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ELECTROMAGNETIC SHOWER DEVELOPMENT IN ORIENTED CRYSTALS

AUTHOR:
Alessia Selmi

SUPERVISORS:
Prof.ssa Michela Prest
Università degli Studi dell'Insubria
Dott. Mattia Soldani
Università degli Studi di Ferrara



*A Michela
e Mattia*

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INTRODUCTION

Crystals are fascinating materials for particle physicists: their behaviour in fact changes as a function of the angle between the particles and the crystal itself. Thus crystals may be "seen" by particles as an amorphous material or a plane or string of atoms, which results in different effects that have been discovered over the years (from the channeling of high energy charged particles to the emission of radiation) and in different possible applications, such as the deflection of high energy beams in bent crystals or the emission of high intensity high energy photons.

The concept of channeling was introduced in 1912 by J. Stark in a paper on the interaction of accelerated protons. He took into account the existence of channels in crystalline solids, and arrived at the conclusion that ions striking such targets from certain directions had a better chance of penetrating deep into the target than they would in amorphous solids. Stark's prediction coincided almost exactly with the discovery of X-ray diffraction. The link between these two approaches was recognized almost immediately by W. H. Bragg, but the experimental techniques of the period were inadequate to demonstrate the feasibility of channeling experiments and these first ideas on the channeling of charged particles in crystals were set aside. It was only in the early 1960s that the channeling effect was re-discovered by computer simulation and experiments. The first comprehensive theoretical treatment of channeling in fact was given in 1965 by Lindhard, who introduced the continuum approximation for the description of the crystalline potentials.

In 1976 Kumakhov demonstrated that the crystalline lattice strongly modifies the features of the electromagnetic processes inside the crystal; both the photon emission from charged particles and of pair production by photons in oriented crystals differ essentially from those of the corresponding processes in amorphous media. In particular, the periodicity of the particles motion, when in channeling, leads to the coherent emission of photons.

The features of the channeling radiation depend strongly on the particle energy: they vary from an undulator-like process with the emission of relatively soft photons at low energies (~ 100 MeV) to a description based on the dipole approximation for the intermediate energies and finally to the synchrotron regime when relativistic effects have to be taken into account, at the GeV range.

At high energies (about tens of GeV) a different phenomenon appears: the average electric field felt by a particle in its rest frame is enhanced by a factor γ because of the Lorentz contraction and the so-called strong field regime is reached, which is characterized by a huge enhancement of radiation emission and pair production. This results in the acceleration of the electromagnetic shower development inside the crystal and therefore in a strong reduction of the radiation length X_0 in comparison with amorphous media.

This thesis work has been performed in the framework of the STORM (STrOng cRys-talline electroMagnetic field) collaboration, with the goal to study the acceleration of the electromagnetic shower inside two PbWO_4 oriented crystals of 1 and 2 X_0 in the strong field regime and the consequent reduction of the radiation length, measuring directly, for the first time ever, the light produced by the energy deposited inside the crystals.

In the first chapter of this thesis, a theoretical description of the behaviour of high energy particles in oriented crystals is given. After an introduction on the crystalline structure, the potential in a crystal and the channeling phenomenon are described following the work of Lindhard. A brief description of the phenomenon of bremsstrahlung in an amorphous medium and of coherent bremsstrahlung in an aligned crystal is presented, along with a description of the features of the channeling radiation. The second part of the chapter focuses on the heart of this thesis work, that is the strong field regime, and on its differences with respect to the channeling radiation. The physical phenomena that lead to a large enhancement of radiation emission and pair production in the strong crystalline field are described in detail.

The second chapter is dedicated to an overview of the experimental techniques required to study in particular the effects of the strong crystalline field, focusing on the parameters that need to be investigated/optimized and on the experimental setups. In the second part of the chapter, the preliminary results, obtained by the AXIAL (Axial and quasi-axial coherent interaction between charged particle beams and crystals) and ELIOT (Electromagnetic processes In Oriented crystals) collaborations, and the goals of STORM are presented, while the last part summarizes some possible applications of oriented crystals.

The description of the crystalline samples tested in the STORM experiment, along with the Silicon PhotoMultiplier (SiPM) matrices used to detect the scintillation light, is given in the first part of chapter 3. The second part is dedicated to the characterization of the STORM matrices performed at the INSULAB laboratory (Insubria University, Como, Italy) using cosmic rays. The goal of the characterization was the measurement of the performance of the detector in terms of signal to noise ratio and efficiency with Minimum Ionizing Particles, thus with a signal much smaller than the one expected on the beam.

Chapter 4 presents the experimental setup and the preliminary tests performed on the H2 line at the CERN SPS North Area during the STORM beamtest in August 2021: each component of the experimental layout and the data acquisition system are described in detail. The second part of the chapter is dedicated to the alignment procedure of the tracking systems, the analysis of the features of the beam (such as the beam divergence) and the calibration procedure of the electromagnetic calorimeter.

The final chapter is dedicated to the analysis procedure and to the results of the 2021 beamtest. The chapter describes in detail the procedure to align the beam with respect to the crystal axis and the analysis of the energy deposit in the crystal (as measured by the SiPM matrices) as a function of the angle. This information is used to compute the reduction in the radiation length and the acceleration of the electromagnetic shower.

PARTICLES INTERACTION WITH ORIENTED CRYSTALS

When an energetic beam of charged particles hits a solid target, a lot of physical phenomena can occur whose cross-section depends on the impact parameter of the collision with individual target atoms (e.g. energy-loss processes, secondary electron emission, X-ray production). If the target material is homogeneous and isotropic (e.g. a misaligned crystal), these parameters are practically independent on the particle direction and the probability distribution of the energy loss depends only on the density of the amorphous medium. The particle motion can be therefore described like a number of uncorrelated collisions with the single atoms.

On the other hand, if the medium is a solid with a highly organized structure (e.g. crystalline medium), the impact parameters are found to be very strongly dependent on the relative orientation of the beam and the target and on the particle energy. In this case, the individual scattering effects are substituted by collective ones, in which the particles are guided by long strings or by planes of atoms, thus being channeled.

In 1965 Lindhard [1] demonstrated that if a charged particle crosses the crystalline medium with a small angle with respect to a crystallographic direction (or plane), because of the ordered structure of the target, it will undergo a correlated series of small-angle collisions (coherent interactions) with the neighboring atoms in the same row (plane). Moreover, if the particle trajectory is aligned with respect to the crystal planes/axes, the particle may be trapped inside the planar/axial potential well, in the so called planar/axial channeling condition. Furthermore, the probability of photon emission from charged particles and the probability of pair production by photons in oriented crystals differ essentially from those of the corresponding processes in amorphous media: particles crossing an amorphous solid produce bremsstrahlung radiation, as they decelerate, while channeled particles and particles crossing multiple channels periodically (i.e over barrier) emit intense beams of photons at specific energies (e.g. coherent bremsstrahlung, channeling radiation). For light particles such as electrons, the coherent effects increase the probability of generation of a photon.

Lindhard described his theory in the framework of classical mechanics. This is true for the motion of MeV-GeV channeled particles due to the larger number of available quantum states [2]. At high energy (above few tens of GeV), the average electric field felt by a particle in its rest frame is enhanced by a factor γ because of the Lorentz contraction and the strong field regime is attained. The interaction of a charged particle with the crystal-

line strong field regime is characterized by the emission of quantum synchrotron radiation with a strong and peaked enhancement in the hard part of the photon spectrum; similarly, the interaction of a photon with this field results in the enhancement of pair production. One of the main consequences of these effects is the acceleration of the electromagnetic shower development, which results in a strong reduction of the radiation length X_0 ¹ in comparison with the one of amorphous materials.

In the first part of this chapter, the potentials in a crystal and the channeling phenomenon are described following the work of Lindhard [1], Andersen et al. [2] and Biryukov et al. [3]. In the second part, a theoretical background of the strong field regime is given along with the study of the enhancement of the electromagnetic radiation resulting from the interaction of particles with the strong crystalline electromagnetic field in an axially oriented crystal.

1.1 CRYSTALS STRUCTURE

A crystal is a solid with a highly organized structure, characterized by a three-dimensional, periodic array of atoms. The spatial location of the atomic nuclei in the array defines the crystal lattice shape and its features. Depending on the orientation, the atoms can appear to an external observer in an unordered structure (misaligned crystal or randomly oriented) or arranged in parallel planes or strings, as shown in figure 1.1.

The crystal planes and axes are identified by the Miller indices (h, k, l) [4], that can be derived from the equation of the plane:

$$\frac{x}{x_0} + \frac{y}{y_0} + \frac{z}{z_0} = 1 \quad (1.1)$$

where x, y, z are the coordinates of an arbitrary point on the plane, and x_0, y_0, z_0 are the coordinates of the intersections between the plane and the axes.

The structure underlying any crystal is the Bravais lattice [5] which is an infinite array of discrete points generated by a set of discrete translations in the three-dimensional space by:

$$\mathbf{r} = n_1\mathbf{a} + n_2\mathbf{b} + n_3\mathbf{c} \quad (1.2)$$

where n_i is an integer and $(\mathbf{a}, \mathbf{b}, \mathbf{c})$ are primitive translation vectors which lie in different directions (not necessarily perpendicular to one another) and span the lattice. There are several Bravais lattice structures. The choice of primitive vectors for a given Bravais lattice is not unique. A fundamental aspect of any Bravais lattice is that the lattice will appear exactly the same from each of the discrete lattice points when looking in a specific direction. Since a crystal plane contains an infinite number of lattice nodes, whose coordinates are given by equation 1.2, one may rewrite equation 1.1 replacing x, y and z with the coordin-

¹ The radiation length X_0 is the mean distance over which a high energy electron loses all but $1/e$ of its energy via bremsstrahlung.

ates n_i of the lattice nodes; considering a common factor m the following expression for (h, k, l) can be obtained:

$$h = \frac{m}{x_0} \quad y = \frac{m}{k}, \quad z = \frac{m}{l} \quad (1.3)$$

Each plane and axis in a crystal is described by these indices: for axes, they specify the direction indicated by the vector (h, k, l) (the indices are within square brackets $[h, k, l]$), while for planes they indicate the surface orthogonal to the corresponding axis (in this case the indices are enclosed in round brackets (h, k, l)). Figure 1.2 shows the planes parallel to the coordinate axes of a simple cubic lattice.

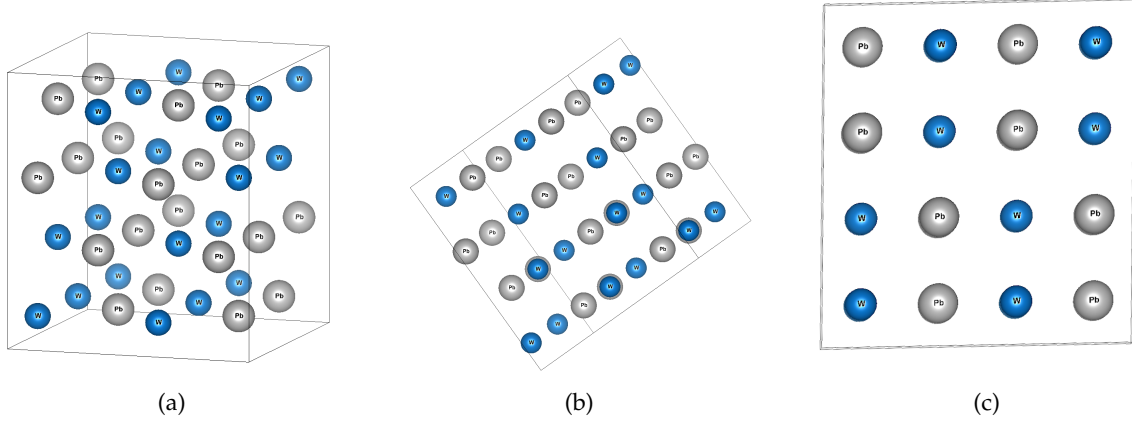


Figure 1.1: The PbWO_4 crystal lattice (used in this thesis), as seen by an external observer: (a) as an unordered structure, (b) arranged in planes, (c) arranged in strings. The oxygen atoms are negligible in the interactions under study, and therefore are neither shown nor considered [6].

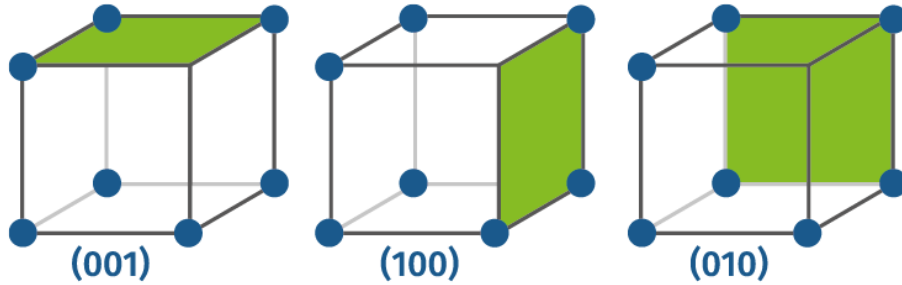


Figure 1.2: Miller indices of parallel crystalline planes in a simple cubic face lattice.

1.2 THE CONTINUUM STRING APPROXIMATION

A major contribution to the description of crystalline potentials was given by Lindhard who, in 1965, laid the theoretical foundations for a statistical treatment of channeling [1], developing the so called axial and planar continuum model, based on the continuous potentials obtained by averaging the lattice potential over atomic strings or planes. The continuum approximation in the axial case is the subject of this thesis and will be treated

in detail.

When a particle crosses a crystal almost aligned with its axes (i.e. the misalignment angle between the particle trajectory and the direction of the atoms is small), the transverse momentum component ($p_{\perp} = \sqrt{p_x^2 + p_y^2}$) is much smaller than the longitudinal one p_z , being z the direction of the axis: since $\theta = \frac{p_{\perp}}{p_z}$, then $\frac{p_{\perp}}{p_z} \ll 1$). Thus, the particle travels a long distance and interacts with many lattice atoms in the longitudinal direction, while remaining close to the array of atoms in the transverse direction. When the particle passes close to one atom in the row, it must also pass by the neighboring atoms in the same row. In other words, each atomic array appears to the particle as a periodic succession of atoms. Therefore, each atomic row can be described by means of a continuous electrostatic potential that is obtained by smearing the atomic charges uniformly along the z direction of the string itself. Similar considerations hold for the planar case.

1.3 PLANAR POTENTIAL AND CHANNELING

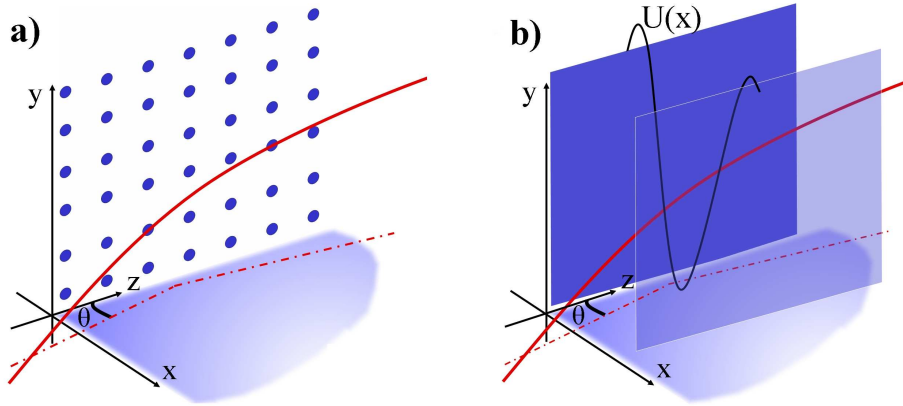


Figure 1.3: a) A charged particle impinges on a crystal with a small angle with respect to a crystallographic plane. b) The particle experiences an average potential $U(x)$, due to the planes, represented by the black line.

The continuous potential for the planar case is represented in figure 1.3:

$$U_{pl}(x) = Nd_p \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} V(x, y, z) dy dz \quad (1.4)$$

where x is the coordinate perpendicular to the planes, N is the volume density of atoms and d_p is the interplanar spacing. Note that indeed $V(x, y, z)$ depends on the three spatial coordinates while $U(x)$ only on x , as expected. An explicit form of this potential can be obtained using the Thomas-Fermi-like potential $V(r)$ with the Lindhard approximation² [1]:

$$V(r) = \frac{Z_i Z e^2}{r} \left[1 - \left(1 + \frac{3a_{TF}^2}{r^2} \right)^{-\frac{1}{2}} \right] \quad (1.5)$$

² Other approximations for the atomic potential can be used, such as the Molière [7] or the Doyle-Turner [8] potential.

r being the distance between the particle and the atom, a_{TF} the screening length of the particle-atom interaction ($a_{TF} \simeq 0.468 \text{\AA} Z_i^{\frac{1}{3}}$), Ze the particle charge and Z_i the atomic number of the crystalline medium. The first term represents the potential of a point-like charge, while the second takes into account the charge distribution of the atom. Equation 1.4 thus becomes:

$$U_{pl}(x) = 2\pi N d_p Z_i Z e^2 \left(\sqrt{x^2 + 3a_{TF}^2} - x \right) \quad (1.6)$$

This expression gives the potential due to a single plane; in the small angle approximation the particle moves in a potential that is the sum of the potentials of neighboring single planes, where the contribution of the two nearest atom planes dominates:

$$U(x) \approx U_{pl} \left(\frac{d_p}{2} - x \right) + U_{pl} \left(\frac{d_p}{2} + x \right) - 2U_{pl} \left(\frac{d_p}{2} \right) \quad (1.7)$$

The origin of the coordinate x is chosen in the middle of the channel between two neighboring atomic planes and the third term considers the potential at the origin ($U(0) = 0$). This potential describes an ideal lattice at a temperature of 0 K; thermally-induced smearing can be taken into account averaging over the distribution of atomic displacements, which can be modelled with a Gaussian distribution. Important differences in the planar channeling dynamics have to be pointed out between positively and negatively charged particles:

- a positive particle sees the crystal as a series of potential wells, $U(x)$, centered at the midpoint between the two planes, while for negatively charged particles the minima of the potential are located at the center of the atomic planes;
- as a consequence, the channeling states for positive particles are much more stable than for negative ones, due to the enhanced probability for the latter of hard collisions with the atomic cores;
- for positively charged particles one can use the harmonic approximation $U \sim x^2$; on the other hand this approximation does not hold for the planar potential for negative particles which is more similar to an "inverted parabola" [9], its minima lying at the bottom of the very narrow wells determined by the edges.

Figure 1.4 shows the planar potential experienced by positive (a) and negative (b) particles channeled in the field of $\langle 110 \rangle$ silicon planes. The vertical lines inside the highlighted regions (regions of large nuclear density) show the position of the atomic planes.

In order for channeling to take place, a particle must impinge on the crystal almost parallel to the atomic planes. If the small angle hypothesis is valid, the transverse momentum component (p_x) is much smaller than the longitudinal one (p_z), and the total energy

$$E = \sqrt{p_x^2 c^2 + p_z^2 c^2 + m^2 c^4} + U(x) \quad (1.8)$$

can be rewritten in the form:

$$E = \frac{p_x^2 c^2}{2E_z} + E_z + U(x) \quad (1.9)$$

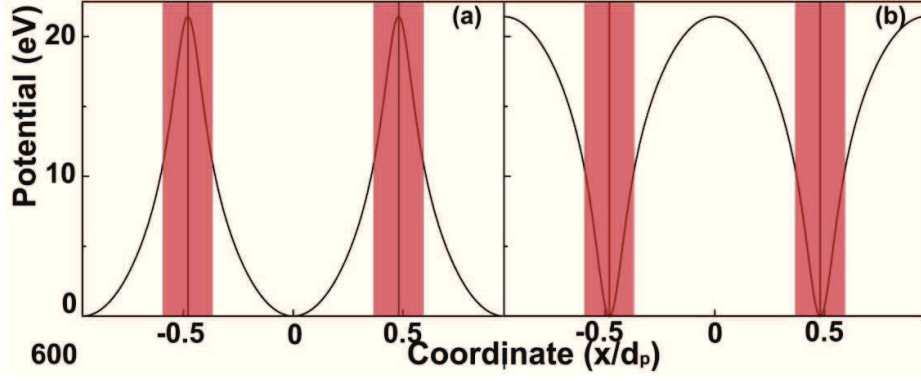


Figure 1.4: Planar potential experienced by positive (a) and negative (b) particles channeled in the field of $\langle 110 \rangle$ silicon planes [10].

being $E_z = \sqrt{p_z^2 c^2 + m^2 c^4}$. The longitudinal component of the momentum, p_z , is not affected by the potential, and hence is conserved, meaning that E_z is conserved too and so is the transverse energy $E_T = \frac{p_x^2 c^2}{2E_z} + U(x)$ due to the conservation of the total energy. The transverse energy can be expressed in terms of the misalignment angle $\theta = \frac{p_x}{p_z}$ between the particle trajectory and the crystal planes:

$$E_T = \frac{p_x^2 c^2}{2E_z} + U(x) = \frac{p_z^2 c^2}{2E_z} \theta^2 + U(x) = \text{const} \quad (1.10)$$

Assuming $E_z \approx E$, $p_z \approx p$ (since $\frac{p_x}{p_z} \ll 1$) and using $pc^2 = vE$, where v is the particle velocity, equation 1.10 can eventually be rewritten as:

$$E_T = \frac{pv}{2} \theta^2 + U(x) = \text{const} \quad (1.11)$$

The particle remains trapped within the channel if its transverse energy is smaller than the potential-well depth $U_0 = U(d_p/2)$. The condition for the capture of the particle into the channeling mode is then:

$$\frac{pv}{2} \theta^2 + U(x) < U_0 \quad (1.12)$$

The case of a particle entering the channel at exactly $x = 0$ ($U(0) = 0$) allows one to obtain, from equation 1.12, an estimate for the angular acceptance limit, the so called Lindhard angle [1]:

$$\theta_L = \sqrt{\frac{2U_0}{pv}} \quad (1.13)$$

It has to be noted that although the maximum of the potential is reached at the position of the plane itself ($x = \frac{d_p}{2}$), here the particle is not in a stable channeling condition because it could be removed from the channel by the scattering with the nuclei; therefore there exists a minimum distance from a plane that ensures the channeling condition is reached. This distance is a_{TF} ; thus, the maximum reachable transverse position is $x_c \approx d_p/2 - a_{TF}$ and

the corresponding potential value is $U(x_c) = U_{max}$. Therefore, the actual critical channeling angle is:

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}} \quad (1.14)$$

Figure 1.5 shows a particle trapped in the channeling condition with a transverse energy smaller than $U(x_c)$. For tungsten crystals, $U(x_c) \approx 60$ eV, thus θ_c is 490 μ rad at 500 MeV,

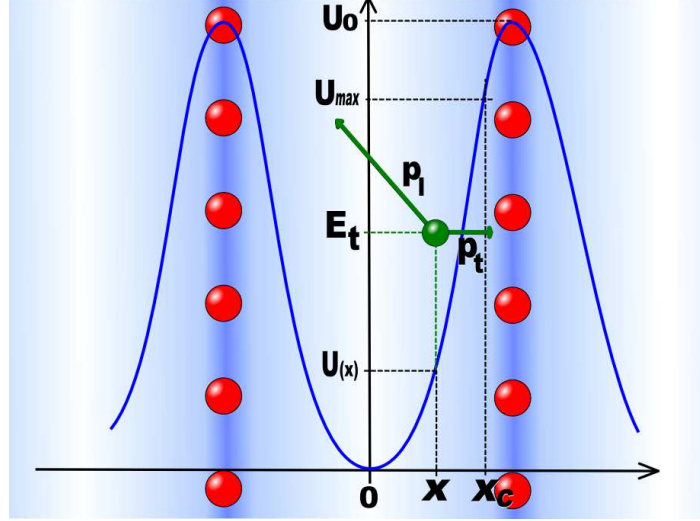


Figure 1.5: Schematic representation of the interplanar potential.

31 μ rad at 120 GeV and 4.1 μ rad at 7 TeV.

1.4 AXIAL POTENTIAL AND CHANNELING

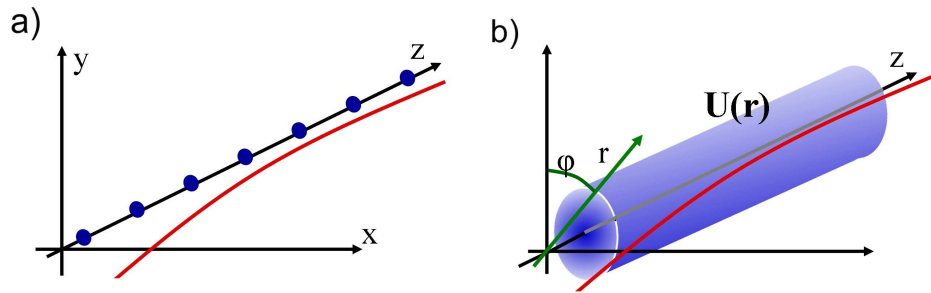


Figure 1.6: Schematic representation of the continuum axial potential.

The treatment of axial channeling will focus only on relativistic electrons, which are the main subject of this thesis. For a full description, see [1] [3] [9].

Analogously to the planar case, the potential of a string of atoms can be expressed in the continuum approximation. In this case, the potential corresponds to a charge distribution smeared in the z direction, which is radial with respect to the axes (as shown in figure 1.6):

$$U(r) = \frac{1}{d} \int_{-\infty}^{+\infty} V(\mathbf{r}, z) dz \quad (1.15)$$

where r is the radial distance between the row and the particle. An example of equipotential surfaces for the diamond crystal at room temperature in the plane orthogonal to the $\langle 100 \rangle$ axis is shown in figure 1.7.

The transverse energy E_T is given by:

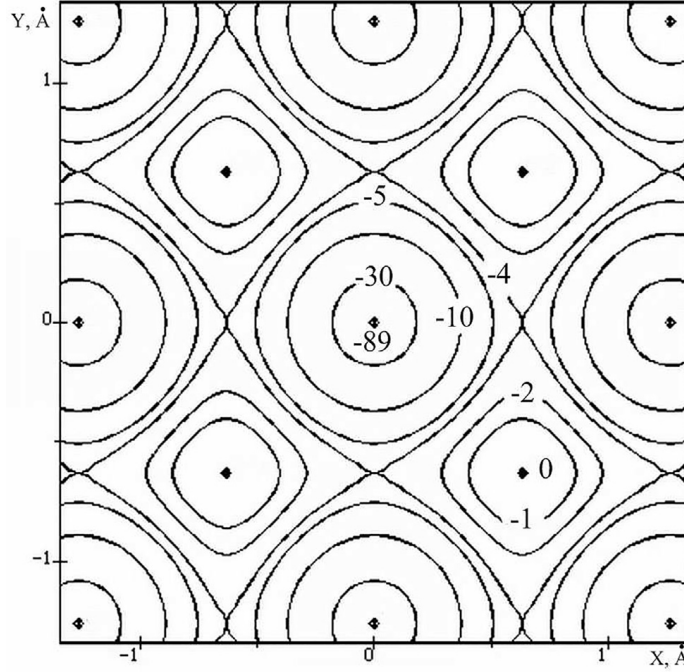


Figure 1.7: Equipotential surfaces for the diamond crystal at room temperature in the plane orthogonal to the $\langle 100 \rangle$ axis; the numbers at lines correspond to the values of the potential energy in eV [11].

$$E_T = U(r) + E\psi^2 \quad (1.16)$$

where $E = \frac{1}{2}pv$ is the relativistic energy and ψ is the angle between the particle trajectory and the string.

The angle ψ can be expressed in polar coordinates [12]:

$$\psi^2 = \psi_\phi^2 + \psi_r^2 = r^2 \left(\frac{d\phi}{dz} \right)^2 + \left(\frac{dr}{dz} \right)^2 \quad (1.17)$$

Therefore, the transverse energy becomes:

$$E_T = U(r) + \frac{1}{2}pv(\psi_\phi^2) + \frac{1}{2}pv(\psi_r^2) \quad (1.18)$$

and, since the angular momentum is $L = pr\psi_\phi$ and $p = m\gamma v$

$$E_T = U(r) + \frac{1}{2}pv\psi_r^2 + \frac{1}{2} \frac{L^2}{m\gamma r^2} \quad (1.19)$$

The motion of a relativistic negative particle that moves with a small angle with respect

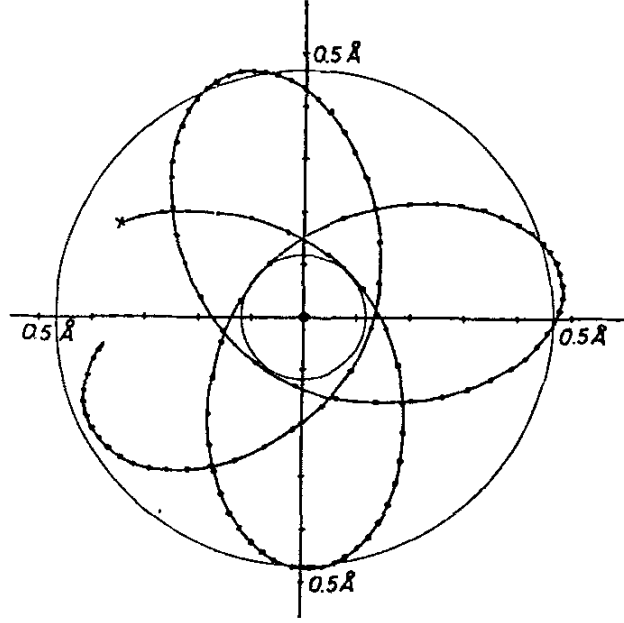


Figure 1.8: Example of Rosette motion for a negative particle with a medium angular momentum in a cubic lattice atom, obtained by computer simulation [13].

to the crystal atomic string is therefore governed by the effective scattering potential:

$$W(r, L) = U(r) + \frac{1}{2} \frac{L^2}{m\gamma r^2} \quad (1.20)$$

For negative particles, $U(r)$ is always negative³, and therefore attractive, while the rotational term is repulsive: E_T can, thus, assume both positive and negative values according to the angular momentum L and the distance r of the particle from the string. Three situations have to be considered:

- at small L the centrifugal term $L^2/2m\gamma r^2$ becomes positive only for r less than a critical distance r_c for which the particle is severely scattered;
- at medium L the centrifugal term becomes positive for a distance $r > r_c$; if $E_T < 0$ the negative particle is captured in a bound state: it spirals around the row and the projection of this trajectory in the transverse plane is a Rosette curve (figure 1.8). During its spiralizing along the string the particle does not approach the atoms closer than r_c and therefore it does not suffer much scattering. The condition $E_T \approx 0$ provides for $r = r_c$ an upper limit of the incidence angle for a bound state; from equation 1.16:

$$\psi_L = \sqrt{\frac{2U(r_c)}{pv}} \quad (1.21)$$

This is also the condition for the critical channeling angle for positive particles.

³ In the continuum approximation one can use the string potential $U(r)$ based on the Thomas-Fermi potential [1].

- At large L the effective potential is repulsive, and the particle cannot be captured by the row of lattice atoms, but it swings from one string to another.

For a tungsten crystal, the potential well depth of the $\langle 100 \rangle$ axial channel is ≈ 840 eV. At 120 GeV the critical angle is thus ~ 110 μrad ; compared to the value of the critical angle θ_L in equation 1.13 for the planar case, ψ_L is a factor ~ 2 -3 larger, favoring the axial channeling with respect to the planar one.

1.5 CHANNELING RADIATION

It has already been pointed out that the crystalline lattice strongly modifies the features of the electromagnetic processes: both the photon emission from charged particles and of pair production by photons in oriented crystals differ essentially from those of the corresponding processes in amorphous media. In particular, if the incidence angle of the particle, θ_0 , with respect to a plane (axis) is larger than the critical angle θ_c , but small enough for the continuum approximation to be valid, the dynamics can be described as a first order perturbation of the particle motion with respect to a straight trajectory, and the phenomenon of coherent bremsstrahlung takes place, i.e. a series of coherent interactions that lead to an enhancement in the radiation spectrum.

On the other hand, if $\theta_0 < \theta_c$ the electron may be captured into a bound state in this transverse potential and the particle is then channeled. In this case, the straight trajectory approximation is no longer valid, since the particle is forced to follow an oscillatory motion with the result of an enhancement in the radiation spectrum.

In this section, a brief description of the phenomenon of bremsstrahlung in an amorphous medium and of coherent bremsstrahlung in an aligned crystal is presented along with a description of the channeling radiation. Section 1.6 is dedicated to the radiation emitted in a strong field regime.

1.5.1 RADIATION EMISSION OF ULTRARELATIVISTIC PARTICLES

In order to understand the features of the radiation emitted by a channeled particle, a few basic concepts have to be introduced, among which the formation length l_f . When an energetic particle interacts with the target atoms, it loses energy mainly via the emission of electromagnetic radiation (bremsstrahlung) due to the scattering in the electric field of the nucleus. It was Ter-Mikaelian [14] [15] who first discovered that it takes a relatively long time, and therefore a long distance, for an energetic particle to create a photon. The interactions the particles undergo along this length affect the radiation spectrum heavily and may lead to an enhancement or reduction of the total emitted intensity; while charged particles propagate within it, in fact, the emitted waves can add up coherently until some perturbation to the particle motion occurs. For ultrarelativistic energies:

$$l_f = \frac{2c\gamma^2}{\omega} \quad (1.22)$$

where ω is the frequency of the emitted photon. Therefore, l_f sharply increases because of the electron γ Lorentz-factor and of the emitted photon energy decrease.

On the other hand, considering the generation of an electron-positron pair, the formation length corresponds to the distance required for the final state particles to separate transversely by two Compton wavelengths⁴.

The presence of an external electromagnetic field across l_f can also modify the bremsstrahlung process. For an ultrarelativistic particle the influence of the longitudinal component of the external force, with respect to the particle motion direction, is negligibly small compared to the role of the transverse component. Thus, the radiation emission is totally determined by the transverse force only. The angular distribution of the radiation emitted by ultrarelativistic particles is a narrow cone, $\theta_\gamma \sim 1/\gamma$, with the axis along the initial momentum of the particle [9]. A schematic representation of synchrotron radiation emission by an energetic electron crossing a magnetic field B is shown in figure 1.9.

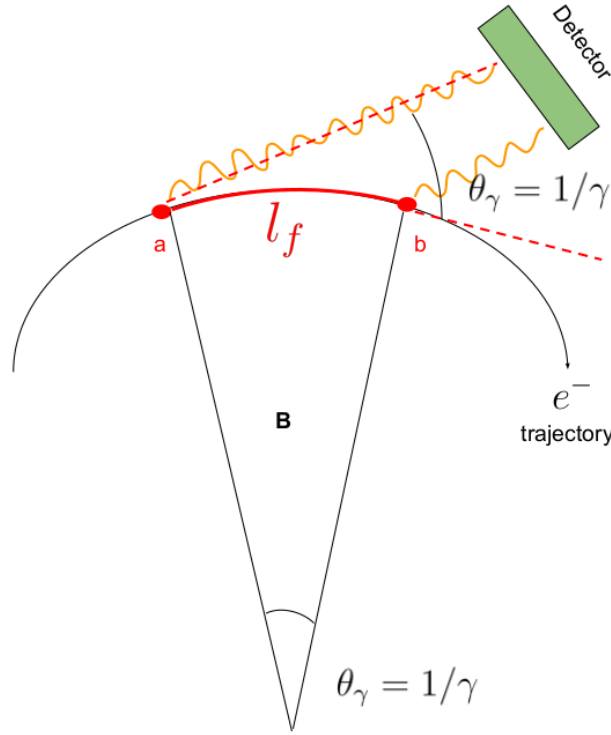


Figure 1.9: Synchrotron radiation emission by an energetic electron propagating across a magnetic field B . The distance ab corresponds to the formation length l_f ; the typical emission angle $\theta_\gamma = 1/\gamma$ makes photon emission from any point within the arc from a to b indistinguishable by any detector.

In order to discuss the radiation spectrum of ultrarelativistic particles, the relation between the total angle of the particle deflection $\Delta\theta$ and the angle $1/\gamma$ becomes essential. The problem can be divided into two characteristic cases:

⁴ The Compton wavelength is equal to the wavelength of a photon whose energy is the same as the mass of the particle and is given by $\lambda_c = h/mc$ where h is the Planck constant and m is the particle rest mass.

- $\Delta\theta \gg 1/\gamma$: the deflection angle is much larger than the opening angle. In this case the particle changes direction rapidly; a series of destructive interferences takes place resulting in the emission of low intensity radiation;
- $\Delta\theta \leq 1/\gamma$: the deflection angle is less than or equal to the opening angle. The particle basically stays on its trajectory; the radiation is produced over many wavelengths, and so the amplitudes of several interactions can add coherently, resulting in a coherent sum of intensities.

1.5.2 BREMSSTRAHLUNG IN AN AMORPHOUS MEDIUM

When charged particles impinge on an amorphous medium (or a misaligned crystal) they lose energy either in collisions with the atoms, in which the stopping power ($\frac{dE}{dx}$, x being the penetration depth) is described by the Bethe-Bloch formula [16], or via the emission of electromagnetic radiation (bremsstrahlung) with a continuous spectrum, due to the scattering in the electric field of a nucleus. At energies larger than the critical energy E_c ⁵

$$E_c = \frac{610 \text{ MeV}}{Z + 1.24} \quad (1.23)$$

bremsstrahlung dominates over the ionization loss; in tungsten $E_c = 8 \text{ MeV}$.

The cross-section for radiation emission in an amorphous medium (the so-called incoherent bremsstrahlung) is well described by the Bethe-Heitler formula [19]. In incoherent bremsstrahlung a single interaction between the electron and the atomic nuclei occurs; the electron scatters outside the emission angle ($\Delta\theta \gg 1/\gamma$) rapidly and no further interaction happens during the formation length. However, at ultrarelativistic energies the quantum mechanical interference between amplitudes from different scattering centers has to be taken into account. L. Landau and I. Pomeranchuk showed [20] that the Bethe-Heitler formula cannot be used at high energy and the effect of multiple Coulomb scattering by neighboring atoms reduces the cross-sections for pair production and bremsstrahlung. If the bremsstrahlung formation length becomes comparable to the distance over which multiple scattering is important, bremsstrahlung will be suppressed. Migdal developed a quantitative theory of this phenomenon [21]. The suppression of bremsstrahlung at high energy is known as “Landau-Pomeranchuk-Migdal” (LPM) effect. In crystalline media, the situation is more complicated, since coherent enhancement or suppression are possible. The cross-section depends on the electron and photon energies and the angles between the particle direction and the crystalline axis (plane). Two major scenarios are possible:

- during the formation length the particle undergoes a series of periodic interferences, which is the case of coherent bremsstrahlung and channeling radiation;
- the particle is subject to a field that can be considered constant along the whole formation length, which is the case of the strong field regime.

⁵ The critical energy E_c is defined as the energy at which the ionization loss rate and the bremsstrahlung loss rate are equal [17]; an alternative definition is that of Rossi [18], who defines the critical energy as the energy at which the ionization loss multiplied by the radiation length, X_0 , is equal to the electron energy.

1.5.3 COHERENT BREMSSTRAHLUNG

When a charged particle crosses a crystal at an angle θ_0 , with respect to its plane (axis), larger than the critical angle θ_c , but small enough for the continuum approximation to be valid ($\theta_0 \gg \theta_c$), the phenomenon of coherent bremsstrahlung occurs (figure 1.10). At an

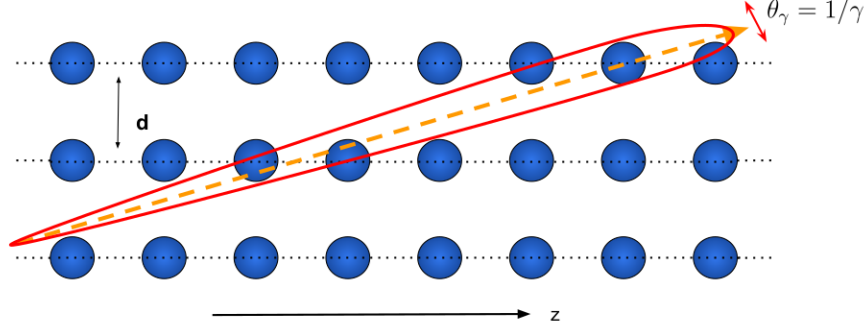


Figure 1.10: A schematic view of the coherent bremsstrahlung by a charged particle in a crystal lattice.

energy high enough, the formation length l_f defined in equation 1.22 may become of the order of the lattice constant d (for GeV emitted photons $l_f \sim \text{nm}$).

As a consequence, the effect of the periodic structure plays an important role for bremsstrahlung radiation: when the electron crosses the crystal planes periodically along the interatomic distance d , it has a fair chance to scatter coherently on many target atoms along its way. The coherence in scattering causes the radiation emission, that adds coherently at every plane crossing. The periodic perturbation of the straight-line path by the planar potential will cause the emission of radiation. The enhancement of the radiation over standard bremsstrahlung is a consequence of the correlation of the deflections by crystal atoms.

The coherent bremsstrahlung radiation exhibits a spectrum quite different from that of the ordinary bremsstrahlung generated in an amorphous target, as shown in figure 1.11. The radiation frequencies and the maxima in the spectrum depend essentially on the angle between the particle trajectory and the atomic string. A complete treatment of the phenomenon of coherent bremsstrahlung can be found in [22] [23].

1.5.4 FEATURES OF CHANNELING RADIATION

In the previous sections, the periodic motion of a charged particle channeled in a potential well around an axis or between two planes has been described. The periodicity of this motion leads to the coherent emission of photons, i.e. channeling radiation. In this case, the formation length l_f is longer than the particles oscillation period inside a single channel. This phenomenon was first predicted by Kumakhov in [25].

The features of the channeling radiation depend strongly on the particle energy:

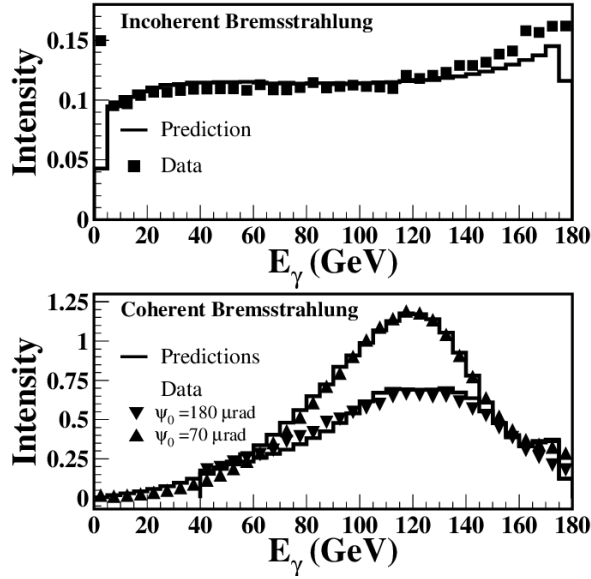


Figure 1.11: Total energy radiated for incoherent (top) and coherent (bottom) bremsstrahlung in 1.5 cm thick silicon crystals. The solid curves represent the Monte Carlo simulation results [24].

- at low energy (10-100 MeV) the classic description is not adequate because of the limited number of quantum states. The channeling radiation process is undulator-like with the emission of relatively soft photons;
- at intermediate energy (100 MeV - 1 GeV) the number of states is so large that a classical calculation of the motion is a good approximation. The emitted radiation is well described by the dipole approximation in classic electrodynamics [26];
- at higher energy ($\simeq$ GeV) the transverse relativistic effects must be taken into account; the radiation process switches from the dipole to the synchrotron regime, in which both the radiation intensity and the emitted photon energy increase [27];
- at very high energy ($\simeq$ 100 GeV), which is the case of major interest for this thesis, the average electric field felt by a particle in its rest frame is enhanced by a factor γ because of the Lorentz contraction and the so-called strong field regime is reached, which is characterized by the emission of quantum synchrotron radiation with intense hard photon emission from electrons/positrons as well as pair production by high energy photons. The strong field regime differs from channeling because it is an over barrier process.

A more detailed description of the features of the channeling radiation at low energy can be found in [28].

At intermediate energy, the deviation angle of the particle channeled by the field of the atomic strings (or planes) is small compared with the effective radiation angle, therefore almost all the radiated energy is contained in the angular interval $\Delta\theta \sim 1/\lambda$. The radiation spectrum in this case is determined by the whole particle trajectory, and corresponds to the dipole approximation of the radiation emitted by charged particles. In the case of

planar channeling, the radiation is enhanced with respect to the case of an amorphous medium because of the large number of atoms located within a formation length. The enhancement of the radiation is due to the coherent mechanism of radiation production by relativistic particles interacting with the atoms of a crystallographic plane. Figure 1.12 shows the radiation emitted by 10 GeV/c positron and electron beams which impinge on a $\langle 110 \rangle$ 0.1 mm thick silicon crystal. In the positron case, sharp peaks appear due to the interference of the waves radiated by the particle in periodically repeated portions of the path. In the electron case, instead, the spectrum shows an increase with respect to the bremsstrahlung one (as for the positron case), but no peaks are present.

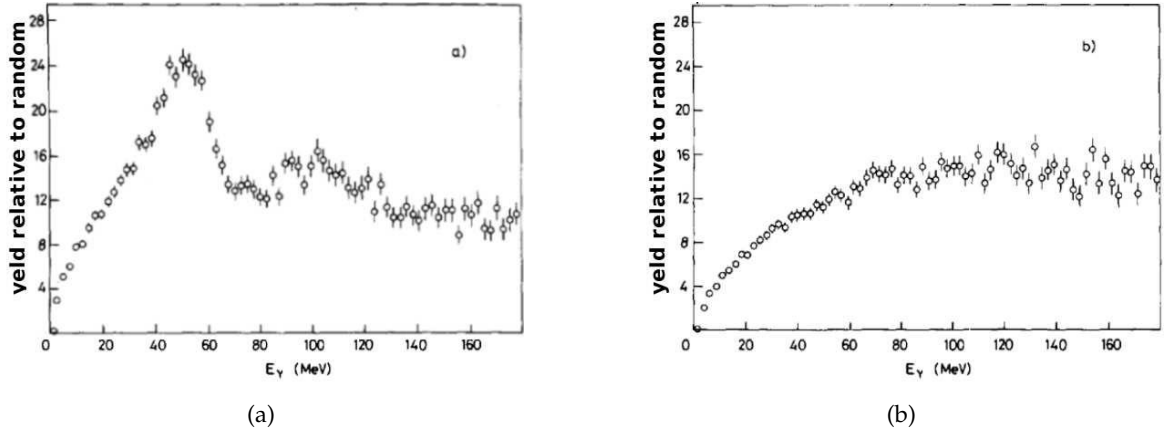


Figure 1.12: Radiation emitted by 10 GeV/c a) positron and b) electron beams which impinge on a $\langle 110 \rangle$ 0.1 mm thick silicon crystal [29].

To calculate the emitted radiation frequency ω inside the angle θ_γ one should take into account the Doppler effect. The oscillatory frequency in the rest frame of the particle is given by:

$$\omega_{RF} = \sqrt{\frac{2U_0\gamma}{m}} = \Omega_0\gamma^{1/2} \quad (1.24)$$

where Ω_0 is the oscillation frequency in the non-relativistic case. The factor γ is due to the Lorentz transformation of the potential $U(x)$ in the laboratory frame into the potential in the frame which moves with the positron along the channel axis. As a consequence of the Doppler effect, one obtains:

$$\omega(\theta) = \frac{\bar{\omega}}{1 - \beta \cos \theta} \quad (1.25)$$

where $\bar{\omega} = \omega_{RF}\gamma^{-1}$ is the oscillation frequency in the laboratory frame, and $\beta = v/c \approx 1$. For $\theta = 0$ the maximum frequency is obtained:

$$\omega_{max} = (1 + \beta)\bar{\omega}\gamma^2 \approx 2\Omega_0\gamma^{3/2} \quad (1.26)$$

Therefore, in the dipole approximation ($v_x/c = \theta_c < 1/\gamma$), the maximum frequency is proportional to $E^{3/2}$. In the case of positron planar channeling, the dipole approximation can be used up to energies of several GeV. The radiation intensity for electrons in planar channeling is larger than for positrons because the potential gradient for the electron channeling is larger than for positron channeling. On the other hand, it has been already men-

tioned that the electron dechanneling is expected to be larger than the positron one, since the electrons are scattered on nuclei while crossing the atomic plane [26].

For particle energies greater than 10 GeV the dipolarity condition is violated, and the radiation characteristics change; in particular, the non-dipole character of the radiation can lead to an increase of the radiation spectral intensity. In this case, taking into account the Doppler effect, the characteristic frequency of the radiation is $\omega \sim \gamma^3$ which is typical of synchrotron radiation [27].

A more detailed description of the features of channeling radiation can be found in [2] [30] [31].

1.6 THE STRONG FIELD REGIME

The term strong field refers to a field value that is close to, or even much greater than, the Quantum ElectroDynamics (QED) critical electric field, also known as the Schwinger critical field:

$$E_0 = \frac{m^2 c^3}{e \hbar} \sim 1.3 \times 10^{18} \frac{\text{V}}{\text{m}} \quad (1.27)$$

Above this value, non-linear field effects occur in vacuum [32]. For a long time, it seemed impossible to study the effects of QED in strong fields in experimental conditions available on earth, since this value is surpassed routinely only in supernovae and other astrophysical phenomena [33]. It was during the Seventies and Eighties that the possibility of observation of the effects of QED in strong crystalline fields was considered [9] [34] [35].

The main features of the crystalline strong field can be described in terms of the following parameter:

$$\chi = \frac{\gamma E}{E_0} \quad (1.28)$$

where E is the average electric field in the laboratory frame. At very high energies, the average electric field experienced by the electron in its rest frame is enhanced by a factor γ because of the Lorentz contraction, and the field can become critical for values of γ achievable with currently available experimental setups. The parameter χ determines the features of the photon emission process: for $\chi < 1$ classical electrodynamics can be used; on the other hand as χ increases, quantum recoil effects become important, and a full quantum description is needed⁶ (already for $\chi \sim 0.1$ quantum effects begin to appear) [37].

An important distinction between the phenomenon of channeling, as it has been described in the previous section, and the coherent effects that appear in the strong field regime has to be pointed out. Channeling is an under-barrier phenomenon: a particle is channeled if the incidence angle is smaller than the critical angle θ_c . When this condition is satisfied, the particle starts to oscillate in a planar/axial well potential and this periodic motion leads to an enhancement in radiation emission with respect to incoherent bremsstrahlung which has dipole-like features. On the other hand, in the strong field re-

⁶ For an electron of 5.6 GeV in PbWO₄ $\chi \sim 0.2$ while for an electron of 120 GeV in PbWO₄ $\chi \sim 4$ [36].

gime the particle is not captured in a potential well and experiences a field that can be considered constant along the strings in the so-called Constant Field Approximation (CFA). Under the effects of this uniform field, the variation of the particle velocity is constant along the whole formation length, which at high energies (equation 1.22) becomes several orders of magnitude larger than the interatomic distance. This nearly constant field acting on the particle during the radiation formation process leads to the emission of quantum synchrotron-like radiation, in which photons may be emitted with a considerable fraction of the electron energy. The trajectory is indeed locally well described as a segment of a circular path and therefore although the crystalline fields are purely electric in the laboratory system, the resulting radiation emission becomes as if the field were magnetic [38]. In figure 1.13 a schematic representation of the different motion types in channeling and strong field regime is shown.

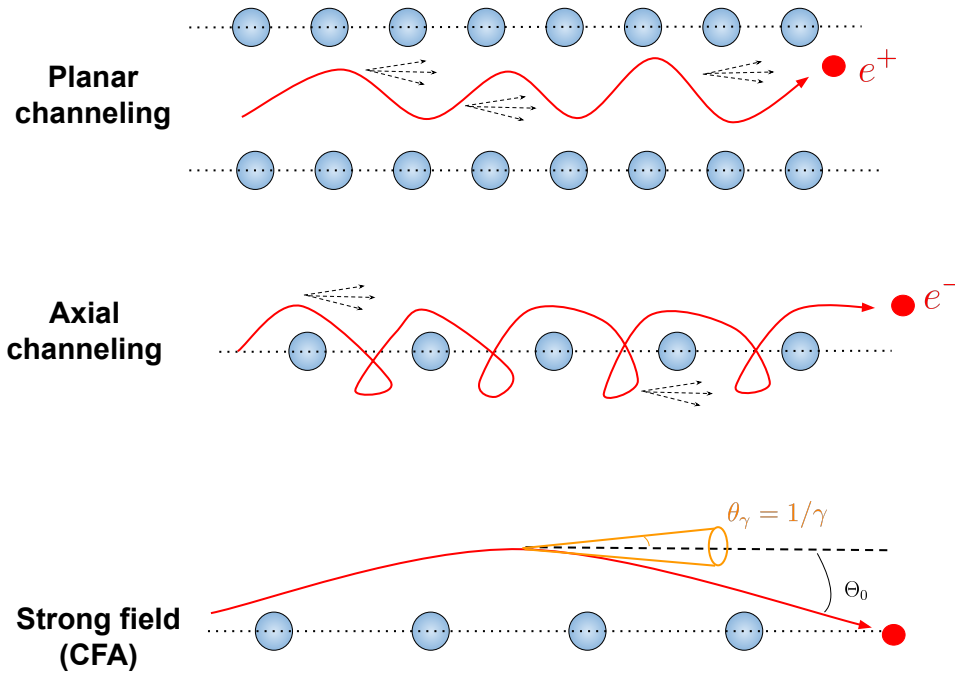


Figure 1.13: A schematic representation of the different types of motion in channeling and strong field regime. (Top) A positron channeled in a planar potential well, and (center) an electron channeled in an axial potential well; in both cases the particle under channeling is forced in an oscillatory motion. (Bottom) An electron/positron in the strong field regime: the trajectory in the constant field approximation is nearly straight and locally well described as a segment of a circular path. The radiation emission appears as in a constant electromagnetic field.

An evaluation of the angular range of such effects has been introduced by Baier et al. [39]:

$$\Theta_0 = \frac{U_0}{mc^2} \quad (1.29)$$

It has to be noted that, differently from the Lindhard critical angle (equation 1.13), Θ_0 does not depend on the particle input energy. Since at very high energy $\theta_c \ll \Theta_0$ (i.e. for $\langle 111 \rangle$ in W, $U_0 \approx 600$ eV, thus at $E \sim 120$ GeV, $\theta_c \approx 100$ μ rad and $\Theta_0 \approx 1.2$ mrad), the strong field regime extends beyond the channeling regime for particles with an energy above a few GeV. An estimate of the radiation critical energy is given by [38] [40]:

$$\hbar\omega_c = \frac{\chi}{1 + \chi} E \quad (1.30)$$

from which it is clear that, as the initial energy increases, harder photons, that is photons with an energy closer to the spectrum end point, are favored [38]. The overall enhancement with respect to random incidence is therefore the result of both the large field in the rest frame of the incident particle and of coherence.

The process of pair production is very closely related to the process of radiation emission; in this case, the field is considered constant over the pair formation length, leading to an enhancement in the pair production cross-section [38] [39].

This huge enhancement of radiation and pair production caused by the strong crystalline field results in the acceleration of the electromagnetic shower development and therefore in a strong reduction of the radiation length X_0 in comparison with amorphous media (Figure 1.14). In case of a scintillating crystal, the larger number of shower particles per unit thickness results in an enhancement in the number of scintillating photons emitted inside the medium. These effects open the way to the development of compact electromagnetic calorimeters/detectors based on oriented scintillating crystals, in which the amount of material can be strongly reduced with respect to the standard design. Since high-Z crystal scintillators are widely exploited in electromagnetic calorimeters for High Energy Physics (HEP), it is rather important to investigate experimentally the strong field influence on the shower development in these materials.

In this thesis work, two PbWO_4 crystalline samples of $1 X_0$ and $2 X_0$ have been tested at CERN SPS in strong field regime; the scintillation light has been collected by a matrix of Silicon PhotoMultipliers (SiPMs) in order to fully characterize the shower development in the crystals themselves.

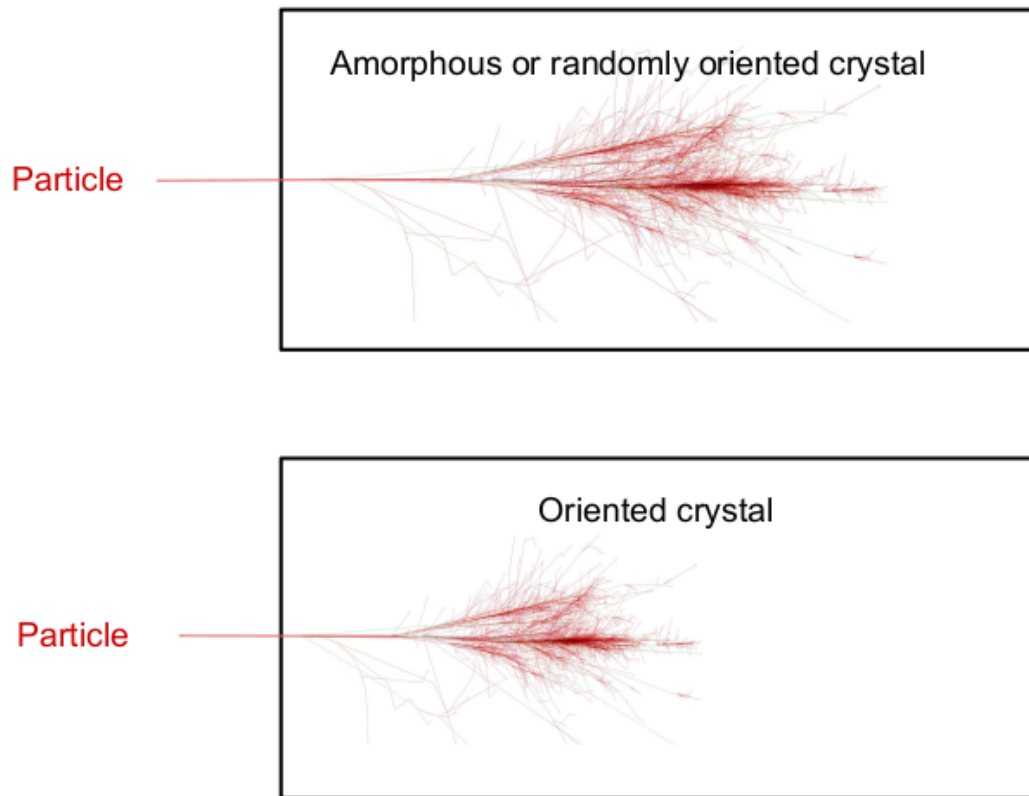


Figure 1.14: A schematic representation of the strong reduction of the radiation length X_0 of the electromagnetic shower in an oriented crystal in comparison with an amorphous medium.

EXPERIMENTAL INVESTIGATION OF THE EM SHOWER DEVELOPMENT IN ORIENTED CRYSTALS

After having introduced from the theoretical point of view the behaviour of high energy particles in oriented crystals, this chapter is dedicated to an overview on the experimental techniques required to study in particular the effects of the strong crystalline field, focusing on the parameters that need to be investigated/optimized and on the experimental setups. The second part of the chapter presents the preliminary results obtained by the AXIAL (Axial and quasi-axial coherent interaction between charged particle beams and crystals) and ELIOT (Electromagnetic processes In Oriented crysTals) collaborations and the goals of STORM (STrOng cRystalline electroMagnetic field), while the last part summarizes some possible applications of oriented crystals.

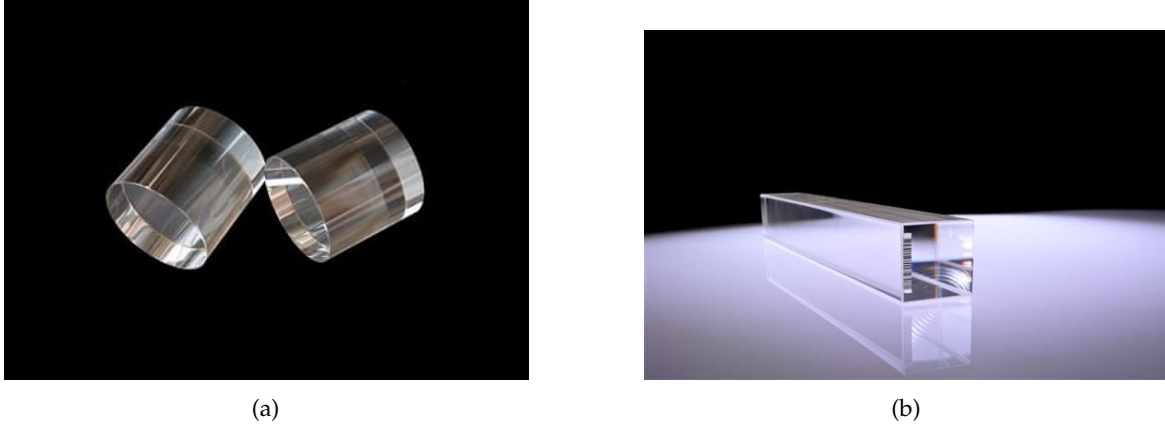
2.1 OVERVIEW ON THE EXPERIMENTAL METHODOLOGIES

In the previous chapter, the effects of the strong crystalline field on a high energy particle crossing an oriented crystal have been described. In particular, the enhancement of the emitted electromagnetic radiation and of the number of electron/positron pairs caused by the strong crystalline field results in the acceleration of the electromagnetic shower development, and therefore in a strong reduction of the radiation length X_0 .

These effects may be exploited for the design of ultra-compact electromagnetic calorimeters for a wide range of applications, such as in accelerator based fixed target experiments at high energy or in the astrophysical field, for instance in satellite-based γ -telescopes. Details on the applications are given in section 2.3.

Inorganic scintillators are widely exploited for homogeneous electromagnetic calorimeters in HEP and astrophysics. Table 2.1 summarizes the main features of the most used scintillators: in particular, BGO and PbWO_4 (figure 2.1) are extensively used because of their high density, the relatively short radiation length and, in the case of PbWO_4 , the high radiation hardness.

Generally, these high-Z scintillator crystals are employed as an amorphous material and the crystalline lattice influence is typically ignored. However, the use of oriented crystal-

Figure 2.1: a) BGO b) PbWO₄ scintillating crystals.

	NaI(Tl)	CsI(Tl)	CsI	BGO	PbWO ₄
Density [g/cm ³]	3.67	4.53	4.53	7.13	8.28
X ₀ [cm]	2.59	1.85	1.85	1.12	0.89
R _M [cm]	4.5	3.8	3.8	2.4	2.2
Decay time [ns]	250	1000	10	300	5
Light yield 10 ⁴ γ/MeV	4	5	4	0.8	0.015
Radiation hardness [Gy]	1	10	1000	1	10 ⁴

Table 2.1: Main characteristics of the most widely used scintillator crystals in high energy physics [41]. R_M is the Molière radius, defined as the radius of a cylinder containing on average 90 % of the shower energy deposit.

line blocks instead of amorphous ones, either along the whole detector thickness or at the front side, would allow a huge reduction of the needed material to contain the whole electromagnetic shower. In fact, the experiments on the investigation of the beam interaction with a strong crystalline electromagnetic field are focusing on these materials.

2.1.1 THE EXPERIMENTAL TECHNIQUES

In order to properly study the beam interaction with the strong electromagnetic field, and more in general, the coherent effects in oriented crystals, one has to study, on an event by event basis, how the response of the crystal under test changes as a function of the input parameters of the incoming particle. These parameters are the following:

- the energy of the e^+/e^- beam: the emission of radiation in oriented crystals changes as a function of the energy of the incoming particles; for a PbWO₄ crystal the strong field threshold, i.e. $\chi = 1$, is ~ 30 GeV/c, so in order to fully characterize the strong field effect one needs a high energy beam with a variable momentum from 20 GeV/c (sub-strong field) to 120 GeV/c (full strong field). For the study of channeling phenomena, the nature of the beam (positrons or electrons) is also important, since the features of the emitted radiation change as a function of the particle charge. For the

strong field effects this is less significant since the features of the radiation are the same for electrons and positrons;

- the x and y impact coordinate of the particle on the crystalline sample transverse plane; to measure these coordinates a high spatial resolution tracking system before the crystalline sample is needed in order to fully reconstruct the particle track. In this thesis work, four silicon microstrip detectors have been used, with a spatial resolution of a few microns;
- the angle of the particle trajectory with respect to the crystalline sample; this is an important parameter since the coherent effects have a strong angular dependence. The angle between the particle trajectory and the crystalline sample, which is independent of the laboratory frame, is called misalignment angle and is given by:

$$\theta_{mis} = \theta_{track} \pm \alpha \theta_{gonio} \quad (2.1)$$

where θ_{track} is the relative angle between the particle track and the tracking system axis (computed from the x, y hit positions as $\theta_{track,x,y} = \frac{\Delta x(y)}{\Delta z}$) and θ_{gonio} is the relative angle between the crystalline sample and the laboratory frame, which is given by the geometrical coordinate of a high resolution goniometer; α is a factor that takes into account the differences in the unit of measurement.

The physical quantities that can be studied as a function of these input parameters are the following:

- the charged particles output multiplicity after a single input particle interaction with the crystal. The multiplicity measurement can be performed with a plastic scintillator positioned after the crystal, since there is a direct proportionality between the number of particles exiting from the crystal and the pulse height of the scintillator, or using a tracking system able to detect the number of particles that hit the detector in a single event.

The multiplicity of the output charged particles is important in the alignment procedure, since an enhancement in the multiplicity itself is expected when the crystal is oriented in channeling or strong field configuration.

In addition, if the crystalline sample is smaller than the beam size, a selection on the events requiring a multiplicity equal to one (i.e. corresponding to particles that have not crossed the crystal) can be made in order to reconstruct the crystal shape;

- the shower development inside the crystal. If the sample is a scintillating crystal, the scintillation light can be directly readout with a photodetector coupled with the crystal; this gives the possibility to study quantitatively the shower development in oriented crystals. The STORM collaboration, in which this thesis was performed, has implemented such a possibility for the first time ever;
- the total energy of the output electromagnetic radiation: to measure it, an electromagnetic calorimeter in the downstream section of the beamline is used. Before the

calorimeter, a bending magnet separates the electrons from the photons: if the energy of the electrons is measured with an electron dedicated electromagnetic calorimeter, considerations on the energy deposited in the crystalline sample can be made.

2.2 EXPERIMENTAL STATE OF THE ART

Starting from the 1980s, several experiments have been performed on the enhancement of radiation and pair production by high-energy $e^\pm$ and photons in strong crystalline fields [38] [42] [43–46].

One of the first experiments was NA43 performed on the H2 beamline in the North Area of the CERN SPS in 1994-1996; the experiment used light elements as targets (25 mm thick germanium (Ge) and 0.6 mm thick silicon (Si) crystals) and diamond scintillating crystals with a thickness $\lesssim X_0$ (1.5 mm), which precluded a full investigation of the electromagnetic shower acceleration caused by the strong crystalline field [38] [47] [48]. If on one hand the theoretical background has been widely explored, on the other the experimental investigation is still an open field in which the STORM experiment plays an important role.

2.2.1 THE AXIAL/ELIOT COLLABORATION

During 2017-2018, a series of experimental investigations on the strong field effects in axially oriented crystalline samples has been performed by the AXIAL/ELIOT team in the North Area of the CERN SPS H2 and H4 beamline using 120 GeV electrons and positrons impinging on a 4 mm thick ($0.45 X_0$) PbWO_4 crystal.

In these tests, the measurement of the charged particles output multiplicity and the total energy of the output electromagnetic radiation in an axially ($\langle 001 \rangle$) and random oriented crystal was performed. A first attempt was made to measure the scintillation light of the crystal with a SiPM, but no remarkable results were obtained. Furthermore, the crystal was too thin for a full investigation of the electromagnetic shower development.

The experimental setup is shown in figure 2.2; the detectors are the same implemented in the STORM experiment and will be described in detail in section 4.1.

The PbWO_4 sample was mounted on a high-precision goniometer. Two plastic scintillators (S1-2) were used for the trigger, while the trajectories of the electrons interacting with the crystal were reconstructed with a telescope system based on high precision microstrip silicon detectors (SD1, SD2, SD3). After the silicon detectors, a bending magnet separated the charged beam from the emitted γ -rays that interacted with the downstream electromagnetic calorimeter.

The energy loss spectrum in the downstream calorimeter (figure 2.3a) presents a significant modification in its shape with respect to the random case; the energy distribution in the random configuration has the typical shape of the Bethe-Heitler spectrum, with a sharp $1/E$ -like decrease in the soft energy region.

In the axially oriented case, the enhancement of the radiation emission and the reduction

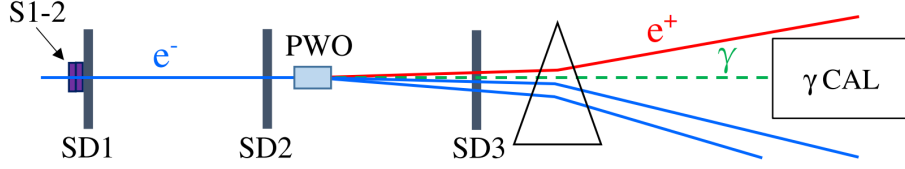


Figure 2.2: Experimental setup of the experiment performed in 2017 at CERN H4 [49]

in the radiation length, caused by the strong field effects inside the oriented crystal, lead to an increase in the deposited energy in the electromagnetic calorimeter and thus the maximum of the spectrum moves to higher energies.

The output charged particle multiplicity was measured with the SD3 silicon detector: figure 2.3b shows the number of particles that hit the detector in a single event. While in the amorphous case there are a lot of single hits (that is single particles exiting the crystal), in the axial case this number increases and for a single particle in input there are many particles in output. Figure 2.4 presents a comparison of the energy loss spectrum for elec-

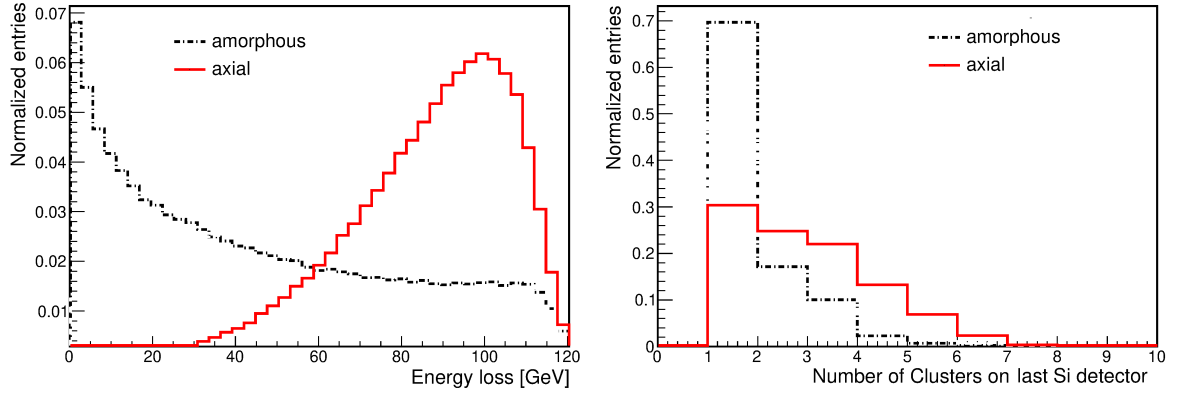


Figure 2.3: (a) Energy loss spectrum in the electromagnetic calorimeter for the random and axial case. (b) Number of particles on the silicon detector positioned after the crystal for the random and axial case.

trons and positrons. When in channeling, a different behavior between e^+ and e^- would be expected, since the channeling states for positive particles are much more stable than for negative ones, due to the enhanced probability for the latter of dechanneling; on the other hand, in the strong field both e^+ and e^- are in an overbarrier state, thus the two spectra are fully compatible with each other. Other tests ¹ were performed at lower energies (in the sub strong field regime) and with ultra-thin oriented crystalline samples, but none implemented the readout of the scintillation light in the crystal itself.

2.2.2 THE STORM COLLABORATION

STORM is a two-year project started in 2021 with the aim to further investigate the effect of the strong crystalline electromagnetic fields in high-Z oriented crystals (in particular PbWO_4) and measure quantitatively the acceleration of the electromagnetic shower devel-

¹ The result are not yet published.

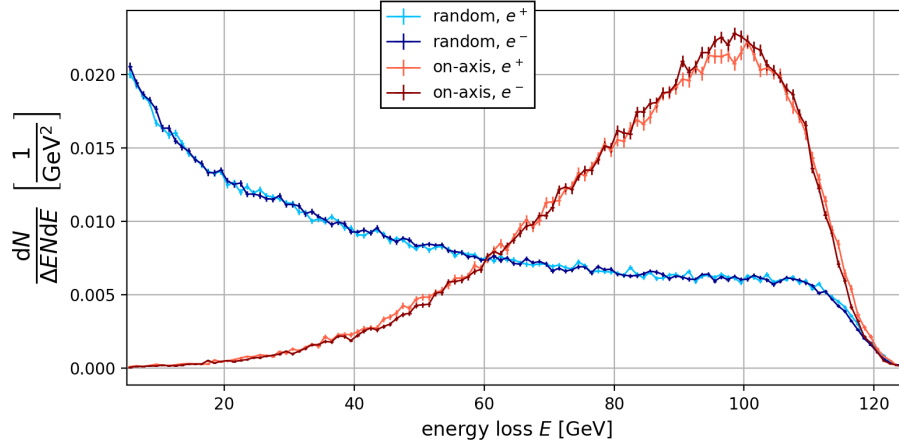


Figure 2.4: Energy loss spectrum in the downstream calorimeter, on axis and in random orientation, for both electrons and positrons [50].

opment and therefore the reduction of the radiation length X_0 .

In August 2021 a beamtest was performed at the CERN SPS H2 beamline focusing on PbWO_4 crystals. The beamtest itself (setup and data acquisition) and the analysis are the subject of this thesis and will be presented in the next chapters.

Two important features characterize this experiment with respect to the previous ones:

- the samples thickness: two PbWO_4 crystals with a thickness of 1 and 2 X_0 have been tested in order to fully investigate the electromagnetic shower acceleration caused by the strong crystalline field;
- the use of Silicon PhotoMultipliers coupled to the oriented crystals, in order to directly measure the enhancement of the scintillation light inside the crystal itself, because of the shower acceleration.

2.3 APPLICATIONS OF ORIENTED CRYSTALS

This section is dedicated to the description of a few possible applications of oriented crystals in the field of high energy physics and in the astrophysical field. As already said, more experimental tests are needed both to obtain the parameters required by the simulation in order to completely describe the phenomena, and to understand the feasibility of systems based on oriented crystals.

2.3.1 INTENSE POSITRON SOURCE FOR FUTURE e^+/e^- COLLIDERS

An intense positron source is a demanding element in the design of future lepton colliders, e.g. FCCee [51]. The conventional way to implement a positron source consists in using a target with a high atomic number Z (for instance tungsten) hit by a high energy primary

electron beam. As shown in figure 2.5, photons are produced via bremsstrahlung within the target and are then converted in e^+/e^- pairs. High energy incident electrons and rather thick targets are needed to reach a large positron yield.

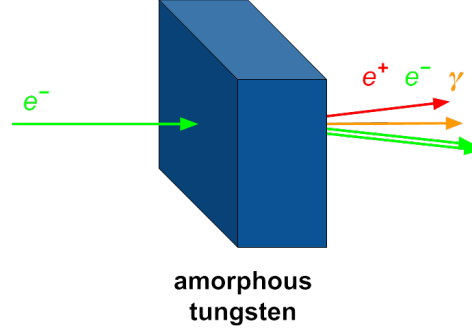


Figure 2.5: A conventional positron source with an amorphous tungsten target.

A crystal-based hybrid positron source could be a convenient alternative. The conceptual idea of the hybrid source is to have two separate objects, as shown in figure 2.6: a photon radiator and a photon-to-positron converter. In such a scheme, an electron beam crosses a thin axially oriented crystal which emits channeling radiation, with an intensity larger than the bremsstrahlung one. The net result is an increase in the number of produced positrons at the converter. In this hybrid scheme, only photons reach the converter, thereby reducing the Peak Energy Deposition Density (PEDD)².

Since positron sources are complex devices, where each stage (production, capture, acceleration, and injection strategy) has an impact on the final efficiency of the system, further deep investigations would be of great importance for an advancement of knowledge in this field [52] [51].

2.3.2 THE K_L EVER SMALL ANGLE CALORIMETER

The K_L EVER (K_L Experiment for VERY Rare events) collaboration [53] is investigating the possibility of performing a measurement of the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ branching ratio, using a high energy secondary neutral beam at the CERN SPS. The main goal is to achieve a sensitivity of about 60 $K_L \rightarrow \pi^0 \nu \bar{\nu}$ events over the total K_L primary flux in five years of data taking (the experiment should be ready for the start of the LHC Run4 (2026)), in order to verify the branching ratio foreseen by the Standard Model: with a signal to background ratio of 1, the experiment would obtain a relative uncertainty of $\delta_{BR}/BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) = 20\%$ with respect to the Standard Model branching ratio. In this way a discrepancy with 5σ significance could be demonstrated if the true rate is a bit more than twice or less than

² The Peak Energy Deposition Density (PEDD) has to be taken into account in positron source design to evaluate the safety margin and to determine the incident beam size to avoid the target damage. The threshold value of the PEDD is about 35 J/g.

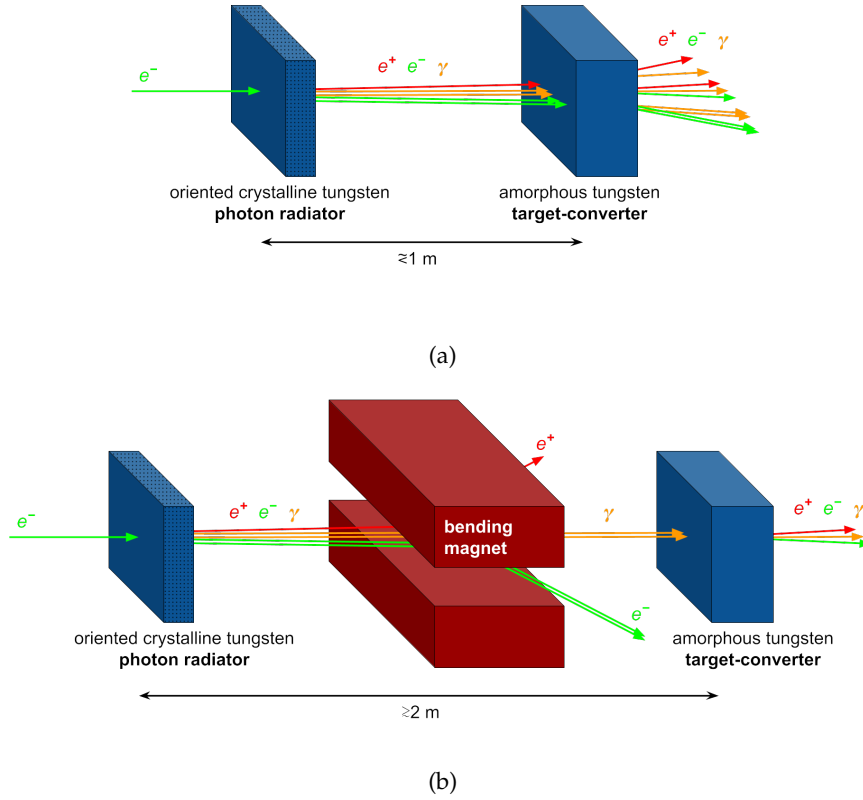


Figure 2.6: Hybrid schemes for the positron source. (a) Simple two-stage version, with a crystalline photon radiator followed by an amorphous converter, and (b) optimized version, in which a bending magnet is placed downstream with respect to the photon converter to sweep away the e^+/e^- pairs generated in the first stage [52].

one-quarter of the predicted Standard Model rate, or with a 3σ significance if the true rate is less than half of the Standard Model one.

The foreseen experimental setup is shown in figure 2.7 and fully described in [54].

The Small Angle Calorimeter (SAC) (figure 2.8) is placed directly on the neutral beam-line to reject photons from K_L decays that would otherwise escape via the downstream beam exit, providing at the same time a good γ/n discrimination. The fundamental feature of this calorimeter is its detection efficiency: the detector can be blind to photons with $E < 5 \text{ GeV}$, but needs a very high detection efficiency for photons with $E > 30 \text{ GeV}$ in order to reject high-energy γ s from the $K_L \rightarrow \pi^0 \pi^0$ decay escaping through the beamline. In addition, due to the 430 MHz neutron background, the SAC must have a good longitudinal and transverse segmentation, in order to provide a good γ/n signal discrimination. A possibility for the construction of an instrument that is sensitive to photons and blind to hadrons is to use a compact sampling calorimeter with crystalline lead tungstate tiles as the absorber material (another candidate is the lead fluoride PbF_2 , which is a Cherenkov emitter with a good time resolution [53]), in which the initial layer is made of oriented crystals. This choice could remarkably reduce the material sensitive to the hadronic components without losing in photon conversion efficiency. In fact, while the strong field effects result in a reduction of the effective X_0 that depends on the particle energy, the so-called nuc-

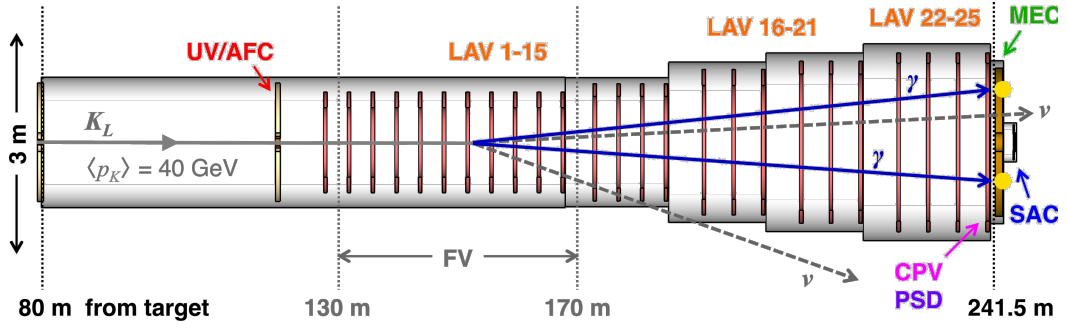


Figure 2.7: The K_L lever beamline layout [53]: upstream veto (UV) and active final collimator (AFC), large-angle photon vetoes (LAV), main electromagnetic calorimeter (MEC), small-angle calorimeter (SAC), charged particle veto (CPV), preshower detector (PSD).

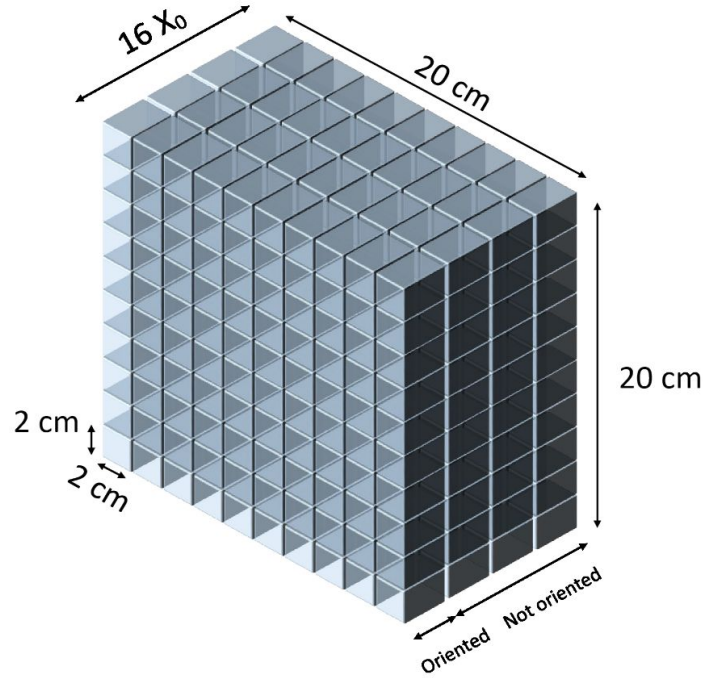


Figure 2.8: The K_L lever Small Angle Calorimeter [53].

le interaction length λ_{int} , i.e. the longitudinal scale of the inelastic hadronic processes, is unaffected by the lattice orientation. Therefore, axially oriented tungsten layers prove appealing to filter out the photon component in hadron beams with a minimum effect on the hadronic component (one might hope to decrease the X_0/λ_{int} ratio by a factor of 2–3.).

2.3.3 HEP SAMPLING CALORIMETERS FOR FIXED-TARGET EXPERIMENTS

Homogeneous and sampling calorimeters are widely used in high-energy physics to measure the particle energy. Sampling calorimeters consist of alternating layers of an absorber, used to degrade the energy of the incident particle, and an active medium that provides the detectable signal. Homogeneous calorimeters, on the other hand, are built of only one type of material that performs both tasks. In order to contain the whole electromagnetic

shower, a calorimeter should have a thickness of $\simeq 25 X_0$ (for PbWO_4 the radiation length is 0.89 cm thus a thickness of 23 cm is needed). Oriented crystals can be exploited in the design of both homogeneous and sampling calorimeters; in the first case, the scintillating medium would consist of oriented crystalline blocks, either along the whole detector thickness or at the front side only; the reduction in the radiation length leads to a reduction in the material needed to contain the whole shower. In case of sampling calorimeters, the shower acceleration can be exploited to develop thinner passive layers (figure 2.9)

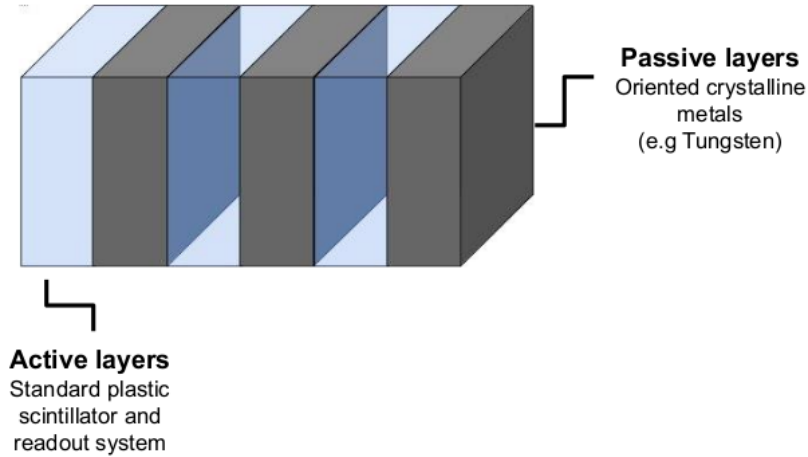


Figure 2.9: A schematic representation of a sampling electromagnetic calorimeter in which the absorber layers are made of an oriented crystalline medium.

2.3.4 SOURCE-POINTING SPACE BORNE γ -RAY TELESCOPES

Detectors based on oriented crystals are particularly appealing for satellite-borne γ -ray detectors. In a satellite with a γ module made of oriented crystals, the shower of γ rays with an energy larger than 100 GeV can be completely contained in a quite compact volume, thus reducing the satellite weight, and therefore the cost. Figure 2.10 shows the Fermi Large Area Telescope (Fermi LAT) as an example [55].

It consists of layers of silicon detectors interleaved with thin W converter foils, while the calorimeter is made of caesium iodide (CsI) crystals. The incoming gamma ray interacts with the W foil, thus converting in a e^+/e^- pair that deposits its energy into the calorimeter.

When pointing to the source, an oriented crystal based calorimeter would strongly enhance the sensitivity of the telescope above few GeV, thus containing the electron/positron showers at energies up to TeV and even more in a smaller volume as compared to standard detectors. Furthermore, if the W conversion foil is substituted by a crystalline W or high-Z crystal scintillator, the tracker length can be reduced and consequently the multiple scattering, with an improvement of the resolution in the localization of the gamma-ray source, thus helping its identification. Moreover, such an apparatus would continue to operate in a standard way in the absence of pointing.

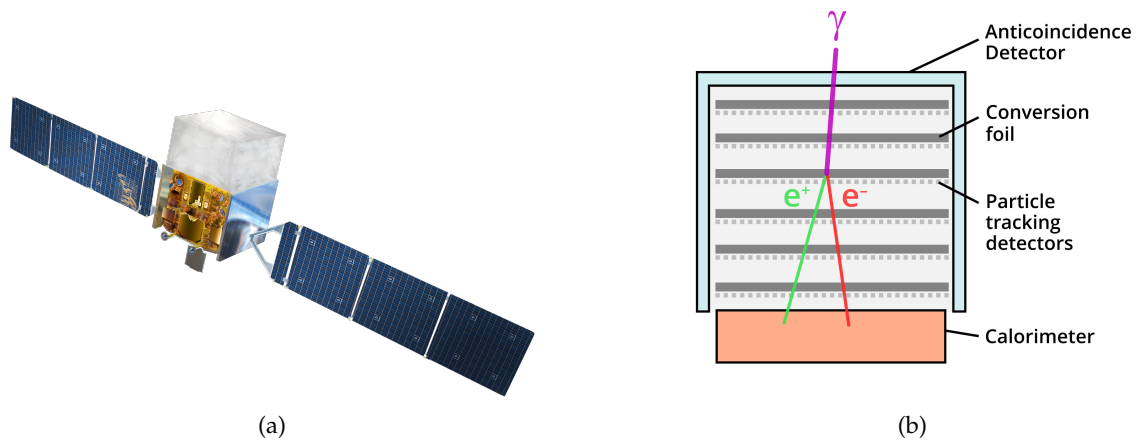


Figure 2.10: (a) The Fermi telescope. (b) The Fermi Large Area Telescope designed to perform an all-sky survey studying astrophysical and cosmological phenomena such as active galactic nuclei, pulsars, other high-energy sources and dark matter [56].

THE STORM MATRICES AND CRYSTALS: PRELIMINARY CHARACTERIZATION

In order to investigate the electromagnetic shower development in oriented crystals, a suitable scintillating crystalline sample, with a thickness of at least $1 X_0$, and a photodetector system are needed. This chapter focuses on the description of the two crystalline samples tested in the STORM experiment, along with the SiPM matrices used to detect the scintillation light.

The second part of the chapter describes the characterization of the STORM matrices performed at the INSULAB laboratory (Insubria University, Como, Italy) using cosmic rays. The goal of the characterization was the measurement of the performance of the detector in terms of signal to noise ratio and efficiency with Minimum Ionizing Particles, thus with a signal much smaller than the one expected on the beam.

3.1 THE STORM CRYSTALS

For the STORM experiment, two PbWO_4 crystals of different thickness have been tested:

- one $1 X_0$ crystal, with a thickness along the beam direction of 9 mm and a transverse area of $3 \times 3 \text{ cm}^2$, produced by the Institute for Nuclear Problems (INP) of the Belarusian State University, Minsk [57]. The measurements have been performed with an electron beam of 120 GeV along the $\langle 100 \rangle$ axis (highlighted in red in figure 3.1);
- one $2 X_0$ crystal with a thickness along the beam direction of 18 mm and a transverse area of $0.9 \times 2.7 \text{ cm}^2$, produced by Moltech (Molecular Technology GmbH, Berlin, Germany). The measurements have been performed with an electron beam of 120 GeV along the $\langle 001 \rangle$ axis (highlighted in green in figure 3.1).

In table 3.1 the main axis properties of the two crystals under test are summarized; the large angular acceptance for the strong field effects ($\sim 1 \text{ mrad}$), if combined with a small beam divergence, allows to measure the effects of the strong field on the electromagnetic shower development for different angular orientations.

The two crystals are shown in figure 3.2; they were mounted on a custom holder structure along with the SiPM matrices; both crystals were coated with a white reflective paint in order to protect them from the ambient light and to minimize the scintillating light loss. On the beamline, the crystals were located inside a black box to obscure them.

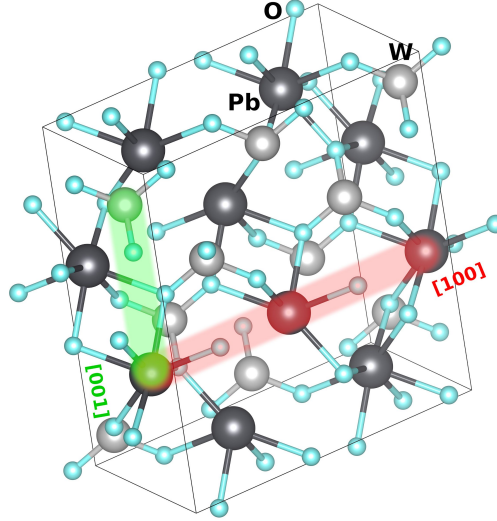


Figure 3.1: The PbWO_4 crystalline structure; the measurements have been performed around the $\langle 100 \rangle$ axis of the $1 X_0$ crystal, highlighted in red, and around the $\langle 001 \rangle$ of the $2 X_0$ one, highlighted in green [6].

	$1 X_0$	$2 X_0$
axis	$\langle 001 \rangle$	$\langle 100 \rangle$
interatomic pitch	$12.020 \text{ \AA}$	$5.456 \text{ \AA}$
U_0	$\sim 600 \text{ eV}$	$\sim 700 \text{ eV}$
Θ_0	$\sim 1 \text{ mrad}$	$\sim 1 \text{ mrad}$
SF threshold ($\chi = 1$)	$\sim 30 \text{ GeV}$	$\sim 30 \text{ GeV}$

Table 3.1: Axis properties of the two crystals under test.

3.2 THE STORM MATRICES

The photodetection system implemented for the STORM experiment is based on Silicon PhotoMultipliers (SiPMs [58]). A SiPM consists of an array of pixels connected to a common output; each pixel is a reverse biased diode working in the Geiger discharge regime (Single Photon Avalanche Diode (SPAD) [59]) with its own quenching resistor. When a photon is absorbed, a Geiger avalanche is produced, causing a photocurrent to flow from the cathode to the anode thus resulting in a voltage drop across the quenching resistor, which in turn reduces the bias across the diode to a value below the breakdown.

Each pixel is a digital device: when hit by a photon an avalanche is generated. Given the fact that the pixels are connected to a common output, the output signal is proportional to the number of hit pixels and thus to the number of photons: the resulting information is an analog one and allows to estimate the light intensity.

SiPMs are fast, linear (on a range which depends on the number of pixels), with a high gain and single photon capability. They need a low voltage bias (a few tens of Volts) and are insensitive to magnetic fields. On the other hand, the noise could be large (from a

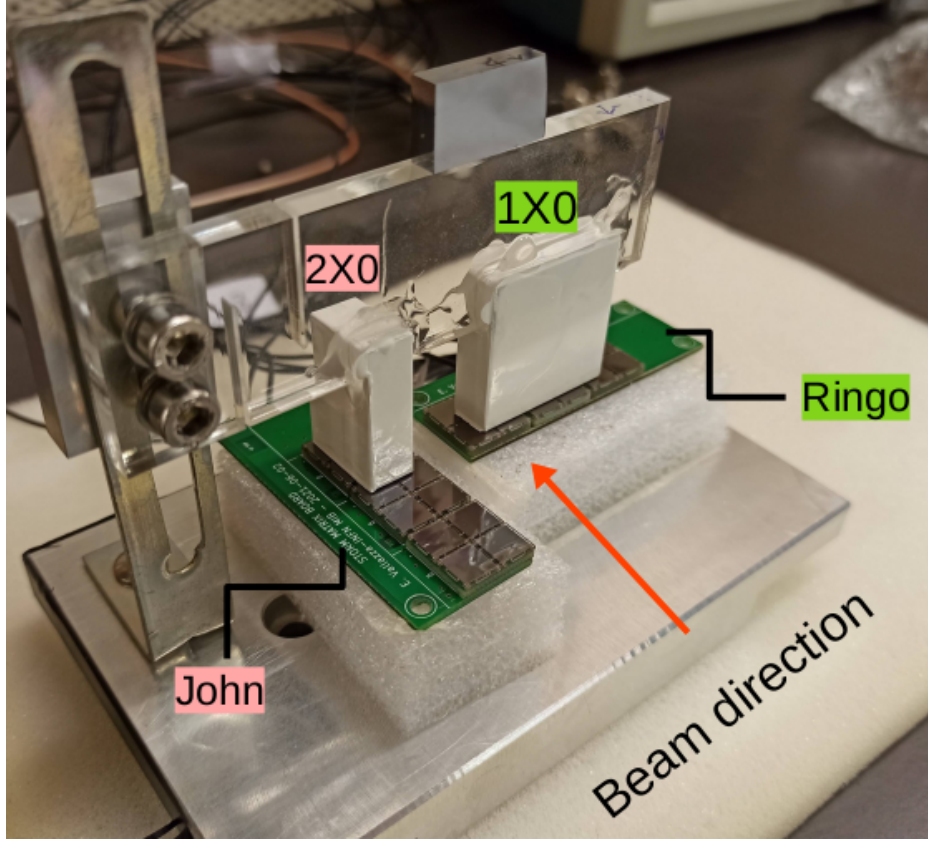


Figure 3.2: The $1 X_0$ and $2 X_0$ PbWO_4 samples mounted on the holder. The readout matrices have been named respectively Ringo and John.

Array size	Sensor type	Readout	Board Size	Sensor pitch	Nr. of connections
2	60035	Sensor	$14.3 \times 14.2 \text{ mm}^2$	7.2 mm	$3 \times 3 \text{ BGA}$

Table 3.2: Features of the ARRAYC-60035-4P-BGA produced by ONSEMI [60].

few kHz to a few MHz per mm^2 , which results in a limit on the sensitivity), and all the parameters depend on the temperature.

The STORM photodetection system is shown in figure 3.3; it consists of three SiPM matrices model ARRAYC-60035-4P-BGA [60] produced by ONSEMI [61] and a custom readout board designed at the INSULAB laboratory.

The ARRAYC-60035-4P-BGA consists of 4 individual 6 mm C-Series sensors [63] arranged in a 2×2 array (figure 3.4). The schematic of the ARRAYC-60035-4P-BGA is shown in figure 3.5. Each C-Series sensor is a low-noise, blue-sensitive and high gain SiPM with a squared pixel of $35 \times 35 \mu\text{m}^2$ [63]. Each sensor is mounted on a PCB that routes out the signals as a BGA (Ball Grid Array). The 4 SiPMs cathodes on the single matrix are connected together thus providing a common connection. The features of the array are summarized in table 3.2.

The readout board (figure 3.3 top) has been designed at the INSULAB laboratory ¹; the schematic is shown in figure 3.6. It is a 2 layer $63 \times 23 \text{ mm}^2$ 1.5 mm thick printed circuit board. The sensors have been assembled on the board itself by SCEN S.r.l. [65]. All the

¹ E. Vallazza, INFN - Sezione di Milano Bicocca, Milano, Italy.



Figure 3.3: The STORM photodetection system: it consists of three SiPM matrices connected on a readout board. V_{bias} (the J4 connector) is the common bias for the three matrices; the signal of each matrix is coupled to a 100 nF capacitor and is taken to the readout system with a Hirose connector/cable [62].

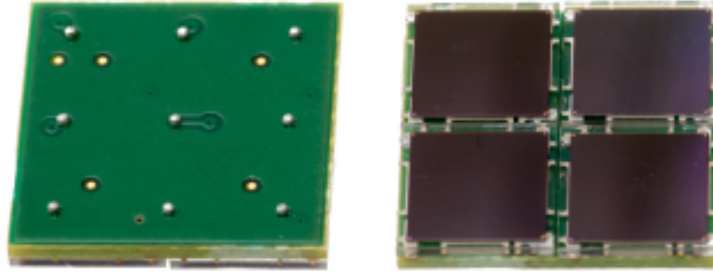


Figure 3.4: A photo of the ARRAYC-60035-4P-BGA; it consists of 4 individual 6 mm C-Series sensors [63] arranged in a 2×2 array [60].

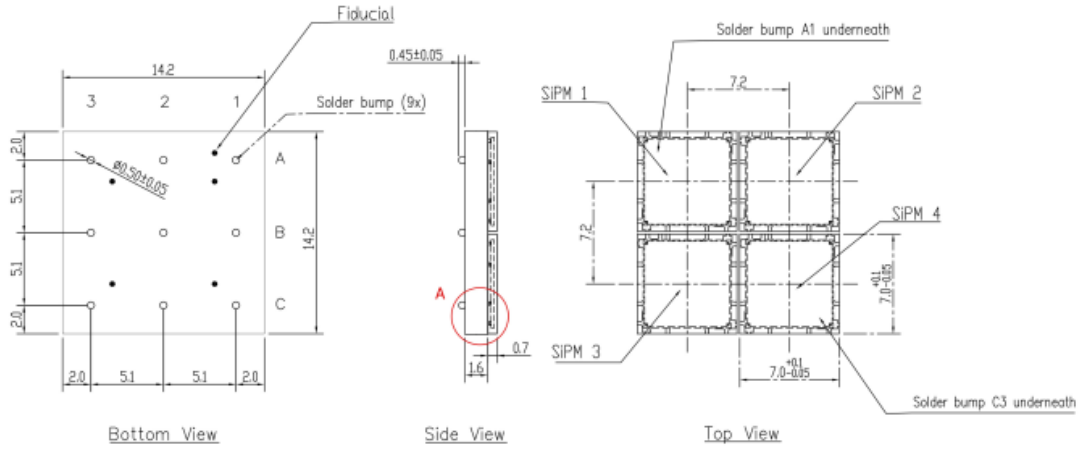


Figure 3.5: The schematics of the ARRAYC-60035-4P-BGA. The A1, A2, B1, B2 are the anodes, while A3, B3, C1-C3 are the cathodes which are connected together [64].

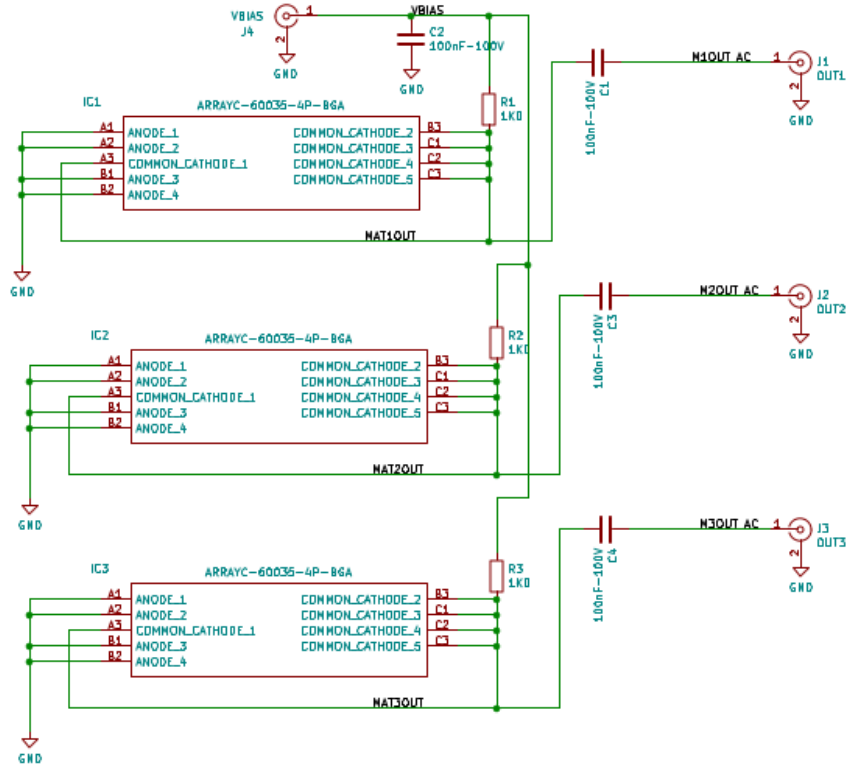


Figure 3.6: Schematics of the readout board: all the matrices have a common bias (V_{bias} , J4 connector); the A1, A2, B1, B2 anodes are set to ground while the common cathode is set to a positive bias. The signal of each matrix is coupled with a 100 nF capacitor and is taken to the readout system with a Hirose connector/cable.

matrices have a common bias (V_{bias} , J4 connector); the A1, A2, B1, B2 anodes are set to ground while the common cathode is set to a positive bias. The signal of each matrix is coupled with a 100 nF capacitor and is taken to the readout system with a Hirose connector/cable [62]. The two detectors assembled for the STORM experiment have been named Ringo (1 X_0 crystal) and John (2 X_0 crystal).

The SiPM sensors are operated at a bias that is typically 10%-25% higher than the breakdown voltage V_{br} . The difference between the V_{br} and the bias is referred to as the overvoltage. The overvoltage value is chosen by observing the current-voltage (IV) curve of the SiPMs. Figure 3.7 presents the IV curve of Ringo and John: the breakdown voltage is around 26 V; the SiPMs on the beamline were biased at 30 V.

An example of a waveform, acquired on the beamline with a 120 GeV electron beam, is shown in figure 3.8. The abscissa is the digitizer acquisition window in which one clock corresponds to 2 ns, while the ordinate corresponds to the SiPM signal in ADC. The rise time of the SiPM is determined by the rise time of the avalanche formation and the variation in the transit times of the signals arriving from different points on the sensor active area. The recovery time of the sensor is determined by the pixel recharge time constant (which depends on the effective capacitance and on the quenching resistor of the pixel itself, the total number of pixels in the sensor and any resistance in series with the sensor)

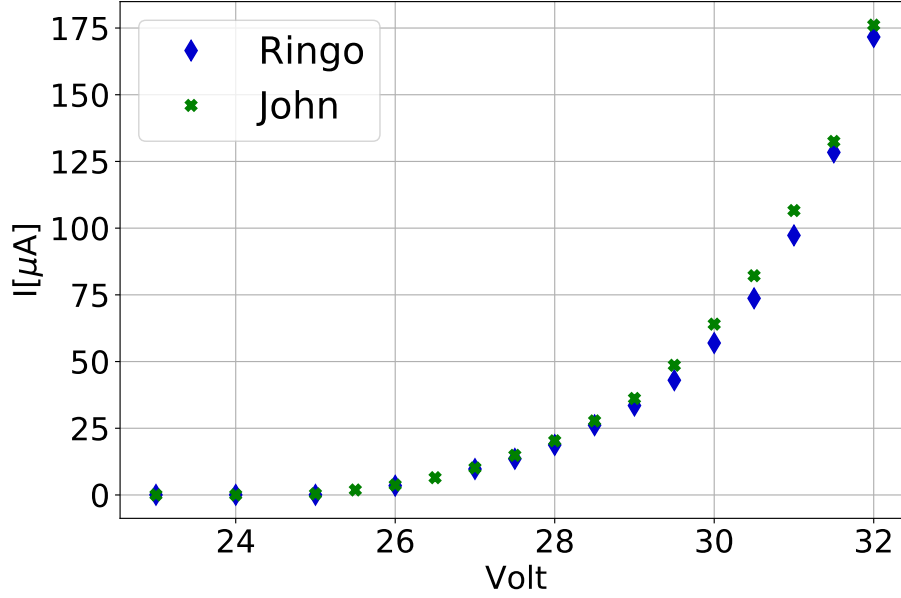


Figure 3.7: The IV curve of Ringo and John; the breakdown voltage is around 26 V; the SiPMs bias at the beamtest was 30 V.

and by the time features of the readout circuit.

In the STORM experiment these signals were sampled by a digitizer at 500 MHz, which allowed an acquisition time window of 500 ns; the data acquisition performed the baseline subtraction computing the maximum of the waveform and the corresponding time, saving all the information (maximum, time and waveform) in the output files. For this data taking a fast recovery time was not needed.

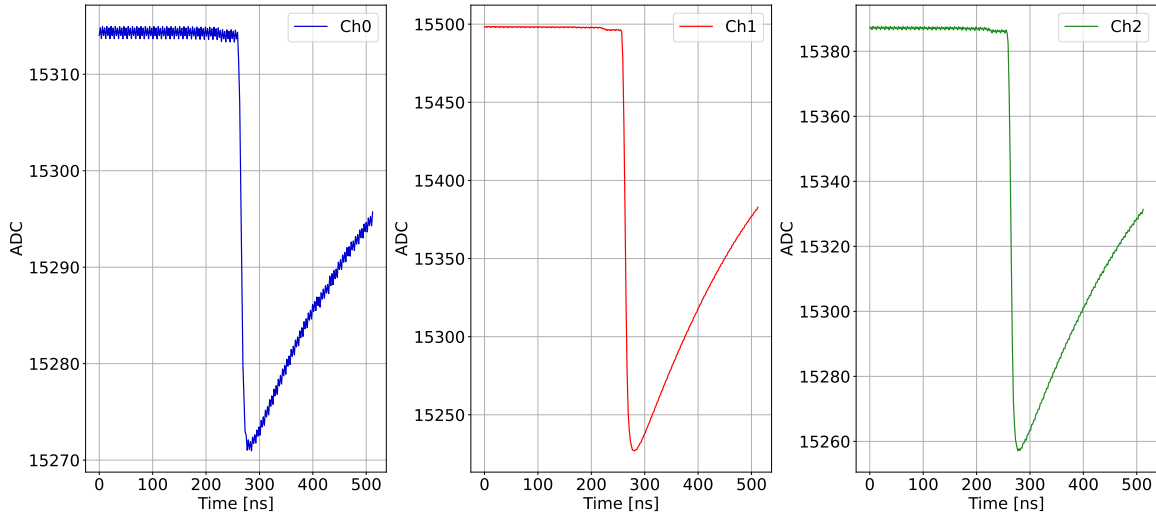


Figure 3.8: The raw waveform of Ringo acquired on the beamline with a 120 GeV electron beam.

3.3 THE STORM MATRICES CHARACTERIZATION

In the following sections, the characterization of the light readout system for the STORM experiment will be presented. The characterization has been performed with cosmic rays and test crystals in order to verify the coupling of the crystals to the matrices and the behaviour of the SiPMs, measuring the signal to noise ratio of the detector and its efficiency. The goal of the test was to set a limit on the sensitivity of the light readout system in an experimental situation which was much worse than the one expected on the beam. Cosmic rays in fact are minimum ionizing particles and thus the energy deposit in the crystal is much less than the one of the first part of an electromagnetic shower, as will be described later on.

3.3.1 THE EXPERIMENTAL SETUP

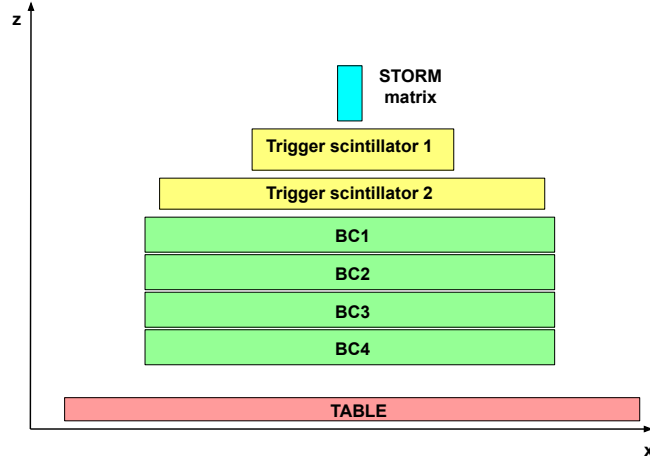
The characterization of the Ringo and John STORM matrices has been performed at the INSULAB laboratory with a test PbWO_4 crystal using cosmic rays. The crystal was 3 cm thick along the cosmic ray direction and had a transverse area of $1 \times 2 \text{ cm}^2$. The measurement of the efficiency, i.e. the ratio of the particles seen by the detector and the total number of the incident ones, has been performed using the setup shown in figure 3.9, which consists of:

- the STORM matrix under test;
- two plastic scintillators readout by PhotoMultiplier tubes (PMTs), used in coincidence for the trigger generation;
- four AGILE Beam Chambers (BCs) each consisting of two single side silicon microstrip detectors [66] in a x - y configuration for the cosmic ray tracking. The silicon detector has an active area of $9.5 \times 9.5 \text{ cm}^2$, with a thickness of $410 \mu\text{m}$ and a strip readout pitch of $242 \mu\text{m}$ (1 floating strip scheme). A more detailed description is given in section 4.1.2.

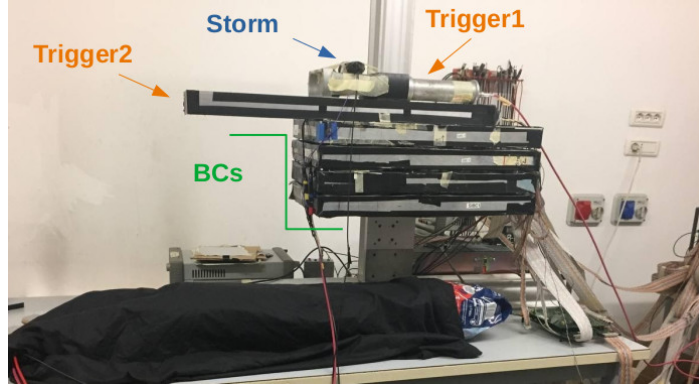
The STORM matrices have been coupled with the test crystal and positioned inside a black 3D printed PLA box in order to protect them from the ambient light (figure 3.10a-b); for the measurement of the efficiency the black box has been fixed on top of the plastic scintillators, as shown in figure 3.10c.

3.3.2 EFFICIENCY MEASUREMENT

In order to select only the events which crossed the crystal, the tracks of the incoming cosmic rays have been reconstructed using the x and y hit positions on the BCs. Only the coordinates from BC1 and BC4 have been considered. Taking into account the scheme



(a)



(b)

Figure 3.9: Scheme and picture of the experimental setup for the efficiency measurement.

shown in figure 3.11, the x coordinate X_{storm} of the hit position of the incoming cosmic ray on the crystal plane can be reconstructed as:

$$x_{storm} = x_4 + (z_{storm} - z_4) \cdot \tan(\theta_x) \quad (3.1)$$

where θ_x is the impinging angle with respect to the vertical axis, which has been calculated in the following way:

$$\theta_x = \arctan\left(\frac{x_1 - x_4}{z_1 - z_4}\right) \quad (3.2)$$

The same was done for the θ_y angle, using the y_i coordinates. The x and y angular distributions obtained for John and Ringo are shown in figure 3.12; the red lines indicate the angular range used in the analysis to select only the tracks that have crossed the crystal with small angles with respect to the vertical axis.

From figure 3.10a it can be seen that the crystal under test covers only two matrices of the readout board; the following analysis has been performed considering only these two matrices both for John and Ringo.

Figure 3.13 presents the correlation of the PH of the two readout channels of Ringo and John; the events with a small PH are noise events. The responses of the two channels are

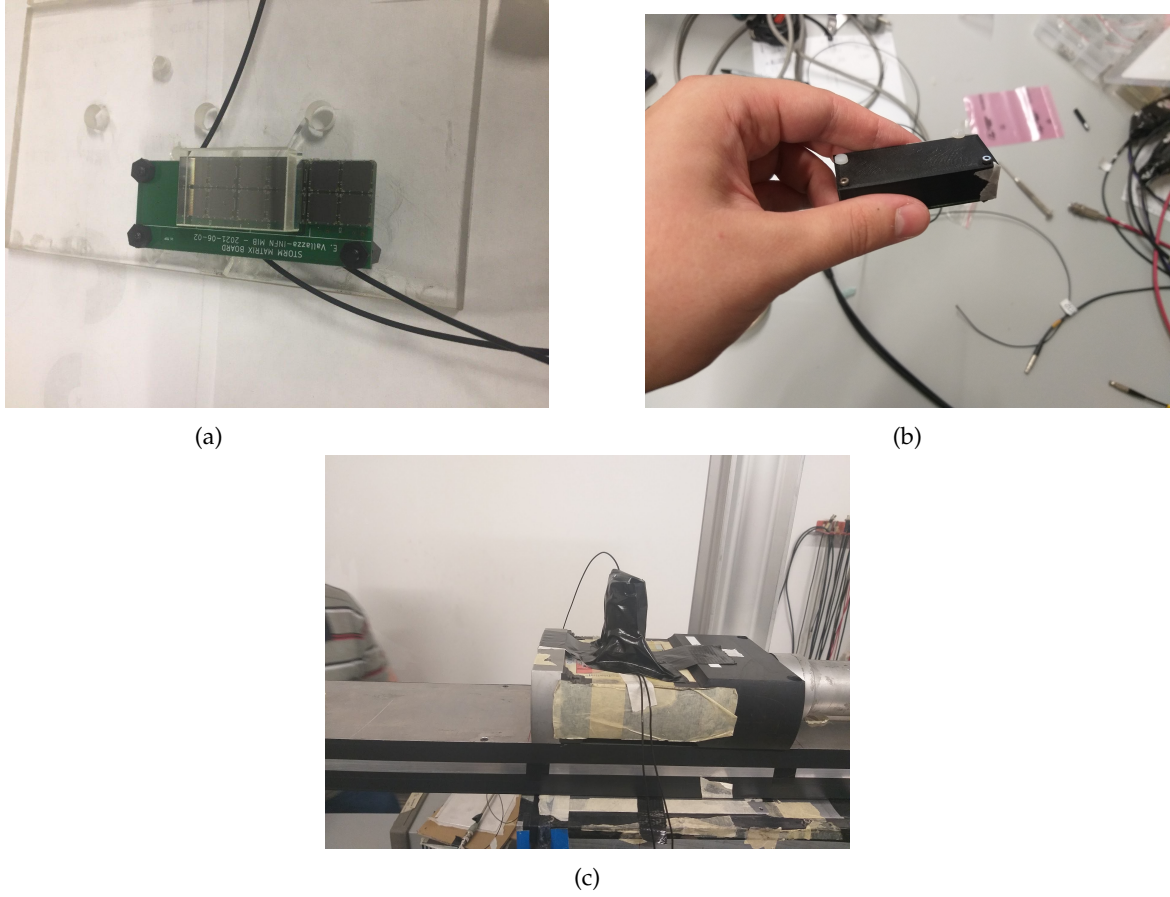


Figure 3.10: a) The test crystal positioned on one of the STORM matrices; b) the STORM and the test crystal positioned inside a black 3D printed PLA box c) and on top of the two plastic scintillators for the efficiency measurement.

correlated, indicating that the light produced by the cosmic rays is spreading in the crystal and thus read out by both the light detectors.

Figure 3.14 presents the PH-time scatter plot of the two channels of the Ringo and John matrices: most of the events with a large PH populate a small part of the time spectrum. In fact, only the particles detected by the two trigger scintillators and the crystal have the same arrival time, while the other ones are due to the noise or particles that have not crossed the detector under test. The red line is the threshold chosen to discriminate these events from the noise. Figure 3.15 presents the PH of the two channels of the Ringo and John matrices, with the chosen threshold; the large number of noise events is due to the small dimension of the crystal+matrix detector with respect to the trigger system.

Figure 3.16 left shows the 2D distribution of all the tracks reconstructed on the crystal plane for Ringo (a) and John (b); among these, the tracks of the particles that crossed the crystal and produced a signal were selected applying the cut on the angle distribution (figure 3.12) and the cut on the pulse height (figure 3.15), and considering the OR of the two matrices signals (that is requiring that at least one of the matrices has seen the particle). Figure 3.16 right presents the resulting 2D distributions.

The efficiency is defined as the ratio between the 2D histograms with the selected tracks and the ones with all the tracks. Figure 3.17 shows the 2D distribution of the efficiency

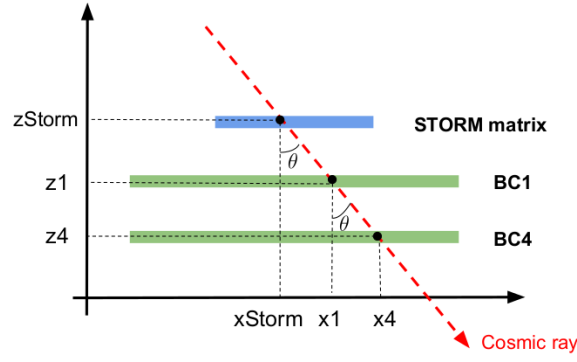


Figure 3.11: Scheme of the tracks reconstruction method, where the x and z coordinates are shown.

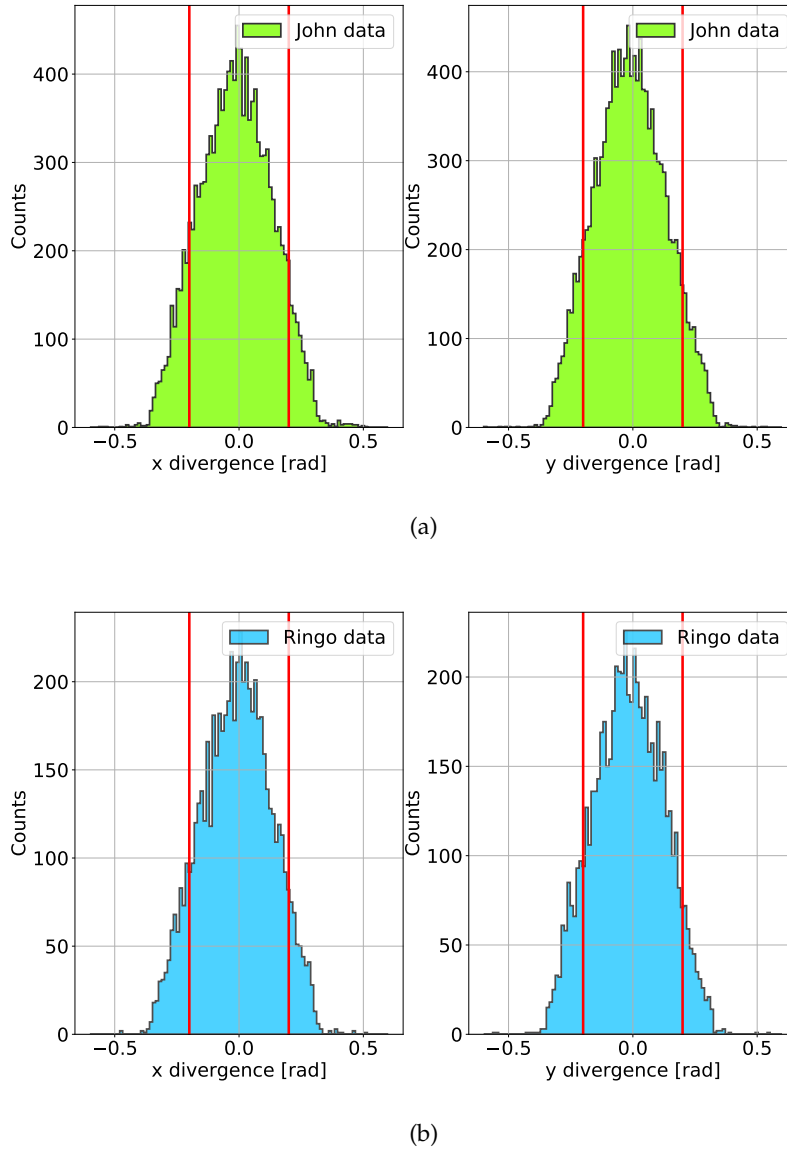
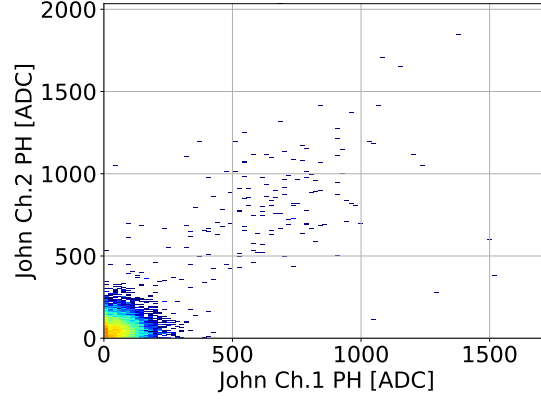
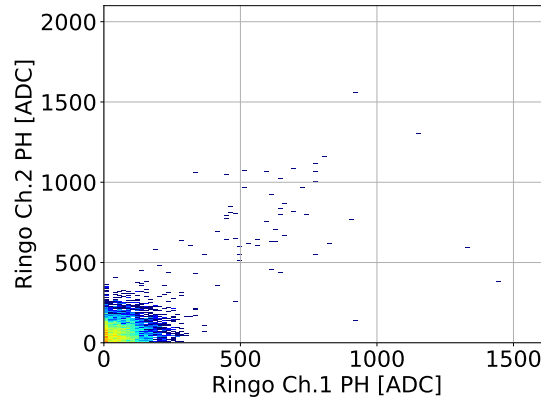


Figure 3.12: Angular distributions of the cosmic rays impinging on the STORM crystal: a) John matrix, b) Ringo matrix. The red lines indicate the angular range used in the analysis to select only the tracks with small angles with respect to the vertical axis.



(a)



(b)

Figure 3.13: Correlation between the PH of the two readout channels of the John (a) and Ringo (b) matrices. The events with a small PH are noise events; a correlation between the response of the two channels is evident.

values respectively for John and Ringo; the white box indicates the effective dimension of the test crystal. The plot in figure 3.18 has been obtained averaging over the y direction; both the matrices show a high efficiency: up to 80% for the John matrix and up to 90% for the Ringo matrix.

As already said, cosmic rays are minimum ionizing particles: the energy deposit of a MIP is approximately $1.2 \text{ MeV/gr}\cdot\text{cm}^2$; this means that the energy deposited in the 3 cm thick PbWO_4 crystal is $\sim 30 \text{ MeV}$. With a 120 GeV electron beam and the oriented crystal, an energy deposit of several hundreds of MeV or even GeVs is expected (given the acceleration of the electromagnetic shower development), which is much larger than the MIP one. The light detector system characterization has demonstrated that the detector itself is able to reconstruct MIPs with a good enough signal to noise ratio and thus no problem with the efficiency was expected on the beam.

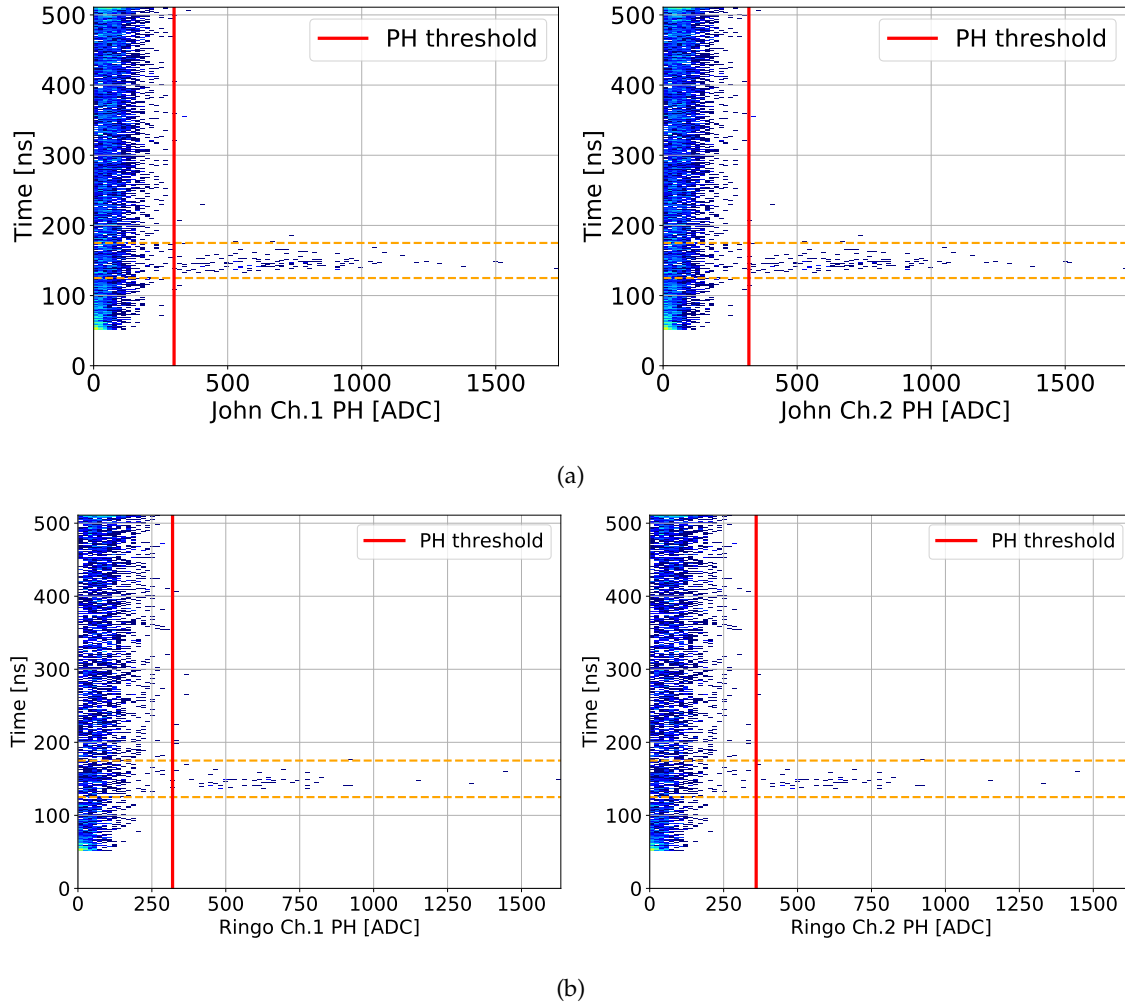
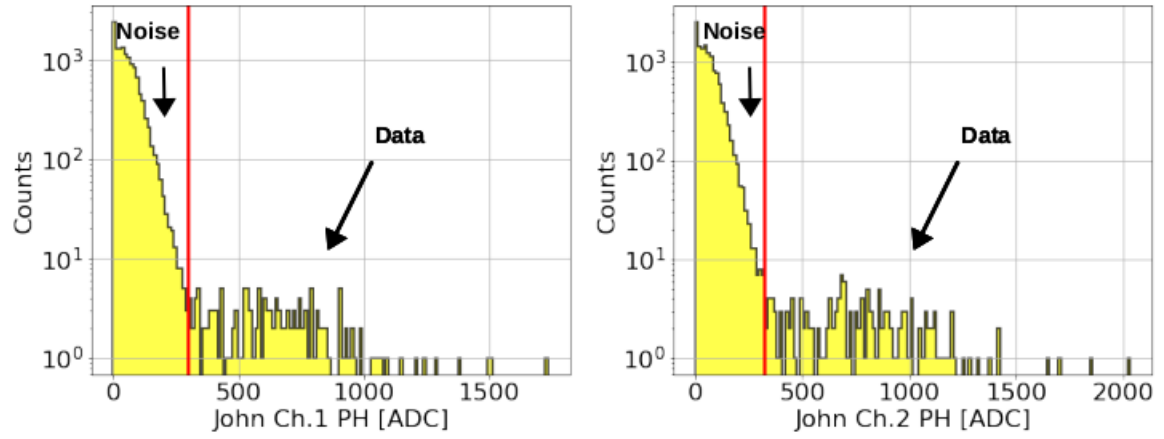
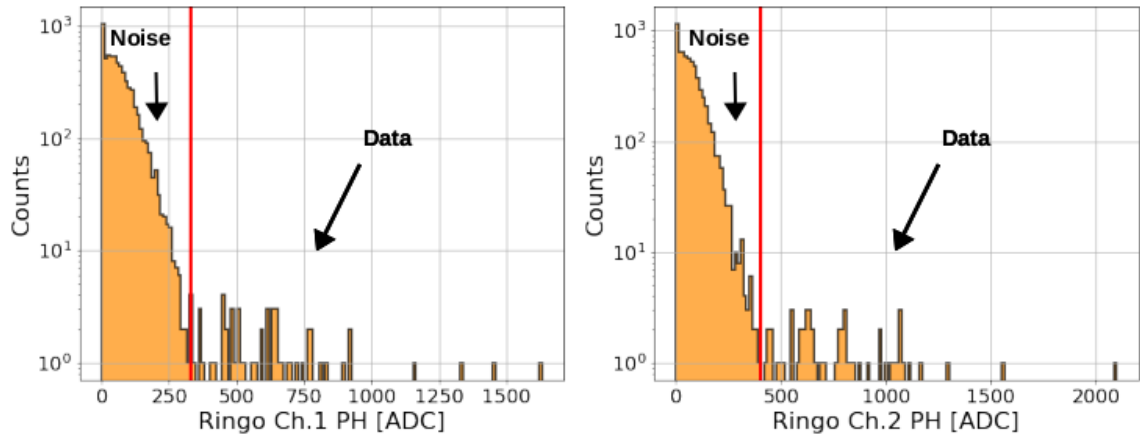


Figure 3.14: PH-time scatter plot: the real events are the ones between the dashed orange lines. The red line is the threshold chosen to discriminate the events in which the particle has really crossed the crystal from the noise ones.



(a)



(b)

Figure 3.15: PH spectra of the STORM matrices (logarithmic scale). The red lines are the thresholds on the PH used in the analysis to determine the events in which the particle has crossed the crystal.

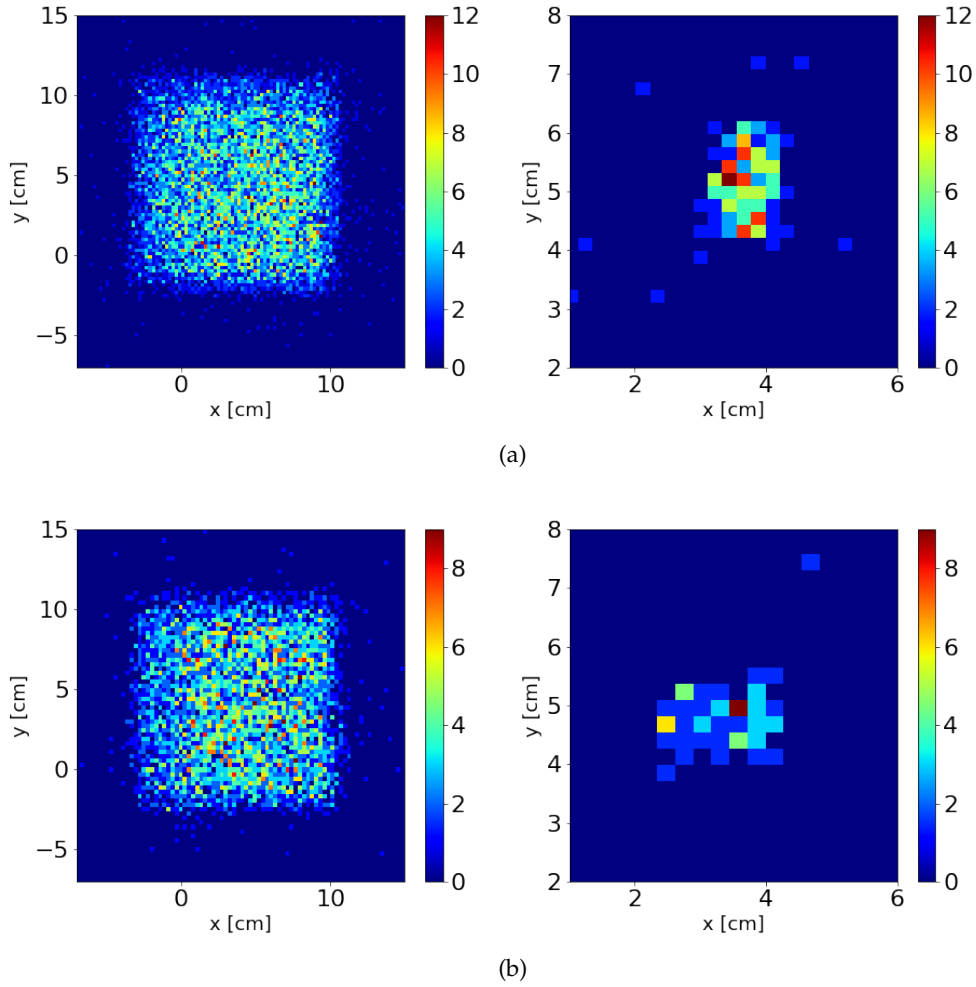
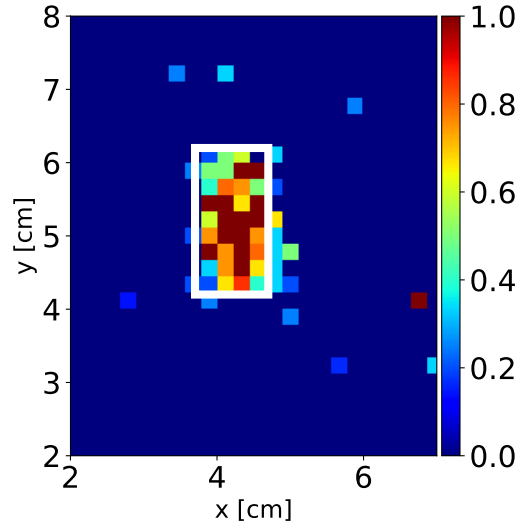
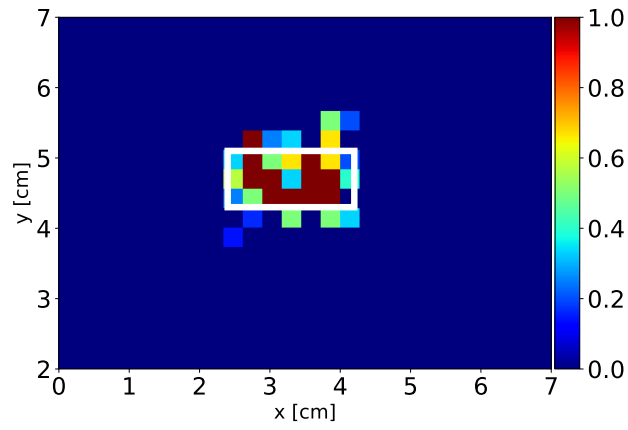


Figure 3.16: (left) 2D distributions of all the tracks reconstructed on the crystal plane for Ringo (a) and John (b); (right) 2D distributions of the tracks of the particles that have crossed the crystal and produced a signal; they are selected applying the cut on PH and on the angle distribution.

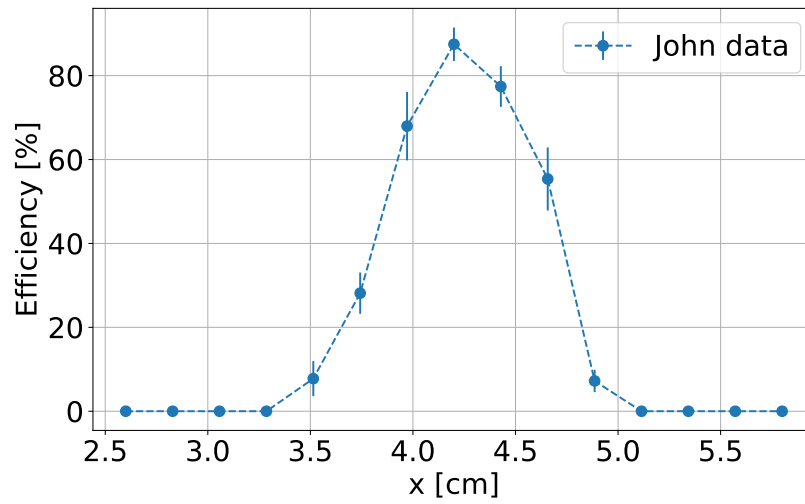


(a)

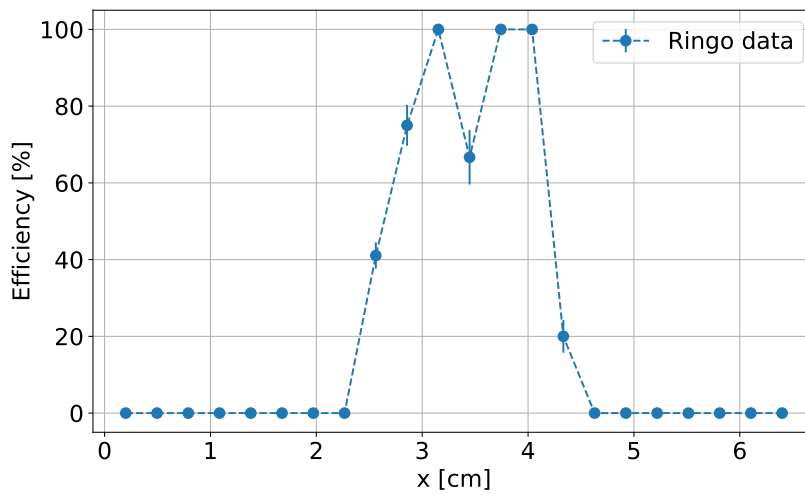


(b)

Figure 3.17: 2D distribution of the efficiency value for a) John and b) Ringo matrices; the white box indicates the real dimension of the test crystal.



(a)



(b)

Figure 3.18: Efficiency profile plot of a) John and b) Ringo, obtained averaging over the y direction; both matrices show a high efficiency.

THE STORM BEAMTEST AT THE CERN SPS

This chapter describes the experimental setup and the preliminary tests performed on the H2 line at the CERN SPS North Area during the STORM beamtest in August 2021. In the first part of the chapter, each component of the experimental layout is described in detail, along with a short description of the Data AcQuisition (DAQ) system. The second part of the chapter presents the alignment procedure of the tracking systems, the features of the beam (such as the beam divergence) and the calibration procedure of the electromagnetic calorimeter.

4.1 EXPERIMENTAL SETUP

CERN [67] is the largest laboratory for high energy studies in the world; it is located in Geneva, Switzerland and its main experimental structure is a wide complex of particle accelerators able to provide many kinds of particle beams both to collider experiments and to extracted beamlines.

The CERN accelerator complex (figure 4.1) is composed by a chain of acceleration stations (both linear and circular), placed in sequence, that accelerate particles to increasingly higher energies. Linear accelerator 4 (Linac4) became the source of proton beams for the CERN accelerator complex in 2020. It accelerates negative hydrogen ions, H^- , to 160 MeV to prepare them to enter the Proton Synchrotron Booster (PSB). The ions are stripped of their two electrons during injection from Linac4 into the PSB, leaving only protons. These are accelerated to 2 GeV for injection into the Proton Synchrotron (PS), which pushes the beam up to 26 GeV. Protons are then sent to the Super Proton Synchrotron (SPS), the second-largest machine in the CERN accelerator complex, measuring nearly 7 kilometers in circumference, which provides particles with a momentum up to 450 GeV/c to external lines, i.e. North Area, COMPASS, NA62 (figure 4.2). The protons are finally transferred to the Large Hadron Collider (LHC), where they are accelerated up to a maximum energy of 6.5 TeV. The two proton beams are brought into collision inside four detectors – ALICE, ATLAS, CMS and LHCb.

The STORM experiment was performed in August 2021 on the H2 extracted beamline of the North Area (figure 4.3).

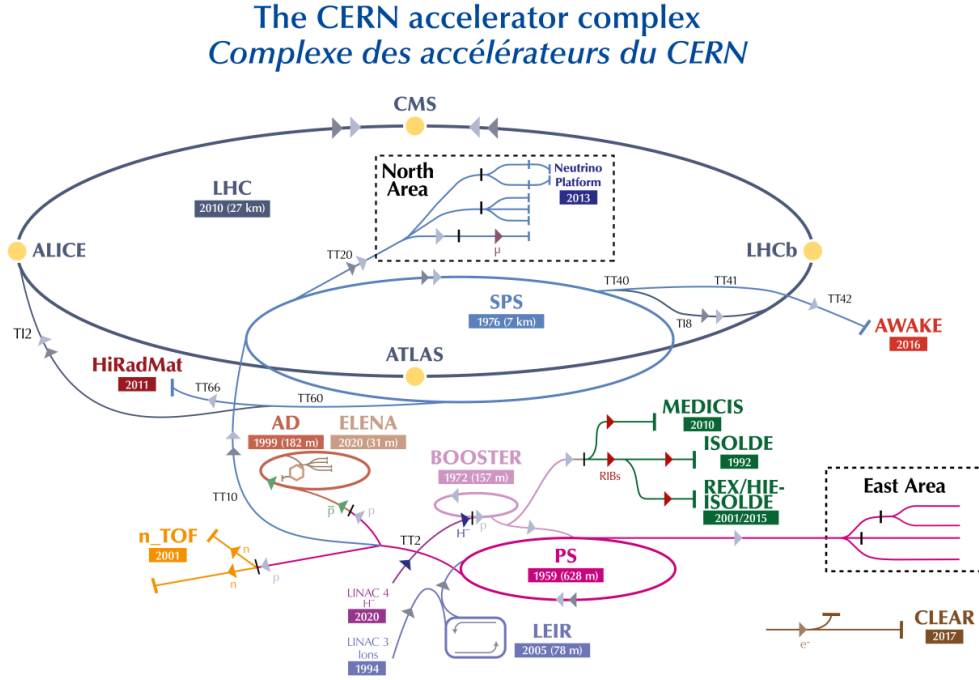


Figure 4.1: The CERN accelerator complex. H2 is a secondary beamline extracted from the SPS ring in the North Area site [68].

4.1.1 GENERAL LAYOUT

Figure 4.4 shows the beamtest layout: the particle beam crosses different detectors and components with different goals and characteristics. Starting from the upstream area, they are the following:

- two small plastic scintillator detectors (S1+S2), used for the trigger;
- two silicon telescopes that is double side x - y small area silicon microstrip detectors (T1 and T2) for the particle tracking;
- the PbWO_4 crystal samples with the SiPM matrices mounted on a high-precision goniometer with a resolution of a few μrad on all the angular axes;
- a large area plastic scintillator read out by a PMT, used as a multiplicity counter;
- the AGILE Beam Chamber (the one also used for the characterization of the STORM matrices at the INSULAB laboratory);
- a dipole bending magnet (BM), deflecting on the horizontal plane the charged particles exiting from the target;
- a second AGILE Beam Chamber;
- a BGO electromagnetic calorimeter named Genni.

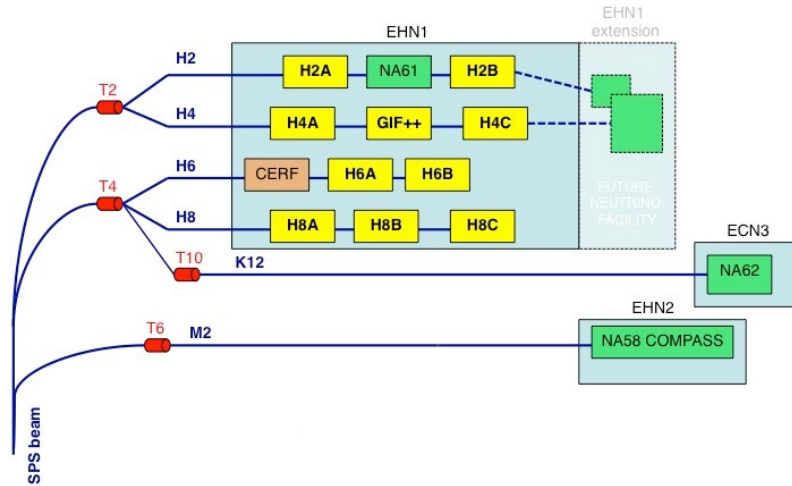


Figure 4.2: A schematic view of the CERN North Area extracted beamlines: STORM was installed in the H2B experimental area at the end of the H2 beamline [69].



(a)



(b)

Figure 4.3: a) Picture of the North Area from above and b) the North Area H2 beamline; the particle beam goes from left to right.

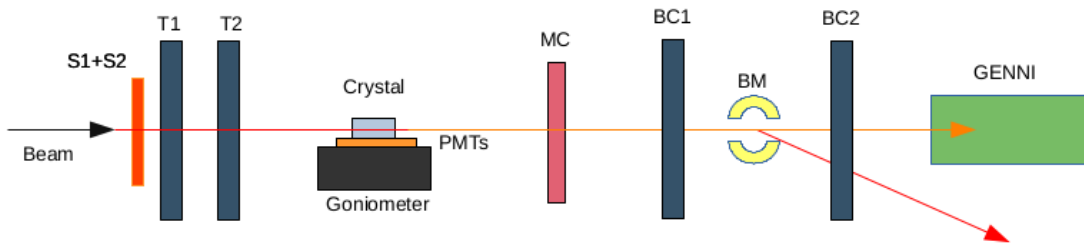


Figure 4.4: A schematic view of the STORM setup on the H2 beamline in August 2021; from left to right, the electron beam crosses the trigger system S1+S2, two silicon microstrip detectors (T1 and T2) for the particle tracking and impinges on the PbWO_4 crystalline sample positioned on a high resolution goniometer; the SiPM matrices read out the produced scintillation light. The electrons and photons, produced after the interaction with the crystal, cross a plastic scintillator, which works as a multiplicity counter, and a beam chamber. A bending magnet separates the electrons from the photons, which are detected by the electromagnetic calorimeter Genni.

4.1.2 THE TRIGGER SYSTEM

The trigger is the start of the physics event selection process. In this beamtest it was provided by two plastic scintillators (S1 and S2) of $4 \times 9 \text{ mm}^2$ of area and 7 mm of thickness in the z direction, both mounted on the front face of the first silicon telescope (T1) and read out by standard high voltage PhotoMultiplier Tubes (figure 4.5). The S1 scintillator has a hole of $3.5 \times 9 \text{ mm}^2$, so that the trigger is given by the coincidence of the beamline spill¹ signal, sent by the accelerator monitoring system, and of the signal from S2 in anti-coincidence with the signal from S1 ($\text{spill} \wedge (\text{S2} \wedge \overline{\text{S1}})$). In this way, the system is forced to acquire only particles that cross the hole of S1, collimating the beam and at the same time defining a maximum beam spot size.

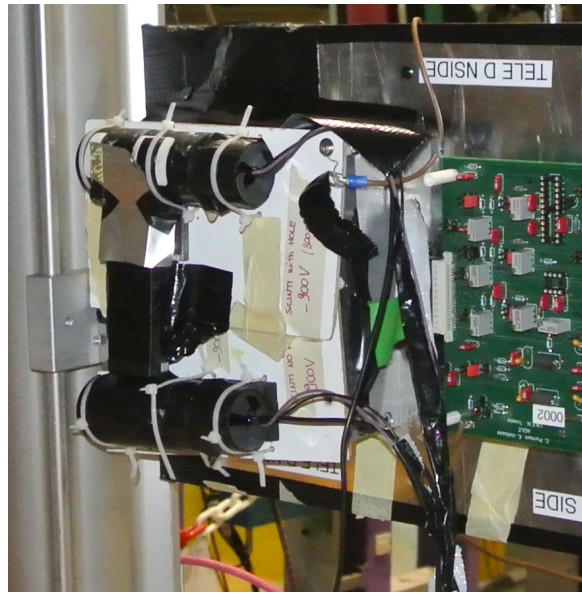


Figure 4.5: The S1 and S2 trigger scintillators assembled in front of the T1 detector.

4.1.3 THE TRACKING SYSTEM

The tracking system is composed by two modules of double side x - y small area silicon microstrip detectors (T1 and T2 telescopes [70]) and two single side silicon microstrip detectors (the AGILE Beam Chambers [66] [71–73]). A high resolution system such as a silicon microstrip system allows to reach a high angular resolution with a compact setup and a small amount of material on the beam to limit the multiple scattering contribution.

One of the two telescopes is shown in figure 4.6. Each module consists of a double side high resistivity $300 \mu\text{m}$ thick $1.92 \times 1.92 \text{ cm}^2$ silicon microstrip detector, and its frontend electronics. The junction side (p^+ side of the silicon tile) of the detector has 384 strips with a readout pitch of $50 \mu\text{m}$, while the implant pitch is $25 \mu\text{m}$ (a floating strip readout scheme is applied, that is only 1 strip over two is actually read). The ohmic side (which is

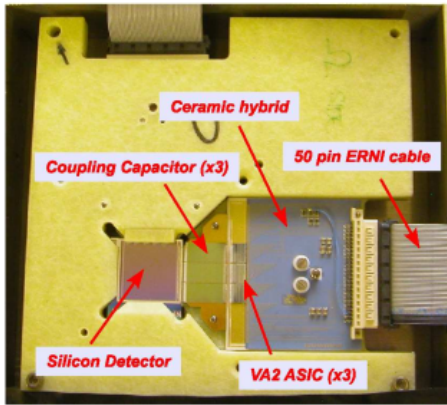
¹ The beam extracted from the SPS ring is fed into the line in “bunches”; the single bunch is called “spill” and lasts about 4 s each cycle (whose period is variable between 20 and 45 s, depending on the machine settings).

perpendicular to the junction one) has 384 readout strips with a pitch of $50\text{ }\mu\text{m}$, separated by p^+ blocking strips and no floating scheme is used. The full depletion voltage is in the 36-54 V range.

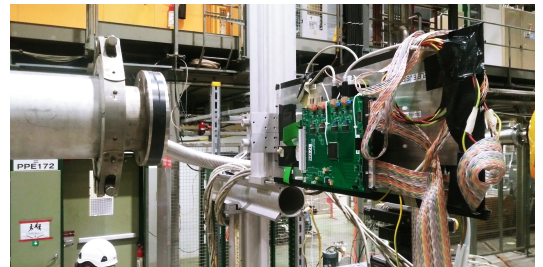
Each silicon side is readout by three VA2 ASICs, 128 channel radiation tolerant integrated circuits built with the $1.2\text{ }\mu\text{m}$ N-well CMOS technology [71]. Each ASIC channel consists of:

- a folded cascode low-noise/low power preamplifier;
- a CR-RC shaper;
- a sample & hold circuit.

The 128 output signals are multiplexed on a single output line, with a maximum frequency for the readout clock of 10 MHz. The three ASICs are AC coupled to the double side silicon detector with external quartz capacitors. They are interfaced with the rest of the frontend electronics with a multi-layer ceramic hybrid. The n-side signals are level shifted by an opto-coupler and the output signals of both sides are conditioned by a repeater card which provides the bias voltage, the power and the control signals to the hybrid. The analog signal is converted to a digital one by an Analog to Digital Converter (ADC) on the VME Readout Board (VRB), which is able to perform the so-called “zero suppression”: the DAQ system stores only the strips which exceed a predefined threshold, reducing the amount of data to transfer. The high spatial resolution of the two modules ($5\text{ }\mu\text{m}$ on the junction side and $10\text{ }\mu\text{m}$ on the ohmic side [70]) allows to measure with high precision the trajectory and the input angle of the charged particles impinging on the crystal sample.



(a)



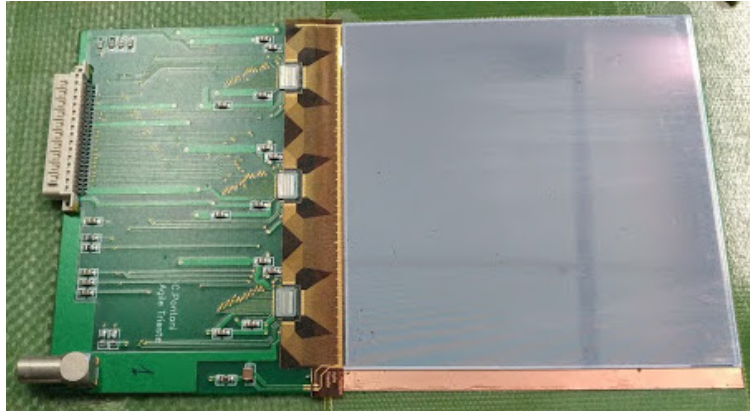
(b)

Figure 4.6: a) The telescope module assembled on the fiberglass frame together with the readout ASICs and the ceramic hybrid. b) The telescope box on the beamline.

The AGILE beam chambers are based on the detectors developed for the AGILE satellite [72]. Each chamber consists of two single side silicon tiles of $9.5 \times 9.5\text{ cm}^2$ and $410\text{ }\mu\text{m}$ thickness arranged in a x - y scheme. The strips have a $121\text{ }\mu\text{m}$ physical pitch [66] [73] and a floating strip scheme is used for the readout, i.e. only one strip every two is read out since the interstrip capacitance, implemented by properly tuning the dimensions of both

the aluminum layer and the implant in the sensor design phase, allows the charge to be shared between adjacent strips. This configuration guarantees the same spatial resolution as if all the strips were read out while halving the number of readout channels and thus reducing the power consumption and the data size. The spatial resolution of the detector is $30\text{ }\mu\text{m}$ [73] [72].

As shown in figure 4.7, the sensors are assembled on 3 or 5 mm thick fiberglass supports together with the ASICs Printed Circuit Board. The strips are connected via $17\text{ }\mu\text{m}$ aluminum wire-bonds to a pitch adapter, i.e. a circuit that adapts the sensor readout pitch ($242\text{ }\mu\text{m}$) to the ASIC channels pitch ($100\text{ }\mu\text{m}$) [66] [71]. Each sensor is read out by three 128-channel, low-noise, analog-digital TA1 ASICs built with the $1.2\text{ }\mu\text{m}$ N-well CMOS technology [71]. Each channel consists of a preamplifier, a CR-RC shaper and a sample & hold circuit; the shaper output is fed also to a high-pass filter and a discriminator with a tunable threshold: every time one of the 128 channels is above threshold, a digital output trigger signal is generated. The readout of the differential analog output is multiplexed, with a maximum clock frequency of 10 MHz.



(a)



(b)

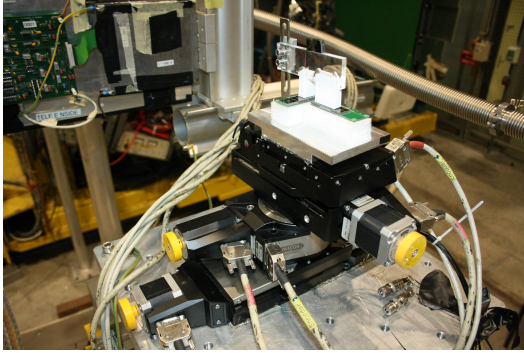
Figure 4.7: a) An AGILE silicon microstrip layer coupled to the ASICs PCB and assembled on the fiberglass support. b) The Agile Beam Chamber on the beamline.

4.1.4 THE GONIOMETER

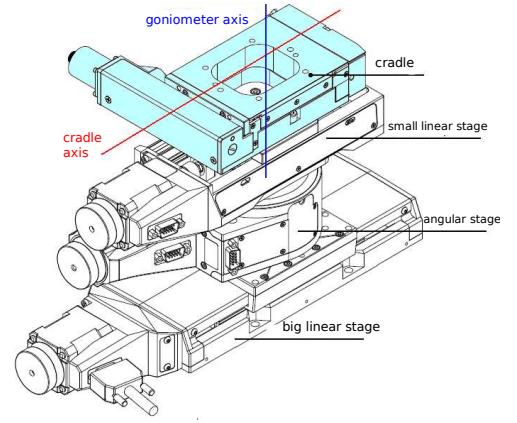
The study of channeling phenomena and of the strong field effects requires a very accurate alignment system to orient the crystals with respect to the charged particle beam. The measurements described in this thesis work use a high precision goniometric system that allows the precise positioning of the crystal on the beam and its alignment [74]. It consists of different stages (figure 4.8):

- a linear one for the horizontal movement along the x direction perpendicular to the beam;
- a rotational stage to align the crystal lattice with respect to the incoming beam on the x - z plane, with an accuracy of the order of a few μrad ;
- a second linear stage;
- an additional rotational stage (named cradle) to align the crystalline planes in the y - z direction.

All the stages are equipped with two-phase microstep motors, and mechanical limit switches are integrated in the two linear stages. The control of the angular rotation is provided by an optical encoder and closed loop mechanism, which guarantees the required angular accuracy and repeatability. The goniometer is remotely controlled by the DAQ system, and the motor positions are stored in the data files and in dedicated control files.



(a)



(b)

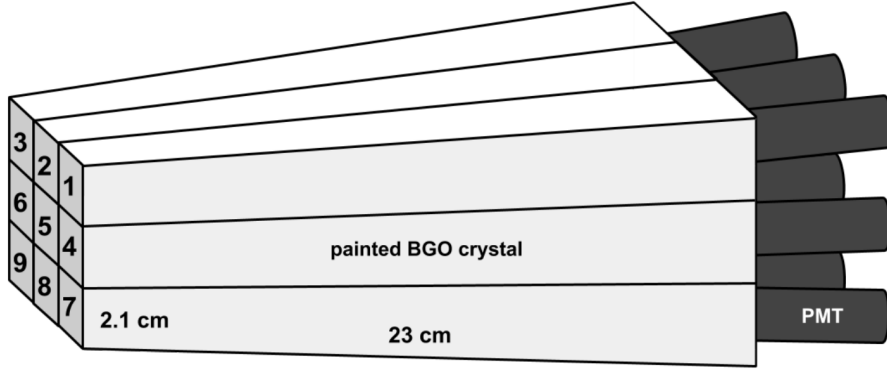
Figure 4.8: a) A photo of the goniometer on the beamline and b) the goniometer scheme; from top to bottom: the cradle, the small linear stage, the angular stage, the big linear stage.

4.1.5 THE GENNI CALORIMETER

Genni is a homogeneous electromagnetic calorimeter composed by a 3×3 matrix of BGO crystals, spare pieces of the PADME calorimeter. The PADME crystals have been obtained

by cutting the bigger crystals of the L3 endcap calorimeter and have an approximate dimension of $2.1 \times 2.1 \times 23 \text{ cm}^3$ ($\sim 25 X_0$) [75] [76]. Each crystal is coupled to a Photonis XP1912 PMT biased up to -850 V [77]. The crystals and the PMTs are mounted on a dedicated structure (figure 4.9), that allows to minimize the dead regions in the active volume to the $\lesssim 1 \text{ mm}$ irreducible gaps created by the white painting. Details on the Genni characterization can be found in [78] [41].

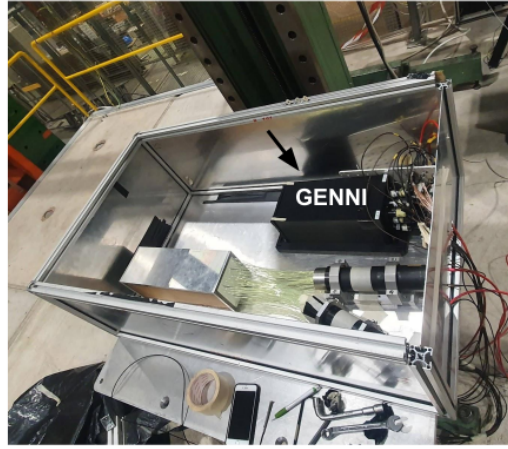
The calorimeter is read out with a V1730C CAEN digitizer, which has a sampling frequency of 500 MHz and a resolution of 14 bits.



(a)



(b)



(c)

Figure 4.9: a) Scheme of Genni. b) A photo of Genni. c) A photo of Genni on the beamline. The calorimeter was positioned inside a box in order to protect it from the ambient light. In the photo, a second calorimeter is present, which has not been used in this thesis work.

4.1.6 THE DATA ACQUISITION (DAQ) SYSTEM

A schematic representation of the DAQ system is shown in figure 4.10. The data taking procedure is the following:

- the signals of the S1 and S2 trigger scintillators are sent to a NIM discriminator which generates digital signals;
- these signals, once properly conditioned, are sent to a VME trigger board along with the SPS spill signal. The trigger board generates the trigger when the particles cross the hole of the S1 scintillator ($\text{spill} \wedge (S2 \wedge \overline{S1})$);
- the VME Readout Board of the first telescope (VRB master) generates a busy signal that acts as the trigger for the slave VRBs (the ones of the other silicon detectors) and for the digitizer (the module for the readout of the calorimeter);
- each VRB generates the hold signal to sample the peak of the shaper output, after a given time interval chosen to optimize the signal to noise ratio;
- each VRB generates then the sequence of digital signals necessary to shift the channels PH values to the ADC where they are converted;
- in the VRB the signals are zero-suppressed and stored into memories, to be read out during the inter-spill period;
- the digitizer receives the busy signal generated by the master VRB and samples the waveform from the SiPMs, the multiplicity counter and the Genni calorimeter. The information (the amplitude of the signal, its time and the waveform itself) are stored into memories and sent to the PC to be read out in the inter-spill period;
- the readout of the angular and linear stages of the goniometric system is performed by optical encoders, remotely controlled by the DAQ;
- the data are saved in HBOOK ntuples;
- an online pre-processing procedure selects the events that present a single cluster (a single particle) in the T1 and T2 detectors, and it produces ASCII files in which every row corresponds to an event while all the information of the single event is arranged in columns: x , y silicon hit positions and number of clusters, the PHs and the times from the digitizer, the goniometer coordinates and the waveform of the SiPMs;
- the final file is a root tree storing the same ASCII file information.

4.2 PRELIMINARY DATA ANALYSIS

The preliminary part of the data analysis has been performed without the crystal on the beamline, and it consists of:

- the alignment of the silicon strip detectors with respect to the first telescope, in order to correct for physical misplacements among the detection planes;

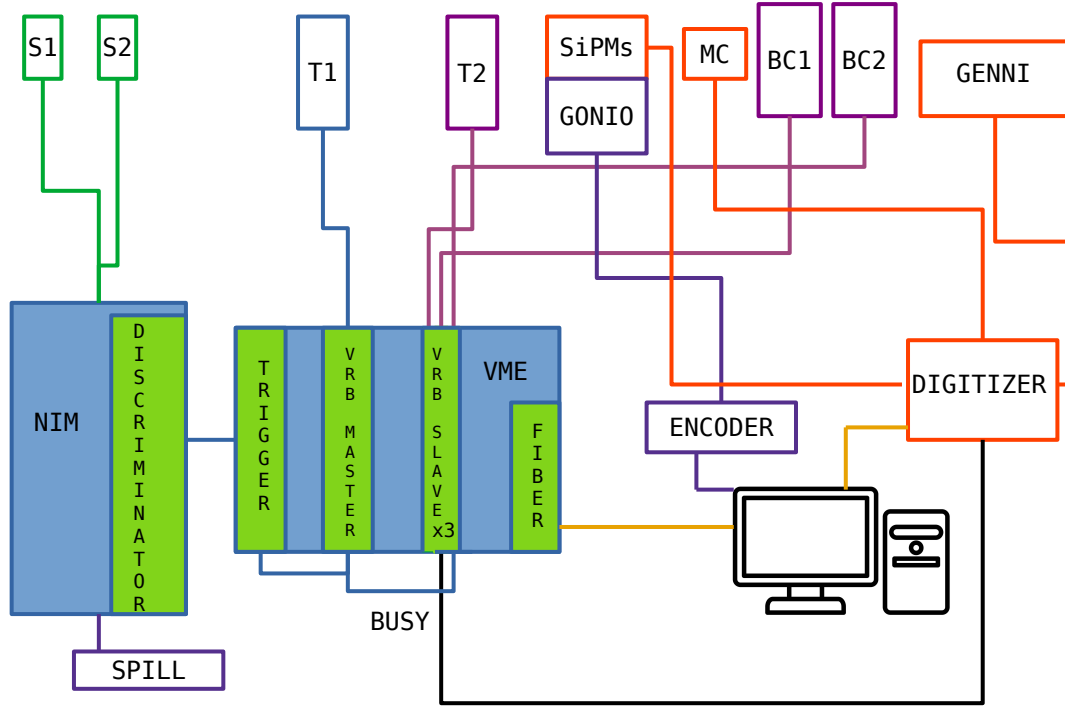


Figure 4.10: The DAQ scheme.

- the study of the beam divergence as a function of the energy to verify that it is small enough to observe the coherent interactions in the oriented crystals;
- the equalization and calibration of the response of the Genni crystals, in order to convert the raw PHs into energy deposits measured in GeV.

The data analysis was performed using the numpy [79], matplotlib [80], scipy.optimize [81] and lmfit [82] Python3 packages.

4.2.1 SILICON STRIP DETECTORS ALIGNMENT

During the assembly phase of the experimental setup, the four silicon strip detectors have been manually aligned with respect to the beam axis; figure 4.11 shows the 2D distributions of the x - y coordinates of the silicon trackers from T1 to BC2. These plots represent the beam spot on each detector. Figure 4.12 shows the distributions of the x and y hit positions on each silicon detector; it can be seen that the modules were not perfectly aligned.

All the silicon detectors have been aligned to the first telescope, in both the x and y axes, with a dedicated software procedure. Taking into account the scheme in figure 4.13, the shift parameter can be evaluated as:

$$\text{shift}_i = \tan(\mu) \cdot (z_i - z_{T1}) \quad (4.1)$$

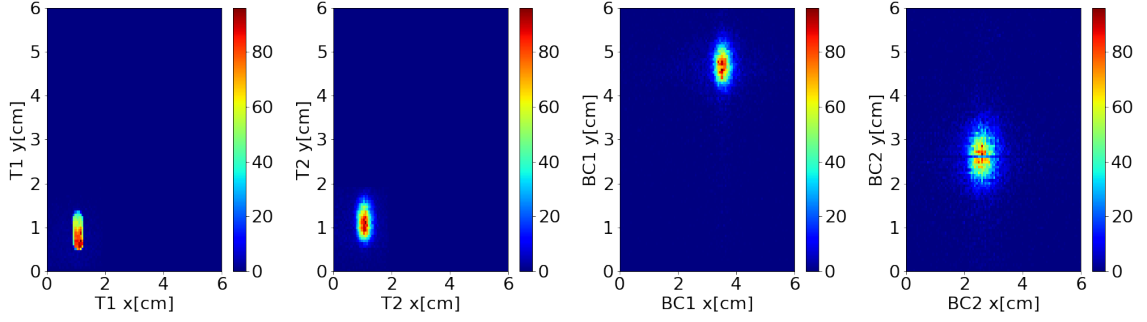


Figure 4.11: 2D distributions of the x - y coordinates of the silicon trackers from T1 to BC2 before the offline alignment. The shape of the beam, evident in the T1 beam profile, is due to the hole of the S1 trigger detector.

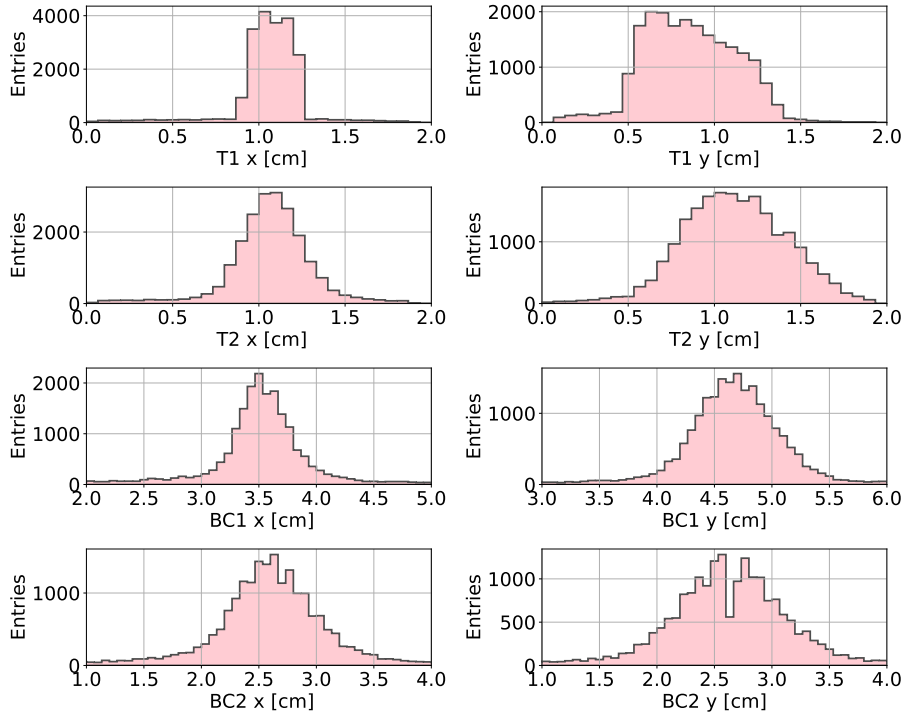


Figure 4.12: 1D distributions of the x - y coordinates of the silicon trackers from T1 to BC2 before the offline alignment.

where z_i is the distance between T1 and all the other modules and μ is the mean value extracted by the Gaussian fit of the distribution of the track angles (figure 4.14), calculated as in equation 3.2. The aligned positions in the x direction, for the i -th silicon detector, are thus:

$$x_{sh,i} = x_i - \text{shift}_{x,i} \quad (4.2)$$

The same has been done for the y coordinate. The 2D distributions of the x - y coordinates of the aligned silicon detectors are shown in figure 4.15.

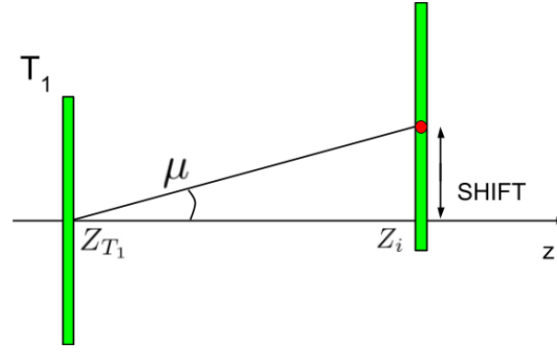


Figure 4.13: Scheme of the offline alignment procedure: all the detectors have been aligned with respect to the first telescope; μ is the mean value extracted by the Gaussian fit of the angular distribution in the x and y directions.

4.2.2 BEAM DIVERGENCE

The beam divergence, i.e. the standard deviation of the Gaussian curve fitted on the T1-T2 angular distribution, should be small enough to allow the measurement of the strong field effects. For a 120 GeV electron beam impinging on a PbWO_4 sample, the acceptance angular range for the strong field once in axial condition is $\Theta_0 \approx 1.2$ mrad.

Figure 4.16 shows the beam divergence for 20 and 120 GeV. For 120 GeV the beam divergence is 92.34 ± 1.35 μrad along the x direction and 100.74 ± 0.97 μrad along the y direction, small enough to observe the coherent interactions; as the energy decreases, the beam divergence becomes larger (~ 300 μrad for the 20 GeV beam) as shown in figure 4.17.

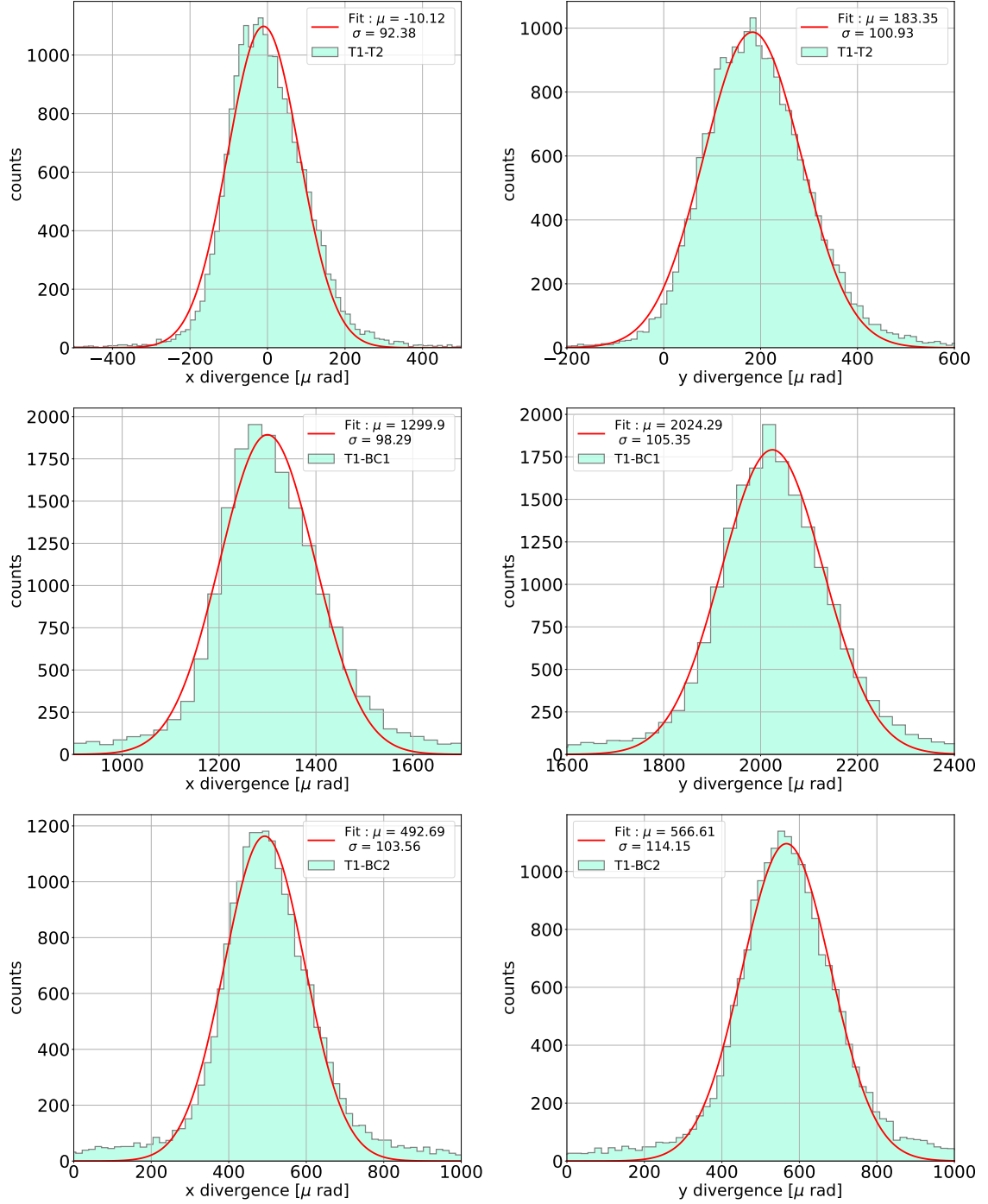
4.3 THE GENNI CALORIMETER ANALYSIS

In order to find the correspondence between the PH (in ADC counts) and the energy (in GeV) deposited in the detector by the incoming particles, a calibration with a monochromatic electron beam is required. The response of all the channels needs first to be equalized in order to have a homogeneous response from the calorimeter and to compute the total calorimeter energy, since each channel returns a different PH even for the same amount of deposited energy.

4.3.1 GENNI EQUALIZATION

The first step in the calorimeter characterization consists in the equalization of the channels, which is performed using a beam of Minimum Ionizing Particles, i.e. a beam of 80 GeV muons, as they deposit the same amount of energy through the calorimeter. The equalization is performed via the following equation:

$$PH_i \rightarrow Q_i \cdot PH_i \quad (4.3)$$

Figure 4.14: Angular distributions in x and y with respect to T1.

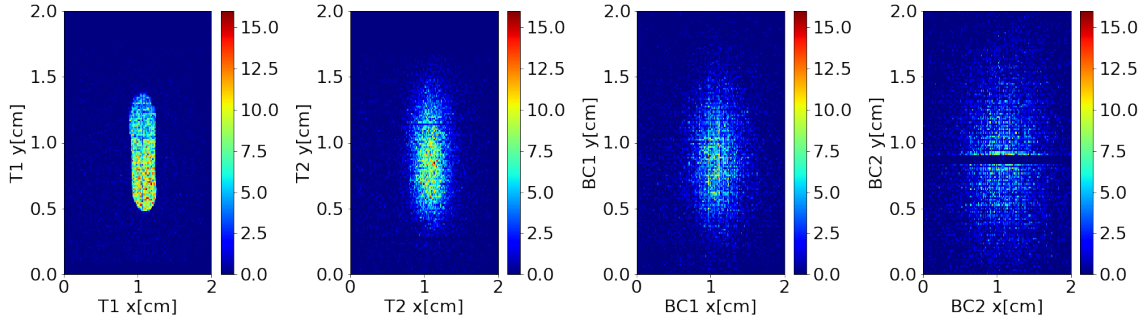


Figure 4.15: 2D distributions of the x - y coordinates of the silicon trackers from T1 to BC2 after the offline alignment.

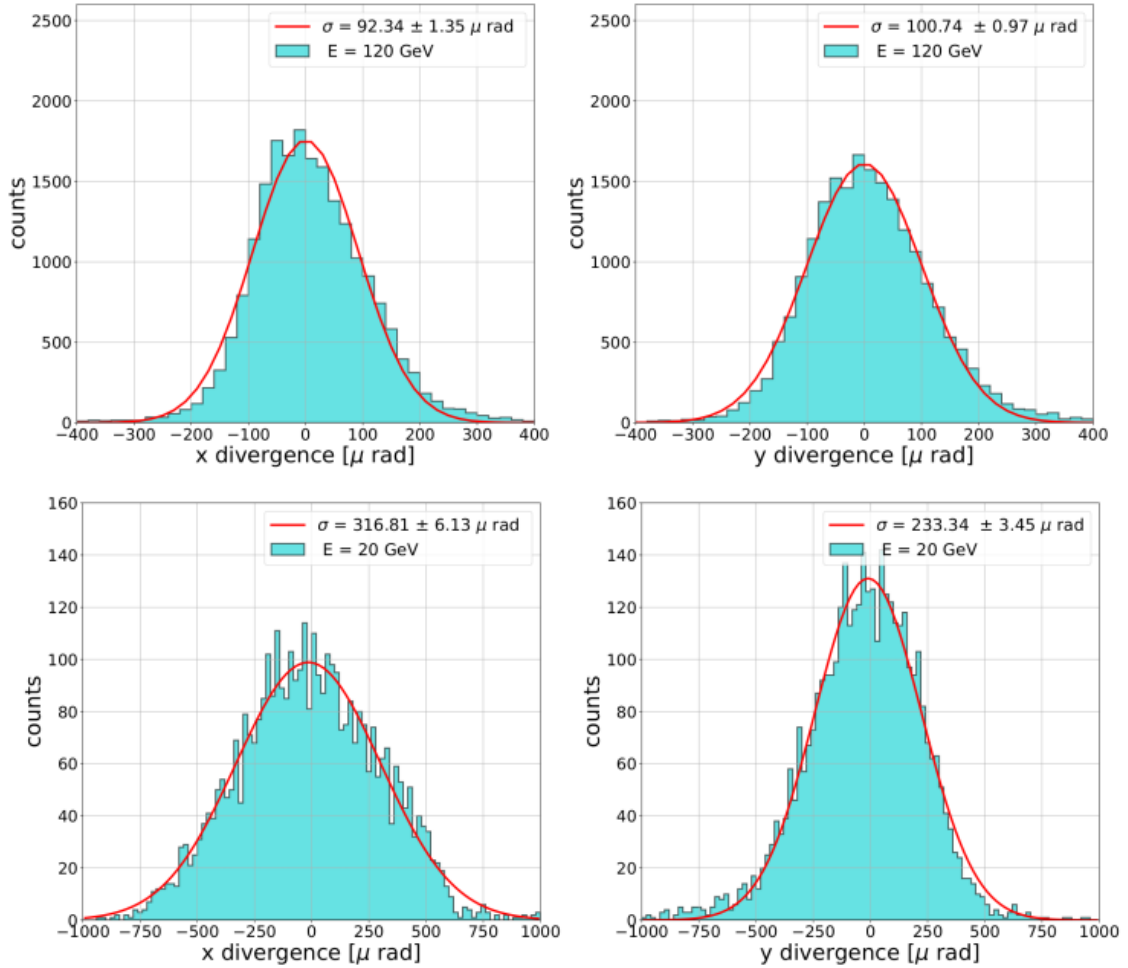


Figure 4.16: x and y angular distribution between T1 and T2 for the 20 and 120 GeV electron beam; the standard deviation of the Gaussian curve is the beam divergence.

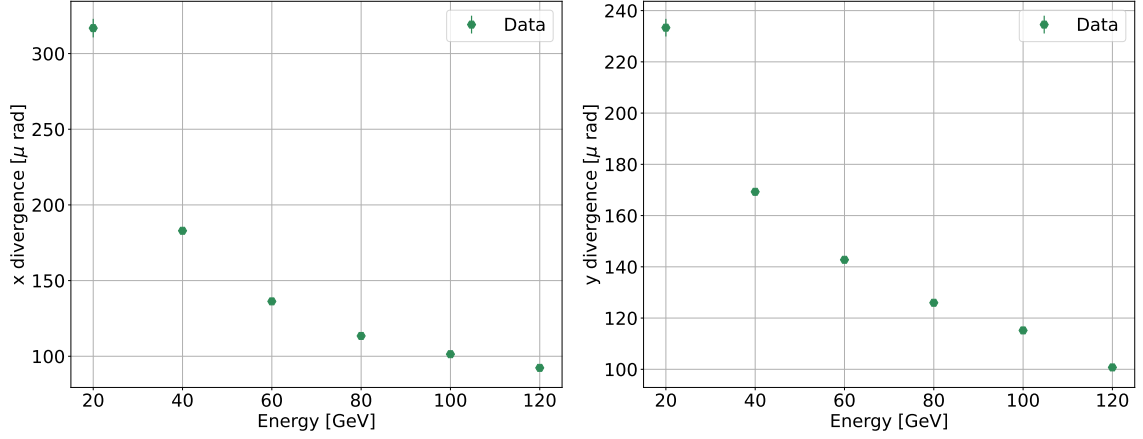


Figure 4.17: x and y angular divergence as a function of the beam energy; as the energy decreases, the beam divergence becomes larger.

where PH_i is the pulse height of the i -th channel and Q_i is the equalization factor defined as the ratio between the MIP peak value of the central channel (ch. 5), taken as the reference channel, and of the i -th channel. Genni was positioned on a DESY table², which is able to move in the vertical and horizontal direction; for every run, the muon beam was aligned with the center of each tower of Genni. For the equalization procedure, the PMTs bias was set to -700 V; during the data taking with the 120 GeV electron beam the bias was set to -500 V in order to avoid the saturation of the signal.

The muon tracks on the calorimeter plane have been extrapolated using BC1 and BC2; in order to reconstruct correctly the tracks of the incoming particles, the analysis has been performed only with single cluster events, i.e. the events in which only one particle has crossed the silicon detectors. Figure 4.18a shows the muon tracks reconstructed on each Genni channel; the red box represents the real area of the Genni tower.

A series of cuts have been applied on the events:

- cuts on the signal time, in order to exclude the baseline fluctuation events; figure 4.19 shows the correlation between the PH and the signal time. It can be seen that most of the events with a large PH populate a small part of the time spectrum. In fact only the real events, i.e. the particles detected by the trigger scintillators and by the calorimeter, have the same arrival time, while the other ones are due to the noise or particles that have not crossed the calorimeter;
- cuts on the beam divergence (figure 4.20), in order to select the events that impinge perpendicularly on the calorimeter.

Figure 4.18b shows the muon tracks reconstructed on each Genni channel after applying the cuts.

² A DESY table is a remote-operated moving platform, which is a standard infrastructure on CERN beamlines.

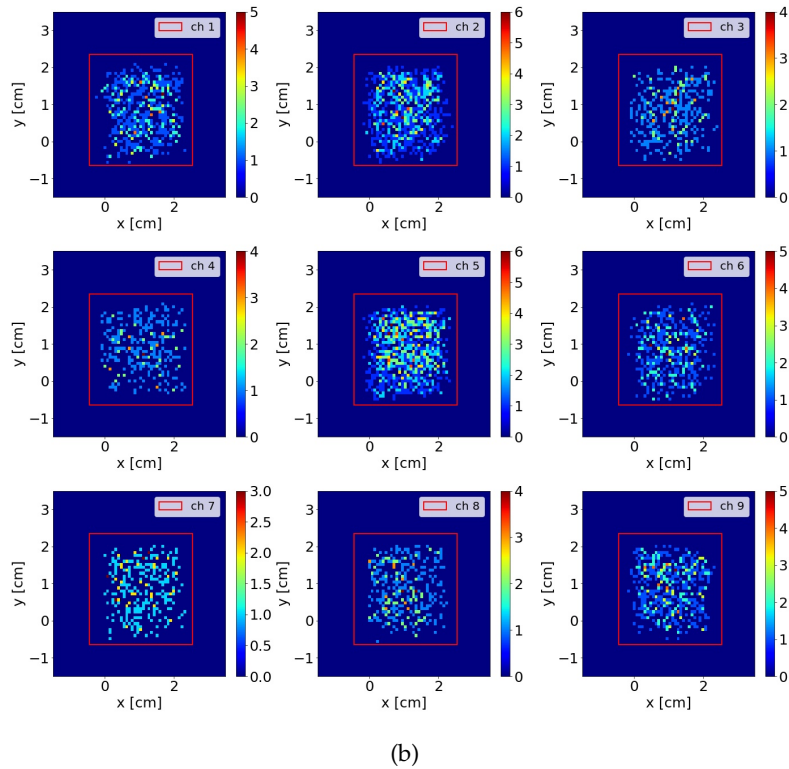
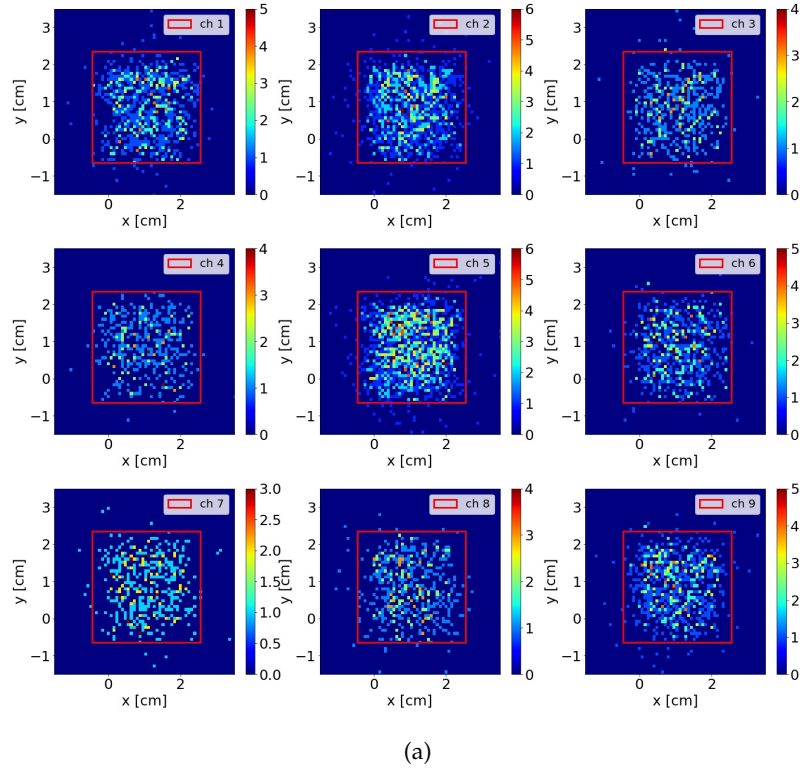


Figure 4.18: a) Muon tracks reconstructed on the front face of Genni for each channel before the selection on the events. b) Muon tracks after the selection in time and divergence. The red box represents the real dimension of each tower.

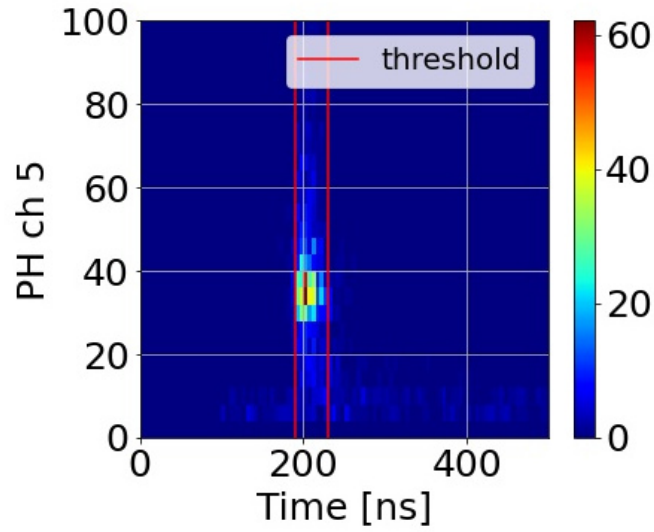
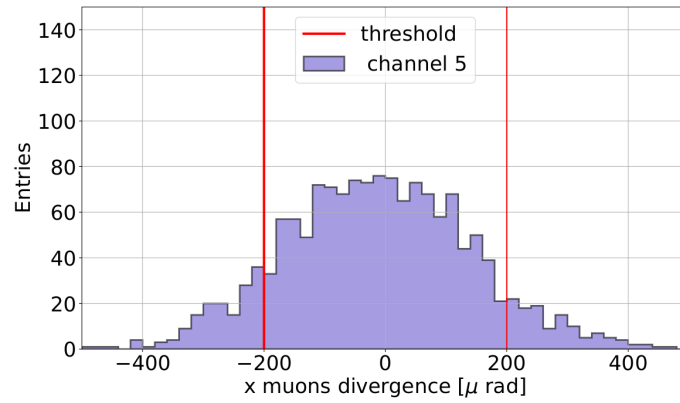
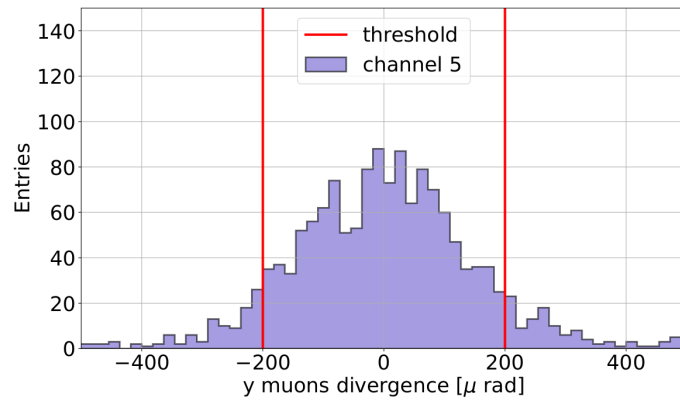


Figure 4.19: PH of the central channel as a function of the time of the maximum of the signal; the red lines are the thresholds chosen to select the real events.



(a)



(b)

Figure 4.20: Muon beam divergence in the x and y directions reconstructed with BC1 and BC2 on the central channel of Genni; the red lines are the thresholds chosen to select the most perpendicular events with respect to the calorimeter front face.

Ch. 1	Ch. 2	Ch. 3
0.276	0.580	0.375
Ch. 4	Ch. 5	Ch. 6
0.434	1	1.025
Ch. 7	Ch. 8	Ch. 9
0.314	0.19	0.615

Table 4.1: Equalization factors of the Genni readout channels.

The muon energy deposit in the BGO crystals is approximately constant (since they are MIPs) and results in a Landau-like distribution, which can be described using the Moyal approximation [83]:

$$f(\lambda) = A \cdot \exp^{-0.5(\lambda + \exp^{-\lambda})} \quad (4.4)$$

where λ is given by:

$$\lambda = \frac{\text{PH} - \text{mpv}}{\text{FWHM}} \quad (4.5)$$

where mpv is the *Most Probable Value* of the Landau curve and FWHM is the *Full Width at Half Maximum*, i.e. the width of the distribution at a level that is just half the maximum of the peak. Figure 4.21 shows the PH distribution of the calorimeter central channel with the Landau fit; the fit was performed using the Python LMFIT package: the errors on the fitted variables are automatically calculated from the covariance matrix. The equalization factors are reported in table 4.1.

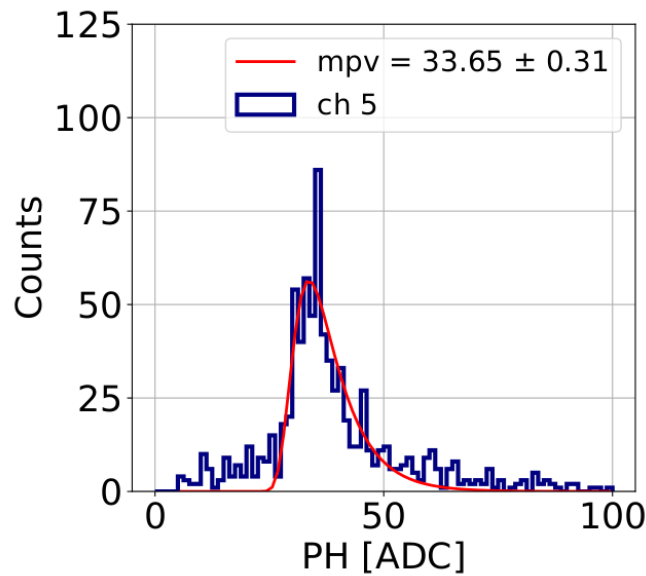


Figure 4.21: Example of the Landau PH distribution of the calorimeter central channel after applying the cuts in time and divergence.

4.3.2 CALIBRATION

Once completed the equalization, the calorimeter has to be calibrated in order to find the correspondence between the PH (measured in ADC) and the energy (in GeV) deposited by the incoming particles. The calibration was performed using different electron beams (from 20 GeV to 120 GeV) aligned with the center of the calorimeter (the Desy table was moved until the correct position was reached). Figure 4.22 shows the PH distribution in each calorimeter channel for a 120 GeV electron beam. As expected, the central channel has a larger value of PH with respect to the neighboring channels, given that the beam was centered on that channel and the Molière radius for BGO is 2.4 cm.

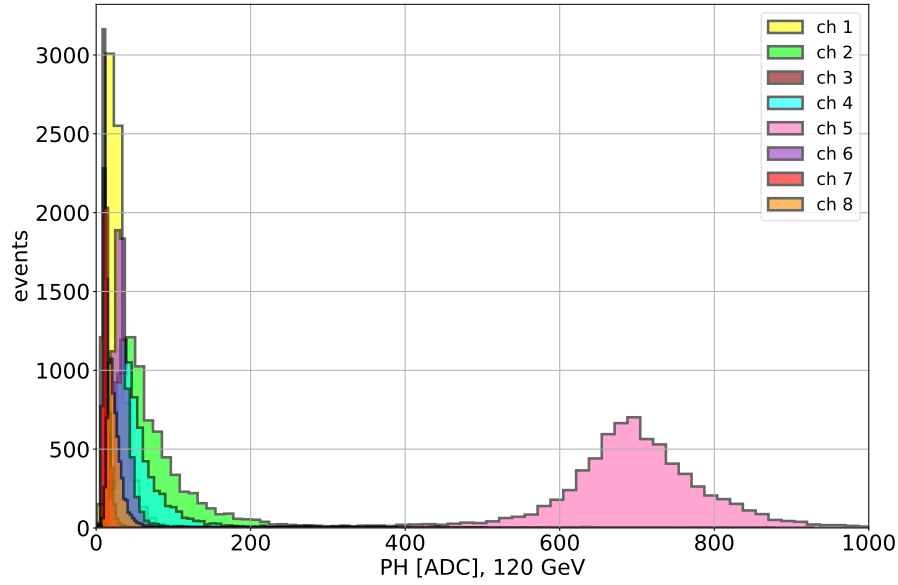


Figure 4.22: PH distributions of the Genni channels; since the beam is aligned with the center of the calorimeter, the central channel has a larger value of PH.

As for the equalization process, cuts in time and divergence have been applied in order to select the events of interest. Figure 4.23 presents an example of the selection in time for the fifth channel for the 120 GeV electron beam; the shift in time is due to the time walk of the trigger scintillators, thus all the events inside the red lines can be considered in time.

Figure 4.24 shows the divergence distributions in x and y for 120 GeV electrons and 20 GeV electrons with the respective threshold. The same cuts have been applied for all the energies. After the equalization, it is possible to sum all the channels and measure the energy deposited by the electrons inside Genni. The electron peak at different energies has been fitted with a Gaussian function (figure 4.25). Since the BGO crystals and the PMTs have a linear response, a linear relation between the PH in ADC and the energy in GeV is expected. The calibration plot fitted with a first-degree polynomial is presented in figure 4.26.

Figure 4.27 presents the percent residuals calculated as $100 \cdot (y_{meas} - y_{fit}) / y_{fit}$. The point at 80 GeV has a percent residual value of $\sim 6\%$, and therefore it has been excluded from

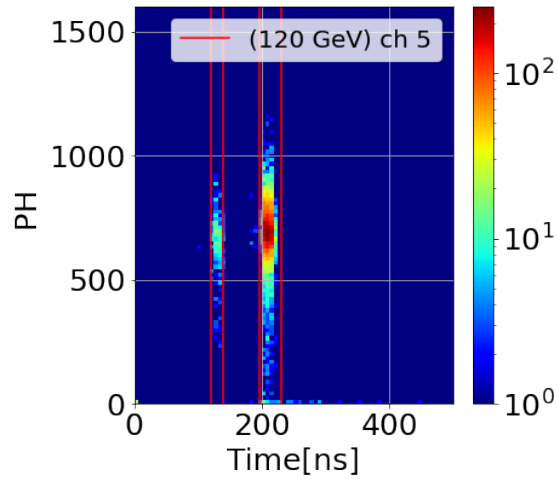


Figure 4.23: Example of the fifth channel PH-time scatter plot for the 120 GeV electron beam. The shift in time of a number of events is due to the time walk of the trigger scintillator; all the events inside the red lines can be considered in time.

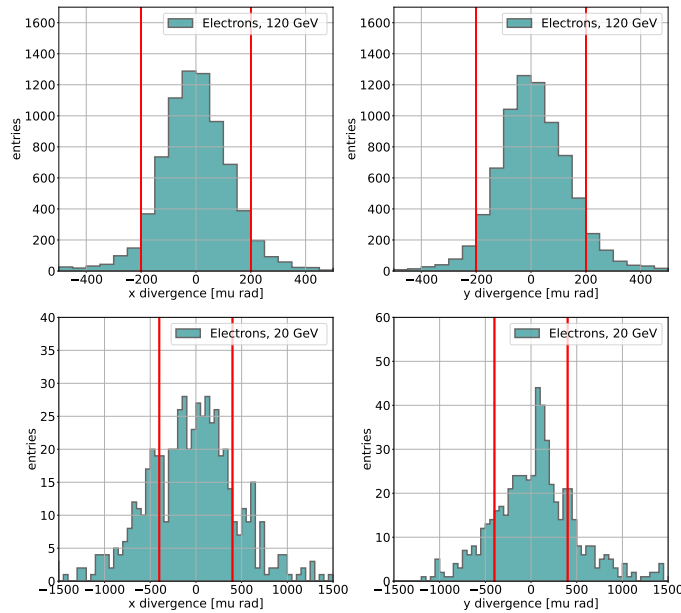


Figure 4.24: x and y divergence for 120 GeV and 20 GeV electrons.

the fit. The larger residual value of this point is probably due to a contamination of the primary electron beam.

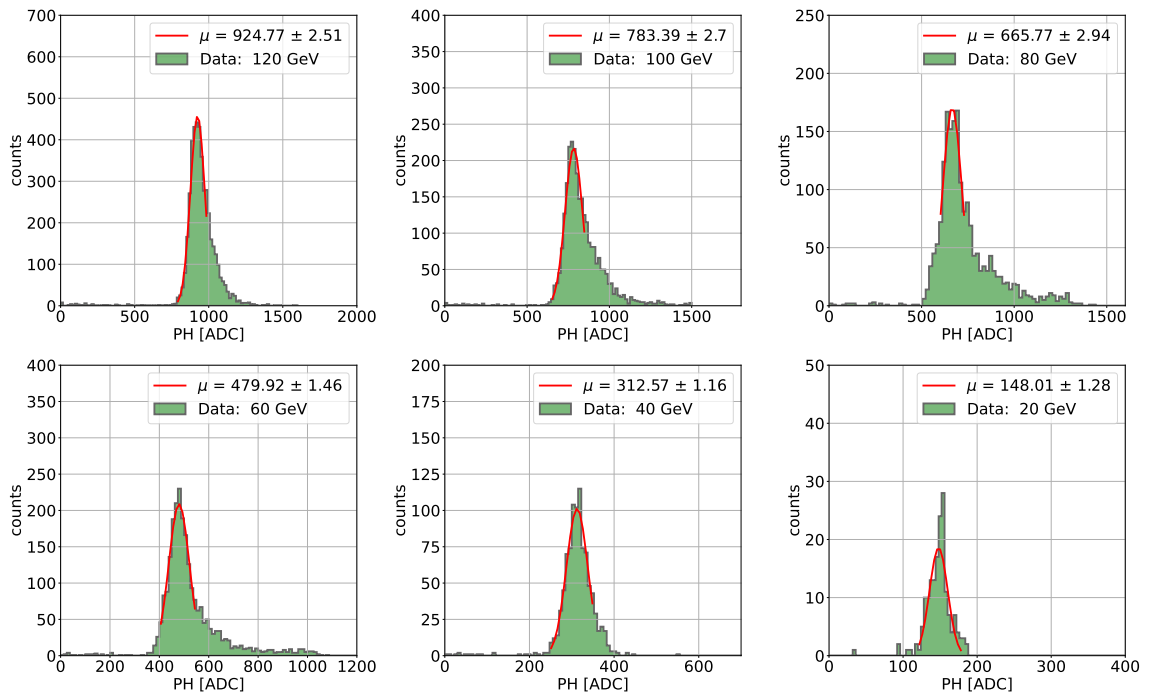


Figure 4.25: Genni PH for different electron beam energies; the peak has been fitted with a Gaussian curve. The large tails in the 100 GeV, 80 GeV and 60 GeV on the right of the spectrum are probably due to a contamination of the primary electron beam.

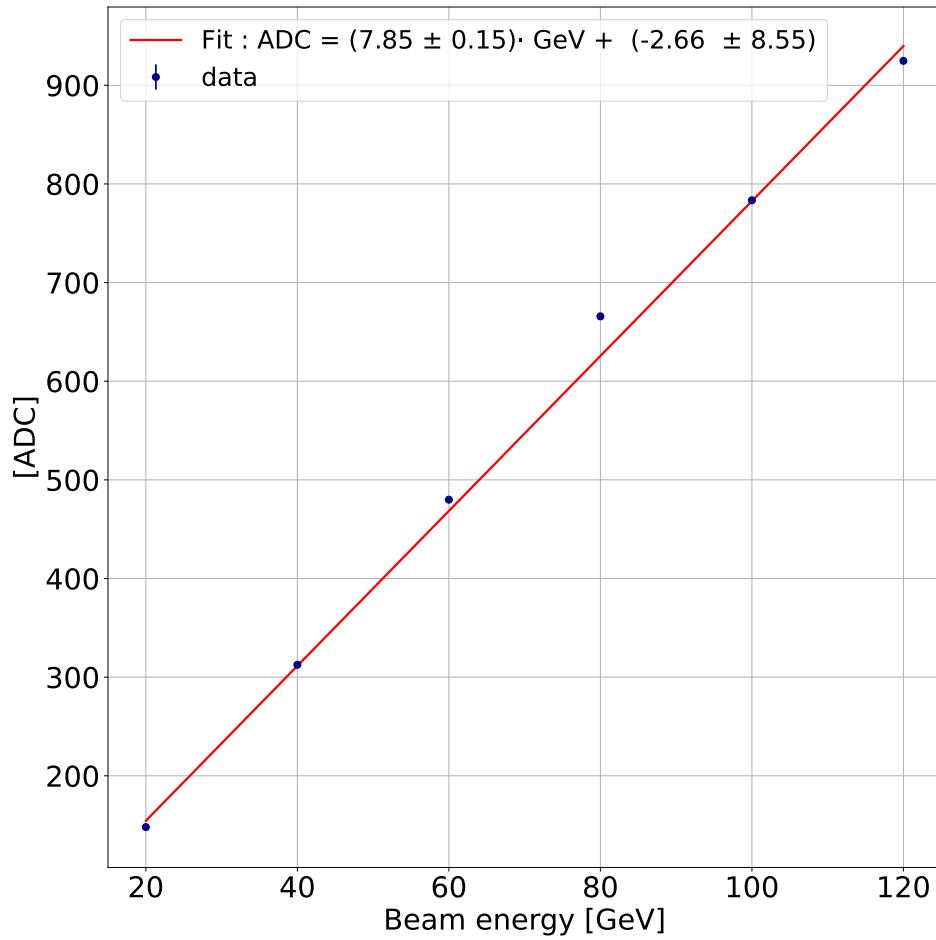


Figure 4.26: Genni calibration curve. The point at 80 GeV has been excluded from the fit.

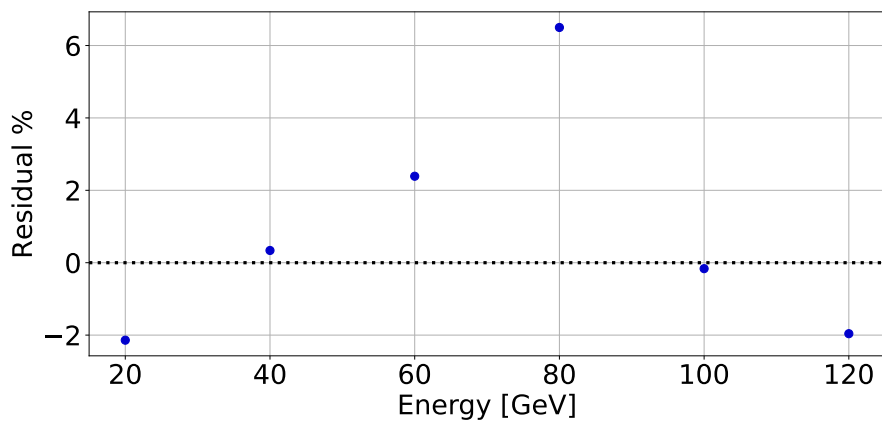


Figure 4.27: Percent residual plot. The point at 80 GeV presents a residual value of $\sim 6\%$, and therefore it has been excluded from the fit.

DATA ANALYSIS AND RESULTS

The goal of the STORM experiment is to study how the response of the oriented crystal changes as a function of the angles of the beam with respect to the axis in the strong field regime. In particular, the electromagnetic shower development inside the oriented crystal is estimated measuring the light produced in the crystal itself and correlating it with the energy loss, measured by the downstream calorimeter.

This chapter will present the experimental steps that have been performed to reach this goal and the results of the 2021 beamtest.

The chapter will describe in detail the following steps:

- the positioning of the crystal on the beam. The presence of the crystal on the beam is generally verified observing the response of the detectors after the crystal. In fact, if the crystal intercepts the beam, an enhancement in the multiplicity of the output particles is expected;
- the crystal is then oriented with the axis aligned with respect to the beam. To do that, a manual pre-alignment procedure is followed which guarantees to align the sample within a few mrad with respect to the particle beam; this procedure is described in section 5.1.1. The fine alignment, which guarantees to start the data taking with the beam aligned with respect to the axis, is performed with data and is described in section 5.1.2. It will be shown that the alignment can be verified either by measuring the multiplicity of charged particles in the scintillator positioned after the crystal, or by measuring the energy deposited in the crystal itself which is read out by the SiPMs;
- after having oriented the crystal axis with respect to the beam, the goniometer coordinate is moved by some fraction of the strong field angular acceptance Θ_0 , and the electromagnetic shower development inside the oriented crystal is studied. The results are described in section 5.2;
- the last part of the chapter focuses on the evaluation of the X_0 reduction.

5.1 THE CRYSTAL ALIGNMENT PROCEDURE

The alignment procedure is performed building the so-called *stereogram* (figure 5.1): the abscissa and the ordinate are the x and y coordinates of the misalignment angles ($\theta_{x,mis}$,

$\theta_{y,mis}$ from equation 2.1), i.e. the angles between the particle trajectory and the crystalline sample; the origin coincides with the axis and the black lines represent some crystalline planes (the axis is the interception point of all the crystalline planes).

In order to find the axis, an alignment procedure is needed; this is done by an initial manual pre-alignment which guarantees the crystal to be positioned aligned within a few mrad with respect to the particle beam. The exact position of the axis is found probing the stereogram and observing the response of the SiPMs and the multiplicity counter, positioned right after the crystal. One expects that the PH of the multiplicity plastic scintillator and the PH of the SiPMs are larger when the beam is close to the axis.

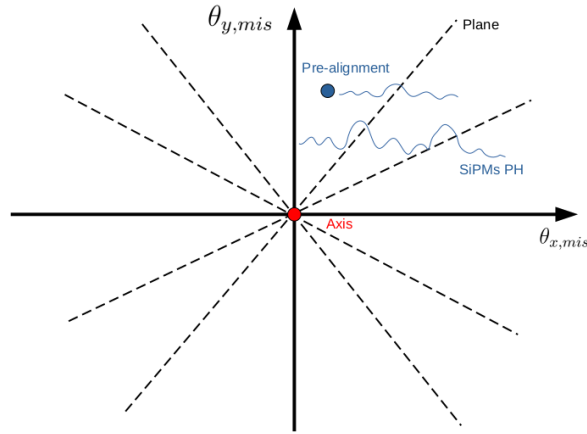


Figure 5.1: The stereogram: the abscissa and the ordinate are the x and y coordinate $\theta_{x,mis}$, $\theta_{y,mis}$ of the angles between the particle trajectory and the crystalline sample; the dashed black lines represent the crystallographic planes, whose intersection point is the axis (red dot). The pre-alignment procedure allows to start the data taking with the sample aligned within a few mrad with respect to the particle beam. The blue lines represent the SiPMs or the multiplicity counter response; the PH of the SiPMs and the one of the multiplicity counter are expected to be larger when the beam is aligned with respect to the axis; a smaller enhancement is expected when it is aligned with planes.

5.1.1 THE PRE-ALIGNMENT

The pre-alignment procedure is performed by means of a laser and several mirrors; if the sample cannot reflect the laser used for the pre-alignement on the beamline, as in the case of the coated PbWO_4 crystals, a mirror mounted on the holder is required. The angular offset between the mirror and the sample is calculated preliminarily in the laboratory using a High-Resolution X-Ray Diffractometer (HRXRD). X-rays can directly probe the angular orientation of the lattice. In addition, Bragg diffraction occurs very precisely when the lattice planes are at θ_{Bragg} with respect to the incoming X-rays; this provides a high angular resolution. The procedure to calculate the offset between the mirror and the sample is the following:

- the samples are mounted on the holder;

- a silicon crystal with polished surfaces is mounted on the holder as a reference mirror (figure 5.2);
- the holder is mounted on a High-Resolution X-ray Diffractometer. The angular position (ω) of each sample and the mirror during the Bragg diffraction is recorded:

$$\omega_{sample} = \theta_{Bragg} + \beta \quad (5.1)$$

where β is the mounting offset;

- the angle $\Delta_{sample} = \omega_{sample} - \theta_{Bragg}$ indicates the angle between each sample on the holder and the incoming X-rays;
- the angular offset between the mirror and the samples can be calculated as $\Delta_{sample} - \Delta_{mirror}$.

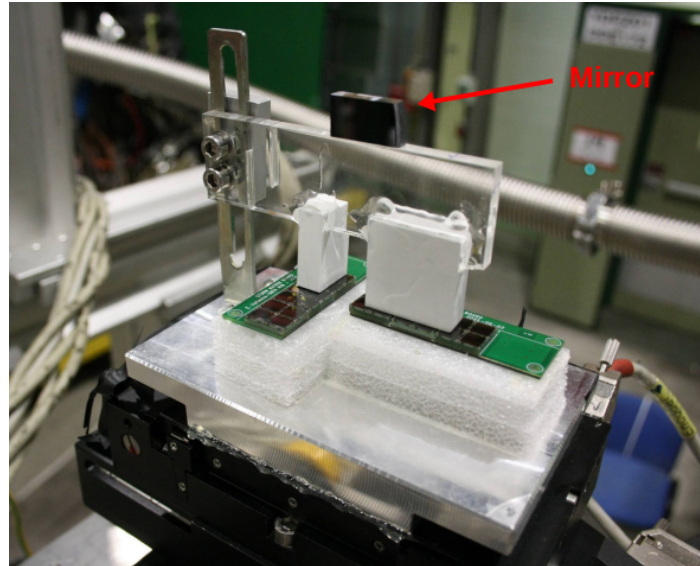


Figure 5.2: The crystalline sample mounted on the holder; the silicon crystal with polished surfaces is used as a reference mirror in the pre-alignment procedure.

On the beamline the pre-alignment procedure is performed using a laser and a pentaprism; the procedure is the following (figure 5.3):

1. the crystalline samples, mounted on the holder with the mirror, are placed on the goniometer on the beamline;
2. a straight line parallel with respect to the beam is drawn on the ground as a reference line;
3. two plummets, set on the reference line, are used to align the laser;
4. a pentaprism is positioned in front of the crystalline samples and reflects the laser light of exactly 90° on the reference mirror on the holder;

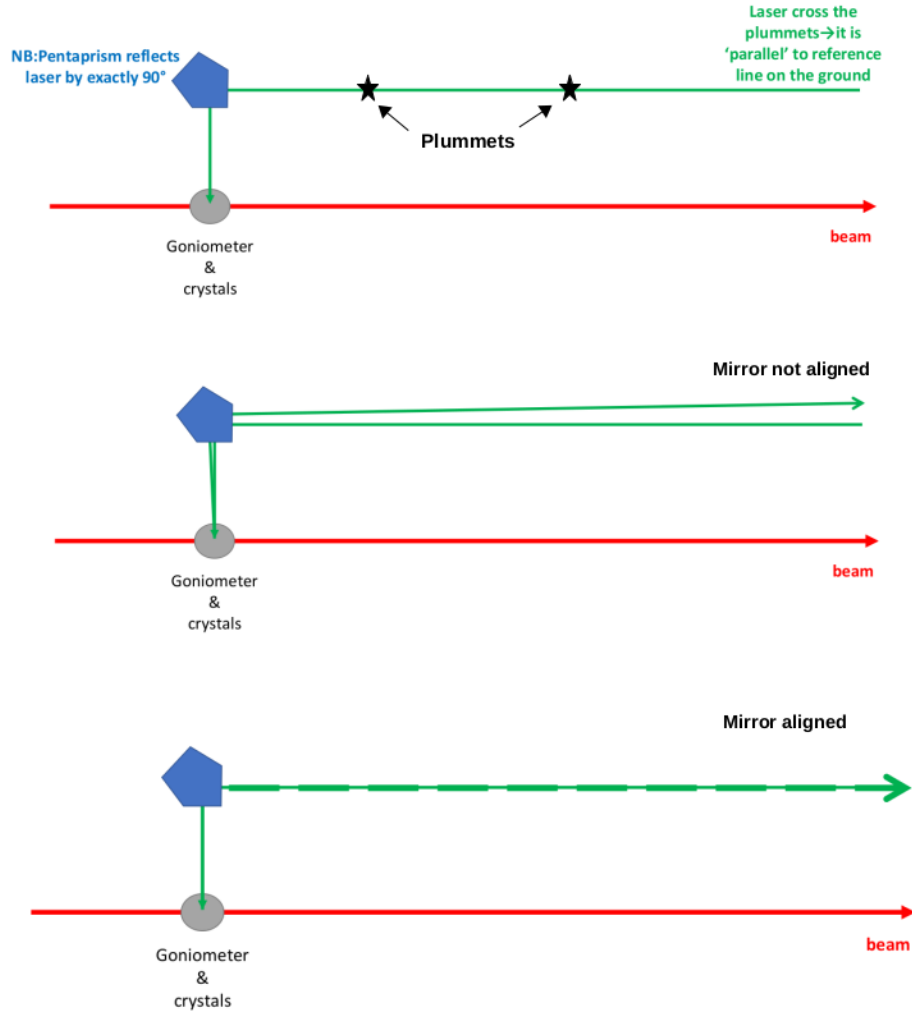


Figure 5.3: Scheme of the manual pre-alignment procedure. The sample is aligned with the beam when the laser returns along the same path.

5. if the reference mirror is not exactly at 90° with respect to the beam, the laser does not return to the starting point; using the goniometer, the mirror is aligned so that the laser returns along the same path;
6. the mirror is aligned with the beam by rotating the holder of 90° ;
7. the samples are finally aligned with the beam using the offset measured in the laboratory.

The found coordinates $\theta_{x,gonio}$ and $\theta_{y,gonio}$ are very close to the axis (within a few mrad). During the online data taking, the axis is found moving the goniometer coordinate in the stereogram and observing the PH of the multiplicity counter (MC): the PH is larger near a plane, because of the coherent effects, and even more in the proximity of the axis. The axis is the point in the stereogram where the PH is the largest.

5.1.2 THE FINAL ALIGNMENT

For the final alignment, the stereogram has been reconstructed with experimental data using the output signal of the Ringo (1 X_0 crystal) and John (2 X_0 crystal) SiPMs and of the multiplicity counter, each acquired with a different data taking.

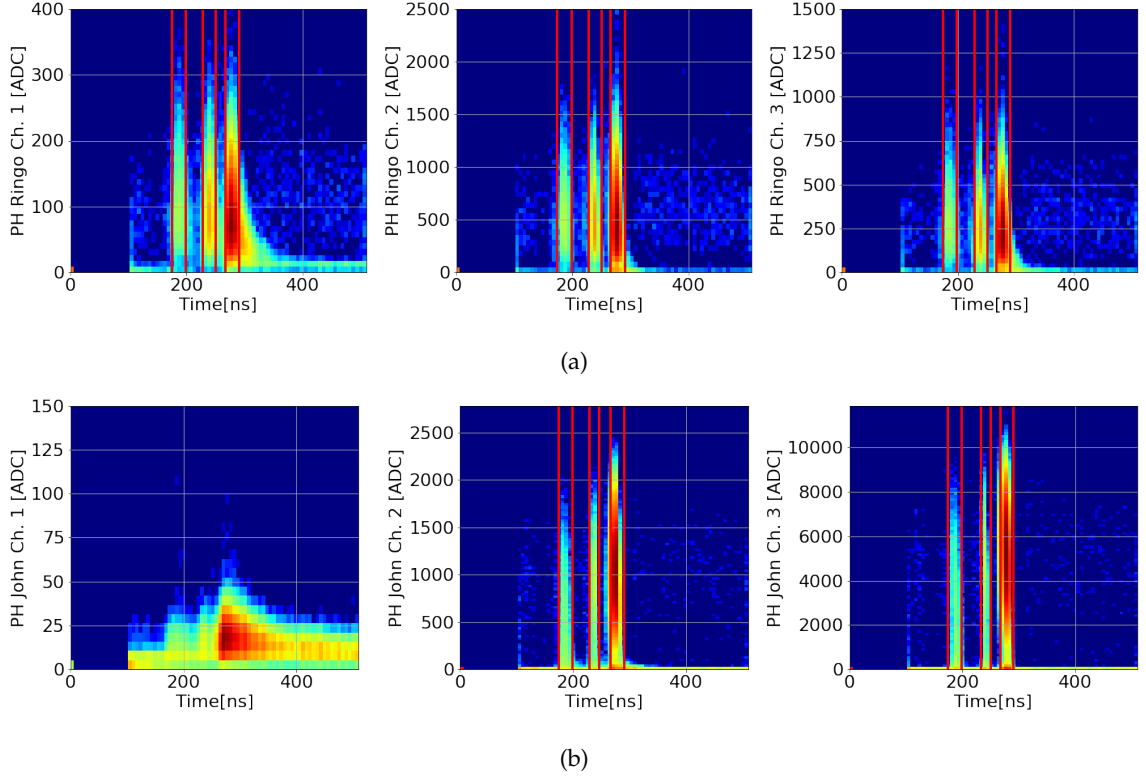


Figure 5.4: a) Ringo PH-time scatter plot. It can be noted that the PH of the second and third matrices are higher than the first one. This is because the 1 X_0 crystal covered completely the central matrix, a large part of the third one and only a small fraction of the first matrix. b) John PH-time scatter plot. The first matrix was not taken into account during the analysis; the low PH is due to the absence of the crystal on it. The shift in time of a number of events, which is evident for both John and Ringo, is due to the time walk of the trigger scintillators; all the events inside the red lines can be considered in time.

A series of preliminary considerations have been made in order to select the events of interest:

- a selection in time in order to exclude the baseline fluctuation events has been applied; figure 5.4 shows the PH-time scatter plot of the three matrices of Ringo and John. The different values in the PH of the three matrices are due to the position of the crystals on the matrices themselves. Ringo was positioned covering completely the central matrix and only partially the other two, while John covered only the third and a part of the second matrix (as it can be seen in figure 3.2). Therefore, since the first matrix was not in contact with the crystal, it was not taken into account during the analysis;

- cuts on the beam divergence to select the most perpendicular particles, since the measurements are extremely sensitive to the angular orientation;
- since the $2 X_0$ crystal is smaller than the beam profile in the x direction, a geometrical cut is possible. The crystal shape has been reconstructed using the multiplicity counter positioned after the crystal. When the incoming particles interact with the crystal, a large multiplicity in output is expected. Figure 5.5 presents the PH of the multiplicity counter; the black line is the threshold chosen to discriminate the events that have interacted with the crystal (large PH) from all the events that have passed without interacting (small PH). Figure 5.6a shows all the tracks reconstructed on the crystal plane, with the T1 and T2 silicon detectors. Selecting among these the events in which the PH of the MC is smaller than the chosen threshold (i.e. particles that have not interacted with the crystal) it is possible to see the shadow of the crystal in the x direction (figure 5.6b).

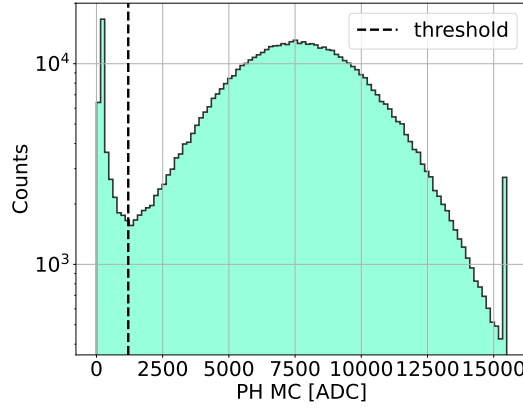


Figure 5.5: PH of the multiplicity counter with the $2 X_0$ crystal. The dashed line is the threshold chosen to discriminate the events that have interacted with the crystal (large PH) from the others.

The first crystalline sample under test was the $1 X_0$ crystal with the Ringo SiPMs. The standard procedure includes a series of angular scans (θ_{ang}), moving, for each step, the cradle coordinate (θ_{crad}). The first scan has been performed along the angular coordinate starting from the pre-alignment coordinates. Figure 5.7 shows the PH of Ringo and of the multiplicity counter as a function of the misalignment angle along x , while figure 5.8 presents the profile plots, i.e. the mean value of y for each bin in x . The enhancements in the PH of Ringo and in the MC are evident for some angular coordinates and could be due to the coherent effects when the particle is aligned with respect to the planes. It has to be noted that the response of the two detectors is equivalent.

The cradle coordinate has then been changed, and another angular scan has been taken around the most evident peak (the central one in figure 5.8, indicated with the orange arrow). The profile plot of the scan is shown in figure 5.9; the enhancement in the PH is even larger. Keeping fixed the angular coordinate corresponding to the peak, a scan moving the cradle has been taken (figure 5.10).

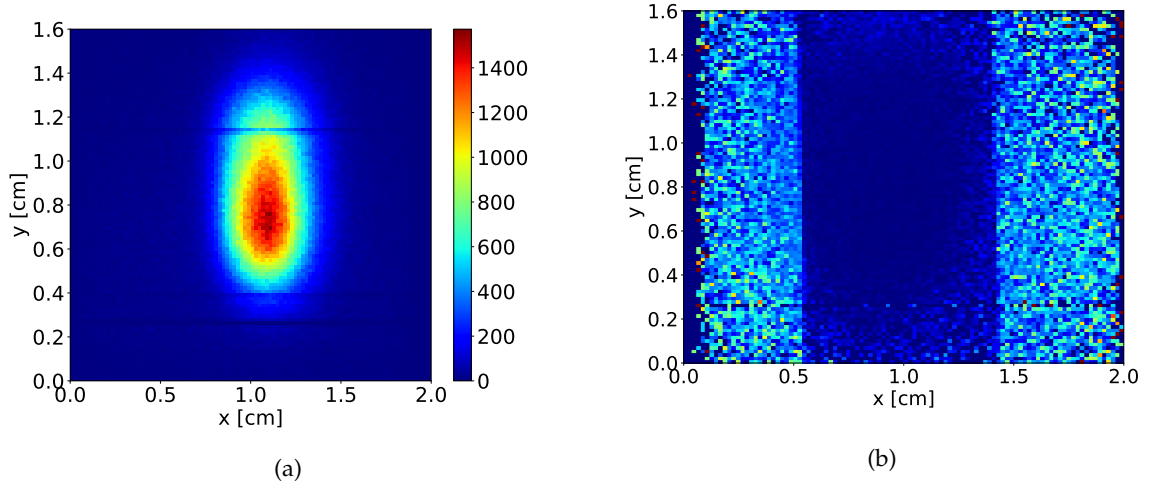


Figure 5.6: a) 2D distribution of all the tracks reconstructed on the $2 X_0$ crystal plane. (b) 2D distribution of the tracks of the particles that have not interacted with the crystal, selecting all the events with a PH in the multiplicity counter smaller than the chosen threshold. The shadow of the crystal is well visible (the crystal is 9 mm large in the x direction and larger than the beam dimension in the other direction).

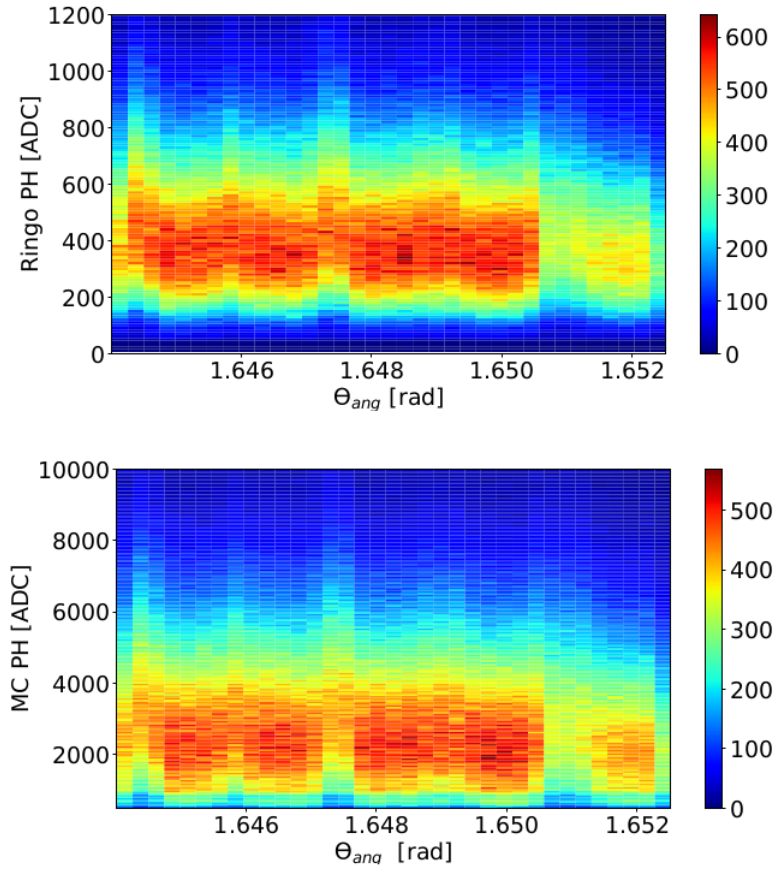


Figure 5.7: 2D distributions of the PH of Ringo (Top) and the multiplicity counter scintillator (Bottom) as a function of θ_{ang} . The response of the two detectors is equivalent: it can be noted an enhancement in the PH for some angular coordinates.

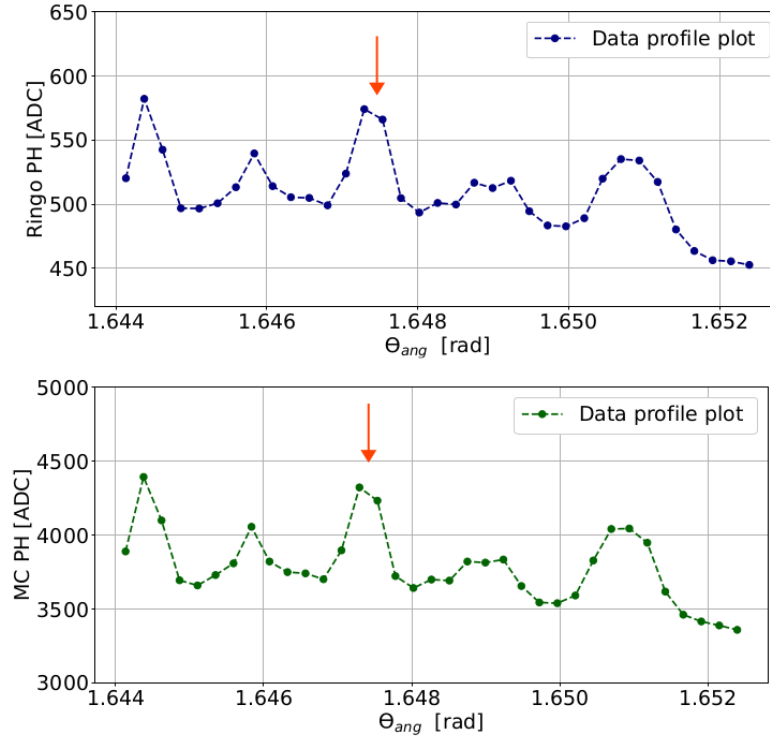


Figure 5.8: Profile plot of the PH of Ringo (Top) and the multiplicity counter (Bottom) as a function of θ_{ang} for the first scan. The peak could be due to the coherent effects when the particle is aligned with respect to the planes.

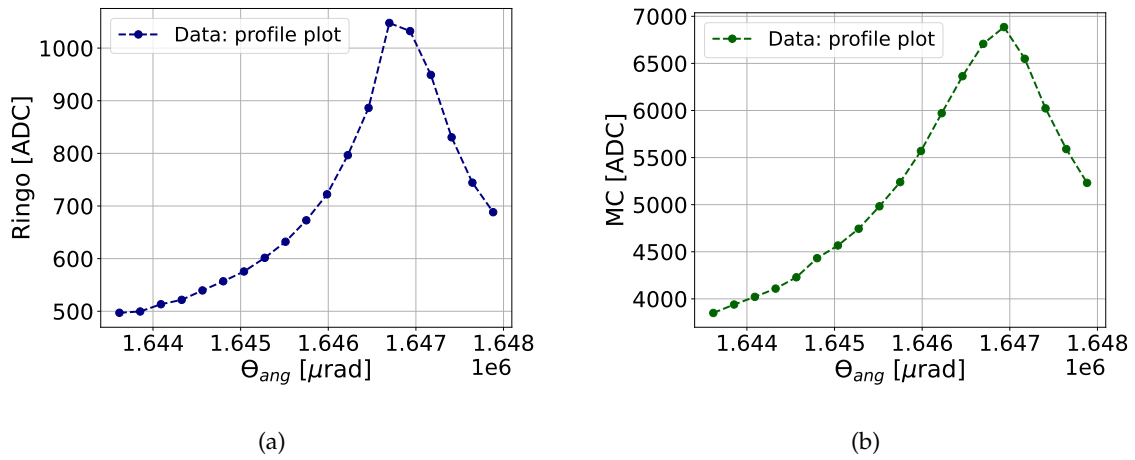


Figure 5.9: Profile plots for the second angular scan; an enhancement in the PH of Ringo (a) and the multiplicity counter (b) is evident.

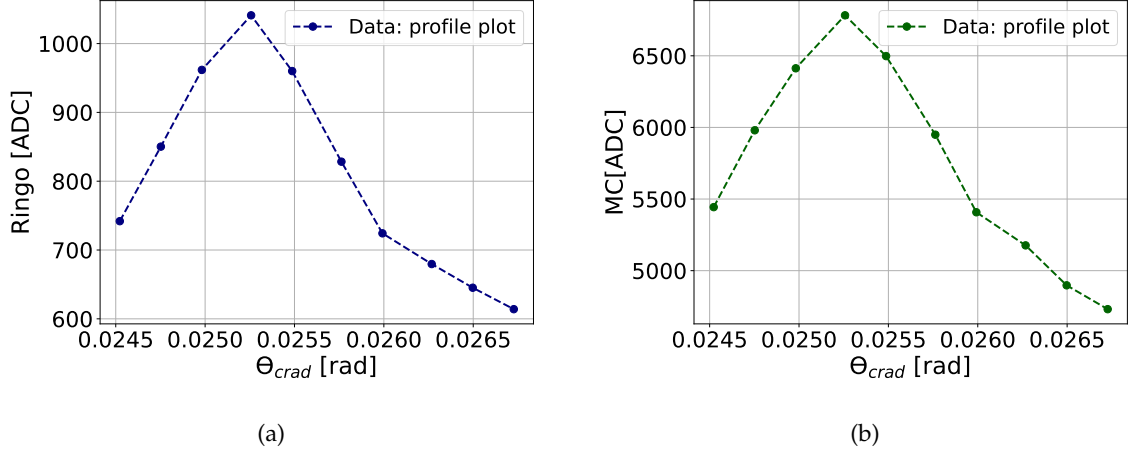


Figure 5.10: Profile plot of the third scan, this time performed moving the cradle. Again, an enhancement in the PH of Ringo (a) and the multiplicity counter (b) is evident.

Figure 5.11 shows the Ringo stereogram obtained putting together all these scans. The axis has been chosen between the two points with the larger PH. The same result is obtained for the multiplicity counter, proving that the alignment procedure can be performed by measuring directly the scintillation light produced in the oriented crystal with the SiPMs without the need for an additional detector after the crystal on the beamline, such as the multiplicity counter. A similar procedure has been performed for the $2 X_0$ crys-

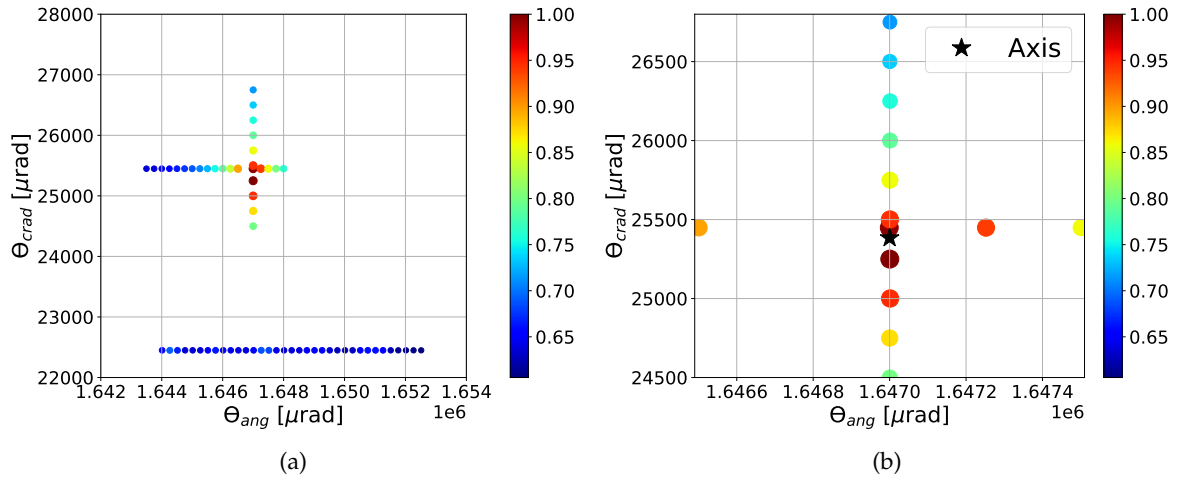


Figure 5.11: (a) The complete stereogram; each dot represents the normalized mean value of the PH of Ringo. (b) A zoom of the stereogram; the axis has been chosen between the two points with the higher PH values.

tal observing the response of John and of the multiplicity counter; the obtained stereogram is shown in figure 5.12. The axis has been chosen between the two points with the higher PH values also in this case.

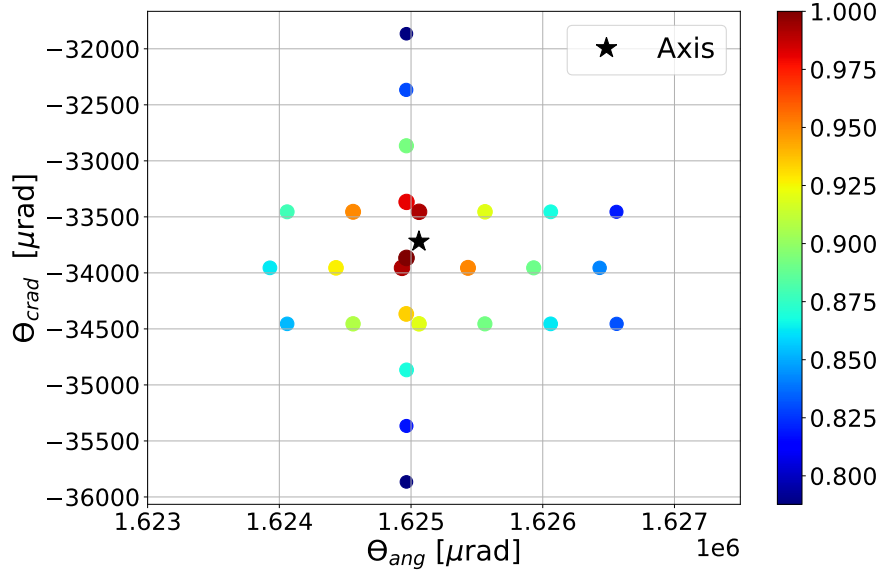


Figure 5.12: Stereogram of the $2 X_0$ crystal obtained performing three angular scans and one cradle scan and analyzing the response of John.

5.2 ENERGY DEPOSIT DISTRIBUTIONS

The following results show quantitatively, for the first time ever, the enhancement in the electromagnetic shower development inside the oriented crystal. The measurements have been performed for different angles of the 120 GeV electron beam with respect to the axis around the strong field angular acceptance Θ_0 (axial, $0.5 \Theta_0$, Θ_0 , $2 \Theta_0$, $8 \Theta_0$) and in random orientation.

For these measurements, the magnet was on, so that the e^+/e^- produced in the electromagnetic shower inside the crystal were deviated and only the γ s were measured in the downstream electromagnetic calorimeter. The following cuts have been applied in order to select the events of interest:

- cuts in time to exclude the baseline fluctuation events;
- cuts on the beam divergence to select the most perpendicular particles;
- for the $2 X_0$ crystal, a geometrical cut.

Figure 5.13a-c show the correlation between the Ringo and John pulse height in ADC when the magnet is kept off, that is the electromagnetic calorimeter measures the part of the shower not contained in the crystal. The profile plot has been calculated as the weighted mean value of y for each bin in x . A linear anti-correlation between the response of the two detectors is evident (figure 5.13b-d): at large energy values detected by the SiPMs, a small value of energy deposit in the calorimeter is detected and vice versa.

Section 4.3.2 has presented the calorimeter calibration that allows to compute the energy deposit in the calorimeter itself in GeV. The same calibration curve cannot be used for the SiPMs, since in principle the ADC responses are very different (the two detectors do

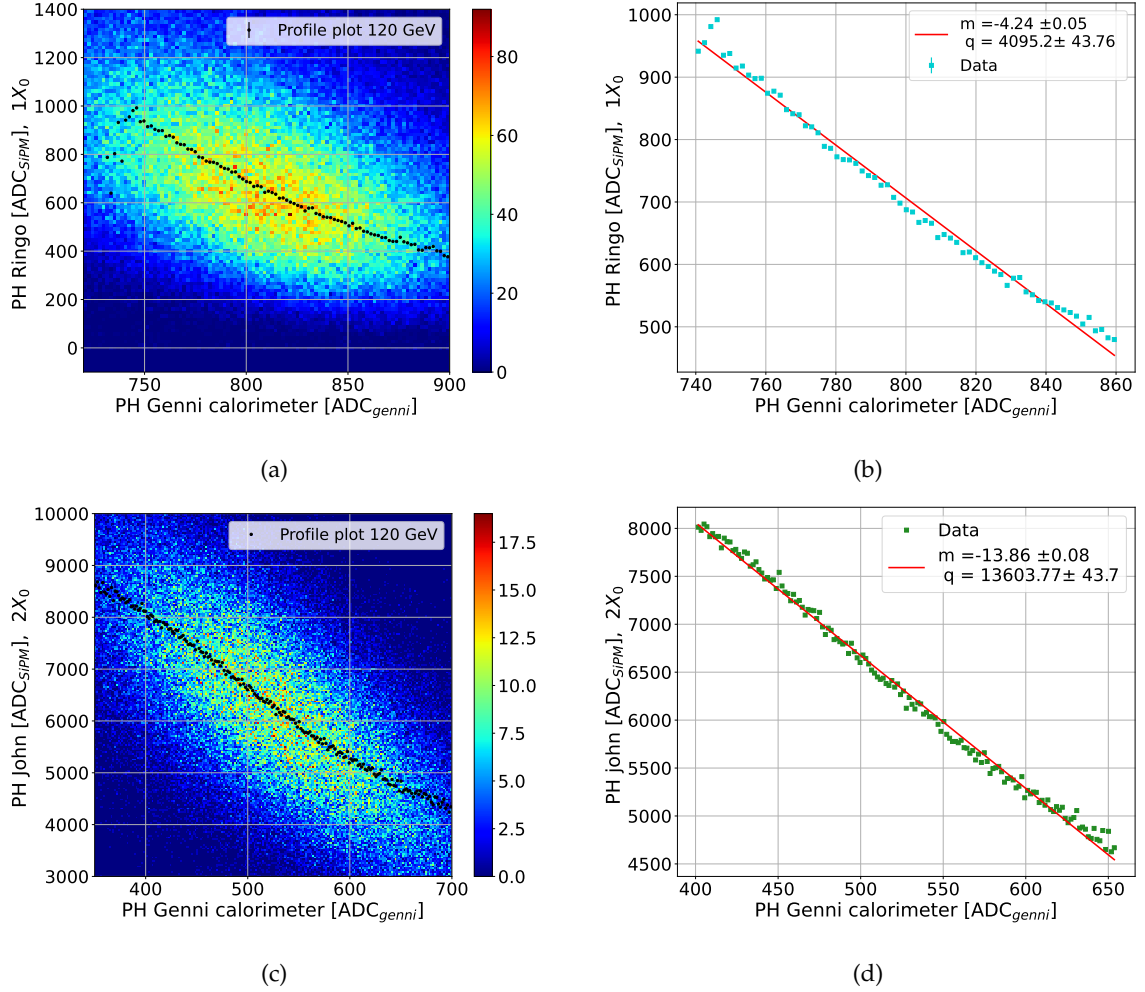
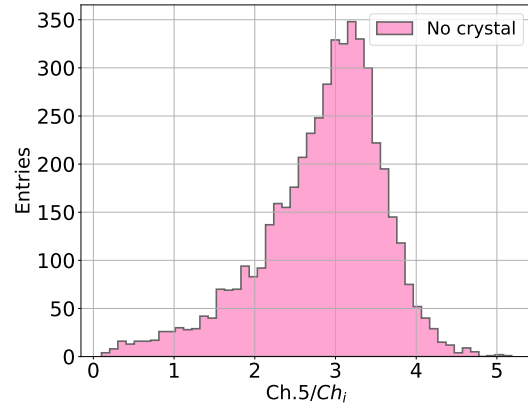


Figure 5.13: (a) Ringo and (c) John PH correlation with the calorimeter signal. At large energy values detected by the SiPMs, a small value of energy deposit in the calorimeter is detected and vice versa. (b) Ringo and (d) John profile plots. A linear fit has been performed demonstrating the anti-correlation.

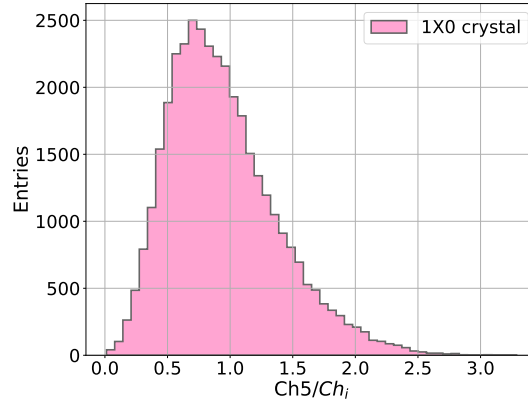
not respond in the same way). Moreover, a Monte Carlo simulation is needed to compute the energy which is detected neither by the crystal nor by the calorimeter (for instance, because of the longitudinal and lateral leakage of the shower in the calorimeter and the particles that are not within the acceptance of the Genni calorimeter). Figure 5.14 presents an example of what happens when the crystal is on the beam considering the ratio of the energy deposited in the central channel of the calorimeter and the sum of the energies in the other 8 channels: while with no crystal the energy is deposited in the central channel given the beam dimension and divergence and the BGO Molière radius, the presence of the crystal widens significantly the angular distribution of the particles hitting the calorimeter. These plots will be compared to the simulation in order to obtain the information for the calibration of the energy deposited in the crystals.

Figure 5.15 presents the energy deposit in Ringo and John in ADC counts. The acceleration of the electromagnetic shower development, due to the interaction of the electron beam with the strong crystalline field, is evident for both Ringo and John.

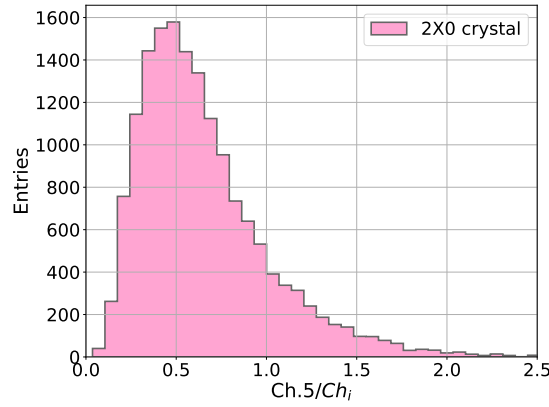
The energy deposited inside the 1 X₀ crystal presents a typical Landau distribution. When



(a)

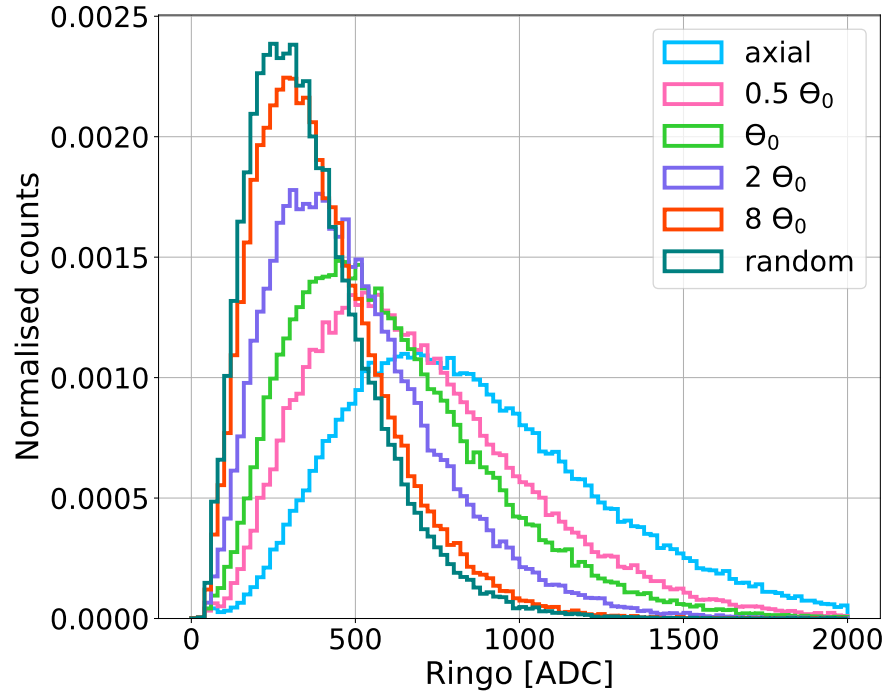


(b)

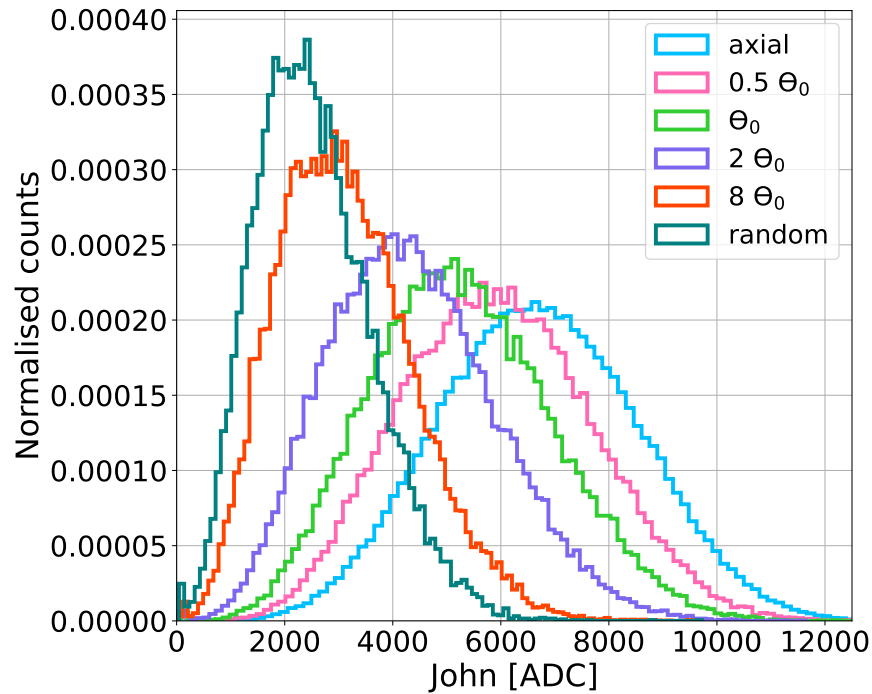


(c)

Figure 5.14: The ratio between the energy seen by the central channel of Genni (ch. 5) and the sum of the remaining 8 channels for (a) no crystal, (b) the $1 X_0$ and (c) $2 X_0$ (axially oriented) crystal on the beam. Without the crystal on the beam, most of the energy is deposited in the central channel of the calorimeter while only a small fraction is detected in the surrounding channels (given the beam dimension and divergence). In the other cases, when the crystal is positioned on the beam, the electromagnetic shower causes a spread of the distribution of the particles that becomes as large as the calorimeter reducing the energy deposited in the central channel (considering also the fact that the calorimeter is positioned ~ 18 m downstream the crystal).



(a) The energy deposited in the $1 X_0$ crystal presents a Landau distribution. When the beam is aligned near to the axis, the reduction of the radiation length experienced by the electrons leads to an increase in the number of shower particles per unit thickness and thus in an enhancement in the number of scintillating photons: the maximum of the spectrum moves to higher energies. The energy deposited in the axial orientation is ~ 2.5 times larger than the one in the random condition.



(b) In random orientation the shape of the energy deposit presents a Landau distribution, in which a small fraction of events deposited a large amount of energy in the crystal itself. In axis, the acceleration of the electromagnetic shower causes an increase in the deposited energy and the distribution shape changes becoming similar to a Gaussian. The energy deposited in the axial orientation is ~ 3 times the random one.

Figure 5.15: Deposited energy inside the oriented crystal measured by Ringo and John.

the beam is aligned near to the axis, the reduction of the radiation length experienced by the electrons leads to an increase in the number of shower particles per unit thickness and thus to an enhancement in the number of scintillating photons: the maximum of the spectrum moves to higher energies.

This effect is even stronger in the $2 X_0$ crystal. In fact, in random orientation the shape of the spectrum presents a Landau distribution. When in axis, the shape changes and becomes more similar to a Gaussian: the acceleration of the electromagnetic shower causes an increase in the deposited energy, which is around three times the random one.

Observing the deposited energy distributions of Ringo and John it is also possible to estimate the effective radiation length $X_{0,eff}$ for the electrons when interacting with the axially oriented crystal. Figure 5.16 presents the cumulative deposited energy as a function of the depth inside the detector, expressed in units of X_0 , for a 100 GeV electron beam impinging on a PbWO_4 crystal. The data have been taken from [84]; the energy of the beam is close to 120 GeV, so no relevant differences are expected in the energy deposit. The energy de-

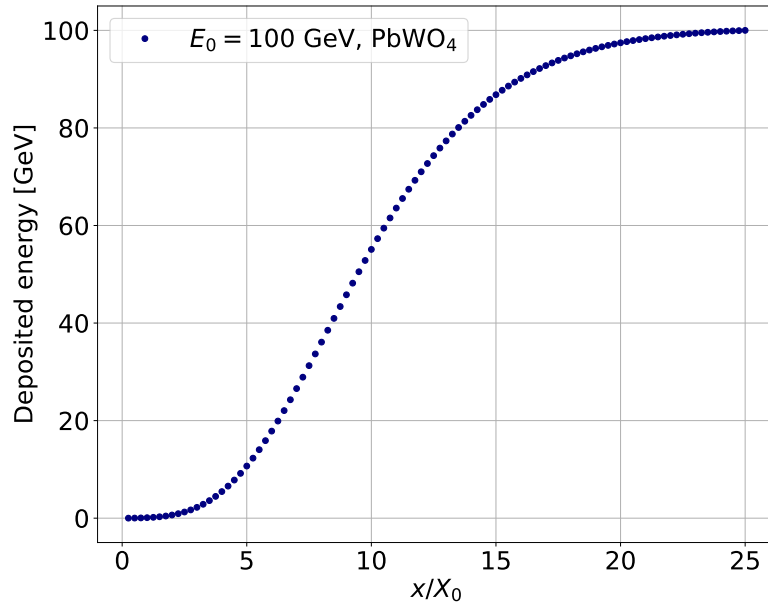


Figure 5.16: Cumulative deposited energy as a function of the thickness of the detector in units of X_0 for a 100 GeV electron beam impinging on a PbWO_4 crystal [84].

posited in the axial condition for Ringo and John is respectively ~ 2.5 and ~ 3 times the random one (figure 5.15). From figure 5.16 the deposited energy in the amorphous case can be evaluated and is found to be respectively 100 MeV and 650 MeV. The $X_{0,eff}$ for the electrons in axial condition can be extrapolated from the simulated data in figure 5.16 considering the factors observed in figure 5.15, that is an energy deposit which is 2.5 and 3 times more. Table 5.1 presents the obtained values.

When the crystal is axially oriented and the electrons experience the effects of the strong field, the deposited energy increases as if the thickness of the crystal were larger or, conversely, as if the radiation length were smaller. To evaluate this effect, the cumulative curve has been considered extrapolating the thickness corresponding to a deposit which is

	Deposited energy random	Deposited energy axial	Thickness in X_0 in axial	Thickness increase
1 X_0	100 MeV	250 MeV	1.41	41%
2 X_0	650 MeV	1.9 GeV	2.87	43%

Table 5.1: Deposited energy and thickness increase for Ringo and John.

respectively 2.5 and 3 times larger than the one expected for a material thickness of 1 and 2 X_0 . The two thickness values are reported in table 5.1 and correspond to an increase in thickness of 41% and 43% which are perfectly compatible. The effective radiation length $X_{0,eff}$ is a fraction of the original one, which is computed as the reciprocal of the increased thickness. In both cases this reciprocal is around 70% indicating a decrease of X_0 of around 30%.

CONCLUSIONS

This thesis work has been performed in the framework of the STORM collaboration, to study the effects on charged particles of the strong field in aligned crystals.

Since the mid 1980s, a number of theoretical developments have led to a thorough understanding of the strong crystalline field and of the features of the interaction of ultrarelativistic electrons or positrons with it.

In the first chapter of this thesis, the behavior of high energy particles in oriented crystals has been described from the theoretical point of view. It has been shown that the interaction of an ultrarelativistic electron/positron with the uniform strong crystalline field is characterized by the emission of quantum synchrotron radiation generating a high intensity of hard photons as well as electron/positron pairs. One of the main consequences of these effects is the acceleration of the electromagnetic shower development in a high Z axially aligned crystalline medium, which results in a reduction of the radiation length X_0 in comparison with the one of amorphous materials.

In this framework, the STORM experiment measured quantitatively, for the first time ever, the acceleration of the electromagnetic shower development inside two PbWO_4 oriented crystals, with a thickness of 1 and 2 X_0 , estimating the reduction of the radiation length.

The innovative feature of this experiment is the implementation of a photodetection system coupled to the oriented crystals, which allows to directly measure the enhancement of the scintillation light inside the crystal itself, caused by the shower acceleration. The previous experiments (some of which are presented in chapter 2) had neither implemented the readout of the scintillation light, or a crystal thick enough to fully investigate the electromagnetic shower acceleration caused by the strong crystalline field.

The photodetection system implemented for the STORM experiment is based on Silicon PhotoMultipliers, and it consists of three SiPM matrices model ARRAYC-60035-4P-BGA by ONSEMI and a custom readout board designed at the INSULAB laboratory (Insubria University, Como, Italy).

The characterization of the SiPMs has been performed with cosmic rays at the INSULAB laboratory using a test crystal, to verify the coupling of the crystals to the matrices and the behaviour of the SiPMs, measuring the signal to noise ratio of the detector and its efficiency in an experimental situation which was much worse than the one expected on the beam from the point of view of deposited energy. It has been demonstrated that the SiPMs are able to reconstruct MIPs with a good enough signal to noise ratio and a high efficiency, so no problems were indeed expected for the beamtest.

During the 2021 beamtest, performed at the CERN-SPS H2 line at the North Area, the change in the response of the oriented crystal as a function of the angle of the beam with respect to the axis in the strong field regime has been studied. The experimental

setup was based on a high spatial resolution tracking system (consisting of four silicon microstrip detectors with a spatial resolution of a few microns), a multiplicity counter, a dipole bending magnet, a high-precision goniometer with a resolution of a few μrad on all the angular axes and a BGO electromagnetic calorimeter positioned downstream with respect to the crystal.

In the first phase of the beamtest, all the silicon detectors have been aligned via software, in order to correct for physical misplacements among the detection planes; the beam divergence has been studied as a function of the energy (it has been verified that for the 120 GeV beam beam divergence was $92.34 \pm 1.35 \mu\text{rad}$ along the x direction and $100.74 \pm 0.97 \mu\text{rad}$ along the y direction, small enough to observe the coherent interactions) and the equalization of the channels of the calorimeter and its calibration have been performed.

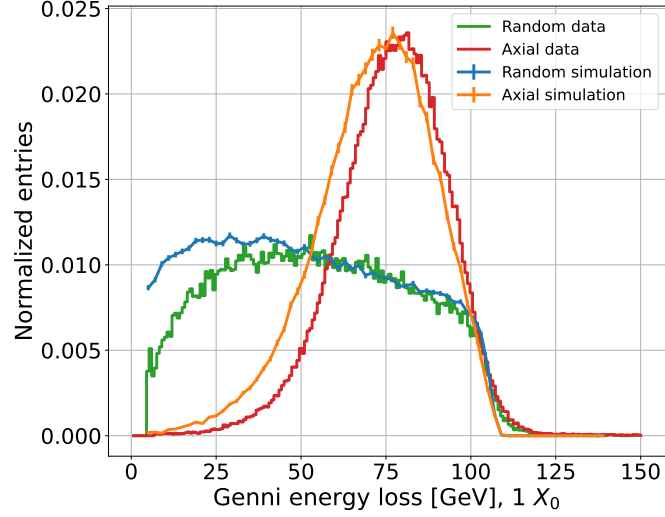
In the second phase, the two crystalline samples, coupled with the SiPMs and mounted on a holder, were positioned on the beam. In order to orient the crystals with the axis aligned with respect to the beam, a manual pre-alignment procedure has been implemented which guarantees to align the sample within a few mrad. The fine alignment has been performed with the experimental data and guarantees to start the data taking with the beam aligned with respect to the axis. The alignment can be verified either by measuring the multiplicity of charged particles in the scintillator positioned after the crystal, or by measuring the energy deposited in the crystal itself, which is read out by the SiPMs. It has been shown that the same results are obtained with both the measurements, therefore the alignment procedure can be performed by measuring directly the scintillation light produced in the oriented crystal with the SiPMs without the need for an additional detector after the crystal on the beamline, such as the multiplicity counter.

The electromagnetic shower development inside the oriented crystal has been studied moving the coordinate of the goniometer by some fraction of the strong field angular acceptance Θ_0 ; in particular data have been taken in axial, $0.5 \Theta_0$, Θ_0 , $2 \Theta_0$, $8 \Theta_0$ and in random orientation. The obtained results have shown an effective acceleration of the electromagnetic shower development when the orientation is close to the axis. It has been found that the energy deposited in the axial orientation is ~ 2.5 times larger than the one in the random condition for the $1 X_0$ crystal and ~ 3 times for the $2 X_0$ one. Moreover, the reduction of the radiation length experienced by the electrons in the strong field has been evaluated to be around 30 %.

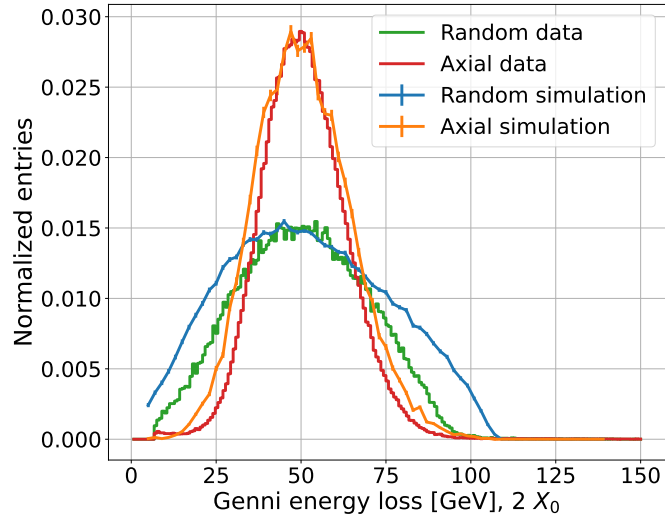
The energy loss in the downstream calorimeter has been simulated via Monte Carlo for both the 1 and $2 X_0$ crystals; the simulation has been performed at Università degli Studi di Ferrara with Geant4 [85]. Figure C. 1 presents the axial and random simulation compared with the experimental data for the 1 and $2 X_0$ crystals. A strong agreement is found for both the crystals, meaning that the simulations are a solid and powerful tool for the investigation of the electromagnetic shower development in oriented crystals.

The next step in the simulation will be the description of the crystal behavior in order to reconstruct the energy deposited in the crystal itself and compare it with the experimental data.

This thesis work has confirmed experimentally the reduction of the radiation length in axially oriented crystals. The future perspective of this work is thus the assembly of a calorimeter prototype with an oriented layer of PbWO_4 , in order to measure the radiation length reduction in a thicker sample and also to study the full shape of an electromagnetic shower.



(a)



(b)

Figure C. 1: Energy loss comparison between the Genat4 simulations and the experimental data for the random and axial orientation for (a) $1 X_0$ and (b) $2 X_0$ crystals. The random spectrum has been simulated with the standard Geant4 [85], while for the axis simulation a modified version of Geant4 has been used [86]. The experimental data are in agreement with the simulated ones, proving that the simulation represents a solid tool for the investigation of the electromagnetic shower development in oriented crystals.

ACRONYMS

ADC Analog to Digital Converter

AGILE Astro-rivelatore Gamma a Immagini LEggero

ALICE A Large Ion Collider Experiment

ASCII American Standard Code for Information Interchange

ASIC Application Specific Integrated Circuit

ATLAS A Toroidal LHC ApparatuS

AXIAL Axial and quasi-axial coherent interaction between charged particle beams and crystals

BC Beam Chamber

BGA Ball Grid Array

BGO Bismuth Germanate

BR Branching Ratio

CERN Conseil Européen pour la Recherche Nucleaire - European Organization for Nuclear Research

CFA Constant Field Approximation

CMOS Complementary Metal Oxide Semiconductor

CMS Compact Muon Solenoid

DAQ Data AcQuisition

DST Data Summary Tape

ELIOT Electromagnetic processes In Oriented crysTals

HEP High Energy Physics

HRXRD High-Resolution X-Ray Diffractometer

INFN Istituto Nazionale di Fisica Nucleare - National Institute for Nuclear Physics

INP Institute for Nuclear Problems

KLEVER K_L Experiment for VErY Rare events

LAT Large Area Telescope

LHC Large Hadron Collider

LHCb Large Hadron Collider beauty

LINAC LINear ACcelerator

LPM Landau-Pomeranchuk-Migdal

MC Multiplicity Counter

MIP Minimum Ionizing Particle

NIM Nuclear Instrumentation Module

PC Personal Computer

PCB Printed Circuit Board

PEDD Peak Energy Deposition Density

PH Pulse Height

PMT PhotoMultiplier Tube

PS Proton Synchrotron

PSB Proton Synchrotron Booster

QED Quantum ElectroDynamics

SAC Small Angle Calorimeter

SF Strong Field

SiPM Silicon PhotoMultiplier

SPAD Single Photon Avalanche Diode

SPS Super Proton Synchrotron

STORM STrOng cRystalline electroMagnetic field

VME Versa Module Eurocard

VRB VME Readout Board

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