LEAPS
LANDSCAPE ANALYSIS

LEAPS League of European Accelerator-based Photon Sources

Table of Contents

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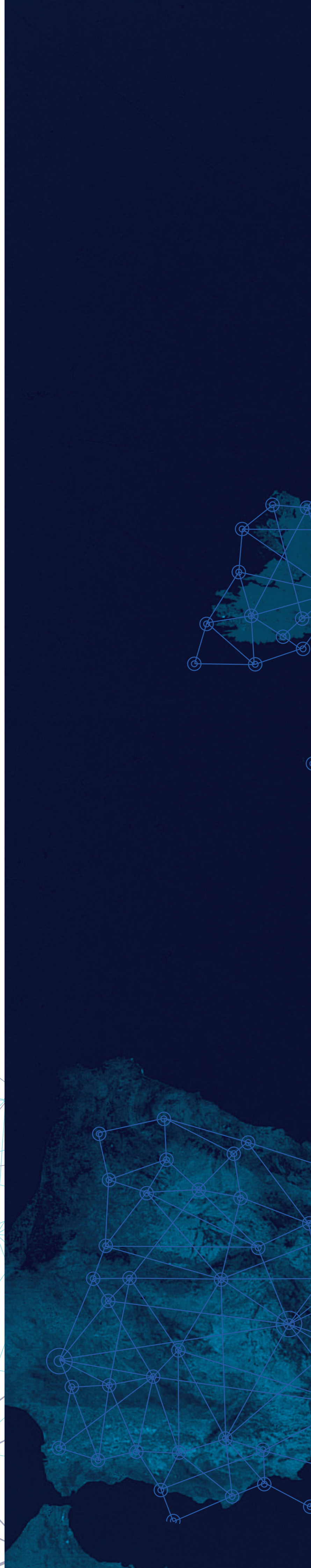
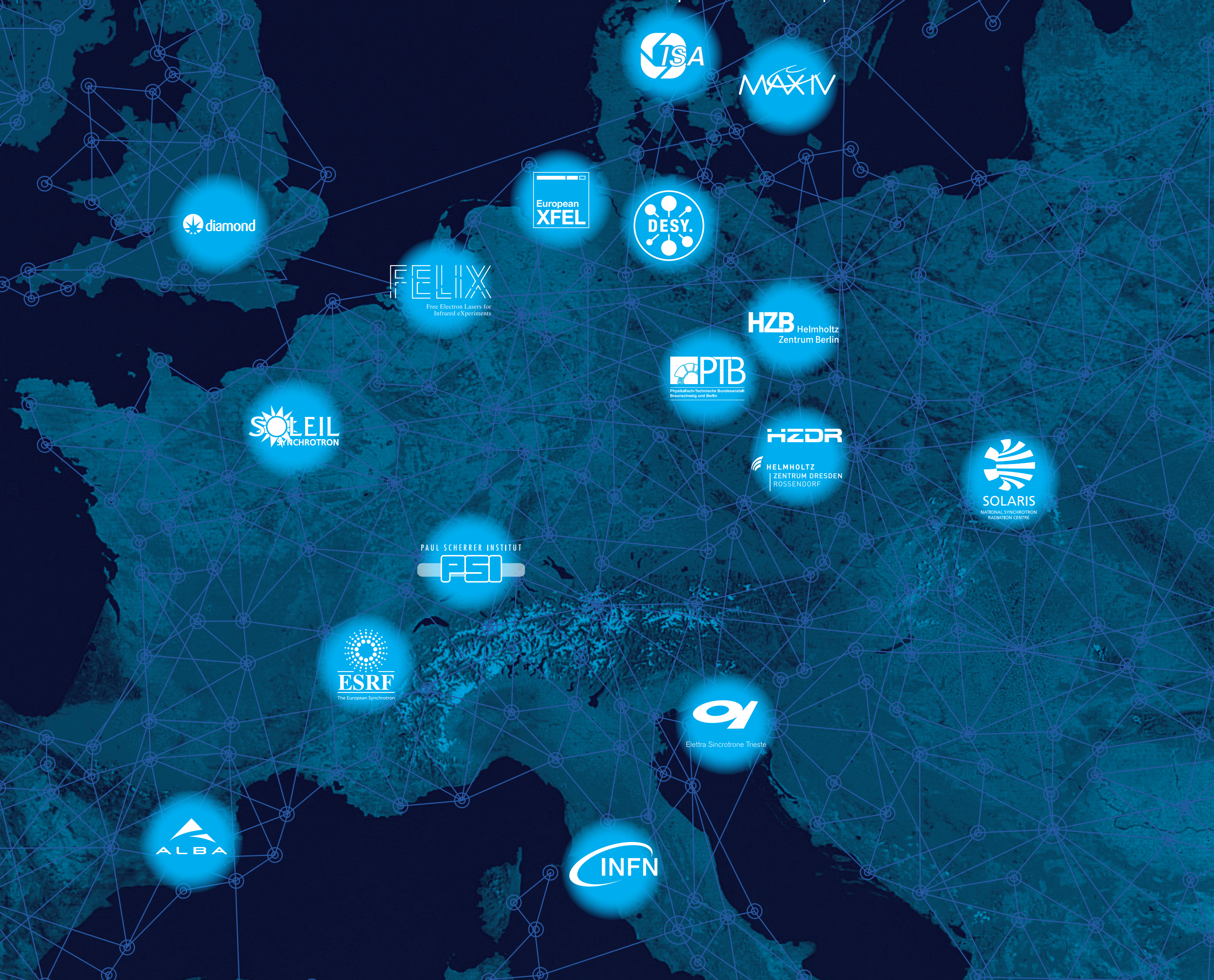


Vision

A world where European science is a catalyst for solving global challenges, a key driver for competitiveness, a compelling force for closer integration, and an initiative for peace through tighter scientific collaboration.

Mission

LEAPS will use the power of its combined resources to ensure that member light source facilities continue to be worldleaders acting as a catalyst for the development and integration of skills and solutions with a view to address 21st century global challenges, and to consolidate Europe's leadership in the field.



Working together in LEAPS

1. Introduction

This document explores the present landscape of photon science facilities and scientific challenges encountered by these unique tools, together with the planned developments, both in terms of key technologies and facility upgrades. It is based on the already elaborated document *LEAPS Strategy 2030* [1] and aims at implementing the first version of the landscape analysis, which in turn represents the first step towards the LEAPS RI Roadmap, as depicted in Fig. 1 (reproduced from Fig. 3 in [1]).

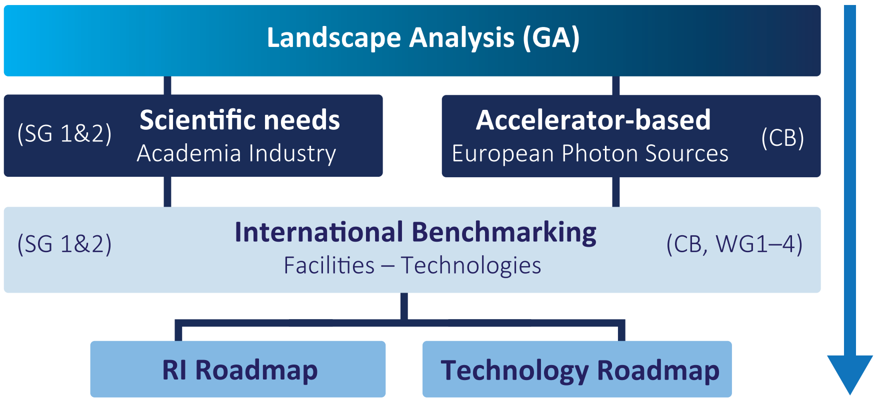


Fig. 1: Overview of the LEAPS Roadmap Process as proposed in [1]. The acronyms correspond to the different bodies of the LEAPS organigram involved in each task. The arrow indicates the direction of the workflow.

The document is organized as follows: section 2 describes the current landscape of operating electron accelerator-based photon sources (storage rings and free electron lasers) in Europe; section 3 and 4 perceive the role of LEAPS in a global context, based on the implements, challenges and scientific needs, both in terms of the international landscape and of complementary techniques; section 5 is devoted to the roadmap, depicting the upgrade plans for expanding the current photon sources performance imposed by the increasing scientific challenges; finally, section 6 explores the key technology developments to be faced in order to make possible the planned upgrades imposed by the scientific challenges. The latter two sections are just a first approach to facility and technology roadmaps, which shall be developed further in subsequent steps. As explained in [1] the analysis in this document should serve as a basis for coordinated activities within LEAPS that will help to implement smart specialisation. Periodic updating should be done according to the evolution of the LEAPS collaboration.

2. Landscape of accelerator-based photon sources in Europe

Starting in the 1960s the use of accelerator driven photon sources where scientists could perform experiments has experienced dramatic growth. While at the end of the 1960s there were only three operational facilities in Europe performing experiments based on synchrotron light (Adone in Italy, Daresbury in the UK, and DESY in Germany [2]), and the first free electron laser (FEL) started in the 21st century, now 14 storage ring synchrotron sources [SRs] and 7 FELs are operated for transnational users (see the information given in Fig. 2, Table 1 and Table 2). These facilities, run by 16 different national or international institutions located in 10 European countries, provide over 300 experimental stations offering a great variety of scattering, spectroscopic and imaging techniques based on photon interactions with matter. They serve a community of more than 24,000 users from all over the world (see Table 1) with an ever-increasing demand which leads already today to a severe oversubscription of many instruments.

LEAPS League of European Accelerator-based Photon Sources

Fig. 2. Location of LEAPS member institutions, all of them operating accelerator driven light sources for users.

While to a casual observer the facilities listed in Tables 1 and 2 seem quite similar, they are actually specialised as indicated by the colour scheme. Storage rings are multi-pass machines in which the electron beam, kept with a lifetime of many hours, delivers synchrotron light simultaneously to many beamlines disposed around its perimeter. The storage rings have optimal performance in specific spectral ranges determined mainly by the electron beam energy. The high energy machines ESRF and PETRA III are capable of delivering powerful photon beams with photon energies exceeding 100 keV, while the softer X-ray machines are optimised to deliver ultimate performance at photon energies in the range of 10–1500 eV. The highest photon energies are needed for penetrating and investigating thick samples, the medium photon energies around 8–10 keV are best suited for structural investigations with atomic precision, whereas softer X-rays are ideally suited to characterise the electronic, magnetic and chemical properties of matter. A special feature of the Metrology Light Source of the PTB in Berlin is its unique and distinguishing program dedicated to metrology services for industry and research in detector and radiation source calibration and characterisation of X-ray optics for advanced lithography. This complementarity of the existing storage ring light sources is illustrated in Fig. 3.

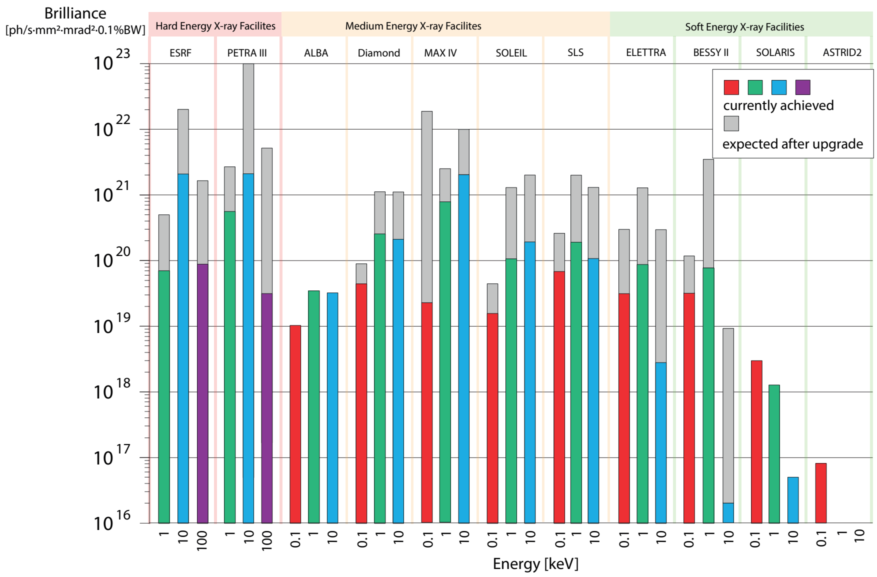


Fig. 3. Brilliance of photon beams for selected photon energies at operational facilities (including new insertion devices foreseen) and after planned upgrades, illustrating complementarity of the different sources.

Efforts sustained by many LEAPS facilities have led to breakthrough developments in accelerator technology, allowing to build so-called 4th generation storage rings (4G SR). The first implementation of such a 4G SR is the MAX IV hard X-ray ring (E=3 GeV) in Sweden. It presents a disruptive technology jump resulting in orders of magnitude improvement in the X-ray brilliance. This hard X-ray ring is complemented with a lower energy storage ring, as indicated separately in Table 1, of which SOLARIS in Poland is a replica. Following the MAX IV concept, the ESRF has pushed the technology even further, enabling another factor of 10 brightness increase. This new ESRF EBS storage ring will come into operation in 2020. Upgrades planned at other facilities will be described in section 5 below.

	Facility	Location Start of user operation	Energy (GeV)	Emittance (nm rad)	No. of beamlines	No. of individual user visits (remote), projects and publications/year
Hard X-ray facilities	ESRF	Grenoble, France 1994	6	4	48 operational[1] 44 funded 50 target	9 024 (650) visits 1 258 projects 1 819 publications
	PETRA III	Hamburg, Germany 2010	6	1.2	20 operational 24 funded 27 target	4 300 visits 700 projects >380 publications
Medium X-ray facilities	ALBA	Barcelona, Spain 2012	3	4.2	8 operational 12 funded 20 target	1 766 (197) visits 256 projects 174 publications
	Diamond	Harwell, UK 2007	3	2.7	28 operational 33 funded	10 437 (4 188) visits 2 623 projects 1 047 publications
	MAX IV	Lund, Sweden 2016	3	0.33	5 operational 10 funded 18 target	User operations ramping up
	SOLEIL	St. Aubin, France 2008	2.75	3.9	29 operational	4 138 visits 687 project 614 publications
	Swiss Light Source	PSI, Villigen, Switzerland 2001	2.4	5.5	16 operational	3 134 visits 1 037 projects 620 publications
Soft X-ray facilities	ELETTRA	Trieste, Italy 1993	2.0–2.4	7–10	25 operational	1 320 visits 510 projects 570 publications
	BESSY II	Berlin, Germany 1998	1.7	7	31 operational	3 200 visits 850 projects >500 publications
	MAX IV	Lund, Sweden 2017	1.5	6	3 operational 5 funded 8 target	User operations ramping up
	SOLARIS	Krakow, Poland 2018	1.5	6	2 operational 4 funded 16 target	User operations ramping up
	ASTRID2	Aarhus, Denmark 2013	0.58	12	6 operational 7 target	120 visits 60 projects 45 publications
	DAFNE-Light	Rome (INFN-LNF), Italy 2000	0.51	280	5 operational 7 target	30 visits 15 projects 7 publications
	MLS	PTB, Berlin (PTB), Germany 2008	0.1–0.63	100	7 operational	90 visits 25 projects 10 publications

Table 1. SR Photon Sources in Europe. The color indicates the specialization of the various facilities with respect to electron beam energy resulting in optimal performance for different photon energy ranges. The column "No. of beamlines" gives the total number of beamlines which can work in parallel, currently operational, funded or planned (target). The column devoted to numbers of user and publications gives the total number of individual user visits (visits), approved user team projects (projects) and publications for the latest 1-year period where data are available when writing this document (typically 2017). The data are based on the individual performance tracking practices of each facility and LEAPS aims at improving standardisation of metrics.

[1] The 48 operational beamlines at the ESRF include 34 ESRF own beamlines and 14 beamlines corresponding to Collaborative Research Groups (CRG).

Free electron lasers are accelerator-based facilities providing ultrashort, very intense, highly coherent radiation from a laser-like radiation process. These sources are tunable by adjusting the electron energy and magnetic field properties, and the radiation output is powered by the total energy stored in the electron bunches. Due to their radiation properties the FELs are key tools for studying structural and electron dynamics at the atomic and molecular scale covering the ultrafast fs-ps time domain. While FELs in the infrared and THz spectral range operate since the early 90s for users (compare Table 2), the first soft X-ray FEL FLASH started user operation in 2005 followed by FERMI as the second one in 2012. These facilities employ single electron pass schemes, either Self-Amplified Spontaneous Emission (SASE) or laser-seeded enabling thereby the FEL process to work for shorter wavelengths, stepping into the hard X-ray regime. Due to the FEL process, the peak brilliance of these sources is typically 5 to 6 orders of magnitude higher than for SRs and their radiation exhibits almost full transverse radiation coherence (SASE) and even a high degree of longitudinal coherence for seeded facilities like FERMI. In 2017 two FEL facilities providing hard X-ray radiation for user experiments started operation and complement now the available X-ray spectral regime, previously only available in the USA and Japan. It is noteworthy that seeding schemes, both for soft and hard X-rays, remain an important area of development for FELs. A list of the presently operating FEL user facilities in Europe is shown in Table 2 together with a selection of characteristic performance data. One observes that also here low, medium and high electron energy accelerators are employed. In addition, two FEL test and development facilities, SPARC (Italy) and CLARA (UK) (compare Table 3), serve the further development and testing of FEL schemes, like, e.g. sub-fs pulses, seeding or harmonic generation. A detailed description and the status of the operational FEL facilities can be found on the website of the FELs of Europe collaboration [3].

SR and FEL light sources are truly complementary in terms of their photon pulse parameters and consequently also in terms of the science performed at these facilities. Some characteristic photon pulse parameters of SRs and FELs are summarised in Table 4. As an example SRs deliver typically about 10^6 photons/pulse with a pulse length of typically 100 ps at repetition rates of up to 500 MHz, whereas FELs are capable of delivering up to 10^{13} photons/pulse within pulse lengths ranging from 10 to few 100 fs at repetition rates varying according to technology between 50 Hz and 30 kHz. This difference in peak flux for similar average flux directly translates into the differentiation of scientific applications. The selection of the type of light source depends on the particular objectives of the scientific application and the processes under investigation. Other relevant radiation properties for such a selection are X-ray pulse duration and coherence properties. The combined suite of end stations, X-ray techniques and X-ray properties offered by SR and FEL facilities allow addressing a very wide range of scientific problems. For example, studying structural or electronic dynamics FELs and SRs together allow spanning in an unprecedented way the whole range of timescales from femtoseconds to hours (18 orders of magnitude). FELs are uniquely suited to explore dynamic processes from femtoseconds to nanoseconds; SRs offer access to time scales from tens of ps to hours.

Facility	FELs lines operating in parallel	Location	Start user operation	Electron energy	Photon energy	Pulse properties	No. of exp. stations
European XFEL	SASE-1 SASE-2 SASE-3	Hamburg/ Schenefeld, Germany	2017 2018 2018	8.5–17.5 GeV	3.0– 20 keV	1–100 fs; 10*2700 pulses/s	2 2 2
SwissFEL	ARAMIS ATHOS	Villigen, Switzerland	2018 2020	2.1–5.8 GeV	1.8–12.4 keV 240–1930 eV	2–40 fs; 100 Hz	3 3
MAX IV	FemtoMAX (spontaneous radiation only)	Lund, Sweden		3.0 GeV	1.8–20 keV	100 fs; 10 Hz	3
FERMI	FEL-1 FEL-2	Trieste, Italy	2012 2016	1.5 GeV	15–90 eV 65–310 eV	seeded FEL 20–90 fs; 10–50 Hz	6
FLASH	FLASH-1 FLASH-2	Hamburg, Germany	2005 2016	0.4–1.25 GeV	26–300 eV 14–400 eV	10–300 fs; up to 10*800 pulses/s	5 2 (5 possible)
ELBE	FELBE TELBE	Dresden, Germany	2005 2016	15–40 MeV	5–250 meV 0.5–10 meV	0.5–30 ps; 13 MHz cw 0.5–30 ps; 13 MHz or 100 kHz cw	7 1
FELIX	FELIX 1/2 FELICE FLARE	Nijmegen, Netherlands	1993 2007 2013	15–50 MeV 15–50 MeV 10–16 MeV	8–400 meV 12–250 meV 0.8–12 meV	0.5–10 ps; 1 GHz/25 MHz, 20 Hz 0.5–10 ps; 1 GHz/16 MHz, 20 Hz 10–80 ps; 3 GHz/20 MHz, 20 Hz	12 2 4

High Energy Medium Energy Low Energy Very low energy

Table 2. FEL user facilities in Europe within the LEAPS collaboration, each operating or having been funded, including a number of FEL sources under construction. Color codes correspond to the different electron energy ranges, as indicated in the legend below the table. Facilities not involved in the LEAPS collaboration, such as CLIO, are not included.

Facility	Location	Start operation	Electron energy	Photon energy	Pulse properties
CLARA	Daresbury, UK	2022	250 MeV	100–400 nm	<fs to >1 ps, up to 400 Hz
SPARC	Frascati, INFN, Italy	2006	150 MeV	550–800 nm in SASE, seeded and 2-colours, HGHG down to 40 nm	30 fs to 10 ps at 10 Hz

Table 3. FEL test/development facilities in Europe

To give an example, the complementarity of these sources may be employed for studying a heterogeneous sample with SR experiments to 'image' the exact sample structure down to atomic resolution, while averaging over temporal fluctuations occurring during the measurement time. The FEL experiment would resolve these temporal fluctuations and provide fs snapshots of the sample. Currently developed special operation modes of SRs, e.g. the variable pulse length storage ring scheme (VSR) or low-alpha mode (see Table 4), add further options to such a scenario.

Another complementarity concerns the study of radiation-sensitive or irreversible processes, in contrast to radiation insensitive and repetitive processes. For the former systems, FELs with their ultrashort and intense pulse provide an unparalleled avenue to obtain information in a single shot, for the latter SRs allow for extreme high sensitivity and precision measurements. Similarly, the high FEL peak brilliance offers the possibility to study very dilute samples, rare species and is a unique tool for exploring non-linear processes, while the high average flux of SRs can provide extremely high precision spectroscopy measurements, e.g. of novel materials and superconductors. Having the appropriate instrumentation both types of sources are well suited for ***operando*** studies, monitoring the evolutions of the arrangement and properties of a specimen under realistic working conditions, using the proper photon energies and the great variety of spectroscopic, imaging and scattering methods, with desired spectral, lateral, depth and time resolution.

The above introduced 4th generation SRs operate with significantly reduced electron beam emittance and thereby achieve a higher degree of transverse coherence. Depending on the design of the 4G SR the X-ray radiation becomes diffraction-limited (i.e. the beam becomes coherent over its full transverse extension) up to a given photon energy. At present, such diffraction-limited radiation over a wide wavelength range is only provided by FEL sources and the combination of FEL and 4G SR light sources will lead to further advances in the development of techniques and will expand scientific applications. Photon pulse properties for the different kinds of light sources are summarised in Table 4, whereas further discussion on the diffraction limit for 4G SR is made in section 4 below.

Photon pulse properties	X-ray FEL	Synchrotron Radiation (SR)	4th generation SR
Photons/pulse	≥ 10^{12}	≥ 10^{6} ($5*10^{5}$)[a]	≥ 10^{6}
Pulse energy	1 mJ	1 nJ (0.5 nJ)[a]	1 nJ
Pulse length	10–100 fs	100 ps (1 ps)[a]	10-100 ps
Repetion rate	30–30 000[b] Hz	100–500 MHz (1.25 MHz)[c]	100–500 MHz
Coherent flux fraction	≈0.99[d]	≈0.01	≈0.5–1 dep.ring design & photon wavelength

Table 4: Photon pulse parameters of the currently operating EUV/X-ray FELs and SRs, including the most recent 4G SRs.
[a] With special operation modes, such as low-alpha (SOLEIL, DIAMOND and BESSY-II) or BESSY VSR.
[b] The average repetition rate of European XFEL has been taken as a reference for the upper bound reported. Higher repetition rates are envisaged for CW upgrades planned for the future.
[c] BESSY VSR.
[d] The coherent flux fraction depends on the wavelength and is expected to be slightly below 100%, while the measured values in experiments performed so far are yet under analysis.

3. International context: cooperation and connections to industry

The driving force for operation and further development of the accelerator-based Photon Sources, as also is the case for other types of large scale research infrastructures, is mainly to consider the manifold challenges that the society is facing. Besides being a pipeline of excellent scientific contributions to shorter-term goals, the offered unique experimental opportunities foster accumulation of inter-multi- disciplinary knowledge that can be used to solve grand challenges on longer time scales with wider economic and societal impacts.

The accelerator-based photon sources are long lasting research infrastructures. Their design and construction phases need several years, and the operational one covers at least two decades. These time scales impose careful planning and a long-term vision allowing for the adaptation and development of the infrastructure in order to respond to the changing scientific environment and technology advances. It is remarkable that all light sources within LEAPS have largely met this frame. Nevertheless, after decades of operation, major upgrades are unavoidable.

Considering the multi-disciplinary aspects of the research areas, the diversity of the necessary analytical tools and the potentials of each large scale facility it is highly desirable to evaluate, select and differentiate the scientific goals and the related technical infrastructure among the Photon sources. These actions should take into account the strength of the national academic groups and also the strategic orientation of the institutions as expressed in the scientific road maps of the different countries and the European Union coordinated by ESFRI.

In this process, the only route to success is the establishment of strong interaction and cooperation between all members of LEAPS. No single partner can carry alone all the developments needed. In this respect, a two-way approach seems to be more suitable: first of all clustering of resources and expertise around established groups should be intensified through stronger coordination and second the inclusion of members who want to develop and create new resources should be initiated.

The LEAPS idea is undoubtedly based on the strengths of the academic and industrial user community in Europe. Cooperation and interactions should be nevertheless extended to the world. Many connections are already established, e.g. SESAME in Jordan or SIRIUS in Brazil and facilities in the USA, China and Japan, among others, have expressed their interest to be part in the LEAPS endeavour within a scheme that should be decided in the near future.

During the conceptual design, construction and upgrade phases the interaction of the facilities with industry has been pursued. Many European small and medium enterprises (SME) are specialised in the construction and delivery of components, starting from the accelerator infrastructure, the production of photons, their transport and characterisation, sample environment and photon detection. In the last years, many of the technical knowledge gained at the academic institutions responsible for the sources have been transferred to active SMEs, or new ones have been created. Often the solutions found are also used in other fields beyond the photon community.

The context in which the developments addressed in this document are taking place is strongly globalised. Accelerator-based light sources in the Americas, mainly located in the USA, but also in Canada and Brazil, are already moving into the diffraction-limited scheme (very advanced at LNLS in Brazil) or planning to do so via suitable upgrades during the next years (APS and ALS). X-ray free-electron laser techniques are advanced at LCLS in Stanford, moving into improved performance via the construction of a high-repetition-rate branch (LCLS-II). In Asia-Oceania advanced accelerator-based light sources are available as well in a number of different countries (Japan, China, Taiwan, Korea, Australia). Hard X-ray free-electron laser facilities are in operation in Japan (SACLA) and Korea (PAL), while upgrades on existing synchrotrons (e.g. Spring-8 in Japan) or construction of new ones (e.g. HEPS in China) are some relevant examples of the main trends. Last, but not least, Russia is strongly engaged in international facilities being members of LEAPS and plans to develop as well its own next-generation synchrotron light source. Information about the different light source facilities, including those not mentioned here, is available in [4].

4. Complementary and competing experimental techniques

In addition to the synchrotron light sources and free electron lasers offering unique research opportunities spanning over all scattering, imaging and spectroscopic methods, there are many other complementary research facilities using laser light, electrons, neutrons and ions. This section accounts briefly for some relevant examples, with the aim of placing the science done at LEAPS facilities in a broader context.

The knowledge gained in the past years with VUV/X-FELs operation and applications rendered evident the importance of performing complementary experiments based on the use of laser sources operated in a laboratory and using a crystal or a gas gain medium, as briefly detailed below. Here we should first consider the Consortium LASERLAB-EUROPE [5], which involves leading institutions providing, e.g. light pulses for research projects exploring dynamic processes from atto- to picosecond timescales. Several centres hosting large scale synchrotron and free electron lasers also have on their campus specialised laboratories and use the remarkable progress in high harmonic generation (HHG) capabilities to carry out experiments complementary or preparatory to those done at LEAPS facilities [6]. Recently some of them, e.g. T-REX at Elettra, has been officially opened for the users to test and find the optimal set-ups for the subsequent FEL experiments. A particularly relevant complement to FEL facilities is the European Extreme Light Infrastructure (ELI) [7], the first international laser research infrastructure hosting the most advanced lasers with some of the beamlines opening to users already in 2019.

The inspiring applications in biomedical, materials or atomic and molecular science using ultrashort (down to attosecond) light pulses will gain from the unique experimental pump-probe capabilities complementing FELs operated by LEAPS members. A very important fraction of the ELI research program is also dedicated to developing novel particle accelerator schemes using lasers to accelerate electrons or even protons. These are of particular interest for the planned activities in LEAPS WP2.

Neutron-based techniques offer many opportunities complementary to the photon-based technologies provided by the LEAPS members. Neutrons can be used as probes for scattering and diffraction much like photons. In general, their cross section is lower than that of X-rays making them the tool of choice for thick samples. A unique feature of neutrons is the isotopic contrast, which is most often used when studying hydrogen based material, which can be substituted by deuterium. Neutron imaging, diffraction and scattering give information complementary to the respective photon-based techniques. Some limitations of this technique are indicated in Table 5 below. Based on nuclear reactors, as ILL [8] or on the spallation process (i.e. accelerator based), notably the European Spallation Source [9], ISIS [10] and SINQ [11], many of the technologies involved have significant overlaps with those present at photon facilities. Neutron sources have an active user community, which is engaged via public access schemes similar to those offered by the LEAPS facilities and it is quite frequent to find in the literature experiments in which both techniques are used to provide the answer to relevant scientific questions. Recently neutron facilities have put forward the initiative LENS [12], wherein they plan to collaborate closely and follow the LEAPS example.

For decades electron microscopy (SEM and TEM) has been a very important experimental technique for characterisation of matter structure and composition with very high spatial resolution. It provides additional information to that obtained using synchrotron light sources, free-electron (FELs) and optical lasers. In particular, these studies are relevant for exploring structures and speciation in matter in 2D, 3D and 4D[1] down to atomic scale, including holography as well, with particularly outstanding performance in 2D experiments and including ***operando*** capabilities. The most recent generation of aberration-corrected electron microscopes achieves superior resolution, while it offers ***in situ-operando*** set-ups as well, allowing exposures of the specimen to ambient gas or liquid environment [13]. Further on the revolutionary technological advances in Cryo-TEM (both single particle imaging and tomographic approaches) have led to unprecedented achievements that have allowed solving biological structures of macromolecules without the need for crystallisation [14, 15]. In recognition of the complementary capabilities of electron microscopes compared to those offered by the existing Large Research Infrastructures, some LEAPS facilities are now offering, or in the process of implementing, electron microscopy platforms as complementary tools to their user communities (a project is currently in preparation for submission to an H2020 call in order to implement a European Research Infrastructure on Electron Microscopy for Materials Science and Biology, closely connected to synchrotron facilities). The evolution of the interplay between these two techniques is for sure a key aspect to be monitored thoroughly over the coming years in such a way that the synergies can be best exploited.

In the context of structural biology at synchrotrons, FELs and aberration-corrected cryo-EMs it is worth mentioning the very recent breakthrough in protein folding prediction by Google-owned artificial intelligence firm

[1] 2D, 3D and 4D stands for, respectively, two-dimensional, three-dimensional and three-dimensional varying as a function of time.

DeepMind in the 13th Critical Assessment of Structure Prediction contest, confirming that the further evolution of this technology [16] should be seriously considered and carefully monitored.

Nuclear Magnetic Resonance (NMR) is a quantitative analytical tool with applications in many fields spanning over chemistry, pharmacy and medicine. It is based on the intrinsic property of the subatomic particles (neutrons, protons, electrons), namely the spin that can be aligned applying a magnetic field. Employing an electromagnetic pulse of selected frequency for perturbing the alignment of the nuclei under investigation, usually radio frequency (RF) the resulting frequency of absorbed and emitted energy encodes physical, chemical, electronic and structural information about molecules, both in solution and in solid state due to chemical shift, Zeeman effect, or Knight shift effect [17].

NMR spectroscopy and imaging are extensively used in chemistry to identify various compounds, but they are particularly desirable in clinical medicine and physiological chemistry allowing in vivo studies of soft tissues and the human organs in action. For identifying the structure of smaller biomolecules NMR makes studies in solution and does not require crystallisation. The key advantage of NMR, compared to X-rays (X-ray Crystallography, SAXS) and other imaging methods that use radioactive compounds or electrons (e.g. cryo-EM), is that it is noninvasive, hazard-free and with high sensitivity to structure and motion at molecular level explored under natural physiological conditions [18].

However, due to intrinsic physics that can detect only nuclei possessing a net spin the NMR is a somewhat not very sensitive technique. In this respect, only hydrogen the common constituent of all types of organic matter, is well-matched since its most abundant isotope (^{1}H) has spin ½. For enhancing the sensitivity to other constituents C, N, O isotope labelling, e.g. ^{13}C and ^{15}N, is necessary. NMR requires 'larger' specimen - high concentration of soluble molecules with limited dimensions and is not applicable to large proteins. For overcoming sensitivity limitations usually, NMR is complemented with other analytical techniques as high-performance liquid chromatography (HPLC) and mass-spectrometry (MS).

Table 5 highlights the strengths and weaknesses of accelerator-based light sources and the other experimental tools described above. Complementarity can be clearly seen by comparing the different entries of the table. Other techniques complementary to photon sources are briefly addressed in the paragraphs below and have not been included in the table for the sake of simplicity.

	Strength	Weakness
LEAPS	• Very high brightness (photons/mm²/s/mrad², 0.1% bandwidth) reaching 10^{23} at the 4G SRs and 10^{33} at XFEL and very broad wavelength range • Up to ~ 100% coherence • Tunability, full polarization options • Variable penetration depth • Time resolution over a wide range approaching few fs range • Multipurpose multi-user specialized beamlines offering many state-of-the art techniques, very reliable • Sensitive to chemical environment	• Radiation damage limits • Time resolution still limited to fs range
Lasers	• Broad wavelenght range from THz-IR to X-ray reaching MeV energies with Compton Source • Fully coherent pulses down to attosecond range • Multipurpose facilities offering different capabilities	• ≈2 orders of magnitude lower peak brightness and lower repetition rate compared to MHz X-ray FELs • Limited tunability at shorter wavelengths, limited polarization
Neutrons (LENS)	• High penetration power • Isotopic contrast • Good for very light elements, e.g. excellent probes for hydrogen, major constituent of organic-life matter • Sample environments for ultra-low temperature, high magnetic field, etc. • Very well suited for large samples • µeV energy resolution for inelastic scattering • Multipurpose multi-user facilities offering different capabilities, very reliable	• Low brightness source • Limited spatial resolution • Limited time resolution • Sample activation for some isotopes
EM	• Very high spatial resolution in crystals, excellent phase measurements • CryoEM to look at non-crystallizing macro-molecules • Requires limited infrastructure	• Penetration depth limited to microns • 3D imaging is destructive for sample • MX only at cryo temperatures, long acquisition time
NMR	• Biological molecule structures without crystallization • Non-invasive, hazardless • Widely used in clinical medicine	• Limited to atoms with net spin • Needs large samples • Not applicable to very large biomolecules

Table 5: Comparison of techniques provided by accelerator-based photon sources and those provided by complementary facilities.

A number of other, so-called offline characterisation techniques, such as optical microscopy, AFM, STM, HPLC, and mass spectrometry, which provide precious complementary information to that obtained at Synchrotron and FEL beamlines, have also already been offered at many of the LEAPS facilities. It should be noted that in the recent years all accelerator-based photon facilities are progressing fast in offering users additional tools for getting complete sets of scientific results that also help for processing and interpreting the data obtained at the beamlines. Therefore, the off-line tools for sample preparation, manipulation and pre-post characterisation are becoming an integral part of the facility infrastructure for the benefit of their users. In fact, one of the subgroups of LEAPS WG1 (and a corresponding pilot project) is focused on development and implementation of various types of sample environments that need to be tested ex-situ using suitable lab-based infrastructures and techniques. In addition, some of these sample environments can be used for both on-line measurements at the beamlines and off-line measurements in the complementary labs (e.g. gas adsorption, in-situ chemical reactions). Such sample environments represent an integral part of these labs.

In this frame of reference, it is also worth mentioning the advances in X-ray laboratory-based characterisation techniques. The laboratory tools (X-ray powder diffraction, X-ray diffraction, small angle X-ray scattering and X-ray photoelectron spectroscopy-XPS) already existing for decades, are continuously expanding their applications and improving their performances by upgrading the photon sources, detectors and sample environments. For instance, near ambient pressure XPS, which was first developed using synchrotron light, has already been commercialised as a lab instrument using a high flux small spot laboratory X-ray source and also offering various sample delivery systems and hosting, if requested, also other characterisation techniques in the experimental system. Many other examples may be found in which developments driven by large photon facilities spill over to lab instruments. Considering all ongoing developments of the laboratory methods is of particular importance for more creative and efficient use of the unique characteristics of synchrotron radiation in methodologies not accessible in the lab.

5. Facility roadmap outline

The development strategies of the institutions in Europe operating electron accelerator photon sources are responding to the scientific challenges presented in [19]. Improvements in the accelerator and beamline technologies aim at revolutionary advances in the characterisation of materials that will enable the design of new materials with desired exotic properties. A few examples of how facility upgrades are meeting some key scientific challenges are given in this section.

In the last decades, the contribution of photon sources to health issues has largely been based on the paradigm “from structure to function” of macro-biomolecules, considered a key for developing drugs to prevent or treat diseases incurable today. Recent advances in the reduction of the electron beam emittance and developments of microfocus beamlines have provided so-called serial crystallography methodology that enabled to obtain structural information from very tiny imperfect crystals. This has opened the unique opportunity for structural studies of membrane proteins under natural conditions that were not possible before. Both synchrotron and XFEL facilities operate serial crystallography beamlines, the former for more standard exploration of the macro-molecular structures whereas the latter are more focused on time-resolved studies. Advances in the beamline instrumentation to accurately maintain the sample, detect and enable successful data collection, analysis and management are on-going efforts as well.

Energy is undoubtedly another crucial grand challenge in our society. All systems relevant to energy production, conversion and storage are complex heterogeneous structures, and their functionality involves multiple energy, time and length-scales. The chief challenge is to understand which are the essential ones for their functionality that requires the development of multi-technique methodologies, based on spectroscopy, imaging and scattering with the necessary spatiotemporal resolution. In this respect developments of the photon sources, aiming at providing smaller beams with high coherence and shorter pulses will increase the characterisation potential of the experimental tools to explore critical physical and chemical phenomena that govern the performance of different energy devices.

Environmental research and food security require an interdisciplinary approach, integrating chemistry, physical and biological sciences to monitor and solve environmental and pollution problems. The scientific cases frequently challenge the limits of the available techniques in terms of trace element sensitivity and ability to screen a variety of particulate nanosized matter in order to shed light on the involved biochemical and atmospheric processes. The development of more advanced tools operated at FELs and 4G SRs is expected to go beyond present limits for understanding the processes and hazards and propose solutions to many problems unsolved today.

Many other areas, like engineering and manufacturing, heritage and a wide range of fundamental sciences need expanding our knowledge to best face grand challenges. In all cases, the capability to explore properties and functionality of the matter under investigation at its natural length and time scales is an invaluable benefit, and here the state-of-the-art techniques provided by FELs and SRs are opening unprecedented new opportunities.

LEAPS implies a concerted effort of all the existing and currently planned facilities in Europe to structure the upgrades and the development of novel accelerator based X-ray sources in such a way that Europe sustains its leadership in science and technology for the next decades. Such concerted effort not only concerns the timeline of the upgrades but also avoids duplication of efforts and allows accelerating the process by jointly developing critical components and technologies, which is mainly dealt with in section 6 below.

As it has been anticipated above, the next major improvement for storage ring light facilities is the rebuilding of the accelerator lattice in order to reduce the electron beam emittance substantially. This results in diffraction limited photon beams at least for photon energies up to the keV regime. In Europe, MAX IV has pioneered this accelerator development. Annex I describes the present plans for individual facility roadmaps, in such a way that their mutual coherence is apparent. Each facility, reporting to its funding agencies, is responsible for designing and implementing plans for the future. LEAPS offers an ideal environment for such individual roadmaps to be seen in a global context and to coordinate a common key technology roadmap to cope with the plans of the individual facility efficiently, via smart specialisation. Another crucial chain for efficient use of the facilities is data management (from readout to storage, including online/offline processing), which is still one of the key challenges roused by the novel scientific result production paradigm. The proper interplay between in-house solutions and external collaboration is one of the key strategic aspects and LEAPS wants to play a leading role assuring that standards are defined, which can be implemented at all facilities making it easy for the users to move between facilities.

The timeline for the upgrades is an essential issue. Obviously, this will depend critically upon the funding decisions. However, it is also very important not to deprive the user community in Europe by upgrading all facilities simultaneously. These activities have to be coordinated to secure that operating facilities in other countries can partially accommodate the users from a facility that is upgrading. These coordinated actions make part of the roadmap efforts. Fig. 4 and 5 show the perspective of the development of accelerator-based storage ring and FEL photon sources in Europe, respectively, presented in the context of the facilities already in operation. It must be stressed that some of the upgrade projects are still at a tentative phase, lacking formal approval, as indicated clearly in the figure legend and caption.

Storage Rings

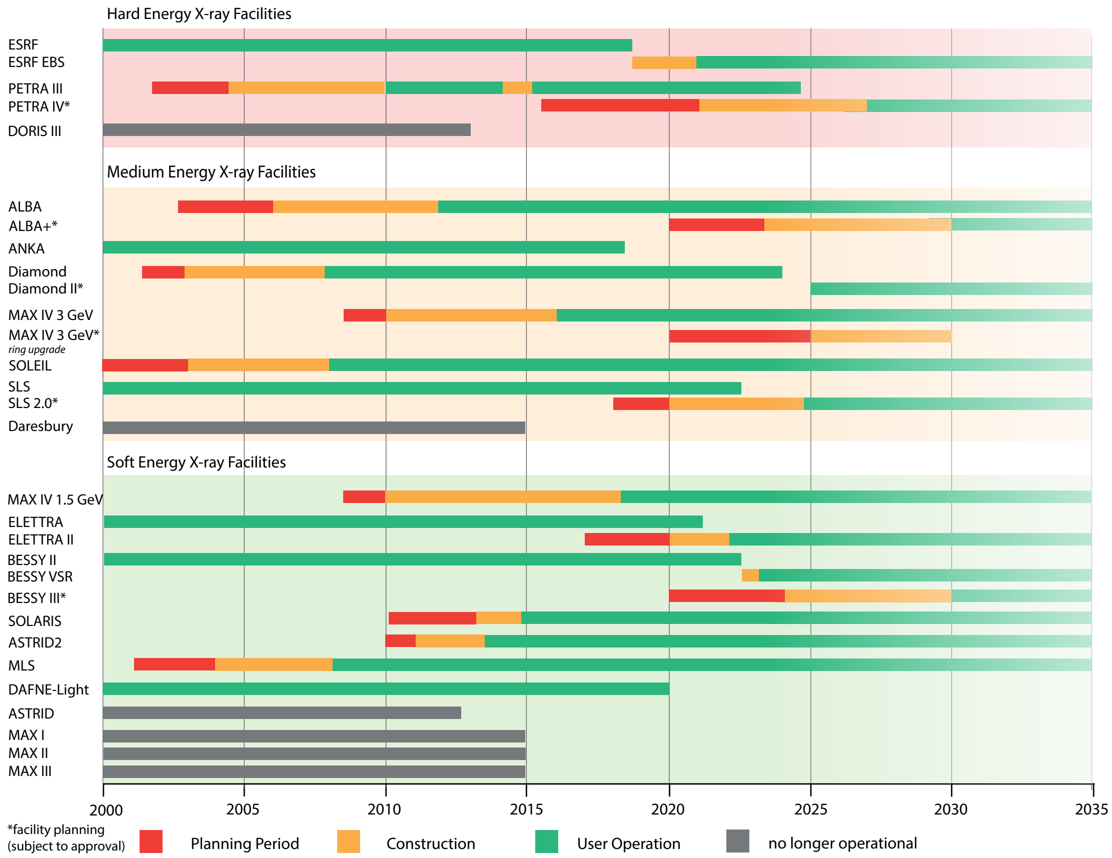


Fig. 4. Timeline of the existing storage ring facilities, approved upgrades and plans for upgrades not yet approved (marked with an asterisk).

Free Electron Lasers

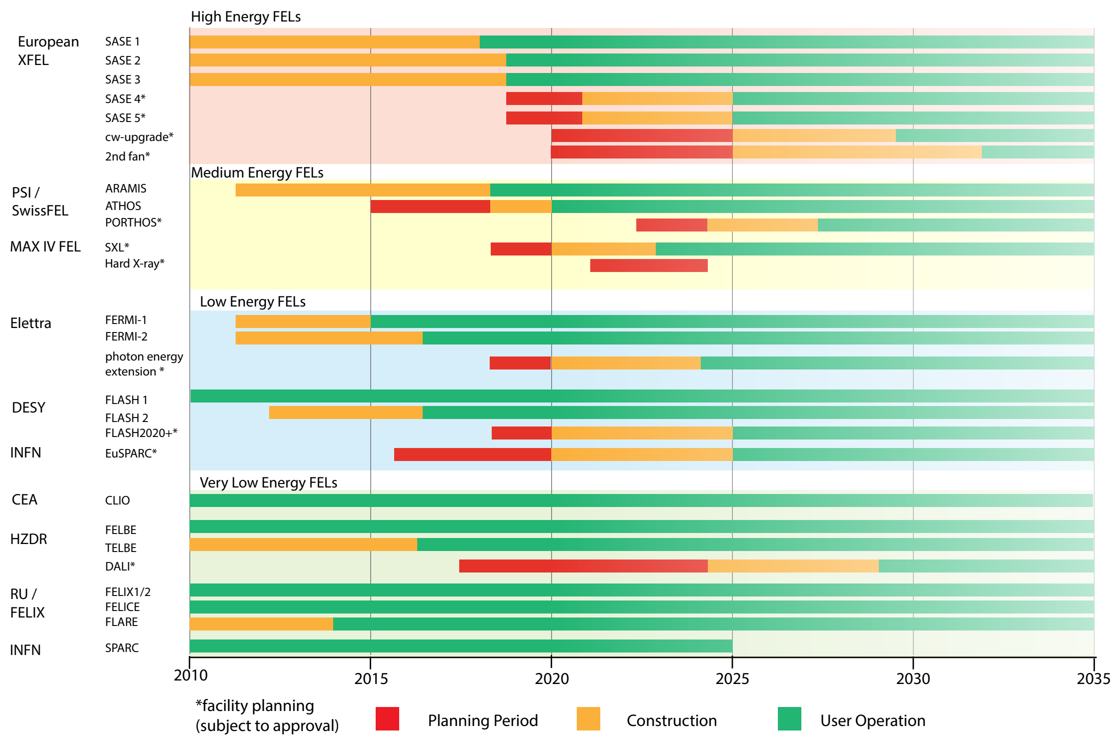


Fig. 5. Timeline of the existing FEL facilities, approved upgrades and plans for upgrades not yet approved (marked with an asterisk).

Fig. 6 shows the photon energy where the diffraction limit is reached of present SR facilities around the world and the potential improvements when the upgrades are implemented. The top of the figure indicates that the diffraction limit is reached for a wavelength of 1 Å, corresponding to atomic resolution. The PETRA-IV upgrade aims to reach this regime. For photon energies up to the diffraction limit, the X-rays are coherent. Even at higher energy (shorter wavelength) the coherent fraction of the X-ray beam is still substantial, but it drops quite rapidly. The improved coherence (brilliance) translates into vastly improved imaging capabilities – i.e. holography with atomic resolution – and better micro- and nano-focus analytics. Furthermore, in using correlation techniques, changes and fluctuations in the sample may be recorded for timescales as short as 100 ps.

Facility plans, including the upgrades depicted in Fig. 4 and 5, are being developed by the corresponding owner institutions, keeping as a reference to the global framework. A brief summary of such plans, complementing the information already presented in this section, is given in Annex I below.

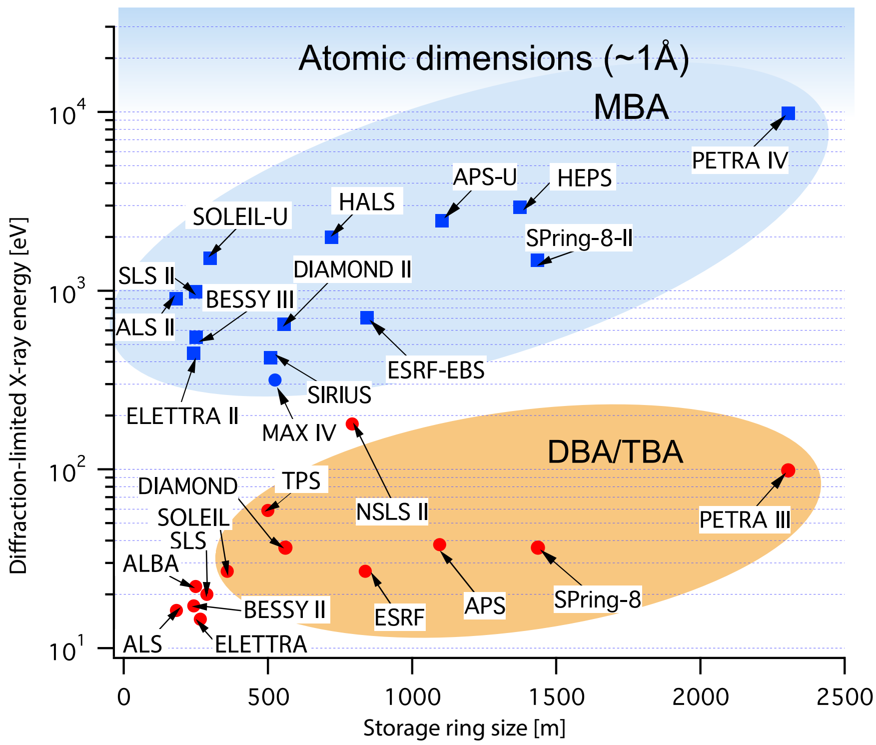


Fig. 6. Diffraction limited photon energy (defined as hc/4πeεx) reached at various existing facilities (full circles) and after planned upgrades (full squares), including some selected extra-European ones. The orange and blue islands denote the disruptive change in accelerator technology in going from the double/triple bend achromat lattice to the newer multi bend achromat storage ring design.
Data are supplied by the different facilities or taken from A. Nadji, SRI June 2018 Taiwan, adapted from C.G. Schroer.

6. LEAPS key technology roadmap

There is much more to the roadmap process than just coordination of the timelines. One of the key aims of LEAPS is to coordinate joint technological developments needed by several facilities and avoid duplication of efforts by applying a smart specialisation strategy. This encompasses far more than accelerator technology since a better performing source also requires more precise optics and more stringent mechanical engineering to maintain the precision of nanometer focused beams. Additionally, detectors with upgraded performance characteristics are needed, sample handling needs to be improved, and data management and analysis challenges are evolving extremely fast, to mention a few of the critical issues to be dealt with. Key technology roadmap directions within LEAPS, mapping to the corresponding WGs, are to be elaborated as an outcome of the ongoing process to define key collaborative projects devoted to technological developments, which reached an inflexion point at the LEAPS general meeting in November 2018. LEAPS technology roadmap takes as a starting point the directions established in *LEAPS Strategy 2030* [1].

Annex I: Brief panorama of facility roadmaps

This Annex contains brief and simplified information on the plans each of the different facilities has to deal with the future challenges for accelerator-based photon sources in Europe, as elaborated by the corresponding institutions. LEAPS aims to generate a framework in which these roadmaps can optimise efforts by implementing smart specialisation.

As mentioned above **MAX IV** has pioneered the multiple bend achromat (MBA) technology in the design, construction and operation of the new 3 GeV synchrotron ring at MAX IV. In addition, MAX IV operates a 1.5 GeV ring and a 3 GeV linac. The 1.5 GeV ring is optimised for VUV and soft X-ray radiation (ca 500 eV), while the linac is used to inject into both rings and for supplying ultra-short (ca 100 fs) pulses to a beamline. The new facility got inaugurated on the 21st of June 2016 and is now ramping up user operations. The MBA concept introduced at the 3 GeV ring consists of 20 cells of 7-bend achromat unit in a 528 m circumference 3 GeV storage ring providing 328 pm.rad bare lattice horizontal emittance. To deliver such ultra-small beam on the sample position without a loss of brightness and with stability matching the beam size presented a number of challenges especially regarding vacuum, stability and precision requirements. The delivered light at the beamlines of MAX IV has led to a factor of 10 increase in both brightness and coherence over existing facilities, paving the way to new science capabilities including the use of nanoprobes, higher resolution (spatial, energy, time), coherent imaging, holography, speckle, and ptychography. The 3 GeV ring can serve up to 19 beamlines of which five are in commissioning/construction phase, and five are in user operation today, delivering a stable, high brilliance beam to the scientific community. Plans for an upgrade of the MAX IV 3 GeV ring lattice to approach the diffraction limit for 10 keV photons have been initiated.

As indicated in section 2, the **ESRF** launched, in 2015, the Extremely Brilliant Source (EBS) program, a facility upgrade focused on the construction of a revolutionary low-emittance light source. This first-of-a-kind new storage ring combines an increase in the number of bending magnets (from two to seven in each of the 32 cells) with smaller sextupole settings and a large dynamic aperture, reducing the horizontal equilibrium emittance by nearly a factor 30 to produce an X-ray beam 100 times more brilliant and coherent than today. Furthermore, the upgrade involves the construction of brand-new flagship beamlines and the deep refurbishment of existing beamlines (high-performance detectors, and cutting-edge experimental control and data analysis tools) which are designed to exploit the enhanced performances of the new source. The upgrade has been in full swing since 2015, with thousands of components designed, manufactured and procured. In December 2018, the ESRF accelerators were switched off. The ESRF staff will have 18 months to dismantle the existing storage ring, install and commission the new ring and restart a maximum number of beamlines, before returning to a full user program in summer 2020. The new and refurbished beamlines will be completed in 2022.

The **PETRA IV** project at DESY comprises the upgrade of PETRA III into a synchrotron radiation source with ultra-small emittance. With a circumference of 2.3 km, the PETRA storage ring is ideal for pushing the limits of multi-bend achromat technology. In this way the spectral brightness of PETRA in the hard X-ray range shall be increased by up to a factor of 100, thus approaching the diffraction limit for X-rays of about 10 keV. This highly brilliant and coherent X-ray radiation enables the scale-bridging investigation of complex chemical, biological and physical processes under realistic conditions with a spatial resolution in the nanometer range. Two additional experimental halls are planned to accommodate a total of 30 ID beamlines, up to five of which, located in very long straight sections, can be optimised for highest brightness. The project is currently in the conceptual design phase, ending with a CDR in 2019 and followed by a technical design phase until 2021. In 2019/2020, DESY will work on strategically preparing PETRA IV. This includes integration into the research infrastructure strategy of the Helmholtz Association and the application for inclusion in the national roadmap for large-scale facilities. At the European level, PETRA IV shall also be anchored in the European strategy to be developed in LEAPS.

Helmholtz-Zentrum Berlin (HZB) is implementing the upgrade of **BESSY** II to the BESSY VSR variable pulse-length storage ring, thereby addressing the increasing demand for exploring the dynamic properties of materials. BESSY VSR will provide ps pulses in combination with high brilliance operation while preserving the superior stability of storage rings. This creates unique opportunities for energy and materials research, which are complementary to those offered by FELs. The technical realisation of BESSY VSR is now being pursued: instrumentation for the optimal use of BESSY VSR's unique pulse pattern is being developed, and HZB is collaborating closely with national and international partners to design the challenging multi-frequency SRF accelerator technology. Looking towards the long-term future and extrapolating the scientific portfolio served by BESSY II and BESSY VSR, HZB currently identifies the desired properties of a future light source ("BESSY III") in the soft and tender X-ray regime. Flexible time- and highest energy resolution will be key aspects of this facility. The combination of a 4G SR with the VSR concept for BESSY III would open up entirely new scientific opportunities and provide diffraction-limited beams in the soft X-ray region to the user community performing time-resolved experiments.

Elettra is in the final design stage for the planned and recently funded upgrade of the Elettra storage ring and beamlines. This next generation Elettra-2 machine will operate in the same tunnel using the current injection system and preserving as much as possible the source points. After examination of many possible technical solutions, considering the most desired light properties (brightness – coherence – stability) in the wide wavelength range required by synchrotron-based science and applications a decade from now the best compromise is a 6-bend achromat lattice operating at 2.0 and 2.4 GeV. Ongoing efforts are also examining different schemes for the production of short photon pulses (down to ~ 1 ps) to complement the experiments performed at FERMI that will have an impact on completing the final design of Elettra-2 and starting project implementation in 2019-2020.

SOLEIL has started to work on a major upgrade of the facility. Following preliminary discussions with funders, studies began in 2017 and are now entering a phase of early prototyping preparing for a Conceptual Design Report (CDR). This upgrade proposal takes place in a long-term vision for SOLEIL, including a multimodal approach for scientific questions and a high level of service. This vision does not end with the new storage ring commissioning which is rather seen as the condition for further developments. Following a rigorous analysis of SOLEIL's present strengths, the proposed storage ring upgrade will offer the same wide spectral range from infra-red to hard X-rays, keeping the complementarity with ESRF-EBS. A preliminary design study, keeping the storage ring circumference unchanged in order to optimize cost, shows that an increase by up to two orders of magnitude in brilliance (sub 100 pm.rad horizontal emittance) could be obtained improving the performances of all beamlines in the UV, soft X-ray and hard X-ray domains, which will all benefit from the upgrade to a large extent. Many beamlines will have multimodal capabilities, reinforcing SOLEIL's well-established strategy to offer complementary methods to tackle a scientific problem. We anticipate that the evolution in beamline technology will lead to a similar evolution in beamline use, where SOLEIL's experience with strategic partnerships will be most valuable.

Diamond is currently developing the science case for the upgrade to the storage ring, Diamond-II, in parallel with ongoing calculations for the performance of new configurations for the machine. These strands will be brought together in a Conceptual Design Report by Spring 2019. While the driving principle for upgrades elsewhere has been to try to achieve the lowest possible emittance for the storage ring, and concomitantly the greatest possible photon brilliance and coherence, we believe that there is also a strong argument to increase the number of insertion devices around our storage ring. This will allow both the upgrade of some of the beamlines currently based on bending magnets and also increase capacity for new beamlines through the provision of new mid-section straights which in turn offer additional new locations for insertion devices. This is possible if the new storage ring is based on multibend achromats containing an even number of bending magnets. The opportunities provided by an increase in the energy of the storage ring from 3 GeV to close to 3.5 GeV are also being explored; these are expected to bring distinctive advantages, for example, to operando studies and materials discovery.

The scientific case for the upgrade of **SLS** towards SLS2.0 has been worked out and has been presented to the Swiss National Science Foundation. The evaluation by an expert panel set the project at the top-level. The accelerator Conceptual Design Report is also finished. A new storage ring lattice providing a lower emittance by more than a factor 30 within the same circumference has been designed taking into account new research needs. A positive decision by the ETH Board (the governing board of PSI and the Swiss Federal Institutions) was made end of 2018. According to the present planning, the construction phase of SLS2.0 will start in Spring 2023 and last until Autumn 2024.

ALBA is one of the youngest SR-based facilities in Europe. Starting operations in 2012 it has focused its activity over the last few years on fully exploiting its capabilities. Starting from a portfolio of seven beamlines ALBA is gradually expanding its offer to users, with a total of twelve beamlines in operation, construction or design at the moment of writing this report (see Table 1 above), and the program to continue growing, targeting a total of circa 20 beamlines. The ALBA SR, with a limited size, is one of the most optimised ones among third-generation facilities, both in terms of emittance and number and length of straight sections available for insertion devices. This fact, combined with the need to fully profit from the investments made in new beamlines, sets the main boundary conditions to the plans for a major upgrade. During the next few years ALBA plans to elaborate a careful study for such an upgrade, based on a well-established scientific case, taking into account the aforementioned schedule boundary conditions (see a tentative schedule in Fig. 4 above, wherein the eventual upgrade is labelled as ALBA+) and profiting the opportunities generated by LEAPS in terms of sharing knowledge, technological solutions and complementarity with other European sources.

DAFNE-Light is the INFN synchrotron radiation facility at the Laboratori Nazionali di Frascati (LNF). Five beamlines are practically operational since the commissioning of the last two XUV beamlines is almost ended. All beamlines are using, in parasitic and dedicated mode, the intense photon emission of DAFNE, a 0.51 GeV storage ring with a routinely circulating electron current higher than 1.5 Ampere and were realised to cover the whole DAFNE photon energy range going from IR to soft X-rays. No upgrades of the DAFNE storage ring are foreseen up to the end of 2019. Within an INFN-CERN MoU, a new UHV beamline for white light desorption studies has been funded and will probably be operational in 2019. The need for exploiting synchrotron radiation to study in detail reflectivity, photo-yield and photo-induced desorption represents a strong scientific case also in the field of high energy physics for designing planned and future circular colliders.

SOLARIS is the only synchrotron in Central and Eastern Europe area. The facility is based on the multiple bend achromat (MBA) technology, and the 1.5 GeV ring will serve mainly as a source of VUV and soft X-ray radiation. The first users started taking measurements in October 2018 on two excellent prepared beamlines – PEEM/XAS and UARPES. UARPES enables angle-resolved photoemission spectroscopy in the photon energy range 8–100 eV delivered by the EPU undulator. PEEM/XAS beamline is equipped with two endstations – the photoemission electron microscope and universal station for X-ray absorption spectroscopy working in the photon energy range 200–2000 eV. The research infrastructure is at the stage of implementing its advanced development plan. Another two beamlines are under construction – PHELIX and XMCD. Both will use radiation from the EPU undulators. The main technique at PHELIX will be photoelectron spectroscopy operating in various modes – angle integrated, angle-resolved and spin-resolved. The photon energy range will be 50–1500 eV. The well-equipped preparation chamber will enable experiments for different kinds of samples. The planned branch end station to PHELIX will be NAPXPS (Near-ambient pressure photoelectron spectroscopy). XMCD beamline is dedicated to soft X-ray absorption spectroscopy, including end station enabling magnetic dichroism measurements in the magnetic field up to 1 T. The planned branch end station will contain STXM (scanning transmission X-ray microscope). The largest so far investment of the Centre – a beamline for structural research – will be constructed within the signed agreement with the Joint Institute for Nuclear Research (JINR) in Dubna (Russia).

The **Metrology Light Source** (MLS) of PTB is a 630 MeV electron storage ring providing synchrotron radiation from the THz regime up to the extreme ultraviolet range. Its capabilities are focused on the use of synchrotron radiation for metrology. This includes applications for industry-related activities as well as scientific purposes, in particular in the field of optical metrology and energy material developments. One of the unique features is the flexible operation with different ring energies and beam conditions like the source size, stored electron beam current, and bunch length. Future developments aim at an extension of the activities; thus the ring undergoes permanent improvements, e.g. to enhance the beam stability at the different electron beam conditions. Improvements of the beamlines (e.g. for the vacuum-ultraviolet spectral range) as well as of the end-station instrumentation (e.g. a large-scale reflectometer for the characterisation of optical surfaces particularly to support PTB's cooperation with industrial partners in the field of EUV lithography for semiconductor manufacturing) will be operational in the near-term future. On a long-term scale, future development will be coordinated with HZB's "BESSY III" facility planning.

The low-energy **ASTRID2** facility provides brilliant photons from the infrared to the soft X-ray region. The photons are emitted from the small and modern low-emittance synchrotron radiation storage ring ASTRID2, which operates in top-up mode. A suite of seven beamlines provides light to user experiments in a collection of unique or more standard end-stations. Improvements to the stability and operation of the accelerators with the addition of a longitudinal feedback system to complement the operational transverse one are planned. However, no major shutdowns of the facility for upgrades are expected. New beamlines and in particular end-stations are being built, expanded or upgraded with various new instruments like for example Scanning Tunnel Microscopes and electron analysers, according to the needs of the users. The ASTRID2 facility is operated by a Physics Department and the access to in-house technical staffs, and support laboratories are an important asset for the facility.

Also in the case of FELs most facilities continuously upgrade their performance or extend their portfolio of experimental platforms and source parameters due to the strong international competition and the large demand for FEL sources and user facilities with improved performance for experiments in a wide range of scientific domains. Several of these improvements can be made gradually and can be installed and commissioned without major interruptions of the user operation.

For example, **FLASH** plans medium-term developments including an afterburner for circular polarization for FLASH2, a transverse deflecting cavity for online diagnostics of temporal shape of photon pulses in FLASH2, the exchange of fixed gap undulators in FLASH1 with variable gap undulators, external seeding for FLASH1, and from 2022 user experiments at a branch line run in an externally seeded mode with an intrabunch repetition rate starting initially at 100 kHz (up to 800 pulses/s) and later 1 MHz (up to 8000 pulses/s).

FELIX is planning to implement a parallel operation of the fourth FEL beamline, advanced pulse schemes for time-resolved/two-colour experiments, high-resolution operation and a new experimental end station including access to 45 T DC magnetic fields.

FERMI is planning an experimental upgrade of FEL-2 to the Echo-Enabled Harmonic Generation (EEHG) mode of operation with a stepwise implementation plan with minimal impact on user operations. The first tests have started in 2018 and are expected to provide the necessary information for comparing a seeded FEL in EEHG mode with the current two-stage HGHG mode for a possible future upgrade of FEL-2. Also, the production of pulses with duration in the femtosecond range is under study.

European XFEL will implement until approximately 2020 self-seeding for soft and hard X-rays and construct two more experimental stations at its SASE2 and SASE3 beamlines.

At **SwissFEL** the construction of the soft X-ray branch with a novel undulator-chicane design, ATHOS, is far advanced, with the goal to have first light by the end of 2019. This new scheme will allow for extremely flexible control of photon beam parameters. The hard X-ray branch is operational, and the first round of user experiments will start in 2019. There are plans to implement hard X-ray self-seeding, in order to enable better control of radiation parameters. Further developments include the delivery of two-colour X-ray pulses with adjustable time delay and variable energy separation, ultrabroad band X-ray spectrum pulses (>5%), as well as the delivery of very short pulses in the sub-femtosecond range. On the long term beyond 2023, the installation of a second hard X-ray branch (PORTHOS) is under consideration.

Beyond the gradual improvements, several larger scale projects are under consideration In the case of FELs. For the THz to IR regime an investigation is currently underway on how a future successor of the **ELBE** accelerator could best serve the user requirements. A new 100 MeV, 1 MHz superconducting accelerator could provide multiple parallel beams with various types of photons at high repetition rates. It would constitute the basis of the Dresden Advanced Light Source (DALI). Provided that the concept proves viable and the project is approved, the construction is envisaged for 2024–2028.

In the XUV to soft X-ray regime, several projects are under consideration. DESY is in the preparation phase for a FLASH upgrade program: "**FLASH2020**". This program will take main trends in FEL development into account, such as laser-electron beam manipulation to generate photon pulses with properties similar to optical lasers (seeding), generation of extremely short attosecond pulses, and exploitation of flexible tunable undulators for novel lasing schemes.

FERMI intends to extend the photon energy range above 310 eV, to cover beside the C K-edge, also the K-edges of N (410 eV) and O (543 eV); this would require an energy upgrade of both the linac to 1.8 GeV and an extension of the FEL-2 radiator line.

SwissFEL will construct in the time frame 2024 to 2026 the additional PORTHOS beamline, a second hard X-ray undulator beamline with very advanced properties based on experience gained with the running facilities.

The current test FEL facility **SPARC** shall be converted in a soft X-ray user facility and deliver first beam to users by 2023.

In the hard X-ray regime, in the time frame from about 2021 to 2024, **European XFEL** is planning to complete the two remaining FEL sources, beamlines, and four to six additional science instruments. On the long time scale, European XFEL is preparing an upgrade of the accelerator enabling to provide a cw-operation mode at flexible frequencies up to the MHz regime. The time span for this upgrade could be 2025 to 2029, while R&D is starting now. An extension of the facility through construction of a second fan of FEL beamlines and another experiment hall would create the space for another approximately five FELs and ten experimental stations. This upgrade might take place in the time span 2025–2032.

There are a number of X-ray FEL projects in the concept phase: POLFEL (Poland); MAX IV FEL (Sweden), wherein the Short Pulse Facility (SPF) and Soft X-ray Laser (SXL) lines shall provide excellent conditions for surface science and liquid structure research; LUMEX (France); and EuSPARC (Italy) that will be driven by an X-band RF linac with an additional option based on a pilot plasma accelerator.

Finally, the storage ring project **SESAME**, in Jordan, and the FEL project **TARLA**, in Turkey, correspond to new accelerator-based photon source facilities very near and in close collaboration with Europe. In the case of SESAME operations are gradually starting at the first few beamlines, whereas TARLA plans to start FEL construction by 2020.

References

[1] LEAPS strategy 2030, https://www.leaps-initiative.eu/about/leaps_strategy_2030/

[2] G. Margaritondo, Rivista del Nuovo Cimento, Vol. 40, N. 9, 411-471.

[3] FELs of Europe collaboration, www.fels-of-europe.eu

[4] www.lightsources.org/lightsources-of-the-world/

[5] https://www.laserlab-europe.eu/

[6] Zhensheng Tao et al, Science 10.1126/science.aaf6793 (2016) and references therein.

[7] https://eli-laser.eu/

[8] https://www.ill.eu/

[9] https://europeanspallationsource.se/

[10] https://www.isis.stfc.ac.uk/Pages/home.aspx

[11] https://www.psi.ch/sinq/

[12] http://www.fill2030.eu/2018/09/12/%F0%9F%87%AA%F0%9F%87%BA-the-league-of-advanced-european-neutron-sources-lens-launched-at-the-international-conference-of-research-infrastructures-icri2018/

[13] J. D. Stoll and A. Kolmakov, “Electron transparent graphene windows for environmental scanning electron microscopy in liquids and dense gases,” Nanotechnology, https://doi.org/10.1088/0957-4484/23/50/505704

[14] E. Gallaway, “The revolution will not be crystallized: a new method sweeps through structural biology”, Nature, 525, 172–174 (2015).

[15] https://www.nobelprize.org/prizes/chemistry/2017/summary/

[16] http://www.sciencemag.org/news/2018/12/google-s-deepmind-aces-protein-folding

[17] L. G. Hanson (2008) Concepts in Magnetic Resonance Part A, 32A(5), 329–340.

[18] ConBau Kang, Int. J. Mol. Sci. 2019, 20, 139 and references therein.

[19] Appendix LEAPS strategy 2030, https://www.leaps-initiative.eu/about/leaps_strategy_2030/

LEAPS members

ALBA – https://www.albasynchrotron.es/en
DESY – http://photon-science.desy.de/
Diamond – http://www.diamond.ac.uk/
Elettra – http://www.elettra.eu/
ESRF – http://www.esrf.eu/
European XFEL – https://www.xfel.eu/
FELIX – https://www.ru.nl/felix/
HZB – https://www.helmholtz-berlin.de/
HZDR – https://www.hzdr.de/
INFN – http://home.infn.it/en/
ISA, Aarhus University – http://www.isa.au.dk/
MAX IV – https://www.maxiv.se/
PSI – https://www.psi.ch/
PTB – https://www.ptb.de/
Solaris – http://www.synchrotron.uj.edu.pl/
Soleil – https://www.synchrotron-soleil.fr/

LEAPS associates

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Looking to the future

The LEAPS members are committed to working in an even more coordinated way in the future, so that collectively they can solve increasingly challenging technological, scientific and societal problems, boost European competitiveness and integration and extend global outreach. There has never been a more important time to do this, both because of the urgency of the challenges themselves, and the massive investment that is boosting the performance and delivery of such facilities elsewhere in the world.

The LEAPS strategy is to:

- Develop and implement next-generation technology for light sources in order to provide Europe with a world-leading network of high-level storage rings and FELs
- Drive forward the development of enabling technology for beamlines to attract and enable new science and meet the challenge of handling and processing increasingly large and complex sets of data
- Base developments on road maps that include smart specialisation, with each facility developing individual strengths in science and technology in a coherent manner so that together they provide Europe with optimum capacity and capability
- Improve the strength and breadth of engagement with industry both as service providers and as the inspiration for new technology, to increase European competitiveness and productivity and ultimately strengthen economies and create jobs
- Enhance access modes and develop new user communities that will aid further integration of European and ultimately global science
- Inspire and develop the next generation of scientists, engineers, technicians and technologists through better outreach, education and training and with enhanced mobility boost the availability of skills and expertise across Europe

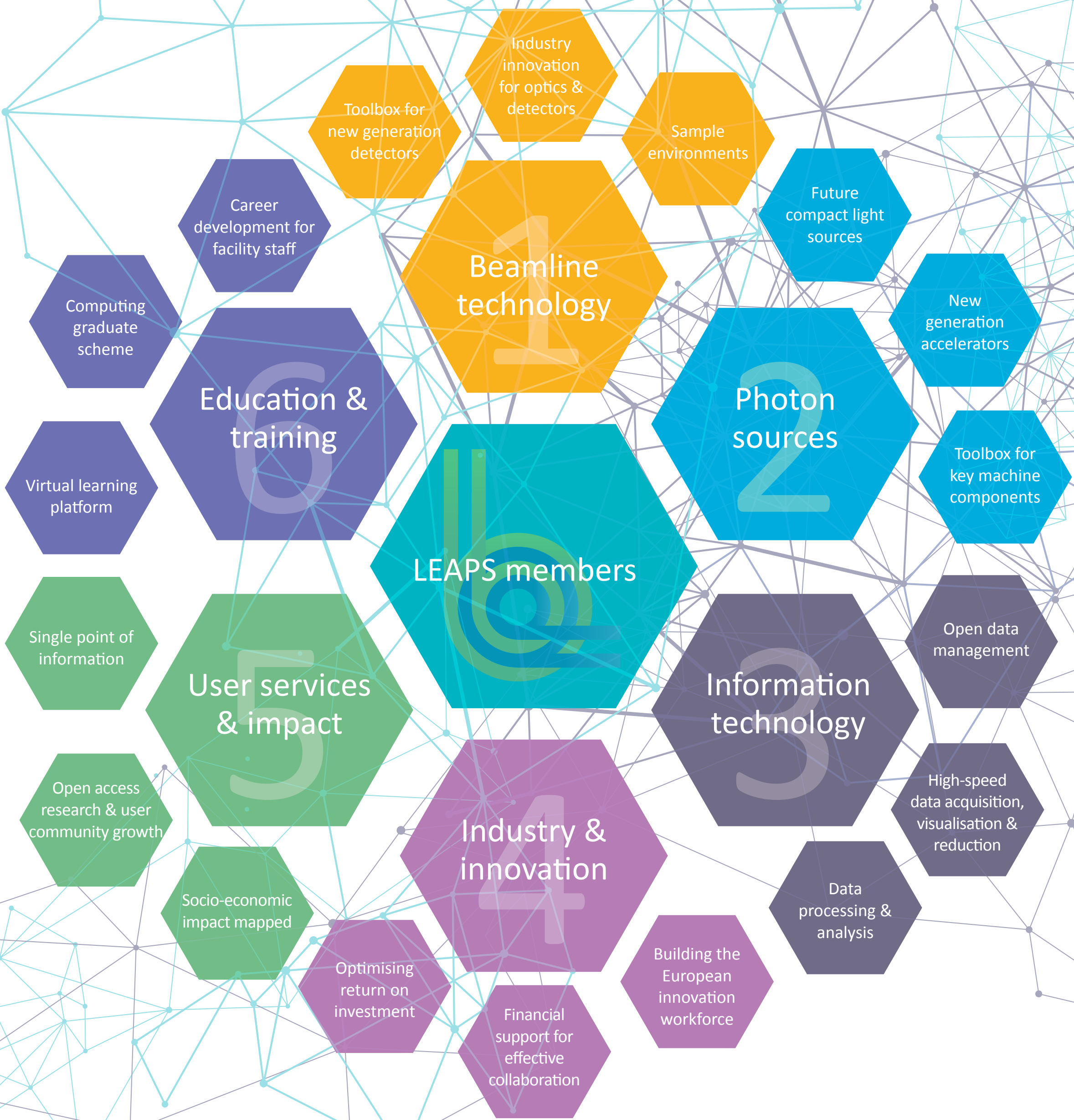
STRATEGIC PRIORITIES

› Drive forward the development of common enabling technology, from accelerators, beamlines and detectors, to the challenge of 'big data'. (1-3)

› Harness the unique strengths of the members of LEAPS for industry and innovation both as service providers and as the inspiration for new technology, to increase European competitiveness and productivity, strengthen the economies and create jobs. (4)

› Create a seamless and unified user experience between facilities, to foster regional development and to map in detail the wider socio-economic impact. (5)

› Inspire and develop the next generation of scientists, engineers, technicians, technologists, and specialists through better education, training and mobility of skills and expertise around Europe. (6)


LEAPS members
Beamline technology
Toolbox for new generation detectors
Industry innovation for optics & detectors
Sample environments
Photon sources
Future compact light sources
New generation accelerators
Toolbox for key machine components
Information technology
Open data management
High-speed data acquisition, visualisation & reduction
Data processing & analysis
Industry & innovation
Building the European innovation workforce
Financial support for effective collaboration
Optimising return on investment
User services & impact
Socio-economic impact mapped
Open access research & user community growth
Single point of information
Education & training
Virtual learning platform
Computing graduate scheme
Career development for facility staff

For further information please
visit the LEAPS website
www.leaps-initiative.eu
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LEAPS League of European Accelerator-based Photon Sources