PROCEEDINGS OF SCIENCE

Beam test characterization of oriented crystals in strong field conditions

Pietro Monti-Guarnieri,[a,b,*] **Laura Bandiera,**[c] **Luca Bomben,**[a,b] **Stefano Carsi,**[a,b] **Davide De Salvador,**[d,e] **Eleonora Diociaiuti,**[f] **Vincenzo Guidi,**[c,g] **Viktar Haurylavets, Mikhail Korjik, Alexander Lobko, Silvia Martellotti,**[f] **Valerio Mascagna,**[h,i] **Andrea Mazzolari,**[c] **Matthew Moulson,**[f] **Daniele Paesani,**[f] **Nadia Pastrone,**[j] **Michela Prest,**[a,b] **Marco Romagnoni,**[c] **Federico Ronchetti,**[a,b] **Ivano Sarra,**[f] **Alessia Selmi,**[a,b] **Francesco Sgarbossa,**[d,e] **Mattia Soldani,**[c,g] **Alexei Sytov,**[c] **Viktor Tikhomirov and Erik Vallazza**[b]

[a] *Università degli Studi dell'Insubria, Via Valleggio 11, Como, Italy*
[b] *INFN Sezione di Milano Bicocca, Piazza della Scienza 3, Milan, Italy*
[c] *INFN Sezione di Ferrara, Via Saragat 1, Ferrara, Italy*
[d] *Università degli Studi di Padova, Via Marzolo 8, Padua, Italy*
[e] *INFN Laboratori Nazionali di Legnaro, Viale dell'Università 2, Legnaro, Italy*
[f] *INFN Laboratori Nazionali di Frascati, Via Enrico Fermi 54, Frascati, Italy*
[g] *Università degli Studi di Ferrara, Via Saragat 1, Ferrara, Italy*
[i] *Università degli Studi di Brescia, Via Branze 38, Brescia, Italy*
[j] *INFN Sezione di Pavia, Via Agostino Bassi 6, Pavia, Italy*
[k] *INFN Sezione di Torino, Via Pietro Giuria 1, Torino, Italy*

E-mail: pmontiguarnieri@studenti.uninsubria.it

It is well known that the lattice structure of a scintillating crystal can influence the development of the electromagnetic processes inside it. For electron and photon beams aligned with the symmetry axis of a crystal, if the Strong Field condition is satisfied, a reduction of the radiation length (X_0) is expected. However, these effects have been experimentally observed only in the last few years, with crystal samples limited in number, composition and length. The lack of experimental data for these phenomena makes it harder to properly account for them in the design and simulation of innovative radiation detectors and equipment, such as active beam dumps or compact electromagnetic calorimeters. Recent experiments, performed by the STORM and KLEVER collaborations at the CERN SPS extracted beam lines, demonstrated a significant reduction of X_0 for photon beams impinging on a crystal within $\sim 0.1°$ from one of its symmetry axes. This contribution will describe such experiments, reporting preliminary results for a 2 X_0 PbF_2 crystal and a 1 X_0 $PbWO_4$ crystal.

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*Speaker

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1. Introduction

It is known since decades that the dominant absorption process for very high energy photons interacting with matter is Pair Production (PP). This phenomenon features the conversion of a primary photon into a lepton pair (e^+ / e^-), with a cross-section which has been extensively studied and is currently well documented [1, 2]. It was already noticed in the Sixties that this cross-section is modified if the impinging photons cross the target material at a small enough angle with respect to a crystallographic axis or plane [3, 4]. This phenomenon, which is known as Coherent Pair Production (CPP), is due to the fact that the electric fields generated by the atoms along a plane or axis add up coherently. As a result, the effective field perceived by the incoming particles (ε) has a much larger amplitude than the lab-frame field and thus the PP probability increases [5, 6]. If the energy of the primary photon is high enough, ε is approximately constant over the entire string of nuclei and can reach a value of 10^{10} V/m: this is called the Strong Field (SF) regime and it features an enormous enhancement of the PP probability. When the SF regime is attained, a similar effect is observable for electrons (positrons) impinging at a small enough angle with respect to an axis (plane) of the crystal lattice. This effect, which is known as Coherent Bremsstrahlung (CB), features a huge enhancement of the bremsstrahlung cross-section and also a change in its angular distribution [7]. The combined presence of the two SF-enhanced processes (i.e., CPP and CB) results in an accelerated development of the electromagnetic shower and thus in a reduction of the "effective" radiation length (X_0^{eff}) of the target material. For showers initiated by electrons or positrons, the condition that must be attained in order to observe the SF regime is:

$$\chi = \frac{\gamma E}{E_0} > 1 \tag{1}$$

where $\gamma = E_{in}/mc^2$ is the Lorentz factor of the particle, E_{in} its initial energy, mc^2 the electron mass energy, E the lab-frame electric field generated by the string of nuclei and $E_0 \approx 1.32 \cdot 10^{18}$ V/m the Schwinger critical field [8]. An estimation of the angular acceptance of the SF processes is given by [9]:

$$\Theta_0 = \frac{\mathrm{U}_0}{mc^2} \tag{2}$$

where U_0 is the continuous potential depth associated to the crystal axis. For electrons incident on a typical high-Z crystal such as tungsten ($\mathrm{U}_0 \approx 1$ keV), the threshold energy for the observation of the SF effects is $\approx$ 22 GeV, while the angular acceptance is $\approx$ 2 mrad.

The SF-induced reduction of the radiation length is quite interesting for particle physics, since it could be employed to develop a highly efficient, hadron-blind electromagnetic calorimeter [10]. This is due to the fact that the lattice structure affects only the electromagnetic interactions and it is not relevant for the hadronic processes. Such a detector is currently being proposed as the main candidate for the Small Angle Calorimeter (SAC) for the KLEVER experiment [11]. Many other applications may also be foreseen, such as pointable $\gamma-$ray telescopes or equipment for beam dump experiments. However, experimental data regarding the SF processes are currently available only for crystal samples limited in number, composition and length [7, 10, 12, 13]: this makes it harder to properly account for these effects in the design and realization of particle detectors based on oriented crystals. For this reason, the STORM and KLEVER collaborations have performed a

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beamtest in August 2021 at the CERN SPS, with the aim of fully characterizing two crystal samples with a high energy tagged photon beam. This contribution describes the setup employed in the beamtest and the results obtained in the (currently ongoing) data analysis.

2. Experimental setup

The crystal samples under test in this study were a 2 X_0 PbF_2 sample (oriented along the $\langle 110 \rangle$ axis) produced by Siccas and a 1 X_0 $PbWO_4$ sample (oriented along the $\langle 100 \rangle$ axis) produced by the Institute for Nuclear Problems of the Belarusian State University. For both materials, the SF regime is assumed to be attained for energies greater than 20 GeV and incidence angles smaller than $\approx$ 1 mrad.

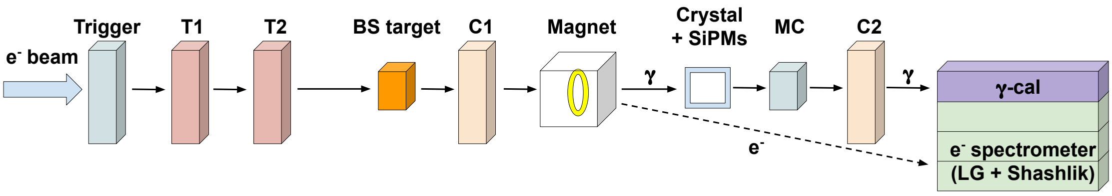

Figure 1: Experimental setup on the H2 extracted beam line (CERN SPS) for the characterization of the Strong Field condition in oriented crystals. The labelling notation used here is described in the text.

The primary beam used for the measurements was composed of electrons with a high purity, an energy of 120 GeV and an acceptance $\Delta p/p \leq 2\%$ [14]. Figure 1 presents a simplified scheme of the experimental setup: the extracted electron beam crosses a plastic scintillator, that generates the trigger, and two beam telescopes (T1, T2), which are double-sided silicon microstrip detectors with a spatial resolution of $\approx 5\,\mu$m [15]. The beam hits then a $\approx$ 3 mm thick (0.2 X_0) copper target (BS), in order to produce photons via bremsstrahlung. The mixed beam (photons + electrons) crosses a silicon chamber (C1), consisting of two single-sided silicon strip detectors in a x-y configuration, with a spatial resolution of $\approx 30\,\mu$m [16]. A bending dipole magnet is then used to split the beam:

- The electrons are deflected and then absorbed by an electron spectrometer (eCAL), which is composed of a shashlik lead-scintillator sampling calorimeter and seven homogenous lead glass calorimeters.
- The photons interact with the crystal under test, which is mounted on a high-resolution goniometer [17]. The crystal is coupled to three matrices of Silicon PhotoMultipliers (SiPMs), which measure the scintillation light emitted as a result of the PP in the crystal. The SiPMs and their frontend electronics are the same described in [18].

  After the goniometer, a plastic scintillator (Multiplicity Counter, MC) and another silicon chamber (C2) are positioned, to measure the multiplicity of the charged pairs produced inside the crystal. Finally, a homogenous BGO calorimeter ($\gamma-$CAL) absorbs the particles emerging from the crystal and measures their energy.

This experimental layout allows to measure the energy of the photons impinging on the sample on an event-by-event basis. Thus, it is possible to study how this energy is correlated with the energy deposited in the crystal and with the multiplicity of the charged particles produced inside it.

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3. Results and discussion

The characterization of the crystal samples was performed by means of dedicated long-statistics runs, each one corresponding to a different angle between the electron beam and the axis of the crystal. For each run, only a fraction of the events was analyzed, since it was required that the electrons had a small enough divergence (≤ 0.25 mrad). Moreover, it was required that the electrons trajectories, which were reconstructed by the silicon detectors (T2, C1), crossed a fiducial region inside a plane located at the center of the crystal. This region was defined by studying the efficiency map of the crystal itself (figure 2), namely the spatial distribution of the fraction of the events where a high multiplicity of charged particles was produced. The multiplicity was measured in terms of the number of clusters detected in at least one side of the C2 module.

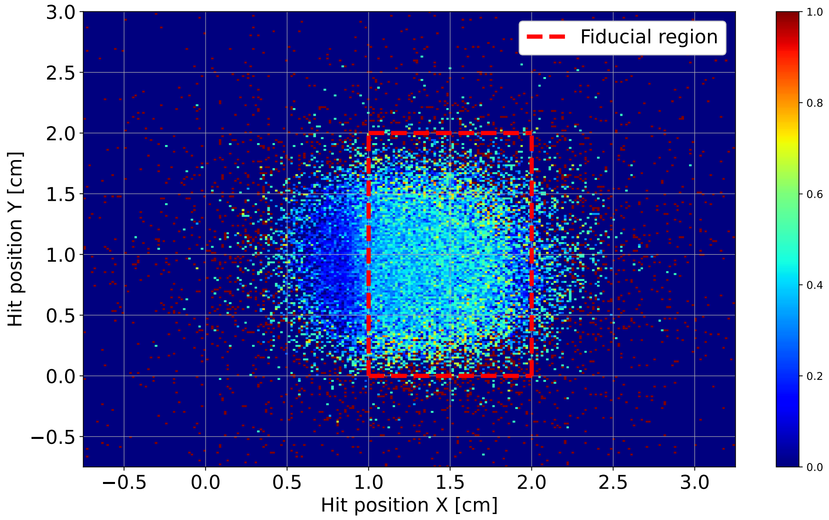

Figure 2: Efficiency map of the PbF_2 crystal, defined as the distribution of the fraction of the events where at least 5 clusters were detected in at least one side of the C2 module. The area corresponding to the largest fraction of events (red, dashed) was used as the fiducial region for the event selection.

In principle, several observables may be used to characterize the reduction of the effective radiation length of a material. In this contribution, the Pulse Height (PH) spectrum of the Multiplicity Counter has been chosen: for a null beam-axis angle, both a higher tail in the spectrum and a greater average PH have been observed, with respect to the case of a randomly-oriented target. Figure 3 presents such spectra for the PbF_2 sample: the high-energy tail grows by a factor $10 \div 50$, while the average PH by a factor ≈ 1.35. Similar results are observed for incidence angles $\leq 1\Theta_0$, where $\Theta_0 \approx 1$ mrad is the expected angular range of the SF regime. At $4\Theta_0$ the enhancement effect is seen to be still evident, even if somewhat less significant. Similar results have been obtained also for the $PbWO_4$ sample: the high-energy tail of the spectrum grows by a factor $10 \div 70$, while the average PH is enhanced by a factor ≈ 1.55. These results already suggest that the radiation length of the two materials is reduced by $\approx (20 \div 30)\%$; a more accurate estimate of this reduction will be soon given by directly studying how the energy deposited in the crystal, measured by the SiPMs, changes as a function of the beam-crystal alignment.

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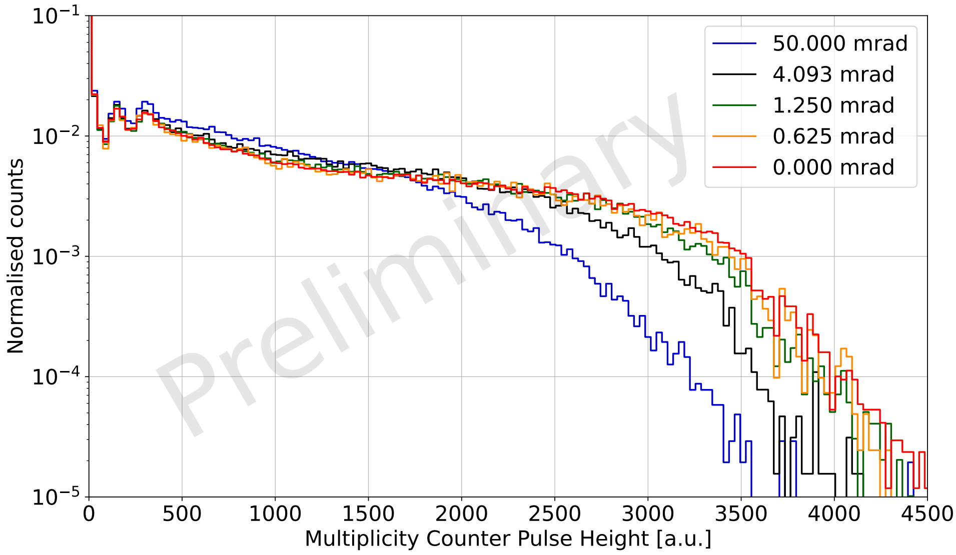

Figure 3: Multiplicity Counter (MC) Pulse Height spectra for several beam-axis incidence angles. An angle of 0 mrad means that the beam is aligned with the axis of the crystal, while 50 mrad corresponds to the beam incident on a randomly-oriented target. Spectra are normalized.

4. Conclusions and outlook

In the last few years, there have been several experimental observations of the Strong Field-enhanced electromagnetic processes inside oriented crystals. In order to acquire more data regarding these effects and to allow for a more precise accounting of them in the design of particle detectors, the STORM and KLEVER collaborations performed a beamtest at the CERN SPS, on the H2 line. While the analysis of the data acquired during this test is still undergoing, there is already evidence of a huge reduction of the effective X_0 of the studied crystals (up to 30%). All the present and future results obtained with these data will be fundamental for the next step, which is the design and construction of the first particle detector conceptually based on oriented crystals.

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References

[1] H. Bethe et al., *Theory of bremsstrahlung and pair production. I. Differential cross section*, *Phys. Rev.* **93** (1954) 768.

[2] J. Hubbell, *Review and history of photon cross section calculations*, *Physics in Medicine & Biology* **51** (2006) R245.

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[3] H. Überall, *High-energy interference effect of bremsstrahlung and pair production in crystals*, *Phys. Rev.* **103** (1956) 1055.

[4] G. Palazzi, *High-energy bremsstrahlung and electron pair production in thin crystals*, *Rev. Mod. Phys.* **40** (1968) 611.

[5] V. Baier et al., *Emission of radiation by high-energy particles in oriented single crystals*, *Soviet Journal of Experimental and Theoretical Physics* **65** (1987) 686.

[6] V. Baier et al., *Interaction of high-energy electrons and photons with crystals*, *Soviet Physics Uspekhi* **32** (1989) 972.

[7] L. Bandiera et al., *Strong reduction of the effective radiation length in an axially oriented scintillator crystal*, *Phys. Rev. Lett.* **121** (2018) 021603.

[8] M. Buchanan, *Past the Schwinger limit*, *Nature Physics* **2** (2006) 721.

[9] U. Uggerhøj, *The interaction of relativistic particles with strong crystalline fields*, *Reviews of modern physics* **77** (2005) 1131.

[10] M. Soldani et al., *Next-generation ultra-compact calorimeters based on oriented crystals*, in *40th International Conference on High Energy Physics*, p. 872, Apr., 2021.

[11] F. Ambrosino et al., *KLEVER: An experiment to measure BR($K_L \to \pi^0 \nu\bar{\nu}$) at the CERN SPS*, 2019. 10.48550/ARXIV.1901.03099.

[12] L. Bandiera et al., *Crystal-based pair production for a lepton collider positron source*, 2022. 10.48550/ARXIV.2203.07541.

[13] M. Soldani et al., *Enhanced electromagnetic radiation in oriented scintillating crystals at the 100-MeV and sub-GeV scales*, in *The European Physical Society Conference on High Energy Physics. 26-30 July 2021. Online conference*, p. 853, 2022.

[14] N. Charitonidis et al., "The Secondary Beam Line of EHN1/SPS." `http://sba.web.cern.ch/sba/BeamsAndAreas/h2/H2manual.html`, 2017.

[15] D. Lietti et al., *A microstrip silicon telescope for high performance particle tracking*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **729** (2013) 527.

[16] G. Barbiellini et al., *The AGILE silicon tracker: testbeam results of the prototype silicon detector*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **490** (2002) 146.

[17] W. Scandale et al., *Apparatus to study crystal channeling and volume reflection phenomena at the SPS H8 beamline*, *Review of Scientific Instruments* **79** (2008) 023303.

[18] M. Soldani et al., *A high-performance custom photodetection system to probe the light yield enhancement in oriented crystals*, 2022. 10.48550/ARXIV.2207.05496.

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