LEAPS Technology Roadmap 2025

STRENGTHENING PHOTON SCIENCE IN EUROPE

LEAPS
League of European Accelerator-based Photon Sources

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EXECUTIVE SUMMARY

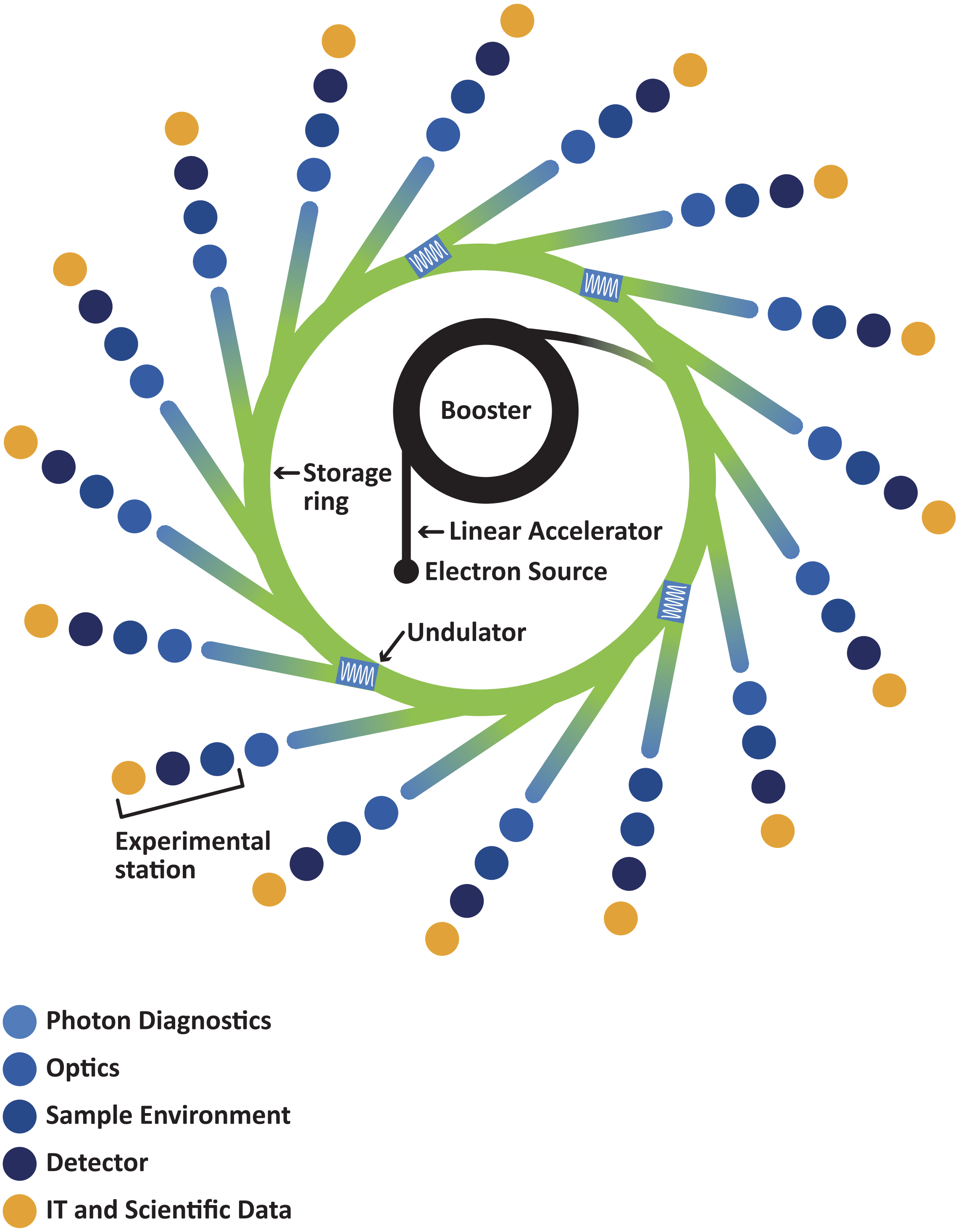
LEAPS—the League of European Accelerator-based Photon Sources— is the largest network of large-scale Research Infrastructures (RIs) in Europe. LEAPS brings together nineteen synchrotron radiation storage rings (SRs) and free-electron laser (FELs) facilities around Europe. These cutting-edge infrastructures are essential tools for advancing fundamental and applied research, and industrial innovation.

This strategic Technology Roadmap, an update of the first installment in 2018, identifies the development needs for the next 10 years in six priority technology areas: Photon Sources, Photon Diagnostics, X-ray Optics, Sample Environment, X-ray Detectors, and Information Technology and Scientific Data. Each requires coordinated investment and development amongst the LEAPS partners. The impact of this collaborative approach is game-changing and will allow LEAPS facilities to adapt effectively to the rapidly evolving technological landscape by applying a smart specialisation strategy, taking advantage of synergies and avoiding duplication of efforts. Many of the foreseen advances build upon the achievements of the Horizon Europe LEAPS-INNOV project, and national initiatives. They are critical for enabling the next-generation of accelerator-based photon sources to provide beams with higher brightness, increased coherence, and to substantially reduce the energy footprint of the facilities.

Standardisation, modular systems, and artificial intelligence (AI) integration will improve the efficiency and resilience of the LEAPS facilities. This will offer the scientific community tools like high throughput kit and workflows for the production of massive data for materials discovery; advanced sample environments and data management for multi-dimensional experiments that enable catalyser improvements for greener chemistry; high-performance photon optics that will give access to precision semi-conductor analytics for next generation chips; and quantum computing materials.

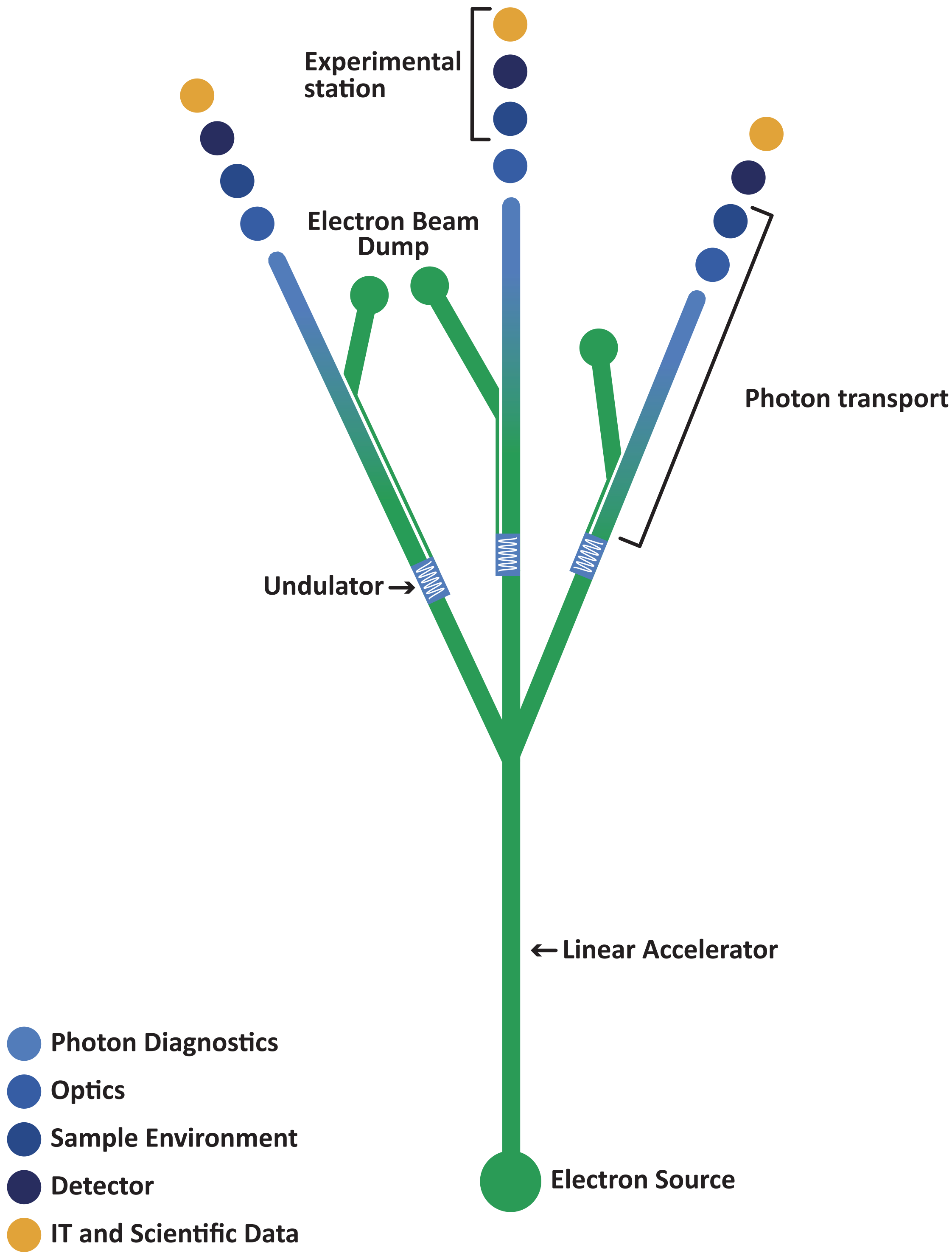
The implementation of this Technology Roadmap is crucial to tackle the emerging needs of the LEAPS scientific community, to maintain global leadership in accelerator-based photon science, to strengthen technological sovereignty, and to ensure RIs meet future societal and industrial needs.

Synchrotron Radiation Storage Ring



Scheme 1a. Drawing illustrating the main parts of a storage ring.

Free Electron Laser



Scheme 1b. Drawing illustrating the main parts of a free electron laser.

INTRODUCTION

LEAPS – the League of European Accelerator-based Photon Sources – was established in 2017 with the primary goal of actively and constructively promoting and ensuring the quality and impact of fundamental, applied, and industrial research conducted at its member facilities.

LEAPS facilities offer highly complementary capabilities, spanning a wide range of photon energies, from infrared to hard X-rays. These photon sources play a crucial role in advancing knowledge and innovation, contributing to tackling health challenges, supporting the scientific response to climate change, enhancing international competitiveness, and strengthening Europe's technological sovereignty.

The member facilities of LEAPS are categorised into two main types: circular machines - synchrotron radiation storage rings (SRs), and linear accelerators - free-electron lasers (FELs) (Schemes 1a and 1b). Over the past fifteen years, the development of fourth-generation SRs—an innovation pioneered in Europe and adopted worldwide—has significantly increased the brightness and coherence of photon beams produced. These advances enable higher performance for users, modularity, and reduced energy consumption. However, further technological progress is required to remain at the forefront of photon science worldwide. Europe currently hosts the world's most complete and complementary collection of accelerator-based photon sources, spanning the full spectrum of photon energies and experimental techniques. Advancing the capabilities of the LEAPS facilities for the 35,000 users is essential to satisfy their expectations of faster experiments and higher spatial resolution, with smart data workflows, and open data procedures. Enabling of key technologies is a top priority for the LEAPS community.

One of LEAPS first actions was to establish a Technology Roadmap as part of a strategic view of the consortium[1] and identifying areas where Europe could reap the largest benefits from establishing common development actions. Joint technological development has a long-standing tradition among LEAPS members. Since the formation of the consortium, the collaboration activities have accelerated[2,3] (Figure 1) - particularly through initiatives like **LEAPS-INNOV**[4], one of the innovation

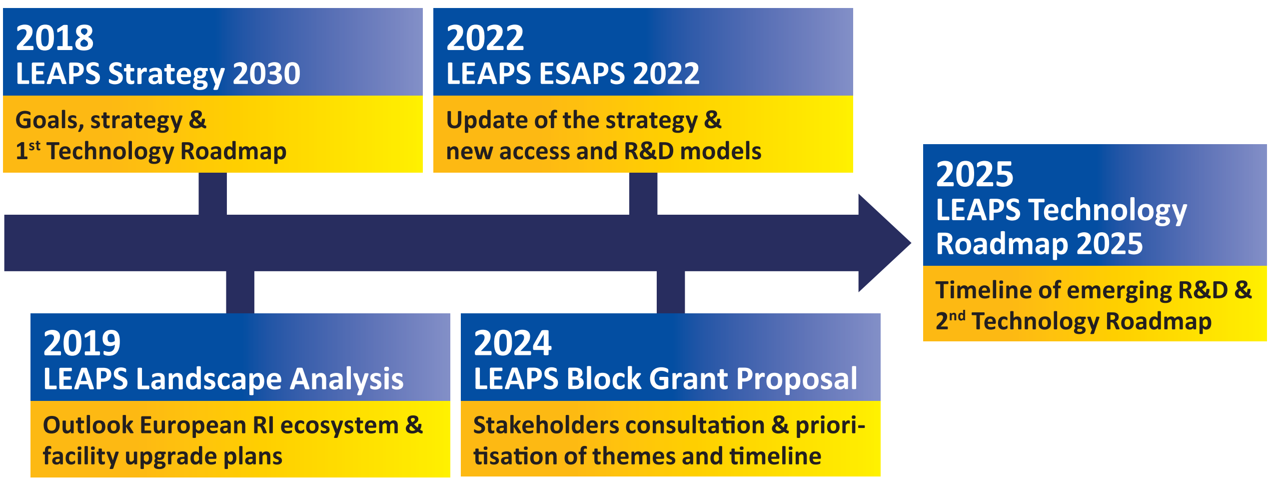


Figure 1. The LEAPS Roadmapping process.

[1] https://www.leaps-initiative.eu/resources/ – LEAPS Strategy 2030
[2] https://www.leaps-initiative.eu/resources/ – LEAPS ESAPS Brochure
[3] https://epjst.epj.org/epjplus-news/2674-epjplus-highlight-introducing-the-european-strategy-for-accelerator-based-photon-science
[4] https://www.leaps-innov.eu/

pilots funded under the Horizon 2020 Research and Innovation programme. A second significant example of collaborative effort is **DIGITAL LEAPS**[5], an internal project launched in response to the COVID-19 pandemic to foster more resilient and environmentally sustainable facilities, driven by the development of digital technologies, including AI concepts.

An updated and enhanced Technology Roadmap for the LEAPS community is now a vital asset to guide future joint developments and quickly address potential gaps. To remain competitive on the global stage, and to continue to provide world-class infrastructures for SRs and FELs users, Europe must keep pace with technological advancements, particularly those driven by substantial investments in Asia and the United States.

The collaborative work of the LEAPS strategy groups and technology working groups[6], established within the consortium from the outset, underpins this roadmap and ensures the standardised implementation of technologies across LEAPS facilities. The integration of AI and machine learning (ML) tools—common to all technology areas—and the promotion of modularisation will result in more efficient, resilient, and user-friendly facilities.

All the technologies outlined here hold strong potential for industrial engagement, mainly via co-creation. At the same time, the technologies aim to improve scientific services to the broad user community of the LEAPS consortium and developments built on user engagement and consultation. This includes foremost **ESUO** (European Synchrotron and FEL User Organisation), which has defined recommendations[7] for improving the technical capabilities of the LEAPS facilities to comply with the future needs of European researchers. The **SESAME**[8] synchrotron photon source in Jordan, as a very relevant associated partner of LEAPS, will both contribute to and benefit from the developments, while SRs and FELs worldwide are keeping an eye out for achievements generated by this strong European consortium.

Building on the first, more facility-centred, Technology Roadmap from 2018 and the completion of initial joint pilot developments in all key technology areas realised through LEAPS-INNOV[4] with essential input also from industry, this new Technology Roadmap aligns with European priorities in digitalisation, standardisation, and green innovation. It is structured around six technology areas that encompass all major aspects of SR and FEL infrastructures: **Photon Sources, Photon Diagnostics, X-ray Optics, Sample Environment, X-ray Detectors, and Information Technology and Scientific Data** (Figure 2).

The areas highlighted by this roadmap apply equally to new generation upgrades and new developments at SR and FEL RIs[2]. They also will find application at, and benefit from, emerging compact X-ray sources based for example on plasma acceleration which are presently being developed within the ESFRI roadmap project EuPRAXIA[9] and supported by European grants like PACRI[10].

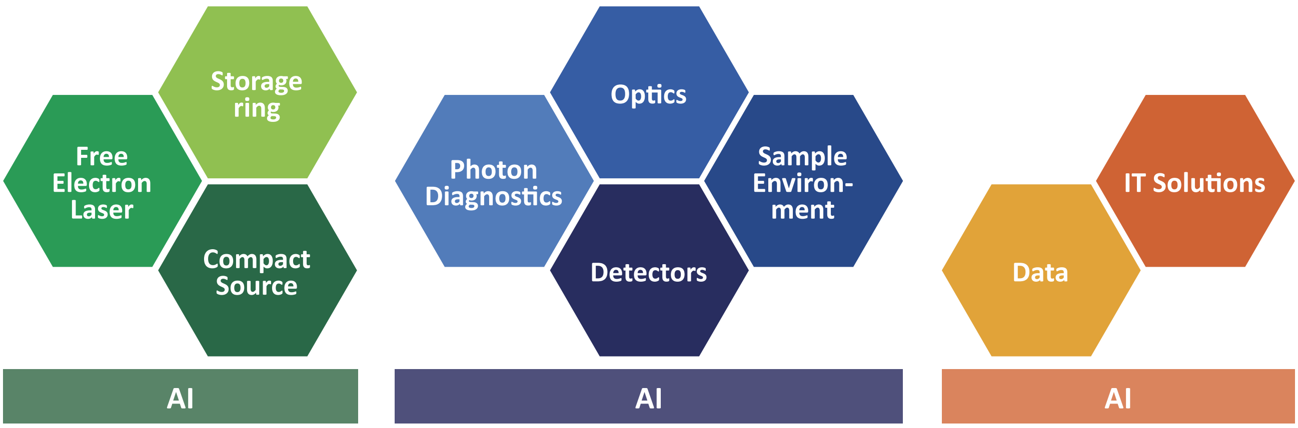
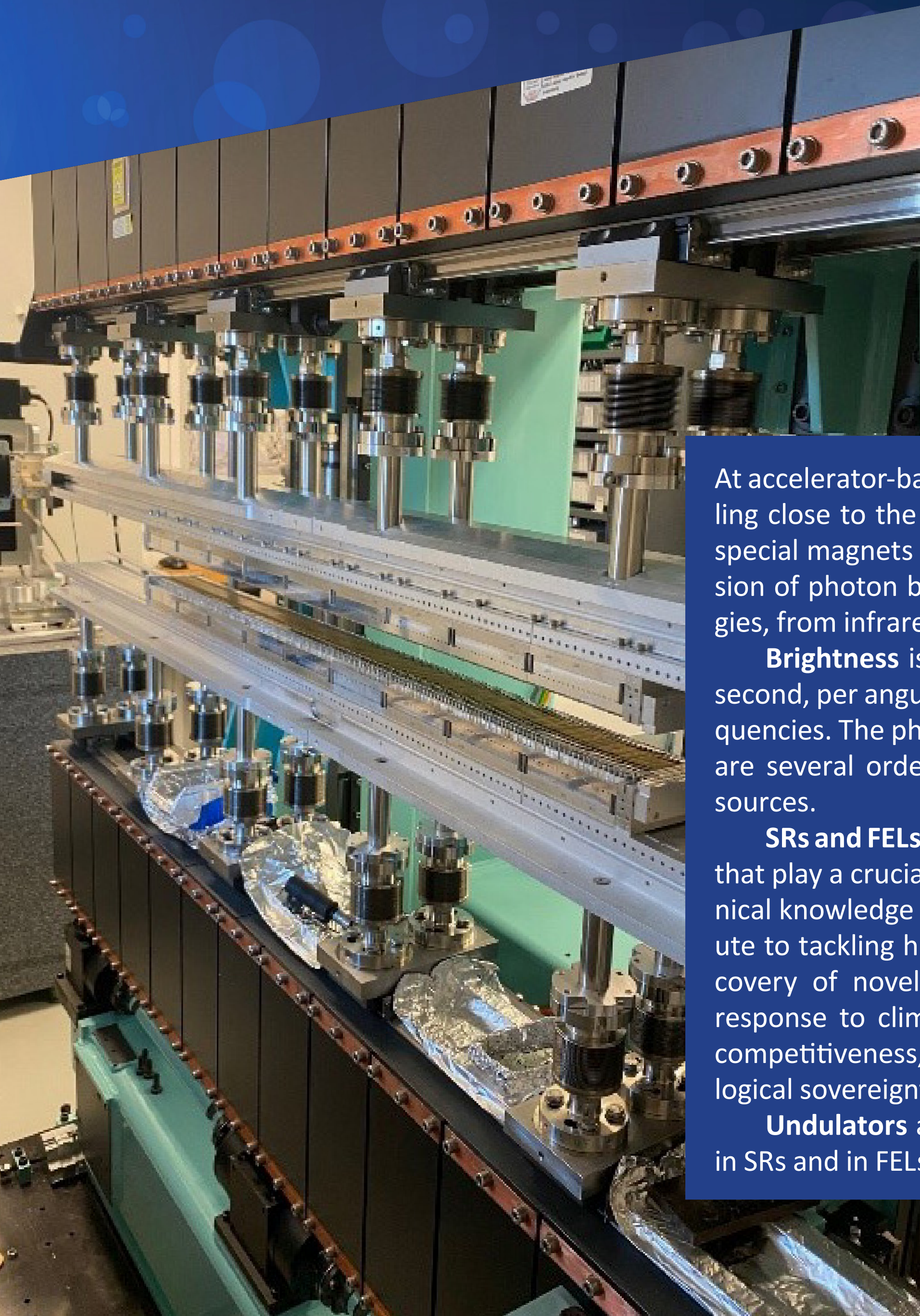


Figure 2. Diagram of the main Technology areas in LEAPS.

[5] https://www.leaps-initiative.eu/digital-leaps/
[6] https://www.leaps-initiative.eu/working-groups/
[7] https://www.esuo.eu/
[8] https://www.sesame.org.jo/
[9] https://www.eupraxia-project.eu/
[10] PACRI grant agreement No. 101188004

TECHNOLOGY ROADMAP

1 Photon Sources



At accelerator-based **Photon Sources**, electrons travelling close to the speed of light are manipulated using special magnets to promote the high-brightness emission of photon beams spanning a wide range of energies, from infrared light to hard X-rays.

Brightness is the number of photons emitted per second, per angular direction, per specific range of frequencies. The photon beams produced at SRs and FELs are several orders of magnitude brighter than other sources.

SRs and FELs are accelerator-based photon sources that play a crucial role in advancing scientific and technical knowledge and innovation. They directly contribute to tackling health challenges, accelerating the discovery of novel materials, supporting the scientific response to climate change, enhancing international competitiveness, and strengthening Europe's technological sovereignty.

Undulators are arrays of magnets employed both in SRs and in FELs to generate photons.

The recent development of fourth-generation SRs has led to significant gains in brightness and coherence, delivering requisite performance upgrades for users. These advances go hand in hand with modularity and reduced energy consumption. However, sustaining Europe's leadership will require further technological innovation to fully leverage these improvements and meet future scientific and industrial demands. A significant innovation will be the development of high-temperature superconductor (HTS) technologies for next-generation undulators. Digital twin technologies, and the use of AI, will further enhance the performance and operation of the photon sources.

Existing European FEL facilities excel in peak power, tunability, coherence and ultra-short pulse duration. Further advancements are still needed to push the boundaries of temporal resolution and transverse coherence. This will enable unparalleled capabilities for time-resolved studies of matter and structural studies of non-crystalline samples. A combination of the technologies identified in the roadmap will ultimately enable ultra-fast and attosecond capabilities, as well as extremely high coherence at FELs, allowing direct observation of electron dynamics in atoms, molecules, biological objects, liquids, soft materials, and solids.

Key Enabling Technologies

Accelerator systems: A key enabler for environmental sustainability is the advancement of permanent magnet technologies[11] for SRs in next-generation photon sources. These developments concentrate on tunability, magnetic field quality, precise characterisation, temperature stability, and aging resistance. They also address sustainability and European sovereignty through materials recycling and efficient use of rare earth elements. Next-generation SRs, which will have even brighter beams and be more efficient compared to the most recent upgrades, require the design of next-generation harmonic radiofrequency (RF) systems[12] to maintain optimal performance.

High-temperature superconductor undulators: Once optimal electron beam parameters are achieved, photons are generated using magnetic devices known as undulators. A major step to achieve ultra-high brightness in SRs and FELs is the development of undulators based on HTS technologies, which will enable shorter periods and higher magnetic fields, potentially increasing brightness by up to two orders of magnitude. HTS-based undulators will enable the generation of higher-energy photons, with enhanced tunability and flexibility.

Digital Twins and Remote Access: Digital twin technologies will further enhance the performance and operation of photon sources. The LEAPS community has started the development of Accelerator Digital Twins, and in particular Python-based twins[13], which will help to design, commission, and improve operation of the photon sources. Modern computing methods will be leveraged, whilst remaining open-source and compatible with diverse control systems across facilities.

During the COVID-19 pandemic, remote access and autonomous operation of the LEAPS facilities became indispensable[14], catalysing the launch of the DIGITAL LEAPS initiative. This included the development of android robots[15] to enhance the accessibility and maintainability of instruments, particularly in radiation-exposed environments. The integration of AI for navigation and object recognition could enable greater automation and reduce human intervention.

Electron beam sources and lasers: The design of future FEL sources with high-brightness and high-repetition-rates will be essential to further advance their performance. This will require the implementation of continuous-wave electron beam sources, which offer unmatched flexibility for studying rare events and unpredictable phenomena - turning FELs into transformative tools for future discoveries. Realising this goal depends on several enabling technologies: the development of photocathodes and dedicated cathode laser systems for electron production; superconducting RF acceleration systems; and advanced instrumentation for electron beam control and diagnostics. The proof of concept of XFEL oscillators16 was very recently successfully demonstrated at the European XFEL. This will offer novel opportunities for generating X-ray radiation with ultra-high spectral purity. The development of high-repetition-rate, short-wavelength table-top lasers (in the ultraviolet range) will allow further optimisation of electron beam sources and open new possibilities for pump-probe experiments in SRs.

[11] https://www.leaps-initiative.eu/wp-content/uploads/5.-leaps-integrated-platform_final-report-june-2024.pdf – Section 1
[12] https://www.leaps-initiative.eu/wp-content/uploads/5.-leaps-integrated-platform_final-report-june-2024.pdf – Section 2
[13] https://www.leaps-initiative.eu/wp-content/uploads/5.-leaps-integrated-platform_final-report-june-2024.pdf – Section 7-PyDiT
[14] https://www.leaps-initiative.eu/resources/ – LEAPS Fighting COVID-19
[15] https://www.leaps-initiative.eu/wp-content/uploads/5.-leaps-integrated-platform_final-report-june-2024.pdf – Section 3
[16] https://accelconf.web.cern.ch/fel2022/doi/jacow-fel2022-tup50/

TECHNOLOGY ROADMAP

2 Photon Diagnostics

Photon Diagnostics are essential for optimal machine operation, experimental station setup, and optical alignment. High-fidelity, single-shot diagnostic data enables users to fully use the unique properties of the photon beams.

Soft and hard X-ray FELs provide unprecedented scientific opportunities for studying dynamics on shortest time scales while also providing photon beams with the highest intensities and exceptional beam quality. The community of FEL experts is still new and small, and joint developments under LEAPS for FEL and SRs will enhance efficiency and user accessibility in several ways. Photon diagnostics are essential, not only for machine operation, experimental stations setup, and optics alignment, but also because high-fidelity single-shot diagnostic data enables users to fully leverage the unique properties of FELs. Standardised diagnostics across facilities has the potential to free up valuable beamtime for user operation in Europe, while joint developments optimally use the valuable expertise of the facilities.

Key Enabling Technologies

Attosecond pulse length diagnostics: Realising the full potential of femtosecond and emerging attosecond X-ray FEL sources demands extremely precise, real-time measurements of pulse duration, as well as ultra-fast timing and synchronisation control. Current solutions, such as THz/Mid-IR or angular streaking techniques, are still complex experiments. Making these diagnostics robust, reliable, and standardised across facilities is critical for optimal synchronisation and for maximising the scientific output of European FELs.

X-ray arrival-time monitors: Precise synchronisation between the X-ray pulse and the experimental laser system is fundamental for time-resolved experiments at FELs. Single-shot arrival-time monitors provide the crucial measurement of the X-ray pulse timing relative to external lasers, impacting directly the achievable temporal resolution of pump-probe studies. Current state-of-the-art techniques are limited to an arrival-time precision of approximately 10 femtoseconds (fs) per shot, which constrains the exploitation of attosecond capabilities at next-generation FELs. Future solutions, including high-energy fibre-based arrival-time diagnostics and advanced multilayer targets, aim to break through this limitation—delivering reliable sub-10 fs, and, ultimately, sub-1 fs resolution. These advances will enable users to access routinely the full temporal potential of FELs.

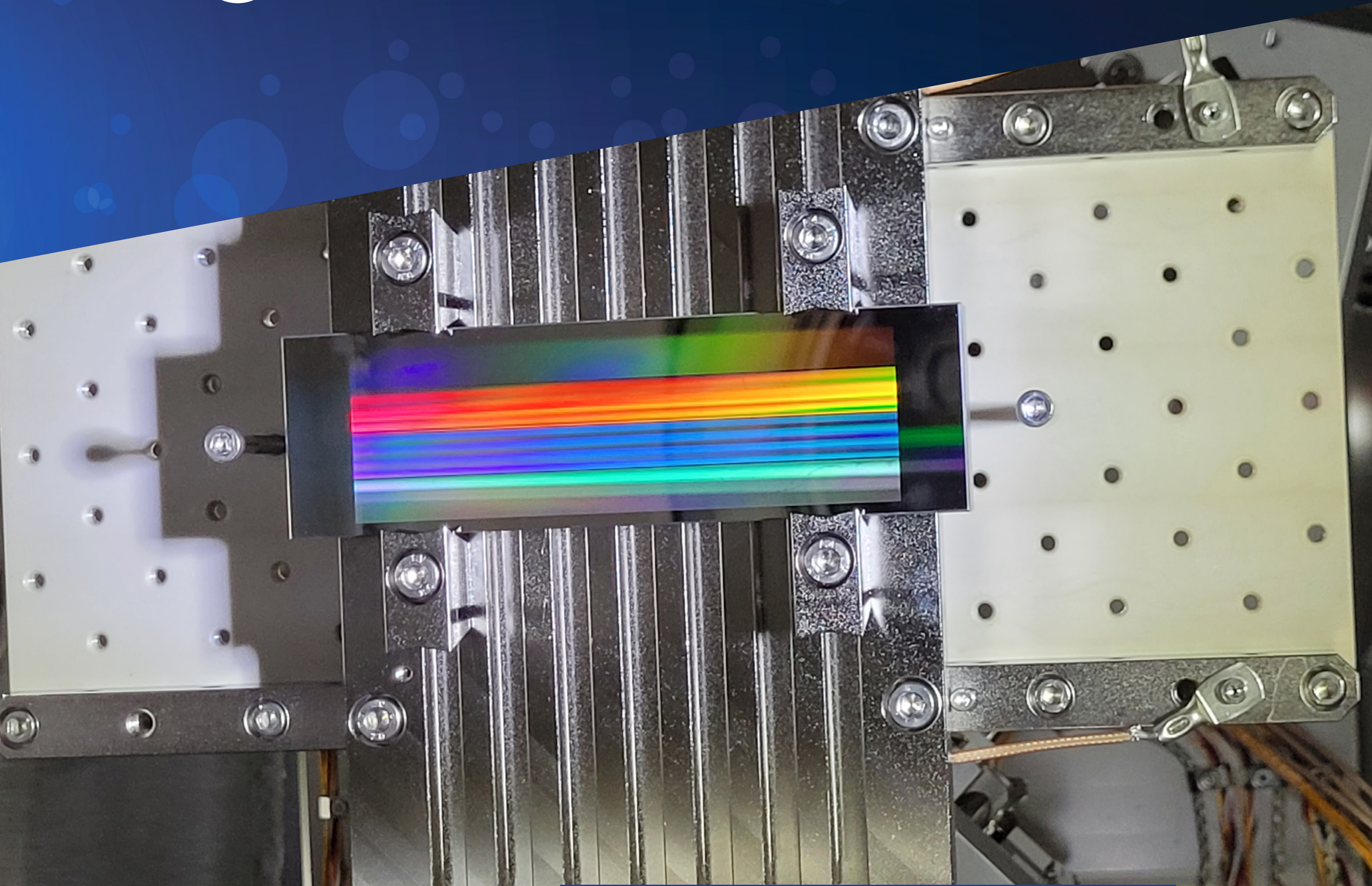
Wavefront and coherence: The exceptional coherence properties of fourth-generation SRs and FELs can only be leveraged with fast, reliable, and user-friendly diagnostic tools for wavefront characterisation and coherence control. FELs can lase in multiple spatial and spectral modes, leading to complex photon beam structures. Developing diagnostic tools—ideally a single platform or suite—for real-time spectral, spatial, and temporal analysis will improve photon sources performance, reproducibility, and experimental success.

Virtual photon diagnostics: Virtual diagnostics, combining AI and physics-based models, allow the reconstruction of photon beam parameters from indirect measurements, minimising the need for invasive diagnostics. This enhances beam stability, increases experiment uptime, and offers deeper insight into FEL operation. Real-time, virtual diagnostics are essential for high-performant SR and FEL facilities.

Photon beam position control: Standardised, online, non-invasive, and AI-supported photon beam position monitors—with enhanced spatial resolution—will streamline automated alignment of the experimental stations and monitoring for both SRs and FELs. Such systems enable fast and efficient set-up of experiments and increase beamtime availability for users. Approaches may include optical fluorescence, gas-phase ionisation, ML-based reconstruction, or advanced detectors (e.g. silicon carbide, diamond) for hard X-rays.

TECHNOLOGY ROADMAP

3 X-ray Optics



X-ray Optics are the critical link between the photon sources and the experiments performed at SRs and FELs. They provide many purposes, including separation of the usable photon beam from the background radiation, high purity monochromatisation, focussing the photon beam onto the sample, and preservation of coherence.

X-ray optics are the critical link between the photon sources and the experiments performed at SRs and FELs. Nowadays, X-ray optics are often the limiting factor for optimal experiment performance. They serve many purposes, including separation of the usable photon beam from the background radiation, high-purity monochromatisation, and focusing the photon beam to the sample whilst preserving the quality of the wavefront. X-ray photon sources have advanced significantly over the past decade, with the construction of extremely high brightness SRs and FELs. However, few advances have occurred for critical X-ray optics, and in some cases withdrawals of commercial suppliers. This roadmap aims to overcome these limitations.

Key Enabling Technologies

Conservation and refurbishment of optics: Conserving and refurbishing X-ray optics is a major benefit to the user community of X-ray sources as replacing these highly specialised optics can lead to long downtimes of the experimental stations. Understanding the essential variables for carbon contamination, and developing methods for in- and ex-situ removal, is of critical importance to the LEAPS facilities. In instances where an X-ray mirror meets the user requirements but has been degraded by long-term exposure to the intense X-ray photon beams produced by the LEAPS facilities, cleaning or refurbishment are sustainable solutions. New and refurbished mirrors need to be (re-)coated, potentially with different materials or multilayer coatings, to increase their reflectivity in the energy ranges of interest.

X-ray mirrors: Mirrors coated with a reflective material tailored to the photon energy range of interest are used on all optics systems at the LEAPS facilities. Following up on the successful SuperFlat work package of the LEAPS-INNOV[4] project, optics scientists plan to extend the method towards the manufacturing of even longer and higher quality plane mirrors, and provide curved mirrors of dedicated geometry to enable beam shaping and focusing under coherence preserving conditions. Such mirrors require the ultimate quality in the sub-nanometre range regarding their figure and finish.

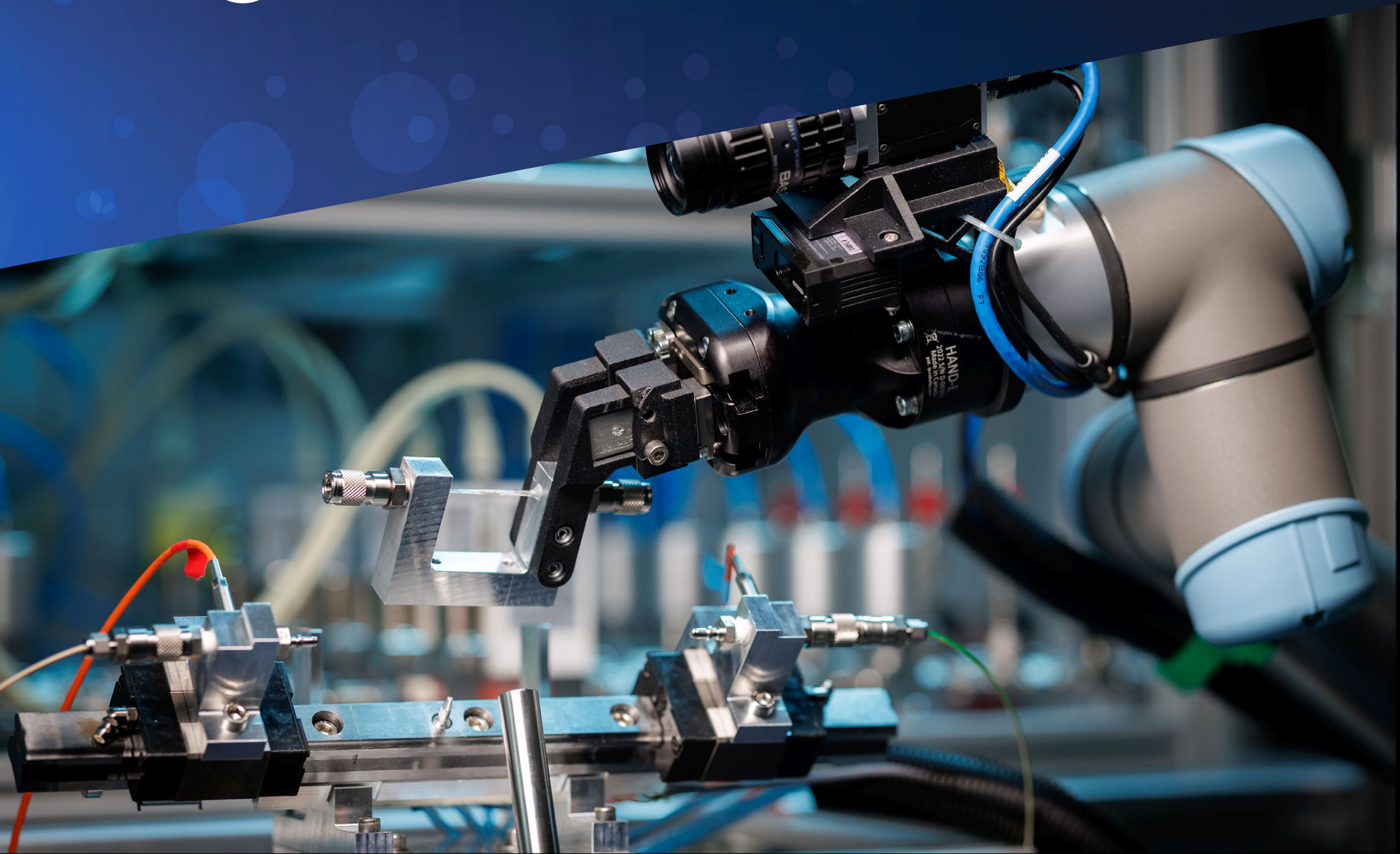
Soft X-ray gratings: Diffraction gratings are critical optical components in soft and tender X-ray applications, enabling dispersion of the X-ray beam either within a monochromator or directly onto a detector. However, their availability remains extremely limited, particularly for blazed (sawtooth-like) gratings. To meet future needs, new technologies must be developed to enable nanometre-precision imprinting onto thick substrates with significantly larger aperture sizes than currently achievable. Building on the promising results of the NeXtgrating project within LEAPS-INNOV4, further technological development offers a strong potential to increase the TRL and reach production readiness. This effort will require close collaboration between the optics experts at LEAPS facilities and the industrial ecosystem to leverage the capabilities of European companies.

Hard X-ray focusing optics: Hard X-rays can be focussed by compound refractive lenses, usually made of beryllium or diamond. Unfortunately, beryllium lenses are no longer commercially available, and new suppliers need to be empowered to produce these important optics. Similarly, diamond can be used to produce refractive and diffractive optical elements, but the European market needs to be developed to reach technological sovereignty. The development of phase correctors to modify or correct wavefront profiles can utilise similar fabrication technologies and is becoming increasingly important for optimising photon transport performance. Finally, multilayer Laue lenses, composed of thousands of nanometre-thick alternating layers of materials, hold the promise to be able to tightly focus hard X-ray photon beams. Further developments are required to make them a universally accessible tool.

Optical metrology: Verifying that delivered optical elements meets specification requires metrology instrumentation of the highest precision for ex-situ measurements or the availability of calibrated in-situ diagnostic techniques for at-wavelength measurements on the experimental stations. For the most demanding applications, topography measurements of the surface as delivered (and ideally as mechanically mounted) can be used for corrective, deterministic polishing techniques, such as ion beam figuring. Collaborations to improve metrology methodology and instrumentation continues through the LEAPS facilities via the exchange of knowledge and resources. New improvements in metrology will allow the optimisation of the measurements and applications of optical systems, and compare the performance of the experimental stations through simulations, to better adapt to the automated alignment and stability tools. This will rely on AI technology and will take advantage of the advancements in beam positioning diagnostics.

TECHNOLOGY ROADMAP

4 Sample Environment



Sample Environment encompasses a diverse range of highly specialised equipment to manipulate and control samples during experiments, particularly under extreme or realistic conditions.

The Sample Environment technology enables cutting-edge research at European accelerator-based photon sources, covering a wide variety of scientific applications. It encompasses diverse and highly specialised sample environment equipment required to manipulate and control samples during experiments, particularly under extreme or realistic conditions. The ability to dynamically vary physical parameters during experiments is key to enabling the discovery of new materials for future applications, including novel data storage paradigms and quantum computing. The technologies for sample environments include advanced positioning systems and environmental controls such as temperature, pressure, strain, magnetic and electric fields, and reactions with liquids and gases. Such capabilities are commonly applied in advanced characterisation at SRs and FELs, especially under in-situ and operando conditions to mimic real, industrial processes.

With the advances of next-generation sources, automation and fast sample exchange or delivery will become essential for the full exploitation of the beamtime by the users. To facilitate pan-European access for both academic and industrial users, standardisation across facilities is essential for equipment, interfaces, and data formats. Special emphasis must be placed on developing complex equipment for in-situ and operando experiments in scientific fields such as electrochemistry and catalysis, contributing to European priorities including clean energy, sustainable mobility, and zero-pollution technologies.

Key Enabling Technologies

Nano-positioning: Ultra-precise, nano-positioning stages are vital for exploiting the brightness and spatial resolution of next-generation sources. LEAPS aims to accelerate the development of time-efficient and precise nano-positioning tools. These mechatronic systems will support imaging, microscopy, and tomography applications relevant to medicine, nanotechnology, and fundamental science.

Automation & high-throughput measurements: Automated sample handling, backed with smart data workflows, boosts experimental efficiency and high-throughput data generation. Robotics and AI-integrated platforms will facilitate faster, more reproducible experiments and advanced applications relying on trusted high-fidelity big data in pharma, biotechnology, and energy industries for faster and more effective drug and materials discovery, etc. Robotics, microfluidics, and AI-driven feedback enable rapid, precise handling of heterogeneous samples, reducing downtime and enhancing reproducibility. Temperature-controlled stages and fast goniometers support seamless shifts between diffraction, scattering, and spectroscopy. Advances are needed for more dynamic, adaptable control in time-resolved and operando studies.

Extreme conditions: Advanced sample environments - capable of sustaining high pressures, low temperatures, and strong magnetic or electric fields - are critical to supporting research on quantum materials, superconductors, and energy materials including fusion-related research. For this reason, the joint development of adequate tools such as diamond anvil cells, cryostats, high-magnetic fields, and laser heating cells is essential.

In-situ, operando & multimodal environments: Developing sample environments for in-situ and operando experiments, while enabling multimodal approaches, is crucial for advancing both fundamental and applied understanding of materials under realistic conditions. Existing systems - such as battery and fuel cells, electronic devices, catalytic reactors, sample-injection and pulsed gas systems, and stress/strain devices - are already in use across many facilities. However, further innovation is needed to fully integrate multimodal capabilities, which are especially important for research and innovation in areas such as clean energy generation and storage.

Advanced tools for time-resolved experiments: Advancing sample environments and delivery tools for pump-probe experiments at FELs and short-pulse modes at SRs are essential for studying fast dynamic processes. Time-resolved techniques will investigate structural dynamics, reaction mechanisms, and phase transitions, enabling a deeper understanding of condensed matter, biological processes, and fundamental chemical reactions such as bond breaking, bond formation, and electron transfer, relevant for instance to address catalytic reactions. Development of liquid sample delivery systems, which replace samples in a few hundred nanoseconds, is of very high importance.

Standards for sample environment equipment, control, data & metadata: The provision of standardised equipment and processes for complex X-ray experiments will enhance measurement reliability and quality control, whilst improving accessibility for academic and industrial researchers. The development of common standards - such as universal sample holders, liquid jets, electrochemical cells, hardware interfaces and software control systems with machine-readable metadata, developed with the relevant academic and industrial user communities. This will facilitate automated sample preparation, cross-facility access, increase experimental efficiency, and enable reproducibility and comparability across European RIs and industrial suppliers. Interoperability and smart workflows are central to truly exploiting standardisation (see also area 6, IT).

TECHNOLOGY ROADMAP

5 X-ray Detectors

X-ray Detectors are devices used to measure the flux, spatial distribution, spectrum, and other properties of X-rays. They are key components of the sample environment and are used to record and process the X-ray signal.

The X-ray detectors technology will mainly target two key aspects: advancement of innovative sensor technologies and their integration into new detectors for both soft and hard X-rays for SRs and FELs. This prioritises high frame rates, low noise levels, and high dynamic range performances of imaging/pixelated detectors. A focus will be on enhanced count-rate capabilities for fourth-generation SRs with higher brightness. A consequence of higher frame rates leads to increased data volumes, faster data transfer, online data processing and reduction, as well as data storage. Furthermore, developing specialised detectors for unique applications in life sciences, catalysis, studies on energy and quantum materials will also be integral to the success of the LEAPS scientific user communities in the coming years to fully capitalise on the photon beams produced at fourth-generation SRs and at FELs.

Key Enabling Technologies

Innovative sensors for hard and soft X-rays: The development of innovative low-gain avalanche diodes (LGADs) for low photon energies (below 2 keV, down to the carbon absorption edge), together with industry and academia, will strengthen Europe's position in the global market of sensors. These new sensors will turn previously unavailable technologies into standard products accessible to a broader audience and facilitate ground-breaking scientific discoveries. Currently, the most common detectors for low photon energies are CCDs and CMOS imagers with a limited area and frame rate. However, introducing large-area, high-frame-rate hybrid pixel imaging detectors for the low photon energy range will dramatically improve scientific opportunities at the LEAPS facilities. A related effort will focus on creating dedicated sensors for higher photon energies (>20 keV) to reduce dependence on a single overseas manufacturer. This development aims to collaborate with European suppliers to facilitate their start-up and, in the longer term, establish a European alternative for specialised sensors. The capability to grow and process cadmium-zinc-telluride crystals is a key target, pursued in collaboration with academic and industrial partners. The new sensors will be used for the currently existing hybrid pixel detectors. On-going and foreseen developments in detectors will profit significantly from the new sensors by extending their energy range to low and high photon energies at high quantum efficiencies. Therefore, these developments, which will be part of a co-creation process with European industry and academia, are currently a top priority.

Integration of through-silicon via (TSV) technology: TSVs allow contacting the application-specific integrated circuit (ASIC) in hybrid pixel detectors on both sides of the ASIC. One side can connect to the sensor pixels and the other to connect the ASICs to the readout electronics. The integration of TSVs as the interconnect between the ASIC and the readout electronics will allow larger gapless sensor areas. These will benefit experimental techniques like ptychography, which rely on high-fidelity 2D data beyond the performance of current detectors with intrinsic gaps between modules.

Ultra-fast large-area photon detector: The advancement of science at SRs and FELs relies on the availability of high-performance large-area imaging detectors, especially those able to detect single photons at low energy, have a high dynamic range, and reach high frame rates in continuous or burst mode operation up to a few MHz. Adequate spatial resolution, as provided by small pixels, is also a key ingredient for materials and life sciences applications.

High count rate single photon measuring detectors: The upgrade of many SRs to fourth-generation diffraction limited photon sources will provide unprecedented photon brightness and coherent flux. To overcome current limitations for many applications at SRs caused by the count rate capability of the existing single photon measuring detectors, the development of high count-rate single photon counting detectors is essential. Using the newly developed sensors for hard and soft X-rays single photon counting detectors will cover the entire energy range available at LEAPS facilities, from about 250 eV to above 100 keV.

Dedicated detectors for specific scientific applications: These dedicated detectors will substantially complement the above-mentioned imaging detectors. Examples include detectors featuring smaller pixels and using advanced techniques like position interpolation with micrometre precision for imaging, ptychography, and time-resolved spectroscopy applications like resonant inelastic X-ray scattering.

Spectroscopic detectors: For medium to high photon energy, the most promising systems are germanium sensors with pulse processing electronics. To achieve good statistics, many channels (>100) with a high count-rate capability are required. Within the LEAPS-INNOV4 framework, a 7-channel prototype is currently undergoing characterisation. In the longer term, the development of an energy-resolving detector based on hybrid pixel technology could be used for full-field X-ray fluorescence or energy dispersive diffraction applications using pink or white beams.

TECHNOLOGY ROADMAP

6 Information Technology and Scientific Data

Information Technology and Scientific Data address the controls of the photon source and experimental stations, as well as the management of unprecedented data volumes, to maximise experimental efficiency. This technology area also develops automated workflows that cover the entire data lifecycle, reducing data volumes while producing FAIR, open, and highly reliable data.

Brighter SRs and FELs present significant challenges for information technology and scientific data (IT), due to the unprecedented data volumes and rates generated by higher frame rates of in-situ, operando, multidimensional scanning, and high-throughput experiments, as well as the increasing size of detectors. Although most challenges are anticipated, overcoming them will require the development of key technologies.

IT is intrinsically present across the Technology Roadmap. Given the global nature of its challenges, it is essential to address them through a coordinated approach, with LEAPS providing the natural framework for this collaboration. The embedding of AI methodologies in different key steps requires a multi-disciplinary approach to be effective and usable.

While the IT resources capacity and competence required for the operation of each of the LEAPS facilities is needed onsite, the downstream processes beyond data acquisition can be located elsewhere. This aspect motivated approaching the **EOSC** (European Open Science Cloud) to define services which could be jointly developed under its umbrella (PaNOSC[17] and ExPaNDS[18], OSCARS[19] projects) and which are based on the FAIR (findable, accessible, interoperable and re-usable) principles. A detailed LEAPS data strategy and its embedding in the framework of the EOSC was published in 2023[20]. Together with the neutron community, **LENS**[21] (League of European Neutron Sources), a PaN-EOSC node[22] and a contribution to the German national node through DAPHNE4NFDI[23] was established to ensure the sustainability of a pan-European collaboration for IT.

Key Enabling Technologies

Competence centres and networks: This will include the design and implementation of competence centres for AI/ML techniques to cover the operation of the photon sources, experimental control and data analysis, and new programming environments. A common framework for AI/ML training will be developed, including a shared software stack and a cloud of shared resources between LEAPS facilities. The creation of a competence centre on control systems is foreseen to encourage new collaborations between facilities to foster interoperability. Best practices for sustainable software development and research software engineering will also be promoted. A comprehensive catalogue of high-quality training materials will be compiled, building on the common training portal[24] developed through the PaNOSC[17] and ExPaNDS[18] projects.

Data and metadata: Adopting rich metadata standards will enhance the traceability, reproducibility, and reusability of data, ensuring that experimental results can be more effectively shared, interpreted, and integrated across disciplines. The development of a common ontology and metadata framework in tight connection with the user community, namely ESUO, will be beneficial to increase the comparability of measurements of scientific data significantly, the compliance with FAIR principles and to make it available for AI-based model training and analysis. Data watermarks, a set of best practices across the LEAPS facilities to prevent scientific fraud, will be designed. Through common authentication and authorisation, a standardised experience for users performing research at multiple facilities will be provided. Unified access to data acquired in different facilities and transfer of (embargoed) data between facilities is foreseen. A mechanism to generate a unique persistent ID to identify samples including adequate description will be developed to make that data FAIR. This will include the agreement on a standardised way to describe the sample (scientific metadata schema) and on the minimum information required depending on the experimental technique.

Data analysis model development and reduction: Modern detectors can produce massive data volumes (up to petabytes per day). To take full advantage of them, high speed data handling techniques will be implemented. This can be obtained by optimising traditional compression algorithms and by adding innovative data management steps early in the data acquisition process, including the integration of AI/ML-based processing (e.g. automatic detection and rejection of "bad" data) and high-performance near-edge (e.g., close to the detector) hardware acceleration to allow high throughput. Apart from on-the-fly data reduction and compression, edge-computing capabilities provide preliminary results, which will guide the user towards a more effective data acquisition. The inclusion of these processing elements will require a paradigm shift, embodied by the design of

[17] PaNOSC grant agreement No. 823852, key achievements: https://zenodo.org/records/7347537
[18] ExPaNDS grant agreement No. 857641
[19] https://oscars-project.eu/
[20] https://doi.org/10.1140/epjp/s13360-023-04189-6
[21] https://lens-initiative.org/
[22] https://eosc.eu/eosc-about/building-the-eosc-federation/
[23] https://www.daphne4nfdi.de/english/index.php
[24] https://pan-training.eu/

modern acquisition, storage and pre-analysis frameworks. Finally, a framework for workflow-based analysis will also be developed to make data analysis more shareable, maintainable and reproducible.

Experiment controls: Efficient orchestration of data acquisition processes and highly reliable controls infrastructure at experimental stations are important to face the increasing speed at which experiments are performed at high brightness sources. Visiting scientists are directly interacting with the experiment through controls software, therefore common approaches on the LEAPS level will foster homogeneous user experiences across facilities. Furthermore, joined developments in this field will help to provide high-quality services in a resource efficient way. Enabling key technologies are distributed control, acquisition, and supervisory systems including detector control, and experiment orchestration frameworks. Finally, data dispatching services will be developed for online data access and remote access solutions for experiments compliant to cybersecurity standards.

Automation and data throughput: The combination of automated sample handling (see also area 4, Sample Environment), backed with smart data workflows, boosts experimental efficiency and supports high-throughput measurement campaigns, which is of outmost importance for industrial users. Robotics and AI-integrated platforms will facilitate faster experiments with increased reproducibility and advanced applications based on high-fidelity big data in e.g. pharma, biotech and energy industries for faster and more effective drug and materials discovery. A smart engine for the coordination of the experimental stations, sample tracking, error and quality checking, and data reduction is foreseen in this Technology Roadmap. It will also promote standardised data and metadata ensuring interoperability and seamless sharing across facilities and platforms such as EOSC.

OUTLOOK AND NEXT STEPS

The LEAPS Technology Roadmap 2025 outlines the essential technologies needed to ensure that European synchrotron radiation and free-electron laser facilities remain at the forefront on the global scientific stage, continuing to provide world-class environments for researchers and innovators. This Technology Roadmap promises significant advances across different key technology areas, ensuring the developments required for improving user services. Due to the complexity of the required technologies, progress can only be effectively achieved through a coordinated pan-European co-development effort between the facilities, European partner institutions, facility users and highly specialised industrial partners, an approach which has been piloted in the LEAPS-INNOV[4] project. Its implementation will strengthen European sovereignty in critical strategic areas, in close collaboration with the industry and existing academic researchers.

Support from the European Commission will be crucial for the implementation of the full roadmap. Under current funding schemes, only a subset of the roadmap can be realised. Within the Horizon Europe framework programme, LEAPS foresees, in the near future, launching early-stage developments, both strategic and achievable within existing time and budgetary constraints. These include: high temperature superconducting undulators; advanced characterisation and synchronisation of attosecond pulses; refurbishment of X-ray optics; next-generation hybrid pixel detector developments; standardisation and quality assurance for electrochemical process studies; cross-facility standardised data workflow management and AI-capacity assessment in LEAPS; and autonomous experimental stations technology for high-throughput X-ray absorption spectroscopy studies.

To fully address the ambitions of this Technology Roadmap, a new European funding framework will be necessary to support long-term commitments to joint, visionary, roadmap-driven technology developments with industry suppliers. Such a framework is essential for maintaining Europe's leadership and impact in an increasingly dynamic and competitive global scientific and technical landscape.

Appendix 1

A comprehensive list of the technologies that are expected to be launched within the LEAPS Technology Roadmap is shown in Table 1. It also contains an overview of the developments undertaken between LEAPS and its partners since the foundation of the consortium, and provides a tentative timeline for future developments. The communities which could contribute to the developments are also indicated, as well as the scientific communities and industrial sectors which could benefit.

LEAPS TECHNOLOGY AREAS

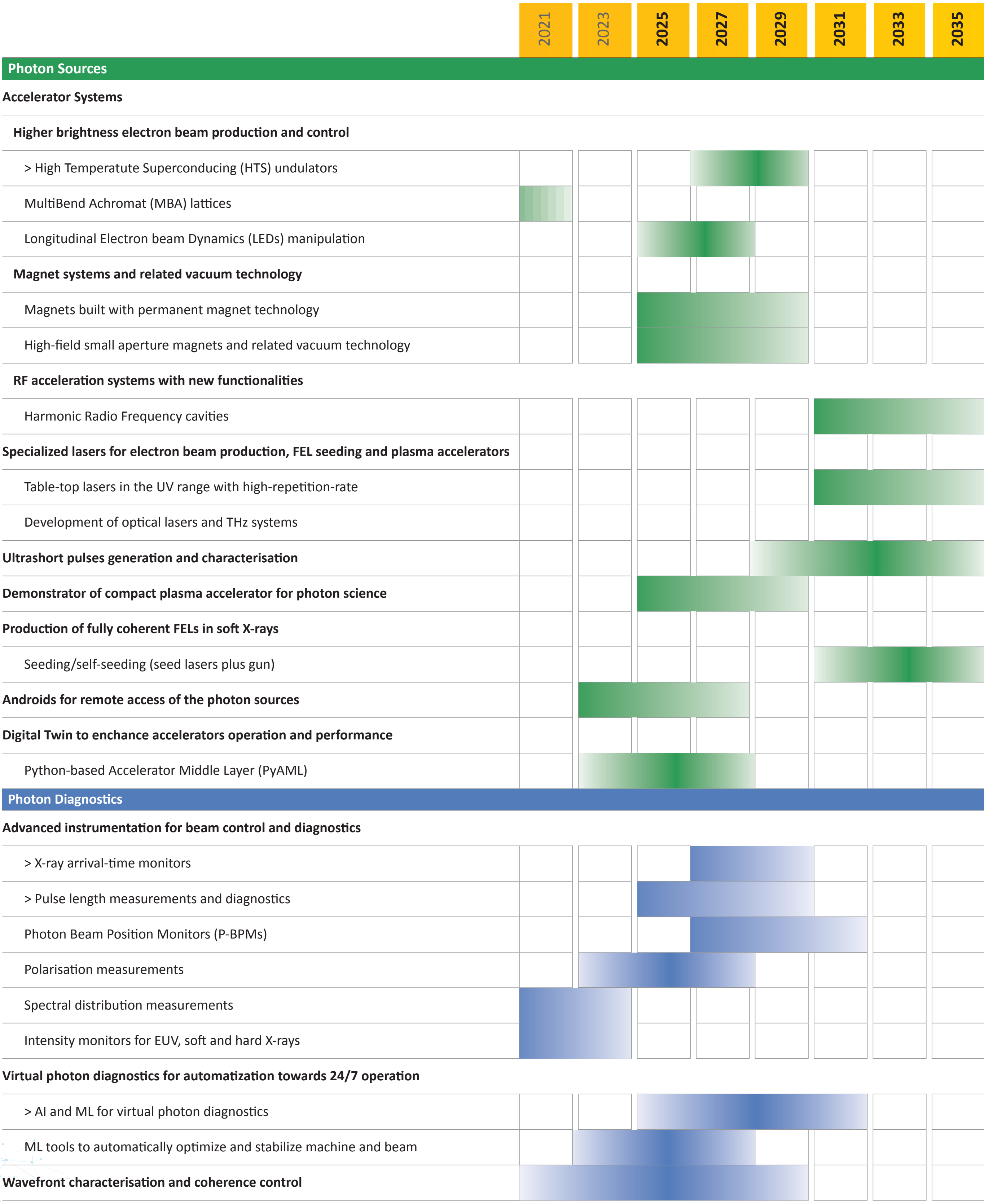


Table 1. List of technologies included in the LEAPS Technology roadmap 2025. The scientific communities as well as the industrial sectors which might be interested in the developments are inditated. Technologies that are prioritised are indicated (>). SR, Synchrotron Radiation Storage Ring; FEL, Free Electron Laser; CS, Compact Source.

LEAPS community			Scientific communities which might be interested in the development	Industrial sectors which might be interested in the development
SR	FEL	CS		
				Manufacturers of HTS
				Manufacturers of magnets
			CERN, Chinese institutions & univ.	Manufacturers of NC and SC RF cavities, lasers
				Providers of advanced materials
			Laser	Providers of advanced materials
			CERN	
			Laser	Manufacturers of lasers
			Laser	
			Laser	
			Laser	Manufacturers of lasers
			Laser	Manufacturers of lasers
			CERN	
			Accelerators, Colliders, Medical installations	Software providers for Accelerators, Fusion energy centres and Radiation therapy
				Optics and Photonic industry
			Laser	
			Laser	
			Laser	
			Laser	
			EUV Lithography, Plasma sources	
			CERN, Laser, LENS	Application for industrial beam diagnostics
			CERN, Laser, LENS	Application for industrial beam diagnostics
			Laser	Optics and Photonic Industry

	2021	2023	2025	2027	2029	2031	2033	2035
X-Ray Optics								
> Conservation and refurbishing of optics								
Minimisation of parasitic X-ray wavefront perturbation								
Efficient transfer of the useful X-ray beam to and from the sample								
Reliable optical systems to maximise experimental stations productivity								
X-ray mirrors								
Coating materials and multilayer-coating-technology								
Reflective optics								
Plane Mirrors (SuperFlat I and SuperFlat II)								
Supercurve mirrors (ultra-precise beam shaping mirrors)								
Ex-situ-metrology to characterise optical elements								
Refractive optics								
Diffractive Optics								
Soft X-ray gratings								
Soft X-ray diffractive gratings (NeXtgrating-I)								
Diffractive optical elements on thick substrates (NeXtgrating-II)								
Fresnel Zone plates								
Hard X-ray gratings								
Multilayer Laue Lenses (MLL) optics								
Beryllium-based Compound Refractive X-ray Lenses (CRLs)								
Optics mounting (optomechanics, nanopositioning and thermal management)								
Optomechanics for sub-nm-precise optical elements								
Simulation and modeling								
Simulation tools and digital-twins (model of complex optics)								
AI-supported automation and control of complex optical setups								
Metrology (attosecond wavelength metrology and test facilities)								
Crystal monochromators and analysers								
Develop systems to optimize optical system performance in-situ								
Diamond material and processing for hard X-ray applications								

LEAPS community			Scientific communities which might be interested in the development	Industrial sectors which might be interested in the development
SR	FEL	CS		
■	■	■	Laser	Optics Industry, EUV-Lithography
■	■	■	X-ray Astronomy, EUV-lithography, Laser	Manufacturers of coatings for optical elements, Semiconductor Industry
■	■			
■	■		X-ray Astronomy, EUV-lithography, Laser	Optics Industry
■	■		X-ray Astronomy, EUV-lithography, Laser	Optics Industry
■	■	■	X-ray Astronomy, Laser	Optics Industry, Semiconductor Industry, Communication
■	■	■	X-ray Astronomy, Laser	Optics Industry
■	■	■		
■	■		Laser	MLL manufacturers
■				Be-based CRLs manufacturers
	■			
■	■		EUV-Lithography	Metrology and Scientific Instrumentation, Semiconductor Industry
■	■	■	X-ray Astronomy, Laser	
■	■	■	Laser, EUV-Lithography	EUV-Lithography, Semiconductor Industry
	■	■	X-ray Astronomy, EUV-lithography, Laser	Optics Industry
■	■		LENS	
■	■		Laser	Optics Industry, Communication
■	■		CERN	Synthetic diamond manufacturers

	2021	2023	2025	2027	2029	2031	2033	2035
Sample Environment								
In-situ, operando, and multimodal experiments								
> Automated operando electrochemical processes								
Automated operando catalysis experiments								
Standards for sample environment equipment, control, data & metadata								
> Standardised sample holders and setups								
> Communication and metadata standards								
Sample delivery fixed target / liquid samples								
Ontologies for sample environment								
Automation and high-throughput sample environment equipment								
Robotics for high throughput sample delivery systems								
Reliable, user-friendly faster container free sample delivery schemes								
Workflow for reliable and repeatable fixed target positioning								
Droplet/sample-on-demand techniques for liquid jets								
Nano-positioning with ultra-precise nanometer resolution and stability								
Mechatronic approach and dynamic modeling of systems								
Reproducible positioning systems (referencing of nm and µm structures)								
Time-resolved experiments								
Specific nozzle development (pump probe)								
Fast mixing								
Extreme conditions (pressure, temperature, eletric- and magnetic-fields)								
HTC Split pair systems (20T+)								
High pressure reaction cells								
X-Ray Detectors								
Innovative sensors for detection								
> Sensors for high photon energies (>20 keV)								
> Sensors for low photon energies (< 2 keV, down to the carbon edge)								
Through Silicon Vias (TSVs) for gapless modules for detectors								
Detectors								
Ultra-high continuous frame rate detector								
Ultra-fast burst mode optimized detector								
High count rate single photon large-area measuring detectors								
MHz UHV Small pixel detector								
Soft X-ray detector								
Integrated silicon photonics for high-speed data transmission								

LEAPS community SR	FEL	CS	Scientific communities which might be interested in the development	Industrial sectors which might be interested in the development
			LENS, Electron Microscopy, Catalysis, and Battery communities	**Battery manufacturers and chemical industry**
			Electron Microscopy, Laser, LENS	Manufacturers of analytical and scientific instrumentation
			Laser, LENS	Manufacturers of analytical and scientific instrumentation
				3D-printing and injecton molding specialists
			High-power laser facilities	
			LENS	Manufacturers of analytical and scientific instrumentation
			Laser, Electron Microscopy	
				Manufacturers of precision positioning devices and encoders
				Electronic devices manufacturers
			Laser	3D-printing and injecton molding specialists
				3D-printing and injecton molding specialists
			Laser, LENS	Manufacturers of scientific instrumentation
				Magnet manufacturers
				Chemical industry
			Laser, Cancer therapy centers, CT in medicine	
				Providers of radiation detection and imaging technologies
				Providers of radiation detection and imaging technologies
			ARIE, CERN, MeV electron sources, CT in medicine	
				X-ray detectors manufacturers
				X-ray detectors manufacturers

	2021	2023	2025	2027	2029	2031	2033	2035

Information Technology and Scientific Data

Competence centres and networks

- Common training portal
- Competence centre for best practices in programming
- Sustainable software and research software engineering
- Knowledge graph on data, software and services
- > AI/ML Competence Center
- Algorithms and techniques for simulation, automation and data analysis
- AI/ML model training and exploitation framework

Data and metadata

- Workflow-based data analysis
- Software catalogue for data analysis
- Modern storage and analysis frameworks
- Data transfer, HPC access and usability for near-real time analysis
- Sample PIDs
- Data watermarks (to prevent scientific fraud)
- Standardisation of data management from data acquisition to publication

Open Data Policy for Open Science

- Common policy toolkit for open data
- Common Standardised Metadata Framework

Data Analysis Model Development and Reduction

- Data reduction (e.g. compression)
- DCS and SCADA (distribution and supervision control and data acquisition)
- Experiment orchestration and scan engines
- Detector Control Interfaces

Federated data catalogue

Cloud services (commercial engagement, Open Science/EOSC)

Cibersecurity

Common authentication framework

- Transfer embargoed data between facilities

Control systems of photon sources and experimental stations

- Control systems: competence centre, software and ML training framework

Experiments control

- Controls Interfaces (Web, QT-gui, command-line)
- Online databroker services and near-real-time data access

Remote Access to Experiments

Software Packaging, Containerisation and Configuration Management

LEAPS community			Scientific communities which might be interested in the development	Industrial sectors which might be interested in the development
SR	FEL	CS		
			ARIE	
			LENS	
			ARIE	
			ARIE	
			LENS	
			LENS	
			LENS, CERN	Vendors of scientific equipment
			LENS, RADIATE	
				Suppliers of X-ray detectors
			ARIE	
			ARIE	
			LENS	
			LENS, CERN	
			LENS	
			LENS	
			LENS, CERN	

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LEAPS AND ITS PARTNERS

SESAME LENS Canadian Light Source Centre canadien de rayonnement synchrotron ESUO EUROPEAN SYNCHROTRON AND FEL USER ORGANISATION

Strengthen Europe's leading role in science and innovation

https://leaps-initiative.eu

LEAPS League of European Accelerator-based Photon Sources