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Enhanced electromagnetic radiation in oriented scintillating crystals at the 100-MeV and sub-GeV scales

Mattia Soldani,[a,b,*] **Laura Bandiera,**[b] **Luca Bomben,**[c,d] **Claudia Brizzolari,**[d,e] **Riccardo Camattari,**[a,b] **Davide De Salvador,**[g,h] **Vincenzo Guidi,**[a,b] **Pascal Klag,**[f] **Werner Lauth,**[f] **Evgeny Lutsenko,**[c,d] **Tais Maiolino,**[i] **Valerio Mascagna,**[c,d] **Andrea Mazzolari,**[b] **Michela Prest,**[c,d] **Marco Romagnoni,**[b,j] **Federico Ronchetti,**[c,d] **Alessia Selmi,**[c,d] **Alexei Sytov,**[b] **Viktor Tikhomirov**[k] **and Erik Vallazza**[d]

[a] *Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara, Ferrara, Italy*
[b] *Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, Ferrara, Italy*
[c] *Dipartimento di Scienza e Alta Tecnologia, Università degli Studi dell'Insubria, Como, Italy*
[d] *Istituto Nazionale di Fisica Nucleare, Sezione di Milano Bicocca, Milan, Italy*
[e] *Dipartimento di Fisica G. Occhialini, Università degli Studi di Milano Bicocca, Milan, Italy*
[f] *Institute for Nuclear Physics, Johannes Gutenberg University Mainz, Mainz, Germany*
[g] *Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Padua, Italy*
[h] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro, Italy*
[i] *Department of Physics, Wuhan University, Wuhan, China*
[j] *Dipartimento di Fisica, Università degli Studi di Milano Statale, Milan, Italy*
[k] *Institute for Nuclear Problems of Belarusian State University, Minsk, Belarus*

E-mail: `mattia.soldani@unife.it`

Nowadays, it is well known that the electromagnetic interaction between high-energy particles and matter experiences substantial modifications when the latter consists of a crystalline medium and its lattice axes are almost parallel to the input beam direction. In particular, a strong boost to the cross section of bremsstrahlung by electrons and positrons in high-density oriented crystals has been observed in the 10-to-100 GeV regime. This effect proves particularly appealing when it comes to inorganic scintillators, given the possibility to exploit it for the development of high-performance, ultra-compact electromagnetic calorimeters. This work provides a detailed discussion of the results obtained by probing a PWO (lead tungstate) oriented sample with 120 GeV/c electrons and positrons at the CERN North Area: in particular, a comparison between the outcomes obtained with electrons and positrons is made. Moreover, output radiation measurements on a thinner oriented PWO sample have been recently performed in the sub-GeV regime at the MAMI-B facility: an overview on the resulting characterisation is given.

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[*] Speaker

1. Coherent interactions of particles with oriented crystals and applications to high-energy calorimetry

The electromagnetic interactions between crystalline matter and charged particles can occur with a small angle between the lattice axes (the periodic strings of nuclei) of the former and the trajectories of the latter. If this is the case, in general, the features of such interactions are substantially different from those occurring in amorphous matter and depend on the angle between the input trajectories and the target axes [1, 2].

When this angle is sufficiently small, the particles experience an electromagnetic potential that consists of transversally periodic peaks whose maxima correspond to the parallel axes [1]. Hence, if positively charged, the particles are confined into potential wells centered between neighbouring axes, whereas if negatively charged, they are confined close to the (positive) atomic nuclei. In both cases, the particles undergo channeling, i.e., they are forced into a nearly oscillatory motion which results in the emission of peculiar electromagnetic radiation [1, 2]. Typically, at sub-GeV energies, the so-called channeling radiation (CR) has dipole nature [1, 2], with an intensity increase to the low-energy part of the bremsstrahlung spectrum [3]. On the other hand, at a few GeV or higher, a synchrotron-like spectrum is obtained, with a further increase of the energy of the boosted spectral components [1, 2].

For channeling to be attained, the incidence angle has to be smaller than the so-called Lindhard angle [4],

$$\theta_\mathrm{c} = \sqrt{\frac{2U_0}{\varepsilon}}, \tag{1}$$

where U_0 is the electromagnetic potential associated to the axis and ε is the input energy. It has to be noted that the Lindhard angle becomes smaller as ε grows; When $U_0 = 1$ keV, which is typical of high-Z crystals such as tungsten, it equals ~ 4 mrad (~ 100 μrad) at 100 MeV (100 GeV).

The crystalline lattice affects the electromagnetic interactions of electrons/positrons also out of the limit set by θ_c and up to $\sim 1^\circ$ due to the so-called coherent bremsstrahlung (CB), which is an over-barrier effect that occurs when the momentum transferred between an input particle and the target nuclei matches a reciprocal lattice vector [5]. CB results in the enhancement of specific components of the emitted radiation spectrum with respect to standard bremsstrahlung [6].

At an initial energy of several GeV or more, the Lorentz boost affects the electromagnetic field experienced by electrons/positrons in the crystal contributing with a factor $\gamma = \varepsilon/mc^2$, m being the particle mass, and the so-called strong field (SF) regime is attained when

$$\chi = \frac{\gamma E}{E_0} > 1, \tag{2}$$

where E is the axis field in the laboratory frame and $E_0 \sim 1.32 \times 10^{18}$ V/m is the Schwinger QED critical field, above which nonlinear field effects occur in vacuum [2]. The interactions with the crystalline SF feature the emission of quantum synchrotron radiation, which shows enhanced intensity and a boost of the hard-photon component, as opposed to the incoherent case [2]. SF radiation exhibits similar features when emitted by photons and by electrons.

Differently from channeling, whose angular acceptance is defined by Eq. 1, the angular range for the SF effects can be estimated as [7, 8]

$$\Theta_0 = \frac{U_0}{mc^2} \tag{3}$$

which is independent on ε. Assuming again $U_0 = 1$ keV and considering the interaction with a 100–GeV electron, $\Theta_0 \sim 2$ mrad $\sim 20\,\theta_c$. Out of the Θ_0 threshold, the CB contributes to the output radiation intensity with a lesser enhancement as already discussed above.

The features of all the aforementioned coherent effects, and hence of the resulting radiation processes, strongly depend on the axis potential U_0, which in turn depends the lattice shape and on the atomic numbers of the elements that compose the crystalline medium. Indeed, Eqs. 1 and 3 show that both the range limit angles grow as U_0 grows. Since U_0 is proportional to the atomic number Z of the atoms that compose the axis, it follows from the latter that higher-Z materials feature larger-acceptance axial effects. Moreover, since U_0 is bigger at smaller distance between the nuclei in the string, lower atomic spacing results in stronger coherent effects. The SF regime features also depend on the axis potential: E in Eq. 2 is proportional to U_0, therefore stronger axes require a lower γ, i.e. a lower input energy, for the SF regime to be attained. On the other hand, the axial radiation enhancement decreases with increasing Z [9].

It has to be noted that, similarly to the radiation emission enhancement that occurs in crystalline SF, the pair production (PP) rate per unit thickness in case of a photon in a strong field is also enhanced [10]. Furthermore, over-barrier photons can undergo coherent PP, whose angular acceptance extends up to angles much larger than Θ_0 [6].

The enhancement of the bremsstrahlung and PP cross sections that occurs in crystals at high energy results in a boost to the development of the electromagnetic showers started by input electrons, positrons or photons when aligned to the axis with respect to the random orientation case; this reflects an overall reduction of the effective radiation length (X_0) experienced by the particles [1, 2]. Moreover, the fact that the enhancement is stronger as ε grows counterbalances the increase in the shower maximum radius depth: overall, the shower peak longitudinal position is expected to depend on the input energy only weakly [2, 11]. 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, 12].

2. Measurements in the hundred-GeV range at the CERN North Area

During the last years, various experimental studies have been performed on oriented lead tungstate ($PbWO_4$, abbr. PWO) crystals with high-energy beams in order to probe the features of the crystalline strong field. In particular, measurements of the radiation emitted by 120 GeV/c electrons and positrons have been performed around the [001] axis of a 4 mm ($0.45X_0$) PWO sample at the H4 beamline extracted from the CERN SPS.

The trajectory of the input particle was reconstructed with a pair of silicon microstrip sensors, with a resolution on the particle input angle reconstruction of $\lesssim 10\ \mu$rad. A high-precision goniometer allowed for the sample position and orientation to be controlled remotely with a resolution of $\lesssim 5\ \mu$m and $\lesssim 5\ \mu$rad respectively [14, 15]. The output charged particles were separated from the photon component by a bending magnet, and the total energy of the latter was measured by an electromagnetic calorimeter. The experimental setup was very similar to the ones described in detail, e.g., in [1, 2, 12, 13]. The beam divergence with both electrons and positrons was $\lesssim 100\ \mu$rad, way below the SF angular threshold estimated with Eq. 3 for PWO to $\sim$ 500 eV.

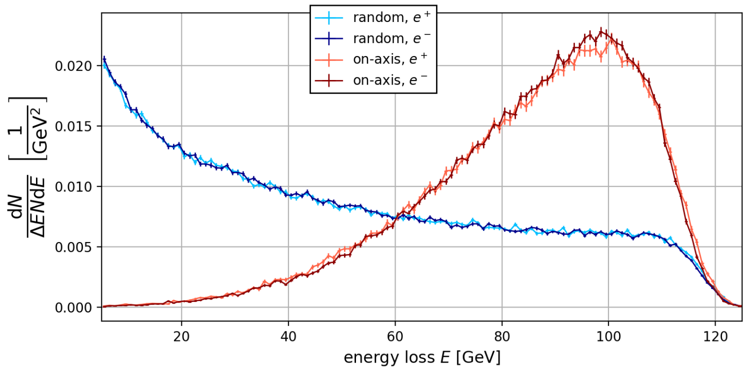

Figure 1: Spectrum of the energy lost by the input particle inside the crystal and radiated to the electromagnetic calorimeter, on axis and in random orientation, for both electrons and positrons.

Figure 1 shows the energy spectrum of the electromagnetic radiation emerging from the crystal after the passage of the input particle. The light and dark blue curves have been obtained with the sample oriented at large angle (several mrad) from the axis: here the typical bremsstrahlung spectrum shape, continuous and decreasing as the total radiated energy grows, can be clearly seen. On the other hand, the orange and red curves have been obtained from on-axis measurements. A significant modification of the spectrum shape with respect to the random case is evident. In particular, these curves show an intensity enhancement above $\sim$ 60 GeV with respect to the latter, featuring a broad peak with most probable value at $\sim$ 100 GeV, and a strong suppression at lower energies. These measurements demonstrate a strong radiation emission enhancement, with subsequent reduction of X_0 for both electrons and positrons. In case of channeling, different behaviour between e^+ and e^- would be expected, whereas Figure 1 highlights that the two spectra are fully compatible with each other. Indeed, given the fact that this high-Z crystal has some mosaicity [1], axial channeling is prevented and most particles are in overbarrier state.

3. Measurements in the sub-GeV range at the MAMI B facility

Low-energy radiation measurements have also been performed at the MAMI (MAinzer MIkrotron) B facility with an ultra-thin ($\sim$ 100 μm), low-divergence (a few tens of μrad) electron beam at 855 MeV. A 500 μm thick PWO sample has been probed. The output radiation resulting from the interactions between the electrons and the crystalline sample at different angular orientations, which could be tuned via a remotely controllable high-precision goniometer, was collected by a NaI detector placed downstream with respect to a 10 cm thick lead collimator with an aperture of 40 mm. Further details on the experimental setup can be found in [3].

Integral energy spectra of the emitted radiation have been measured both on axis and in random orientation. The ratio between the resulting curves obtained in these two configurations promptly

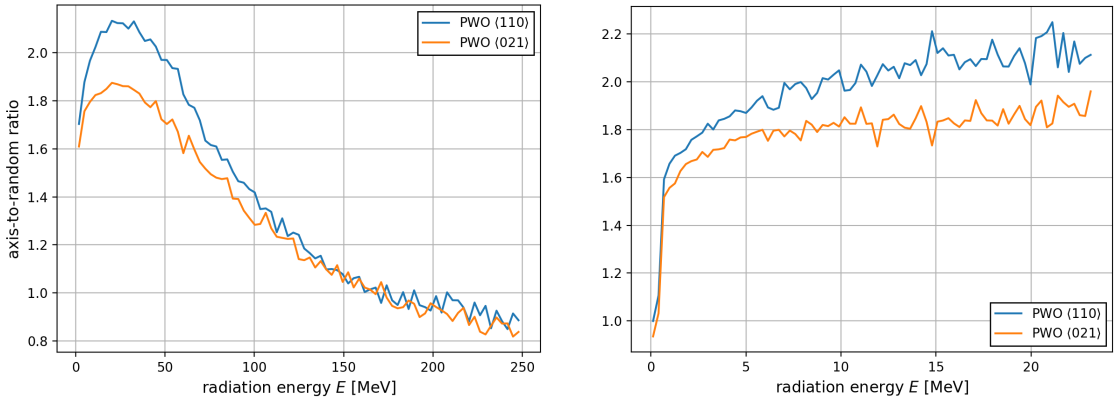

Figure 2: Ratio between spectra of the energy lost inside the crystal and radiated to the downstream detector obtained on axis and in random orientation at 855 MeV, with high-range (left – from 0 to 250 MeV) and low-range (right – from 0 to 25 MeV) acquisition.

shows the radiation on-axis enhancement between a few MeV and ~ 100 MeV as a function of the radiated energy. Figure 2 shows this ratio for two different PWO axes, [110] and [021], both at ~ 45° with respect to the sample front surface. The CR trend, i.e., the enhancement of the soft part of the spectra under axial alignment, as opposed to the random case, can be clearly observed. In particular, an enhancement of ~ 190% and ~ 210% has been obtained at 15–30 MeV with the [021] and [110] samples respectively. Indeed, the [110] axes are stronger than the [021], resulting in a stronger enhancement of emitted radiation. Nevertheless, these measurements demonstrate that the radiation enhancement occurs for different orientations of the crystal lattice and could be used as a benchmark for future Monte Carlo simulations of calorimeters based on oriented crystals, in order to take into account all the possible crystal-to-beam orientations.

4. Conclusions

Axially oriented scintillators such as PWO can represent the key item in the design of innovative, ultra-compact homogeneous calorimeters, with the key feature of a reduced depth needed to contain the shower initiated by a high-energy electromagnetic particle as compared to the current state of the art. The reduction of the electromagnetic shower length would make the calorimeter relatively insensitive to hadronic interactions, allowing the detection of photons in a neutral hadron beam without being blinded by the beam itself [16]. This detector would be crucial for the success of KLEVER, a next-generation experiment dedicated to the study of $K_L = \pi^0 \nu \overline{\nu}$.

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