IL NUOVO CIMENTO **46 C** (2023) 98
DOI 10.1393/ncc/i2023-23098-5

COMMUNICATIONS: SIF Congress 2022

Development of an advanced modular setup for the on beam characterization of oriented crystals

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received 26 January 2023

Summary. — Recently, the particle physics community has put an increasing effort in developing radiation detectors and equipment based on oriented crystals. A key feature that distinguishes an oriented crystal from the ordinary matter is the reduction of the radiation length (X_0) seen by electrons, positrons and photons crossing the lattice along one of its symmetry axes. This effect has been experimentally observed only in the last few decades and with samples limited in number, composition and length. In order to characterize a variety of oriented crystals with a standardized procedure, the STORM Collaboration has developed an advanced modular setup, which allows to study the features of any crystal sample with both electron (or positron) and photon beams. This contribution describes the key elements of this setup, namely silicon strip tracking detectors, plastic scintillators, Silicon Photo-Multipliers (SiPMs) coupled to the crystal under test, a photon calorimeter and an electromagnetic spectrometer.

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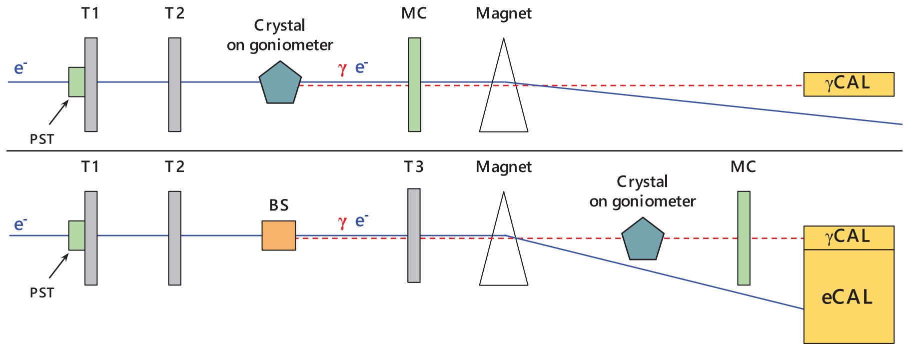

Fig. 1. – The STORM experimental setup for the beamtest characterization of oriented crystals in SF conditions. Top: "electron" mode. Bottom: "photon" mode.

1. – Introduction

It is known since the 1970s that the bremsstrahlung cross-section differs from the result of the Bethe-Heitler calculation, if the medium in which the process takes place is an ordered structure, such as an oriented single crystal. If the radiating particle features an energy larger than $\sim$10 GeV and a small enough incidence angle with respect to a crystalline axis or plane, the Strong Field (SF) regime is attained [1]. In this condition, the intensity of the emitted radiation is enhanced by a factor $10-100$. For incidence angles larger than a critical value ($\Theta_0 \sim 1$ mrad), which depends only on the properties of the target crystal, the Strong Field regime breaks down and the coherent bremsstrahlung phenomenon takes place. A similar enhancement has been observed for the electron-positron pair production [1]. Due to these effects, the electromagnetic shower develops in a much more compact space, when it is produced inside an oriented crystal in SF condition [2]. This phenomenon could be exploited in a number of particle physics applications, such as a compact and hadron-blind electromagnetic calorimeter [3]; however, in order to account for the SF regime in an arbitrary material, it would be necessary to have access to a large amount of experimental data. Unfortunately, these data are not available yet, since the SF regime has been experimentally observed only in the past few decades and with crystal samples severely limited in terms of number, composition and length (*i.e.*, $\lesssim 1\mathrm{X}_0$) [1, 4]. For these reasons, in the last few years, the STORM collaboration has investigated the Strong Field effects in a variety of crystals (*e.g.*, W, $PbWO_4$ and PbF_2), with a thickness of $\sim$0.5–3X_0 [3, 5, 6]. This study required the development of a standardized experimental setup, which allows the beamtest characterization of oriented crystals in the SF regime with high-energy electrons, positrons and photons. This contribution aims at briefly describing this setup and its key elements.

2. – The standard STORM experimental setup

The STORM experimental setup can be installed on any beamline capable of providing an $e^{\pm}$ beam, with a high energy ($\gtrsim 20$ GeV) and a low divergence ($\lesssim 100\,\mu$rad). The

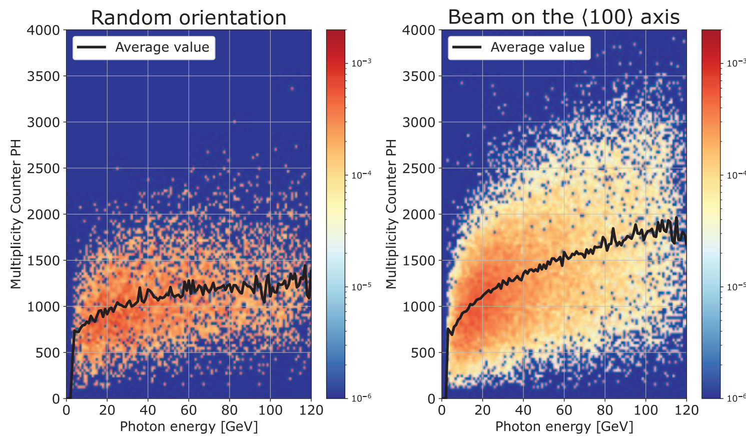

Fig. 2. – Correlation between the energies of the photons incident on a 1 X_0 $PbWO_4$ crystal and the PH of the MC. Left: photon beam incident on the crystal, in random alignment condition. Right: photon beam incident on the ⟨100⟩ axis of the crystal. The entries in both histograms are normalized. Data were selected requiring the detection of at least 5 clusters in both planes of a silicon tracker placed downstream of the MC. It was also required that the photons crossed a fiducial region in the center of the crystal. The increase of the average PH of the MC of a factor ∼1.5, for a large enough photon energy, is due to the SF enhancement of the pair production cross-section.

beam intensity should allow to maximize the number of acquired single-track events([1]), since these are the only ones useful for the data analysis. This setup is modular, meaning that its elements may be rearranged with minimal effort, in order to test a crystal sample using either the primary charged beam ("electron" mode, fig. 1) or a secondary tagged photon beam ("photon" mode). In "electron" mode, the primary beam particles impinge on a plastic scintillator trigger (PST) and their trajectories are reconstructed by several double sided silicon microstrip telescopes (T1, T2, T3), which feature a small active area ($2\,\mathrm{cm} \times 2\,\mathrm{cm}$) and a spatial resolution of $\sim 5\,\mu\mathrm{m}$ on the junction side [7]. The crystal sample under test is mounted on a high-precision goniometer, composed of two translational and two rotational stages, with a $5\,\mu\mathrm{m}$ and a $0.25\,\mu\mathrm{rad}$ resolution [8]. If the crystal is a scintillator or a Cherenkov radiator, Silicon PhotoMultipliers (SiPMs) are used to directly measure the energy deposited by the beam particles in the active material [6]. The multiplicity of the charged particles exiting from the crystal is evaluated by measuring the signal of the Multiplicity Counter (MC), a $\sim 5\,\mathrm{cm}$ thick plastic scintillator, and comparing it with the signal given by a Minimum Ionizing Particle (MIP). The charged particles are then deflected by a dipole magnet. A homogeneous electromagnetic calorimeter composed of BGO crystals (γCAL) measures the energy of the photons produced inside the crystal, with an energy resolution of $\sim \frac{3\%}{\sqrt{E}} \oplus \frac{2\%}{E} \oplus 2\%$, where E is the energy in GeV. This measurement is a fundamental step in the characterization of the SF effects, since the radiation spectrum is one of the few observables

([1]) For instance, in the beamtests performed on the H2 beamline (CERN SPS), the beam intensity was of $\sim 10^4$–10^5 particles/spill (with a spill length of 4.8 s), corresponding to $\sim 10^3$–10^4 single-track events/spill.

which can be easily compared with the predictions of the theory [1]. All these detectors are readout by commercial digitizers, such as the CAEN V1742 and DT5730 modules. The Data AcQuisition system (DAQ) is based on custom VME readout/memory boards. The maximum acquisition rate allowed by the DAQ, due to the irreducible time required for the initialization of the boards and the readout of the data, is $\sim 6\,\mathrm{kHz}$ [7].

When the setup is used in the "photon" mode, a tagged photon beam is produced by replacing the crystal with a non-oriented copper converter (BS, $\sim 0.1\,\mathrm{X}_0$). The primary electron beam, which exits from the converter, is deflected by the bending magnet and then absorbed by a spectrometer (eCAL), which is composed of several lead glass calorimeters, which feature an energy resolution of $\sim \frac{9\%}{\sqrt{E}} \oplus 1\%$ [3]. The difference between the energy of the primary beam and the one measured by eCAL gives the energy of the photons which impinge on the crystal. The efficiency and spatial coverage of the spectrometer can be estimated with a Geant4 simulation: typically, the maximum efficiency ($\sim 100\%$) is achieved in the 20–90 GeV energy range. The multiplicity of the charged particles produced in the sample is measured by the Multiplicity Counter, while the energy of all the exiting particles is measured by γCAL. Figure 2 presents a typical plot obtained during the data taking stage.

3. – Conclusions

In the last few years, the STORM collaboration has studied the Strong Field regime in oriented single crystals. To perform this study, a standardized experimental setup and a custom DAQ system have been developed and optimized. Using this setup, it has been possible to measure the energy deposited in several oriented crystals by high energy electron and photon beams and the multiplicity of the charged particles exiting from the crystals. The data acquired in these years will be fundamental for the future development of the first electromagnetic calorimeter based on oriented crystals.

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The authors acknowledge the support of the CERN PS/SPS physics coordinator and of the CERN SPS and EN-EA group technical staff. This work has been partially supported by INFN CSN1 (NA62 experiment/KLEVER project) and CSN5 (STORM experiment).

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