ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPC80

NOVEL HIGH-INTENSITY AND GAMMA-RAYS SOURCES USING CRYSTALS

R. Negrello*, L. Bandiera, N. Canale, V. Guidi L. Malagutti, A. Mazzolari,
G. Paternò, M.Romagnoni, A. Sytov, INFN Ferrara & University of Ferrara, Ferrara, Italy
D. De Salvador, F. Sgarbossa, D. Valzani, INFN Laboratori Nazionali di Legnaro, Legnaro, Italy
P. Klag, W. Lauth, Institut für Kernphysik der Universität Mainz, Mainz, Germany

Abstract

Recent advancements in gamma-ray light sources have catalyzed the exploration of novel methods alternative to the traditional Free-Electron Lasers (FELs) and Inverse Compton Scattering techniques. The TECHNO-CLS project, under the European Innovation Council's PATHFINDER initiative, investigates the use of crystalline light sources (CLSs) employing linear, bent, and periodically bent crystals. By leveraging the intrinsic electrostatic fields within these crystals, akin to magnetic undulators, sub-millimeter oscillation periods are achieved, allowing GeV electron beams to generate high-intensity, monochromatic X- and gamma-rays up to tens of MeV. We ouline the foundational techniques for creating crystalline undulators and the channeling phenomena in various crystal configurations, along with preliminary simulation results. These insights are crucial for the development of the next generation of gamma-ray sources.

INTRODUCTION

Crystalline Light Sources (CLSs), employing linear, bent, and periodically bent crystals, represent a new approach for hard X and γ radiation sources. These memthods are based on the intaraction of ultrarelativistic $e^{\pm}$ interacting with the strong electrostatic fields within crystals to achieve shorter oscillation periods, enabling GeV particle beams to produce 100 keV − 100 MeV photons. The adaptability of CLSs offers practical benefits over traditional methods by allowing adjustments in the sample design to meet specific application requirements. This paper will discuss the essential concepts and methods for using crystal structures to manipulate cherged particle beams and improve radiation output. We'll explore the operational principles, address manufacturing challenges of crystalline undulators, their potential as effective and versatile γ-ray sources.

RADIATION EMISSION IN CRYSTALS

Straight Crystals

When charged particles traverse a crystal at a small angle to a principal axis or plane, they experience coherent interactions. This alignment results in correlated collisions with atoms along the same row or plane, thus the particle collectively interacts with entire crystalline planes or axes. Such interactions not only alter the dynamics of charged particles within the crystal but also modify the bremsstrahlung radiation emission process. The first discovered phenomenon, known as coherent bremsstrahlung (CB), occurs when the particle's momentum transfer aligns with a reciprocal lattice vector, akin to Bragg/Laue diffraction processes [1]. Under these conditions, the bremsstrahlung cross-section, typically averaged over interactions with individual atoms, acquires an additional component through constructive interference.

At even smaller incidence angle, when the velocity of a charged particle is nearly parallel to a crystal axis/plane, *channeling* occurs provided the incidence angle is less than the critical angle, $\theta_c = \sqrt{\frac{2U_0}{pv}}$, where U_0 denotes the potential well depth, p the particle's momentum and v its velocity [2]. Under these circumstances, the particle's path becomes confined within the planar or axial potential wells, leading to an oscillatory motion, which in turn triggers a distinct type of electromagnetic radiation called channeling radiation (CR) [3]. The frequency spectrum of this radiation is influenced by the harmonic oscillation of the particle's trajectory, with the angular frequency of the first harmonic photon being calculated approximately as: $\omega = 2\gamma^2\omega_0 = 4\gamma^{3/2}/d_p\sqrt{2U_0/m}$. While CR typically exhibits a softer yet more intense radiation than CB, it is constrained by a narrow angular range defined by the Lindhard angle and is affected by the scattering with crystal nuclei and electrons, particles can escape from the channeling condition, i.e., the dechanneling effect [4].

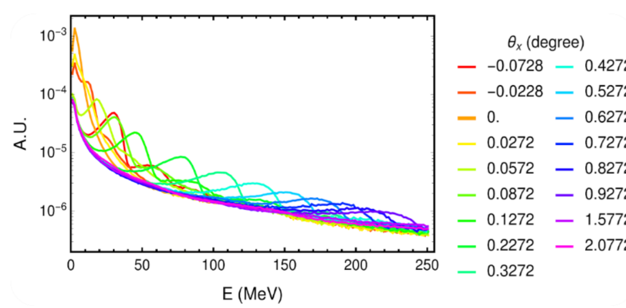

Figure 1: Radiation spectra emitted by 600 MeV e- interacting with a diamond crystal of 0.31 mm thickness along (100) planes at different orientations, channeling and CB peaks can be observed.

Example of radiation spectra from CR and CB can be observed in Fig. 1. This experiment was conducted at the Mainzer Mikrotron (MAMI), where a beam of electrons of 600 MeV impinges on a 0.31 mm thick diamond crystal along the (110) plane at various angles. Directly at angle 0 µrad, the channeling condition is respected, showcasing

* riccardo.negrello@unife.it

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPC80

a peak at low energy. At increasing angles, the peak position shifts towards harder photon's energies. Indeed the periodicity of particle's motion under CB depends on the incidence angle, θ, as d/θ, where d is the interplanar distance. At larger θ, the period is smaller, thereby leading to harder photon energies, but lower intensities. CB is currently used in different facilities to generate linearly polarized hard gamma-rays [5].

On the other hand, even if CR is more intense than CB in the MeV region and may found application in, for instance, medical physics [6], its utilization for applications is still absent.

Bent Crystals

Bent crystals have attracted considerable attention for their beam deflection properties, which are critical in applications such as beam collimation and extraction in current and future colliders [7]. Recent research has expanded to include the study of radiation emissions from e^+ and e^- in these settings [8]. In bent crystals, a unique phenomenon known as volume reflection (VR) occurs. VR involves the reflection of a particle's trajectory off the bent crystal planes when the incidence angle slightly exceeds the Lindhard angle [9]. This process affects particles that are not channeled, termed over-barrier particles, and is notably immune to dechanneling. Consequently, VR provides higher deflection efficiency than channeling, although the deflection angles are similar to those observed in θ_c. However, VR's efficiency is often moderated by volume capture (VC), a process where over-barrier particles become trapped in a channeling state due to incoherent scattering with lattice atoms at points near the crystal's reflective surface.

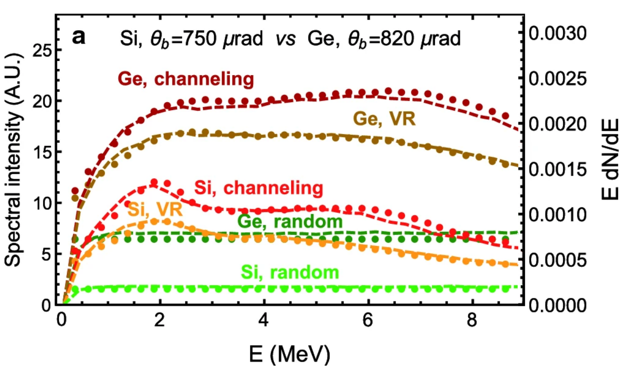

Figure 2: Experimental and simulated radiation spectral intensities for Si and Ge samples under various orientations. The experimental data are represented by lines, and the simulation data by points. Si and Ge crystals were bent to angles of 750 μrad and 820 μrad, respectively. Adapted from [10].

Volume reflection not only deflects particles but also leads to the emission of radiation, which is documented in recent studies [8, 10]. The experiments discussed here, adapted from [10] and depicted in Fig. 2, were conducted at MAMI using ultrashort bent crystals of silicon (Si) and germanium (Ge) as a target of an 855 MeV electron beam. The beam exhibited a size and angular divergence of 105 μm and 21 μrad, respectively, in the plane parallel to the crystal bending. The crystals themselves were 15 μm thick [11]. These measurements varied the angular alignment between the crystals and the beam (θ_{in}), exploring positions such as channeling alignment ($\theta_{in} \approx 0$), volume reflection ($\theta_{in} \approx -\theta_{in}/2$), and random ($\theta_{in} \gg -\theta_C$). The spectral range was selected from 0.5 MeV to 8 MeV, focusing on the region pertinent to channeling radiation (CR). Notably, the Ge samples produced more intense radiation than their Si counterparts under comparable alignments, attributed to Ge's higher atomic number. Research indicates [8] that particles captured in the channeling regime at the reflection point predominantly sustain the CR peak in VR configurations. A reduction in the number of these captured particles corresponds with a diminished VR radiation peak, suggesting that the radiation in VR settings comprises contributions from both purely reflected particles and those trapped in channeling conditions. This radiation is associated with both CR, due to volume capture (VC), and CB, resulting from the general orientation of the crystals. VR radiation is particularly notable for its broader angular acceptance relative to CR, matching the bending angle of the crystal [8], while maintaining radiation intensity levels comparable to both CR and CB. These properties of VR radiation demonstrate its potential for the development of powerful radiation sources with reduced beam emittance and for the creation of VR-based crystalline undulators [8]. Furthermore, the combination of the high-intensity of radiation emission and the deflection power of VR can be exploited for the collimation of future linear e^+e^- colliders [12].

Crystalline Undulator

The concept of a crystalline undulator (CU), which exploits periodically bent crystals to produce intense and monochromatic electromagnetic radiation, was originally proposed in the late 1970s [13]. A CU emulates magnetic undulators through its utilization of strong electrostatic fields between crystal planes, that can reach values of the order of 10^9 V cm^{-1}. In contrast to magnetic undulators, where the oscillation period λ_u cannot be less than 1 cm, a CU allows for significantly smaller periods, down to the sub-millimeter range. The wavelength of the emitted γ-rays is determined by the formula: $\lambda = \frac{\lambda_u}{2\gamma^2}(1 + k^2/2)$ here γ the Lorentz factor of the beam impinging the CU, and k the so-called undulator strength parameter. This configuration enables the generation of harder photons compared to those produced by magnetic undulators. For instance, a CU with a period on the order of 10 μm to 100 μm can generate MeV photons using a GeV electron beam. Over time, several studies have demonstrated the feasibility of CUs [14]. The advantage of using periodically bent crystals lies in the ability to fine-tune the bending amplitude and period to match specific beam parameters. This adaptability ensures that the emitted radiation can be adjusted to meet the requirements of various applications.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPC80

The initial methods for CU manufacturing included patterned ion implantation using swift ions. This process induces an amorphized region that exerts coercive forces on the crystal bulk, creating an elastic strain field and inducing curvature within the crystal. Specifically, the implantation of 150 keV He^{+} ions has proven effective for CU fabrication [15]. An alternative approach involves depositing a strained layer of silicon nitride on a silicon monocrystal via low-pressure chemical vapor deposition (LPCVD). Conducted at high temperatures, typically around 800 °C, this method induces thermal stress upon cooling, given the differential thermal expansion coefficients of the film and substrate [16]. Additionally, the grooving technique, which involves engraving a series of grooves along the major surfaces of a crystal, has also been used to induce a permanent and reproducible deformation across the crystal [17]. This deformation is essential for achieving the desired modulation in the crystal lattice.

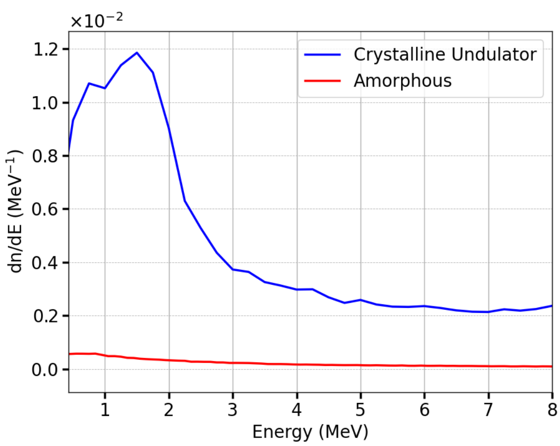

Figure 3: Simulated radiation emission probability for a 10 GeV positron beam interacting with sample 1 (solid line) and the Bethe-Heitler amorphous emission probability for a Si sample of the same thickness (Adapted from [18]).

As an example from [18], Fig. 3 the simulation of the radiation emission probability by a 10 GeV positron beam with 30 µrad of divergence on silicon CU with λ_u=334 µm, amplitude $A = 1.28$ nm and strength parameter $k = 0.46$. The amplitude A surpasses the interplanar spacing d, aligning with the requirements for a feasible CU in regimes of large amplitude and period [14]. The spectrum in Fig. 3 shows a pronounced peak at approximately 1.5 MeV, markedly higher—over twentyfold—than the radiation from an equivalent amorphous silicon sample within the 0.5 MeV to 2 MeV range.

All this kind of X and γ-ray sources based on oriented crystals should be compared to the others already existing in the literature. The most promising of which is ICS, where an intense laser beam of visible or near-infrared photons is scattered off an electron beam with typically a few hundred MeV energy. Crystal-based sources offer cost advantages, as they do not necessitate powerful, short-pulse laser systems. However, the non-monochromatic contribution of standard bremsstrahlung to CB/CR emissions persists, although reducible with proper collimation. Nevertheless, this is not a problem for several applications in medical physics, while in nuclear physics the photo-tagging method is normally used with CB sources to know exactly the photon energy [19].

CONCLUSION

This paper reviewed the application of crystalline structures to develop high-intensity, quasi-monochromatic and tunable γ-ray sources. Using linear, bent, and periodically bent crystals, nearly monochromatic radiation can be effectively produced. CLSs offer a sustainable alternative over traditional technologies like FELs and ICS by allowing for specific tuning of radiation properties to suit various applications. We discussed the principles of coherent bremsstrahlung, channeling and volume reflection radiation. Future developments focus on refining the manufacturing techniques, promising more precise structures for enhanced performance. The results from simulations and experiments suggest a fruitful future for crystalline-based radiation sources, with potential impacts across material science, medical imaging, and nuclear physics.

ACKNOWLEDGEMENTS

The authors acknowledge financial support from the European Commission's Horizon Europe-EIC-Pathfinder-Open TECHNO-CLS (G.A. 101046458) project and from the H2020 MSCA-RISE-NLIGHT project (G.A. 872196).

REFERENCES

[1] M. L. Ter-Mikaelian and L. S. Osborne, "High-Energy electromagnetic Processes in condensed media," *Physics today*, vol. 26, no. 3, pp. 69–71, 1973. doi:10.1063/1.3127988

[2] J. Lindhard, "Influence of crystal lattice on motion of energetic charged particles," *UFN*, pp. 249–96, 1965. doi:10.3367/UFNr.0099.196910c.0249

[3] M. Kumakhov, "On the theory of electromagnetic radiation of charged particles in a crystal," *Physics letters. A*, vol. 57, no. 1, pp. 17–18, 1976. doi:10.1016/0375-9601(76)90438-2

[4] V. V. Beloshitsky, M. A. Kumakhov, and V. A. Muralev, "Multiple scattering of channeling ions in crystals-II. Planar channeling," *Radiation effects*, vol. 20, no. 1-2, pp. 95–109, 1973. doi:10.1080/00337577308232272

[5] F. Rambo *et al.*, "Enhancement of the linear polarization of coherent bremsstrahlung by collimation of the photon beam," *Phys. Rev. C*, vol. 58, no. 1, pp. 489–501, 1998. doi:10.1103/physrevc.58.489

[6] S. Polozov and T. Bondarenko, "X-ray Radiation Source for Low Dose Angiography based on Channeling Radiation," *5th Int. Particle Accelerator Conf. (IPAC'14), Dresden, Germany, June 15-20, 2014*, pp. 2186–2188, 2014. doi:10.18429/jacow-ipac2014-wepro096

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPC80

[7] W. Scandale *et al.*, "Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC," *Physics letters. B*, vol. 758, pp. 129–133, 2016. doi:10.1016/j.physletb.2016.05.004

[8] L. e. a. Bandiera, "Investigation of the electromagnetic radiation emitted by Sub-GEV electrons in a bent crystal," *Physical review letters*, vol. 115, no. 2, 2015. doi:10.1103/physrevlett.115.025504

[9] A. Taratin and S. Vorobiev, "“Volume reflection” of high-energy charged particles in quasi-channeling states in bent crystals," *Physics letters. A*, vol. 119, no. 8, pp. 425–428, 1987. doi:10.1016/0375-9601(87)90587-1

[10] L. e. a. Bandiera, "Investigation on radiation generated by sub-GeV electrons in ultrashort silicon and germanium bent crystals," *European physical journal. C, Particles and fields*, vol. 81, no. 4, 2021. doi:10.1140/epjc/s10052-021-09071-2

[11] V. Guidi, L. Bandiera, and V. Tikhomirov, "Radiation generated by single and multiple volume reflection of ultrarelativistic electrons and positrons in bent crystals," *Phys. Rev. A: At. Mol. Opt. Phys.*, vol. 86, no. 4, 2012. doi:10.1103/physreva.86.042903

[12] A. Seryi, "Future prospects of accelerator science for particle physics," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 623, no. 1, pp. 23–28, 2010. doi:10.1016/j.nima.2010.02.145

[13] V. G. Baryshevskiĭ and V. V. Tikhomirov, "Synchrotron-type radiation processes in crystals and polarization phenomena accompanying them," *Soviet physics. Uspekhi*, vol. 32, no. 11, pp. 1013–1032, 1989. doi:10.1070/pu1989v032n11abeh002778

[14] A. V. Korol, A. V. Solov'yov, and W. Greiner, *Channeling and radiation in periodically bent crystals*. Springer Berlin, Heidelberg, 2014. doi:10.1007/978-3-642-54933-5

[15] S. e. a. Bellucci, "Experimental study for the feasibility of a crystalline undulator," *Physical review letters*, vol. 90, no. 3, 2003. doi:10.1103/physrevlett.90.034801

[16] V. Guidi, L. Lanzoni, A. Mazzolari, G. Martinelli, and A. Tralli, "Design of a crystalline undulator based on patterning by tensile Si3N4 strips on a Si crystal," *Applied physics letters*, vol. 90, no. 11, 2007. doi:10.1063/1.2712510

[17] V. e. a. Bellucci, "Ion implantation for manufacturing bent and periodically bent crystals," *Applied physics letters*, vol. 107, no. 6, 2015. doi:10.1063/1.4928553

[18] R. a. Camattari, "Silicon crystalline undulator prototypes: Manufacturing and x-ray characterization," *Physical review. Accelerators and beams*, vol. 22, no. 4, 2019. doi:10.1103/physrevaccelbeams.22.044701

[19] D. e. a. Lohmann, "Linearly polarized photons at MAMI (Mainz)," *Nucl. Instrum. Methods Phys. Res., Sect. At*, vol. 343, no. 2-3, pp. 494–507, 1994. doi:10.1016/0168-9002(94)90230-5