CRYSTAL RADIATORS FOR ACCELERATORS

P. Fedeli*, L. Bandiera, N. Canale, F. Cescato, V. Guidi, L. Malagutti, A. Mazzolari,
R. Negrello, G. Paternò, M. Romagnoni, A. Sytov, A. Tralli
INFN Sezione di Ferrara, Ferrara, Italy, University of Ferrara, Ferrara, Italy
J. Reyes Garrido, INFN Sezione di Ferrara, Ferrara, Italy, University of Sapienza, Rome, Italy
S. Mangiacavalli, M. Prest, E. Vallazza
University of Insubria, Varese, Italy, INFN Sezione di Milano-Bicocca, Milan, Italy
D. De Salvador, F. Sgarbossa, D. Valzani
INFN Laboratori Nazionali di Legnaro, Legnaro, Italy, University of Padua, Padua, Italy
A. Bacci, I. Drebot, V. Petrillo, M. Rossetti Conti, S. Samsam, L. Serafini
INFN Sezione di Milano, Milan, Italy, University of Milan, Milan, Italy
M. Soldani, CERN, Geneva, Switzerland

Abstract

The interaction of relativistic charged particles with an oriented crystalline medium gives rise to coherent electromagnetic processes that strongly modify the broad Bethe-Heitler Bremsstrahlung spectrum typical of amorphous targets. These mechanisms produce enhanced, quasi-monochromatic photon peaks with reduced angular divergence and tunable spectral characteristics. For electron and positron beams in the 50 MeV to multi-GeV range, the photon yield and spectral profile can be tuned through precise control of crystal material, thickness, and orientation, making crystalline radiators attractive for accelerator-based applications requiring high brilliance and spectral selectivity.

Within the INFN CORAL (Crystal radiatORs for AcceLerators) project, we develop and optimize oriented crystal radiators as advanced alternatives to conventional bremsstrahlung targets. Dedicated Geant4 simulations guide the selection of materials and geometries tailored to specific energy ranges and flux requirements.

INTRODUCTION

The interaction of charged particles with crystals with an incident angle relatively small with respect to a crystallographic plane or axis leads to coherent electromagnetic interactions, where the correlated interactions with the lattice atoms can be described by a continuous potential obtained by averaging the atomic potentials along the crystal plane or axis. These coherent processes lead to effects such as *channeling radiation* (CR) and *coherent bremsstrahlung* (CB) that can significantly modify the spectrum of the standard bremsstrahlung radiation [1]. The channeling effects occur when a charged particle impinges on the oriented lattice with a relative angle with respect to the incident plane or axis less than the Lindhard Angle [1–3],

$$\theta_L = \sqrt{\frac{2U_0}{pv}} \tag{1}$$

where U_0 is the well depth of the average continuous planar/axial potential, p represents the particle momentum and v its velocity. In this phenomenon, a charged particle is forced into a transverse oscillatory motion, within the planar/axial potential well. This oscillation naturally generates the *channeling radiation*. For angles bigger than the Lindhard Angle, in the straight trajectory approximation, subsequent coherent interactions with the atoms of the lattice strings or planes can give momentum kicks which match the reciprocal lattice vector. In analogy to the Bragg diffraction, this effect produces an enhanced radiation at specific angles and energies known as *Coherent Bremsstrahlung* [4].

Figure 1 shows the photon spectrum emerging from coherent interactions of a charged beam with an oriented diamond crystal. It is possible to observe that the spectrum exhibits a pronounced peak, which becomes increasingly enhanced as the collimation is tightened. Indeed, channeling radiation shows a characteristic correlation between the photon energy and its polar emission angles. This behavior is typical of emission processes involving a Doppler boost from ultrarelativistic particles oscillating in strong transverse electromagnetic fields, generated in this case by the crystal lattice.

Due to these characteristics, crystalline radiators are highly suited for uses that require exceptional spectral brightness, adjustability, and highly focused beams. Typical applications include generating polarized photons, enhanced positrons production, and creating X-rays for biological research or detector calibration. Additionally, these crystals represent promising candidates for investigating strong-field quantum electrodynamics and serving as miniaturized gamma-ray sources within particle accelerators. At present, producing linearly polarized photons via coherent bremsstrahlung is the most standard application, typically operating at moderate flux levels. Pushing this technology into high-flux regimes creates new hurdles, however, as it requires precise optimization of the crystal's material, dimensions, and alignment to endure powerful beams while ensuring consistent radiation output.

This contribution will present an overview of the Crystal radiatOR for AcceLerators (CORAL) project, which aims to bridge theory and practical applications, advancing crystal radiators as replacements for conventional bremsstrahlung

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* pierluigi.fedeli@fe.infn.it

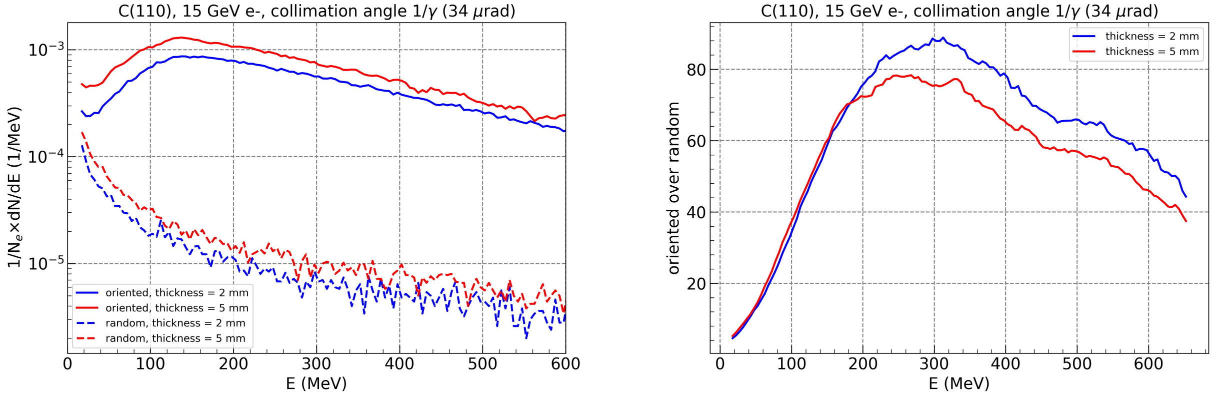

Figure 1: Geant4-simulated photon spectra produced by an electron beam with characteristics similar to those of the European XFEL facility, impinging on diamond crystals of different thicknesses aligned along the (110) plane and in random orientation. The peak average brilliance, calculated within a $1/\gamma$ collimation angle, reaches 0.85×10^{11} and 1.2×10^{11} photons/s/mm^2/mrad^2/0.1% BW for a beam current of 1 μA and crystal thicknesses of 2 mm and 5 mm, respectively.

targets where enhanced intensity and spectral control are critical.

SIMULATIONS

The CORAL project starts from previous experimental results [5–8] and aims to develop optimized crystalline radiators capable of sustaining high electron currents and delivering photon fluxes $> 10^{10}$ γ/s in the 0.1–500 MeV range, namely beyond the state of the art. The photon beam intensity will depend on the primary electron beam energy, as well as on the spectral purity needed in applications. The first crucial step toward realizing an optimal crystal-based photon source will be identifying the most suitable crystalline targets for various use cases, considering photon energy, desired monochromaticity, and primary beam parameters. For high-intensity crystal-based gamma sources, material selection must balance yield, spectral quality, and durability. Different materials, such as W to maximize the photon yield or diamond, Si and SiC for applications requiring higher monochromaticity, are investigated. Dedicated simulations, implementing models of coherent radiation in oriented crystals, were thus developed by the CORAL team, [9], and recently introduced in Geant4 [10].

Figure 2 shows an example of simulations performed with the Geant4 ChannelingFastSimModel for different types of oriented crystals. The model can predict the spatial motion of a charged particle inside the crystal [11](Fig. 2, Left) and the resulting emitted radiation (Fig. 2, Right). In the latter case, superimposing the simulation results with experimental data validates its accuracy. Geant4 provides a unique framework that allows the simultaneous simulation of coherent crystal effects and the full experimental setup within a single environment.

EXPERIMENTAL DATA

The crystal samples investigated in this work, funded within the INFN CORAL project, include diamond, tungsten, and silicon targets specifically developed for high-brilliance

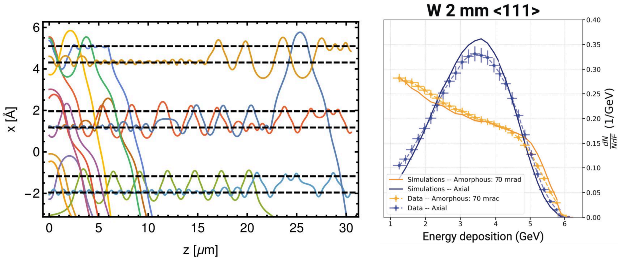

Figure 2: Left: Examples of e$^-$ trajectories in co-moving reference systems generated with ChannelingFastSimModel for planar channeling in (111) Si planes (horizontal dashed lines). Adapted from [10]. Right: Geant4 simulation of energy loss of 6 GeV electrons in a 2 mm thick W crystal in axial <111> and random orientation, compared with experimental results. Adapted from [12].

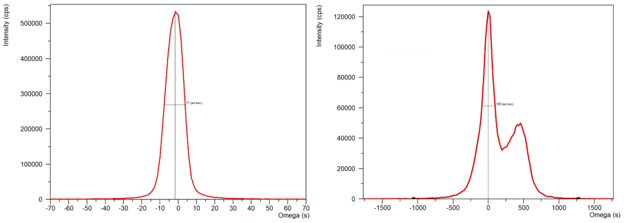

Figure 3: High-resolution X-ray diffraction rocking curves measured on silicon and tungsten samples using a PANalytical X'Pert PRO XL diffractometer with Cu Kα_1 radiation (8.04 keV). The silicon sample, shown on the left, exhibits a very narrow second-order diffraction peak from the (110) planes, with an angular width of approximately 10 arcsec, indicating very low mosaicity and high crystalline uniformity. In contrast, the tungsten sample, shown on the right, displays a much broader angular distribution, about one order of magnitude larger, with multiple peaks. This indicates the presence of more than one crystalline domain and a less uniform lattice orientation, with local misorientations extending over several tenths of a degree.

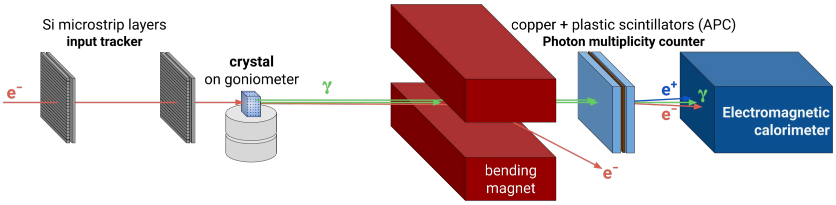

Figure 4: Example of a beam test setup performed at PS T9 or DESY. The crystalline target will be mounted on the high-precision goniometer equipped with 2 rotational and 2 linear stages to orient the crystal lattice with respect to the beam direction with a precision of a few microradians. Two silicon detectors, with dimensions of $10 \times 10 \times 0.08$ cm^3, placed before the crystal will be used to measure the impinging angles of the incoming particles. After interaction with the crystal, the primary electrons (positrons) and the possible pairs generated and not contained in the crystalline sample will be swept away by a bending magnet, while the emitted photons, after collimation, will be counted through a photon multiplicity counter [5] and collected at the downstream calorimeter. Adapted from [12].

photon production applications. The thickness of crystalline samples will range from a few tens of microns to a few millimeters, depending on the material and application, to preserve spectral enhancement and avoid the onset of electromagnetic shower development. Thicker targets may be used at beam energies above 1 GeV, where reduced multiple scattering allows coherent enhancement to persist over longer electron paths. After designing the characteristics of the oriented crystal, a series of steps for crystal target preparation and subsequent experiments on the beam must be performed to ensure its final validation.

Crystal Target Preparation and Characterization

The key parameters influencing crystal quality are mosaicity and defect density. Mosaicity quantifies the angular spread of crystal plane orientations, typically caused by dislocations, and is modeled as a distribution of slightly misoriented crystallites. When mosaicity exceeds the angular acceptance of orientational effects, coherent enhancement is significantly reduced. Mosaic spread and defect density are measured using a high-resolution X-ray diffractometer (see, for instance, Fig. 3). Surface lattice order is assessed via Rutherford Backscattering in channeling mode, using proton beams from the AN2000 and CN accelerators to probe the top 10 µm with nanometer resolution.

Experiments on Beam

Validated samples will be integrated into precision holders, allowing angular alignment and stable operation under beam-induced thermal loads. Beam tests will be performed at MAMI and CERN PS in the 0.1–6 GeV e-/e+ energy range to measure radiation yield, spectra, and angular distributions. The setup of each beam test is very similar and is schematically shown in Fig. 4. In dedicated tests at high current at MAMI, we will investigate the target resistance to assess the modification of the lattice electric potential and the possible influence on the radiation emission. Testbeam results will be compared to Geant4 simulations using dedicated models for coherent interactions in crystals, including energy deposition evaluation. Currently, offline analysis of the different test beam campaigns is ongoing for diamond, tungsten, and silicon crystals.

CONCLUSIONS

The CORAL project demonstrates the significant potential of crystalline radiators to advance the state of the art in photon beam generation for next-generation accelerators. By leveraging channeling radiation and coherent bremsstrahlung, these targets overcome the inherent limitations of amorphous materials, providing enhanced spectral brilliance, narrow angular divergence, and precisely tunable peaks. The integration of advanced coherent models into the Geant4 framework has established a robust pipeline for predicting radiator performance and optimizing target geometry, as validated by the consistency between simulations and preliminary experimental benchmarks.

The investigation into specific application regimes highlights the versatility of this technology. In the 1–20 MeV range, crystal radiators offer a viable path to achieving the extreme photon fluxes required for nuclear photofission and potential energy production applications. At higher energies, the prospect of reaching fluxes near 10^{12} γ/s above 100 MeV opens new frontiers in fundamental physics, including the first experimental observation of true muonium. Furthermore, the exploration of novel inverse Compton scattering regimes, such as Full Inverse Compton Scattering and Symmetric Compton Scattering [13, 14], provides a unique platform for studying Unruh-Hawking effects and generating quasi-monochromatic sources with minimal energy spread.

The ongoing experimental campaigns at MAMI and CERN are crucial for validating the thermo-mechanical stability of various materials, including diamond, tungsten, and silicon, under high-current conditions. Future work will focus on refining target alignment systems and finalizing the characterization of the spectral purity of the emitted radiation. These results will pave the way for a new generation of high-intensity, crystal-based gamma-ray sources, marking a transformative shift in the capabilities of particle accelerator facilities worldwide.

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