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Crystal-based Positron Sources: the e^+ BOOST experiment

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Ai miei genitori, alla mia famiglia, a Daniele, Filippo, Luca, Ilaria, Marta, Chiara, e tutti gli amici e colleghi che hanno scelto di condividere con me parte delle loro energie. Ai miei compagni di corso, passati e presenti, e a tutte le persone interessanti con cui ho scambiato opinioni e condiviso fasi della crescita. A Michela ed Erik che mi hanno accolto e guidato nel loro gruppo di ricerca, in un percorso ricco di opportunità. A Stefano, compagno di viaggio e fornitore di un aiuto inestimabile.

Otros caminarán en las huellas que he dejado...

A. Pérez Reverte, Eva

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Introduction

Efficient positron sources represent a key element in enabling advanced research in several fields, such as high-energy physics, medical imaging, material science and solid-state physics. The generation of positron beams with an intensity and an emittance comparable to the ones of electron beams has long been a crucial challenge. Unlike electrons, in fact, positrons cannot be easily extracted from ordinary matter and their prompt annihilation further hampers their detection and manipulation. Therefore, dedicated setups are required for positrons production and acceleration.

Nowadays, there are two main ways to generate positron beams: β^+ radioactive sources and pair production by photons in matter. The former relies on weak interaction processes and typically occurs in specific isotopes, whereas the latter generates positrons through photon beams interacting with matter. In this last configuration, positrons are produced in much larger quantities and with higher energies, making them suitable to be used in high-energy physics (HEP) experiments, such as those in positron-electron colliders or high-energy particle accelerators. Currently, all high-energy lepton machines employ the so-called *conventional* positron source scheme: a part of the electron beam is sent onto a high-Z, high-density, several radiation length thick target, generating an electromagnetic shower and thus photons, electrons and positrons. Charged particles can then be separated using a magnetic system to select only the positrons.

Although this method is well established, it cannot be employed for next-generation e^+e^- colliders, such as the Future Circular Collider (FCC) and the International Linear Collider (ILC). These projects, in fact, require beam intensities that would cause the target to experience severe heating and radiation damage, preventing to reach the required emittance levels. As a matter of fact, next-generation colliders aim at widening the boundaries of energy, luminosity, emittance and other main beam parameters, to allow more precise studies of fundamental particles and rare processes. Hence, to address these challenges, novel approaches to the design of low-emittance positron sources for high-intensity beams are under investigation, some of which involve crystals.

Since the 1970s, researchers in solid-state physics investigated the interaction of radiation with crystals which depends on their orientation with respect to the beam. Different experiments have already pointed out how electromag-

netic showers in high-energy regimes develop more rapidly inside oriented crystals, with respect to what happens in amorphous materials or randomly oriented crystals. This phenomenon is based upon the relativistic length contraction: the oriented crystal appears shorter in the reference frame of a high-energy particle, which thus experiences a smaller value of the radiation length. For the same reason, ultra-relativistic electrons perceive higher density in their frame of reference. As a result, due to the combined effect of the strong electromagnetic fields generated by the lattice potentials and the relativistic length contraction within the crystal, high-energy particles experience enhanced electromagnetic forces. This effect increases the overall interaction cross-section, making it possible to boost electron interactions by selecting appropriate crystal types without the need to increase the input energy or the physical dimensions of the material.

The interest of particle physics in the aforementioned cross section enhancement has grown significantly in recent years. In the field of positron sources, for instance, the electromagnetic shower boost inside oriented crystals would allow to increase the overall photon yield, and so the rate of high-energy positrons produced by photons. Therefore, the study of crystal-based positron sources represents a way to address existing challenges and to improve the current strategies up to the needs of future high-energy colliders. The oriented crystals not only would allow to enhance the photon yield and thus the positron generation, but could also be combined with elements of existing positron sources in order to better deal with problems such as the target heating and radiation damage that would lead to material activation. In this regard, the *e+BOOST* (Intense positron source Based On Oriented crySTals) project has been commissioned and financed by the Italian Ministry of Research, in order to study one interesting application of straight axially oriented crystals for next-generation particle accelerators and detectors, namely an optimized positron source.

The present thesis work has been performed in the framework of the *e+BOOST* project and deals with the analysis of the data collected in the three CERN beamtests of August 2022, August 2023 and June 2024, dedicated to the feasibility tests of such a source. The first chapter introduces the state of the art positron sources, and the theoretical bases for an innovative positron-source setup based on oriented crystals. This kind of project requires dedicated simulations to optimize the design of the source: the last section of this chapter describes the Geant4 simulations developed for *e+BOOST*, in collaboration with IJCLab in Orsay, France. The second chapter presents a review of crystal physics describing crystal-related phenomena,

such as channeling and other coherent effects that arise when high-energy particles interact in high-Z, high-density, axially oriented materials.

The third and fourth chapters represent the core of this thesis, describing the experimental framework, the crystals that have been tested and the data analysis. The employed analytical techniques, beam characterization, and resulting data are also presented, paving the way for a discussion on the feasibility of a crystal-based positron source and a comparison with preliminary simulations.

Chapter 1

Positron Sources: conventional design and new approaches

Currently, positrons can be produced through two methods: β^+ radioactive sources and pair production by photons in matter. In e^+e^- colliders, for instance, an electron beam — typically generated by a linear accelerator (LINAC) — produces photons via bremsstrahlung. These photons then undergo pair production, and the resulting positrons are extracted using a magnetic selection system.

This chapter starts focusing onto the conventional strategies implemented for the positron sources currently in use inside all e^+e^- accelerators, defining the parameters characterizing the sources themselves such as emittance, angular distribution, intensity and timing characteristics. Next, the innovative concept of hybrid crystal-based positron sources considered, together with the dedicated simulations that have been performed within the e+BOOST project.

1.1 Conventional positron sources

Positrons inside colliders are currently generated by high-energy photons interacting with an amorphous, high-Z material via pair production. This concept is the one referred to as the *conventional* or *two-stage* positron source [1]. The amorphous material can play the role of either a target, within which bremsstrahlung occurs, or simultaneously a target-converter,

where both bremsstrahlung and pair production happen as a product of the radiation-matter interaction (figures 1.1 and 1.2). Although the former method has the advantage of reducing the target-heating, the latter represents the common standard for positron production, since it can deliver larger photon yields without the need for an additional deflecting apparatus (e.g. magnetic dipoles), as electrons get slowed down directly inside the target-converter.

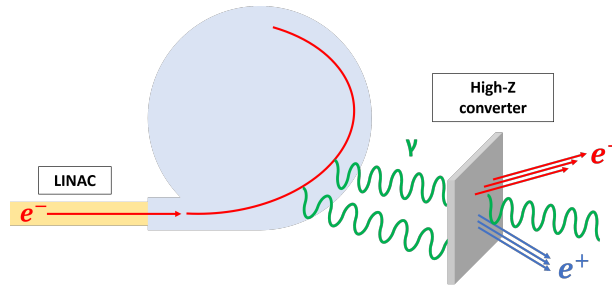


Figure 1.1: Basic positron source scheme: electrons are initially accelerated through a LINAC and photons are generated as synchrotron radiation in the curved trajectory. Positrons are then the outcome of pair production inside the high-Z converter.

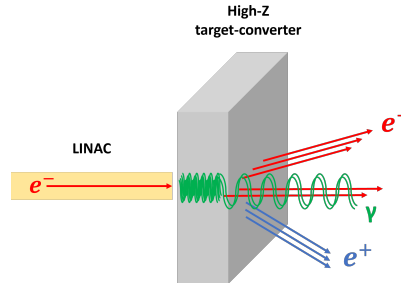


Figure 1.2: Two-stage positron source scheme: electrons are initially accelerated through a LINAC. Photons are then generated via bremsstrahlung of electrons directly inside the high-Z target-converter, where they undergo pair production.

Moreover, in the arrangement displayed in figure 1.2, the energy of the emitted photons lies within a fixed controllable range. After the pair production, a mixed beam of electrons, positrons and photons is obtained: positrons can then be selected through a magnetic dipole system (figure 1.3).

In terms of energy, conventional positron sources are typically in the GeV range (1 – 50 GeV): SuperKEKB [1] operates with a positron beam energy of around 4 GeV; the Large Electron-Positron Collider (LEP), which operated at CERN until 2000, achieved energies up to 104.5 GeV [1]. The SLC

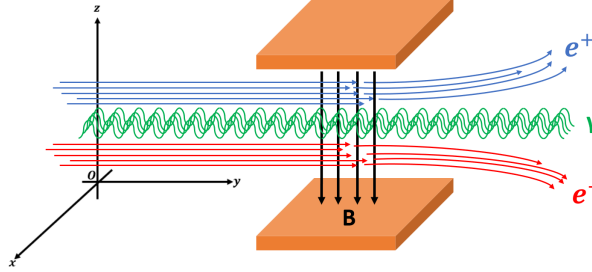


Figure 1.3: Magnetic filtering system after the first stage of e^+e^- production in the high-Z target-converter. In the selected frame of reference, supposing particles travel parallel to the y direction and the magnetic field is oriented along z , the magnet will add to the particle momentum a component parallel to the x direction.

machine, which holds the record for the highest-intensity positron beam, was able to deliver e^+e^- beams with a luminosity¹ of the order of $\sim 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ [3] reaching a positron production rate of $\sim 8 \times 10^{10} e^+/\text{s}$ [4]. Next-generation accelerators like the FCC-ee [1] aim at operating in the 45 – 182.5 GeV range, while the ILC [1] proposes a 250 – 500 GeV energy range, upgradable to 1 TeV. All the aforementioned facilities are currently based on the conventional positron source design which is integrated in a more complex beamline (figure 1.4). Figure 1.4 underlines how the basic ingredients and products for any possible positron source are e^+e^- charged particles and photons. Control over them can be achieved through the existing technologies for beam manipulation, which involve matching devices, beam dumps, shapers and damping rings [4]. While all these technologies have always been upgradable quite easily, the same cannot be said for positron production. The feasibility study of alternative designs for positron sources, such as the scheme previously shown in figure 1.1, are still being performed. A possible way to produce bremsstrahlung photons by electrons following a curved trajectory was firstly considered by Flöttmann [5] in 1994, in the framework of these feasibility studies. Flöttmann proposed the so-called *undulator* system in order to enhance the performances of the existing SLC-type² positron source (SLAC still holds the record of delivered positron intensity [5]).

¹ Luminosity in a collider is a measure of the collision rate within a given area, expressed in inverse barn per second (1 barn = 10^{-24} cm^2). It is defined as the product of the number of particles in two beams, N_1 and N_2 respectively, colliding over a time t across a surface S , thus: $L = (N_1 N_2)/(t S)$ [2].

² Stanford Linear Collider, a facility located in the larger Stanford Linear Accelerator Center (SLAC), Menlo-Park, California.

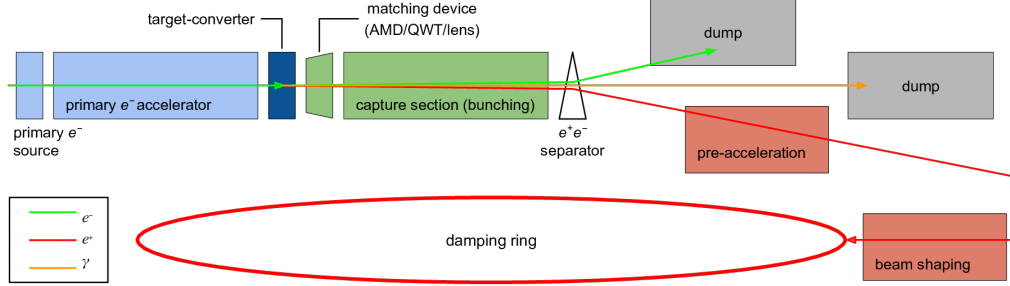


Figure 1.4: Different components of the positron source basic scheme [4]. The schematics shows the different steps of the positrons handling, from the primary electron beam up to the injection process inside the damping ring.

The core of Flöttmann’s design consisted in a series of magnets with alternate polarity, whose magnetic fields are oriented transversely with respect to the beam direction (figure 1.5). In this way the continuous changes in the electrons trajectory generate the so called *wiggler* radiation: its parameters, such as the luminosity and the emittance³, can be adjusted for instance through the magnets location, the electrons pulse frequency and so on. The wiggler-undulator design presents several advantages [6]:

- High efficiency: photons are generated with a larger intensity and narrow angular spread compared to other radiation mechanisms like bremsstrahlung inside high-Z materials [5].
- Control of the photon energy: by tuning the undulator magnetic field strength, the energy spectrum of the emitted photons can be tailored to optimize the pair production for the positron generation [5].
- Possibility of generating polarized positron beams, combining pre-damping rings and a capture-optics system. The same apparatus can also be applied to focus the beam, thus decreasing the emittance and reaching a luminosity larger than $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ [5].
- Reduced beam losses: compared to traditional positron production

³ The beam emittance is a quantity that describes the spread of particles in a beam in position and momentum space. For a beam propagating along the z direction orthogonal to the 2D plane, the emittance along x (or y) is expressed as: $\epsilon = \pi \sigma_x \sigma_\theta \sqrt{1 - \rho^2}$, where σ_x and σ_θ represent respectively the RMS of either the beam size along x or of the angular divergence $\theta = \tan^{-1}(x/z)$.

methods that rely on thick high-Z targets, undulator-based sources can reduce target overheating and radiation damage [1].

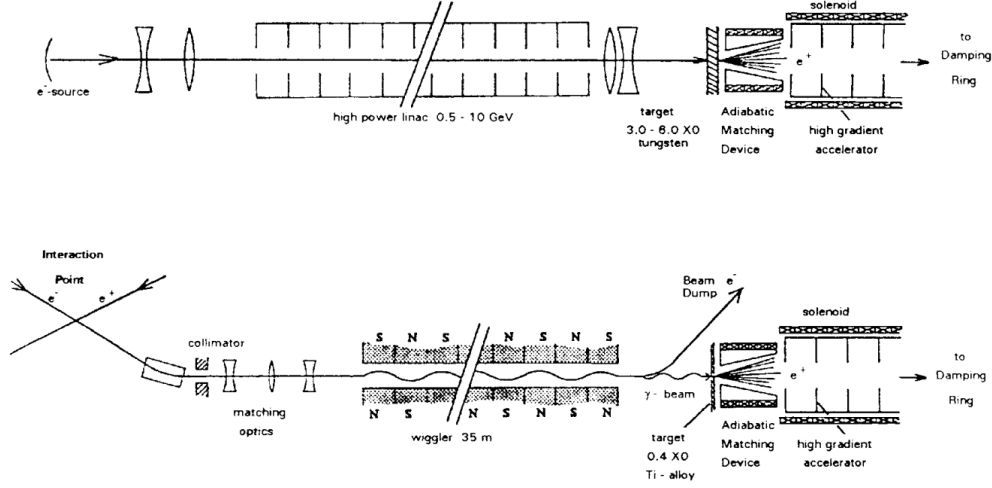


Figure 1.5: Comparison of two SLC-type positron sources. The top scheme represents the positron source previously in use at SLC [5], whereas the bottom one is Flöttmann's wiggler-undulator design.

Although Flöttmann's original design mainly focused on the capability of producing a beam of polarized positrons [5], the last point of the list represents the most notable one when it comes to the needs of future higher-energy positron colliders. However, implementing undulator-based positron sources requires first of all the integration of undulator magnets into the accelerator existing design, which can be challenging in terms of space, cost, and beam quality maintenance [1]. Therefore, the use of such kind of positron sources is still in the R&D phase, with still no large-scale accelerator or collider facility implementing them [1]. Nonetheless, the undulator-based source has been identified as a possible way to meet the ILC demanding beam emittance and polarization requirements [5]. This positron source would use 125 GeV electron beams to produce circularly polarized photons in a helical undulator, with photons later converted into positrons in a target.

Table 1.1 summarizes the most important parameters for both present and future positron sources, offering a comparison between state of the art results and the necessary efforts to match future requirements. As it can be devised from the values in table 1.1, there are still fundamental intensity limits in existing positron sources, mainly due to the thermal stress suffered by the high-Z target because of the primary beam energy deposit. When

dealing with target materials in a radiation-hard environment, two significant quantities shall be considered: the total amount of deposited energy in the target and the peak energy deposit density (PEDD) [7]. The former can be limited by a rotating wheel and evacuated by efficient cooling systems [7], whereas the latter needs additional care as mechanical stresses can develop in the target due to thermal gradients [7]. In fact, the strain can be particularly strong on the downstream side of the converter, where the electromagnetic shower is at its maximum, presenting a peak of the deposited power density. A maximum value of 35 J/g, based on a SLC damaged target, has been established for the deposited energy in tungsten [8].

	SLC	SuperKEKB	ILC	FCC-ee
Collider Type	Linear	Circular	Linear	Circular
Positron Source Input Energy [GeV]	30-33	3.5	3	6
e^+ Energy [GeV]	50	4	125	45.6
Pulse Frequency [Hz]	120	50	300	200
Bunches per Pulse	1	2	66	2
Particles per Bunch [$10^{10} e^\pm/\text{bunch}$]	5	6.25	3	2.1
Intensity [$10^{12} e^\pm/\text{s}$]	6	6.25	594	8.4
Luminosity [$\frac{10^9}{\text{barn}\cdot\text{s}}$]	0.003	800	14-49	2300
Vertical Emittance [μm]	2	20	0.035	0.09
Horizontal Emittance [μm]	30	100	5	24
e^+ Flux [$10^{12} e^+/\text{s}$]	6	2.5	200	6
e^+/e^- Ratio	0.8-1.2	0.6	1.5	0.5
Intensity = Particles per Bunch $\times$ Bunches per Pulse $\times$ Pulse Frequency				

Table 1.1: Parameters and requirements for present and future positron sources [1]. The labels related to the future machines (third and fourth column) correspond to the benchmark for ongoing and planned experiments. More specifically, in the case of ILC, tabulated values refer to the conventional scheme under study as a backup solution [1, 4].

The same breakdown of the SLC target due to the thermal stresses also led to the systematic determination of the PEDD, which could then be used as a reference for further simulations (table 1.2). An alternative strategy

to address the thermal stress problem is to divide the target-converter into multiple stages, placing them far apart in order to dump part of the energy deposit. Current strategies to mitigate this issue involve the handling of the time-spacing of pulsed particle beams, or, as already pointed out, the target rotation to better dissipate the heat (like rotating anodes inside X-ray machines), or even a combination of the two methods [5].

Positron Source scheme	Conventional	Hybrid
Target thickness (mm)	17.6	12
e^+ production rate (N_{e^+}/N_{e^-})	14.4	15.1
Target deposited Energy (GeV/e^-)	1.44	0.946
PEDD ($\frac{\text{GeV}}{\text{mm}^3 e^-}$)	0.0416	0.0156

Table 1.2: Results of the Geant4 simulations for a tungsten crystalline radiator inserted in a positron production scheme [9]. The simulation has compared some of the characteristic parameters in the conventional and the hybrid design.

The research nowadays is looking for an innovative setup able to overcome these challenges through a more efficient approach. Crystal-based positron sources might represent a possible alternative. As anticipated, when high-energy electrons interact with the crystalline components, coherent bremsstrahlung effects may come into play, allowing to increase the photon yield due to electrons channeling through an oriented lattice [9]. Such a kind of source would boost the pair production and the use of compact radiators in the first place, that would need to dissipate less heat thanks to the electromagnetic shower earlier development. Section 1.2 will describe this source design, while the physics of crystals will be described in the next chapter.

Figure 1.6 presents a comparison between past, present and future positron sources, in terms of power consumption and efficiency. The values for future positron sources have been retrieved from simulations and represent the present day benchmark.

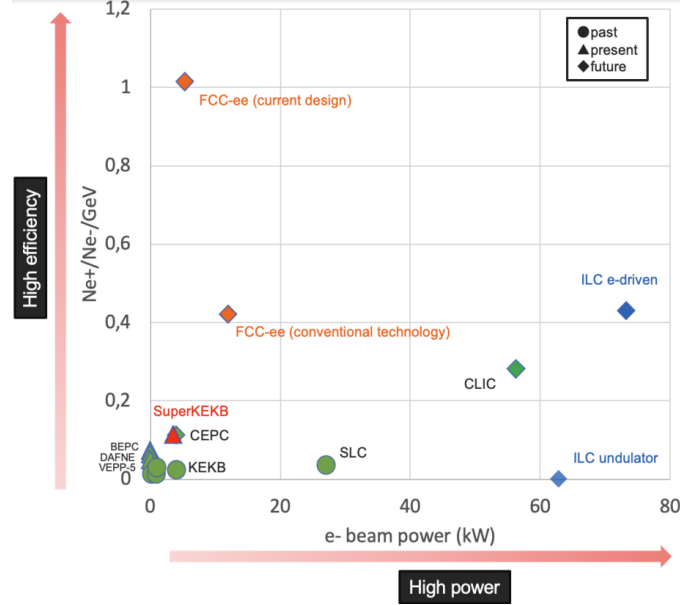


Figure 1.6: Comparison of e^- beam power and efficiency values for past, present and future positron sources [10]. Note that the FCC-ee current design is the one that requires the lowest beam power to operate, but with the highest achievable efficiency.

1.2 Hybrid crystal-based positron sources

This section explores some of the alternative strategies to the conventional positron source (section 1.1). In particular, it highlights the benefits and limitations of using a crystalline unpolarized positron source, able to produce high photon fluxes through the axial channeling of electrons. Since the axial channeling can only be obtained within a specific angular range between the axes orientation and the incident particles trajectories, from now on the expression “axially-oriented” will refer to the crystalline lattices that satisfy this condition. The physics of this phenomenon will be treated in detail in chapter 2.

A positron source driven by channeling radiation was first proposed in 1989 [11] and it involves two components: a photon radiator and a photon-to-positron target-converter. In such a configuration (referred to as *hybrid*), the main benefit comes from a considerably lower peak energy deposit density inside the materials, thus allowing to dissipate the heat through the implementation of a single target instead of multi-stage systems. In this configuration, an electron beam crosses a thin, axially oriented crystal, emitting

channeling radiation, which produces significantly more photons than the traditional Bethe-Heitler bremsstrahlung (section 2.2). Following the same concept of a conventional positron source, an enhancement in the photon yield eventually leads to a larger production of positrons within the converter. Figure 1.7 shows an example of a general hybrid positron source, like the ones tested at CERN and proposed to operate at KEK, with no undulator behaviour and with the radiator and target representing two separated stages. As for the possible crystalline materials, a good candidate is tungsten, due to the large value of its $\langle 111 \rangle$ axis potential (1000 V, at normal temperature) [8]. The simulations performed by Artru et al. [12] to study the photon yield increase in an axially-oriented tungsten crystal [8, 12] showed results with a promising enhancement of the bremsstrahlung photons production, with a strong dependence on both the incident electron energy and the crystal thickness. Figure 1.8 shows the simulations output for a 5 GeV and 10 GeV electron beam. As expected, the average photon yield is larger for lower cut-off energy thresholds (E_{CO}), which are usually set to filter out the low-energy part of the photon spectrum.

Crystal-based positron source designs are still in the feasibility study phase. A proof of principle experiment at the Orsay LINAC [9] studied γ production in germanium (Ge) and silicon (Si) crystals, with their subsequent conversion into e^+e^- pairs in a W amorphous target, for a 20 GeV e^- beam impinging on a 1 cm thick Ge crystal. The resulting photon yield was larger than 20γ per e^- [9]. Similar outcomes were also achieved for energies larger than 0.7 GeV for tungsten, 1.3 and 1.9 GeV for Si and Ge, respectively. At these energies, the output channeling radiation is composed essentially of soft photons, which eventually generate soft e^+e^- pairs ranging from some MeV to some tens of MeV kinetic energy [9]. Despite the innovation brought by the hybrid source concept, even in such an arrangement the energy deposit in the converter is still far from being homogeneous, leading again to thermal stress issues. Furthermore, it is still not clear what could be the best strategy to combine a crystalline radiator and an amorphous converter, keeping under consideration all their combined properties. In this context, extensive theoretical studies and simulations are ongoing, performed by INFN - Sezione di Ferrara (Italy) and IJCLab (Orsay).

Once the materials for the crystalline radiator and the amorphous converter were chosen, and taking into account the need for a magnetic system to separate photons from charged particles, a hybrid crystal-based positron source can be built following different arrangements, either placing the target-converter right after the crystal (figure 1.9), or after the magnetic dipole

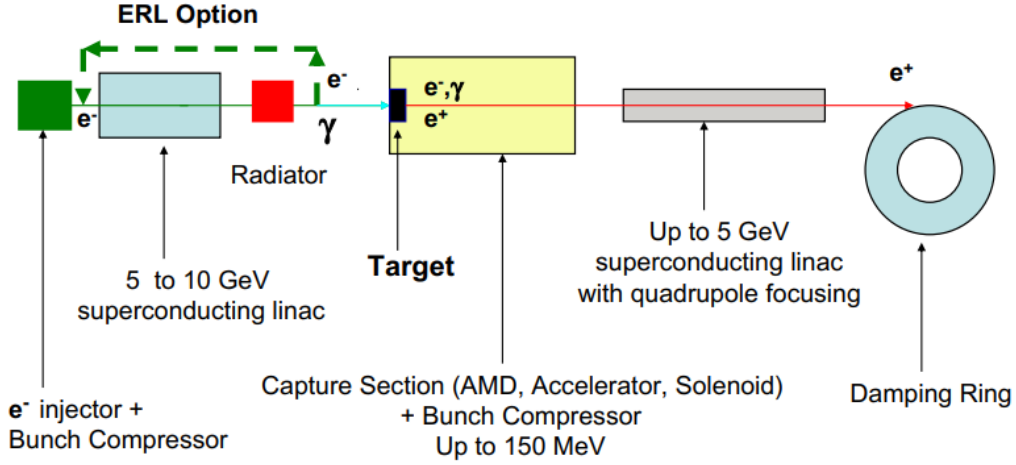


Figure 1.7: Basic design of a crystal-based positron source proposed to be implemented at KEK [8]. The ERL (Electrons Recovery Linac) is not an essential component, but rather an option to recycle part of the incident beam.

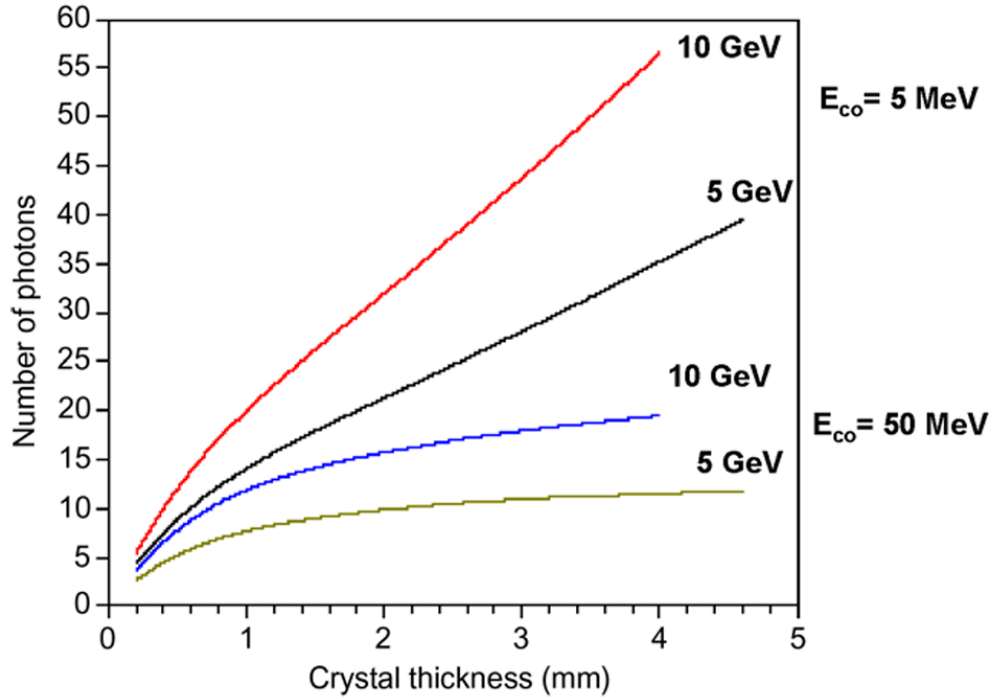


Figure 1.8: Simulation of the total photon yield as a function of a $\langle 111 \rangle$ tungsten crystal thickness for incident electron energies of 5 GeV and 10 GeV. The cut-off energies of 5 MeV (upper curves) and 50 MeV (lower curves) represent the lowest thresholds set to eliminate the soft photons from the spectra [8].

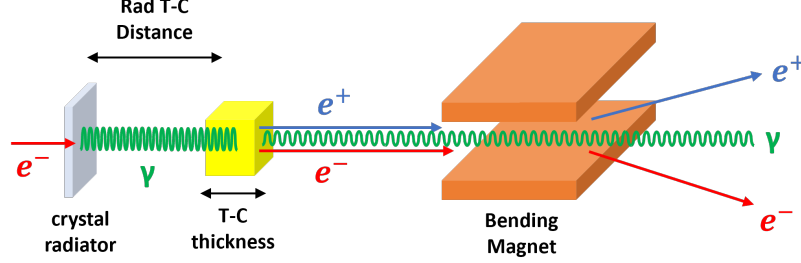


Figure 1.9: Two-stage hybrid positron source setup: the crystal-radiator and the target-converter are placed before the magnetic dipole. T-C stands for *Target Converter*.

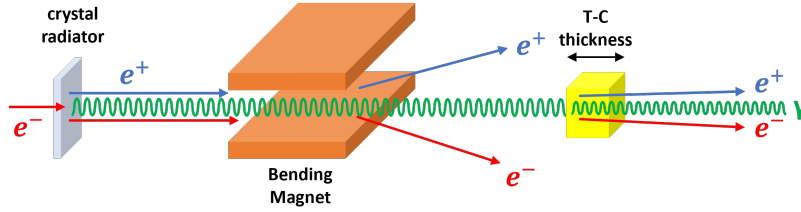


Figure 1.10: Two-stage hybrid positron source setup: the magnetic dipole is placed in between the crystal-radiator and the target-converter. T-C stands for *Target Converter*.

(figure 1.10). Moreover inside the crystalline radiator the incident particles produce an electromagnetic shower, so both designs must account for a partial loss of the initially irradiated photons. Although the second design (figure 1.10) would better deal with the thermal stress problem, due to the larger separation between the radiator and the target, it is the first one (figure 1.9) that truly minimizes the loss of generated positrons.

Therefore, the focus of this thesis was placed on this kind of arrangement. As a result of the collaboration between the University of Insubria and INFN Ferrara groups, several simulations have been performed to choose the optimal combination of the target-converter thickness and the distance between the converter and the crystal radiator. It is in fact necessary to evaluate the best trade-off among the maximization of particles production and the minimization of their emittance, knowing that both quantities grow proportionally with the converter thickness. Section 1.3 will describe the simulations and their results.

1.3 The e+BOOST simulations

As the ongoing projects for future positron sources are still far from their final implementation, simulations represent the main ingredient for the feasibility studies in the field. Part of these studies, mainly involving feasibility projects for FCC-ee, are currently performed inside the e+BOOST collaboration as well, where they constitute an essential benchmark for both the theoretical description and some of the beamtest-oriented strategies. Despite advanced mathematical and physical models being available for the description of the channeling phenomena, the state of the art computational tools are still based on approximations when it comes to simulate innovative applications such as a positron source, and this ends up in limiting the predictive potential they could provide. The experimental data provided by the e+BOOST beamtests allow to improve the existing models and their predictive power for future studies.

This section highlights the steps taken by the e+BOOST researchers prior to the beamtest phase. For the e+BOOST simulations two different energy values have been used [7]: 2.86 GeV, that is the threshold energy that prevents resonances of e^+e^- particles before they get inside the damping ring, and 6 GeV which corresponds to the maximum energy obtainable from tertiary electron beams at the CERN experimental area (section 3.1.1). All the simulations have been performed with the *Geant4* toolkit, where a hybrid positron source setup was designed, from the input beam up to the target-converter, together with virtual screens⁴ placed to measure the positrons rate. An example of the toolkit graphical output is presented in figure 1.11.

In a real-life scenario, the virtual screens of figure 1.11 would be replaced, for instance, by plastic scintillators to allow positrons counting. Furthermore, the simulated crystals are ideal, whereas real-life crystals have a number of impurities that grows with the material thickness. The main simulation strategy considered the trajectories of classical charged particles in crystals with averaged atomic potentials of their planes and axes. Moreover, the applied models needed to take into account at every step both single and multiple scattering, as well as ionization. A magnetic dipole was always placed down-

⁴ In *Geant4*, virtual screens are user-defined planes or surfaces placed within a simulation to capture and analyze information about particles. These screens do not physically interact with particles or influence their trajectories but serve as diagnostic tools.

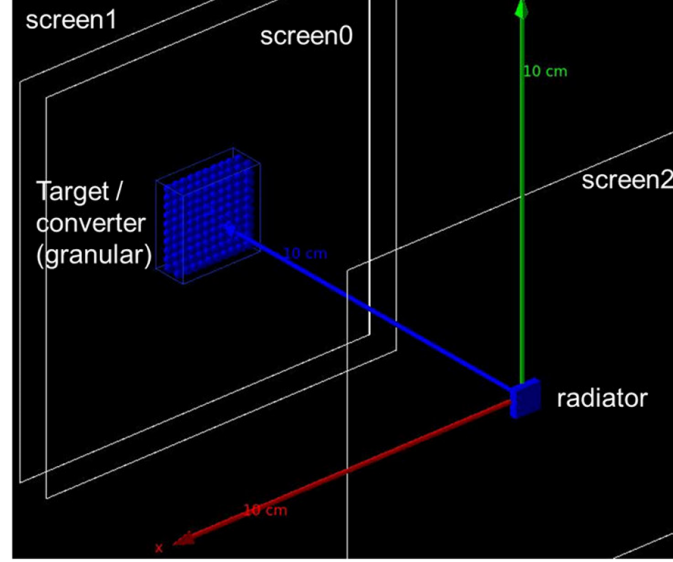


Figure 1.11: Geant4 simulation of the hybrid crystal-based positron source [7]. The image shows a basic setup containing the radiator, converter and virtual screens to detect the emitted particles.

stream with respect to the hybrid positron source, and room temperature and atmospheric pressure were considered. To implement these tasks in Geant4, it was necessary to integrate special classes into the toolkit, specifically those related to *channeling* physics and the Baier-Katkov quantum model⁵. A detailed explanation of these integrations is provided in the crystalline lattice description (section 2.2). Furthermore, the final two-stage setup already shown in figure 1.10 was used as a reference. This design required to consider three primary degrees of freedom, namely the:

- oriented crystal-radiator thickness;
- amorphous target-converter thickness;
- radiator-converter distance.

The goal of the simulations is to find the optimal combination of these features in order to maximize the positrons yield and to minimize other values,

⁵ The Bayer-Katkov formula is a modification of the classical plane-wave propagation formula which takes into account recoil and spin effects [13]. It will not be treated here.

such as the deposited energy, the power consumption and the PEDD. On the materials side, a 2 mm tungsten crystalline sample was first considered, with an orientation along its $\langle 111 \rangle$ plane. Nonetheless, other thickness values have been simulated as well. The target-converter thickness was arranged in a wider interval of $[0 - 15]$ mm, while the radiator-converter distance in the $[0 - 60]$ cm range. The first results as a function of the converter thickness are displayed in figure 1.12. It is clear that varying the converter thickness alone is not enough to retrieve the same yield provided by a conventional positron source, despite a lower delivered PEDD. It can also be noticed how the former grows with the thickness, reaching a plateau, while the latter maintains an overall constant trend, anyway below the FCC-ee safety requirements [7]. A similar behaviour was already pointed out by previous simulations from the IJCLab group, where it was clear that the energy deposit inside the target is far from being homogeneous, and hence the presence of critical regions that must be taken into account to handle the thermal stress problems (figure 1.13).

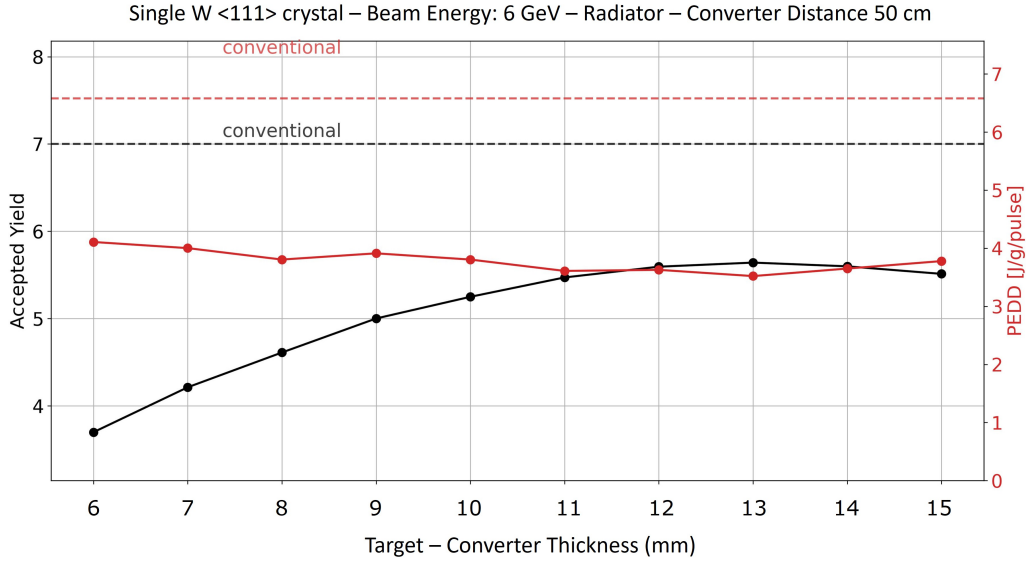


Figure 1.12: e+BOOST simulations: comparison of the output yield and PEDD as a function of the target-converter thickness [10]. The dashed lines refer to the existing upper limits of the corresponding quantities for the conventional positron source. Simulations considered an oriented $\langle 111 \rangle$ 2 mm tungsten crystalline sample at room temperature.

Looking at the results in figure 1.12, the target thickness should be fixed around 11 mm, in order to maximize the positrons yield. However, the analysis for the deposited power trend showed how such a thickness would

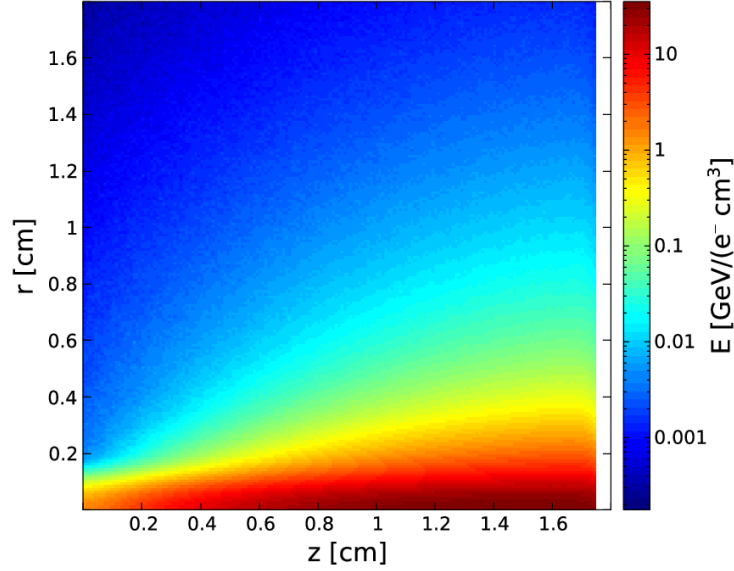


Figure 1.13: e+BOOST simulations: energy deposit map in the tungsten target-converter, as a function of the target thickness (z) and the radiator-target distance (r). The energy deposit is not homogeneous and reaches its maximum at the exit of the target, where the electromagnetic shower is fully developed. The simulation was performed for an electron beam energy of 6 GeV and a beam spot size on the target of 0.5 mm [4].

lead to overcome the required safety levels (figure 1.14). Therefore, a trade-off between the yield and the maximum power threshold had to be made, leading to select a converter thickness of 9 mm.

After this first compromise, the second stage of the simulations considered the distance between the oriented crystal and the amorphous target. In this case, only preliminary assumptions could be made about the emittance levels, which increases with distance, except for the presence of a focusing optical system. The simulations aimed at finding the distance for an optimal output yield, still keeping the energy deposit as small as possible. The obtained results are shown in figure 1.15. The better positron source performances were achieved when the radiator-converter distance is kept at minimum, regardless how the other parameters could change. This conclusion is valid for both the positron yield and the PEDD value. Therefore, even though a non-null separating distance might be useful to reduce the target-heating, a converter coupled to the radiator also keeps at minimum the particles emittance.

The last degree of freedom was the crystal-radiator thickness. A trade-off had to be made here as well, as a larger radiator enhances the bremsstrahlung

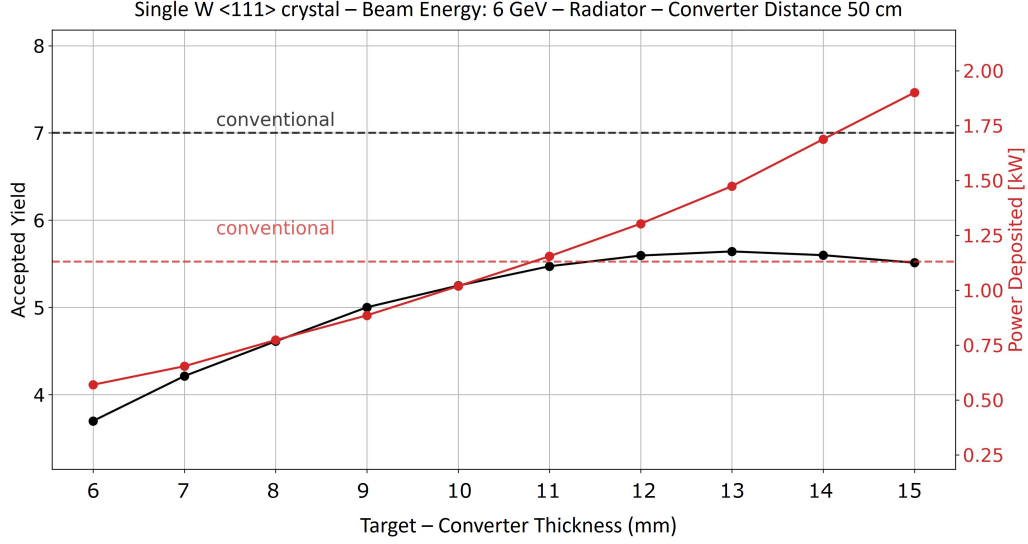


Figure 1.14: e+BOOST simulations: comparison of the output yield and deposited power as a function of the target-converter thickness [10]. The dashed lines refer to the existing upper limits of the corresponding quantities for a conventional positron source. Simulations considered an oriented $\langle 111 \rangle$ 2 mm tungsten crystalline sample at room temperature.

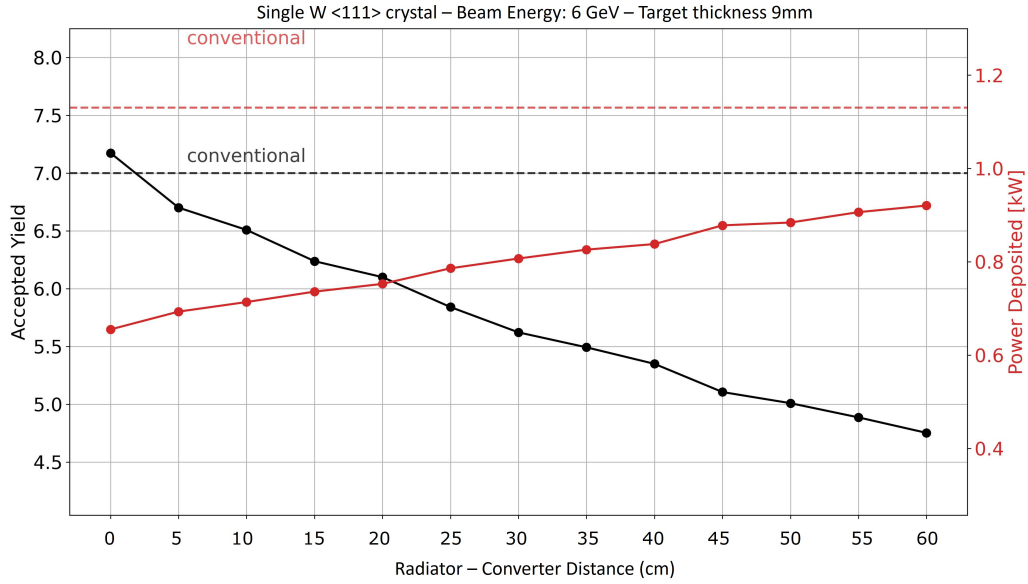


Figure 1.15: e+BOOST simulations: comparison of the output yield and PEDD as a function of the radiator-converter distance [10]. The dashed lines refer to the existing upper limits of the corresponding quantities for a conventional positron source. Simulations considered an oriented $\langle 111 \rangle$ 2 mm tungsten crystalline sample at room temperature.

but a too thick one would risk to cut a large part of the electromagnetic shower. Preliminary simulations demonstrated an increasing number of emitted photons inside an increasingly thick radiator. Table 1.3 in fact shows a larger γ production for an oriented crystal. Moreover, these enhancements hold regardless of the cut-off energies of the photon spectra. As shown in figure 1.16 with a nominal crystal thickness range of $[1 - 2]$ mm, the PEDD remains almost constant and at the same level of the conventional design. on the other hand, the deposited power increases with the radiator thickness, along with the output yield. The promising result is highlighted by the fact that the former and the latter are respectively below and above the required level, compared to the conventional positron source design. In fact, the overall deposited power is smaller, whereas the output yield is larger in a 5 – 10 % range. Therefore, Geant4 simulations led the design of a positron source as the one in figure 1.17. Additional work on the geometry of the setup was performed as well: further simulations helped estimating the crystal-orientation range within which the hybrid positron source would still deliver an enhancement with respect to the conventional one. The results are presented in figure 1.18 and were a valid reference when performing the data acquisition during the beamtests.

Crystal thickness (mm)	1	2	3	4	5
≤ 100 MeV, amorphous	1.1	2.6	4.6	7.4	10.9
≤ 100 MeV, $\langle 111 \rangle$ axis	6.1	11.3	17.2	24.0	31.8
Full spectrum, amorphous	2.3	4.7	7.5	11.0	15.1
Full spectrum, $\langle 111 \rangle$ axis	11.0	17.6	24.0	31.0	38.8

Table 1.3: Simulated γ production rate (N_γ/N_{e^-}) generated by one incident 6 GeV electron for two tungsten crystal orientations: crystal aligned along the $\langle 111 \rangle$ axis and random orientation. The low energy cutoff used in simulations is 5 MeV [9].

After the introduction to the positron source concept, the next chapter is devoted to the description of the physics of oriented crystals, from a mathematical and physical point of view.

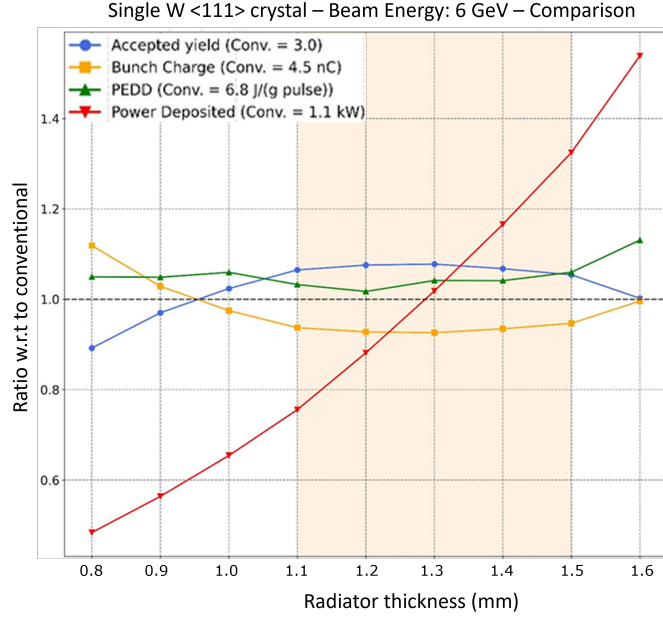


Figure 1.16: e+BOOST simulations: comparison of the output yield features from two positron source designs as a function of the radiator thickness [10]. The dashed line represents the match between a conventional and a crystalline setup. Simulations considered an oriented <111> 2 mm tungsten crystalline sample at room temperature.

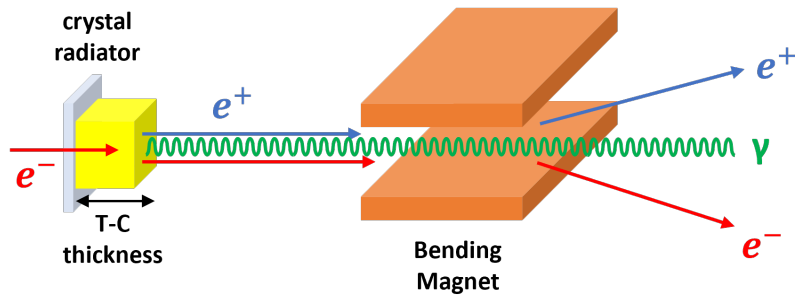


Figure 1.17: Final design for the crystal-based positron source, after the parameters found with the Geant4 simulations. This configuration is characterized by the fact the crystal radiator and the target converter are placed as close as possible.

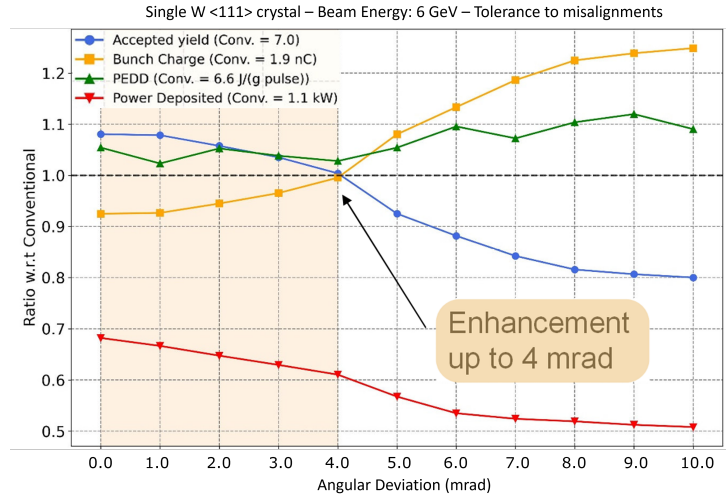


Figure 1.18: e+BOOST simulations: comparison between a conventional and a hybrid positron source varying the angular orientation of the crystal. The threshold for maintaining the enhancement is estimated around 4 mrad, even under high temperature conditions (~ 600 K) [7].

Chapter 2

The Physics of Oriented Crystals

Electromagnetic interactions of particles inside crystals experience significant alterations compared to those occurring in amorphous materials. This happens when the incident particles are nearly aligned with the ordered atomic distributions of the crystalline lattice, or more specifically, the crystal planes and axes. The emission of characteristic electromagnetic radiation by electrons and positrons, in fact, depends on both the energy and the angle between the incident beam and the crystalline lattice. The radiation emission inside oriented crystals happens through two main mechanisms: *channeling* and *coherent bremsstrahlung*. In channeling, charged particles oscillate within potential wells created by the atomic planes or axes. As far as coherent bremsstrahlung, the electromagnetic field experienced by the charged particles is the result of the combined contributions from all the atoms in the lattice. These phenomena and their combination can also lead to further more complex effects [14]. Moreover, at high energies, the relativistic length contraction causes the incident particles to perceive a significantly higher atomic density of the lattice and, as a result, the perceived electromagnetic field intensifies and the relativistic X_0 decreases [15]. At the multi-GeV scales, this field may even be larger than the critical threshold set by quantum electrodynamics, often referred to as the Schwinger limit [16]. When this happens, the probability of emitting hard photons or producing e^+e^- pairs increases.

In this chapter, the phenomenon of channeling and the radiative processes resulting from electrons/positrons and photons interactions within oriented crystals are discussed.

2.1 The crystalline lattice

Crystals consist of solid materials in which the atoms are arranged in a definite pattern and whose surface regularity reflects the internal symmetry. From a geometrical perspective, these solids are characterized by a regular three-dimensional lattice, also known as crystalline lattice or *Bravais lattice* [17], in which atoms, molecules and ions are arranged in an ordered and periodic way. This regular structure extends uniformly in all the spatial directions, giving specific properties to the crystal, such as transparency and hardness. A Bravais lattice is an infinite array of discrete points, arranged in a way that looks identical from any viewing angle. This symmetry can be described through a set of discrete translational operations, in which three dimensional points are described through the *Bravais vector* $\mathbf{R}$:

$$\mathbf{R} = n_1\mathbf{a}_1 + n_2\mathbf{a}_2 + n_3\mathbf{a}_3 \quad (2.1)$$

where $\mathbf{a}_1$, $\mathbf{a}_2$ and $\mathbf{a}_3$ are any three vectors belonging to different planes, and n_1 , n_2 and n_3 are integer values. The Bravais vector $\mathbf{R}$ represents a generic lattice point, whereas the $\mathbf{a}_i$ vectors are called *primitive vectors* as they are responsible to generate (or “span”) the lattice through their linear combinations. The number of possible Bravais lattices in a 3-dimensional space is fixed and equal to 14 (figure 2.1), namely the number of every possible combination of the crystal family lattice systems [17]. To describe the crystalline geometry and its contribution to particle physics, two subsets of crystal nodes are essential, namely the **planes** and **axes** (or strings). Given a particular Bravais lattice, its axes are parallel to the Bravais vectors 3D reference frame (equation 2.1), while lattice planes are defined to be any flat surface containing at least three non collinear lattice points. In the description of physical phenomena such as channeling, diffraction and wave propagation inside crystals, **reciprocal lattice vectors** represent a powerful tool to simplify the representation of the Bravais lattices. A reciprocal lattice, in fact, has its planes orthogonal to the ones from the direct lattice, thus allowing a more straightforward representation through the use of *Miller indices* [17].

First the reciprocal lattice basis has to be considered, whose vectors are defined starting from the standard three dimensional basis $\{\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3\}$:

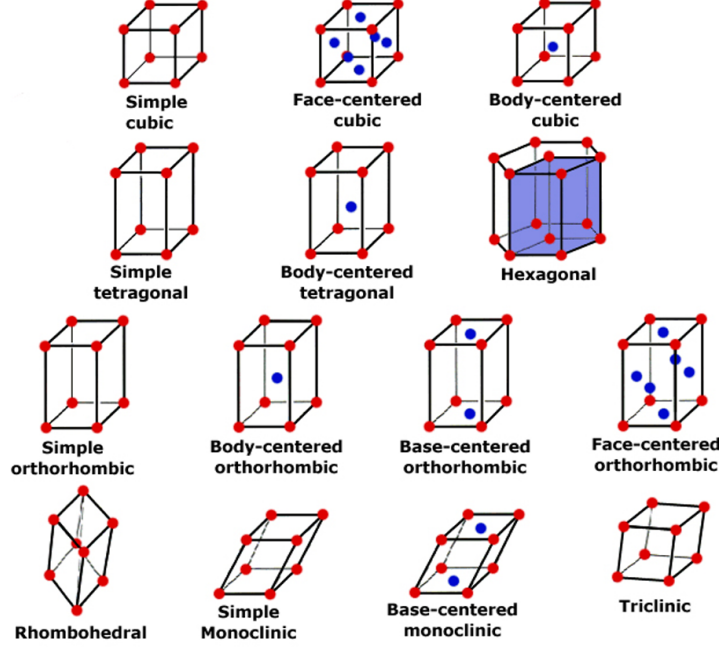


Figure 2.1: Types of Bravais lattices. The red points represent the cell vertexes while the blue points represent the atoms positioned inside the cell bodies [18].

$$b_1 \equiv 2\pi \frac{\mathbf{a}_2 \times \mathbf{a}_3}{\mathbf{a}_1 \cdot (\mathbf{a}_2 \times \mathbf{a}_3)} \quad b_2 \equiv 2\pi \frac{\mathbf{a}_3 \times \mathbf{a}_1}{\mathbf{a}_2 \cdot (\mathbf{a}_3 \times \mathbf{a}_1)} \quad b_3 \equiv 2\pi \frac{\mathbf{a}_1 \times \mathbf{a}_2}{\mathbf{a}_3 \cdot (\mathbf{a}_1 \times \mathbf{a}_2)}$$

Assuming the triplet $ijk = 1, 2, 3$, these expressions can be generalized:

$$b_i = 2\pi \frac{\mathbf{a}_j \times \mathbf{a}_k}{\mathbf{a}_i \cdot (\mathbf{a}_j \times \mathbf{a}_k)} \quad \text{with} \quad i \neq j \neq k \quad (2.2)$$

Then a generic lattice plane is considered, which intersects the basis vectors at amplitudes given by n_{01} , n_{02} , and n_{03} . Miller indices (h, k, l) are then defined as the set of smallest integers proportional to the reciprocal values of the intercepts (n_{01}, n_{02}, n_{03}) , i.e.

$$(h, k, l) \propto \left(\frac{1}{n_{01}}, \frac{1}{n_{02}}, \frac{1}{n_{03}} \right)$$

By definition, Miller indices must be natural numbers, so an arbitrary

integer n can be used to transform the proportionality into an equality relation:

$$(h, k, l) = \left(\frac{n}{n_{01}}, \frac{n}{n_{02}}, \frac{n}{n_{03}} \right) \quad (2.3)$$

Therefore, Miller indices just depend on the particular choice of primitive vectors and equation 2.3 holds as long as n is the lowest possible value that ensures h , k and l to be rational numbers. Figure 2.2 shows the Miller notation for the most common reciprocal planes orientations in crystals lattices, with the normalized associate indices.

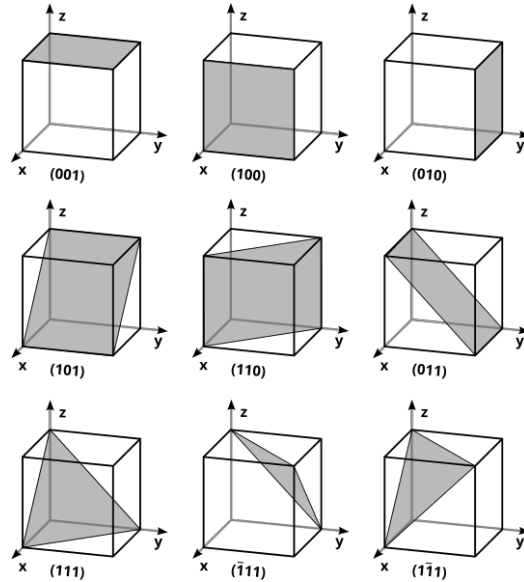


Figure 2.2: Example of crystallographic planes and Miller indices for a cubic structure. The Miller-index notation for the most commonly studied axes and planes is highlighted [19].

In this way, a compact notation for the reciprocal lattice planes is obtained [17]:

- **(hkl)** denotes a generic plane. In this way, every time a 0 appears inside the notation, it means that the reciprocal lattice plane is parallel to the corresponding direction. For instance, the plane (010) is orthogonal just to the y axis (figure 2.2, top right).

- $(\tilde{h}\tilde{k}\tilde{l})$ denotes the reciprocal lattice plane of (hkl) . For instance, a plane with indices $(1\tilde{1}\tilde{1})$ intersects the x and z axis and the intersection point between (100) , (010) and (001) planes (figure 2.2, bottom right).
- $[hkl]$ denotes all the axes which are orthogonal to the (hkl) plane.
- $\langle hkl \rangle$ denotes all the axes which are identical to $[hkl]$, under global rotations.

Eventually, knowing how to retrieve Miller indices and the reciprocal lattice basis (equation 2.2), a reciprocal lattice vector can be written in the new basis $\{\mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3\}$ using the same linear combination of equation 2.1:

$$\mathbf{G} = h \mathbf{b}_1 + k \mathbf{b}_2 + l \mathbf{b}_3 \quad (2.4)$$

such that a plane with Miller indices (h, k, l) is orthogonal to the reciprocal lattice vector [17]. Miller indices are particularly useful when modeling the mathematical and physical equations that combine the lattice geometry with the radiation-matter interactions.

From the point of view of an external observer, such as a particle beam, crystals can have different orientations (figure 2.3). In fact, depending on the angle of incidence between the incident particles and the target, the lattice can appear oriented according either to its planes, or to its axes, or with no particular symmetry (this is the so called *random* or *amorphous* orientation) [20].

Figure 2.4 shows the case of an oriented and non oriented crystal as seen by an external frontal observer.

As anticipated, the lattice electromagnetic fields can experience significant changes in the reference frame of charged particles that interact with the crystal. An important radiation-matter phenomenon, mainly based on the lattice orientation, is *channeling*, as described more in detail in the next section 2.2.

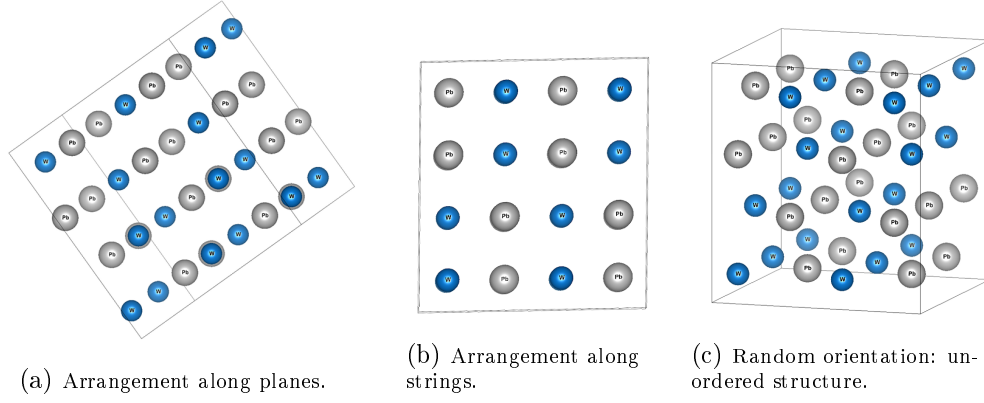


Figure 2.3: Examples of different orientations for the PbWO_4 crystal lattice, from the point of view of an observer facing orthogonally at the screen [21].

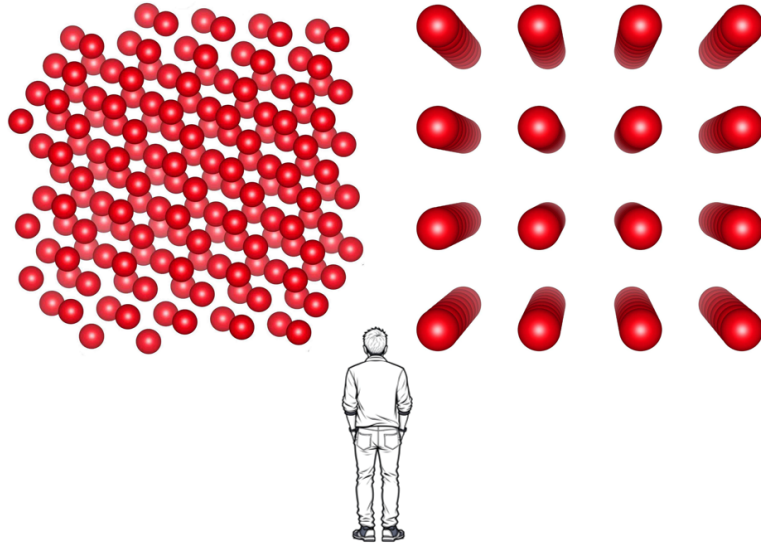


Figure 2.4: Different crystalline orientations from the point of view of an impinging particle beam. On the left side, the random orientation is equivalent to the beam interacting with an amorphous material, while in the oriented case (right side), the beam direction becomes almost parallel to the lattice axes, and the perceived crystalline electromagnetic field will be maximum [22].

2.2 The channeling phenomenon

According to Stark: “channeling is the effect of the penetration of charged particles through a mono-crystal quasi parallel to its atomic axes or planes” [23]. This physical phenomenon can be exploited not only to maximize the bremsstrahlung photons emission, but also to curve the paths of charged particles that interact with the crystalline lattice, obtaining trajectories deviations that would only be possible through ultra-high magnetic fields [24]. A major contribution to the description of crystalline potentials was provided by Lindhard in 1965 [25], who developed the so called *planar* and *axial* continuum models, based on the continuous potentials obtained by averaging the lattice potential over atomic planes and axes respectively. The distinction between *planar* and *axial* depends on the geometry of the oscillation from the point of view of an impinging high-energy charged particle [25]. Moreover, each mode is characterized by a specific angular acceptance, cross section and radiation emission, depending on the sign of the interacting particles and on the lattice orientation.

Section 2.3 delves into the mathematical framework governing the barrier potentials associated with channeling.

2.2.1 Planar channeling

Planar channeling occurs when a charged particle moves within the potential well formed by two parallel crystal planes [15]. In fact, a particle experiences the electrostatic field of atoms along a plane, creating a one-dimensional potential well orthogonal to the propagation direction. As these potential wells are evenly distributed within the lattice, this results in the particle periodically oscillating between the two planes, confined by the overall potential (figure 2.5).

The continuous potential energy in the planar case can be formulated as:

$$U_{pl}(x) = N d_p \int_{\mathbb{R}^2} \int V(x, y, z) dy dz \quad (2.5)$$

where N denotes the atomic volume density and d_p the inter-planar spacing. The continuous potential $V(x, y, z)$ can then be extracted through the

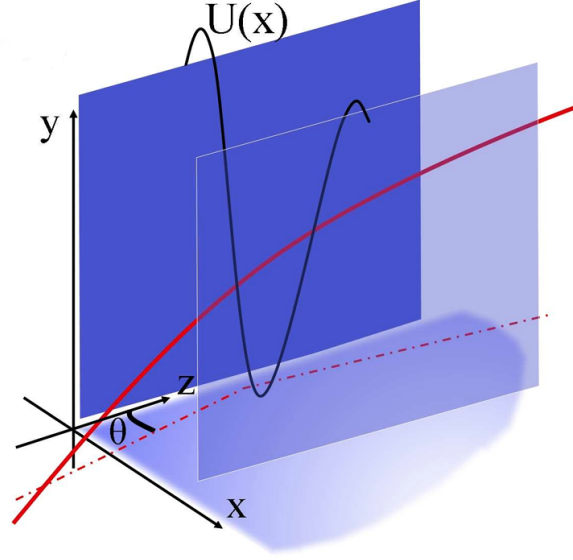


Figure 2.5: Schematization of a planar channeling potential, with planes parallel to the particle motion direction along the z axis [26]. Charged particles are locally attracted towards the potential minimum (hole).

Lindhard approximation [25]:

$$V(r) = \frac{Z_i Z_e^2}{r} \left[1 - \left(1 + \frac{3a_{TF}^2}{r^2} \right)^{-\frac{1}{2}} \right] \quad (2.6)$$

where Z_i denotes the crystalline atomic number, Z_e the particle charge and a_{TF} is the screening length of the particle-atom interaction:

$$a_{TF} \simeq 0.468 \text{ \AA} Z^{\frac{1}{3}}$$

Substituting $V(r)$ and calculating the integral, equation 2.5 becomes

$$U_{pl}(x) = 2\pi N d_p Z_i Z_e^2 (\sqrt{x^2 + 3a_{TF}^2} - x) \quad (2.7)$$

Equation 2.7 represents a single-plane potential. In the case of small-angle approximation, the contribution of two nearest-atom planes can also be expressed [23]:

$$U(x) \simeq U_{pl}\left(\frac{d_p}{2} - x\right) + U_{pl}\left(\frac{d_p}{2} + x\right) - 2U_{pl}\left(\frac{d_p}{2}\right) \quad (2.8)$$

Indicating with p the particle momentum, considering z as the propagation direction and x as the transverse direction, the condition for particles to stay in the former channeling condition is given by

$$p_z \gg p_x$$

which is equivalent to the so-called *small-angle* approximation, as the contribution of one direction is much larger than the orthogonal one. As far as the total energy is concerned, it can be written under the relativistic formalism, adding the kinetic contribution to the potential term:

$$E_{TOT} = \sqrt{p_x^2 c^2 + p_z^2 c^2 + m^2 c^4} + U(x)$$

while for the transverse energy, remembering the small angle approximation:

$$\frac{p_x}{p_z} = \sin \theta \sim \theta$$

which allows to rewrite the total energy as

$$E_T = \frac{p_x^2 c^2}{2E_z} + U(x) = \frac{p_z^2 c^2}{2E_z} \theta^2 + U(x) = \text{const.} \quad (2.9)$$

The small angle approximation, together with the high-energy regime, implies also that $E_z \simeq E$, $p_z \simeq p$ thus simplifying equation 2.9 into

$$E_T \simeq \frac{pv}{2} \theta^2 + U(x) = \text{const.}$$

where the equality $pc^2 = vE$ has been plugged in as well.

Considering the potential barrier, for the planar channeling the transverse energy has to be:

$$E_T = \frac{pv}{2}\theta^2 + U(x) < U(x_c) \equiv U_{max} \quad (2.10)$$

where $x_c \simeq \frac{d_p}{2} - a_{TF}$. Equation 2.10 can then be used to express the channeling condition as a function of the incidence angle [23]. In this situation, when a particle starts interacting with the lattice, $U(x=0) = 0$ and thus $E_T = U_{max} = \frac{pv}{2}\theta^2$, which allows to extract the critical angle:

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}} \quad (2.11)$$

with U_{max} which corresponds to the maximum kinetic transverse energy. A possible wider acceptance threshold can be set considering the *Lindhard angle* [25], defined as:

$$\theta_L = \sqrt{\frac{2U_0}{pv}} \quad (2.12)$$

where U_0 represents the threshold barrier of the planes potential, namely the maximum planar potential reachable by the crystalline lattice (figure 2.6).

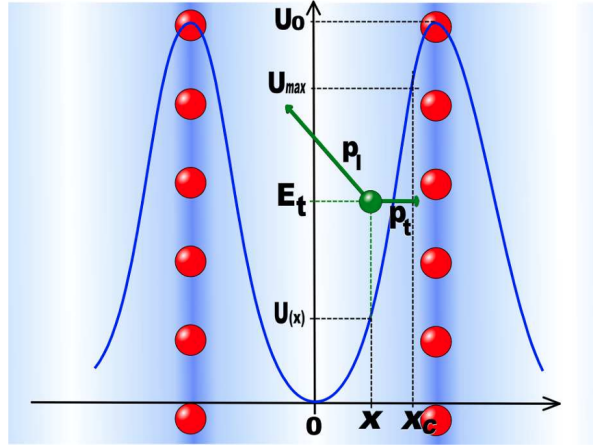


Figure 2.6: Schematization of a planar channeling potential for a frontal observer, with planes parallel to the particles motion [26]. Positively charged particles are locally attracted towards the potential minimum. The critical and Lindhard energy thresholds are visible, indicated as U_{max} and U_0 .

Planar channeling provides weaker confinement compared to the one from axial channeling, as the potential wells are one-dimensional and shallower [23]. The critical angle for planar channeling ($\propto \sqrt{2U/pv}$), moreover, is larger than the one for axial channeling, thus making the former regime easier to achieve [25]. Typical values for the lattice potentials in materials like tungsten or silicon are 10 – 20 eV [20]. Thus, for a particle with ~ 1 GeV energy this would correspond to a critical angle of ~ 500 μrad .

2.2.2 Axial channeling

Axial channeling occurs when a charged particle propagates within the cylindrical potential well formed by the axes (or “strings”) of atoms in a crystal (i.e., the lines of atoms along high-symmetry directions) [15]. The cylindrical symmetry arises from the radial potential surrounding the crystal axes. As a consequence, a positively charged particle undergoing axial channeling experiences the combined electrostatic field of all the atoms aligned with the crystal axis, providing a stronger confinement than the planar case, despite a narrower critical angle to enter in the axial motion [23].

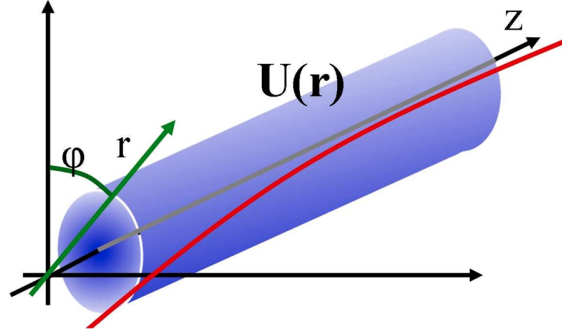


Figure 2.7: Schematization of an axial channeling potential, with planes parallel to the particle motion direction along the z axis [26].

In order to deal with the mathematical description, a relativistic treatment in continuous approximation is necessary [23]. The integration of the potential is written in only one dimension:

$$U_{ax}(x) = \frac{1}{d} \int_{-\infty}^{\infty} V(\vec{r}, z) dz \quad (2.13)$$

where $\vec{r}$ represents the radial distance between the potential string and the particle. Referring again to the transverse energy E_T , indicating with ψ the trajectory angle and relying once more onto the small-angle approximation, the transverse energy can be expressed as:

$$E_T = U(r) + E\psi^2 \quad (2.14)$$

where $E = \frac{1}{2}pv$. As a potential with radial symmetry is being treated, it can be convenient to switch to a polar representation, in the form

$$\psi^2 = \psi_r^2 + \psi_\phi^2 = \left(\frac{dr}{dz}\right)^2 + r^2\left(\frac{d\phi}{dz}\right)^2$$

with a radial (ψ_r^2) and azimuthal (ψ_ϕ^2) contribution. Equation 2.14 can be rewritten:

$$E_T = U(r) + \frac{1}{2}pv\psi_\phi^2 + \frac{1}{2}pv\psi_r^2$$

From the azimuthal point of view, the axial potential and the particle momentum can be connected through the angular momentum, i.e.

$$L = pr\psi_\phi \quad \text{so that} \quad \psi_\phi = \frac{L}{pr}$$

In the relativistic regime it is also true that $p = m\gamma v$, so the expression for the transverse energy becomes

$$E_T = U(r) + \frac{1}{2}pv\psi_r^2 + \frac{1}{2}\frac{L^2}{m\gamma r^2}$$

Moreover, as a combination of radial oscillations and angular precession, due to the symmetry of the potential and the varying forces, a positive particle undergoing axial channeling enters a quasi-periodic dynamics resembling a flower-like or spiral pattern, called *rosette motion* [23]. This contribution is in fact visible from the last equation, as it can be expressed through the transverse potential:

$$W(r, L) = U(r) + \frac{1}{2} \frac{L^2}{m\gamma r^2} \quad (2.15)$$

As for the planar case, the transverse energy is a fundamental parameter to characterize the conditions that allow the particle to stay in the axial channeling. More specifically, three different situations shall be considered [15]:

- $E_T \ll U_0$: the particle is confined within the potential well, following a rosette-shaped orbit around its axis. This condition, known as *hyperchanneling* [27], is represented in blue in figure 2.8;
- $E_T \lesssim U_0$: the particle remains trapped within the potential well, but thermal fluctuations are enough to occasionally overcome the barrier, allowing the particle to move between axes [27]. This state is highlighted in green in figure 2.8;
- $E_T > U_0$: the particle becomes unbound and is free to move through the crystal lattice, as long as it keeps an over-barrier energy [27]. This condition is represented by the red line in figure 2.8.

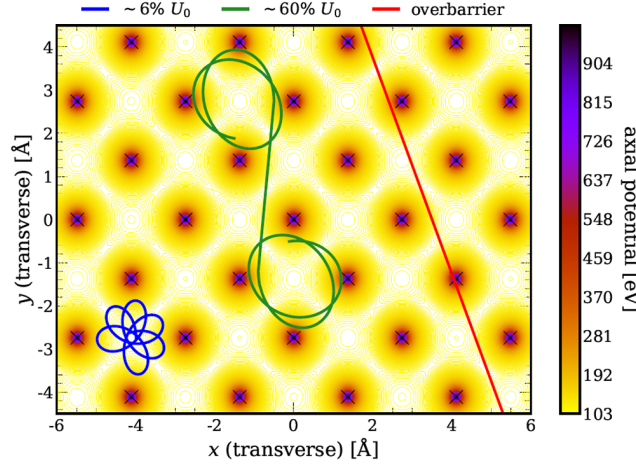


Figure 2.8: Contour plot of the tungsten $\langle 111 \rangle$ axis potential in the plane perpendicular to the axis direction (z). The colored points indicate the string positions, whereas the different colored lines refer to different particle trajectories depending on the initial transversal energy [27]. Blue: under barrier rosette motion; green: barrier occasionally overcome due to thermal fluctuations; red: over barrier motion.

Concerning the critical angle for the channeling condition, the different expressions for the potential energy influence the geometry of the two channeling modes. In fact, in the planar case the potential energy was expressed in the periodic form

$$U(x) = U_0 \cos\left(\frac{2\pi x}{d}\right)$$

while the cylindrical symmetry of the axial channeling corresponds to a radial potential in the form

$$U(r) = \frac{U_0}{r}$$

The former case leads to a channeling critical angle $\theta_c \simeq \sqrt{\frac{2U_0}{pv}}$ whereas in the latter case, the critical angle becomes:

$$\psi_c = \sqrt{\frac{U_0}{pv}} \quad (2.16)$$

Therefore, the critical angle for axial channeling is smaller compared to the planar channeling, with the trade-off consisting in a larger photon yield [15]. Typical values for the lattice potentials in materials like tungsten or silicon are 10 – 20 eV [20]. Thus, for a particle with ~ 1 GeV energy this would correspond to a critical angle of ~ 100 μ rad.

2.2.3 Channeling of positive and negative particles

The treatment described in the previous subsection involved only positively charged particles. When negatively charged particles are considered, the interaction potential appears equal in shape but of opposite sign as compared to the potential governing the motion of the positively charged ones [23]. When dealing with lattice potentials, the focus should be placed onto the regions corresponding to the potential minima (or *holes*). In the continuum picture, negative particles experience potentials with the minima placed at the center of strings or planes, as shown schematically in figure 2.9 for the planar case.

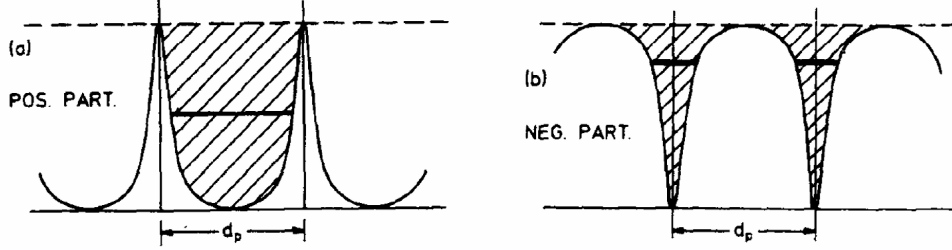


Figure 2.9: Planar continuum potentials for positively (a) and negatively (b) charged particles. d_p represent the lattice spacing [23].

For positively charged particles in the planar channeling the holes are attractive (*negative field divergence*) instead, resulting into a transverse potential barrier responsible for the confined oscillations. As a consequence, the channeling of positrons inside crystals reflects an *undulator* behaviour (section 1.1), with the propagating particle emitting synchrotron radiation while being confined in transverse oscillations [15]. On the other hand, negatively charged particles feel the regions as repulsive (*positive field divergence*) and thus get expelled from them. This last case is the one referred to as *de-channeling* phenomenon [23].

In summary, as the potential maxima and minima switch together with the sign of the particle charge, channeled negative particles tend to concentrate near the atomic nuclei, in contrast to their positive counterparts. As a result, they are more likely to drift towards the planes during channeling [15]. This difference in channeling behavior between oppositely charged particles becomes even more pronounced in the axial configuration. While positively charged particles can move freely between axes, negatively charged particles are confined to a single string or, in some cases, a pair of strings [15]. Therefore, the frequent interactions of negatively charged particles with target nuclei significantly increase the likelihood of de-channeling.

2.3 Radiation emission

The present section outlines some of the high-energy physical processes responsible for radiation emission of charged particles interacting with crystalline lattices, such as standard bremsstrahlung, pair production, coherent bremsstrahlung and the strong field regime [13]. While channeling radiation emission and coherent bremsstrahlung are characteristic of radiation-

crystalline matter interaction, pair production and bremsstrahlung typically occur inside electromagnetic showers. However, if the electromagnetic shower develops in an oriented crystal rather than an amorphous medium, channeling effects may come into play, influencing the overall process [13].

Both planar and axial channeling have been described as *under-barrier* effects. The coherent bremsstrahlung, instead, is labeled as an *over-barrier* effect, whereas the *strong field regime* represents an ultra-relativistic limit for this kind of radiation-matter interaction [13]. In every case the term “barrier” refers to the crystalline maximum potential levels, either in the planar or in the axial case.

2.3.1 Standard bremsstrahlung and pair production

In order to fully characterize the radiation emitted by an electron (or positron) crossing a properly oriented crystalline lattice in different energy regimes, it is useful to introduce the concept of *spectral intensity* [28], defined as

$$I(\omega) = \hbar\omega \frac{dNq}{d(\hbar\omega)} \quad (2.17)$$

where $\hbar \simeq 1.055 \times 10^{-34}$ Js is the reduced Planck constant and $\hbar\omega$ is the energy of the Nq emitted radiation quanta. In quantum models for radiation emission, the spectral intensity is directly proportional to the radiation emission differential cross section $\Phi(\omega; E_0)$, for a parent electron with initial energy E_0 [16]. Bremsstrahlung, on the other hand, refers to the emission of electromagnetic radiation resulting from the scattering of fast charged particles in the electric field of an atomic nucleus. The standard bremsstrahlung theory, firstly introduced by Bethe and Heitler [16], describes the process of photon emission in amorphous media or randomly oriented crystals, in which the interactions are independent on one another and the emitted radiation results from the contributions of all the single collisions adding up incoherently [16]. For the considered energetic regimes, it can be useful to refer to the high-energy Bethe-Heitler model, where the cross section for the photons emission is evaluated. More specifically, for a photon of energy $\hbar\omega = h\nu = E_0 - E_1$, with E_1 being the final energy of the parent particle, the afore-mentioned cross section can be expressed like:

$$\Phi(\omega; E_0) \propto \frac{\alpha Z^2 r_p^2}{\hbar \omega E_0^2} \left[\left(E_0^2 + E_1^2 - \frac{2}{3} E_0 E_1 \right) \ln \left(\frac{183}{Z^{1/3}} \right) + \frac{E_0 E_1}{9} \right] \quad (2.18)$$

where

- $\alpha \sim 1/137$ is the fine-structure constant.
- $r_p \propto (Z_p e)^2 / mc^2$ is the classical particle radius, with the charge expressed in a number Z_p of units of e .

In particular, expression 2.18 is the equivalent for the

$$\frac{dNq}{d(\hbar\omega)}$$

term of the spectral intensity (equation 2.17). It can be noticed how the cross section is quadratically dependent on the atomic number of the nucleus Z . Equation 2.18, moreover, underlines a strong dependence on the particle mass, due to the factor $r_p \propto 1/mc^2$. The connection between the Bethe-Heitler bremsstrahlung and the spectral intensity through the factor $\hbar\omega$, gives to the bremsstrahlung radiation energy spectrum the characteristic trend shown in the theoretical curves in figure 2.10.

From figure 2.10 it is clear that the energy loss via collision dominates at small E_0 , whereas bremsstrahlung sets on at high E_0 . Furthermore, the spectra reveal the existence of a medium-dependent critical energy, $E_c = E_c(Z)$, which is defined as the energy at which the energy loss rates from radiation emission and collisions become equal. An estimate [16] of this critical energy for solids and gases is given by

$$E_c = \frac{610 \text{ MeV}}{Z + 1.24} \quad (2.19)$$

Therefore, the larger the atomic number of the target, the lower the energy threshold for radiation emission to become dominant. In synthesis, the Bethe-Heitler description covers the radiation emission of particles interacting with an amorphous medium, with no focus on the consequences that can

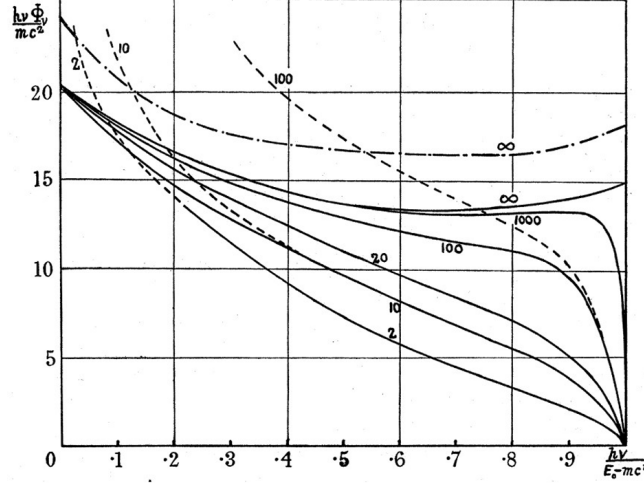


Figure 2.10: Spectral intensity of the standard bremsstrahlung as a function of the fraction of initial energy taken by the emitted photon, for lead with (solid lines) and without (dashed lines) the contribution of the screening, for different values of E_0 (numbers affixed to the curves, in units of mc^2) [29].

arise in more specific cases, such as constructive interference [16]. Hence it is often referred to as *incoherent bremsstrahlung*. However, the Bethe-Heitler model starts losing its validity when dealing with ultra-relativistic particles, mainly due to the presence of quantum interference effects and nonlinear Compton scattering (NCS) effects [13].

When it comes to ultra-relativistic particles, and from a geometrical perspective, it takes a relatively long time (and so a long distance) for a charged particle to create a photon via bremsstrahlung [13]. The interactions that particles undergo through this length, called *formation length* (l_f), heavily affect the radiation spectrum and may lead to an enhancement or reduction of the total emitted intensity [13]. For ultra-relativistic energies, the radiation length can be defined as

$$l_f = \frac{2c\gamma^2}{\omega} \quad (2.20)$$

The bremsstrahlung process can also be influenced by the presence of an external electromagnetic field across l_f [13]. For electron-positron pair production, on the other hand, the formation length represents the distance over which the final state particles separate transversely by two Compton wave-

lengths¹. As expressed by equation 2.20, l_f increases significantly due to the electron Lorentz factor γ and the reduction in the energy of the emitted photon. Figure 2.11 shows the two different Feynman diagrams that describe either bremsstrahlung or pair production. The angular distribution of the radiation emitted via bremsstrahlung by ultra-relativistic particles forms a narrow cone, $\theta_\gamma \sim 1/\gamma$, aligned with the particle initial momentum [26]. The relationship between the formation length and radiation emission is illustrated in figure 2.12, which depicts an ultra-relativistic electron emitting synchrotron radiation.

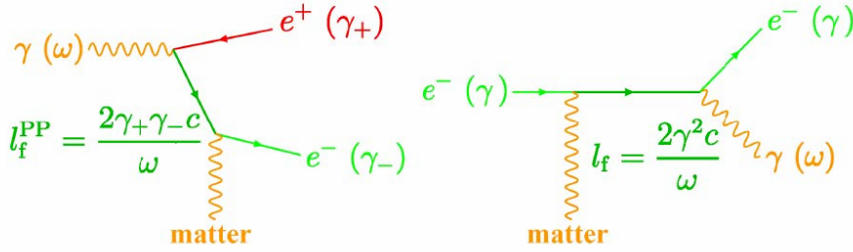


Figure 2.11: Feynman diagrams of electron-positron pair production (left) and bremsstrahlung (right) [30].

A more detailed explanation regarding electron-positron pair production is described in appendix 4.5. Anyway, for the hybrid positron source design, the main aspect of interest consists in the optimization of the electromagnetic shower of electrons inside an oriented crystal radiator. To characterize an electromagnetic shower, parameters like the shower extension, radiation length, critical energy, Molière radius and shape profiles (longitudinal and lateral) are most commonly analyzed [2]. These quantities are critical to understand the shower development in detectors and to optimize the design of calorimeters for particle physics experiments. The radiation length (X_0) is defined as the mean distance over which a high-energy electron loses about $1/e$ of its energy due to bremsstrahlung, and represents a fundamental material property used to scale the shower depth and spread [2]. The critical energy, on the other hand, is the energy at which the energy loss due to bremsstrahlung equals the energy loss due to ionization [2]. A representation of an electromagnetic shower is presented in figure 2.13.

¹ The Compton wavelength is a quantum mechanical property of a particle, defined as the wavelength of a photon whose energy is the same as the rest energy of that particle. The standard Compton wavelength λ_c of a particle of mass m is given by $\lambda_c = \frac{h}{mc}$.

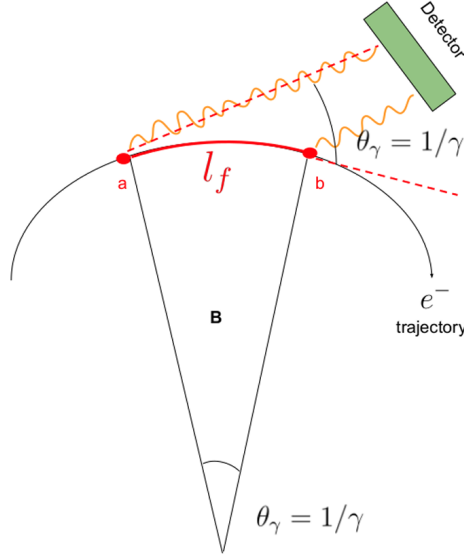


Figure 2.12: Synchrotron radiation emission by an energetic electron propagating across a magnetic field B . The distance ab corresponds to the formation length l_f ; the typical emission angle $\theta_\gamma = 1/\gamma$ makes photon emission from any point within the arc from a to b indistinguishable by any detector [26].

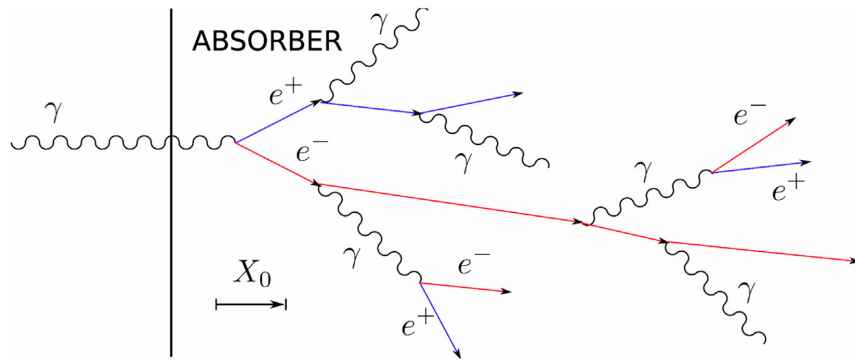


Figure 2.13: Representation of an electromagnetic shower development started by a photon interacting with a thick absorber. The photons annihilate in e^+e^- pairs, who in turn emit bremsstrahlung photons.

Oriented crystals allow to achieve larger yields of bremsstrahlung photons, compared to amorphous high-Z materials with the same thickness, and with the electromagnetic shower absorbed only partially. In this way, more photons would be obtained and with a lower energy deposit inside the target. For charged particles, the emission of radiation requires electrons or positrons to interact with an electromagnetic field. As a consequence of the axial orientation (section 2.2.2), the electromagnetic fields generated by the crystalline lattice are enhanced in the reference frame of the incident particle. For this reason, the cross section of radiation-matter interaction phenomena, such as an electromagnetic shower, increases as well, resulting in a contraction of the actual radiation length (figure 2.14). Having outlined the basic concepts underlying the bremsstrahlung radiation and the pair production phenomena, in the next section the phenomenon of coherent bremsstrahlung will be explored.

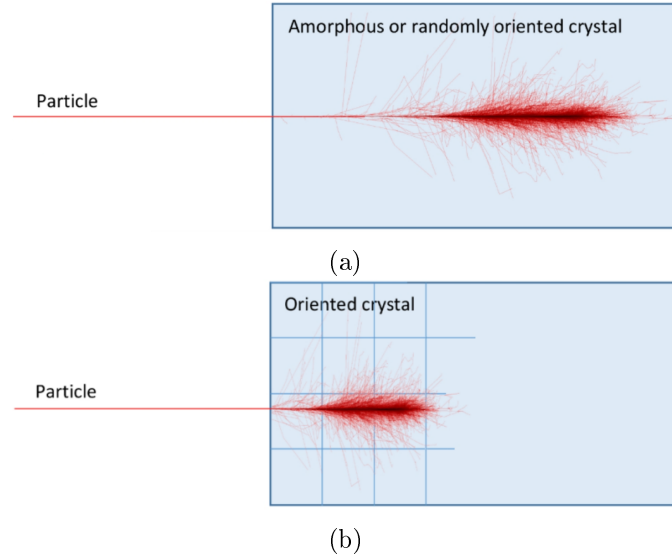


Figure 2.14: Transverse sections of an electromagnetic shower development in the same crystalline material with different orientations. (a) amorphous or random oriented or axial. (b) in this case the shower develops earlier [22].

2.3.2 Coherent bremsstrahlung

Between the end of the Fifties and the beginning of the Sixties, coherent bremsstrahlung was studied theoretically and experimentally [13]. Coherent bremsstrahlung is the radiation emitted by high-energy charged particles as they cross a periodically ordered structure, such as a crystalline

lattice. Coherent bremsstrahlung consists in an enhanced and directional radiation emission phenomenon, caused by the constructive interference of bremsstrahlung photons emitted coherently² within a crystalline lattice. The lattice periodicity, in fact, can favor the superposition effects of the emitted photons, leading to an enhancement of the emitted radiation at specific energies and wavelengths [13]. The distribution of these energies corresponds to precise peaks in the photon spectrum, governed by Bragg's law:

$$2d \sin \theta = n \lambda \quad (2.21)$$

where d is the spacing between the lattice planes, θ is the angle of the particle trajectory relative to the lattice planes, n is an integer (called *order of diffraction*), and λ is the wavelength of the emitted photon. The essence of Bragg's law lies in describing how, at specific incidence angles θ , the waves reflected by the crystalline lattice interfere either constructively or destructively (figure 2.15).

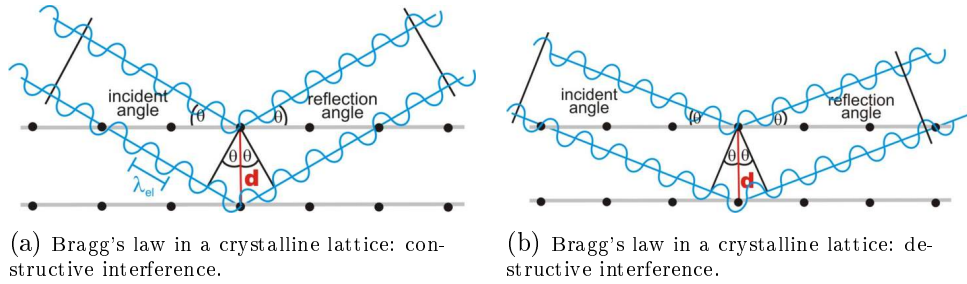


Figure 2.15: Comparison of the two main modes of interference for monochromatic waves impinging on an ordered lattice structure, as described in equation 2.21. The output interference is a consequence of the incidence angle [31].

Contrarily to channeling, coherent bremsstrahlung represents an example of *over-barrier* effect, meaning that there are no constraints on the transverse energy of the particles undergoing this regime, thus modifying the overall radiation emission mechanism [32]. From a geometrical perspective, in fact, coherent bremsstrahlung occurs when the incidence angle of a particle is larger than the channeling critical angle, but still within the boundaries that allow to keep the continuum approximation. Figure 2.16 illustrates a typ-

² *Coherence* is the effect from undulatory physics corresponding to two or more waves that maintain their reciprocal phase constant.

ical coherent bremsstrahlung spectrum, with its peaks associated with the different angles that resulted in a constructive interference.

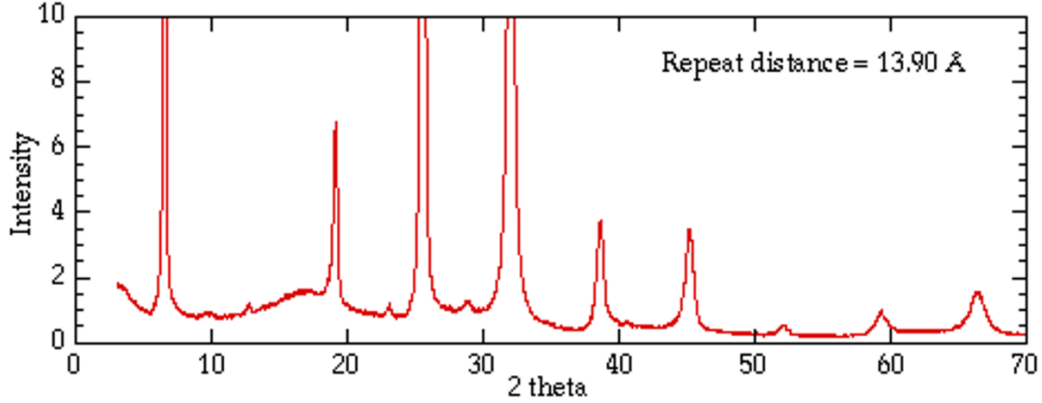


Figure 2.16: Presence of Bragg interference peaks in a silicon crystal under X-ray spectroscopy analysis [33]. It can be noticed how the peak values corresponding to constructive interference can only be achieved for specific values of the incident radiation angle.

The spectrum exhibited by coherent bremsstrahlung radiation is quite different from that of the ordinary bremsstrahlung spectra in amorphous targets, as shown in figure 2.17. In fact, as for the coherent case, the spectrum is more peaked with a larger average energy. Under ideal conditions, such as the absence of thermal effects and approximately null beam divergence, the coherent bremsstrahlung spectrum should be monochromatic, namely consisting in just one energy line. However, such circumstances are out of reach, as it is nearly impossible to rule out external dissipative contributions [32]. The photon emission of a high-energy particle undergoing coherent bremsstrahlung is contained in a radiation cone with its width inversely proportional to the particle velocity [26] (figure 2.18).

Contrarily to the axial channeling, for ultra-relativistic particles in coherent bremsstrahlung, the longitudinal component of the external force relative to the particle direction of motion, has a negligible effect compared to the transverse component [32]. Consequently, radiation emission is entirely determined by the transverse force. Considering the amplitude $\Delta\theta$ of the transverse oscillations, there are two cases to consider in the spectrum of relativistic particles undergoing coherent bremsstrahlung [35]:

- $\Delta\theta \gg 1/\gamma$: there are rapid changes in direction, with an overall destructive interference that corresponds to the emission of low-intensity radiation [35].

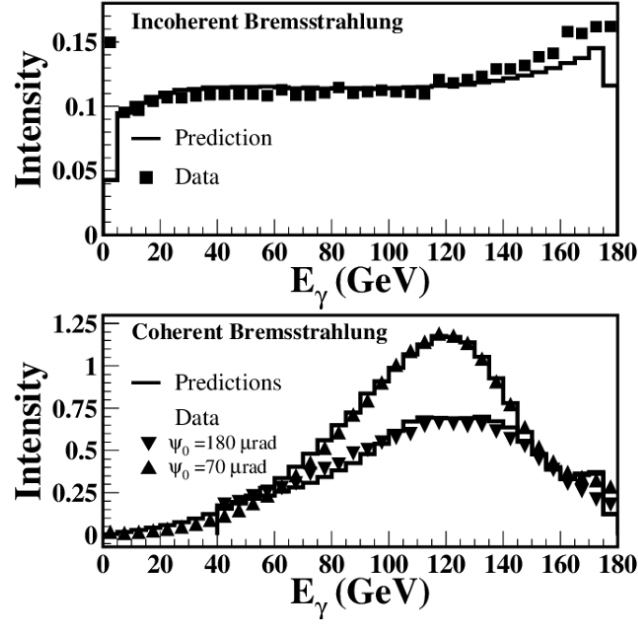


Figure 2.17: Total energy radiated for incoherent (top) and coherent (bottom) bremsstrahlung in 1.5 cm thick silicon crystals. The solid curves represent the Monte Carlo simulation results [34].

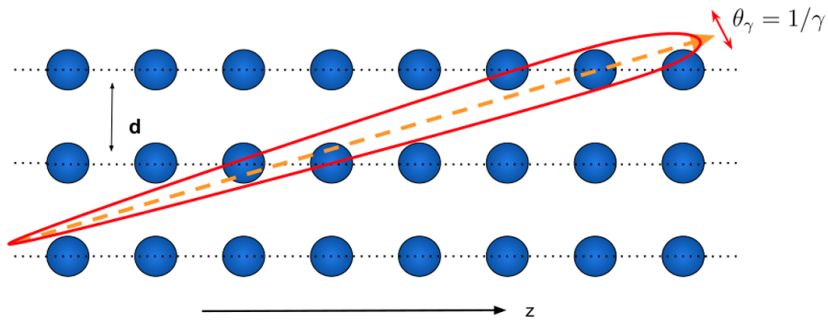


Figure 2.18: Schematization of the emission angle for a high-energy charged particle undergoing coherent bremsstrahlung in a crystalline lattice [26].

- $\Delta\theta \leq 1/\gamma$: the particle trajectory stays within a bounded region, emitting radiation over many Compton wavelengths [35].

Therefore, coherent radiation is highly directional and can be strongly influenced even by small misalignments between the trajectory and the optimal angle [35]. Being an over-barrier effect, high-energy particles in the GeV range are typically expected to achieve this regime, as in the case of the crystal-based positron sources.

In summary, coherent bremsstrahlung originates from the periodic structure of the crystal and typically occurs in weaker fields compared to channeling radiation [32]. In both channeling and coherent bremsstrahlung, the emitted photons can interact with the lattice electromagnetic field and may induce pair production (e^+e^-) if their energy is larger than $2m_e c^2$ [32]. Eventually, under specific conditions, such as high particle energies and precise crystal alignment, coherent bremsstrahlung can enter a regime that mimics strong field effects [35].

2.3.3 The strong field regime

For energies larger than 10 GeV and incidence angles smaller than 1 mrad, the angular oscillations of the particle are small enough for the lattice potential to be described as approximately constant [35]. It may be shown that the resulting particle trajectory is a sequence of circular arcs, interrupted by the emission of hard synchrotron radiation: this condition is known as the strong field regime (sometimes called magnetic bremsstrahlung [28]).

This phenomenon refers to situations where the electromagnetic field experienced by a particle approaches or exceeds the critical field strength of quantum electrodynamics (QED) [32]. Coulombian repulsion, in fact, increases inversely proportionally to the atomic radius. So at low distances from the nucleus, an extremely strong electric field is generated by the combined nucleons or even by the core electrons (the ones at lower orbits), whose influence further increases with the atomic number of elements [16]. Figure 2.19 shows the different geometries associated with the radiation emission from either channeling effects or the strong field regime, highlighting how this last one is an over-barrier phenomenon with lower confinement.

The strong field plays a crucial role in understanding other phenomena like

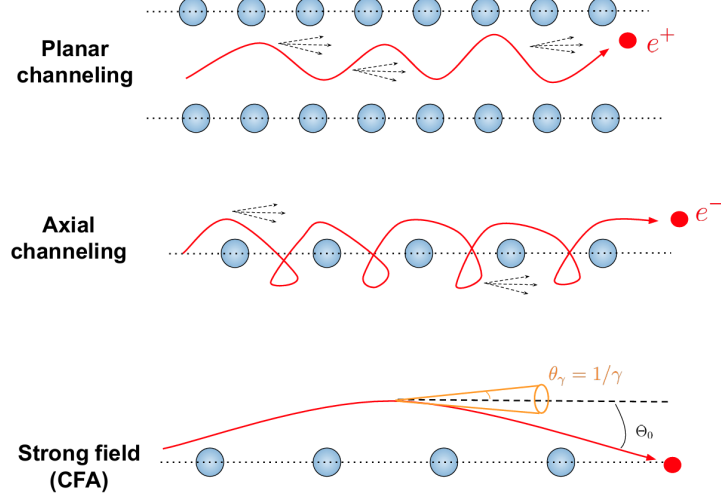


Figure 2.19: Schematic comparison of the trajectories of an electron emitting bremsstrahlung radiation (dashed arrows) when undergoing different channeling regimes (CFA stands for Constant Field Approximation) [26].

nonlinear QED effects, enhanced radiation emission, and particle production in oriented crystals. In addition, it represents a bridge effect between classical and quantum physics [32], offering insights into both fundamental QED and practical applications, such as in high-energy accelerator physics.

The *critical field* of QED is defined as the field strength at which the energy required to separate a particle-antiparticle pair over one Compton wavelength equals the particle rest energy [32]. This critical value is often referred to as the *Schwinger limit*, for an electric field E_c :

$$E_C = \frac{m_e^2 c^3}{e \hbar} \simeq 1.32 \times 10^{18} \frac{\text{V}}{\text{m}} \quad (2.22)$$

and for the magnetic field B_c :

$$B_C = \frac{m_e^2 c^2}{e \hbar} \simeq 4.41 \times 10^9 \text{ T} \quad (2.23)$$

The strong field threshold for a particle in motion relative to the electromagnetic field is described by the *field strength* parameter χ [16]:

$$\chi = \gamma \frac{E}{E_C} = \frac{e\hbar}{m_e^3 c^4} \sqrt{-(F_{\mu\nu} p^\nu)^2} \quad (2.24)$$

where $F_{\mu\nu}$ is the electromagnetic field tensor, $p^\nu = (\frac{E}{c}, \mathbf{p})$ is the four-momentum of the particle and E is the average electrical field in the laboratory frame³, enhanced by the Lorentz factor γ . The power radiated by an electron in strong fields, on the other hand, can be described by the Landau-Lifshitz radiation reaction relation, a modification of the classical Larmor formula [16]:

$$P \simeq \frac{2}{3} \frac{e^2}{4\pi\epsilon_0} \frac{\gamma^4}{c^3} (E^2 + B^2) \quad (2.25)$$

where E and B are the electric and magnetic field components. If for a particle interacting with a medium $\chi \sim 0.1$, the strong field regime is achieved and thus nonlinear QED effects start to dominate [16]. More in general, the main consequences of the strong field are the following:

- The emitted radiation is highly directional [16].
- Nonlinear Compton Scattering (NCS): it is a scattering process belonging to the category of light-matter interaction phenomena. The absorption of multiple photons of the electromagnetic field by the charged particle causes the emission of a X-ray or a gamma ray with an energy comparable or larger with respect to the charged particle rest energy [16].
- Vacuum Pair Production (VPR): the field can create electron-positron pairs directly from the vacuum⁴.

The angular acceptance of the phenomenon has been estimated by Baier and Katkov [32]; considering a crystalline electromagnetic potential U_0 :

$$\Theta_c = \frac{U_0}{mc^2} \quad (2.26)$$

³ The $(-)$ sign in equation 2.24 is needed as the product $F_{\mu\nu} p^\nu$ is antisymmetric.

⁴ This is often referred to as the *Schwinger effect* [28].

An estimate of the photon critical energy (E) has been also evaluated as

$$\frac{h\omega_c}{E} \simeq \frac{\chi}{1 + \chi} \quad (2.27)$$

From equation 2.27 it is clear that, as the initial energy increases, harder photons (i.e. photons with an energy closer to the spectrum end point) are favored. In the limit $\chi \rightarrow \infty$, it can be observed how the energy of the emitted photon is not smaller than the energy of the parent electron.

Radiation emission in crystals, including processes such as coherent bremsstrahlung, strong-field radiation, and channeling radiation, plays a pivotal role in the design of advanced positron source setups, such as crystal-based positron sources. Next chapter will describe in detail the e+BOOST beamtests performed at CERN, the experimental area, the goals and the setup.

Chapter 3

The e+BOOST Beamtests

In the framework of the e+BOOST project, this thesis has dealt with the analysis of the data collected in a series of beamtests performed for the feasibility study of a crystalline positron source. The main goal of the beamtests was the measurement of the photon yield enhancement in different crystals. The data acquisition took place in the T9 beamline of the CERN East Area. This chapter summarizes the measurements performed and the experimental setup in the T9 extracted beamline.

3.1 The beamtest facility

The accelerator complex at CERN is composed of a series of machines that sequentially accelerate particles to higher energies (figure 3.1). Each machine increases the energy of the particle beam before transferring it to the next in the sequence. The process begins with the linear accelerator (Linac 4) which accelerates negative hydrogen ions to 160 MeV/c [36]. At this stage, the ions are stripped of their two electrons, leaving protons that are then injected into the Proton Synchrotron Booster (PSB). The PSB, consisting of four superimposed synchrotron rings, accelerates protons to 2 GeV/c [36]. The protons are then sent to the Proton Synchrotron (PS), where their momentum is increased to 24 GeV/c. From there, the protons can either be extracted to the East Area beamlines (figure 3.2) or transferred to the Super Proton Synchrotron (SPS), which boosts their momentum further to 450 GeV/c. In this case, the protons may be delivered to the North Area beamlines or

injected into the world largest and most powerful particle accelerator, the Large Hadron Collider (LHC) [24, 36]. The CERN accelerator complex also includes several additional machines and facilities, which are not described here as they are beyond the scope of this thesis.

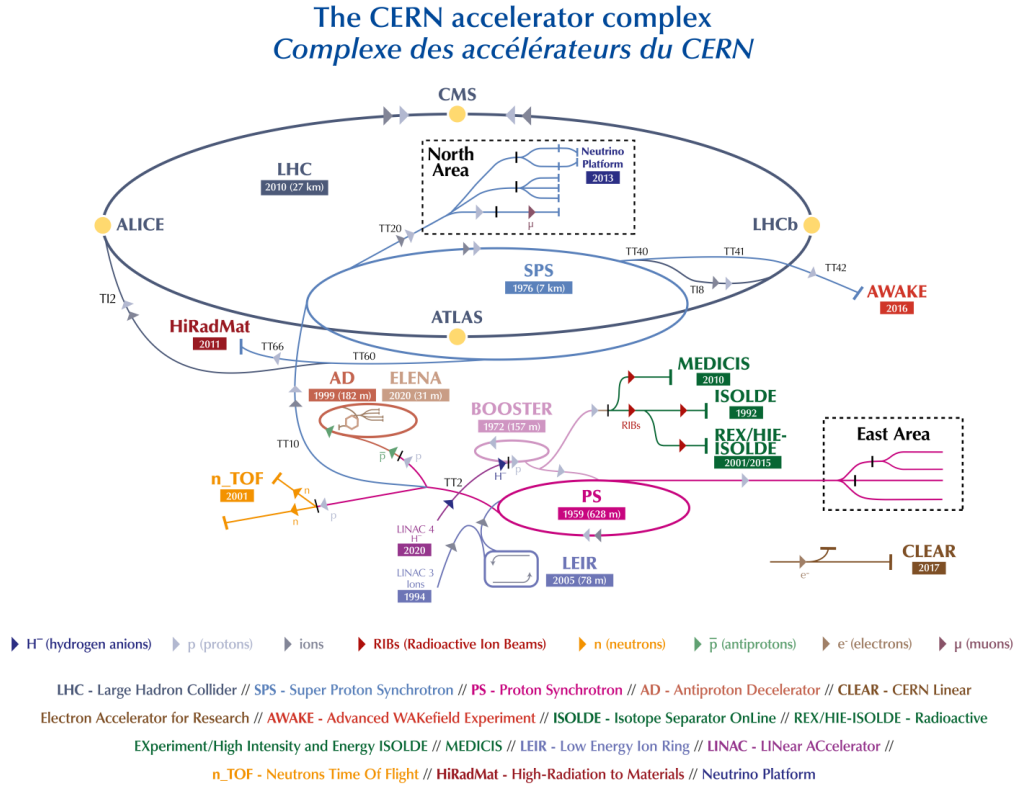


Figure 3.1: CERN accelerator complex [36]. The e+BOOST setup was located in the East Area (bottom right highlighted in pink).

3.1.1 T9 extracted beamline

The e+BOOST experiment was located in the T9 extracted beamline which is capable of delivering secondary and tertiary particle beams for detector tests and experiments (figure 3.2). Figure 3.3 shows the inside of the East Area building, where some of the experimental areas are visible from above.

The generation of a tertiary beam goes through different stages [24]:

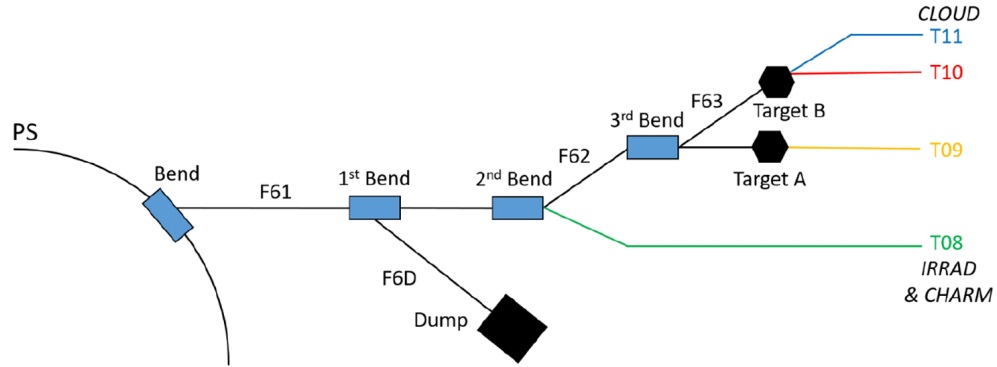


Figure 3.2: CERN East Area beamlines. [37]. The e+BOOST setup was located on the T9 extracted beamline, highlighted in yellow.

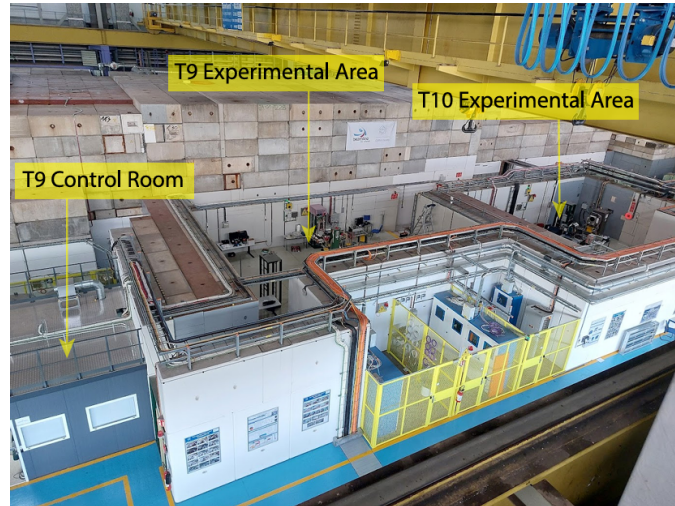


Figure 3.3: East Area control rooms (view from above). The beam propagates in the direction from the experimental areas towards the control room.

- The primary 24 GeV/c protons interact with the primary target: charged particles are generated, along with neutral pions that almost exclusively decay in flight in two high energy photons carrying around 12 GeV/c each.
- After the target, two magnets with a maximum field of 0.3 Tm are employed to sweep the charged particles towards a thick concrete beam dump.
- A 2 – 8 mm lead conversion layer is placed 8 m after, to convert the photons into electron-positron pairs that will carry half of the previous 12 GeV/c momentum, thus ending up to around 6 GeV/c.
- Downstream of the lead converter, a combination of magnets and slits is employed to better filter the charge and momentum range of the beam. A common choice is to set the slits at ± 3 mm, resulting in a beam momentum spread $\Delta p/p \sim 1$ % [36].

At momenta larger than 6 GeV/c, there is still a small fraction of electrons in the beam. Moreover, the tertiary beam contains some muons, mainly due to the decay of charged pions and kaons generated in the primary target. The intensity of such tertiary beam is $\sim 10^4$ particles per spill¹ [39]. The T9 beamline is also capable of delivering a secondary beam of mixed hadrons up to 15 GeV/c, generated by the collision of the primary proton [24].

3.2 The experimental setup

The e+BOOST beamtests required the following detectors in the setup:

- The Cherenkov detectors (section 3.2.2), provided by the beamline, upstream of the experimental area to discriminate electrons.
- The silicon microstrip detectors (section 3.2.3) to reconstruct the particle track.

¹ Particles are sent to beamlines in bunches called *spills*. A spill has a duration which depends on the beamline and the cycle. For the East Area beam, the spill duration is around 400 ms, and one or more spills may be sent in each 20 – 40 s cycle [38].

- The crystalline samples (section 3.2.1) mounted on a high-precision goniometer, to study their optimal orientation. The goniometer was remotely controlled by the DAQ software and had a micrometric precision.
- The plastic scintillators (section 3.2.6) that were used as multiplicity counters for charged particles, providing further information about the irradiated energy.
- The Lead Glass calorimeters (section 3.2.7) at the end of the line to measure the photon intensity.

The experimental area was further equipped with a bending dipole magnet with a maximum field of 0.6 Tm. In addition, remotely controlled moving platforms, such as the XSCA table and the DESY tables, were used to place and move the goniometer and the calorimeters. The Cherenkov detectors, scintillators and calorimeters were readout by CAEN digitizers (such as the V1730) with a 500 MHz sampling frequency. The total time for the acquisition of a single detector was set to $2^{11} = 2048$ ticks (1 tick = 2 ns), thus corresponding to a total of $2048 \times 2 = 4096$ ns $\simeq 4$ μ s. The silicon microstrips, on the other hand, were readout by a custom-made electronics (section 3.2.3). Table 3.1 summarizes several parameters for the different beamtests.

Beam Parameters vs Beamtests	2022	2023	2024
Cherenkov pressure	300 mbar	100 mbar	300 mbar
Sampling frequency	500 MHz	500 MHz	500 MHz
tick amplitude	2 ns	2 ns	2 ns
Sampling windows	2048 ticks	2048 ticks	2048 ticks
Magnet nominal current	200 A	200 A	-100 A
CAEN DT1730 Digitizer: 1 tick = 2 ns			

Table 3.1: Main parameters for the different e+BOOST beamtests. A sampling window of 2048 ticks corresponds to 2048×2 ns = 4096 ns $\simeq 4$ μ s.

The different arrangements of the beamlines for the e+BOOST beamtests are presented in figures 3.4, 3.6 and 3.7. The main differences between the setups are the following:

- The use of two Cherenkov detectors for the 2022 beamtest; for the 2023 and 2024 beamtests only one was employed since the other one was not working properly.
- The positioning of all the crystals onto the goniometer from the 2023 beamtest, placing them close to each other to increase the acquired statistics. In this way, the axial (optimal) orientation of one of them would provide random (amorphous) data for the other ones.
- Two more plastic scintillators in the 2024 setup, for positrons counting and improved particle discrimination.

Figure 3.5 shows a photo of the experimental area with part of the setup.

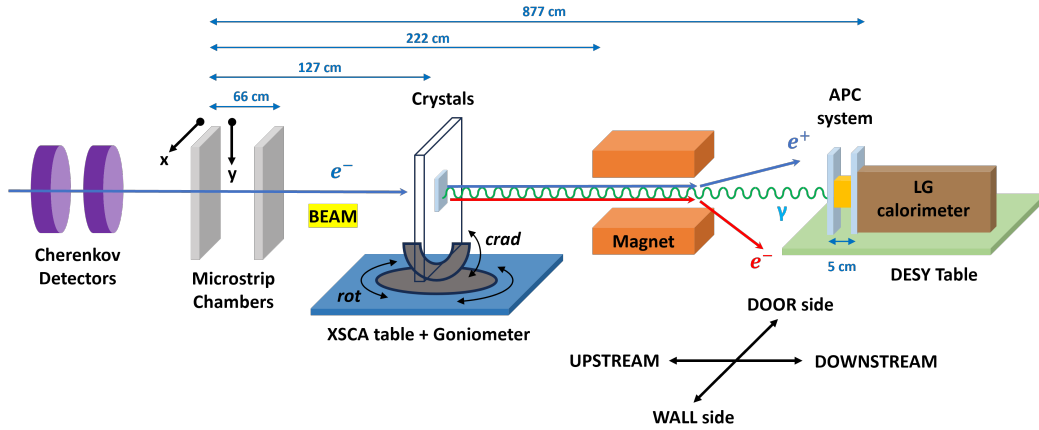


Figure 3.4: 2022 setup: the coordinates frame of reference is placed on the top left corner of the first BC.

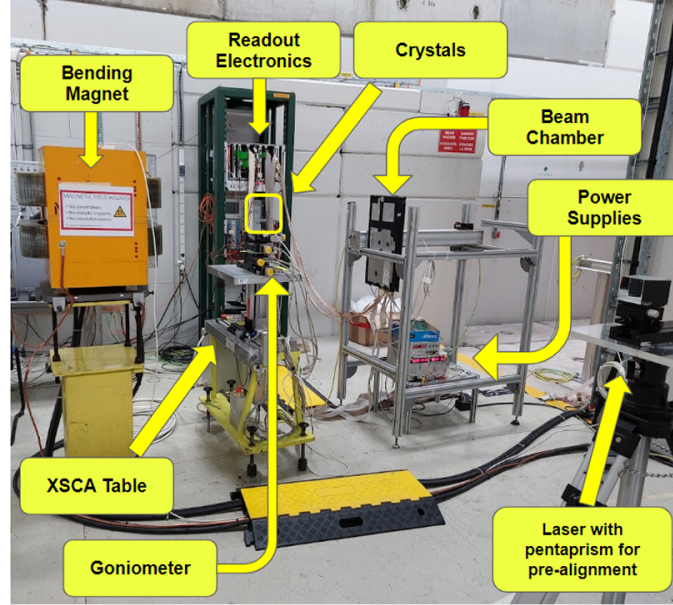


Figure 3.5: 2023 e+BOOST setup inside the T9 experimental area. [24]. The laser-pentaprism system was essential to line up the beam with the desired crystals orientation.

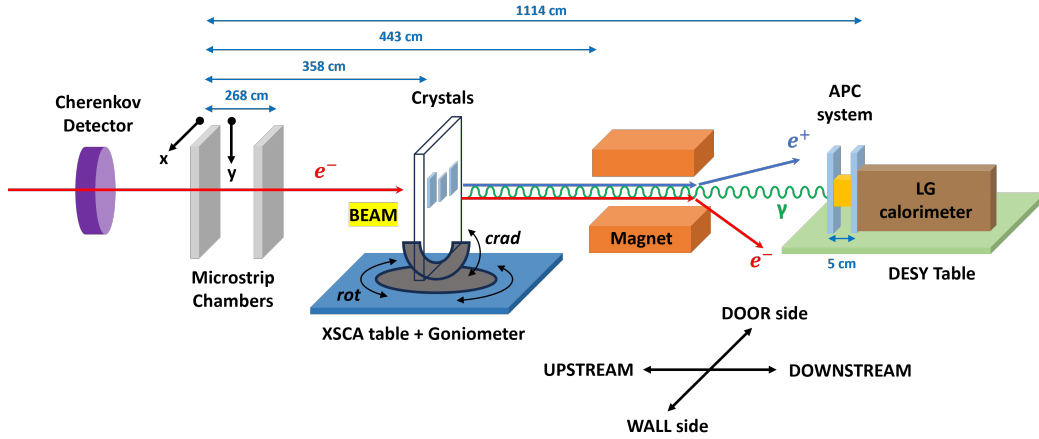


Figure 3.6: 2023 setup: the coordinates frame of reference is placed on the top left corner of the first BC. A single Cherenkov detector was employed, while the crystal samples were assembled on the same support.

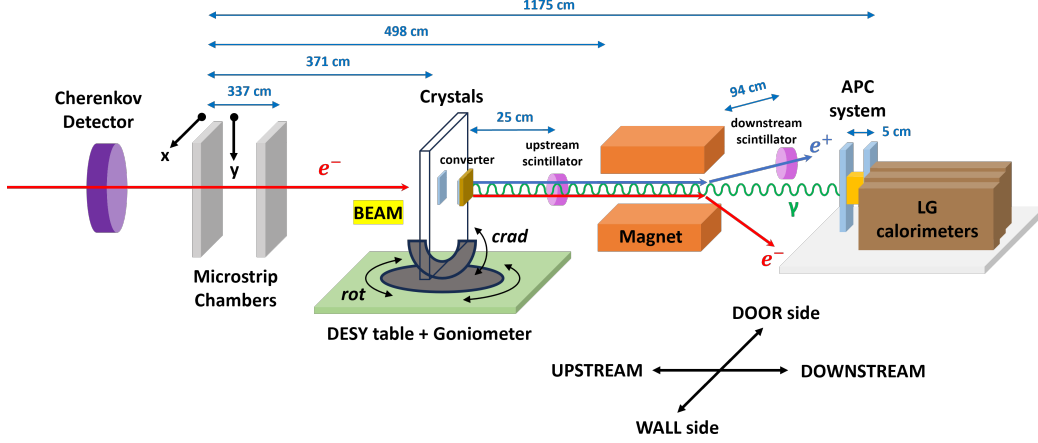


Figure 3.7: 2024 setup: the coordinates frame of reference is placed on the top left corner of the first BC. A single Cherenkov detector was employed, with two crystalline samples, a converter and additional scintillators to measure the positrons rate. Two more Lead Glass calorimeters were present as well.

3.2.1 The crystalline samples

The crystalline radiators for the hybrid positron source setup consist in a series of industrially manufactured crystal samples with different characteristics, such as material, thickness and the optimal channeling axis. As showed in table 3.2, the channeling axis was $\langle 110 \rangle$ for iridium and $\langle 111 \rangle$ for tungsten. The radiation thickness ranged from 0.4 to $2.8 X_0$, thus removing the risk of fully absorbing the electromagnetic shower in the crystal. Moreover, the simulations evaluated an angular acceptance of ~ 5 mrad within which the photon yield enhancement would still be seen, regardless of the specific material [7].

Iridium ($Z = 77$) and tungsten ($Z = 74$) are among the densest elements and have high atomic numbers, which increase the photon yield through processes like bremsstrahlung and channeling radiation. In addition, both materials are mechanically robust and capable of withstanding radiation hard conditions. With high melting points and excellent corrosion resistance, they are good candidates to stand radiation damage and target heating. Moreover, their crystallographic properties enable the generation of polarized photons when used as radiators, which can be used in several applications, such as creating polarized positron beams [12]. The main properties of the elements employed in the beamtests are summarized in table 3.3.

e+BOOST Samples	2022		2023			2024	
Material	Ir	W	Ir	W	W	W	W
Thickness [mm]	1	2	2	1.5	2.5	1.5	10
Radiation length [X_0]	0.3	0.6	0.6	0.4	0.7	0.4	2.8
Surface [mm ²]	7×8	13×15	8×8	8×8	8×8	8×8	10×10
Channeling axis	$\langle 110 \rangle$	$\langle 111 \rangle$	$\langle 110 \rangle$	$\langle 111 \rangle$	$\langle 111 \rangle$	$\langle 111 \rangle$	$\langle 111 \rangle$
Ir = Iridium W = Tungsten							

Table 3.2: Technical parameters of the crystalline samples used in the different e+BOOST beamtests.

	Iridium (Ir)	Tungsten (W)
Atomic Number (Z)	77	74
Density (g/cm ³)	22.6	19.3
X_0 (mm)	3.2	3.5
Melting Point (°C)	2446	3422
Thermal Conductivity	Moderate	High

Table 3.3: Comparison of the iridium and tungsten chemical properties. Both materials are characterized by a high radiation resistance and thus represent good candidates for channeling applications.

For the 2024 beamtest, a 8 mm thick amorphous tungsten converter was placed right after the 1.5 mm crystalline sample, 1 mm apart. Data have been collected with and without the additional converter. The first case represented a hybrid positron source configuration like the one described in section 1.2. Since a 1.5 mm tungsten crystal corresponds to $0.4 X_0$ (table 3.2), the overall crystal-converter system corresponded to $3 X_0$.

3.2.2 The Cherenkov detectors

The PS extracted beamlines typically include Cherenkov detectors as part of their instrumentation for the particle identification through the Cherenkov effect, that is the light emission by charged particles travelling faster than the phase velocity of light in a medium. The T9 Cherenkov detectors (figure 3.8) are gas threshold detectors and they allow to distinguish particles in mixed beams, depending on the gas and its pressure [2].

The light emission cone of the Cherenkov effect is shown in figure 3.9, and the plane wave radiation angle can be expressed as a function of the medium refractive index n and the particle relativistic velocity $\beta = \frac{v}{c}$ [2]:

$$\cos \theta = \frac{1}{n\beta} \quad (3.1)$$

These Cherenkov detectors are often referred to as “threshold devices”, since they they do not measure the light cone but just the presence of light, through photomultiplier tubes.

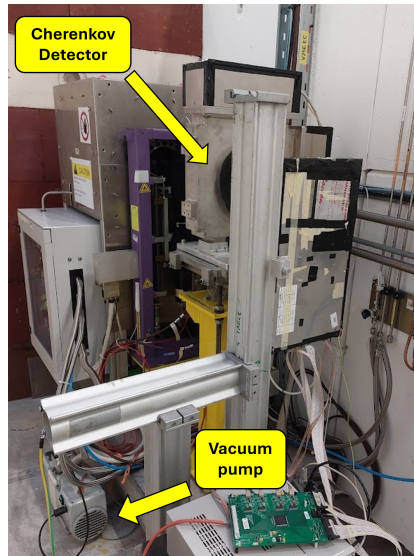


Figure 3.8: T9 Cherenkov detector, immediately followed by the upstream microstrip chamber. The vacuum pump allows the proper adjustment of the pressure inside the apparatus.

The T9 beamline typically delivers particles with momenta in the range from 0.5 to 15 GeV/c [28]. Therefore, a pressure level of the order of a few

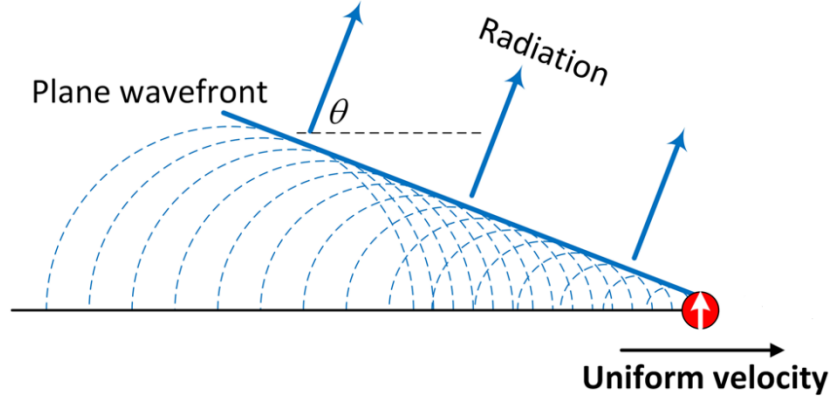


Figure 3.9: Cherenkov light-emission angle for a relativistic non-accelerating particle. The radiation emission angle is orthogonal to the angle that delimits the light cone [40].

hundreds of millibars can be set to ensure the tagging of electrons in the beam, as shown in appendix B, together with the estimation of the detector efficiency and purity.

3.2.3 The tracking system

For a crystal-based positron source relying on the channeling phenomenon, high-resolution particle tracking is required to reconstruct the hit position of each particle on the crystal and its angular direction. As anticipated in section 3.2, for the e+BOOST experiment two tracking modules, referred to as Beam Chambers, were used. Each tracking module consists of two single side silicon strip detectors with an area of $9.5 \times 9.5 \text{ cm}^2$ and a thickness of $410 \text{ }\mu\text{m}$, organized in a $x - y$ configuration. They have been developed for the AGILE satellite [41]. Each side presents 384 readout strips with a pitch of $242 \text{ }\mu\text{m}$, arranged in one floating strip readout scheme. The physical pitch in fact is $121 \text{ }\mu\text{m}$ but only one strip out of two is read out. This allows to reduce the number of electronics channels (and thus the power consumption), maintaining a good spatial resolution. In fact, the spatial resolution can be improved applying a center of gravity (COG) algorithm to reconstruct the particle crossing position. The measured spatial resolution resulted to be $\sim 40 \text{ }\mu\text{m}$ in a wide range of incidence angles of the particles [24]. Each silicon side is readout by three TA1 ASICs with 128 channels, each consisting of a pre-amplifier, a CR-RC shaper and a discriminator for the generation of the output trigger [41, 42].

The beam chambers electronics may be divided into two parts: the front-end electronics, placed close to each detector, whose task is to sample the analog signals from the silicon modules, and the readout electronics, which includes custom FPGA based boards that have to manage the trigger for all the detectors, digitize the sampled signals, store data in fast memories during the spill and transfer them to the DAQ PC at the end of the spill itself [1]. Figure 3.10 shows the silicon module of a beam chamber.

The first element of the readout chain is the *repeater*, that provides the power and the configuration signals to the ASICs, amplifies the output signals and delivers the bias to the silicon detectors [41]. Each tracking module features a pair of repeaters (one for each side). The output of the ASIC is digitized by a dedicated ADC board. Depending on the number of tracking modules and on the distance between them, one or more VME crates host the last part of the chain, i.e., the VRBs (VME Readout Boards, one per tracking module), which read the ADC output data during the spill, store them in a dedicated RAM (Random Access Memory) and transfer them to the DAQ PC during the inter-spill period [24]. The VRBs also generate the hold for the sampling of the strip signals and the clock for their multiplexing. Moreover, the crate hosts the trigger board and a bus adapter to connect the DAQ to the PC via an optical fiber (figure 3.21).

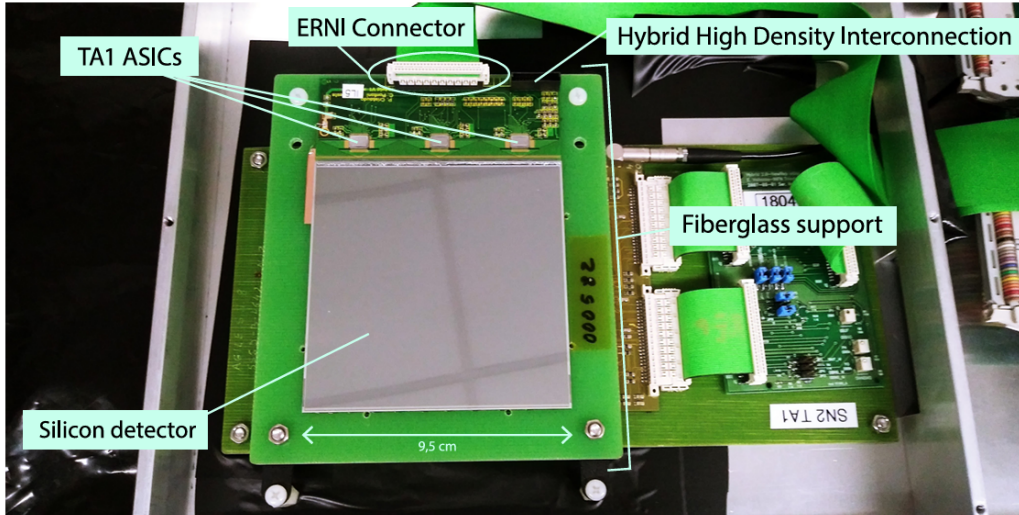


Figure 3.10: Photo of a silicon strip beam chamber, where the silicon module, the readout ASICs and the HDI (High Density interconnection) hybrid can be seen [24].

The tracking system can be read out in both normal and *zero-suppressed* mode [1]. In the former, the output of the ADCs is de-multiplexed and all

the channels (i.e., 384 per side, with 2 sides per module) are stored in the RAM; the number of events per spill is limited to 4096. On the other hand, when in zero-suppressed mode, only the strips whose signal is above a given threshold value are stored in the RAM. This allows to read a much smaller number of strips, increasing the speed and thus the collected statistics [41]. To operate in zero suppression, the strips common mode noise should be small [41]. The maximum number of strips that can be stored per side per event is limited to 16 due to the hardware configuration, and the number of events per spill is limited to a few tens of thousands of events. The choice of the readout mode affects the overall acquisition rate [1].

Given the fact that the TA1 ASICs present a discriminator per channel, it is possible to use the silicon detectors to generate the DAQ trigger (*self-triggering* mode). Enabling only the strips in the region corresponding to the crystal samples, only the more relevant part of the beam can be selected to maximize the useful statistics. The upstream beam chamber was positioned right after the Cherenkov detector (figure 3.11), while the downstream beam chamber right before the crystal samples holder. The separation between the two ranged in an interval from 0.5 to 4 meters, as shown in section 3.2.

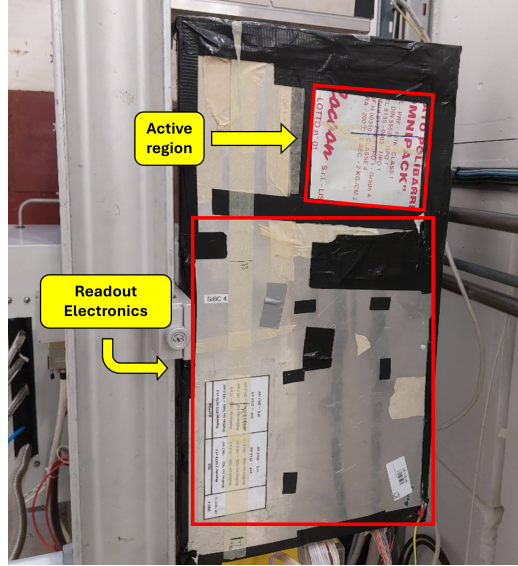


Figure 3.11: Silicon Beam Chamber mounted upstream during the e+BOOST 2024 beamtest.

3.2.4 The goniometer

To ensure that the particle beam enters the channeling angular acceptance, the crystals under test must be precisely aligned. This task is achieved with a multi-stage goniometer offering micrometric precision (figure 3.12), capable of hosting one or more crystal samples. Manufactured by PI [43], the goniometer comprises several stages, each controllable independently through the DAQ software (section 3.2.8):

- The WT-100 cradle stage provides a rotational range of 10° , supports a maximum load of 2 kg, and offers a repeatability of $8.7\,\mu\text{rad}$. Using an encoder and an active feedback system, it achieves a resolution of $1.57\,\mu\text{rad}$. This stage allows the alignment of the crystal in the $y - z$ plane relative to the beam. Movements along this degree of freedom are labeled as *ROT*.
- The WT-90 cradle stage, similar to the WT-100, features a rotational range of 90° , a repeatability of $2.7\,\mu\text{rad}$, and a maximum load capacity of 8 kg. With an active feedback system, it achieves a resolution of $2.69\,\mu\text{rad}$. Movements along this degree of freedom are labeled as *CRAD*.
- The PRS-110 rotational stage enables full 360° rotation in the $x - z$ plane, corresponding to rotation around the y axis.
- Two linear stages (VT-80 and L-511) allow the precise positioning along the x axis, with an accuracy of $1.5\,\mu\text{m}$, bidirectional repeatability of $2\,\mu\text{m}$, and resolution of $5\,\mu\text{m}$. The VT-80 provides a range of 102 mm, while the L-511 has a range of 52 mm.
- The L-310 vertical stage features a full range of 26 mm and supports a maximum load of 10 kg. It allows the crystal positioning along the vertical y axis, achieving a maximum resolution of $0.2\,\mu\text{m}$ with the help of an encoder.

The stages are connected to dedicated controllers, such as the Corvus, Pollux, and Mercury, all manufactured by PI [43]. These motors communicate with the DAQ computer via a RS-232 serial port [24]. Depending on the experimental setup, different combinations of the aforementioned stages are used. The goniometer was mounted on remotely controlled platforms like the DESY table or the XSCA table, which provide two extra translational degrees of freedom along the x and y axes, orthogonally to the beam.

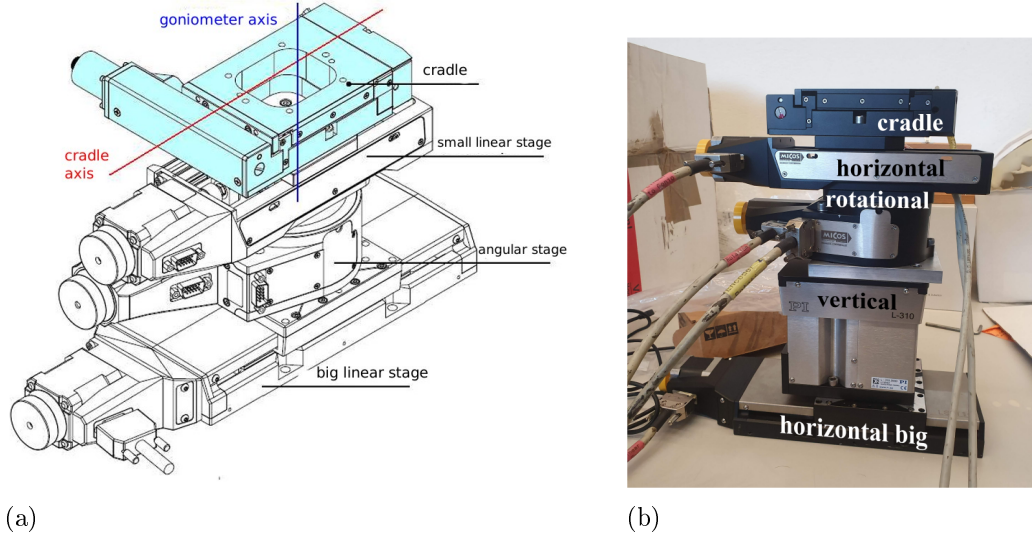


Figure 3.12: High-precision goniometer with five degrees of freedom and micrometric movements. (a) Schematics. (b) Photo [1].

3.2.5 The dipole magnet

When the high-energy electron beam interacts with the crystals, secondary photons and charged particles are generated in the process. The outcoming mixed beam enters then the square gap of the bending dipole magnet, 1 m long and 11 cm wide (figure 3.13). At the maximum operating current of 850 A, the dipole magnet is able to generate a 0.6 Tm magnetic field, oriented towards the vertical axis, and thus deviating charged particles along the horizontal direction [24] (during the beamtests, however, it was suggested not to overcome the nominal current limit of 200 A). The photons are not affected by the magnetic field and thus impinge directly on the downstream calorimeter, which records a full photon spectrum.

3.2.6 The plastic scintillators

Additional scintillator modules have been employed within the beamline, both from the INSULAB group and from CERN. Since they are made of low Z materials such as plastic, they are not suitable to detect photons but rather charged particles. During the beamtests, these detectors were used for the trigger or as multiplicity counters. The most important scintillating system was the Active Photon Converter (APC), a multi-layer detector made



Figure 3.13: Front view (a) and side view (b) of the dipole magnet in the beamline, for the curvature of charged particles after the interactions with the crystalline radiators.

of a thin copper layer ($0.1 - 0.4 X_0$) placed in between a couple of 1 cm thick plastic scintillators (figure 3.14). The goal of the beamtest was to evaluate the photon yield enhancement with an oriented crystal, measuring it with the calorimeter positioned at the end of the setup. The APC provides information that is then used by the simulation to compute the number of produced photons and not only their overall energy. This is the reason why it consists of several elements:

- the upstream scintillator acts as a “veto”, to discard the events due to residual charged particles, or electrons and positrons produced by photons after the magnet. These spurious events could also be ascribed to electrons that back-splashed in the middle copper layer;
- after the first veto, within the copper layer, a small fraction of the photons may convert into electron-positron pairs, which are then detected by the downstream plastic scintillator.

Figure 3.15 shows the transverse section of one of the scintillators with its casing removed.

In addition to the APC, two plastic scintillators were employed in the 2024 beamtest. Their goal was to measure the multiplicity of the positrons emitted

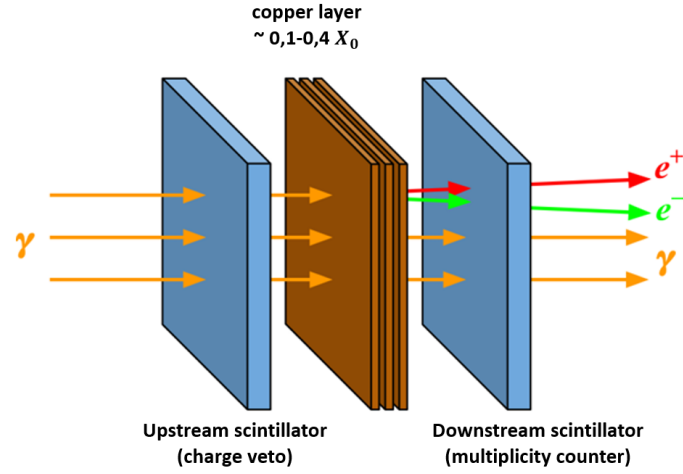


Figure 3.14: The APC system: after the first veto for charged particles and the e^+e^- emission in copper, the downstream scintillator receives a mixed beam of electrons, positrons and photons, allowing to estimate the multiplicity.

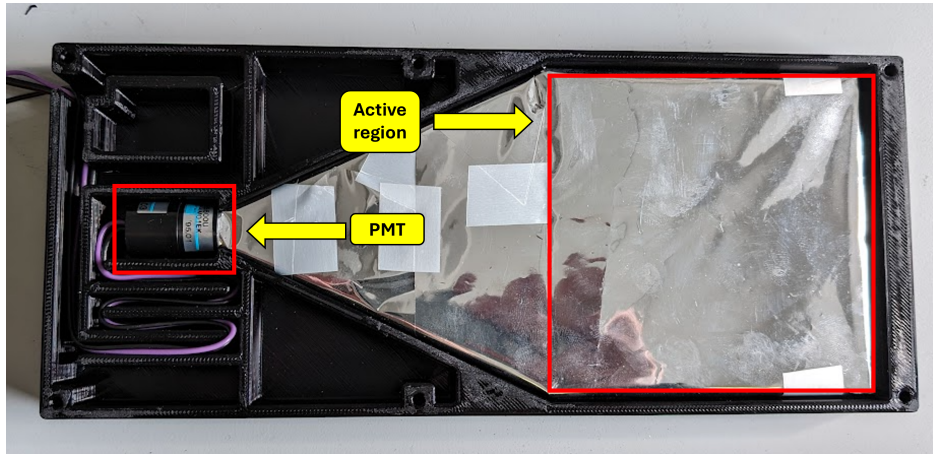


Figure 3.15: Photo of the APC. The active region emits the scintillating light that is read out by the PMT. The scintillator is coupled to the PMT through a plastic PMMA light guide.

in the 1.5 mm thick tungsten crystal, when the hybrid positron source was mounted. They are a 2.8 mm thick disc of 10 cm diameter, made of the EJ-200 scintillator manufactured by [ELJEN Technology](#) [44]. The disc is coupled to a photomultiplier tube (model 9813) from [ET Enterprises](#) [45] via a PMMA light guide. The assembled detectors are visible in figure 3.16, while their position in the 2024 setup is shown in figure 3.17.



Figure 3.16: Photo of the scintillator modules used in the 2024 beamtest.

3.2.7 The Lead Glass calorimeters

The calorimeters used to measure the deposited energy were originally employed in the 2001 OPAL experiment [46]. The calorimeters consist in an electromagnetic homogeneous Lead Glass scintillator, read by PMTs (figure 3.18). As already shown in figures 3.4 and 3.6, the Lead Glass calorimeter was always placed at the end of the beamline. In some cases, such as for the 2024 beamtest, more than one calorimeter were placed close to each other (figure 3.7), in order to improve the analysis on features such as the beam shape and the energy deposit. In any case, the APC system was positioned just in front of the calorimeter on the photons direction (figure 3.19). All the calorimeters were covered by duct tape in order to prevent environmental light exposure, and thus the presence of either noisy or saturating signals.

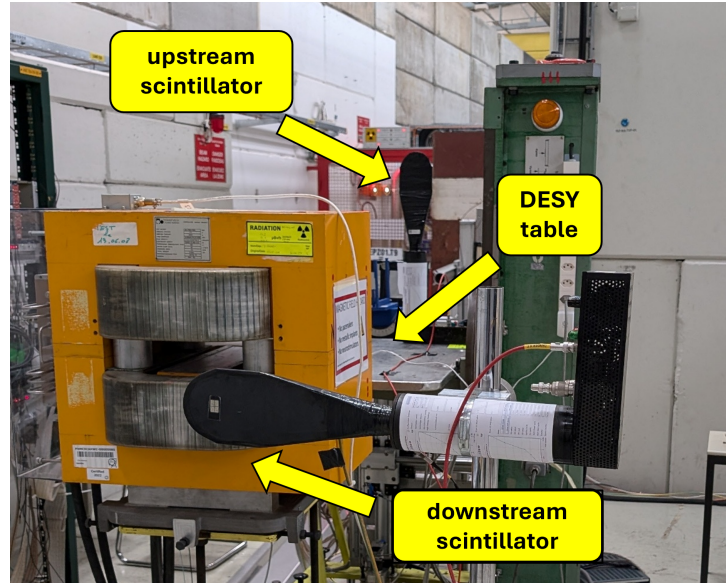


Figure 3.17: Additional plastic scintillators for positrons counting and improved particles discrimination.

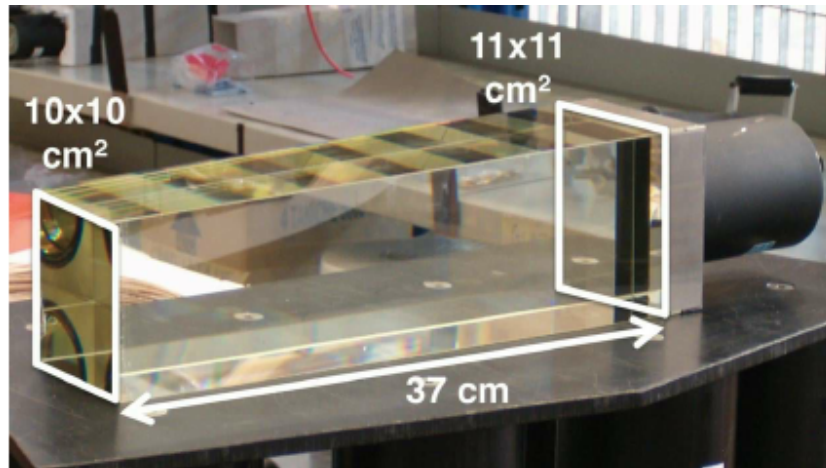


Figure 3.18: Uncovered Lead Glass calorimeter module initially installed in the OPAL detector and eventually implemented in the e+BOOST experiment [46].

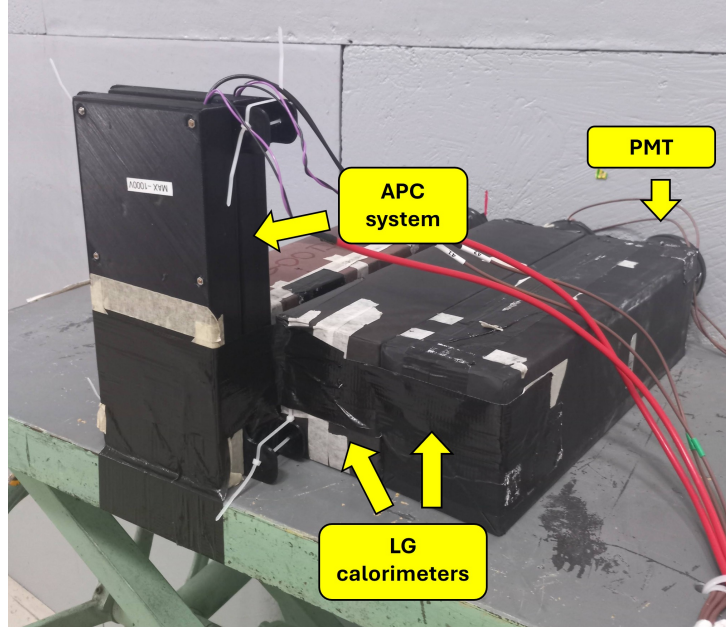


Figure 3.19: APC and calorimeters in the 2024 beamtest. The APC covers just the calorimeter on the photon line.

3.2.8 The data acquisition

The data acquisition (DAQ) system is controlled by a software running on a Linux based PC. The source code consists of a set of C routines, called by a GUI (Graphical User Interface) written in TCL (Tool Command Language), a dynamic programming language. The main tasks performed by the DAQ software are the following:

- It defines the trigger logic to be implemented in the trigger board.
- It allows to load the trigger mask and the trigger thresholds in the ASICs through the trigger configuration board.
- It sets the hold for all the silicon detectors and generates the clock to read out the ASICs.
- It allows to load the pedestal values and the noise threshold for the silicon detectors in the zero suppression mode.
- It controls the goniometer stages.

The DAQ software allows to acquire both pedestal and data runs. The pedestal run exploits the random trigger to sample the baseline of the readout electronics chain of each silicon strip, which has to be subtracted in order to compute the correct pulse height, and the noise RMS.

Figure 3.20 presents the windows of the DAQ software. In particular, the upper left one is the main window, from which the different features may be accessed. The DAQ software assigns a unique 6 digit number to each run and it supports two main acquisition modes:

- The *SINGLE* data taking allows to choose the trigger logic for the trigger board and to store the data corresponding to a single, arbitrarily long acquisition.
- The *SCAN* option allows to acquire data moving in steps the goniometer motors. This was useful during the search of the optimal crystal orientation.

To understand the effect of the crystal on a particle, it is fundamental to work with single particles. Thus, one of the key factors to consider when testing a crystal on a beamline is the beam intensity, namely the flux of incident particles within the beamline. Although a high intensity is required to collect a large enough statistics in a reasonable amount of time, as this quantity increases, the probability of single particle events decreases.

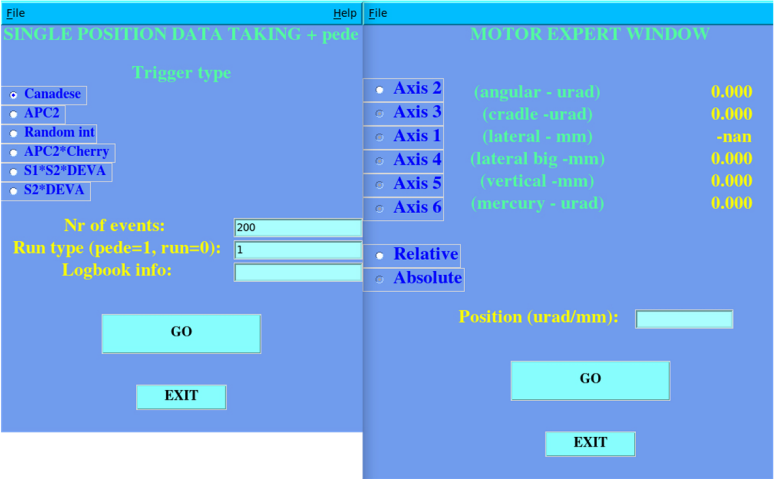
To select single track events, an online *stripping* procedure (based on a FORTRAN code) computes the number of clusters, defined as the groups of neighboring strips where a particle deposits its charge. The overall crossing position, for each silicon module, is then reconstructed with a COG algorithm, averaging the strips position with a weight associated with the deposited charge. If more than one cluster is detected, the event is discarded. By doing so, it is possible to select only the single particles events. The stripping algorithm saves all the information in ASCII files, one per each spill of the beam². The data of the ASCII files were reprocessed in real-time into hierarchical data formats (HDF) files³. In fact, HDF files can be easily

² If the software is not running in zero suppression mode, the stripping procedure can also subtract the common mode on an event by event basis [24].

³ HDF is a standard used to handle large amount of information and optimal to be unpacked through arrays.



(a) Left panel: main software window. Right panel: data acquisition for the SCAN modality, where the trigger and the scan boundaries can be set.



(b) Left panel: trigger selection options for a single acquisition. Right panel: controls for the goniometer position.

Figure 3.20: Interface with the different panels of the DAQ software, written in TCL.

loaded through specific Python libraries that convert them into a dictionary of `numpy`⁴ arrays. Each array contains different information, such as the hit positions, the pulse heights, time, the baseline of the digitizer channels, and the position of the goniometer motors. Figure 3.21 provides a schematic representation of the primary connections for the readout electronics and the triggering system.

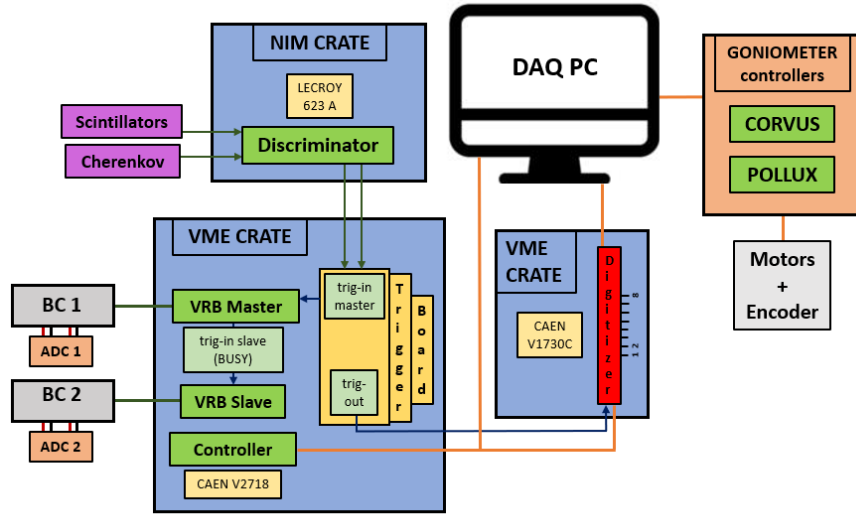


Figure 3.21: Scheme of the readout electronics. The connections between the DAQ PC, the controller and the discriminator were arranged following a daisy chain logic. The signals were transmitted via optical fibers through the CONET communication protocol, developed by CAEN.

3.2.9 The signal digitalization

When dealing with the signals coming from the beamline detectors, their sampling and digitalization follows a logic based on the time features presented in figure 3.22. The main temporal parameters to control are the pre-trigger and post-trigger values. These parameters, added together, return the total value of the sampling window ($4\text{ }\mu\text{s}$, as shown in table 3.1) and they must be tuned depending on the detector which provides the trigger.

⁴ `numpy` (*numerical python*) represents one of the fundamental packages for scientific computing with Python (cfr. www.numpy.org).

In this regard, the time-walk must be considered, namely the time required by a signal to overcome a fixed threshold and reach its peak. Fast detectors (e.g. Cherenkov detectors) are associated with shorter time-walks with respect to slow detectors (e.g. BCs), due to the difference in their electronics and architecture. When the trigger is generated by a fast detector, the slower ones will read and store their signals with a certain delay. In this case, it is preferable to use a larger post-trigger value, in order to ensure the storage of the relevant part of the signal from the slower detectors. On the other hand, if the trigger is generated by to a slow detector, as for the self-triggering system of the BCs which had a $\sim \mu\text{s}$ time-walk, a shorter pre-trigger and a longer post-trigger have be set.

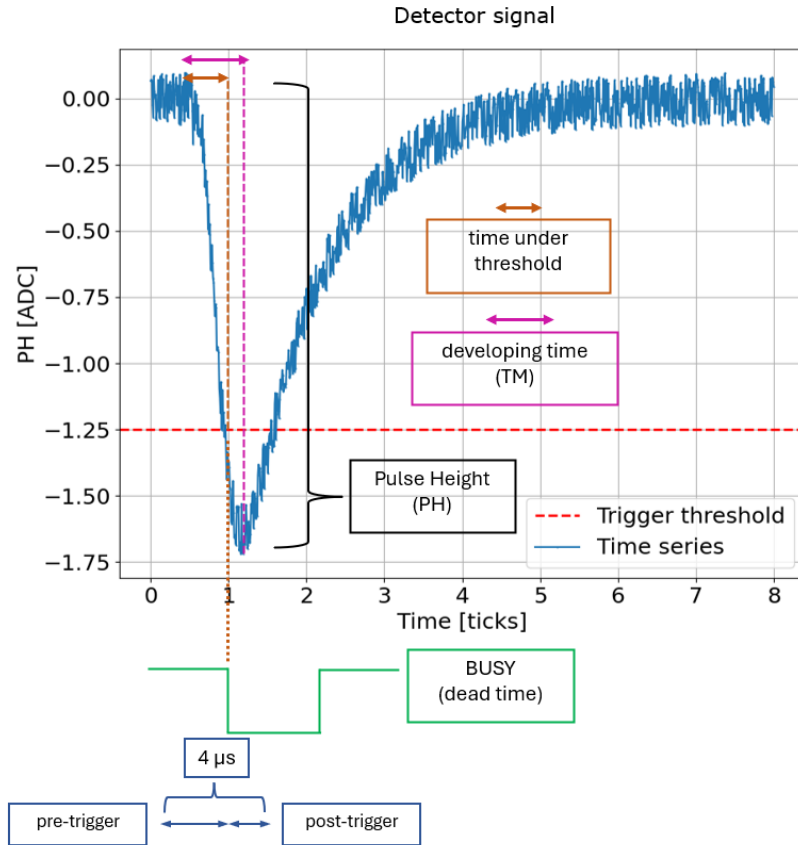


Figure 3.22: The time features of the trigger signal. There are negative values as the overall signal has been subtracted from its baseline.

3.2.10 Beam shape configuration

Based on the experimental needs, a trade-off between angular divergence and beam dimension must be made. The beamline controls, in fact, allow to switch between two different beam configurations, namely the *parallel* optics (figure 3.23) and the *focusing* optics (figure 3.24). As suggested by these labels, the first system aims at maintaining the particles trajectory as straight as possible, minimizing the beam divergence, whereas the second one becomes useful to reduce the dimension, resulting in a divergence increase but with a smaller beam spot onto the selected focus. Minimizing the beam divergence increases the likelihood of events with a reasonable chance of channeling within the crystal. However, reducing the divergence also results in a broader beam profile, which is not fit to the small size of the crystals under test. Therefore, a balance must be achieved between divergence and beam size, or equivalently, intensity over a fixed area.

Working with self-triggering tracking detectors helps in maximizing the collected statistics, independently from the beam dimension. Once the position of the crystalline radiators is set, the self-triggering acquisition can be enabled to consider only the geometrically relevant events and thus optimize the statistics collection. This feature allows to use a parallel optics to minimize the particle divergence.

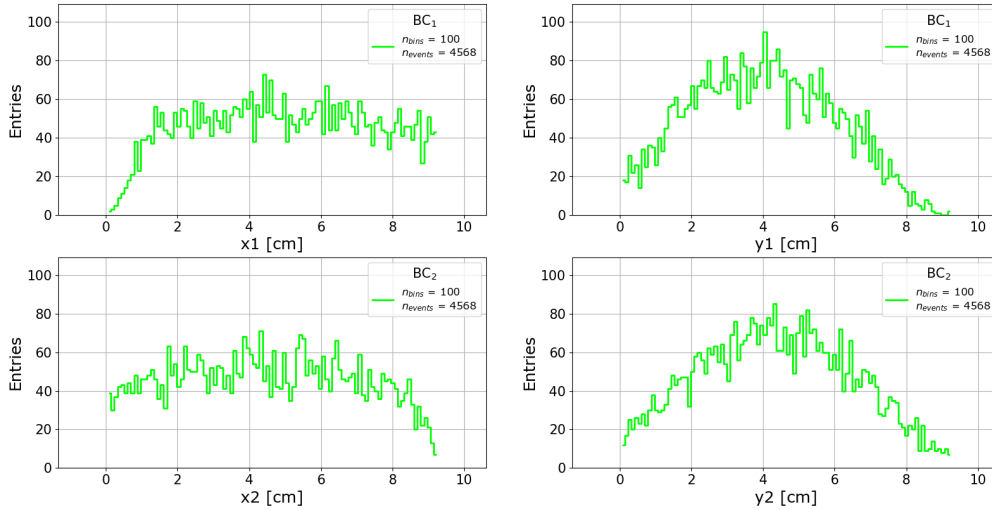


Figure 3.23: Beam chambers profile plots: parallel beam.

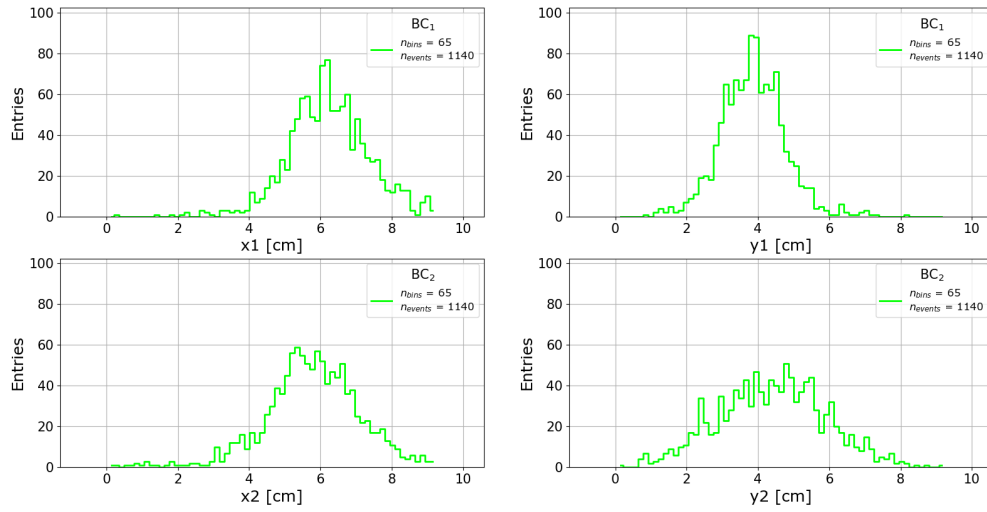


Figure 3.24: Beam chambers profile plots: focused beam.

Chapter 4

Data Analysis and Results

This chapter describes in detail the data analysis, performed either in real-time during the acquisition or offline after the beamtest. The data analysis aimed at investigating the behaviour of dedicated crystalline samples with a thickness ranging in the $[1 - 10]$ mm interval, made of commercial materials such as iridium or tungsten, and irradiated by high-energy electrons. More specifically, the idea was to describe the behaviour of these crystals when used as compact photon radiators. The main features under study were the beam-to-axis angle, the crystals orientation and the total deposited energy in the calorimeter. As anticipated in section 3.2.1, during the 2024 beamtest, one of the crystalline radiator sources was followed by an additional high-Z amorphous converter in order to simulate a hybrid positron source configuration. The overall investigation allowed to assess the feasibility of oriented crystals as compact photon radiators.

4.1 Analysis procedure

The standard procedure for the analysis involved the following steps:

- the realignment of the BCs coordinates;
- the evaluation of the beam divergence (section 4.3);
- the selection of a threshold for the Cherenkov detector(s) pulse heights, to tag only the events associated with electrons (section 4.2);

- the selection of an additional threshold based on the beam divergence in order to keep only the electrons that are most likely to undergo channeling and coherent effects inside the crystals;
- the projection of the trajectories of the electrons onto the goniometer plane, where the crystals were mounted. In this way, a correlation plot could be built weighting each 2D bin with the corresponding energy detected by the calorimeter, obtaining the profiles of the crystalline radiators. This allowed to define the region for the self-triggering DAQ mode (section 4.3.1);
- the selection of a threshold on the upstream APC (veto) in order to filter the residual charged particles, as discussed in section 3.2.6;
- the selection of a threshold on the downstream APC, to select only the photons that converted into the copper layer. Moreover, the APC spectra could be analyzed to obtain information about the e^+e^- multiplicity;
- the measurement of the energy deposited in the calorimeter.

The next sections describe in detail each of these steps.

4.2 Cherenkov analysis

Cherenkov threshold detectors are fast devices with a peaking time of a few hundreds nanoseconds. Their speed often makes them a good time reference to analyze other devices. Figure 4.1 displays the main features of the spectra of the two Cherenkov detectors on the T9 beamline, namely the pulse height (PH) and the time of the maximum of the signal (TM), either in 1D or 2D correlation plots. The plots in figure 4.1 allowed to establish different thresholds for both PH and TM values. In this way it was possible to select electrons. As an example, figure 4.2 shows the pulse height distributions of figure 4.1 after the cut on the PH and TM thresholds.

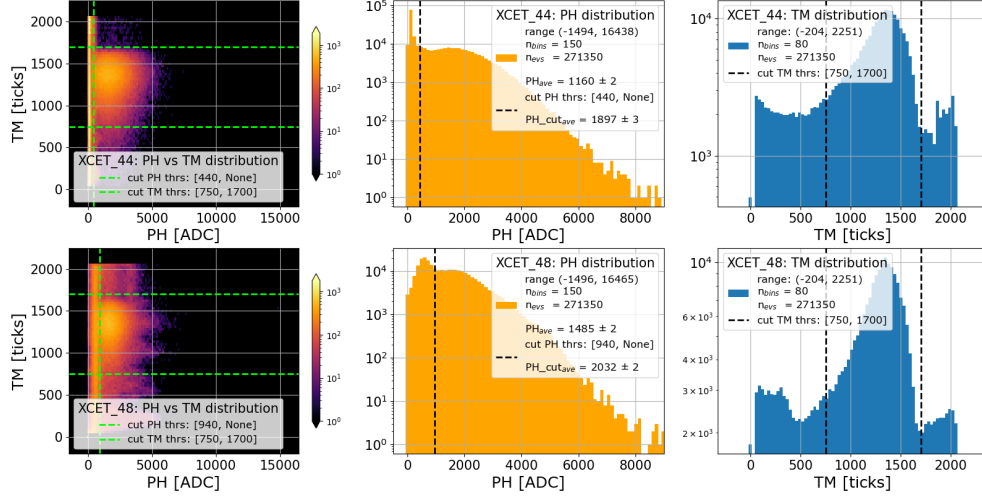


Figure 4.1: Cherenkov spectra: PH and TM distributions for each of the Cherenkov detectors on the T9 beamline. Left region: 2D correlation of PH and TM signals. Central region: PH distributions. Right region: TM distributions. For every plot, the dashed lines indicate the chosen PH/TM thresholds.

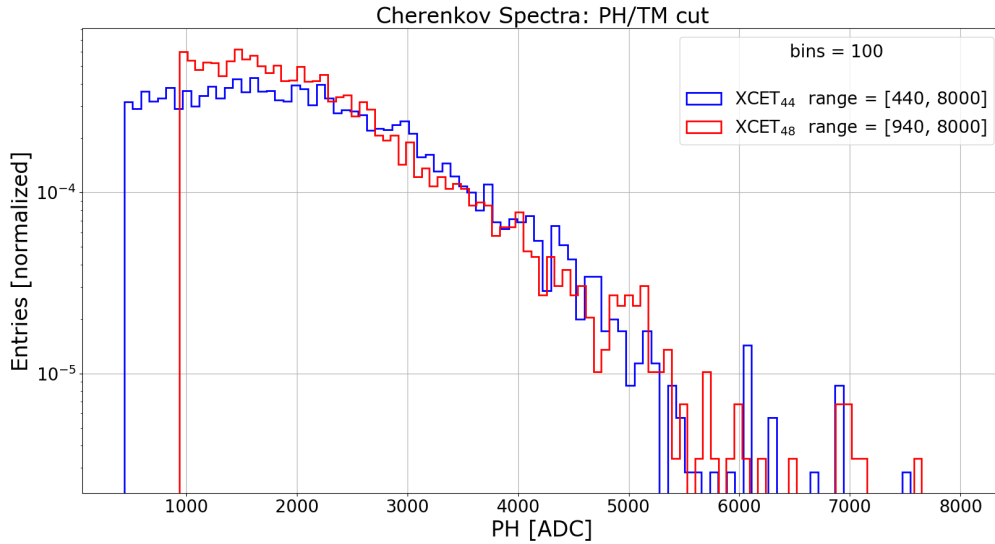


Figure 4.2: Superposition of the pulse heights of the two Cherenkov detectors, after performing a cut on both PH and TM, based on the thresholds from figure 4.1.

4.3 Beam profile

Knowing the coordinates of the impact points, it was possible to compute the beam divergence, both horizontally and vertically, defined as the angle of the particle trajectory with respect to the beam direction. Thus, the divergence is calculated as the tangent of the angle that connects the hit points of the track onto the different BCs, either for the x coordinate (θ_{xz}) or for the y coordinate (θ_{yz}):

$$\theta_{xz} = \frac{x_{2i} - x_{1i}}{z_{12}} = \frac{\Delta x_i}{z_{12}}$$

$$\theta_{yz} = \frac{y_{2i} - y_{1i}}{z_{12}} = \frac{\Delta y_i}{z_{12}}$$

In this way, two angular distributions, associated with θ_{xz} and θ_{yz} respectively, were obtained. These histograms were then studied to evaluate the angular divergence, expressed as the σ of the two curves in figure 4.3, fitted according to a Gaussian model. The interpolation also allowed to retrieve the average misalignment between the two chambers. Figure 4.4 illustrates the same divergence distributions after the offline realignment of the two BCs. As the reference frame was set on one of the vertexes of the upstream module, the realignment was performed through a shift on the $x - y$ coordinates of the downstream chamber.

After implementing the Gaussian interpolations, as shown in figures 4.3 and 4.4, it was possible to compute the angular divergence. Given the fact that the divergence is a fundamental parameter when working with crystals, it had to be checked regularly. Table 4.1 summarizes the average angular divergence values in the different beamtests. The same divergence distributions along the x and y directions could then be arranged in a 2D correlation plot, to show the beam profile before and after the alignment (figure 4.5). A 1 mrad divergence threshold was chosen (green dashed line around the origin) as it represented the optimal compromise between the possibility to acquire a statistics large enough and the angular acceptance predicted by the positron source simulations.

Before moving to the next step, it is worth mentioning that during the reconstruction of the events trajectories, multiple Coulomb scattering (MCS)

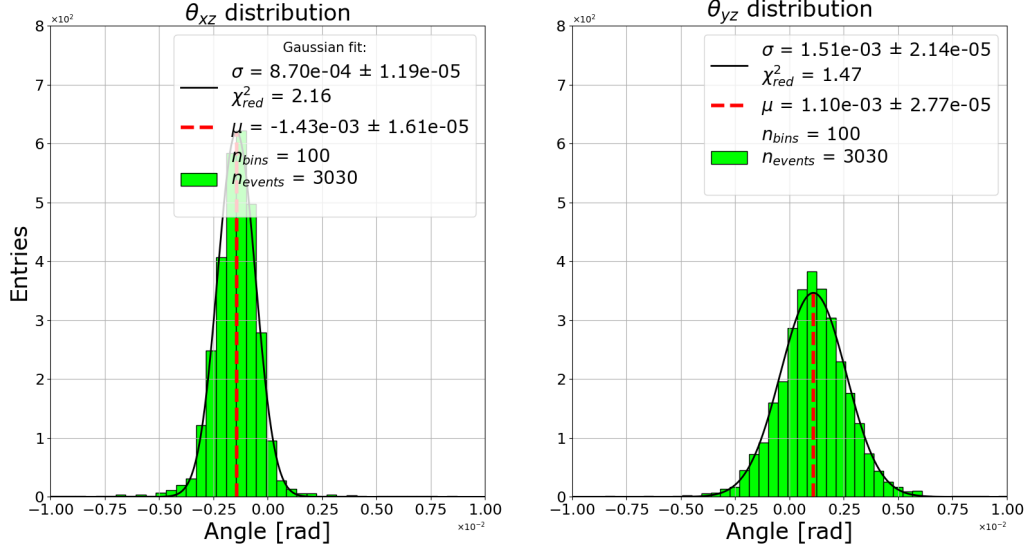


Figure 4.3: 1D beam divergence distributions along the x and y coordinates. The distributions have been interpolated with a normalized Gaussian model in order to estimate the angular divergence and the overall misalignment.

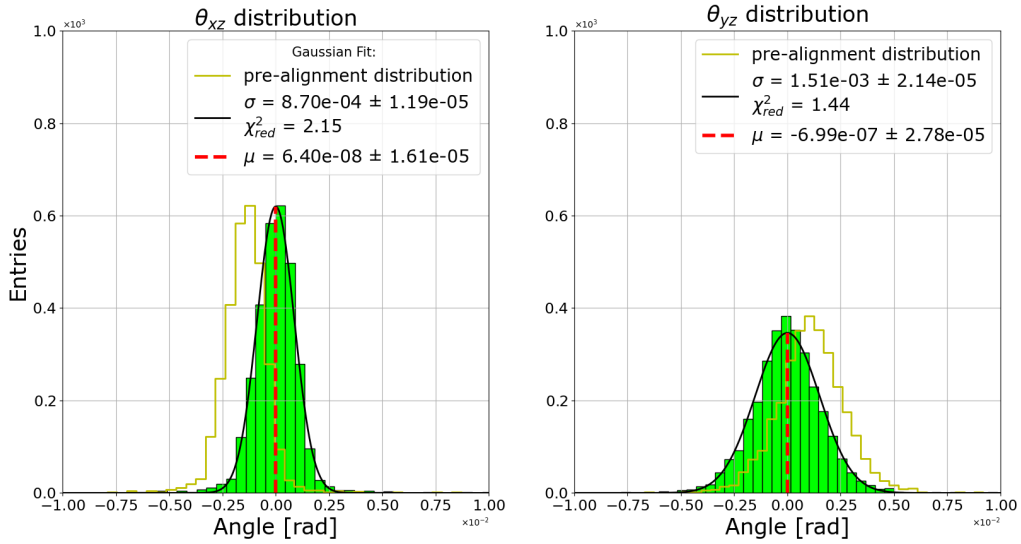


Figure 4.4: 1D beam divergence distributions along the x and y coordinates. The yellow curve represents the previously misaligned histograms.

	2022	2023	2024
Div_{xz} [mrad]	0.75	0.75	1.48
Div_{yz} [mrad]	1.23	1.27	2.12
BCs distance [cm]	66	268	337
# datasets	90	109	55
$\sigma_{\text{Div}} \sim 10 \text{ } \mu\text{rad}$			

Table 4.1: Average angular divergence values associated with the profile plots. Results were computed from the σ of the Gaussian fits in figure 4.4. The errors associated with the angular divergence were of the order of $\sim 10 \text{ } \mu\text{rad}$.

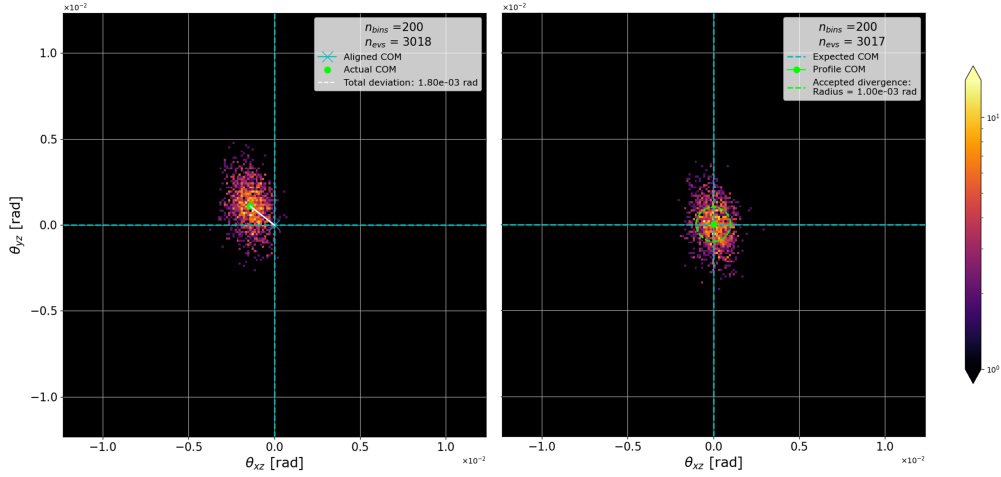


Figure 4.5: 2D divergence distributions: correlation of the x and y residuals divided by the distance between the two BCs. The 2D distribution allowed to estimate the overall misalignment and to select a cut on the beam divergence (green dashed line).

effects could also occur, given the materials the particle has to cross. If this happens, the extrapolated trajectory would not be correct, as shown in figure 4.6. The multiple Coulomb scattering of a charged particle traveling through a medium can be estimated using the Highland formula, which expresses the RMS scattering angle (θ_{MCS}) due to multiple small-angle deflections [47]:

$$\theta_{\text{MCS}} \approx \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \left(\frac{x}{X_0} \right) \right] \quad (4.1)$$

- p : the momentum of the electron (for a 6 GeV electron, $p \simeq 6 \times 10^3$ MeV/c);
- z : the charge number of the incident particle (for an electron, $z = 1$);
- x : the thickness of the material (in radiation lengths);
- X_0 : the radiation length of the material (for silicon $X_0 = 9.36$ mm);
- $\beta \approx 1$: for ultra-relativistic particles.

Thus, when a 6 GeV electron crosses a 300 μm thick silicon beam chamber, considering that

$$\frac{x}{X_0} = \frac{0.3 \text{ mm}}{9.36 \text{ mm}} \approx 0.032 \quad (4.2)$$

and referring to formula 4.1, one obtains:

$$\theta_{\text{MCS}} \approx 350 \text{ } \mu\text{rad} \quad (4.3)$$

Therefore, given the energy of the beam and the selection of a 1 mrad divergence profile, the MCS contributions could be neglected.

4.3.1 Crystals position reconstruction

After the selection of the events within a 1 mrad divergence, the following step consisted in reconstructing the region occupied by a single crystalline

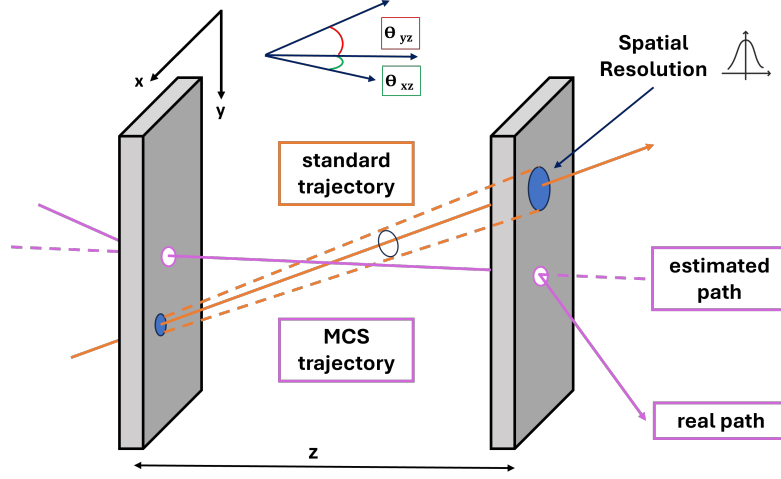


Figure 4.6: Trajectory scheme of two events across the BCs. The orange line represents the natural path of a particle that crosses the BCs in a straight line, whereas the pink line represents a possible MCS event.

sample. As anticipated, this allowed to focus the analysis onto the events that most likely underwent channeling and coherent effects. In addition, once the tracking microstrips associated with the crystals positions were known, it was possible to switch to the self-triggering mode.

The crystal samples were mounted on a holder with a known horizontal distance from the BCs. In this way, it was possible to estimate the coordinates projections for each event onto the holder plane. Next, correlating the x and y coordinates projections and weighting each event with the corresponding calorimeter pulse height, the crystal profile was reconstructed. In fact, since the magnet was on, only bremsstrahlung photons could be detected by the calorimeter. Given the fact that the bremsstrahlung of electrons across the crystal had a larger yield than the bremsstrahlung generated by the magnetic field, the samples position was associated with the highest calorimeter pulse heights, as shown in figure 4.7.

Figure 4.8 shows a projection plot from a high-statistics run during the 2023 beamtest, where three crystals were mounted together onto the goniometer. Once the crystal regions had been clearly identified, a tighter selection could be made to ensure to keep only the events from the interaction between electrons and the lattice (green dashed lines). As mentioned before, the tracking microstrips associated with this region were assigned to the self-triggering system. When the self-triggering mode was activated, a profile directly focused on the region of interest was obtained (figure 4.9).

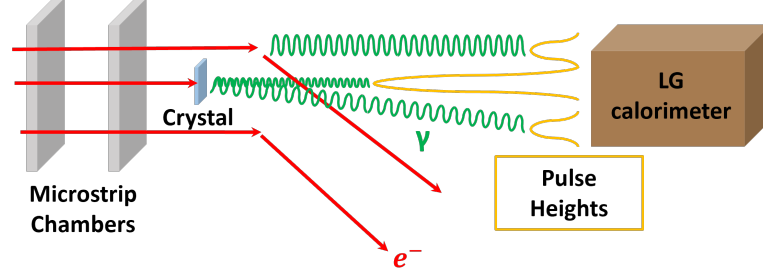


Figure 4.7: Schematization of the photons interacting with the calorimeter. Photons produced within the crystal are associated with the highest pulse heights of the calorimeter. Smaller pulse height values, instead, are associated with electrons not deviated by the magnet, bremsstrahlung photons from non-channeled electrons, or even to electrons that emitted synchrotron radiation due to the magnetic field.

Insofar, three cuts on the overall statistics were performed, namely the Cherenkov pulse height threshold to select electrons, the beam divergence to select events in the channeling angular range and the crystal region. Table 4.2 summarizes the percentage values of the statistical loss after these cuts. For every sample and beamtest the ultimate available statistics amounted to a 10 % fraction of the initial one. Hence the importance of collecting high-statistics long runs.

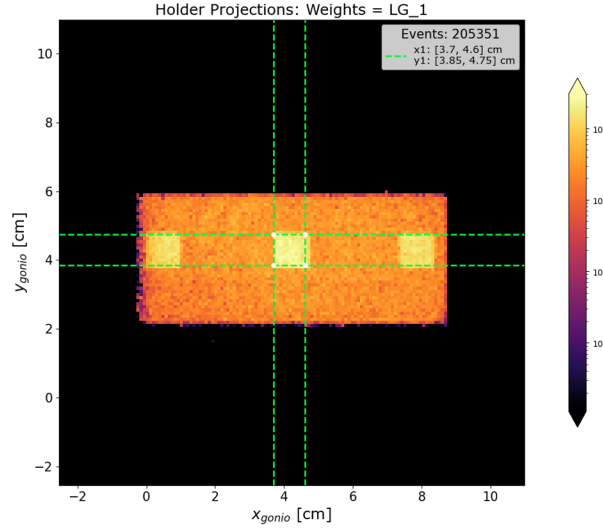


Figure 4.8: Projections of the coordinates onto the crystal plane in the 2023 beamtest. The green dashed lines represent the crystal region selected to analyze the calorimeter energy associated with the 1.5 mm tungsten sample.

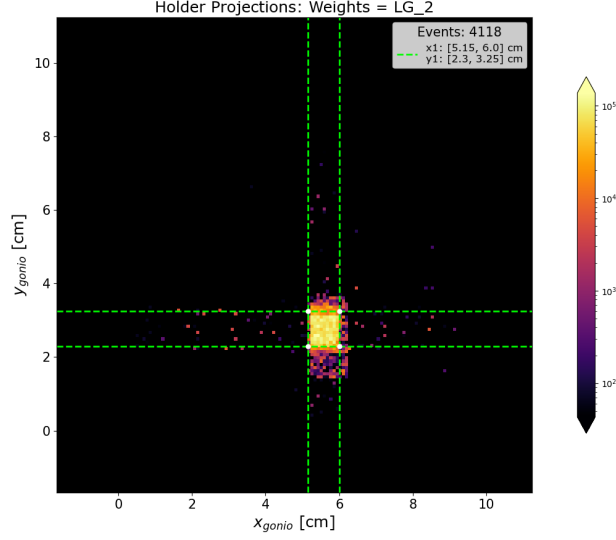


Figure 4.9: Position of the 1 mm iridium sample on the goniometer plane, in the 2022 beamtest. The green dashed lines represent the crystal region selected to analyze the calorimeter energy. Only a small portion of the area surrounding the sample is highlighted, due to the self-triggering system.

	2022		2023		2024	
Crystal	$\text{Ir}_{1\text{mm}}^{(110)}$	$\text{W}_{2\text{mm}}^{(111)}$	$\text{Ir}_{2\text{mm}}^{(110)}$	$\text{W}_{1.5\text{mm}}^{(111)}$	$\text{W}_{1.5\text{mm}}^{(111)}$	$\text{W}_{10\text{mm}}^{(111)}$
Surface [mm ²]	7×8	13×15	8×8	8×8	8×8	10×10
Cherenkov	$\sim 60 \%$	$\sim 60 \%$	$\sim 60 \%$	$\sim 60 \%$	$\sim 30 \%$	$\sim 20 \%$
Crystal region	$\sim 95 \%$	$\sim 90 \%$	$\sim 99 \%$	$\sim 99 \%$	$\sim 97 \%$	$\sim 95 \%$
n datasets	24	66	51	58	24	21
Percentage values calculated from high-statistics acquisitions ($\sim 10^5$ events)						

Table 4.2: Statistics loss after selecting the crystal regions changed by a factor $\sim 5\%$ based on the sample surface. In 2024 the statistical loss was mainly due to the geometrical cuts.

4.4 Calorimeter Analysis

This section describes the calorimeter analysis, from the calibration phase to the estimation of the photon yield enhancement. As a preliminary step, the LG profile was reconstructed correlating the BCs coordinates of each event onto the calorimeter plane, and weighting each projection with the corresponding LG pulse height. This procedure ensured that the LG front surface was aligned with the beam (figure 4.10).

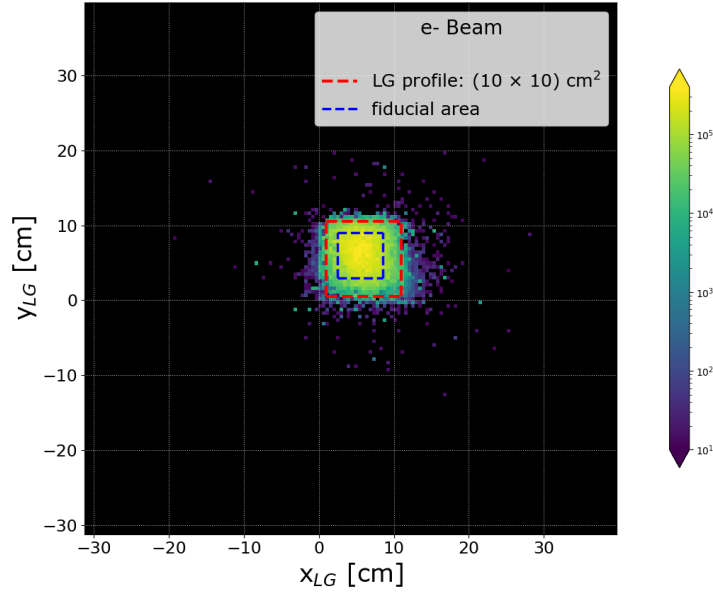


Figure 4.10: LG profile reconstructed through the weighted projections method, with a beam of 6 GeV electrons. A fiducial area (in blue) was selected within the $10 \times 10 \text{ cm}^2$ square (in red).

4.4.1 Lead Glass calibration

The LG calibration allowed to convert the deposited energy from the ADC units into energy expressed in GeV. For the calibration the crystal samples were moved out of the beam path and the magnet was switched off. In this way it was guaranteed that only electrons would interact with the calorimeter, within the limits of the beam purity (appendix B). Once the setup was prepared, the calibration went through the following steps:

- a focused-optics mono-energetic electron beam was directed onto the calorimeter. The self-triggering system was activated as it was already tuned to acquire only the events in the fiducial region;
- the beam energy was varied within the [1–6] GeV range, thus leading to a total of six acquisitions. A statistics around 10^4 events was collected for each run (figure 4.11);
- the peak of each energy was interpolated with a Gaussian model to estimate its central ADC value and standard deviation:

$$y(x) = \frac{A}{\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (4.4)$$

An example of a 6 GeV spectrum and its interpolation are visible in figures 4.12 and 4.13;

- as the PMT gain was set to operate linearly, a linear regression was implemented between the real energy values in GeV and the fitted values in ADC (figure 4.14);
- the mean and standard deviation values were then employed to compute the calorimeter energy resolution (section 4.4.2).

The above procedure was repeated each year, since even slight changes in the experimental setup influenced the ADC-to-GeV conversion. In fact, despite the employed calorimeters belonged to the same models, each PMT needed its custom calibration factors, summarized in table 4.3.

	2022	2023	2024
m [ADC / GeV]	1468 ± 4	1170 ± 2	196 ± 1
q [ADC]	-31 ± 16	-40 ± 8	-19 ± 1
$E_{\text{ADC}} = m \cdot E_{\text{GeV}} + q$			

Table 4.3: Calibration factors for each calorimeter in the three beamtests.

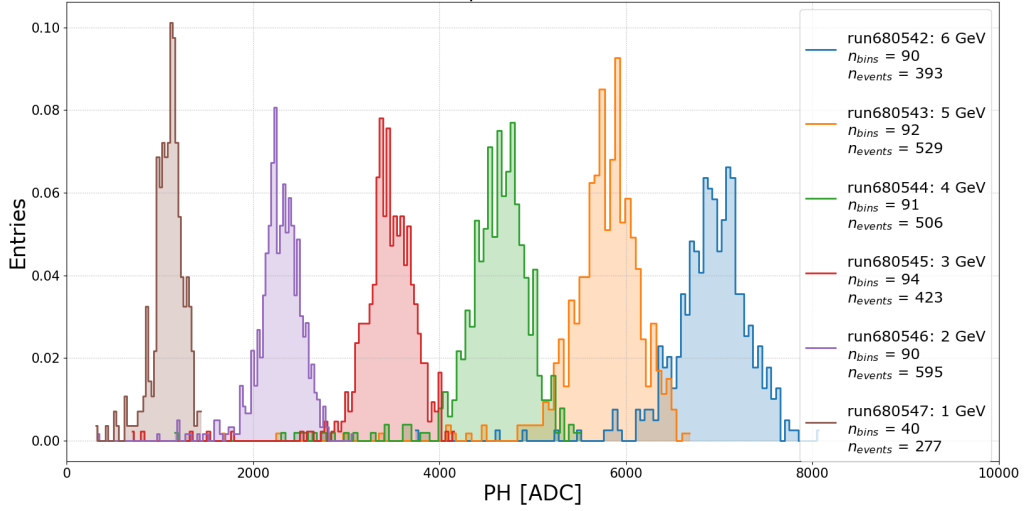


Figure 4.11: Comparison of the electrons normalized distributions measured by the calorimeter in the [1 – 6] GeV range, after a cut on the Cherenkov detector pulse height was applied.

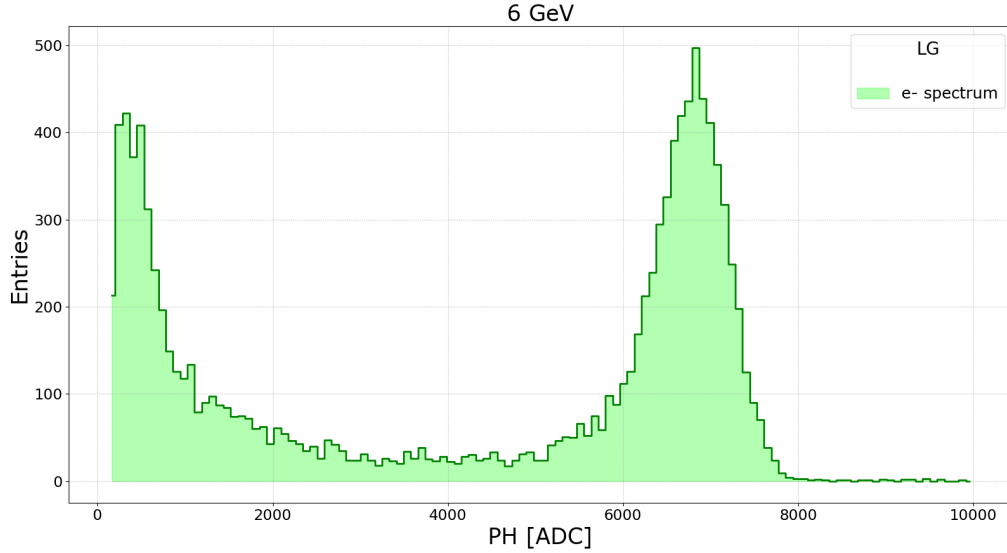


Figure 4.12: LG raw spectrum for a 6 GeV calibration run. The peak on the left corresponds to MIPs (muons), which can be removed through a cut on the Cherenkov pulse height.

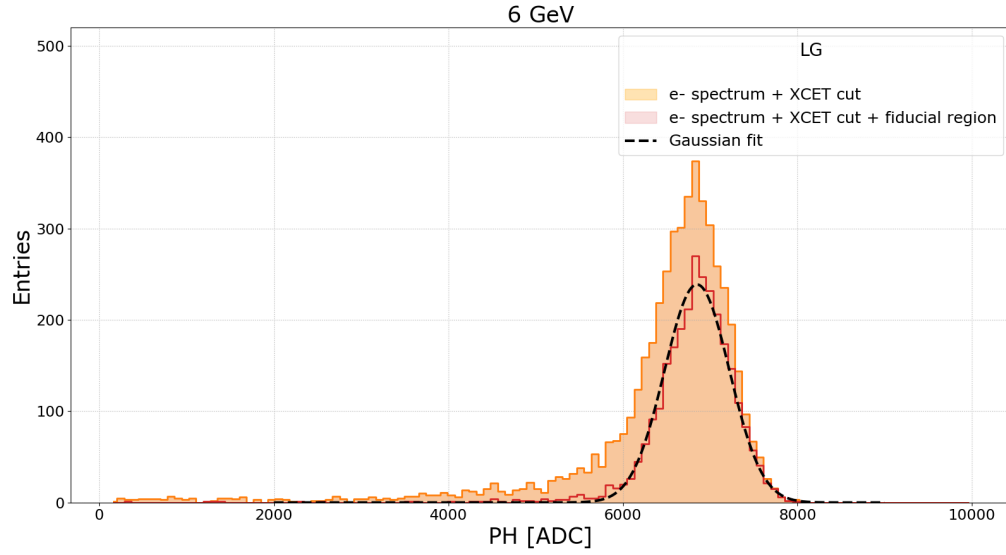


Figure 4.13: LG filtered spectrum for the 6 GeV run showed in figure 4.12. The Gaussian fit was implemented on the red curve, after both the Cherenkov and fiducial area cuts.

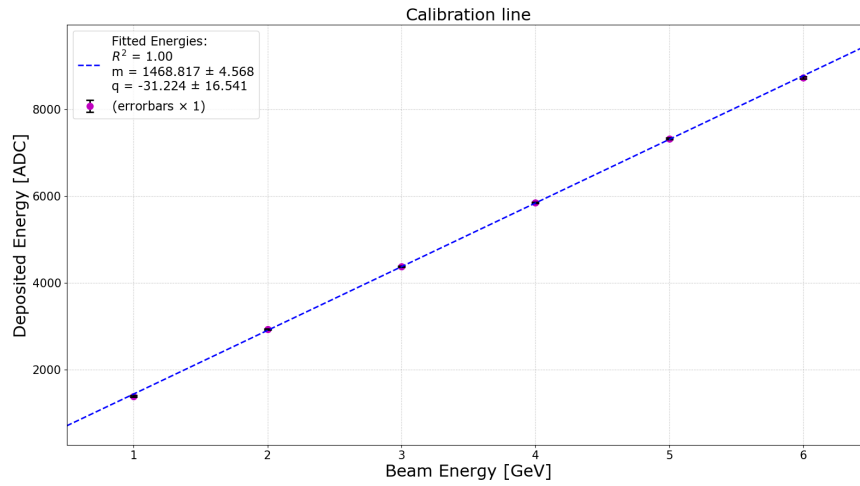


Figure 4.14: Linear regression to retrieve the calibration factors. The fit errors were of the order of a few hundreds ADC.

4.4.2 Energy resolution

The energy resolution is defined as the ratio of the signal distribution width (σ) and the corresponding mean value (μ):

$$\text{Res}_E = \frac{\sigma}{E} \quad (4.5)$$

The energy resolution of an electromagnetic calorimeter is expressed as a sum of different contributions (equation 4.6):

$$\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right) \oplus \left(\frac{b}{E}\right) \oplus c} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2} \quad (4.6)$$

The single terms of equation 4.6 are the following:

- a is the **stochastic term**: it depends on the fluctuations in the shower physical development. In homogeneous calorimeters the intrinsic fluctuations are small because the energy deposited in the active volume does not change event by event.
- b is the **noise term**: it is due to the electronic noise of the readout chain and depends on the detection technique and on the characteristics of the readout circuit. Calorimeters with their signal collected in the form of light are characterized by a lower noise compared to calorimeters with a charge signal that need an amplifier.
- c is the **constant term**: it does not depend on the energy of the particle but rather on imperfections in the mechanical structure of the calorimeter or in the readout system. This contribution tends to increase over time, mainly due to radiation damage.

In the present analysis, the noise term b could be neglected due to the use of low-noise PMTs in the calorimeter readout chain.

During the calibration phase, the mean and standard deviation values of the energy distributions were determined and subsequently substituted into equation 4.5. A further fit was then performed based on equation 4.6. Since

the resolution is expressed as a ratio, the uncertainties associated with its values were calculated using the standard error propagation formula:

$$\sigma_y = \sqrt{\sum_{i=1}^N \left(\frac{\partial y}{\partial x_i} \sigma_{x_i} \right)^2} \quad (4.7)$$

The energy resolution fit is shown in figure 4.15 and presented in table 4.4.

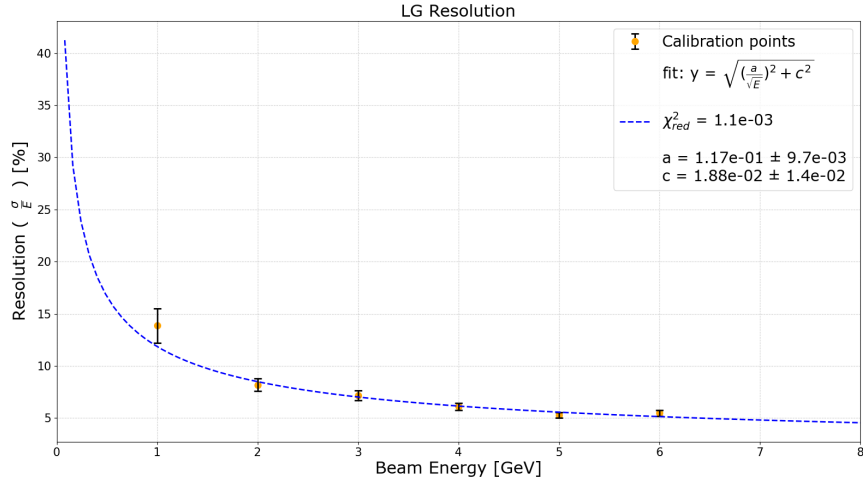


Figure 4.15: Energy resolution of the calibrated LG calorimeter.

	2022	2023	2024
a [%]	11	13	16
c [%]	2.0	1.5	2.7
$\sigma_a \sim 1\%$ $\sigma_c \sim 1\%$			

Table 4.4: Characteristic energy resolutions parameters for the different Lead Glasses.

4.4.3 LG photon spectrum

Except for the calibration phase, where a pure electron beam was used, the dipole magnet was usually switched on to acquire the bremsstrahlung photons generated in the crystals. Figure 4.16 shows the effects of the dipole magnet on the spectrum sampled by the calorimeters. In the left plot the magnet was switched off, and the electron and MIP peaks are visible. In the right plot, the magnet was switched on, and the bremsstrahlung photon spectrum is shown. Since the beamtests were focused on the increase of the production of the high-energy photons thanks to the oriented crystals, the soft part of the spectrum in the low-energy region has been removed during the offline analysis selecting a proper threshold, in order to study only the energy deposit of the channeling and coherent bremsstrahlung events.

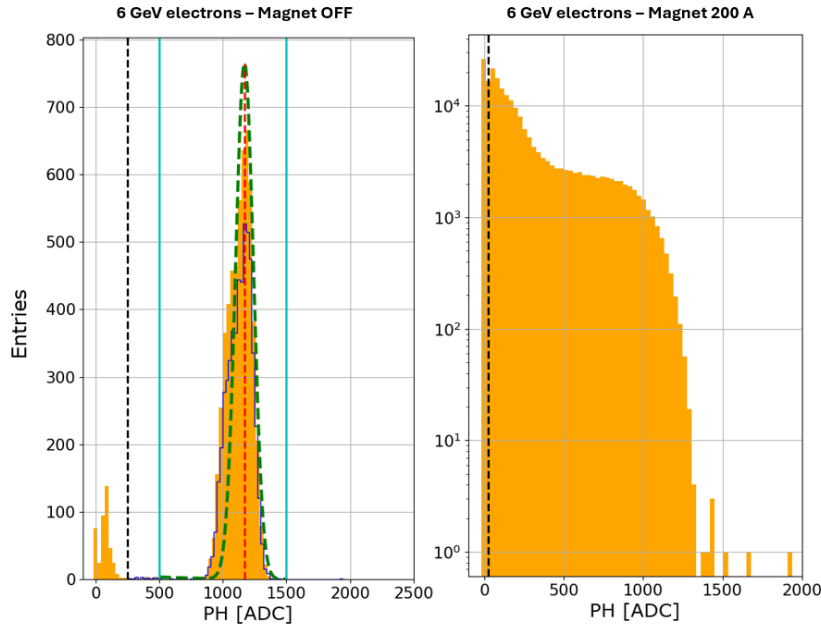


Figure 4.16: Comparison of two 6 GeV electrons energy spectra sampled by the LG calorimeter.

The photon spectra were eventually compared and averaged to provide the enhancement results, which are presented in the next section.

4.5 Photon enhancement results

This last section presents the strategy to assess the optimal orientation for the crystals under test, along with their photon yield enhancement capability in the context of a e^+ source. Once the self-triggering system was operating, the following procedure was adopted:

- with the crystals mounted onto the goniometer, this was moved to align the crystal lattice with the beam through a pentaprism and a dedicated mirroring system. In this way, the lattice was oriented orthogonally to the beam;
- different angular scans were launched along a degree of freedom of the goniometer (ROTATIONAL or CRADLE), computing the average pulse height of the calorimeter;
- the plots of the average pulse height as a function of the particle angle were observed in real time in order to assess the approximate optimal orientation along the degree of freedom under study (figure 4.17), namely the one that returned the highest photon yield. Sometimes local approximate interpolations were made to help estimating the optimal position in a more precise way. Since these fitting methods were performed on a limited number of points and through basic polynomial models, there was no need for an accurate analysis on the goodness of the fit;
- once the optimal channeling axis had been found in one direction, the estimated optimal angle was fixed and the procedure was repeated rotating the goniometer along the orthogonal direction, looking again for the highest value of the calorimeter pulse height.

After finding the optimal orientation, two high-statistics runs were acquired in the so called *random* (amorphous lattice) and *axial* (oriented lattice) conditions. The first one refers to a position of the goniometer very far from the estimated optimal axis, resembling the interaction with an amorphous material, whereas the second one corresponds to the optimal orientation. In some cases, data were acquired to measure the transition from the amorphous to the oriented lattice. The comparison between the amorphous and axial orientations was displayed plotting the calorimeter distributions (re-scaled from ADC to GeV) together, or through *stereogram* plots. The

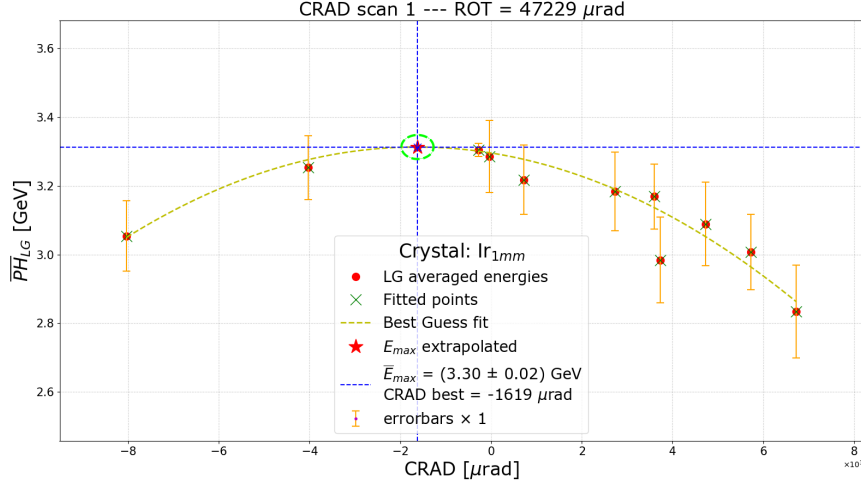


Figure 4.17: Angular scan along the CRADLE degree of freedom of the goniometer. The maximum pulse height was estimated through a local parabolic fit near the alleged maximum, in the intersection point of the two blue lines.

stereogram represents a scatter plot used to compare the different LG pulse heights, in order to assess the lattice alignment: the horizontal and vertical axes correspond to the angular degrees of freedom of the goniometer (ROTATIONAL and CRADLE), while the colored scatter points are associated with the average energies of the calorimeter spectrum. Every spectrum, both for the LG and for the APC, was normalized to the number of events that impinged on the crystal.

The following considerations about the 2023 and 2024 beamtests provide a better insight on the analysis process:

- in the case of the 2023 beamtest, since the crystals were mounted on the same support and were oriented with respect to different planes (table 3.2), the statistics corresponding to the axial orientation of the iridium crystal was used as the amorphous orientation statistics for the tungsten crystal, and vice-versa. This allowed a large enough statistics with shorter acquisition times;
- in the case of the 2024 beamtest, the 1.5 mm tungsten sample was combined at a given point with a 8 mm thick tungsten converter to allow simulate a hybrid positron source setup, $3 X_0$ thick. Therefore, the results of the 2024 beamtest refer to both configurations, either

with or without the converter.

Figures 4.18, 4.19 and 4.20 present the obtained results for all the e+BOOST beamtests. For each beamtest, the order of the plots was arranged to show the stereograms first, then the LG energy spectra and the APC signal which depends on the photon multiplicity. Each couple of plots shows the two different crystals studied during the corresponding beamtest. Table 4.5 summarizes both the photon energy and the APC signal enhancements comparing the amorphous and axial orientations. In the case of the calorimeter energy, the corresponding spectra were cut in correspondence of the low energy left tail, in order to focus only on the photons that more likely were produced in channeling or coherent effects. On the other hand, the APC signals were compared in terms of the total area of their corresponding distributions. For the majority of the crystalline samples, moreover, the energy increase was compared to the results obtained in the corresponding simulations.

Chapter 4. Data Analysis and Results

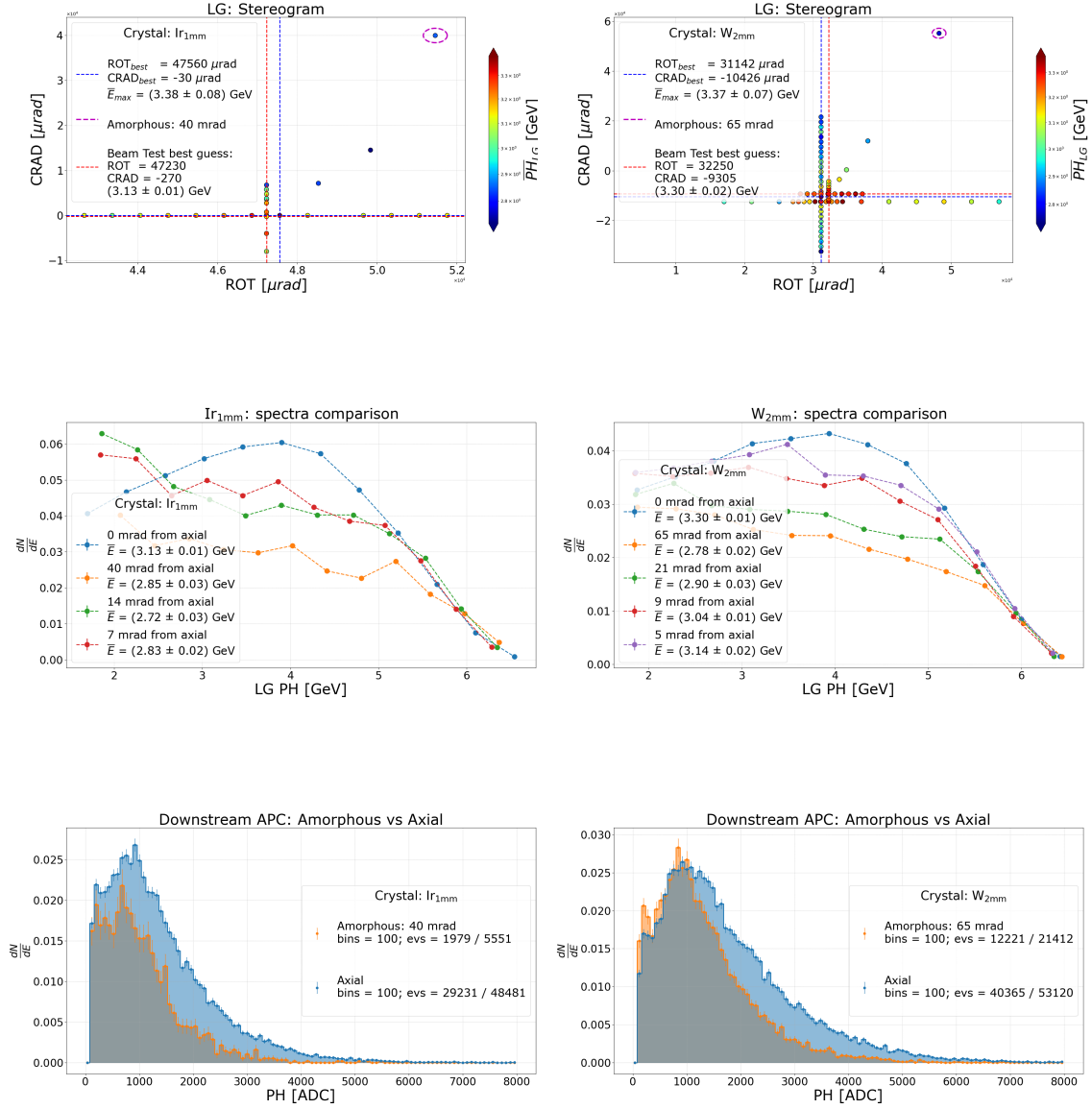


Figure 4.18: Results of the 2022 beamtest.

Chapter 4. Data Analysis and Results

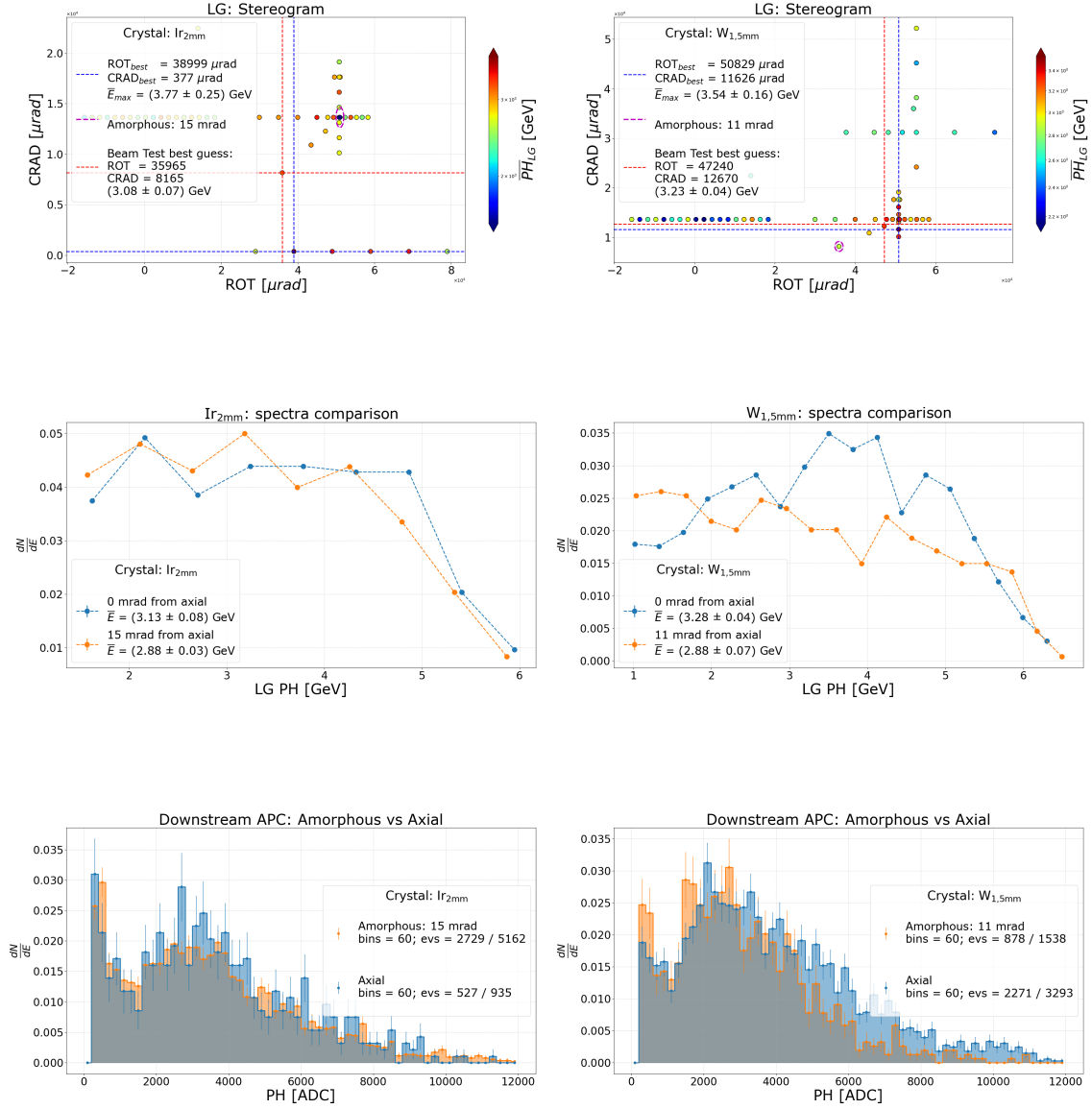


Figure 4.19: Results of the 2023 beamtest.

Chapter 4. Data Analysis and Results

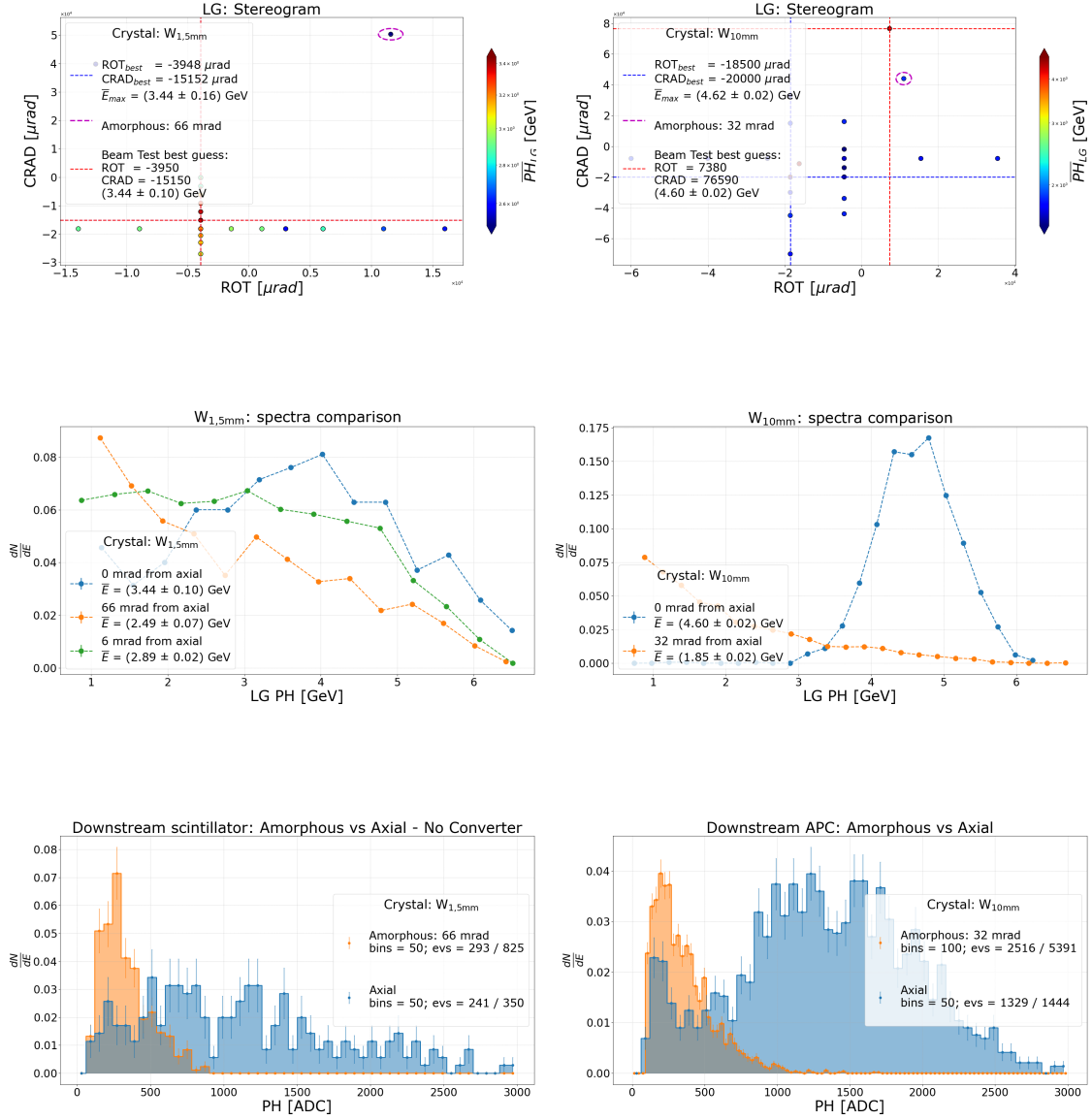


Figure 4.20: Results of the 2024 beamtest.

As a result of the offline data analysis, the following considerations hold:

- the amount of statistics of the 2023 beamtest was an order of magnitude smaller than the one collected in the other beamtests. This also prevented from analyzing the third crystalline sample mounted on the goniometer (2.5 mm tungsten);
- in the case of the 2024 beamtest with the hybrid positron source setup, the plastic scintillators placed to measure the positrons rate were saturated because of a too large PMT bias. This allowed to see an increase in the multiplicity but no quantitative estimation was possible. As a result, for the 10.5 mm thick hybrid setup only the calorimeter could be used to characterize the photon enhancement;
- during the high multiplicity axial run launched for the hybrid positron source, the goniometer was not aligned with the optimal crystalline axis found without the converter, due to a wrong estimation of the highest calorimeter pulse height. Despite the other axis was only a few hundreds microradians far from the optimal, the obtained results with the converter did not show an enhancement in the deposited energy, but only a small increase in the APC multiplicity, around $\sim 7\%$ (figure 4.21).

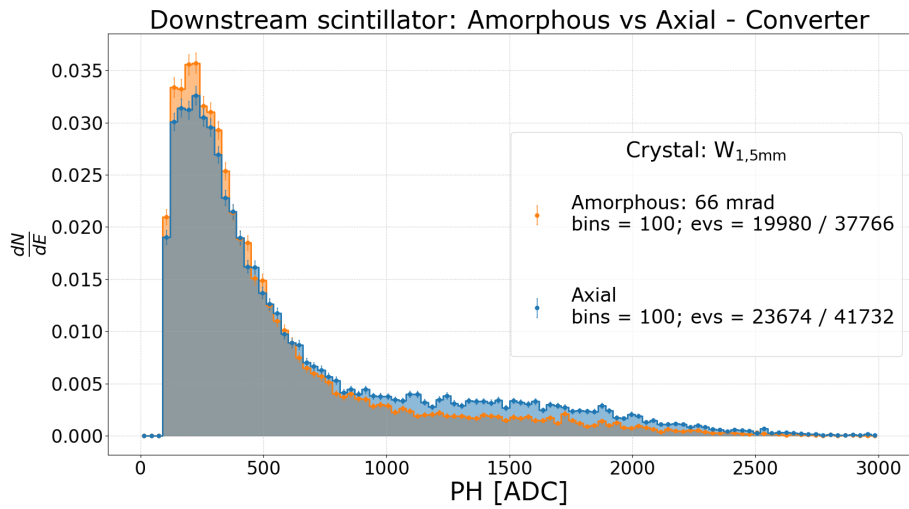


Figure 4.21: APC spectra for the 1.5 mm tungsten crystal tested in 2024, plus the 8 mm amorphous converter. A slight multiplicity increase is visible, around 7%.

e+BOOST enhancement results	2022		2023		2024	
Crystals	$\text{Ir}_{1\text{mm}}^{\langle 110 \rangle}$	$\text{W}_{2\text{mm}}^{\langle 111 \rangle}$	$\text{Ir}_{2\text{mm}}^{\langle 110 \rangle}$	$\text{W}_{1.5\text{mm}}^{\langle 111 \rangle}$	$\text{W}_{1.5\text{mm}}^{\langle 111 \rangle}$	$\text{W}_{10\text{mm}}^{\langle 111 \rangle}$
Radiation length [X_0]	0.3	0.6	0.6	0.4	0.4	2.8
$\bar{E}_{\text{amorphous}}$ [GeV]	2.85	2.78	2.84	2.84	2.50	1.85
$\bar{E}_{\text{axial}}$ [GeV]	3.13	3.30	3.08	3.23	3.44	4.60
σ_E [GeV]	0.01	0.02	0.04	0.07	0.10	0.02
$\bar{E}_{\text{simulations}}$ [GeV]	3.15	3.23	$\times$	2.88	2.88	$\times$
$E_{\text{enhancement}}$ [%]	9.8	18	8.5	13	37	150
$\text{APC}_{\text{enhancement}}$ [%]	69	33	6.6	20	93	100
$E_{\text{enhancement}} = [(E_{\text{axial}} - E_{\text{amorphous}}) / E_{\text{amorphous}}] \times 100$						
$\text{APC}_{\text{enhancement}} = [(\text{APC area}_{\text{axial}} - \text{APC area}_{\text{amorphous}}) / \text{APC area}_{\text{amorphous}}] \times 100$						

Table 4.5: Summary of the enhancement results for the e+BOOST beamtests. The values refer to the LG calorimeter energies and the downstream APC pulse heights, for a total of five different crystalline samples in terms of material and radiation length. In the case of the 2024 beamtest, only the results of the 1.5 mm thick tungsten without the converter have been reported. The samples that were not simulated have been labeled with a $\times$ in the corresponding cell.

As far as the presented plots and the numerical results in table 4.5 are concerned, the following observations hold:

- when looking at the LG photon spectra (for instance, figures 4.18c and 4.18d), the closer to the axial orientation, the more peaked the spectrum becomes, due to the larger presence of photons generated through channeling and other coherent effects;
- the average energy laid in the $[3 - 3.5]$ GeV range for all the samples in the $[1 - 2]$ mm thickness range. For the 10 mm sample, on the other hand, an average value of 4.6 GeV was obtained, along with the largest multiplicity enhancement of a factor 2;
- the energy increase, for all the crystals under test in 2022, is associated with an inverse trend of the multiplicity increase. In fact, the energy enhancement was smaller by a factor of two for the crystal sample with half of the thickness (1 mm iridium), while its multiplicity enhancement was greater also by a factor of two; a possible interpretation is that a fraction of less energetic photons were produced, more likely to undergo pair production within the copper layer of the APC;
- a good match between the estimated average energies and the simulated energy was found in the 2022 beamtest. The same cannot be said for the 1.5 mm thick tungsten, since the corresponding simulated photon spectrum was estimated under 3 GeV. On the other hand, the average energy of the 1.5 mm thick tungsten matched the estimated energy for the 2 mm thick tungsten tested in 2022. This could be due to nonlinear effects with respect to the crystal thickness that were not considered by the simulations;
- as far as the 1.5 mm thick tungsten is concerned, it can be noticed an increase of both its average energy and the APC multiplicity from the 2023 to the 2024 beamtest. This could be due to a better estimate of the axial orientation;
- the largest multiplicity enhancement was registered in the 2024 beamtest, with the thickest (10 mm) tungsten sample. Despite its thickness was the same of the hybrid setup (10.5 mm thick), the 10 mm tungsten sample had a larger surface (cfr. table 3.2) and a whole crystalline structure, rather than the combination of a crystalline lattice and an amorphous target. For this reason, its contribution resulted into twice a larger photon yield.

As far as the crystals studied in the 2024 setup are concerned, the most recent simulations allowed to estimate a deposited power around 5.65 kW in the 8 mm thick converter, along with a 5.8 J/g/pulse PEDD. These same values could also be referred to the 10 mm thick tungsten sample, since it served both as a radiator and a converter, containing a larger electromagnetic shower.

Conclusions

The present thesis work was performed in the framework of e+BOOST (Intense positron source Based On Oriented crySTals), a project funded by the Italian Ministry of Research which aimed at investigating the feasibility of a crystal-based positron source for future lepton colliders. The technology of present day positron sources still faces several challenges that must be overcome for the needs of future accelerators, like the ILC or the FCC-ee, such as the thermal stress experienced by the photon converters in the beamline. Conventional positron sources rely on high-energy photons which interact with an amorphous, high-Z material, generating e^+e^- pairs that can be separated with a magnetic field. Several strategies are being developed to address problems like the heat dissipation within the target and the radiation damage caused by the overall energy deposit, which shall not be larger than the 35 J/g limit.

The e+BOOST project aims at developing a hybrid (or two stage) crystal-based positron source, consisting of a crystalline radiator and an amorphous high-Z converter. In fact, the higher e^+e^- luminosities required by future colliders will be reached only increasing the yield of the photons responsible for the electron-positron pair production. Moreover, the separation of the positron source setup in two different stages would allow to handle a better dissipation of both the heat and the ionizing radiation. In the context of the source feasibility study, Geant4 simulations showed how the hybrid positron source represents a feasible way to address problems like the deposited power within the target, while still maintaining an increase of the output photon yield. The same investigation also provided an estimate of the angular acceptance for the photon increase to be measured.

The goal of the present thesis was to discuss the data analysis of the e+BOOST beamtests, which took place at the CERN T9 beamline between 2022 and 2024. Several crystal samples with different radiation lengths were

tested, in order to evaluate the feasibility of using them as compact photon radiators. From solid state physics, it is well known that the interaction of high-energy charged particles with an oriented lattice can result in an increase of the bremsstrahlung photon yield, compared to the standard Bethe-Heitler bremsstrahlung. This enhancement can be ascribed either to planar and axial channeling, or, when the lattice is rotated along specific orientations, to coherent and strong field effects. These interaction phenomena are intrinsically nonlinear and can be properly described only under quantum and relativistic treatment. Nonetheless, they can be exploited to boost the photon emission in terms of yield and energy, depending on the characteristics of the crystals under test. These include the lattice axes, planes (expressed in terms of Miller indices) and their material. In this regard, iridium and tungsten were considered as the best candidates due to their large atomic number and their resistance in radiation-hard environments.

The beamtests goals were achieved studying the photon yield enhancement in different crystal samples with 6 GeV electron beams. In this context, the features under study involved the beam divergence, the beam-to-axis angle and the photon yield as a function of the orientation of the different lattices. The geometric properties of the beam were measured using a pair of microstrip tracking chambers, developed by the INSULAB group and characterized by a spatial resolution of $\sim 40 \mu\text{m}$. The deposited energy and the photon multiplicity increase, on the other hand, were measured using a set of plastic scintillators and a Lead Glass calorimeter. The plastic scintillators had the same dimensions and were placed close to each other, separated by a thin copper layer, a few millimeters thick ($0.1 - 0.4 X_0$). Altogether, these formed the APC (Active Photon Converter) system, which allowed to eliminate the residual charged particles after the magnet and to estimate the multiplicity increase thanks to the photons converting in the copper layer. The setup featured also Cherenkov detectors for the electron identification, a high-precision goniometer to control the crystalline lattice orientation with a $\sim \mu\text{rad}$ precision, and a dipole magnet to deviate the charged particles generated within the crystal or the converter, ensuring that only photons interacted with the calorimeter. The photon spectrum was measured by the calorimeter, applying a cut on the soft photons region to select only the events most likely caused by channeling and coherent bremsstrahlung. The total areas of the APC pulse height distributions were compared as well, providing an insight about the photon multiplicity increase.

Considering the energy deposit in the amorphous and axial orientation, the majority of the samples under test generated photons with an energy be-

tween 3 and 3.5 GeV, and a corresponding energy enhancement with respect to the amorphous case in the $[10 - 40]$ % interval. The results associated with the highest enhancements were found in the 2024 beamtest, both in terms of the LG energy and the APC signal. In fact, the 1.5 mm thick tungsten presented both a larger energy deposit and a larger multiplicity increase compared to the same crystal tested in 2023. This more recent result represents an improvement in the evaluation of the axial orientation. As for the 10 mm tungsten crystal, this sample delivered the maximum photon energy (4.60 GeV) and the largest multiplicity increase (100%) compared to all the other samples. Its larger thickness was associated with a significant absorption of the electromagnetic shower, which also increases the thermal stress. The obtained results, in terms of photon energy, were compared with the Geant4 simulations performed by the Ferrara group, finding a match for the 1 mm thick iridium and the 2 mm thick tungsten. The results involving the other samples, such as the 2 mm thick iridium and the 10 mm thick tungsten, showed that the real energy values were probably underestimated by the simulations. These results will provide a useful reference to tune the parameters for future simulations.

The 2025 beamtest will require to focus onto the hybrid positron source setup, evaluating the positron multiplicity in addition to the photon yield increase. The crystals radiation resistance will have to be evaluated using a dedicated setup able to measure the power deposit and the thermal gradients that affect the lattice integrity. The specific energy ranges and particle beams will be selected to fit the needs of the future positron sources.

Appendix A

Hereafter one of the main ingredients for the feasibility of every positron source is described, namely the electron-positron pair production. This phenomenon represents one of the many ways through which photons interact with matter, with a cross section that depends on their energy.

A.1 Electron-Positron pair production

To develop a positron source, one of the phenomena to investigate is the *pair production*, in which high-energy photons convert into electron-positron pairs. It is one of the mechanisms with which photons interact with matter and generally the creation of a particle-antiparticle pair [48]. This can occur either from the decay of a neutral particle or from a pulse of electromagnetic energy passing through matter, typically in the vicinity of an atomic nucleus [48]. For this reason, pair production occurs more easily in the presence of strong electromagnetic fields, like those near atomic nuclei or the ones generated by periodic crystalline potentials. Pair production is part of the Bethe-Heitler processes [16], described by QED. The process is very closely related to the process of radiation emission; in the case of pair production, the field is considered constant over the pair formation length, leading to an enhancement in the pair production cross-section. It is expressed as follows:

$$\gamma + Z \longrightarrow e^+ + e^- + Z \tag{A.1}$$

From a mathematical point of view, the energy equation that describes a single pair production is given by:

$$E_\gamma = E_{e^-} + E_{e^+} + E_{recoil} \quad (\text{A.2})$$

where E_{recoil} represents the recoil energy of the target nucleus, which becomes negligible only in a relativistic regime due to nucleons large masses with respect to e^+e^- masses [48].

The $E_{e^\pm}$ terms include both the kinetic energy and rest energy of electrons and positrons, namely

$$E_{e^\pm} = E_0^{e^\pm} + T_{e^\pm} \quad \text{with} \quad E_0^{e^\pm} = m_e c^2 \simeq 0.511 \text{ MeV}$$

so that the process threshold can be expressed as

$$E_\gamma \geq 2E_0^{e^\pm}$$

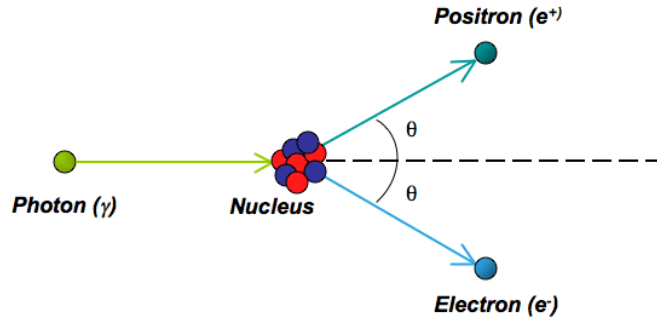


Figure A.1: Schematization of the pair production process of a photon interacting with a target nucleus. The electron-positron pair is emitted with an angle depending on the incoming photon energy.

It must also be noted that the angle between the outgoing particles depends on the incoming photon energy, and is influenced by both energy and momentum conservation. More precisely, referring to figure A.1:

$$2\theta \simeq \frac{m_e c^2}{p_{e^\pm}} \quad (\text{A.3})$$

where $p_{e^\pm}$ are the momenta of the outgoing electron-positron pair, given by

$$p_{e^\pm} \simeq \frac{E_\gamma}{2c}$$

Substituting this relation into equation A.3:

$$2\theta \simeq \frac{2m_e c^2}{E_\gamma} = \frac{1.022 \text{ MeV}}{E_\gamma} \quad (\text{A.4})$$

Therefore, gamma pair production can only happen if the incoming photon has at least twice the rest-energy of an electron, namely $2 \times 511 \text{ keV}$. The pair production angle of emission is expressed as the ratio between the energy threshold for the process and the energy of the incident photon [48].

Higher energies are preferable when dealing with a two-stage positron source, as lower emittances allow better beam focusing, enhanced luminosity, and positrons extraction through the magnetic filtering system. This is valid for the cross section as well. In fact, the overall interaction probability of photons scattering is given by the contribution of different processes cross sections (photoelectric, Compton, pair production, etc.).

For a positron source the electron-positron pair production cross section should be maximized. In this regard, the differential cross section for this process is computed in the Maximon theory [48] as

$$\sigma_{pp} \simeq Z^2 \alpha r_e^2 \left[\ln \frac{2 E_\gamma}{m_e c^2} - f(\delta) \right] \quad (\text{A.5})$$

where:

- Z is the atomic number of the target nucleus;
- $\alpha = \frac{1}{137}$ is the fine structure constant;
- $r_e = 2.282 \text{ fm}$ is the classical electron radius;
- $f(\delta)$ indicates the screening parameter, given by the electrons charge contribution to the nucleus potential.

Although the screening parameter $f(\delta)$ scales with Z , thus becoming non negligible in dense materials such as tungsten crystals, it approximates to $\frac{1}{2}$ under high energy (GeV) regimes, as in the e+BOOST beamtests.

In the Bethe-Heitler theory [16], the mean free path of the pair production effect is estimated as

$$\lambda_{pp} = \frac{9}{7} X_0 \tag{A.6}$$

Considering QED, the threshold for electron-positron pair production is given by the critical electric field (also referred to as the Schwinger electric field) [16], expressed as

$$E_C = \frac{m_e^2 c^3}{e \hbar} \simeq 1.32 \times 10^{18} \frac{\text{V}}{\text{m}}$$

More specifically, if the energy carried by the field is equal to the rest mass of an electron (511 keV) over a distance of around one Compton radiation length ($\lambda_{\text{compt}} \simeq 2.4$ pm), a e^+e^- pair is pulled out of vacuum [16].

Appendix B

This section describes the characterization of one of the Cherenkov detectors, the XCET₄₄, which served during all the e+BOOST beamtests.

B.1 Cherenkov characterization

Cherenkov threshold detectors are based on the light emission within a mixture of gas at a pressure level defined by the user. When performing particle identification based on the relation between the gas pressure and the particle momentum, the threshold velocities ($\beta_{thr} = \frac{v}{c}$) are set based on the momentum range and particle type [2]. The beams from the PS mainly consist in:

- electrons: momentum threshold ~ 70 MeV/c;
- pions: momentum threshold ~ 1 GeV/c;
- kaons: momentum threshold $\sim 3 - 4$ GeV/c;
- protons: momentum threshold $\sim 7 - 8$ GeV/c.

These threshold values hold as long as particles are accelerated in the GeV regime [2]. It can be seen how the smaller the mass, the lower the threshold, since heavier particles need a much larger momentum to achieve the same velocity as lighter particles. In order to set the operational pressure, the following relation for Cherenkov detectors is used [2]:

$$p_{thr} = \frac{m}{\sqrt{1 - \frac{1}{n^2}}} \tag{B.1}$$

where p_{thr} indicates the minimum momentum threshold to label different high-energy particles¹. It should also be reminded that for low density gases, such as CO₂, the refraction index n can be expressed as a linear function of the pressure P :

$$n \simeq 1 + k P \quad (\text{B.2})$$

where k is the *absorption coefficient*, which depends on density. Its value for CO₂ is

$$k = 2.7 \times 10^{-4} \frac{1}{\text{atm}}$$

Combining all the above relations, the calculations can be rearranged to express the proper pressure threshold for relativistic electrons in the GeV regime. First of all, from equation B.1 the refractive index can be isolated:

$$n = \frac{1}{\sqrt{1 - \left(\frac{m}{p_{thr}}\right)^2}}$$

This value for n can then be plugged into equation B.2, allowing to write the pressure P explicitly:

$$P = \frac{1}{k} \left(\frac{1}{\sqrt{1 - \left(\frac{m}{p_{thr}}\right)^2}} - 1 \right)$$

Considering that:

$$m_e = 0.511 \text{ MeV} \quad p_{thr} = 70 \text{ MeV} \quad k = 2.7 \times 10^{-4} \frac{1}{\text{atm}}$$

it is possible to obtain the minimum Cherenkov pressure for electrons (P_e) in the GeV regime:

¹ Note that the quantities are referred to the natural units of special relativity, where $c = 1$.

$$P_e = 0.098 \text{ atm} \approx 100 \text{ mbar}$$

When dealing with this detector, not only it was necessary to set an adequate pressure to discriminate electrons during the data taking, but also to choose a proper threshold in terms of pulse height and time during the offline analysis (figure B.1).

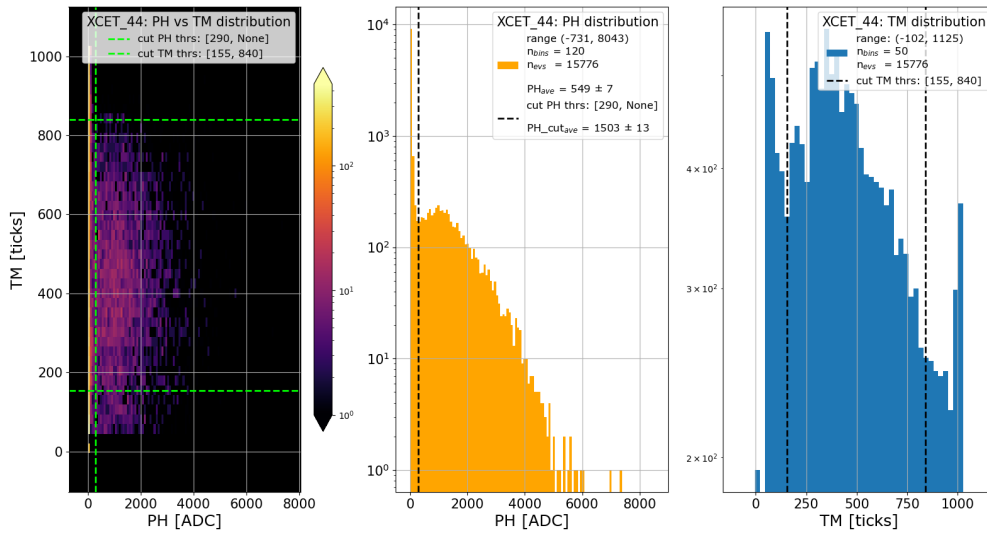


Figure B.1: Pulse height and time distributions of the XCET₄₄ Cherenkov detector. The dashed lines correspond to the selected threshold for both PH and TM intervals.

The following parameters were used to estimate the Cherenkov performances:

- the *efficiency* which is the ratio of the number of the electrons detected by the Cherenkov and the number of the electrons detected by the LG.
- the *purity* which is the ratio of the number of the electrons detected by the Cherenkov and the LG, and the number of the electrons detected by the Cherenkov.

Efficiency and purity have opposite trends, meaning that a trade-off must be made. As far as the beamtest is concerned, a large purity was needed. In order to allow a proper comparison between the events detected by both the calorimeter and the Cherenkov, the 6 GeV calibration run was selected

(section 4.4.1). Moreover, thanks to the geometrical tracking offered by the beam chambers and the knowledge of the calorimeter profile, the LG position was reconstructed (figure B.2), allowing to select a narrower fiducial area where the electromagnetic shower is contained.

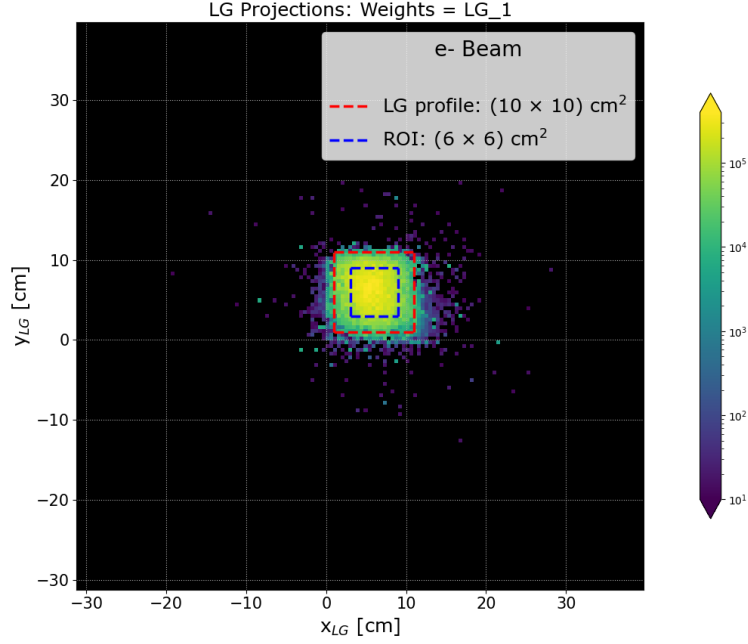


Figure B.2: Selection of a fiducial area (blue) for the electrons that impinged on the calorimeter, with respect to the overall detector profile (red). ROI stands for Region of Interest.

Figure B.2 highlights the presence of events outside the estimated profile region. These could have been caused by multiple Coulomb scattering or by bremsstrahlung from mid-air electrons. To compute the number of electrons, the LG pulse height spectrum was fitted with a Gaussian and an interval width of 3σ was selected (figure B.3). The events with pulse height in the range $[\mu - 3\sigma, \mu + 3\sigma]$ were labeled as electrons, where μ represents the mean value of the Gaussian. Efficiency was determined as the ratio of the events identified as electrons by the Cherenkov counter and the LG calorimeter (green histogram in the blue area) and the events identified as electrons by the LG (red histogram in the blue area). The purity was computed as the ratio of events identified as electrons by both the Cherenkov counter and the LG calorimeter (green histogram in the blue area) and the total number of events identified as electrons by the Cherenkov counter (green histogram). The numerical results are listed in table B.1.

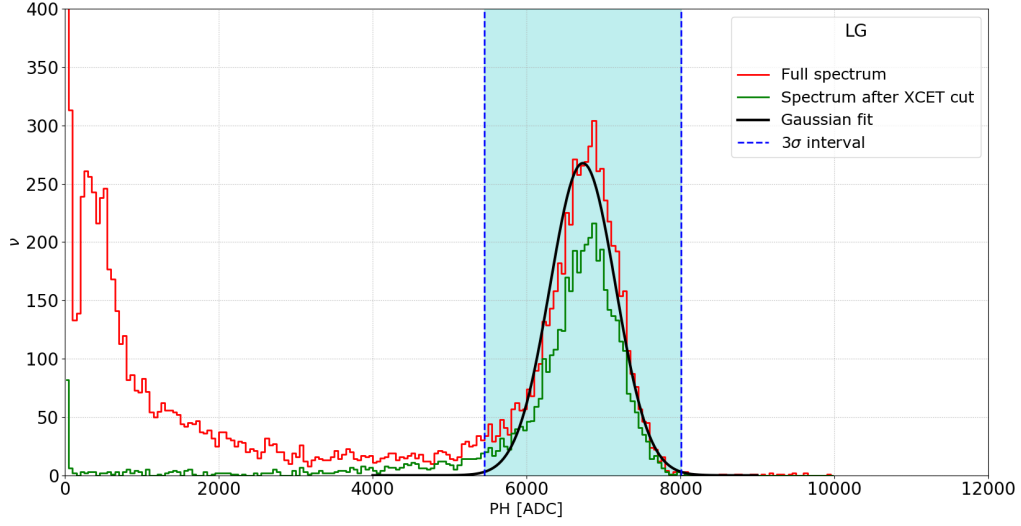


Figure B.3: LG pulse height: in red, the overall LG pulse height distribution; in green, the LG pulse height distribution of the events above the Cherenkov threshold. The blue area indicates the region used to count electrons.

PH threshold [ADC]	Efficiency	Purity
290	70 %	89 %
XCET ₄₄ Cherenkov counter - 2023 beamtest		

Table B.1: Performance of the XCET₄₄ Cherenkov counter, operating at a pressure of 100 mbar.

Acronyms

e+BOOST	Intense positron source Based On Oriented crySTals
ADC	Analog to Digital Converter
AGILE	Astrorivelatore Gamma a Immagini LEggero
AMD	Adiabatic Matching Device
APC	Active Photon Converter
ASCII	American Standard Code for Information Interchange
ASIC	Application Specific Integrated Circuit
BC	Beam Chamber
CFA	Constant Field Approximation
CLIC	Compact LInear Collider
COG	Center Of Gravity
CMRR	Common Mode Rejection Ratio
DAQ	Data AcQuisition
EBS	Electron BackScatter Diffraction
ERL	Energy Recovery Linac
ESRF	European Synchrotron Radiation Facility
FCC	Future Circular Collider
FPGA	Field Programmable Gate Array

FWHM	Full Width Half Maximum
GUI	Graphical User Interface
HEP	High Energy Physics
HDF	Hierarchical Data Format
HDI	High Density Interconnection
IJCLab	Irène Joliot-Curie Laboratory
ILC	International Linear Collider
LINAC	LINEar ACcelerator
LHC	Large Hadron Collider
LNF	Laboratori Nazionali di Frascati
LNL	Laboratori Nazionali di Legnaro
MCS	Multiple Coulomb Scattering
MIP	Minimum Ionizing Particle
NCS	Nonlinear Compton Scattering
NIM	Nuclear Instrumentation Module
OPAL	Omni-Purpose Apparatus for LEP
PCB	Printed Circuit Board
PH	Pulse Height
PEDD	Peak Energy Deposition Density
PID	Particle IDentification
PLA	PolyLactic Acid
POV	Point Of View
PMT	PhotoMultiplier Tube
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster

PWO	Lead Tungstate
QED	Quantum ElectroDynamics
ROI	Region Of Interest
RMS	Root Mean Square
SiPM	Silicon PhotoMultiplier
SLAC	Stanford Linear Accelerator Center
SLC	Stanford Linear Collider
SPS	Super Proton Synchrotron
TCL	Tool Command Language
TM	Time of the maximum of the signal
TPC	Time Projection Chamber
VME	Versa Module Eurocard
VPR	Vacuum Pair Production
VRB	VME Readout Board
XCET	Cherenkov detector
XFEL	European X-ray Free Electron Laser

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A chess game can be carried out either by amateurs or by professionals, but is not just a fistfight between two brains. It can be soft and brutal, it can entertain the laziest beginner and the smartest living brain, yet it portrays an inner reflection of the involved players and why not, their most remote feelings. Indeed, the combination of an aim, a strategy and a worthy opponent is able to materialize all human emotions through this triumph of logic in black and white colours.

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