TECHNO-CLS Newsletter

Scientific and Technological Highlights from the Third Year

The TECHNO-CLS project aims to pioneer the development of next-generation gamma-ray light sources based on the channelling of ultra-relativistic particles through linearly, bent, or periodically bent crystals. The project unites multiple scientific disciplines, from multiscale modelling and materials science, to beamline engineering and optical diagnostics, in pursuit of Crystal-based Light Sources (CLS) capable of operating at photon energies greater than 10^2 keV.
This newsletter provides a comprehensive summary of progress made during the third year of the project.

Third Year Summary May 2024 - June 2025

Theory and Modelling

In the third year of the TECHNO-CLS project, the MBN Research Center continued to lead the development of multiscale simulation tools for modelling radiation processes and particle propagation in crystalline fields. A major focus was the advancement of relativistic molecular dynamics simulations to analyse the behaviour of positron and electron beams in both bent and periodically bent crystals.

The key results obtained was the demonstration that CLSs are more intense that light sources based on contemporary laser-Compton scattering. Simulations were conducted with 10 GeV electrons and positrons, and 855 MeV electrons. For 10 GeV positrons with a beam current of 1 µA the number of photons produced was 10^{11} photons/s, greater than the total number of photons at the High Intensity γ-Ray Source (HIγS). Similarly, with 855 MeV electrons with a beam currently of 10 µA, 10^{10} photons/s photons being produced, more than are produced at HIγS for a beam current of 10 mA. These results have been published in Sushko, *et al. Phys. Rev. Accel. Beams* **27**, 100703 (2024).

The MBN Research Center also performed detailed simulations of 530 MeV positrons deflection in quasi-mosaic silicon crystals, directly benchmarking the results against experimental data from the Mainz Microtron (MAMI). The simulations reproduced key features such as planar channelling, dechannelling, volume reflection, and capture phenomena, with additional predictions made for untested crystal orientations. The crystal's geometry, emittance of the collimated particle beams, as well as their alignment with respect to the crystal, have been taken into account as they are essential for an accurate quantitative description of the processes. There results have been published in Ibañez-Almaguer, *et al J. Phys. B* **57** 175203 (2024).

Radiation emission simulations were also conducted for 530 MeV positrons and 270–1500 MeV electrons in single diamond, silicon, and germanium crystals, accounting for ionising collisions. The results show that ionising collisions have negligible impact on electron channelling and radiation, while for positrons they reduce channelling efficiency but do not diminish the resulting radiation intensity. These results have been published in Sushko, *et al. Nucl. Instrum. Methods Phys. Res. B* **569**, 165911 (2025).

Additionally, the MBN Research Center finalised a comprehensive analysis of the operational parameter space for acoustically driven crystalline undulators, establishing feasible ranges of bending amplitude, period, and acoustic frequency for positron energies at both MAMI and CERN. These results provided essential design constraints for ongoing device development at the Hellenic Mediterranean University. The team also advanced the modelling of radiation emission from periodically bent boron-doped diamond crystals and periodically bent Si crystals fabricated using surface patterning, with computational results underpinning recent experimental observations at MAMI and CERN.

During the third year of the project, the Hellenic Mediterranean University significantly advanced their finite element modelling programme to support the design and optimisation of acoustically driven crystalline undulators. Numerical simulations were performed to investigate the excitation of silicon and germanium crystals by means of piezoelectric transducers, optimised for both sub-GeV and multi-GeV positron beams. These simulations accounted for newly constructed device geometries and operating parameters, enabling precise predictions of acoustic wave propagation, lattice displacement profiles, and associated stresses within the crystal bulk. The results of this work have been published in Kaleris, *et al.* *Phys. Rev. Accel. Beams* **28**, 033502 (2025).

Key results included transient mechanical analyses demonstrating nearly sinusoidal lattice displacements in 1 mm thick silicon crystals driven at 20 MHz, achieving displacements up to 1.9 nm, values well within the operational range required for undulator radiation with ultra-relativistic positrons. Additionally, simulations at 60 MHz excitation frequencies showed the potential to reach bending amplitudes exceeding twice the silicon lattice constant with moderate pressure amplitudes (8–10 MPa). Further studies on 4 mm thick silicon crystals confirmed the feasibility of generating multiple undulation periods suitable for positron energies beyond 20 GeV. These findings, integrating finite element and frequency domain analyses, provide critical input for the multiscale simulation framework led by MBN Research Center and pave the way for future experimental validation of acoustically driven crystalline undulators at CERN and MAMI.

During the third year of the project the University of Kent extended their atomistic modelling programme to investigate the structural effects of boron doping in diamond crystals, in collaboration with the MBN Research Center. Using advanced molecular dynamics simulations with MBN Explorer, the University of Kent conducted systematic studies on diamond crystals doped with 1–5% boron, incorporating periodic boundary conditions in the lateral directions and a fixed substrate layer to replicate realistic chemical vapour deposition (CVD) methods.

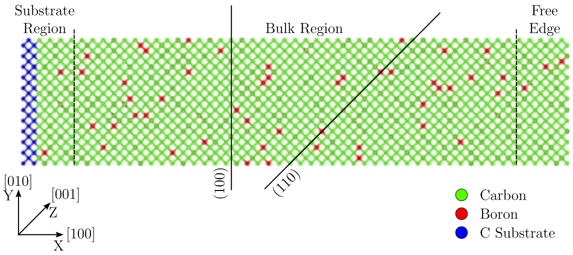

Figure 1: Diagram of the crystal configuration used in MD simulations showing carbon atoms are shown in green, boron atoms in red, substrate carbon atoms in blue, the (1 1 0) and (1 0 0) crystallographic planes, and the boundaries between the three analysis regions.

These simulations quantified how dopant concentration influenced inter-planar spacings along both the (101) and (001) crystallographic directions, revealing a near-linear dependence in line with Vegard's Law. By dividing each crystal into distinct regions: near the substrate, bulk, and free surface, the study provides a insight into the localised structural responses to doping, offering valuable predictions for crystal design and growth optimisation. The validity of their crystal generation methodologies were confirmed based on analysis of dopant distributions via calculations of boron–boron nearest neighbour distances. The results can be found in Dickers, *et al.* *arXiv preprint arXiv:2509.13045*.

In the third year of the project, the ESRF continued its theoretical and computational investigations into boron-doped diamond crystalline undulators (CUs). Building on earlier work, ESRF conducted detailed theoretical analyses of the deformation profiles of (110) crystallographic planes in boron-doped diamond layers, focusing on periodic doping schemes. The study examined idealised doping distributions such as sinusoidal, cosine, and sawtooth profiles, as well as experimentally measured doping profiles obtained via Secondary Ion Mass Spectrometry (SIMS) from samples produced by Microwave Plasma Chemical Vapour Deposition (MPCVD).

These analyses aimed to derive precise mathematical descriptions of the resulting undulation amplitudes and periods in response to different boron concentration profiles. By correlating these theoretical profiles with the SIMS-characterised doping distributions in fabricated samples, ESRF was able to assess the feasibility of achieving well-controlled periodic bending suitable for crystalline undulator radiation. The results of this work are being prepared for publication and will provide important input for both crystal fabrication strategies and future beamline experiments aimed at validating the undulator effect in boron-doped diamond structures.

During the third year of the project, INFN and the University of Ferrara made important contributions to the multiscale modelling of periodically bent crystals. Working in collaboration with MBN Research Center, the teams performed finite element method simulations to model the sinusoidal deformation profiles induced in silicon (110) crystals by patterned silicon nitride surface stressor layers, a key fabrication technology developed by their teams for periodically bent crystalline undulators.

The deformation profiles generated by the finite element method simulations were then used as input for relativistic MD simulations with MBN Explorer, enabling the simulation of positron channelling at 10 GeV beam energies, representative of conditions at facilities such as SLAC's FACET-II. Trajectory simulations of around 1000 positrons were conducted to evaluate beam propagation and channelling stability in these periodically bent structures. This work has yielded promising results, now in preparation for publication, which inform both the experimental beamline tests and the optimisation of fabrication parameters for next-generation crystalline undulators.

Additionally, INFN, the University of Ferrara, and their collaborators prepared case studies for forthcoming atomistic simulations of 10 GeV positron propagation through crystals manufactured using Pulsed Laser Melting, a complementary fabrication technique led by the University of Padova. These modelling activities continue to play a central role in bridging crystal fabrication technologies with experimental CLS validation.

Experimental Issues

Throughout the third year of the project, INFN, the University of Ferrara, and the University of Padova jointly carried out extensive structural characterisation of periodically bent silicon and germanium crystals fabricated via silicon nitride surface stressors and crystals pulsed laser melting techniques, respectively. Using advanced X-ray diffraction imaging methods at the BM05 beamline at ESRF and the B16 beamline at the Diamond Light Source in the UK, the teams conducted high-resolution mapping of lattice curvature, periodicity, and crystalline quality in silicon and germanium PBC samples. These measurements confirmed the presence of highly uniform periodic undulation profiles, and verified the absence of bulk defects, which are critical for maintaining high channelling efficiency in CLS applications.

Figure 2: Consortium partner from INFN, UNIFE and UNIPD at the B16 beamline at the Diamond Light Source.

A two-week experimental campaign was undertaken by INFN, the University of Ferrara, and the University of Padova at the CERN SPS H2 beamline, where periodically bent silicon crystals fabricated by INFN and the University of Ferrara teams were tested with high-energy positron beams. These experiments successfully recorded undulator radiation peaks, demonstrating the structural integrity and functional performance of the PBC devices under operational beam conditions. This is a crucial milestone for the project's CLS development programme.

During the third year of the project, ESRF performed advanced structural characterisation of boron-doped diamond samples intended for crystalline undulator applications. Using high-resolution X-ray diffraction imaging techniques at the BM05 beamline, ESRF applied projection Rocking Curve Imaging to assess the crystalline quality, defect distribution, and undulation periodicity of boron-doped diamond superlattice samples. These measurements provided two-dimensional strain and curvature maps, confirming the presence and regularity of undulated (110) planes, a critical requirement for efficient positron channelling and undulator radiation.

In the third year of the project the Hellenic Mediterranean University continued the experimental characterisation of acoustically driven crystalline undulator prototypes. Their primary focus was on the characterisation of multi-MHz acoustic wave excitation in thin, high-quality silicon single crystals with dislocation densities below 300 cm^{-2}. Using a custom optical interferometry system, the Hellenic Mediterranean University successfully measured both static and dynamic deformations induced by piezoelectric transducers, validating the generation of controlled undulator-like lattice displacements in silicon crystals of various sizes and geometries.

These interferometric measurements confirmed the stable propagation of acoustic waves at MHz-range frequencies, an essential requirement for dynamic undulator operation with ultra-relativistic positron beams at facilities such as CERN. The experimental results also provided crucial input for refining simulation parameters in multiscale modelling studies and established key performance benchmarks for future acoustically driven crystalline undulator prototypes designed for gamma-ray generation experiments. The results of this work have been published in Kaniolakis-Kaloudis, *et al.*, *J. Acoust. Soc. Am.* **158**, 4007 (2025).

In the third year of the TECHNO-CLS project, the University of Mainz (Uni-Mainz) completed the commissioning of their dedicated low-divergence 600 MeV positron beamline at the Mainz Microtron (MAMI), marking a major milestone for experimental CLS studies. Initial characterisation experiments confirmed stable positron beam delivery, while simulations using the FLUKA code were performed to optimise radiation shielding configurations for future high-intensity beam runs. This fully operational beamline now enables direct measurements of positron channelling and radiation emission in crystalline targets, forming a key infrastructure component for the project's experimental programme.

Uni-Mainz also conducted multiple channelling experiments with both positron and electron beams. Key achievements included the characterisation of scattering distributions in various materials, and the first observation of crystalline undulator radiation from a boron-doped diamond superlattice at sub-GeV energies. These results can be found in Backe, *et al.* *arXiv preprint arXiv:2504.17988*, 2025.

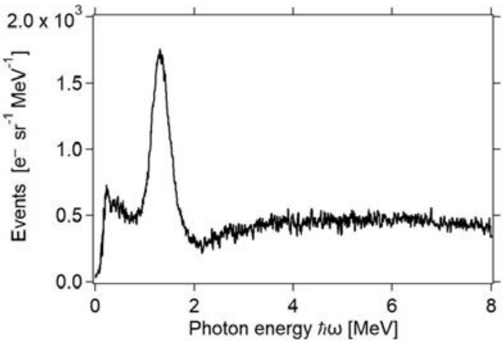

Figure 3: Experimental radiation spectra of the undulator crystal.

Additional experiments examined the channelling properties of periodically bent diamond samples, with radiation spectra and PBC geometries evaluated via beam-induced channelling radiation measurements. Furthermore, collaborative campaigns with INFN, the University of Ferrara, and the University of Padova tested bent silicon crystals using the new positron beamline, verifying their channelling and radiation emission performance under controlled conditions.

Figure 4: The UNIFE, UNIPD and UniMainz teams at the positron beamline at MAMI.

CLS Technology

During the third year of the TECHNO-CLS project, UNIPD, INFN, and UNIFE filed an innovative patent aimed at improving the design of crystalline undulators based on elastic deformation induced by surface layers. The Transverse Sinusoidal Patterning (TSP) of the surface layer, the core of the invention, ensures greater uniformity and regularity of the periodic deformation within the bulk of the material, preventing regions where the particle trajectory might experience discontinuities. The concept has been applied both to periodic crystals produced through silicon nitride layers by UNIFE and INFN, using high-quality silicon as the channeling crystal, and to the development of prototypes based on germanium crystals, in which the stress was induced through a pulsed-laser process by the UNIPD team. [Italy – Patent Application No. 102024000022335 dated 10/08/2024]

Building on this innovation, INFN and UNIFE made substantial advances in the fabrication of periodically bent silicon crystals (PBCs) for crystalline undulator (CU) applications. Building on their earlier simulation work, the teams produced a new series of crystalline undulators tailored for high-energy positron beams at the CERN SPS. These devices, developed in collaboration with the Institute Theoretical analyses were also extended to examine expected channelling and radiation behaviour in periodically bent silicon crystals prepared via surface patterning, offering predictions to support parallel experimental campaigns at the CERN. for Microelectronics and Microsystems in Bologna, utilised patterned silicon nitride stressor layers to induce precise sinusoidal lattice deformations. The manufactured undulators featured 10 undulation periods, each 334 µm long, and were fabricated in both standard and TSP pattern design configurations for comparative beamline testing.

Following fabrication, the structural properties of these PBCs were assessed using advanced interferometric techniques to verify the alignment of stressor patterns on both wafer surfaces. Notably, one of the INFN–UNIFE fabricated samples was successfully tested at the CERN SPS H2 beamline, where a distinct crystalline undulator radiation peak was observed at 35 GeV positron beam energy. This marked a major achievement for the project, confirming the operational feasibility of periodically bent silicon crystals produced via the surface-stressor method for high-energy gamma-ray light source applications.

In the third year of the TECHNO-CLS project, the ESRF continued its development of boron-doped diamond crystalline undulator (CU) samples using MPCVD. Two new boron-doped diamond crystals were successfully fabricated, targeting the short-period doping profiles defined by theoretical models developed previously developed. These samples were produced to induce periodic lattice deformations along the (110) planes, providing candidate structures for generating crystalline undulator radiation with sub-GeV and multi-GeV positron beams.

In addition to sample fabrication, ESRF collaborated with other project partners to characterise the boron distribution profiles in these crystals using Secondary Ion Mass Spectrometry (SIMS) in partnership with IAF Fraunhofer (Germany). These measurements verified the periodicity and concentration ranges of boron incorporation achieved during synthesis, confirming that the resulting structures met the specifications necessary for CLS testing campaigns at MAMI and CERN. This work directly supports the ongoing optimisation of MPCVD growth protocols for producing crystalline undulator-grade diamond materials.

In the third year of the project, the University of Padova advanced its development of periodically bent germanium crystals using the pulsed laser melting technique. Four new (110)-oriented germanium periodically bnt crystals were fabricated, each tailored for high-energy CLS experiments with positron beams of 20 GeV and above. These crystals incorporated surface stressor layers produced via controlled pulsed laser melting, designed to induce periodic bending suitable for crystalline undulator applications.

Following fabrication, these germanium samples underwent comprehensive structural characterisation using synchrotron X-ray diffraction imaging techniques at the ESRF BM05 beamline, and the Diamind Light Source C16 beamline, in collaboration with INFN and the University of Ferrara. These analyses confirmed the periodicity, curvature profiles, and crystalline quality of the fabricated structures, ensuring their readiness for forthcoming beamline experiments. The successful production and validation of these large-period Ge periodically bent crystals represent a critical milestone in broadening the material options available for high-energy CLS prototypes.

During the third year of the project, the Hellenic Mediterranean University (HMU) made important advances in the development of acoustic-wave-driven crystalline undulator prototypes. The team successfully designed and fabricated new piezoelectric transducers tailored for generating multi-MHz acoustic waves in both silicon and germanium crystals. These devices employed thin, high-quality quartz plates measuring 30 × 10 × 0.1 mm, enabling precise coupling of acoustic waves into monocrystalline samples with controlled amplitude and frequency parameters.

These improved transducers were specifically developed for proof-of-principle studies of gamma-ray generation via acoustic wave-induced periodic bending, with crystal geometries optimised for both the 530 MeV positron beam at MAMI and the 20–35 GeV positron beams at CERN. The availability of these devices marks a critical step toward the first experimental tests of acoustic-wave-driven crystalline undulator prototypes in high-energy accelerator environments and will directly support future beamline campaigns within the project.

In the third year of the project, the MBN Research Center contributed important theoretical groundwork to support the development of periodically bent crystalline structures for CLS applications. Specifically, the MBN Research Center performed a detailed theoretical analysis of the relationship between boron dopant concentration profiles and the resulting lattice bending amplitudes and periods in diamond crystals. This work provided quantitative predictions for the variation in boron concentration required to achieve periodic, harmonic lattice deformations of specified amplitude and wavelength. These are essential parameters for designing efficient crystalline undulators. The full details are available in Korol & Solov'yov, *arXiv preprint arXiv:2505.20037*, 2025.

These theoretical results served as a crucial reference for experimental partners involved in fabricating boron-doped diamond superlattices by MPCVD, guiding the selection of doping profiles and process parameters. The analysis also informed expectations for achievable undulator parameters in these materials, helping to refine both crystal growth strategies and experimental characterisation protocols for the ongoing development of boron-doped diamond CLS prototypes.

Dissemination and Outreach

In the third year of the TECHNO-CLS project, dissemination and outreach activities continued to be a strong focus for the consortium, ensuring the wide communication of project results to both the academic community and industrial stakeholders. Across the reporting period, consortium members collectively produced an impressive body of work, including 11 peer-reviewed journal publications and 16 conference contributions, many of which were joint efforts between multiple project partners. Several open-access preprints were also submitted to arXiv, ensuring rapid dissemination of new results within the field of high-energy channelling physics. These outputs covered key advances in theoretical modelling, crystal fabrication techniques, beamline experiments, and radiation emission studies, reflecting the highly interdisciplinary nature of the project.

The consortium maintained a strong presence at international scientific conferences and specialised workshops. Project results were presented at prominent meetings including

Channeling 2024, DySoN 2024, and the *Anglo-French Physical Acoustics Conference (AF-PAC)*, with oral and poster presentations delivered by researchers from all consortium members. These events provided valuable opportunities for the consortium to engage with the broader CLS and accelerator physics communities, gather feedback on experimental results, and explore potential avenues for future collaboration. The second TECHNO-CLS Workshop was also held in the third year of the project, in Rehtymnon, Crete on October 9–11, 2024, organised by the Hellenic Mediterranean University.

Figure 5: Participants of the second TECHNO-CLS workshop on October 9–11, 2024 in Rehtymnon, Crete.

In addition to academic dissemination, the TECHNO-CLS consortium continued to maintain and update the official project website and its LinkedIn[1] and Twitter (X)[2] social media pages, managed by the University of Kent. These platforms were actively used to announce publications, conference presentations, project milestones, and outreach initiatives, contributing to the visibility of the project within both the scientific community and among prospective industrial partners. Consortium members also participated in a number of in-person outreach activities, including European Researchers' Night's in both Ferrara and Rethymnon.

The project's innovation management activities also progressed, with two new innovations formally added to the TECHNO-CLS Innovation Portfolio, and one of these innovations successfully registered for Horizon Results Booster services, gaining access to EU-funded support for exploitation strategy development. The consortium continued to track the innovations previously flagged by the European Commission's Innovation Radar, several of which were recognised as having "very high market creation potential."

Finally, outreach to industry and application stakeholders was strengthened through targeted engagement with potential collaborators in high-energy accelerator technology, materials engineering, and medical imaging. An updated list of prospective industrial partners and CLS end-users was compiled, laying the groundwork for future exploitation and technology transfer opportunities as the project transitions towards operational prototype demonstrations.

The third year of the TECHNO-CLS project has marked a period of significant technological and scientific progress in the development of crystal-based gamma-ray light sources. Most notably, the first observation of crystalline undulator radiation in boron-doped diamond crystals during beamline experiments at MAMI. This experimental breakthrough confirms the core concept of crystalline light sources under operational conditions and represents a major milestone for both the project and the wider field of high-energy channelling physics.

The consortium have made significant advances in crystal fabrication, structural characterisation, and radiation modelling, supported by a productive dissemination programme spanning journal publications, conference presentations, and open-access preprints. With operational prototypes on the horizon, TECHNO-CLS enters its fourth year well positioned to deliver practical, high-brilliance gamma-ray sources and to establish the technological standards that will underpin their future exploitation.

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[1] linkedin.com/company/techno-cls-project/

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