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Next-generation ultra-compact calorimeters based on oriented crystals

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Calorimeters based on oriented crystals provide unparalleled compactness and resolution in measuring the energy of electromagnetic particles. Recent experiments performed at CERN and DESY beamlines by the AXIAL/ELIOT experiments demonstrated a significant reduction in the radiation length inside tungsten and $PbWO_4$, the latter being the scintillator used for the CMS ECAL, observed when the incident particle trajectory is aligned with a lattice axis within $\sim 1°$. This remarkable effect, being observed over the wide energy range from a few GeV to 1 TeV or higher, paves the way for the development of innovative calorimeters based on oriented crystals, featuring a design significantly more compact than currently achievable while rivaling the current state of the art in terms of energy resolution in the range of interest for present and future forward detectors (such as the KLEVER Small Angle Calorimeter at CERN SPS) and source-pointing space-borne γ-ray telescopes.

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1. Axial alignment and strong field effects

It is well known since the Fifties that, when a high-energy particle impinges on a crystalline medium with small angle with respect to a lattice axis, that is, a periodic string of nuclei, the features of the electromagnetic processes it undergoes macroscopically differ from the amorphous target case. In particular, the spectra of Bremsstrahlung radiation emission by electrons/positrons and pair production (PP) by photons in crystals depend on the angle with respect to the axis, and on the input particle energy [1].

Above few tens of GeV, the relativistic boost affects the crystal electromagnetic field experienced by the particle by a Lorentz factor γ and the so-called strong field (SF) regime is attained when

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

E being the axis field in the laboratory frame and $E_0 \sim 1.32 \times 10^{18}$ V/m being the Schwinger QED critical field, above which nonlinear field effects occur in vacuum [2]. The interaction between a charged particle and the crystalline SF regime features the emission of quantum synchrotron radiation, which is characterised by a strong and peaked enhancement in the hard part of the photon spectrum with respect to the Bethe-Heitler, i.e. incoherent, case [1]; similarly, the PP rate per unit thickness in case of a photon in a strong field is enhanced [3]. SF-related effects with limited strenght can be observed down to $\chi \sim 0.1$; on the other hand, a saturation is expected to occur at about 100 times the SF threshold energy, i.e. in the multi-TeV range [4], far beyond the current experimental upper limit.

An evaluation of the angular range of such effects has been introduced by Baier et al. [5] and is defined as

$$\Theta_0 = \frac{U_0}{mc^2},$$

U_0 being the electromagnetic potential associated to the axis. It has to be noted that Θ_0 differs from the channeling angular range, the so-called Lindhard angle

$$\theta_c = \sqrt{\frac{2U_0}{\varepsilon}},$$

ε being the input energy, within which the charged particle is forced into an oscillatory motion around the axis with specific electromagnetic radiation emission – either undulator-like (at sub-GeV energies) or synchrotron-like (at-few-GeV energies) [1]; in fact, the Lindhard angle depends on the input energy and is $\ll \Theta_0$ in the SF regime.

A lesser enhancement in the output radiation intensity by electrons/positrons (number of e^+e^- pairs by photons) is attained also out of the Θ_0 threshold and up to $\sim 1°$, due to the periodic interactions with the single-nucleus Coulomb-like fields that occur when the particle momentum transfer matches a reciprocal lattice vector – the so-called Coherent Bremsstrahlung (Coherent Pair Production) is attained [5].

As a consequence of the enhancement in the radiation emission and PP cross sections that occurs in crystalline SF, the electromagnetic shower started by an input electron, positron or photon in the medium is much more compact when on-axis with respect to the random orientation case; this corresponds to an overall reduction of the medium effective radiation length X_0. Furthermore,

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the fact that the enhancement factor grows with the input energy counterbalances the increase in the shower maximum radius depth: as a result, the shower peak longitudinal position is expected to depend on the input energy only weakly [6]. In case of scintillating crystals, the higher number of shower particles per unit thickness results in an enhancement in the number of scintillation photons emitted inside the medium.

2. Status of the investigation

Recently, different tests have been performed on the strong field effects in axially oriented crystalline samples by the AXIAL/ELIOT team. Both $PbWO_4$, the inorganic scintillator used for the CMS ECAL [7], and high-purity tungsten samples, which might prove excellent absorbing elements in sampling calorimeters, have been tested. Since 2017, these studies have been performed with charged beams in the SF (120 GeV$/c$ electrons, $\chi(PbWO_4) \sim 4$) and sub-SF (5.6 GeV$/c$ electrons, $\chi(PbWO_4) \sim 0.2$) regimes, at the CERN North Area H2 and H4 beamlines and at the DESY T21 beamline respectively. Furthermore, the Strong Field Pair Production (SFPP) by Bremsstrahlung photons (with spectrum endpoint at 120 GeV$/c$) impinging on an oriented tungsten crystal has been studied in a dedicated beamtest at the CERN H2 beamline in 2018; details on the latter can be found in [9, 10].

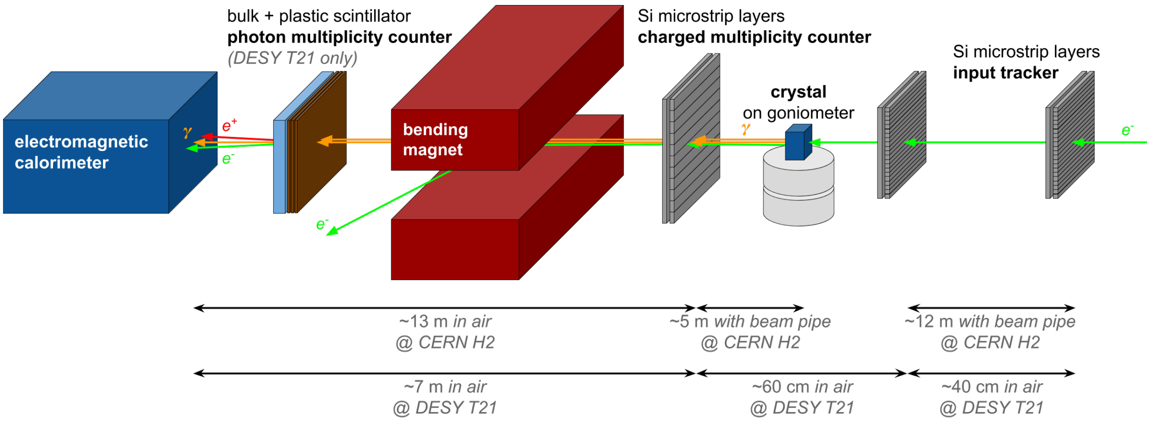

Figure 1: Experimental setup for the study of SF-related radiation processes by electrons inpinging on oriented crystalline samples. Detailes are given in the text body.

The experimental setup for measurements with input charged beams is shown in figure 1. The single input particle trajectory is reconstructed by means of a pair of silicon microstrip telescopes with a single-hit spatial resolution of $\sim 10\ \mu$m [11, 12]. The tracked particle then impinges on the crystalline sample, installed on a remote-controlled, high-precision goniometer [13]. In general, the interaction output consists of both charged particles and photons, characterised by a continuous energy spectrum; the charged component is detected by a pair of $\sim 100 \times 100$ mm^2 silicon microstrip sensors [14] and a plastic scintillator used as multiplicity counters. The charged particles are then swiped away by a bending magnet, and an electromagnetic calorimeter measures the (event-by-event) integral energy spectrum of the crystal output radiation – several detectors with different features have been exploited over the years; details on many of them can be found in [15].

Outstanding results have already come from the 2017 studies, carried on at the CERN H4 beamline, which demonstrated a five-fold reduction in the effective radiation length in [001]-axially oriented $PbWO_4$. The latter was directly observed in the spectra of the energy loss inside the sample (figure 2) – details can be found in [1].

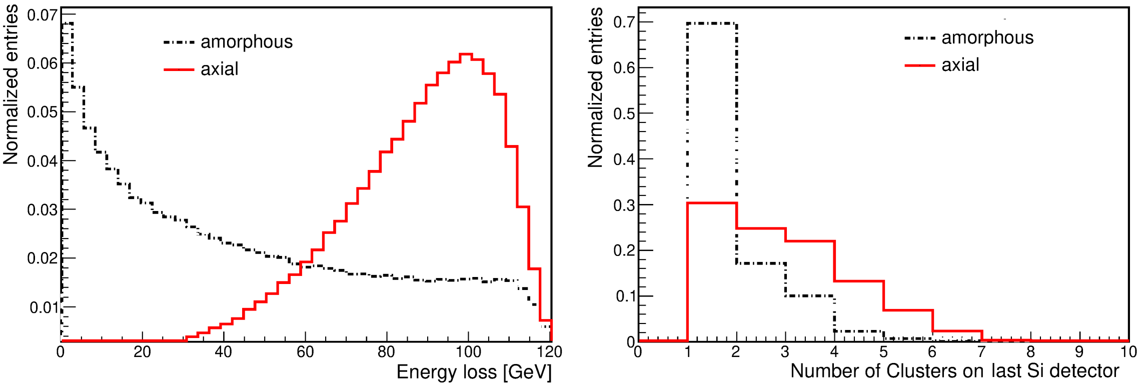

Figure 2: Results of the 2017 beamtest of the SF regime in [001]-axially oriented $PbWO_4$. Energy loss inside the crystalline sample (left, adapted from [1]) and output charged particle multiplicity measured by the downstream silicon microstrip layers (right) in random and axial angular orientations.

One of the key features of this experimental configuration is the sensitivity to the angular orientation of the sample under study. In case of heavy metals and scintillators, in general the lattice orientation affects the output charge multiplicity and radiation intensity; therefore, prompt information on the sample alignment can be obtained by means of the output charge or photon number. In particular, when probing thick ($\gtrsim X_0$) crystals in the SF regime, the enhancement in the number of charged particles resulting from the interaction along an axis is strong enough to be clearly detected via multiplicity counters placed upstream with respect to the bending magnet – see, for example, figure 2 right.

On the other hand, at lower energies and when studying thin crystals, in most cases the enhancement in the output charged multiplicity is not strong enough to be easily detected and the electromagnetic radiation intensity provides information on the alignment with better resolution. The concept of a detector for the measurement of the number of photons, consisting of a series of thin copper foils for photon conversion and plastic scintillators, was recently developed and tested in December 2019 at DESY – results in probing the [100] axis of a $\sim 0.24X_0$ thick $PbWO_4$ sample are shown in figure 3; in particular, it is clear from the latter that in this case the enhancement has a $\sim \pm 2$ mrad range and is maximum within ~ 1 mrad $\sim \Theta_0$ from the axis.

3. Application overview

The reduction in the overall shower length in axially-oriented crystalline media might represent a key item in the development of next-generation calorimeters, which would rival the current state of the art in terms of energy resolution while featuring improved compactness and lower material cost. This configuration is particularly appealing for accelerator-based fixed-target experiments at high energy, in which all processes experience a forward boost in the laboratory frame.

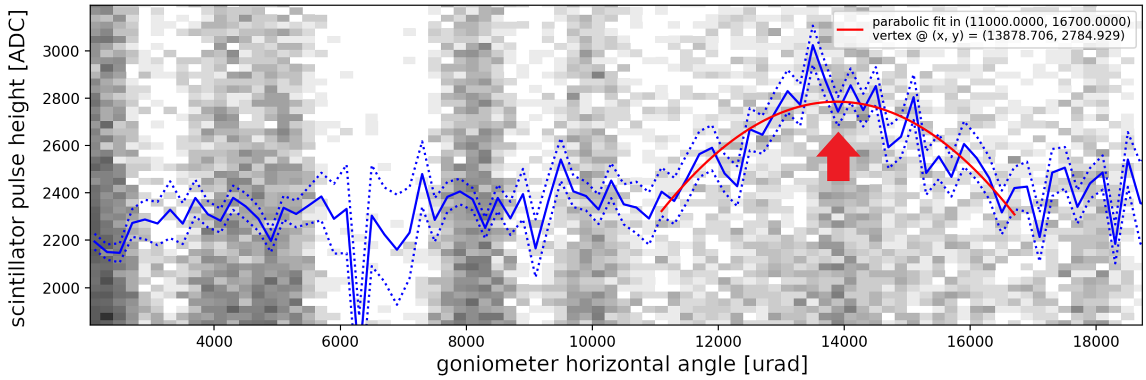

Figure 3: Response of the downstream photon counter installed in the DESY 2019 setup as a function of the relative alignment of a [100]-axially oriented thin $PbWO_4$ sample. The axis position, which features a strong enhancement in the detector mean signal, is highlighted with a red arrow.

Oriented crystalline layers 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; in the second case, oriented metallic layers could be used as passive stages, while the active stages would comprise the same technology as the current state of the art. Both solutions are currently under study as suitable options for the design of the Small Angle Calorimeter (SAC) for the KLEVER (K_L Experiment for VEry Rare events) experiment, which might start its measurements at the CERN SPS at the beginning of Run 4 [16].

Moreover, detectors based on oriented crystals are particularly appealing for satellite-borne γ-ray observers, which aim to the study of high-energy ($\gtrsim$ 100 GeV) photons from well-localised, point-like sources: the important reduction in the detectors weight and volume would meet the strict limitations to the rocket payloads and to the budget for space-borne missions. Furthermore, currently available satellite pointing systems can aim at the γ-ray sources with an angular resolution of less than 1°, i.e. within the SF angular acceptance.

4. Conclusions

In the last years, several experimental studies on SF effects in oriented crystals have been performed by the AXIAL/ELIOT team. Many outstanding results have already been obtained, which can pave the way to the concept of innovative, ultra-compact detectors.

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