être traitées pour vérifier le fonctionnement des filtres.

Ce projet a pour but de répondre à trois objectifs. Une application LabVIEW connectée à l'analyseur de réseau vectoriel a été développée, permettant une mesure ainsi qu'un enregistrement des données rapides. Un système mécanique d'attache des connecteurs sur la structure permet une prise de mesure plus répétable des filtres sur chaque bride. Enfin un programme permet une analyse statistique des données collectées lors d'actions de mesures afin de déterminer si un filtre semble détérioré par rapport à son comportement idéal sur la plage de fréquence. Ce set-up sera utilisé chaque année les des campagnes de mesures.

Zusammenfassung

Das CERN, die Europäische Organisation für Kernforschung, führt Versuche durch, um die Grundlagenphysik und die Gesetze des Universums zu erforschen. Die Hauptmaschinen sind Teilchenbeschleuniger, die zu einer Kette verbunden sind, um die maximale Energie im letzten Kettenglied, dem LHC (Large Hadron Collider), zu erhalten. In diesem zirkularen Beschleuniger strömen zwei Teilchenbündel in Rohren mit annähernder Lichtgeschwindigkeit und einer sehr hohen Energie in entgegengesetzter Richtung und kollidieren an vier Interaktionspunkten, den Experimenten. Dort werden die Kollisionen beobachtet, um die Grundlagenphysik zu verstehen.

In diesem Beschleunigernetz beschleunigen die zwei ersten zirkularen Maschinen, der Proton Synchrotron Booster (PSB) und der Proton Synchrotron (PS), die Teilchen und erhöhen ihre Energie. Die Teilchen strömen in Vakuumkammern in welcher sich Vorrichtungen befinden, wie zum Beispiel Beschleunigungskavitäten, Prüfwerkzeuge oder Magneten, die den Teilchenweg beugen. Da die Teilchen geladen sind, wird ein Spiegelstrom in den Metallrohren den Bündeln folgen. In diesen beiden Maschinen werden isolierte Flansche eingesetzt, die von einer Klemme zusammengedrückt werden, um zu unterbinden, dass sich der von den Magneten induzierte Strom in der Struktur ausbreitet, was den Teilchenstrahl destabilisieren könnte.

Diese Isolationen bilden einen elektrischen Stromkreis, der elektromagnetische Felder abstrahlt. Deswegen wurden Radiofrequenz Filter (RF- Bypasses) in den beiden Maschinen installiert. Der Grund dafür ist die Resonanzfrequenz zu verschieben und eine kleine Impedanz in dem von dem Teilchenstrahl genutzten Frequenzbereich sicherzustellen. Deshalb ist es wichtig, die Funktionsfähigkeit des RF-Bypass jedes Jahr während die Beschleuniger stillstehen zu prüfen. Da es viele Filter in beiden Ringen, PSB und PS, gibt, ist es nötig ein schnelles Prüfmittel zu entwickeln. Es soll auch wiederholbar sein, weil es gewünscht ist, eine Datenbank mit allen über Jahre genommenen Messungen zu speichern, um vorbeugende Instandhaltung durchführen zu können. Die gewonnenen Daten können dann verarbeitet werden, um die RF-Bypasse zu prüfen.

Die Arbeit ist in drei Bereiche unterteilt. Eine mit einem Netzwerkanalysator verbundene LabVIEW Applikation erlaubt die schnelle Messung des RF-Bypass und ein schnelles Speichern der Daten. Eine mechanische Messklemme ermöglicht die Messpunkte wiederholbar auf die Flansche zu drücken, um vergleichbare Daten zu speichern. Schließlich wird eine statistische Analyse auf den gesammelten Daten durchgeführt, um die Filterbeschädigung zu bewerten. Dieses Setup wird bei der jährlichen Messaktion benutzt.

Abstract

The CERN, European Organization for Nuclear Research, performs experiments in order to understand the laws of fundamental physics and of the universe. The main machines are particle accelerators, connected as a chain, to achieve a very high energy in the last link, the Large Hadron Collider (LHC). In this circular accelerator, two particle beams travel in vacuum pipes in opposite direction at almost the speed of light and with very high energy (7 TeV) and collide at four precise places, called interaction points where the experiments are located. At these places the interactions are observed to understand the laws of fundamental physics.

In this accelerator chain, the two first circular machines, the Proton Synchrotron Booster (PSB) and the Proton Synchrotron (PS) accelerate the particles and increase their energy. The particles are circulating in vacuum chamber beam pipes, which are passing through different machine elements such as; accelerating cavities, beam instrumentation for measuring beam parameters or magnets needed to bend the trajectory of the beams. As the particles are charged, an image current is propagating along the conducting beam pipe. In addition, both machines feature isolated flanges, tightened with clamps, in the beam pipe to avoid that induced currents created e.g., by the magnets are spreading throughout the structure where it could perturb the beam or interact with sensitive measurement equipment.

These isolations create an equivalent electrical circuit emitting resonances. Therefore, radiofrequency (RF) filters, so called RF-bypasses, have been integrated into both machines. These filters shift the resonance but also ensure to reduce the contribution to the beam-coupling impedance in the frequency range that is harmful for the beam. It is therefore important to perform annual checks on the functionality of these elements during the shutdown period of the accelerator complex. Because there is a large number of RF-bypasses in both the PSB and PS rings, it is necessary to have a fast measurement system. The measurement system also has to provide a good reproducibility such that a database can be created over the years of all measurements in order to predict RF-bypass failure and to allow for preventive maintenance.

This project is split into three main objectives. A LabVIEW application connected to a vector network analyzer (VNA) is developed for a fast measurement and for data storage. A mechanical clamp needs to be created to attach the measurement pin to the structure and improve the reproducibility of the measure for every RF-bypass fixed on the clamp. Finally, a program statistically analyzes all the data collected during the measurement campaign to determine if the bypass is damaged compared to the ideal response over the frequency range. This set-up will be used during the yearly maintenance campaign.

Acknowledgement

First, I would like to thank the CERN, European Organization for Nuclear Research, and in particular my professional supervisor at CERN, Dr. Christine Völlinger, for giving me the opportunity of writing my master thesis in this amazing research center, unique in the world. She was always ready to advise me and giving her time to explain me the complex accelerating facilities. I also would like to express my gratitude to all the people I worked with at CERN in my own section and in the collaborating ones. They always gave me useful remarks and comments, as everyone has his expertise in defined domains, but they also integrated me into the friendly team. This has been a nice experience on the work side as on the human side.

I would also like to thank both of my university Supervisors, Dr. Lennart Rubbert from INSA Strasbourg and Prof. Dr. rer. nat. Michael Wülker from Offenburg University, for their support and advises for my work at CERN as also for my semesters spent in both universities.

I would also like to especially acknowledge my different native English-speaking colleagues, who read my thesis even in busy times.

Finally, I want to express my gratitude to my relatives for their constant support and encouragement during the studies and this thesis.

Xavier Dreyer

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1 CERN Presentation

The European Organization for Nuclear Research (CERN) was founded in 1953 by twelve European countries and is one of the world's largest scientific research center, located at the Swiss-French border next to Geneva. Today the CERN Council consists of 22 European member states who lead the organization CERN is associated with many other countries in the world which actively contribute to its work. The motivation at CERN is to explain fundamental physics, in way to understand how the universe have been formed and how it evolved. For this purpose, CERN creates particle accelerators to enable the study of fundamental particles. Over the years, the accelerator chain has been extended to increase the capacity of the machine and achieve higher energies. Bunches of charged particles are accelerated in opposite direction to reach almost the speed of light in the LHC machine, where they collide, and the resulting fragments are analyzed using particle detectors such as ATLAS and CMS. The work performed at CERN has led to numerous scientific discoveries including; engineering development and new technologies applicable and used in other field such as the World Wide Web (WWW) in 1989, and most notably the discovery of the Higgs boson.

1.1 CERN Experiments and Structure

The main facility at CERN is a complex of linear and circular particle accelerators, which are used to generate high energy beams for use in several experiments all along the accelerator to evaluate the fundamental physic of particles. The accelerators use electrical fields in radiofrequency cavities to provide energy to the beam of particles to accelerate it close to the light speed and hence achieving a maximum of 7 TeV[1] of energy which is used when colliding in the LHC. This energy is calculated with the Einstein's special theory of relativity; as the energy cannot be converted into higher velocities because the particles are already traveling at the speed of light, the mass of the particles is increasing. Magnets are used to keep the beam focused and to steer the particles around the ring in the circular accelerators. A circular machine is constructed of a series of straight sections where equipment is installed and a series of arcs where the beam is bent. To achieve higher energy, the machine should be as large as possible, as the bending radius of the dipole magnets limits the energy the particles can reach. This is why the CERN's accelerator complex has always been increased with bigger machines (Figure 1). The bunches of protons are all passing through the same succession of acceleration stages, from one to the other machine.

The initial acceleration is given by a linear accelerator, followed by the circular machines. CERN's first operating accelerator, the Synchro-Cyclotron, was built in 1954, in parallel with the Proton Synchrotron (PS). The PS is today the backbone of CERN's particle beam factory, feeding other accelerators with different types of particles. CERN now has ten accelerators, and the biggest is the Large Hadron Collider (LHC). The accelerator chain is used to gradually increase the energy of particles. Because straight accelerators have the

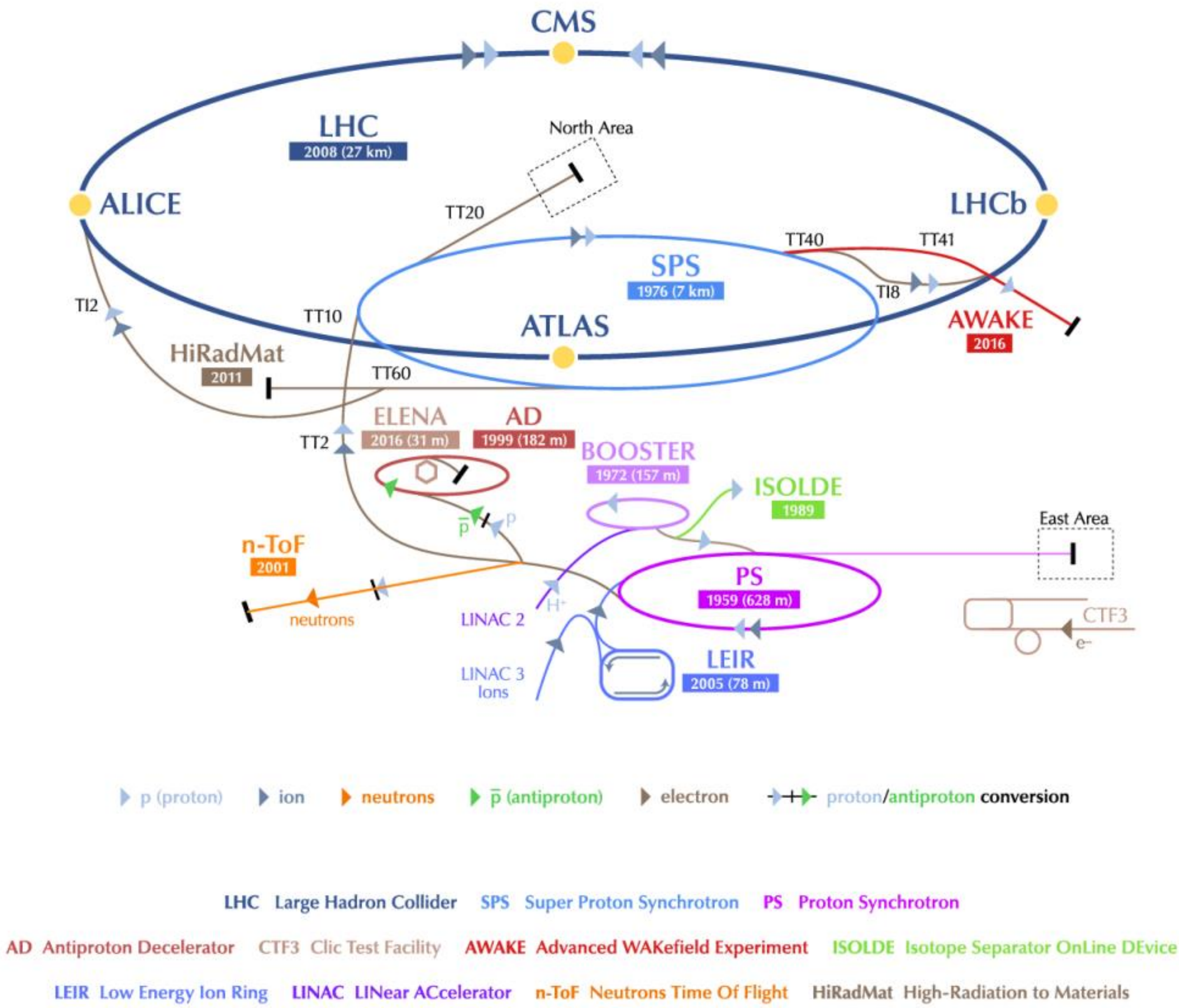


Figure 1: CERN accelerator complex [1]

disadvantage to see only the beam passing once and therefore to give only one impulse to the beam, the circular accelerators, "synchrotrons", can increase energy of the particles on multiple passes storing them during an acceleration cycle. Resonant cavities are used for acceleration. In a synchrotron, the frequency is chosen such that the radiofrequency (RF) voltage is in phase with the particle bunches traveling around the machine. In order to stay in phase with the electric field, the particle bunches pass after an integer number of RF periods. If the particle, in this example with a positive charge, passes at a zero of RF voltage,

[1] eV: The electronvolt is a unit of energy. The value is $1.602 \cdot 10^{-19}$ joules, defined as the energy gained by an electron accelerated from an electric potential difference of one volt. Therefore, the value is the elementary charge ($e=1.602 \cdot 10^{-19}$ C) multiply by the potential (1 V).

it will not be accelerated, whereas a positive field will accelerate, and a negative field will decelerate it. To increase the chances of collisions, particles are bounded into bunches. As such a bunch has an energy distribution, some will arrive earlier or later in the cavity, the RF voltage will give them a decelerating or accelerating kick, and after many turns of the machine, an equilibrium is reached. The RF cavities will create modifications on the bunches to optimize the collisions and to create different possibilities.

At the moment, experiments are done with protons. These elements come from a hydrogen atom, as it only contains a proton and an electron, which is pulled off from the proton with an electrical field. The linear accelerator, LINAC 2 then accelerates the particles to one third of the speed of light and injects them in the Proton Synchrotron Booster (PSB), the smallest circular accelerator at CERN, which has been made to increase the injected energy in the next circular accelerator, the Proton Synchrotron (PS). In this machine, the speed of light is almost reached and as the relativity theory explains this as the impassable limit, the particles are starting to gain mass. The bunches are injected to the Super Proton Synchrotron (SPS) where they reach an energy of 450 GeV. This machine is one of the largest accelerators in use and was originally used as a collider before being used as an injector for first the LEP and then the LHC. The last accelerator of the CERN structure is the LHC, measuring almost 27 km in circumference and needing 20 minutes to fill the machine and giving the particles the wanted energy. This machine is made of 2 beam pipes, in such a way to make two particle bunches, travelling in opposite direction to collide at four well defined points, called experiments, where the results of the collisions are observed. These points are ATLAS, CMS, LHC-b and ALICE (see Figure 1). The particles in the LHC are reaching an energy of 7 TeV, and this machine allows two counter-rotating particle beams to collide. In comparison with collision on targets as it was previously done where only a small fraction of the beam energy is used to create new particles, the total energy of the collision in the LHC is available for the interactions.

CERN also provides particles to other experiments, for other scientific observations on matter and particles. This work will focus on two accelerators of the LHC injector chain, the PS and PSB, in which so-called RF-bypasses are implemented, and their purpose will be explained in the next chapter.

1.2 Proton Synchrotron Booster

The Proton Synchrotron Booster (PSB) is the first circular accelerator, synchrotron, of the LHC injector chain, placed after the linear accelerator LINAC 2. It is made of four stacked rings (see Figure 2), each one with a circumference of 157 m and spaced by 36 cm between each of them. The motivation of stacking four rings is that the final ejected beam intensity provided by the PSB can be higher than by using one ring. Previously the beam was directly injected from the linear accelerator to the PS. As a bunch is injected from a single linear accelerator, special magnets are used to fill the rings one after the other by deviating the beam in the appropriate direction.

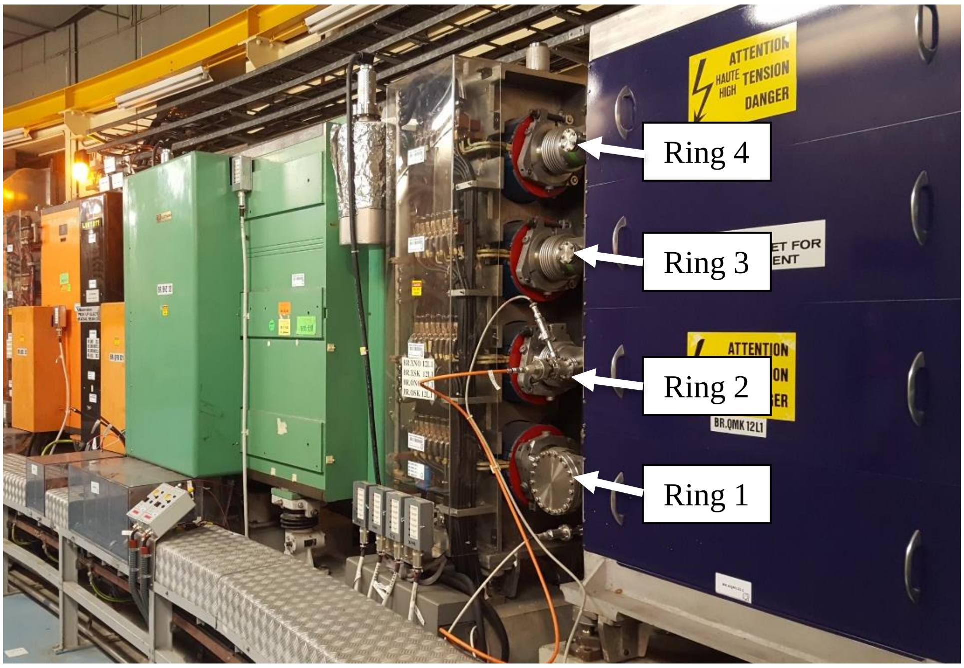


Figure 2: Proton Synchrotron Booster accelerator, with the four beam pipes

The structure is made of magnets which bend and focus the particles in the beam pipe and acceleration cavities to increase the beam energy. The PSB is made of 16 sections (see Figure 3), as the machine is not a perfect circle but made of straight and bended sections. This naming is also used for defining the elements, for example to name the bypass with the correspondent place in the machine.

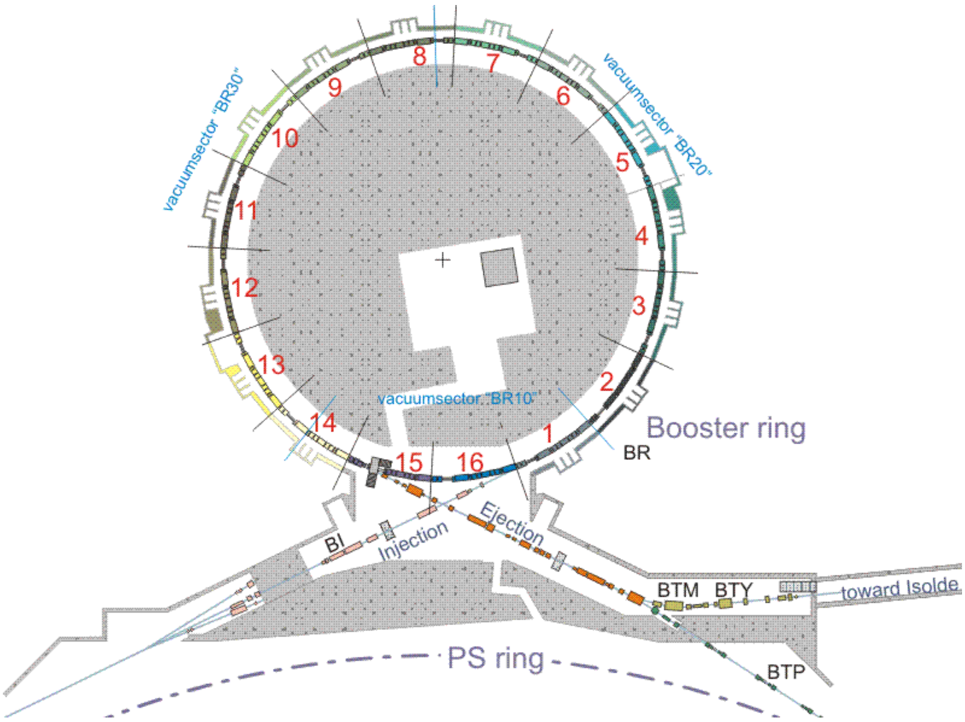


Figure 3: PSB sections and transfer lines [2]

The particles are accelerated in a cycle of approximately one second from an energy of 50 MeV to 1.4 GeV and ejected to the next circular accelerator, the PS. The particles are approximately rotating during half a second, needing less than 1 µs per turn, making 500 000 turns during the acceleration. This short acceleration time makes the magnetic field variation very fast. Bunches are then ejected to the PS or to the ISOLDE experiment.

1.3 Proton Synchrotron

The Proton Synchrotron (PS) (see Figure 4) is the second synchrotron of the LHC injector chain. It comes after the PSB, even if it was built earlier. Thanks to the PS Booster, the PS can now accept over 100 times more protons than before, increasing the beam intensity for further collisions [3]. Experiments in this machine have been done with several different particles including; electrons, positrons or antiprotons. The PS ring has a circumference of 628 m and is made of 100 straight sections (see Figure 5) placed between main magnet units and in which different elements are installed, for example accelerating cavities, injection and extraction elements, to link the different accelerators, or beam diagnostic devices to measure the state of the beam and adapt the command regulation. The particles in the accelerator reach an energy up to 25 GeV. This energy is given by RF accelerator cavities, which can also perform so-called RF-gymnastics, creating the beam filling scheme. Because of its short cycle, the magnetic field is also varying very quickly. The PS is located after the PSB and before the SPS, the second-largest CERN accelerator complex, measuring about 7 km in circumference and last part of the injector chain before the LHC.

Figure 4: Proton Synchrotron accelerator

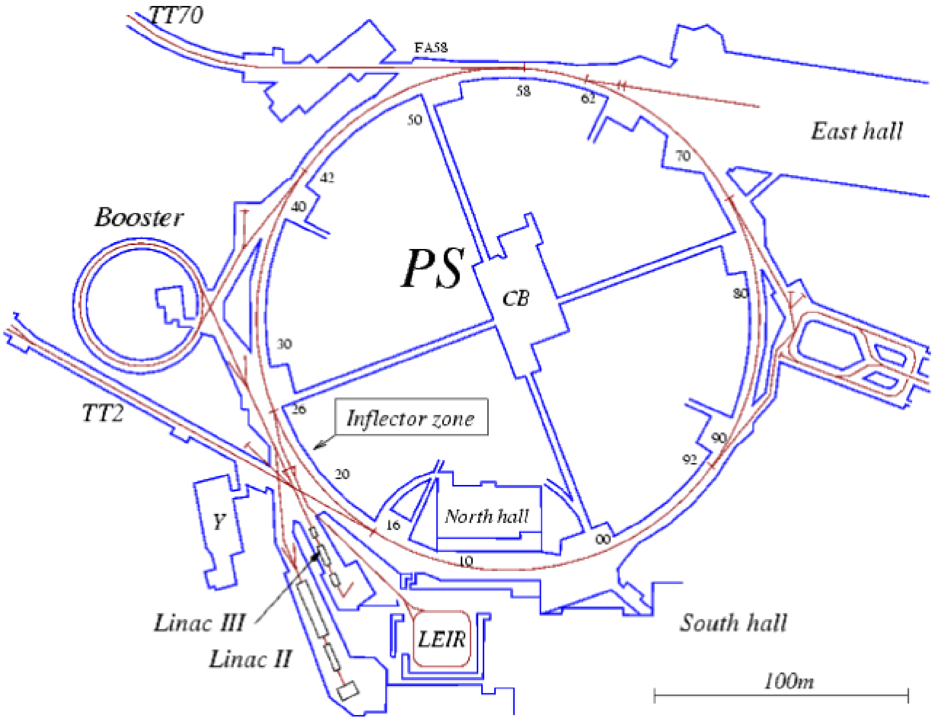


Figure 5: PS sections and transfer lines [4]

2 Motivation and Background

This project aims to optimize the measurement for the RF-bypasses integrated in both the PSB and the PS. This has several advantages, in data acquisition and analysis optimization as well as in human safety as it will be detailed in this chapter. This should help to make faster and more reproducible measurements and to foresee eventual deterioration of RF-bypasses. In this part the background of this project is explained as the bypasses have been part of optimization and are now a very important element in the machine.

This chapter explains the choice of the structure of the machine and how the RF circuits have been implemented, with the background of theoretical calculations. Main problems have been identified, and a verified solution has been implemented.

2.1 Structure Background

The beam is circulating in a beam pipe, hermetic to the exterior to allow a very high vacuum inside, of the order of 10^{-6} mbar. This vacuum means that there are very few particles in the beam pipe, which could collide inadvertently with the circulating beam. These unwanted collisions are harmful for the experiments because they cause the loss of elements and perturb the beam.

It is also important to make the beam pipe conductive, because the particles circulating in the structure are charged, in this case with a positive charge. These charges are creating an image current on the structure, which follows the beam along the accelerator. Therefore, the electrical contact has to be continuous in the whole accelerator chain. Electromagnetic perturbations are also created by the so called resistive wall wakefield, generated because of the beam pipe aperture changes [5].

An important aspect of the machine is also the definition of the machine impedance, which has to be as low as possible to enable the machine to operate at higher intensities. Every element of the accelerator has an impedance and thus creates a resistance for the beam. It is impossible to reach zero impedance but the work of engineers to develop the structure is also made for reducing the impedance.

2.2 Main Problem

As explained there are many magnets around the structure in order to bend the beam trajectory. In the PS and PSB the cycle of acceleration is very short, and in this way the variation of the magnetic field is very quick. This magnetic field variation along the conductive chamber and the ground connections found by pumps, cavities or other straight section elements, is inducing a current on the beam pipe (see Figure 6). This current can reach tens of amperes and perturb the beam that may cause losses.

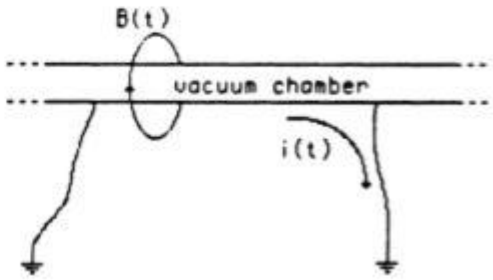


Figure 6: Induced current in the vacuum chamber [6]

As the ground connections are impossible to overcome, the solutions have been to cut the vacuum chamber and reconnect it with insulated flanges, tighten by clamps. For this purpose, many insulated flanges have been installed in the PS and PSB. But this solution has created a second problem. The flanges form a capacitor in parallel with the ground connections, creating an equivalent RLC circuit (see Figure 7).

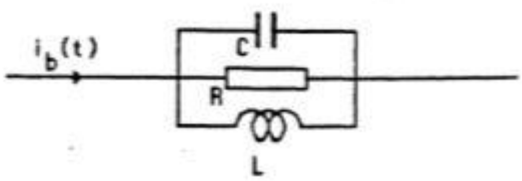


Figure 7: Equivalent circuit with isolated flanges [6]

The circuit acts like a resonator, traversed by the image current of the beam, and can cause longitudinal and transverse instabilities. It also emits electromagnetic interferences, at the frequency of 1.5 MHz, perturbating the electrical measurement elements in the structure. The resonance frequency will be shifted to lower frequency values by the effect of the RF-bypass. The circuit will also lower the impedance, thus improving the performance of the machine.

With the bypass the structure has another equivalent electrical circuit. The purpose of the bypass is to shift the resonance frequency to lower frequency values, which are not used by the accelerator, in order to avoid beam perturbations. The bypass plays an important role in machine performance and its functionality needs to be ensured. The resultant equivalent circuit is shown in Figure 8, where the RLC series circuit, made of C_1, R_1 and L_1 is the

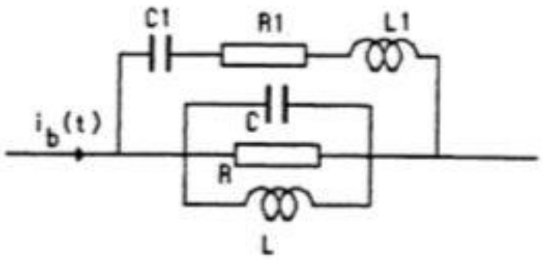


Figure 8: Equivalent circuit on isolated flanges with bypass [6]

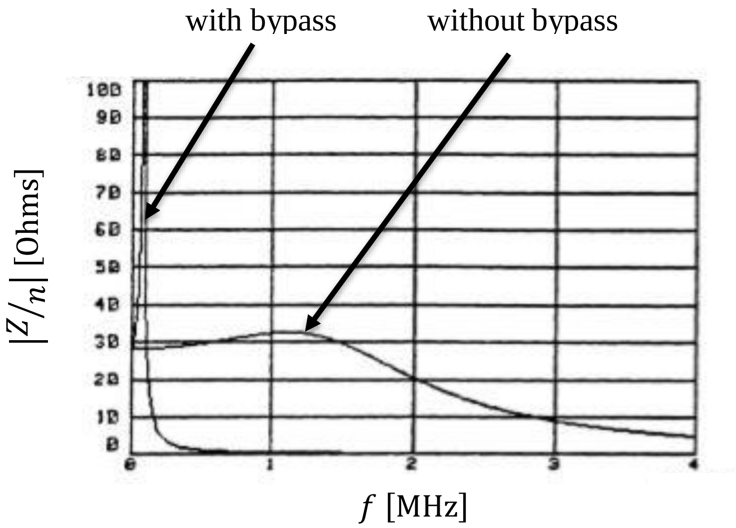


Figure 9: Frequency answer with and without bypass [6]

n is a corrector factor $n = \frac{f}{f_0}$, with f_0 the revolution frequency.

RF-bypass. The bypass is only made of a small resistor in series with a capacitor. The inductance is calculated as the stray inductance of the support and components.

Figure 9 is showing the impedance evolution of the flanges with respect to the frequency with and without the bypass. Without bypass the resonance is at approximately 1.4 MHz and the impedance stays high, while the resonance with bypass is in very low frequency and lower the impedance to almost zero from 500 kHz.

2.3 Composition of an RF-Bypass

The RF-bypass is an electronic filter circuit made of a capacitor and a resistance. The equivalent circuit is an RLC-circuit, considering the self-inductance of the connections. The values of the components have been calculated to shift the frequency to lower values depending on the values of the equivalent RLC circuit made by the structure. As the flanges are isolated, this makes the beam pipe open ends at these places. The RF-bypass makes the connection between both flanges, attached to the vacuum chambers, and is crossed by the image current, and therefore needs to be capable of supporting a high current passing through it.

The bypass in the PS is made of one resistance and three capacitors (see Figure 10.a). The components are welded on a copper plate. Both parts of the circuit are separated from the copper plate by a ceramic layer, to avoid a short circuit. The contact on one side of the bypass is connected by a screw to the clamp. On the other side, the contact is made by springs pushing on the conductive flange. The bypass contains a 1 Ω resistor in series with three parallel capacitors, which equivalent to a 400 nF capacitor.

The bypass in the PSB is made of three circuits in parallel, each one made of one 1 Ω

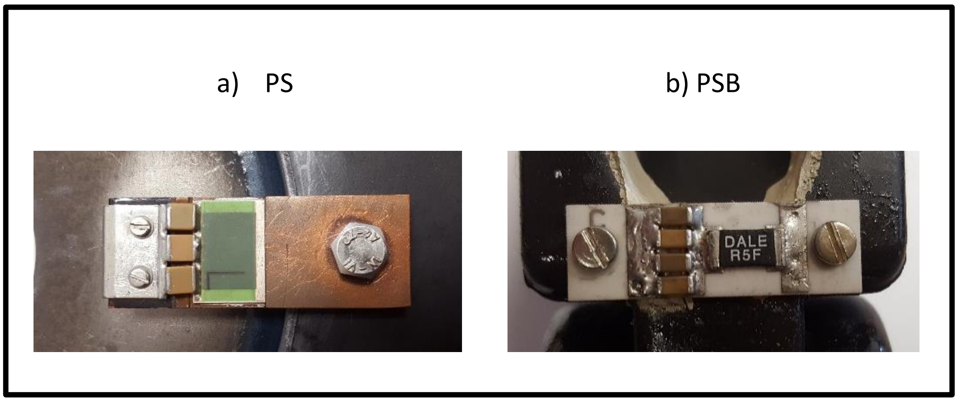


Figure 10: a) PS-bypass and b) PSB-bypass

resistance in series with a 400 nF capacitor, made of four in parallel 100 nF capacitors (see Figure 10.b). The components are fixed on a ceramic plate, screwed inside the clamp. On the bottom pads are making the connections. As they are in parallel, if one is broken, the machine can still run. In addition, as the circuits are in parallel, the value of the impedance would increase, but only to a small value.

2.4 Implementation of the RF-Bypass in the Structure

The implementation of the bypasses is different on each structure, as the bypasses also are of different shapes, as explained in the previous section. In the PSB the three identical bypasses are fixed in the isolated clamp, which tightens both flanges together (see Figure 11). The flanges are conducting but there is an enamel cover in the middle part of one, pressing on the joint, to avoid the short circuit contact. The clamp is made of three parts linked together, and therefore there will be one bypass on each of them. As the clamp is anodized the contact is done with a conducting paint layer applied to the contact surface where the flanges are pressing. The beam pipe is connected on both sides with the flanges and therefore the contact is ensured by the bypasses to allow the current to flow through.

Figure 11: Bypass on PSB clamp (left) and entire clamp (right)

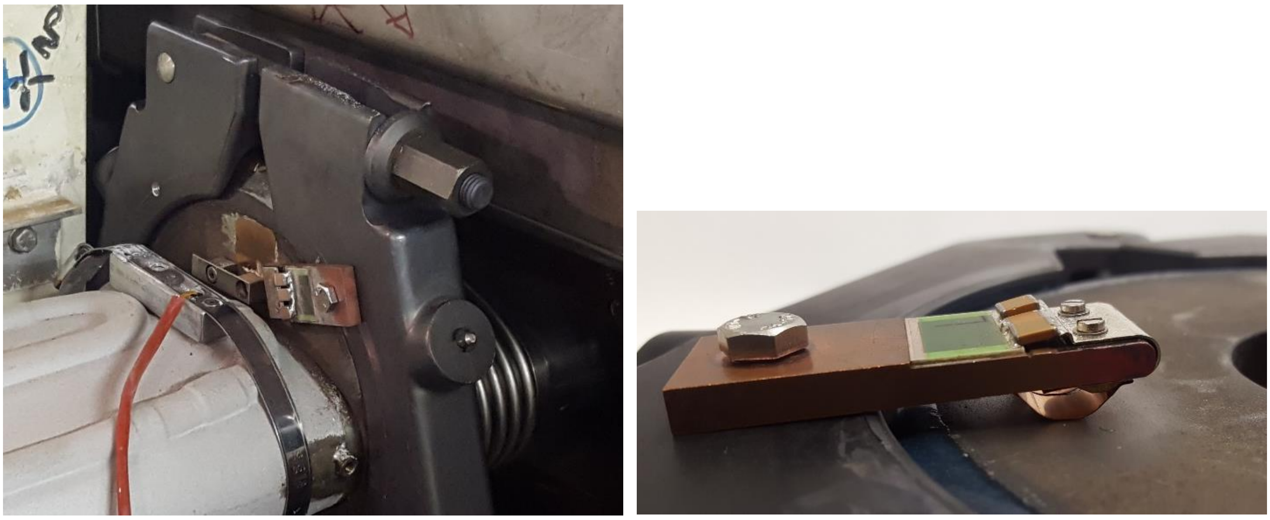


Figure 12: Bypass implementation in the PS

There are 132 isolated flanges PSB with approximately 32 per ring and also some in the transfer lines, each one containing three bypasses. The bypasses are screwed on the silver paint layers, to make the contact between the bypass conductive pad and the flanges.

In the PS, there is only one bypass fixed per isolated flanges, on about 200 different ones (see Figure 12). In this machine the clamp is not anodized and therefore one flange is covered with an enamel layer on the contact surface with the clamp. This flange is also isolated in the middle at the contact with the joint to make this side isolated from the next element, like in the PSB. The bypass makes the electrical contact on the flange due to flat copper springs on the opposite side as shown in the Figure 12 between this flange and the clamp. A little copper plate has to be glued on the flanges if the contact on it isn't good enough, for example due to an oxide layer, appearing after exposition time to the natural exterior elements. The flange surface is cleaned before applying the conductive glue and placing the pad over it. For conductive reason this pad should always been placed under the bypass even after interventions. Like in the PSB the flanges are welded to the beam pipe. And on the other side the flange is only made of aluminum and contacts directly the clamp to the pipe. To make the contact on the isolated side, the bypass is installed between the isolated flange and the clamp. Therefore, the current will flow through the bypass for passing from the upstream to the downstream beam pipe.

The installation of isolated clamp with bypasses depends on the straight sections and its connections to the ground. The straight section is always placed between two bending magnets, inducing the current discussed in the introduction. Isolated flanges are installed on both sides of the straight section. If the straight section is isolated from the ground, only one clamp has to be connected with a bypass while the other will be short circuited. However, if the straight section is connected to the ground, both clamp will be connected with bypasses. The bypass is needed between all both ground connections. This is illustrated in Figure 13.

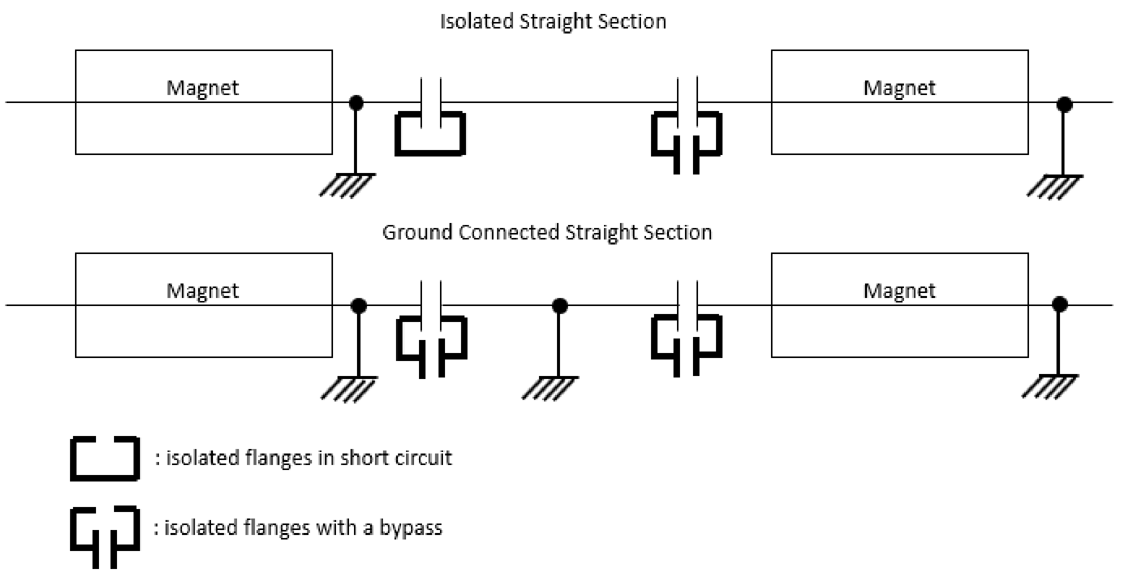


Figure 13: Diagram indicating where bypasses have to be installed

3 Measurement Objectives

3.1 Functioning Check

The CERN accelerator chain and experiences are running 24 hours a day during ten months between the middle of February to the middle of December. The two left months are used for maintenance, check-ups and improvements in the machine. These bypass measurements are done during this period every year. All bypasses in the PS and PSB will be measured after all interventions on vacuum flanges are done, to ensure the functioning of every single bypass in the structures, as a failing one would be enough to compromise the experiment.

The optimal linear magnitude curve over the measured frequency is known thanks to elements measurements, theory and experience over the years. It is important to ensure that there is no short circuit at low frequency, because otherwise the induced current by the magnet will perturb the beam. It is also important to check that the impedance at the operational frequency, from 680 kHz to 5 MHz, is low to optimize the image current path. Furthermore, there should not be an open circuit, corresponding to an infinite impedance, which would lead to an accumulation of charges. This could lead to vacuum loss due to an electrical shock, which can puncture the joint or beam pipe.

As the bypasses are constantly in contact with the environment, they can be deteriorated by for example humidity, radiation or dust. Their effects could change the frequency answer. This point is what the department is trying to foresee in the data values.

The set-up will also be used for quick checking, for example after interventions on the vacuum flanges and associated clamp. During the shut-down, interventions often need the clamps to be open. In this case, the bypasses in the PS are taken away to avoid damages. After the closing of the clamp and before screwing the bypass, the connection between the two beam pipes has to be verified. In this case, a good isolated flange without bypass should show an open circuit curve. This has to be done directly after the intervention because the air will be pumped inside and a short circuit at the flanges would cause the opening of the clamp. This would provoke the loss of the vacuum and an important loss of time, as the air must be pumped during several days to reach the required level. The measurements clamp also allows the frequency response analysis to be continuous also when a worker needs to do an intervention nearby to try to solve a problem. In this case, nobody needs to come and go near the machine to connect the measurements points.

3.2 Safety Aspects

This project also represents an important safety aspect, as the CERN accelerator is producing radioactive emissions. If a bypass has to be changed, the technician intervening in the machine will operate very close to the elements, and therefore be exposed to radiation. The ideal case is to spend the minimum possible time in the tunnel and to operate the minimum time close to the machine, as the radiation exposure reduces with the distance.

A fast data acquisition will therefore allow the user to spend a short time for every bypass measurements. The clamp is also set to obtain a good contact first time once it is tightened to the flanges. The measurement with the actual method is very dependent on the user manipulation and is unstable. The clamp should make sure that the signal is usable after the first measurement, while the current method makes it uncertain because of tremor, creating perturbations on the signal. The user hanging the measurement clamp can therefore step back during the acquisition.

The data analysis is done to try to foresee deterioration of bypasses. Because the machine is running ten months a year, the two months shut down are used for technical intervention. If a bypass shows deterioration over the years it can be changed at this time as a precautionary measure. Otherwise, if the bypass breaks during the run of the machine, the beam is perturbed and the experiments at the LHC will not get good results, or could even not been provided, depending on the gravity of the defect. If there is a problem because of a defective bypass, an intervention has to be planned directly in the machine, in way to stop the beam for the shortest possible time. In this case the technician would intervene in a highly radioactive area. In this case a high radiation will be taken, as the residual radiation in the machine is decreasing with the time, and the person could not go for further interventions in the machine to limit the yearly radiation exposition.

There is therefore a highly important safety aspect by checking the bypasses and trying to avoid breaking during the machine run. CERN sets yearly experiments objectives and a shut down because of bypass problems would affect the final results.

3.3 Actual Set-up State

Over the years, thanks to the technological development, the measurement has been improved. The main part is the evolution of the Vector Network Analyzer (VNA). In the past the VNA was big and heavy, which made it difficult to carry, but also very slow for saving data, having a little intern screen, which made it difficult to see the curve while doing the measurement and taking many actions and clicks to save data on USB sticks. All these elements made it very difficult to use the VNA and make the measurement in a comfortable way [7].

The VNA has now become smaller and lighter and works through a USB-connection to a computer, which runs the corresponding application. The VNA also measures over the frequency range in a little time. The computer is displaying the graphs and allows to save in a faster way over the USB-connection from the VNA to the laptop hard disk. But the problem is that time is needed to navigate in the application menu to save the data traces, the data values in Excel and the raw data, S-parameters. Saving the three files therefore needs a long time, which is also unsafe for the technician who has to stay near the machine to hold the measurements probes on the vacuum pipe to keep the contact.

Because of the long time needed for saving the data, it has not been done every time and usually only the graphs have been saved as image. With only this data it is not possible to make statistical analysis. It is only possible to observe the curves and as there are many bypasses, this can be imprecise. Only some data of PSB bypass measurements have been saved and gives a base for the creation of a more rigorous statistical analysis.

The measurements probes connected to the beam pipe are two points plugged in the coaxial cable. These points are push on the beam pipe by the user, in way to obtain a good contact and therefore a good measurement. Thanks to the length of the connections, the points can reach the beam pipe and measures the whole isolated flanges structure.

3.4 Actual Measurement Set-up Problems

The actual set-up shows inconvenience in several points. As the problem of the slow and heavy VNA has been resolved by the technology improvement, it is still very slow to save the data because it needs to browse through the application menu. This still slows the measurements even if the frequency sweep is very fast.

The actual measurement points (see Figure 14) are easy to handle but the measurement is very sensitive to pressure changes. For example, if the user holding the points on the beam pipe is moving a bit, the sliding of the points on the vacuum chamber causes a peak in the measurement, which makes it unusable for further analysis. Additionally, the pressure also

Figure 14: Measurement points

changes the impedance which is observed. Because of this uncertainty, even the measurement of the same bypass under different conditions can give different results. The points also need to be handle with care because the vacuum pipe is very thin and could be punctured by too high pressure applied on them. This problem would lead to a major intervention and take up many people's time.

In order to make a statistical analysis of the measurements over the years, it is important to get reliable data. As a result of the different uncertainties due to the material and human handling, the measurements can be incorrect. It is therefore necessary to improve the reliability of the measurement technique if analysis is to be done on the data.

Since this work is taking place in a radioactive area, it is necessary to avoid any possible slowdowns while making measurements. It is therefore important to improve the acquisition speed, in addition to making the data more reliable in order to run a post-processing analysis.

3.5 Measurement Set-up Optimization

The aims for the developed set-up are to improve the actual state to solve the described problems or at least create solutions offering the best compromises. The main points needed to be improved are as follows: the speed for saving all the data and therefore create a data bank for every year measurements, the improvement of the measurement reliability and the optimization of the time spent in the tunnel in a radioactive area. A post-processing routine should then be able to read the data saved during the measurement and apply calculations on them in order to evaluate the results.

The data acquisition can be optimized by using a custom LabVIEW program connected to the VNA application. The clicking and browsing through the menu could be avoided, which is the highest loss of time. A software could use these saved data on the computer hard disk to create a data structure that is directly available for the users.

The reliability of the measurements can be improved by changing the measurement device and make it less susceptible to human error; thus, a measurement clamp fixed with a defined system allows a more precise acquisition. The measurements point could also be changed as the measurement on the thin vacuum chamber presents risks due to mishandling. The flanges on both sides represent the same potential as the correspondent beam pipes and are more mechanically robust to take pressure on the surface. A measurement clamp fixed on the flanges would apply a constant pressure on every clamp and therefore make the measurement more reliable.

The user can also perform the measurement alone if the measurement clamp does not need to be held. The possibility to secure the clamp to the structure and work from a few meters from the machine also reduces the radiation dose received by the user. Although this would take to long for the yearly machine checkup, this could be done for a few samples.

As a data bank is created, a software program could analyze the data to look for signs of deterioration of bypasses. Criterion can be used to try to define the evolution over the years of the bypasses frequency answer and justify preventive interventions. This database would be useful to improve the materials quality, make maintenance decisions and improve user safety.

4 Developed Measurement Set-up

The set-up is made of three principles parts:

- An application for a fast acquisition;
- A measurement clamp for improving the reliability of the measurements;
- A statistical data analysis program.

A LabVIEW application is created, allowing a fast acquisition of all necessary data. It saves the data traces, the values in excel data files and the raw data files, all in a short time. It will also create zip files containing the previous named data to transfer and access it rapidly.

The set-up also consists of a clamp to improve the reproducibility and stability of the measurement. Therefore, a mechanical clamp is developed, which should be quickly fixed to the measurement points to reduce measurement set-up time in order to limit the total time spent in the tunnel. The clamp should always apply the same force on the structure to improve the reproducibility and consistency of the measurements. Additionally, human error is reduced by using a clamp, compared to the previous probe being handheld.

The last part is a data analysis program to foresee deterioration of the bypass, by using a statistical analysis in a programming software like Python, which will read the data given by the LabVIEW application and treat them. In this case, it should be possible to see if bypasses are not showing the right behavior over the frequency and a preventive intervention can be made in order to ensure the state against a suddenly damage and an intervention in highly radioactive tunnel.

4.1 Set-up Material

The set-up requires different application and components for the measurements as also for the acquisition and analysis. The measurements are done with a computer running a LabVIEW application, which is connected to the VNA TR5048 from Copper Mountain Technologies [8]. The measurements method of a VNA will be explained in a following section. LabVIEW is a programming software, where the data are represented by wires and connecting blocks, which are responsible for operation on the values.

The statistical analysis is done in the Python programming language, which contains several packages useful for data analysis and visualization. This language shows also a good readability of the program in case the program has to be changed in the future by user who have not use it before.

The notepad++ program also needs to be installed, which is used in the LabVIEW application to take notes during the measurement. This software has the advantage against window's notepad in that it is easier to implement and called at a defined line with LabVIEW.

A document explaining all the software installations needed for the new set-up has been created and can be followed if this method needs to be used with a new computer.

4.2 VNA: Vector Network Analyzer

A vector network analyzer (VNA) is an instrument used in the radiofrequency measurements as explained in [9] and [10]. With a VNA, the characteristics of a circuit are described by wave quantities and not over currents and voltages. In this case we take into account an incident wave, called *a*, and a reflected wave, called *b*. The stimulus goes from the source (VNA) to the device under test and then can be reflected in the opposite direction or transmitted if there are more than one port. The VNA measurement is equivalent to a measurement with the voltage and current calculation. A VNA measures both the amplitude and the phase properties, while a Scalar Network Analyzer (SNA) only measures the amplitude. This device analyses a device or electrical circuit from very low frequency (a few kHz) to very high frequencies (up to some THz). This device measures electrical network characteristics as for example the impedance. The network can respond in two different ways, as a reflection or transmission, and the reaction of the circuit is then measured in scattering parameters.

In this project, the measurement will be done with a reflection analysis, which uses the response of the circuit after a sine generator stimulates the device under test (DUT). The receiver measures the phase and amplitude of the reflected signal in comparison with the incident one. The software then computes a ratio, after eliminating the errors thanks to the calibration, and produces the S_{11}, the scattering parameter of the measurement of the reflection on the port 1.

4.2.1 Scattering Parameters

The VNA measures the S-Parameters of a DUT, these parameters compare incident and reflected signals. The index number of the S-parameters are due to the port where the waves is sent from, and where it is get back.

A typical case is a two port VNA with the S-parameter S_{11}, S_{21}, S_{22}, S_{12}. This is illustrated in Figure 15 and the equation for the calculation of the reflected values are the following:

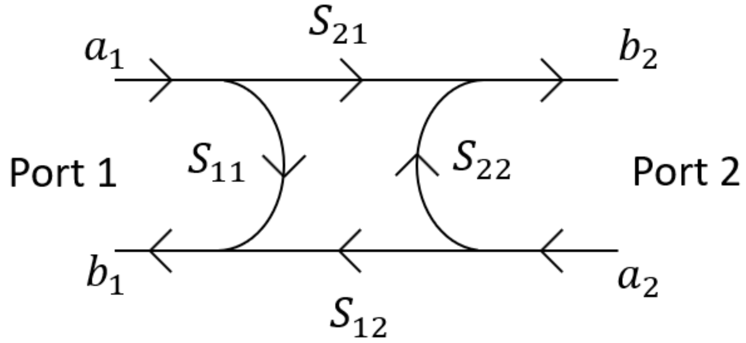


Figure 15:Possible S-Parameters with a two-port VNA [9]

$$b_1 = S_{11}a_1 + S_{12}a_2 \quad (4.2.1.1)$$
$$b_2 = S_{21}a_1 + S_{22}a_2 \quad (4.2.1.2)$$

The incident signal a is generated by the VNA and b is the reflected signal from the DUT that is measured by the VNA. The four scattering parameters will then be calculated as ratios of the values as following:

$$S_{11} = \frac{b_1}{a_1} \text{ and } a_2 = 0 \quad (4.2.1.3)$$
$$S_{12} = \frac{b_1}{a_2} \text{ and } a_1 = 0 \quad (4.2.1.4)$$
$$S_{21} = \frac{b_2}{a_1} \text{ and } a_2 = 0 \quad (4.2.1.5)$$
$$S_{22} = \frac{b_2}{a_2} \text{ and } a_1 = 0 \quad (4.2.1.6)$$

The ratio is a complex value and the S-Parameter contains the magnitude and phase elements functions of the frequency.

In this project, the scattering parameter S_{11} will be used, which means the reflection signal measured at port 1 from an incident signal from port 1.

4.2.2 Calibration

The calibration is an important step for the measurement with a vector network analyzer. In order to get precise measurements of the DUT, the losses due to the impedance of the cable or the delay produced by the cable length have to be evaluated beforehand. Due to the short wavelengths of radiofrequencies, the phase component of the S_{11} is very dependent on the length of the cable and thus the cable length needs to be calibrated out by moving the measurement plane directly to the DUT. The calibration is done to simulate the measurement directly at the DUT without taking into account the material used to link it with the VNA.

As some responses from defined DUT are known, the internal software will use the reflected signal of these known measurements to adapt the calibration to the material. The VNA of this measurement set-up uses a full one port calibration. This consists in the measurement of a short circuit, an open circuit and a 50 Ω (the characteristic impedance of the VNA). The full calibration means that these three different standards are used to be achieve an accurate calibration.

Therefore, the calibration has to be done for every different measurement configuration, as the cables can have different lengths and/or have different losses.

4.2.3 Value Evaluation

The scattering parameter contains a real and imaginary part for every measured frequency. The scattering parameters can then be manipulated to obtain the wanted representation, by showing either both the real and imaginary part or only one. A common method to display the values gained by the device is the Smith chart. This chart shows both real and imaginary parts on one graph for multiple frequency points.

In this project it is important to know the impedance at every frequency. The elements along the machine are optimized in order to lower the impedance at the used frequency to optimize the beam circulation. The scattering parameters contain all the information for displaying afterwards the searched values. Therefore, this data will be saved to keep the entire data measurement and allows some post processing calculations.

4.3 LabVIEW Application

A key component of this measurement setup is the LabVIEW program. Not only does the program have the purpose to enhance the speed of measurement but also create a database, which will be used over the future yearly maintenance campaigns. As there are two different machines in which the bypasses are used, the Proton Synchrotron Booster (PSB) and the Proton Synchrotron (PS), it has been decided to create two similar applications, functioning in the same way but with certain details adapted to each machine. The development is optimized by sharing many sub-programs to both the main programs for the PSB and PS applications. LabVIEW is always made of a main program, the so called main VI which contains sub-programs, called sub-VI (see Figure 16).

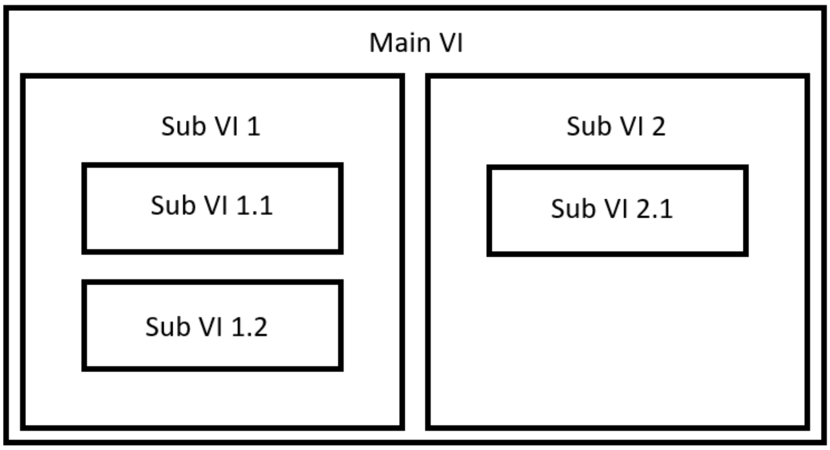


Figure 16: LabVIEW program interweaving

LabVIEW is a special programming software, that uses the data flow to link the elements and operations and therefore providing an appropriate compilation. The programming is based on a visual interface. Actions are signified by blocks and data flow by wires. To use the VNA application, a special driver has been provided with subprograms but also a description to use Standard Commands for Programmable Instruments (SCPI) connection through invoke nodes in LabVIEW (see the VNA Documentation for more information [11]), allowing to handle all actions that could be done by the user over actions on the application menu.

The program can then be saved as an application executable file. The application will contain a user interface, which will be described in the following section. The different possible user actions will also be described in the following section.

4.3.1 Purpose of Application

This application offers the possibility to acquire more data with a simple user action and also in a shorter time than before. The user can save the four necessary files by one button. The program stores all the necessary files for future analysis in a folder architecture: the image from the graphs, the excel data from the curves, the raw data, the scattering parameters, and the calibration. This program allows a fast execution because it saves all the files at once just after one user action triggers the signal, when he sees a stable behavior. This will make the acquisition fast, as the wish is to reach a quasi-instantaneous saving after the clicking. By the end of all the measurements in the machine, the application has created the file architecture.

4.3.2 Program Description

The program is built as a consumer producer design pattern (see Figure 17), containing a producer (upper loop) and consumer (lower loop) while-loop. Both are while loops because they need to run continuously until the user enables an action stopping both loops or if an error occurs. The producer loop detects the user event on the interface with the Event-Structure and enqueue (put an element in the queue) the correspondent element in the queue to pass it to the consumer loop. The consumer loop reads the received element by dequeuing it. This element selects the case from the LabVIEW case-structure in which a sub-program

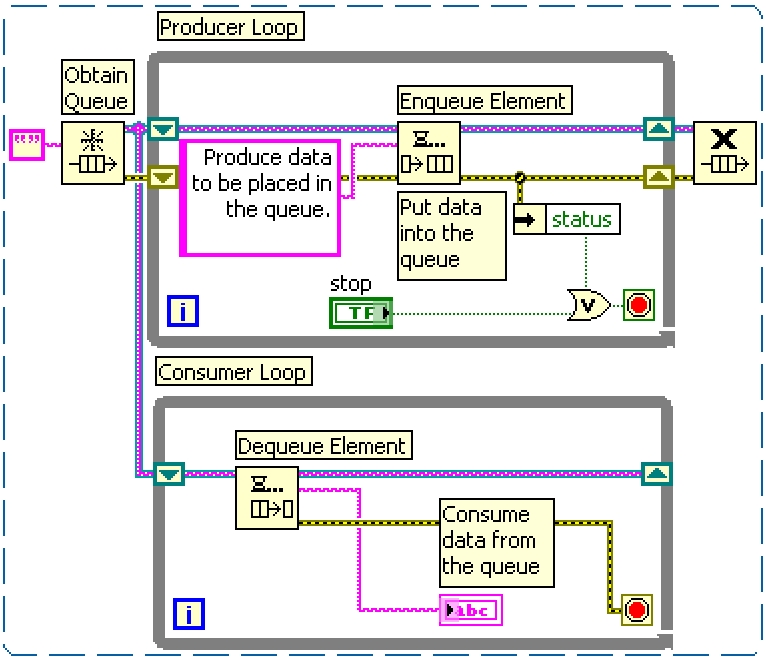


Figure 17: Producer-Consumer Design Pattern with the queue (in purple) passing the information from on loop to the other [12]

is executed, for example saving the measurement, commenting, triggering the trace or closing the application. Both loops are linked by the queue to pass the different states. The queue piles the elements up, until they are read. The queue normally works with a first in first out “fifo” method. This producer-consumer architecture allows easy changes by adding, modifying or deleting the cases in the while loops.

- Producer Loop

The producer loop is made of an event structure inside a while loop to make the program duration indefinite, until the user makes an action stopping the loop or an error occurs. The principle of the programming is showed in Figure 18. There is a central state, which makes the loop wait for an event. When a button is pressed on the user interface,

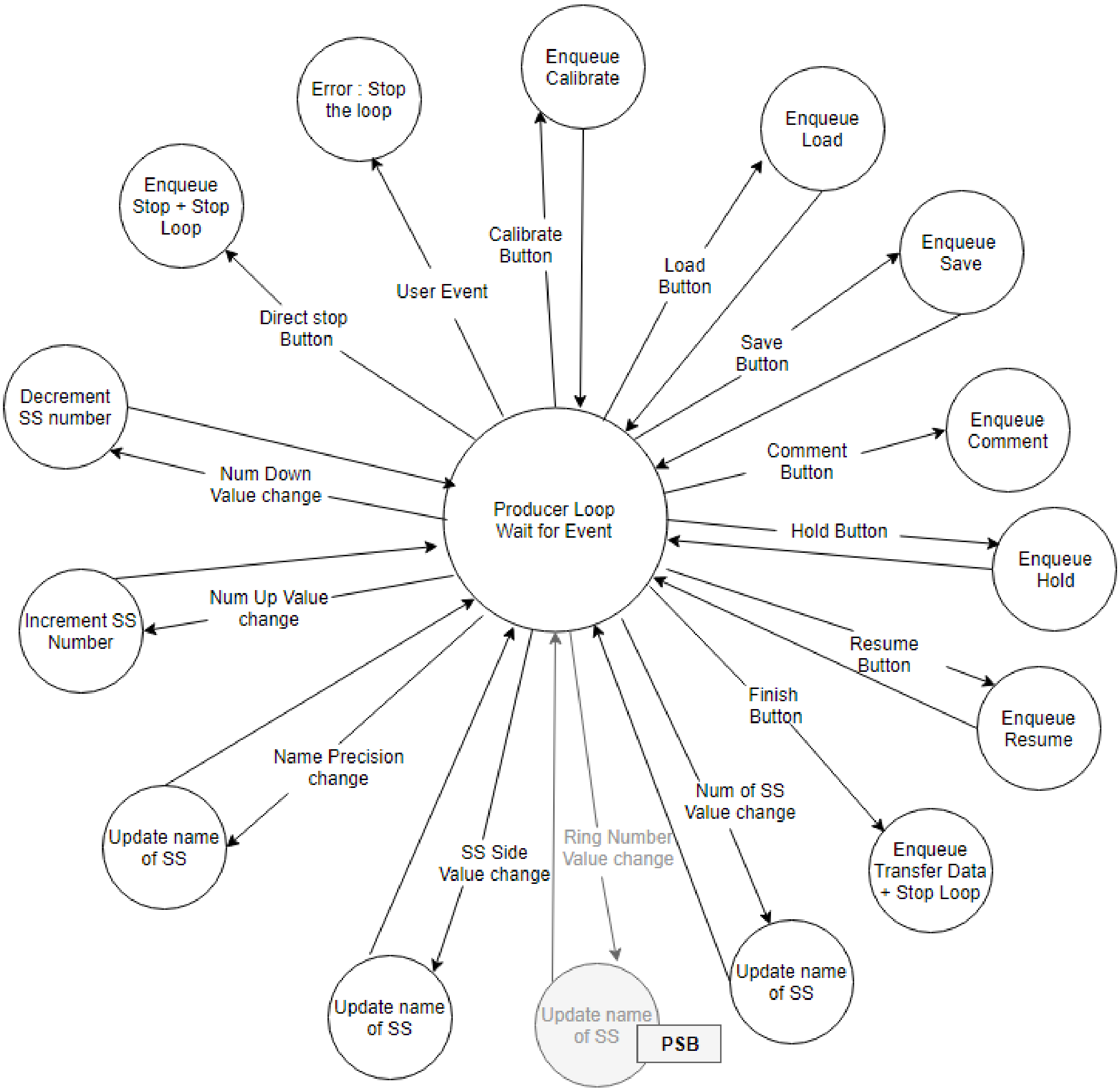


Figure 18: Event structure from the producer loop

explained further in details in the next section, the event structure detects it and run the appropriate case. In this program and user interface, there are two main parts. One is the definition of the straight section which is measured, and another part is the button describing the actions the program has to execute. When an indication of the bypass name is changed, number or side for example, the program updates the name of the straight section in a global variable. This global variable can be reached by every VI in the project. When a button is pressed, the case will enqueue the corresponding element in the queue to pass it to the consumer loop.

- Consumer Loop

The consumer loop is made of a case structure inside an indefinite while loop, stopped either by a subprogram or by an error. The architecture of the state succession is showed in Figure 19. The central state is the default one, when the while loop is waiting for the "dequeue element" block to give an element. This one is read and inputted in a case structure.

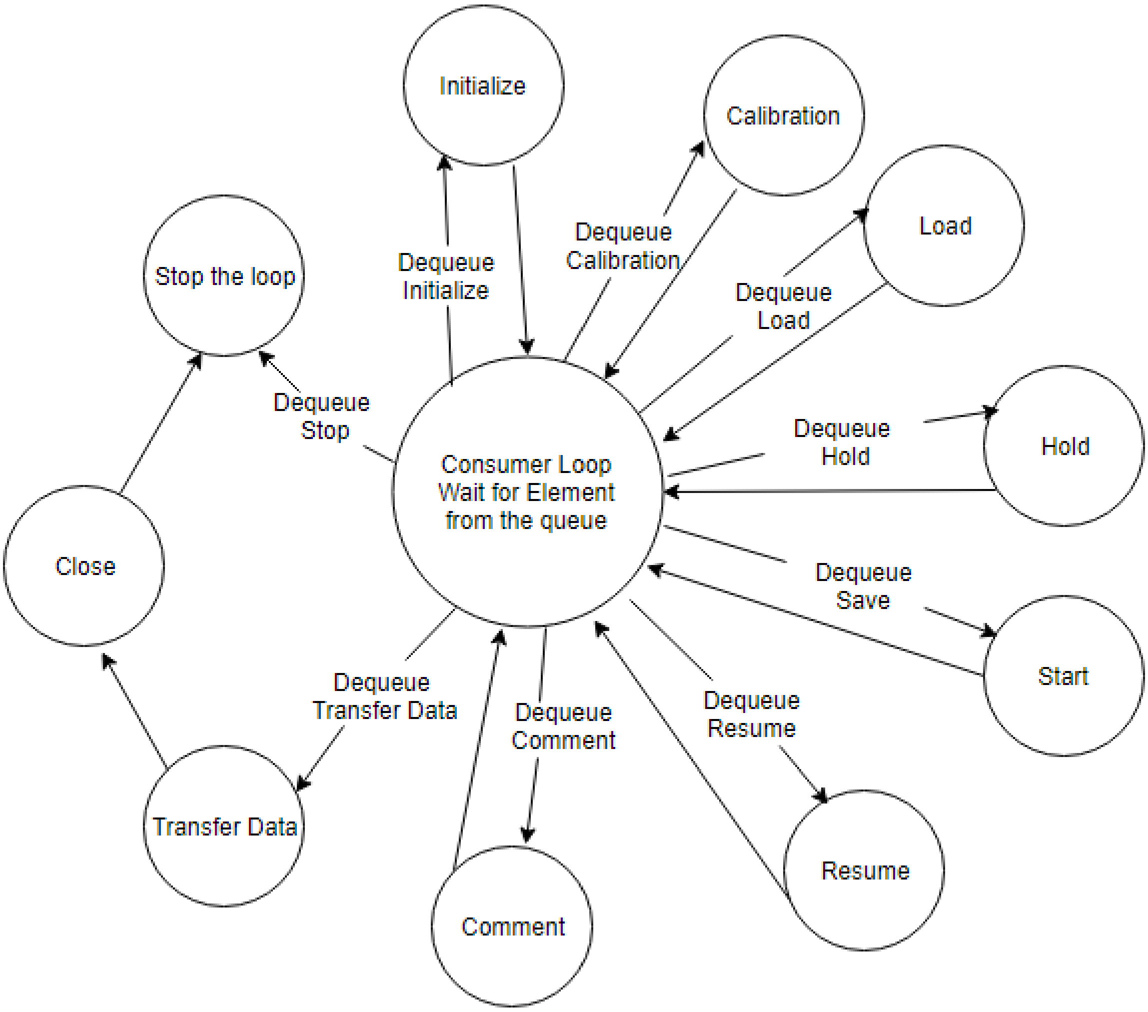


Figure 19: Consumer loop dequeues the element and run the correspondant sub-program

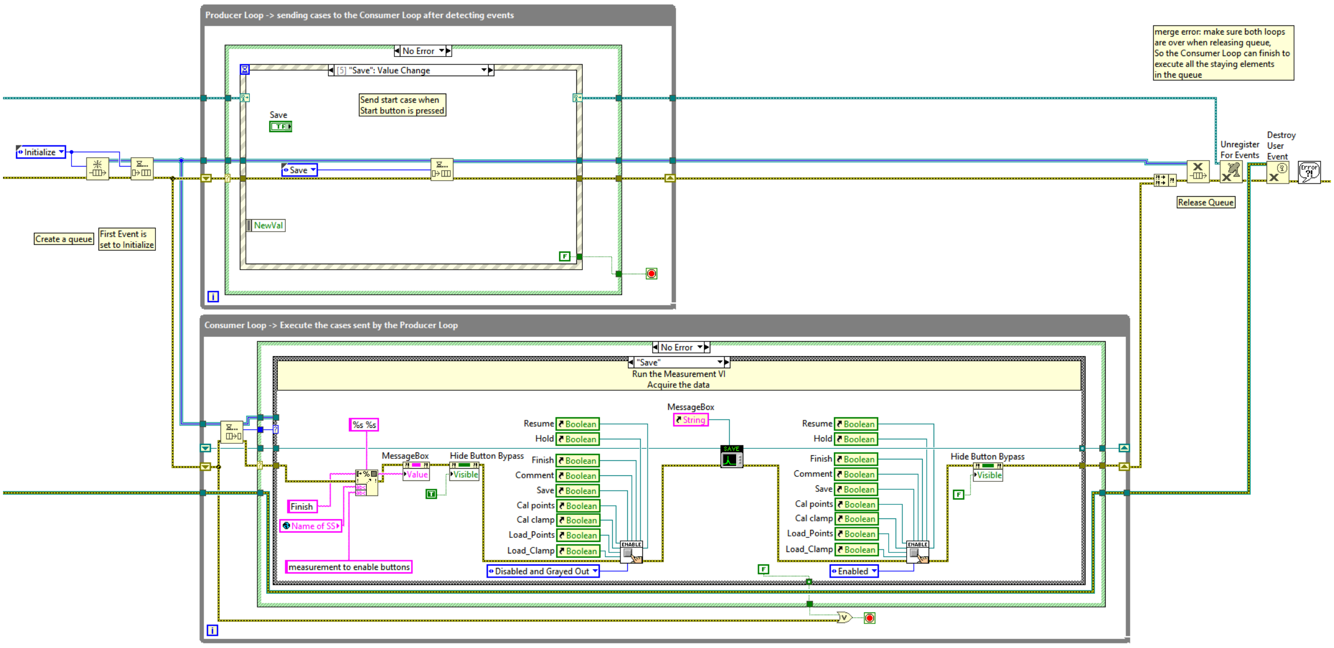


Figure 20: Application producer-consumer loop

For each different state there is a correspondent sub-program running the action through interaction with the VNA, for example to save a measurement or running the notepad to write a comment. When the action is executed, the program comes back to the waiting state, in which it waits for the next element from the queue.

In the Figure 20, the producer consumer loop from the created application is shown. Visible are both while loops and the structure inside; an event-based structure in the upper producer loop and a case structure in the bottom consumer loop. Both structures are also included in error case structure, which handle the errors in the program, because if an error occurs, the application has to stop and display the cause. In this program, the queue contains elements from an enumeration containing the possible cases the consumer loop can handle. The queue is created before both loops, on the left and closed after both loops on the right on the Figure 20. The upper loop in this example enqueues the “save” element. The lower loop will then select the case after the element is dequeued and run the sub-program.

4.3.3 User Interface

To interact with the user, the program has a user interface (see Figure 21), which will appear on the computer screen, next to the VNA application. On the front panel, buttons for the several options are available, such as calibrate, load calibration, hold, start, resume, comment or finish. There is also a part used to define the name of the measured bypass. It contains a numeric control to select the number of the straight section, and there is also list selectors to indicate the side of the bypass in relation to the straight section. In the Figure 21 the selectors UP and DN means upstream and downstream, defining the side of the straight section in comparison with the beam direction. There is also a comment box to add characters to the name in case the same bypass is measured a second time, with another configuration like after a fixing. This avoids overwriting the older one if it is not the purpose. Otherwise, if a file with the same name is already saved, it will overwrite the previous saved one. This has been chosen because the signal can be perturbed, which make the data analysis impossible. Therefore, this file can be overwritten by a good one afterwards.

The user can calibrate two different material, as he will have to use the old measurement points and the new measurement clamp. To change it quickly in the tunnel and adapt the calibration, as explained in the VNA section, two buttons will load the calibration saved before. The "Hold" button makes a trigger of the graph without saving anything and the "Resume" button switches the VNA to the continuous sweep. The "Save" button stores the data to the hard disk. If the user wants to write an explanation or remark from the measurement, the "Comment" button opens the notepad. To finish the measurement and create the folder architecture, the users has to click on "Finish". To avoid pressure by error, if this button is pressed, a pop-up window asks if the user really wants to stop the application or if it was a mistake and just cancels the action.

This interface allows an easy handle by the user, because it only contains the necessary

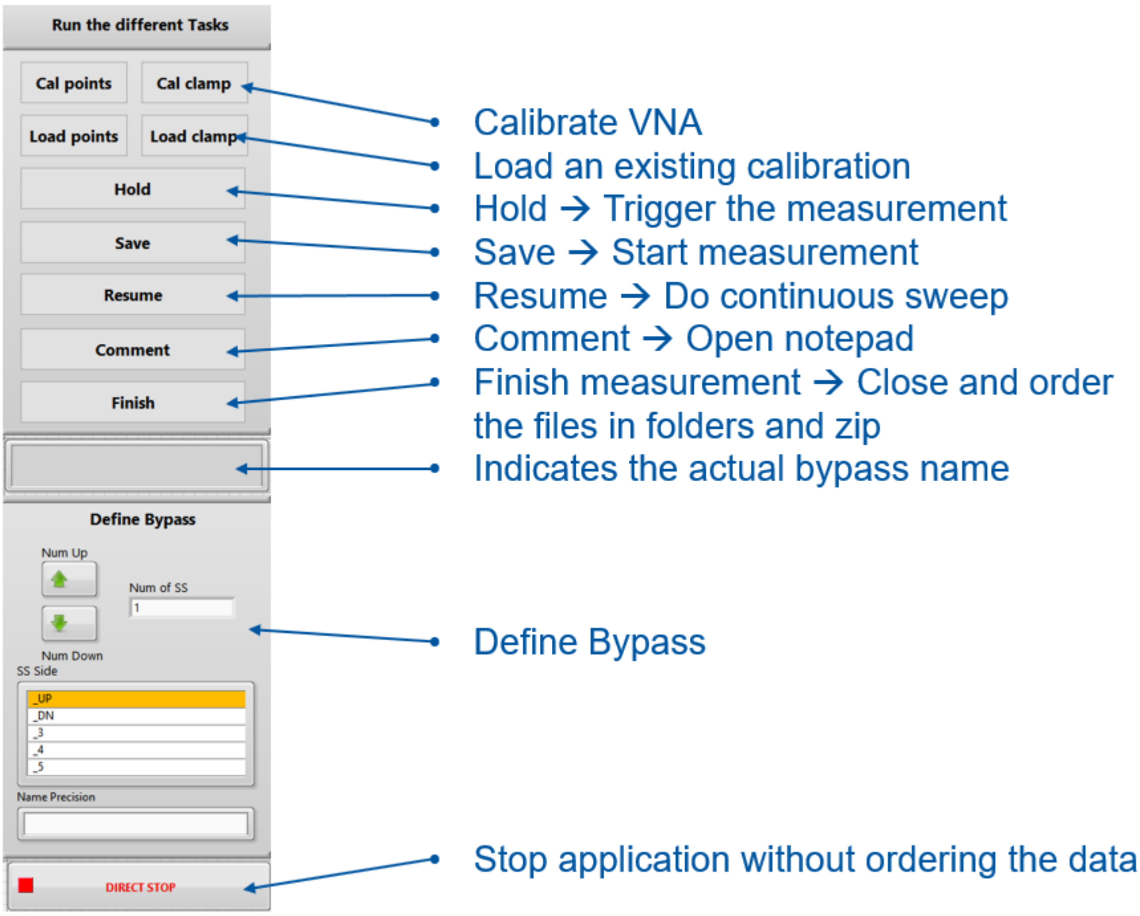


Figure 21: User Interface of the LabVIEW application

buttons. It also takes little space on the screen to place the VNA application next to it, with the maximum possible size in order to be able to observe the traces during the measurement.

4.3.4 Application Folder

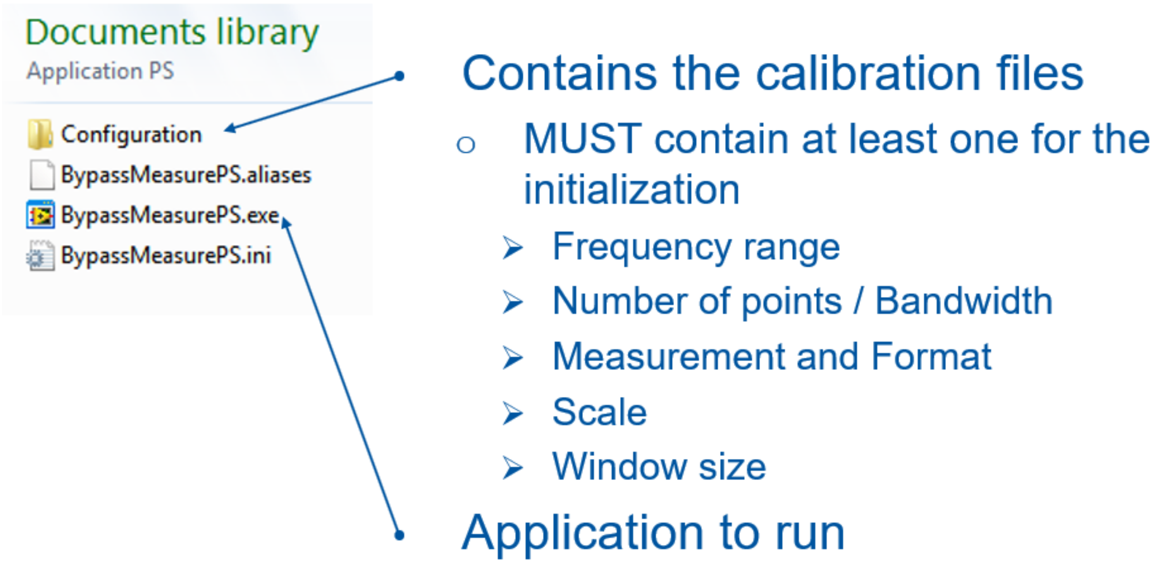


Figure 22: Application folder at the beginning

The LabVIEW application is created with the software. It creates the folder containing the files in Figure 22. The application to run is the executable file. The folder also imports a folder containing the calibration. At least one is mandatory as this folder is open during the initialization to choose a file. It is important to do it because the file is also setting all the parameters (frequency range, number of points, measurement and forma, scale…) which have been used the past years, otherwise it would take a long time to renew the set-up of the VNA application.

In order to make a data analysis, all the data are saved during the measurement. Therefore, by the end of the application, after the user indicates the willingness to close it because he finished every bypass measurement, a subprogram is launched. This will automatically create folders, subfolders and build zip files to make the transfer, exchange and reading from the data easier for the next users. The data will all be assembled and can be called by a program to analyze them. There will be a folder “Data” containing sub-folders for every straight section, which then contains the raw data, the image, the csv file from the curve data and the used calibration. A folder for every data type (image, comma separated value, scattering parameter) is also created, if it is needed to only use a defined type during post-processing. The created comment text-file opened when the user presses the “Comment” button in the application is also saved at this place. Finally, two zip files are created, one containing the folders from every data type, and the other one containing all the

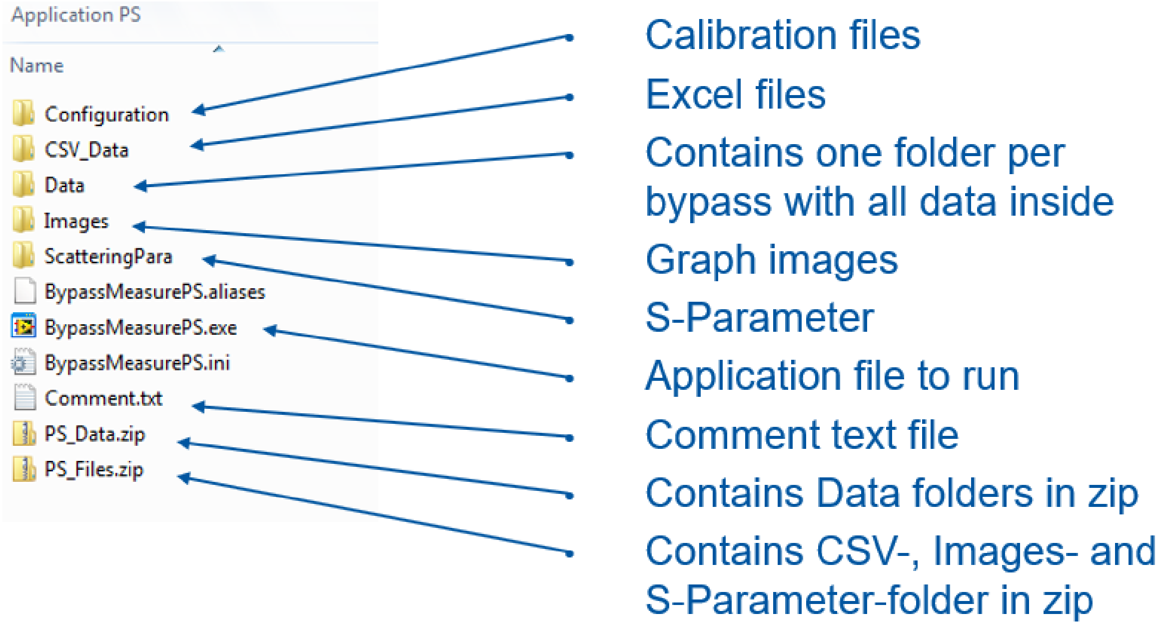


Figure 23: Folder architecture after the application organizes the data

bypass folders like in “Data”. The folder architecture is to see in Figure 23.

4.4 Mechanical Clamp Development

The second part of the project is the development of a mechanical clamp, capable of fixing the measurement pins on the structure while the LabVIEW application makes the measurement. This clamp is made to improve the general condition of measurement, as well for the technical purpose as for the human safety. This solution should be usable on the most possible flanges of the beam pipe, on the PS as well as on the PSB. The system needs to make the tightening quick in order to spend little time in the tunnel and even less near the machine and also ensure a stability on the data trace.

For this element, several possibilities have been considered. It has then been studied to achieve the construction before the end of the 2018 measurement campaign, as the measurement clamp also has to be built in the CERN workshops, with the available facilities.

4.4.1 Measurement Clamp Fixation

The measurement clamp ensures a good contact for the acquisition, independent of the pressure applied by the user like with the measurement points. The clamp has to be fixed with a certain constant pressure on every flange. This force will always be the same as a result of the construction and because the fixation is almost done at the same place by every bypass, which makes the measurement more reproducible. This is also required for the statistical analysis, since it can only be precise and done with comparable and reliable values. The force must be sufficient to hold the measurement clamp without any help of the user. It

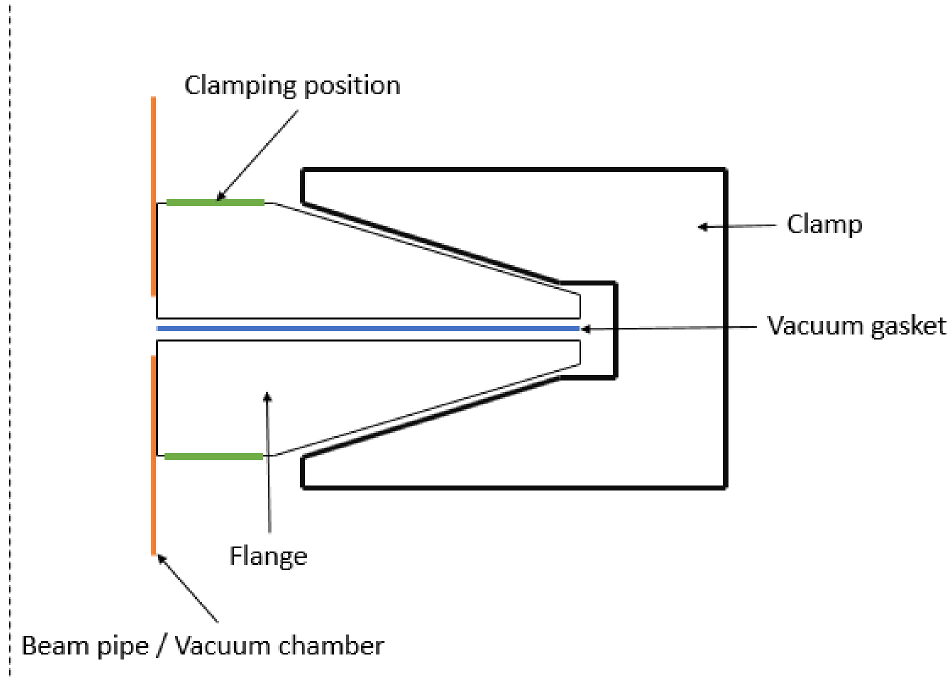


Figure 24: Schema of the clamp with the flanges and highlighted position for the measurement clamp

has to support its own weight and the connected cable. To avoid pressing on the thin vacuum chamber, it is preferable to clamp on the flanges, which are insensitive to pressure. It is therefore possible to ensure the good contact with a high applied force.

In order to save time spent in the tunnel and therefore to get a minimum radiation level, the measurement clamp should be fixed quickly. This means it contains a feature permitting a fast fixation. The solutions should therefore include a quick tightening system. This allows the user to quickly go from one to the other bypass and have only a little time next to the machine. It also improves the handling as the user does not have to change the position or the applied force like with the measurement points. The construction should also be simple to make the fixation by an easy handling of the clamp, and in addition it should fit the accelerator structures from both the PS and PSB. The clamp also had to be design considering the fixing and loosing phase, when the clamp is open. The geometrical parameter of the environment has been considered as shown in Figure 24.

The clamp is made to do the measurement in both the PS and PSB. In order to analyze the data, every measure should ideally be taken with the help of the clamp, because the reproducibility is increased, as explained before. Every clamp is unfortunately not the same, as well as the implementation of the isolated flanges, needed next to different machine elements. The machines are constructed with very little gaps and the access to the flanges is very difficult at some straight sections because of the lack of space between the clamp and the nearest installation (see Figure 25). Some clamps are also different than the most used one and a same system could not fit on both. Therefore, a unique measurement clamp will

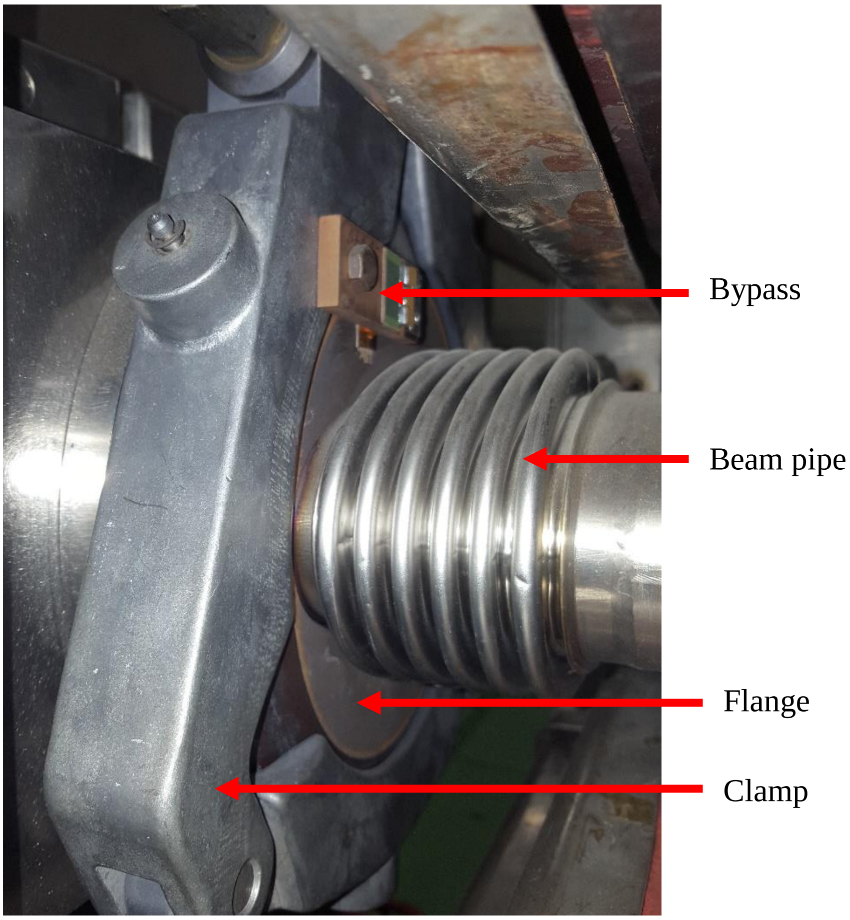


Figure 25: Clamp on which the measurement element has to be fixed

not be able to measure every bypass. Because the few exceptional cases are different (see Figure 26), many clamps would have to be developed and used in the tunnel, which is not practical, and it would take time to often change between clamps. Therefore, the measurement at these places will still be done with the actual measurement points. However, the clamp has to be adapted to the measurement of almost every place on the machine on

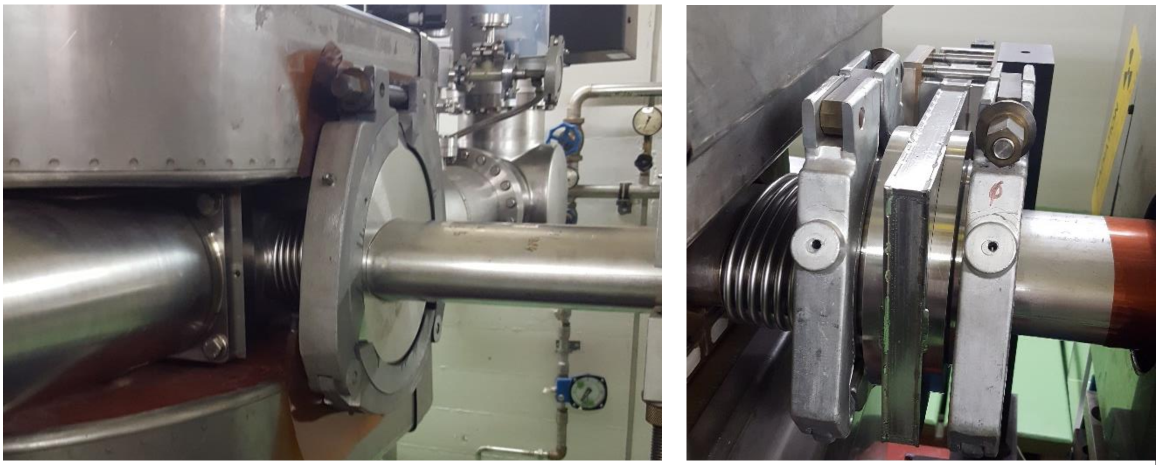


Figure 26: Problematic cases for measurement fixation; larger clamp (left), no spacing (right)

both the PS and PSB.

As there is often one side of the clamp, which has a small space to access (usually on the magnet side), this forces the clamp to be very thin on a least one side. In this case, the biggest amount of data would be collected with the measurement clamp, and the user does not need to change the material very often. This would be uncomfortable because by changing the clamp, the calibration has to be renewed, because the length and structure will not be the same, as explained in the VNA section. This is why the clamp is designed to work on the most possible bypasses.

4.4.2 Clamp Possible Solutions

To design this clamp, several possibilities have been compared. All have the same feature by being thin on one side to access between the little gap in the structure. They also have a fast tightening system which makes sure to apply the same force at every use and makes the manipulation fast.

- Spring clip

A spring clip would be made of two folded metal sheets with a rotation link in the middle. The spring would apply the force pressing both sides together on the front. The pins are closed by default, so the user should press the spring to unlock the clamp and release it to fix it on the structure. This system can be handled only with one hand, which is a good point because of the difficult access to some flange-clamps. The metal sheets allow a relative free form as the possibility to bend the material can make the shape adapted to the flange-clamp. In this system the measurement pins would be the end of both sheets. The connection with a coaxial cable should then be made by isolating both pins from the other. The measurement clamp is close to the system used in the past to insert the bypasses in the structure, before these have been screwed directly on the isolated clamp. There is therefore a return on experience of the functioning of this system.

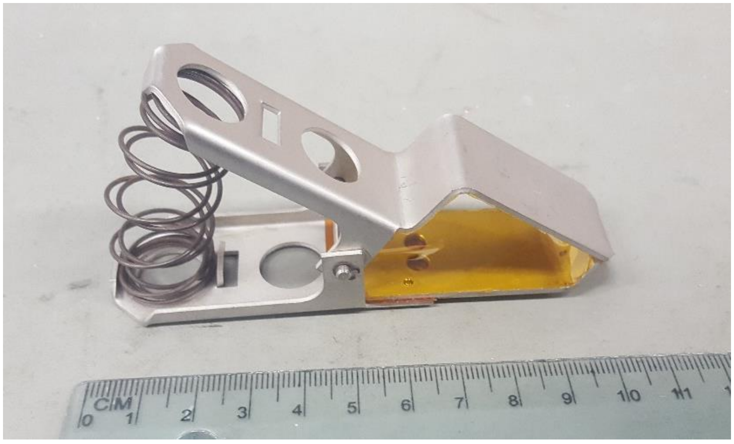


Figure 27: Spring clip used before for the bypasses

- Eccentric rotation

Figure 28: Fixation with eccentric rotation [13]

Another possibility for making a fast tightening system is a clamp with an eccentric rotation as shown in Figure 28. Although it is possible to adapt this structure to fit the machine, the main problem is that this type of fixation does not allow a sufficient displacement between the open and closed positions to tighten. In the machines the difference between the pins at open and closed should at least be 10 mm. This displacement is difficult with a small structure but could be done with a mechanical movement transformation; this would make the structure complex and delicate if there are many links. Such a mechanism should preferably be handled with two hands, which is also an inconvenient. This solution has therefore not been improved further.

- Pliers

The third solution would be a measurement clamp based on a commonly used clamp for the fixation of materials to allow work with tools. It can be realized with two different systems, where one is fixed and the other has an adaptable height. The adaptable clamp is based on a movement and fixation thanks to mechanical links but also needs a spring element. This can be located at the back of the clamp and allows large changes in the fixation dimension (see Figure 29), but always applying the same force. In the machine, all flanges have the same dimensions and a variable possibility is not necessary. The other fixation pin would be based on a mechanical movement (see Figure 29) and the pressure is ensured by an elastomer making a spring effect, avoiding slippage of the clamp. Both solutions have a sufficient opening displacement to pass over the clamp and grab the flanges. There would also be a possibility of translating the upper pin to access large clamps. The measurements pins would be integrated in the shaft and on a flat extension in the lower part.

Figure 29: Plier with adaptable height [14] (left) and Plier with unique height adjustment [15] (right)

- Contacting on the beam pipe

A further possibility has been considered in case the electrical contact with the flanges is not good enough. In this case, the signal would have to be taken directly on the beam pipe which is also the vacuum chamber. It could have been possible to use the same system described before and add an extension which would press on the beam pipe with the help of springs. The clamping would be done on a hard part like the flanges or the correspondent clamp. The pins would be pressed on the beam pipe with torsion springs (see Figure 30). In this position there is no risk of puncturing the vacuum chamber. As contact with the flanges is sufficient enough to make the measurement, this solution should not have to be used, allowing a more compact solution.

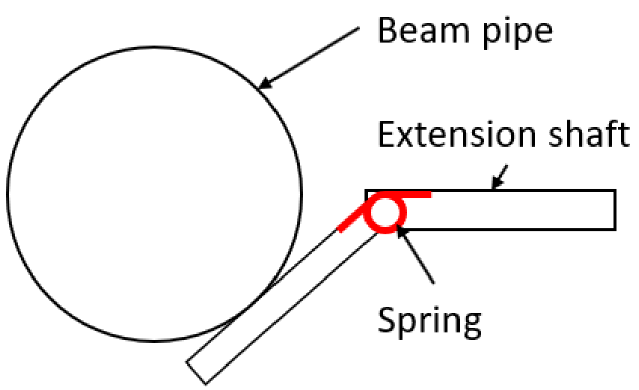


Figure 30: Extension shaft and spring for contact with the beam pipe

4.4.3 Development of the Chosen Solution

The solution offering the best performance is the spring clamp, as the structure can be folded to fit to the flange-clamp. A similar system has been used to integrate the bypasses in the structure before these have been screwed on the clamp. The method is hence proven, and the CERN workshops have the material and expertise to build it. Therefore, this method has been adapted for this measurement set-up. The measurement clamp presents a similar shape but separates the two contacting points with isolation and additional holes where the coaxial cable has to be fixed.

The isolation of both part is done by construction of the lower straight and flat part in two pieces screwed together. A layer of isolation adhesive tape, known as Kapton® developed by the company DuPont™, is inserted between both surfaces. To attach the coaxial cable, two taped holes have been added, in order to screw connector terminal onto it. The technical drawings are shown in Appendix 1 and the computer design view is shown in Figure 31. These connectors have then been extended to a coaxial connector. The next optimization is the electrical isolation of the clamp with the exterior, as tests showed that it is possible to short circuit the signal by touching the structure. The most important part to isolate is the inner of the measurement clamp as this part contact the conducting clamps in the PS. Additionally, tests also point out possible problems at the edges of the measurement clamp. Two methods have been implemented; one with Kapton® adhesive band and one with a resin layer. The adhesive band protects from short circuiting but is difficult to stick on irregular surfaces. The resin also avoids a short-circuit, but the surface covering is not optimal as the resin runs from the edges. A better resin covering practice could be used, but the process is not available at CERN workshop and to have it done by external companies would be too expensive for prototypes. The final measurement clamps are presented in Figure 32.

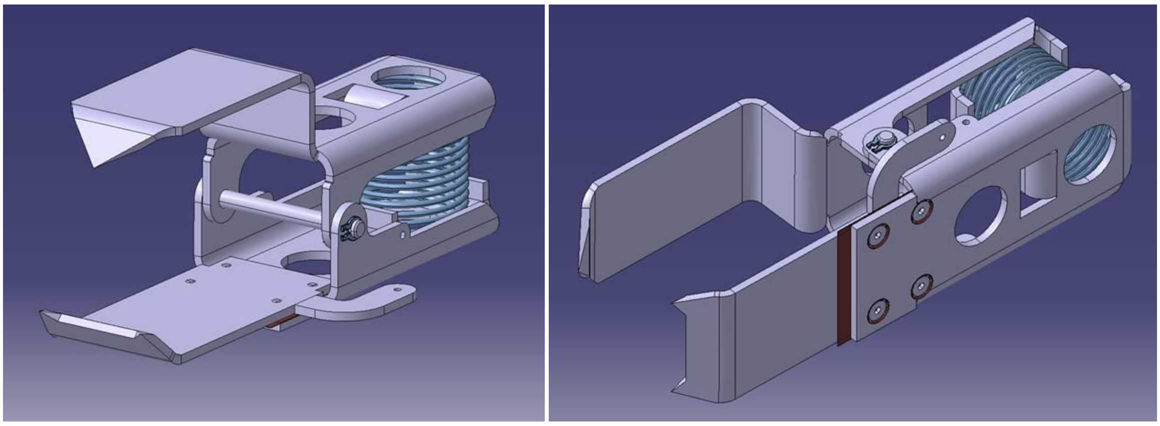


Figure 31: Clamp computer design. Drawing made by Pascal Secouet

Figure 32: New clamp, left with resin and right with Kapton adhesive band

4.5 Data Analysis

In order to prevent bypass from breaking and stopping the machine for intervention, a data analysis is performed with the data collected by the measurement. The analysis will be using the programming language Python, which is the most used in the team such that the program can be easily understood and upgraded in the future if needed. Also, this language allows a good readability and therefore a fast understanding even for people who are not used to working with programming software.

The main purpose is to detect, with the help of the linear magnitude data values, if a deterioration can be foreseen in the behavior of the bypass over an excitation frequency range. It is meant to detect the changes and detect if bypasses are tending to the behavior which is not acceptable for the machine anymore, by not completing their role. It has to be analyzed to determine whether the changes or the gap between the behavior of one curve in relation to the other one is revealing a deterioration. If this is the case, the bypass is probably getting worse and it is preferable to change it before it breaks and creates a short or an open connection instead of the bypass circuit, which would completely change the reaction and creates the problems explained in the background section.

It is important to distinguish two possible analysis types. The first type compares all the bypasses measured in one measurement campaign in a machine. As all bypasses are exactly the same, the impedance response over the frequency should be very similar. But in

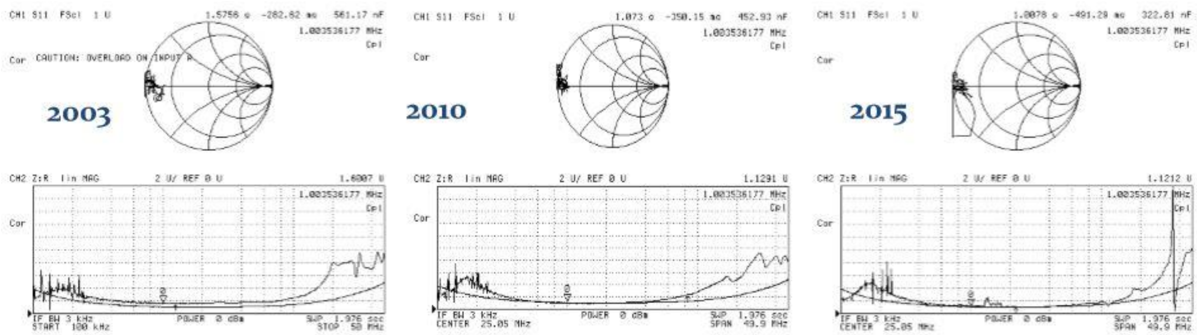


Figure 33: Evolution over the year and deterioration of the bypass [16]

the frequency range measured with the VNA, the environment can have an influence, which means that the curves can differ at some points, for example because of the length of the ground loop or cavities nearby. In this case the analysis will be concentrated in the frequency range where the impedance has to be low, between 680 kHz and 10 MHz [17] [18]. In this range all measurements are similar and can be compared.

The second analysis is based on the measurement of the same bypass over several different years and measurement campaigns (see Figure 33). In this case, the environment should not have any influence because it is not usually changed. Therefore, the analysis can be based on the entire curve from the lowest to the highest measured frequency. The main inconvenience of this method is that a long time is needed to get a large enough database for statistical analysis.

4.5.1 Statistical Evaluation

The data will be analyzed with the help of a statistical evaluation. In this case, a method has to be chosen, but also a range in which we can confirm the deterioration of the bypass in order to proceed to a replacement or not.

To evaluate the data, the program will analyze the data values enquired during the measurement. This data can be represented as curves and the main purpose is to determine which one does not have the same and correct behavior over the frequency range. To detect this, the analysis will be based on the outlier detection. An outlier is an element, which is with a defined probability not in the same repartition as the other ones and therefore does not belong to the same sample. In our case, this tells us that this point is due to a bypass problem and hence why it is out of range compared to the other values. The values from every bypass are all compared to the other ones at the same frequency. As all bypasses are the same, they should react by approximately the same curve. Therefore, the distribution should be Gaussian and make it possible to proceed such an analysis.

To detect outliers, there are several criterions, which are tested to see which one is the most efficient to detect problematic bypasses. To check the plausibility of the program, the results will initially be compared to the visual analysis to bundle both results and analyze the differences.

4.5.2 Outliers Criterions

Different criterions have been selected as possible solutions for the analysis and these have to be tested after programming them. The criterions are all based on the same basis by evaluating the gap between a representative value and the outliers in different ways. All criterions are based on a percentage of confidence. The wanted confidence and precision will define the acceptable error range and from which value the sample can be considered as representing a defective bypass.

The outlier detection methods are based on a calculation for data following a normal distribution. In this case the data is near to a normal distribution and therefore the tried criteria work on the data sets. The maximum amount of data is center to a median impedance and there are some higher and lower values representing the tails of the normal repartition. The methods are also based on a univariate population, because at each frequency there is only one parameter influencing the impedance value, which is the bypass change.

The analysis could also check the maximum gap between the outlier and the normal values in case of peaks in the value. A peak would only represent a few outliers but very far from the normal value and even if the number of outliers was small, the peak would cause important perturbation to the circuit response. This response has to be checked as it also may come from the measurement method or perturbation.

The analysis is done by taking the impedance values at every frequency as a population. The criterion is applied on every population, which means that outliers are tracked at every frequency. The linear magnitude values are therefore analyzed step by step, thanks to an automatic calculation over the complete frequency range.

Another method for trying to detect outliers in the data is to fit the values repartition to a known repartition function with which it is possible to calculate probabilities to belong to a given interval. It appears that the data possess a long right tail, coming from the fact that there is more possibility for a value to have a higher impedance than a lower one compared to the median. Comparing the repartition with known ones with a long right tail, the Log-Normal repartition is found to be a good approximation. This distribution will be detailed in the next subchapter as well as the outlier detection, which can be made with it.

It can also be possible to join multiple outlier detection methods and compared the results. If a value is defined as an outlier by different methods, there is more probability for this one to be a real outlier.

The different criterion will be explained and described with the algorithm for each technique. For each explanation there is a given population X with n elements $x_1, x_2 \dots x_n$. The mean is given as $\bar{x}$ and the standard deviation as s. Detailed explanations are to find in the references [19], [20] and [21].

4.5.2.1 Chauvenet's Test

- Calculate the sample mean $\bar{x}$.
- Calculate the sample standard deviation s.
- Calculate the standard deviation from the mean for all suspected outliers, data value "i".

$$T = n \cdot erfc\left(\frac{|x_i - \bar{x}|}{s}\right)$$

- If $T < 0{,}5$ the value x_i is an outlier.

The Chauvenet's test use the complementary error function "erfc".

4.5.2.2 Grubbs Test

- Calculate the sample mean $\bar{x}$.

- Calculate the sample standard deviation s.
- Calculate the maximum value of G for:

$$G = \frac{\max\limits_{i=1,\dots,n} |x_i - \bar{x}|}{s}$$

- Compare the value of G with

$$V = \frac{n-1}{\sqrt{n}} \sqrt{\frac{t^2_{\frac{\alpha}{2\cdot n},n-2}}{n-2+t^2_{\frac{\alpha}{2\cdot n},n-2}}}$$

  with $t_{\frac{\alpha}{2\cdot n},n-2}$ the critical value of the Student's t-distribution and n-2 degrees of freedom and α the statistical significance [22].
- If $G > V$, the value x_i is an outlier.
- Renew the test with n-1 elements and repeat until no more outliers are detected.

4.5.2.3 Peirce's Criterion

- Calculate the sample mean $\bar{x}$.
- Calculate the sample standard deviation s.
- With the Peirce table calculate R with the number of samples and the number of suspected outliers. At the beginning assume there is only one doubtful value.
- Calculate $|x_i - \bar{x}|_{max} = s * R$, as the maximum allowable deviation.
- Look for the sample where: $|x_i - \bar{x}| > |x_i - \bar{x}|_{max}$.
- If one sample corresponds to this criterion, renew the value of $|x_i - \bar{x}|_{max}$ by changing only R from the table by adding a suspected value and keeping the mean, standard deviation and number of elements.
- If outliers are still detected, increase the value of the suspected value in the table until no more value need to be eliminated.
- Renew the criterion after calculating the new values of $\bar{x}$ and s of the reduced data set.

4.5.2.4 Q Test of Dixon

- Arrange the values in ascending order
- Hypothesize that the maximum or minimum value is an outlier. Take the one with the biggest absolute gap compare to the nearest value.
- Calculate the maximum value of Q with

$$Q = \frac{\text{gap}}{\text{range}} = \frac{|x_1 - x_2|}{x_n - x_1} \text{ or } \frac{|x_n - x_{n-1}|}{x_n - x_1}.$$

- Compare Q with Q_{max} from the table.
- If $Q > Q_{max}$, the value is an outlier.

This criterion does not work if there are more than one outlier far from the rest but close to each other, as it would give a small gap but still a big range. In this case, no outlier would be detected.

4.5.2.5 Rosner's Test

- Arrange the values in ascending order.
- Select a group of suspected values at one tail of the sample.
- Use the nearest value to the not suspected values and remove the ones from the samples.
- Calculate the mean $\bar{x}$ and standard deviation s, and calculate R:

$$R = \frac{|x_i - \bar{x}|}{s}.$$

- Compare the value with the table.
- If it is over the table value, the value is an outlier, and the further ones too.
- If it is not over the table value, renew the test with the next suspected value.

4.5.2.6 Tukey's Criterion

This criterion is also known as the quartile appreciation, as it is based on the quartile calculation.

- Calculate the Quartile Q_1 and Q_3 using the formula:

$$Q_1 = x_{\mathrm{E}\left[\frac{n+1}{4}\right]} + 0.75 \cdot \left(x_{\mathrm{E}\left[\frac{n+1}{4}\right]+1} - x_{\mathrm{E}\left[\frac{n+1}{4}\right]}\right)$$

$$Q_3 = x_{3\cdot\mathrm{E}\left[\frac{n+1}{4}\right]} + 0.75 \cdot \left(x_{3\cdot\mathrm{E}\left[\frac{n+1}{4}\right]+1} - x_{3\cdot\mathrm{E}\left[\frac{n+1}{4}\right]}\right)$$

  with E[z] being the entire value of z.
- Calculate the interquartile using the formula:

$$IQR = Q_3 - Q_1\,.$$

- x_i is an outlier if $x_i < Q_1 - k * IQR = A$ or $X_i > Q_3 + k * IQR = B$ with k to choose but often set to k=1.5.

This criterion can usually be displayed as boxplot (see Figure 34).

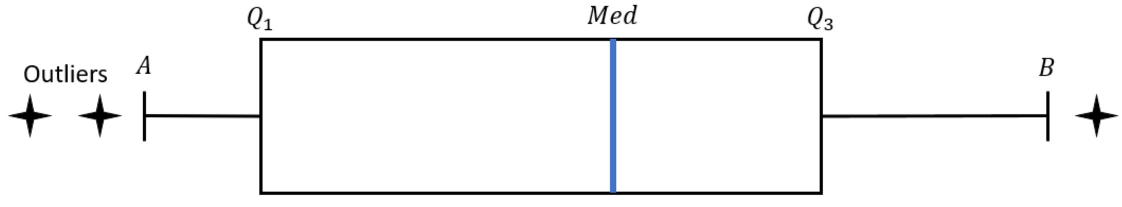


Figure 34: Boxplot visualization of Tukey's criterion

4.5.2.7 Confidence Interval

The interval is calculated with the mean $\bar{x}$, the standard deviation s and the number of element n.

It claims that the values are located in the interval $I_c = \left[\bar{x} - t_\alpha \frac{s}{\sqrt{n}}; \bar{x} + t_\alpha \frac{s}{\sqrt{n}}\right]$.

t_α is dependent on the probability percentage the user wants to set, claiming the percentage of value contained between both limit with a perfect normal distribution with the calculated value of mean and standard deviation.

Percentage in I_c	99%	98%	95%	90%
t_α	2.576	2.326	1.96	1.645

If a measured value is not in the interval, it can be considered as an outlier.

4.5.2.8 Modified Thompson Tau Test

- Identify a potential outlier:
  - Calculate the sample mean $\bar{x}$.
  - Calculate the absolute difference $\delta = \max_{i=1,\dots,n} |x_i - \bar{x}|$ of the maximum and minimum value with the mean save the highest one.
- Test the saved value:
  - Calculate *Tau* with the formula or use the table for the number of samples *n*.
  - Calculate the standard deviation *s*.
  - Multiply *Tau* by *s*.
  - Compare the absolute difference δ for the data with the product of *Tau* by *s*. If $\delta = Tau \cdot s$, the data is an outlier.
- Remove the outlier from the samples to recalculate the mean and standard deviation and finding the new value of Tau.
- Repeat the steps with the next largest difference, until this one is not an outlier.

  The Tau Formula is: $Tau = \frac{t_{\alpha/2}(n-1)}{\sqrt{n}\sqrt{n-2+t_{\alpha/2}^2}}$ with t the Student's t critical value (based on an alpha of 5%) with two degrees of freedom [22].

4.5.2.9 Z-score Method

The z-score is using the relationship between mean and standard deviation.

- Calculate the mean $\bar{x}$ of the values.
- Calculate the standard deviation s of the values.
- Calculate the z-score with: $z = \frac{|x_i - \bar{x}|}{s}$.
- Check if the z-score is greater than a threshold (usually set to 3) or compare to the product

of the standard deviation with a factor.

This method does not work well on small data sets and there could be a masking problem; less extreme outliers can be masked by most extreme ones.

4.5.2.10 Modified z-score Method

This method is also called MAD (median absolute deviation) method. This uses the same principle as the z-score method but uses the median and absolute median deviation to be less influence by outliers for the limit definition.

- Calculate the median $\tilde{x}$ of the values.
- Calculate the median absolute deviation: $MAD = med(|x_i - \tilde{x}|)$.
- Calculate the modified z-score with: $z = \frac{0.6745 \cdot |x_i - \tilde{x}|}{MAD}$.
- Check if the z-score is greater than a threshold (for example 3.5) or compare to the product of the *MAD* value with a factor.

This method reduces the influence of extreme outliers on the outlier detection.

4.5.3 Log-Normal Method

The logarithm used here is the natural logarithm which is defined:

$$e^{\ln x} = x \text{ and}$$
$$\ln(e^x) = x.$$

The log-normal distribution is continuous as the impedance values necessary are in the measurements. This distribution contains values whose logarithm shows a normal distribution. This means that if the population *X* is log-normally distributed, the population *Y*, in which $y_i = \ln(x_i)$, is normally distributed [23]. The log-normal distribution presents a long right tail as it is observed in the measurement. This is logical because the median is very close to the theoretical value, calculated by the components and because it is impossible to get lower. On the contrary it is more easily possible to get higher impedance than the mean, with bad contact or influence of the closest elements in the machine for example. The log-normal distribution is also strictly positive, as the logarithm is only defined in the range $]0; +\infty]$. This is coherent to the measurement values, which can only be positive as there represent the linear impedance. From the known distributions with a long right tail, the Log-Normal repartition is found to be a good approximation. With this approximation it is possible to use the integrated probability density function, or the equivalent cumulative distribution function, to find the maximum limit $l_{\max}$ to have for example a probability of 95 % for a value in this distribution to be contained under $l_{\max}$. The value is defined with: P $(x_i < l_{\max}) = 95$ %. $l_{\max}$ is defined with empiric method and the higher values can then be set as suspected values.

The probability density function of a log-normal distribution is defined as

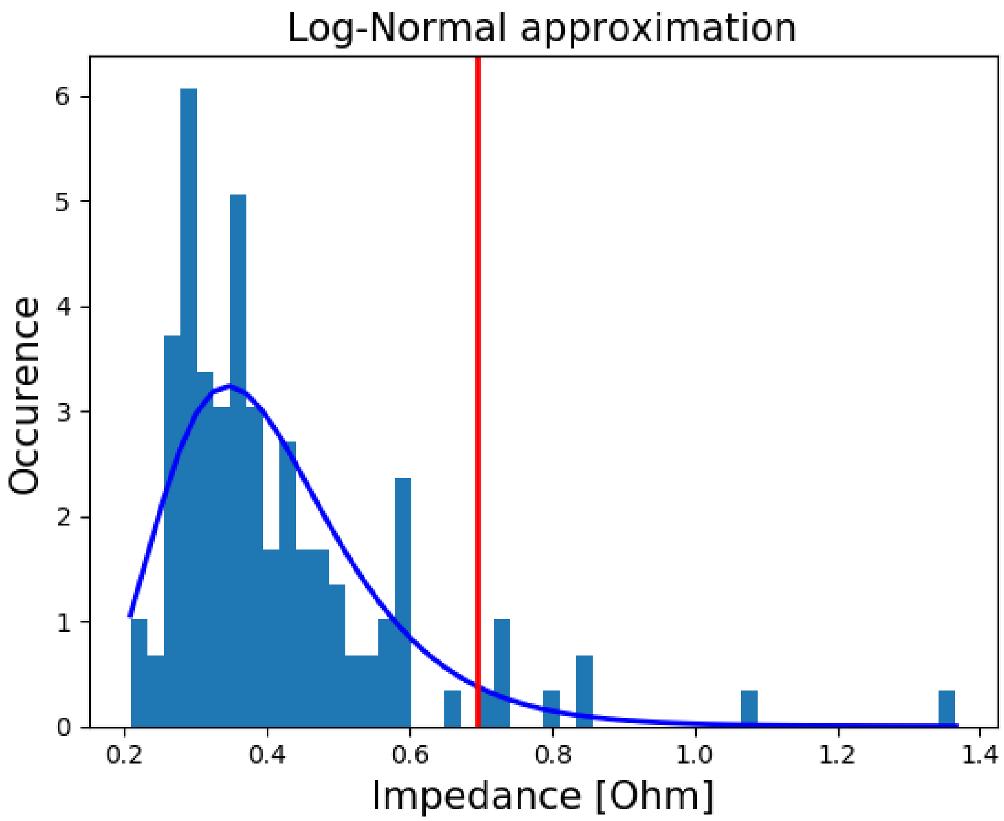


Figure 35: Log-Normal approximation and $l_{\max}$ (in red)

With the linear magnitude on the *x*-axis and the distribution on the *y*-axis

$$\frac{1}{x \cdot \sigma \cdot \sqrt{2 \cdot \pi}} e^{-\frac{(\ln x - \bar{x})^2}{2 \cdot \sigma^2}}$$

with $\bar{x}$ the mean and σ the standard deviation of the logarithm of the values, in this case the values are calculated with the population *Y* as defined above. *x* is the value defining the upper limit of the probability and will be replaced in the data analysis with the $l_{\max}$ found. An empiric evaluation of the value for $x = l_{\max}$ will give the maximum limit until which the sample can be considered as correct. Over this limit the values can be considered as outliers. A graph is shown as example for a fixed frequency value in Figure 35.

The number of values above the limit can vary as the distribution is only an approximation of the repartition, calculated with the mean and standard deviation. It this therefore possible to exclude more than 5% of the measured population. This method could give outliers even if every real value is considered as correct because the program is set to a 95% limit. It is therefore always useful to check with an observation of the repartition of the bypasses considered as deteriorated or with the real value. Another solution is to couple this method with a typical outlier detection program written above.

4.5.4 Program Implementation

To implement the program in Python, every value has been attributed to the same general class, containing the straight section name, the value of this point and a Boolean to indicate if it is an outlier or not, initialized to false. The analyzer will then handle the data in the growing frequency order. Every frequency represents a population and each different value corresponding to the bypass are the samples. For each frequency, the criterion will be applied and if an outlier is detected, the Boolean value from the class will be updated to true. After running the criterion for each frequency, the program will count the number of outliers per corresponding bypass. It can therefore declare which curve probably lie out of the confidence ranges.

Another possibility is to create a general class and attribute every bypass to this class. It contains the straight section name, the impedance values, the corresponding frequency values and two arrays for copying the outlier values, one with the impedance value and another one for the frequency. Both are initialized as empty and will grow when outliers are detected. It is then easy to count the number of outlier points for every bypass, but it is also better to trace the curves as this list can be used for highlighting the outliers (see Figure 36).

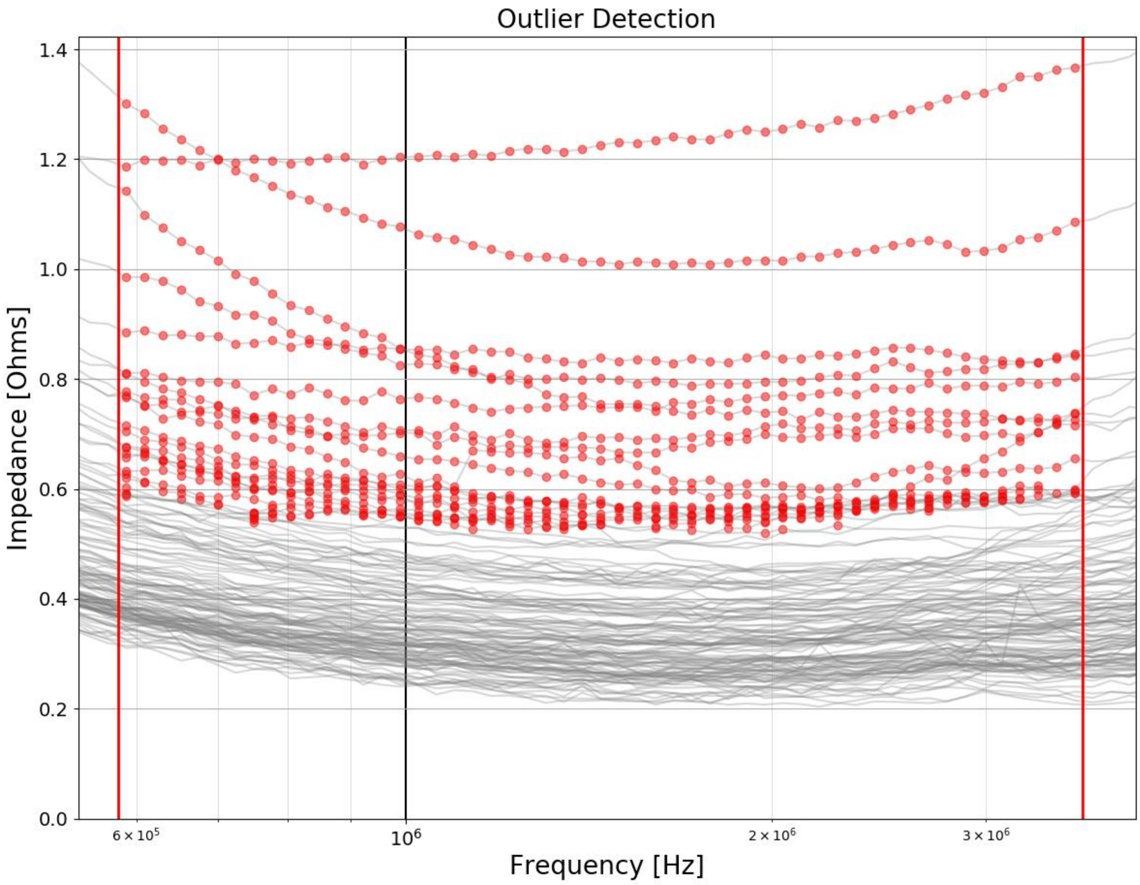


Figure 36: Graph of all bypass responses over the frequency range where red dot on points considered as outliers

With the frequency on the *x*-axis and the linear magnitude on the *y*-axis

To check the information, a program will also plot the different curves. The figure indicates and approves the result by showing curves away from the main bunch. Points can be set on the places outliers have been detected and to make the reading more comfortable the data are plotted in transparent gray and by activating them, they become yellow. This allows a better readability, even more if there are many curves.

5 Results

5.1 Test Bench

For the testing of the clamp and developed program, a test bench has been installed. This contains spare parts of the isolated flanges and clamps from both the PS and the PSB machines and includes the correspondent bypasses. Due to this, the set up can be tested and improved without accessing the machine. This is very advantageous as access to the tunnel is limited even during the shutdown. The parts can test the adjustment of the measurement clamp and check the reproducibility of the measurement. It also ensures an electrical isolation between the flange-clamp and the measurement clamp.

The spare parts are also used for testing features of the LabVIEW application. It has to be verified that the program works on real measurements. The rapidity of execution is also defined for the bypass measurement as also for the folder architecture creation. It is therefore possible to optimize the system in real time without needing to wait for access to the tunnel. Additionally, it would not be reasonable to enter a high radioactive dose area for software

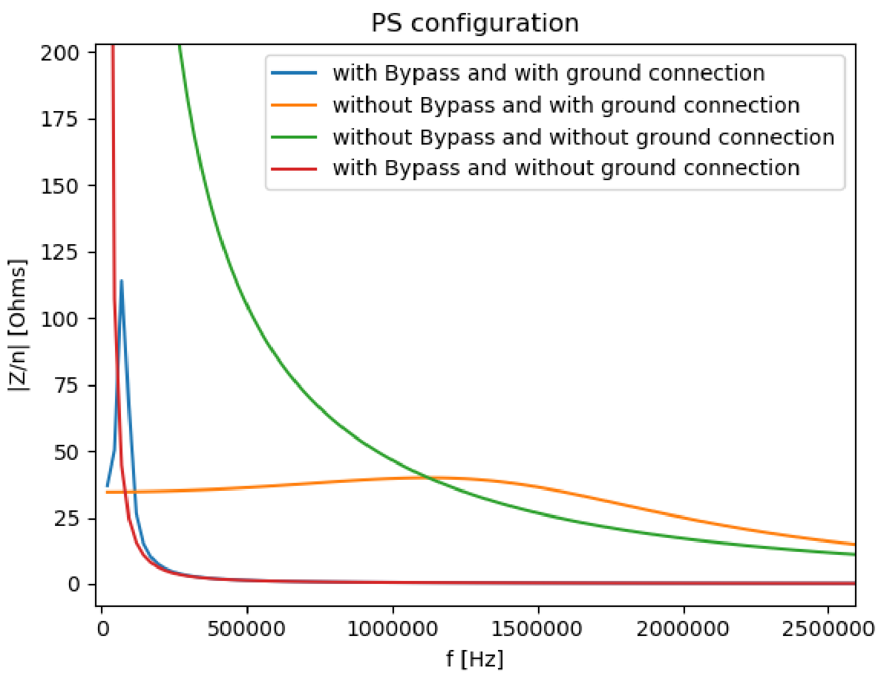


Figure 37: Simulation with and without ground connection with Python

testing. The data curves have to be observed in detail as the bench simulation is not exactly equivalent to the machine measurement. Different elements are causing this difference. The laboratory parts are not influenced by neighboring machine parts, especially the ground connections. The ground connection is adding an impedance which changes the low frequency impedance response (see Figure 37).

The test bench also tested deterioration or response changes as a result of configuration changes. To simulate failing bypasses the fixation of the bypass has been loose. The contact surface from the bypass on the conducting surface was also lowered by inserting isolation layers. This method didn't show changes in the measurement as the contact was either closed or opened but the pressure didn't play a role.

The results and observations on the test parts can't really be compared to the real ones as the environment is different. The used bypass for the test are also new and have never been used in the machine. It is therefore difficult to foresee the deterioration with these tests, as the wear of the bypass can happen in the electronic elements or contacts in the circuit and not necessarily in the contact. This is also the reason why creating a databank to observe the evolution of the bypasses in the time can give indications of the impact on radiation, humidity, vibration or aging.

5.2 Measurement Campaign

As planned, the 2018 measurement campaigns in the PSB and PS was done with the new measurement set-up developed in this thesis. The results obtained with this new method are described and presented in this part. The set-up was installed on a trolley, to transport all the necessary elements: computer, VNA, UPS (uninterruptible power supply), measurement cables, points and clamp and material for intervention in case of detected problem. The measurement is always done by at least two people. One is handling the computer while the other goes from one clamp to the other to take the measurement.

The main objective of creating databases for both machines has been achieved. The LabVIEW application shows efficiency in the data saving as the acquisition is very fast. The handling is also convenient as the name of the bypass can quickly be changed with the selectors and the "Save" button stores all files in less than one second. After the measurement the folder presents an organized architecture in which access to the desired data is easy. The files can also be uploaded directly to the CERN platform.

The measurement clamp also showed good results as the graph displays a stable impedance when it is tightened on the flanges. The traces are good at almost every first try and the values are reproducible as the pressure is applied by the springs. This method therefore creates a comparable dataset for the post-processing analysis. The clamp is as expected not adaptable to every clamp in the structure, as the gap is too small, the clamp is bigger due to bigger beam pipes at the injection and ejection section or some PS flanges are oxidized which reduces the contact. But for these cases the change with the measurement points is fast, both mechanically with the coaxial connection as well as in the application for loading the correspondent calibration. The measurement points fit to every bypass, as the structure allows contacting different places, dependent on the structure. But this method shows, as observed in the past and in the lab, a real dependence of the impedance with the pressure applied. However, this measurement method shows the principle aspect of the maintenance, to check if the bypass is still working, by checking the impedance at characteristic frequencies. It is still possible to identify a bad connection like a short-circuit or an open-circuit.

Even if there is analysis done afterwards, it is important to check the behavior during the measurement. As there is no database yet to foresee deterioration, the checking is binary, either the bypass is working, and the impedance is as expected, or the bypass is not working, and a solution has to be found immediately. This case happened sometimes in the machine and the bad contact can find its origin in different areas. For example, it is possible that the clamp of the bypass is contacting the neighboring metallic magnet housing, that the copper structure of the PS-bypass touches the conductive clamp and creates a short circuit or that the current flowing through small contacts at the spring of the PS-bypasses creates a carbon layer at the contact, causing an open-circuit. When the problem is causing a completely different behavior, this can be seen immediately and can be solved as soon as possible, because some interventions needs a coordination of several teams (transport, radiofrequency, radioprotection, vacuum).

It is therefore expected to be able to foresee these problems with yearly analysis and evolution, because when the machine is running, there are no bypass check and a problem would cause important perturbations. Due to the lack of previous data sets, it is at the moment not known how long such a problem will take to develop into a bad contact. The vibration of the machine during the run can also create instantaneous deterioration. If the developed problems are developing over a long time, this can be observed in the analysis. The log-normal method explained before helps to get the outlying values. As the environment can create different behaviors, it is in this case only compared between two frequencies where the impedance is comparable. This method gives the bypass suspected by the criterion and improves the checking time as it is not necessary to browse every single bypass impedance graph.

The analysis from the data over the different yearly shut downs could highlight problems but a database has to be built to allow a statistical analysis. In this case it is also important not to forget to update the values if a bypass is changed. Its older values have to be deleted and the analysis will start from zero again.

6 Conclusion

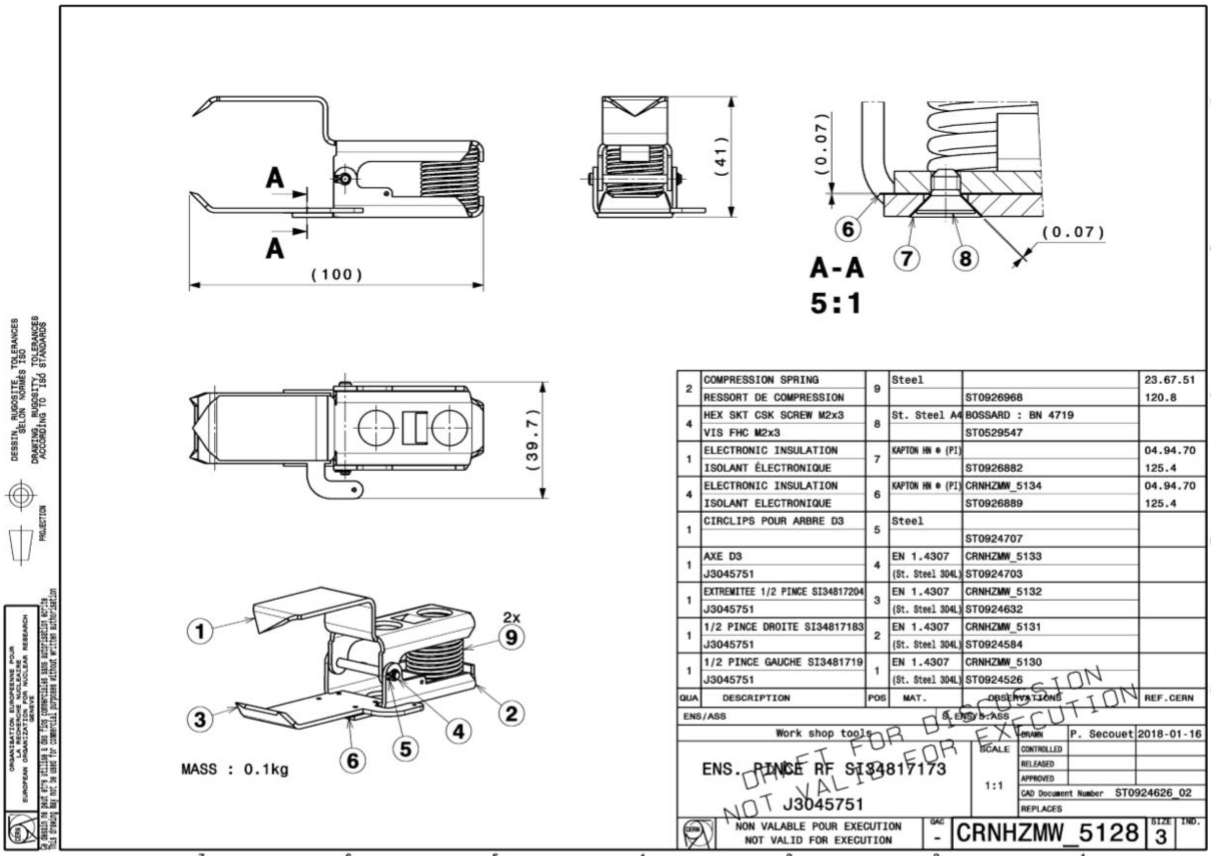
6.1 Summary

This work developed a new measurement set-up for testing of the RF-bypasses in the Proton Synchrotron Booster and Proton Synchrotron. These electrical filters are important for machine operation and hence influence the quality of the LHC experiments. The LabVIEW application makes the acquisition of the data very fast, saving the necessary files for future data analysis. It also creates a folder architecture for keeping the files in a database, allowing an easy distribution between people working with the data. For statistical analysis the data has to be comparable. Therefore, a measurement clamp has been developed using unique acquisition material, making the measurements reliable in order to compare them to each other. The measurement clamp also possesses a better handling and apply pressure on resistant part, avoiding contact with the thin vacuum chamber beam pipe. This set-up can clearly directly identify broken bypass or bad contact at the measured flange-clamp. If the bad contact is not obvious, all the data is analyzed afterwards to determine the worst functioning bypasses. Several criterions have been tested but the log-normal law showed a good repartition approximation and is used for analysis. This can also be coupled with another criterion, such as the modified z-score which is one of the most robust method against outliers. This system helps for indicating the suspicious bypass behavior. The set-up can therefore be used in the coming years to create a database to foresee deterioration of bypasses but also reducing the time spent by workers in the machine for saving the measurements.

6.2 Development Perspective

This set-up improves the speed of saving the data but also its quality. As an aim for CERN is to reduce the radiation taken by every worker, a development could be seen in this way to speed up the measurements. This could be dependent on the hardware, currently it is necessary to carry a UPS and a computer in addition to the VNA, and therefore requires the use of trolley. A smaller VNA with low consumption could be supplied by a smaller battery and a mobile phone application could replace the computer. A method could also be found to cover more measurements with a unique material like the measurement clamp. This could come from structure changes or optimization of the clamp with more modularity without increasing the size. The data analysis will probably be updated in the future following experience gained from the initial data-sets. The problem stays if the deterioration is happening during less than the yearly running time of the machine. If a constant control is necessary it would need a solution to measure during the machine run and also cover more than 100 bypasses per machine, which would represent an important investment. A further optimization would be a bypass hardware optimization, especially in the Proton Synchrotron, where the circuits are screwed on the clamp with risk to contact neighboring conduction parts. The PS-bypass can also lose contact because of the springs. The PSB bypasses are implemented in the clamp, which protect them, and even if the initial construction is more difficult, the parts are more reliable. There are also three parallel bypasses in the PSB-clamps, which keep the bypasses operating even if one is broken.

Appendix



Appendix 1: Measurement clamp technical drawing. Document made by Pascal Secouet

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