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Photon Science Community Roadmap 2024

Update of Swiss Community Needs for Research Infrastructures 2029–2032

Swiss Society for Photon Science

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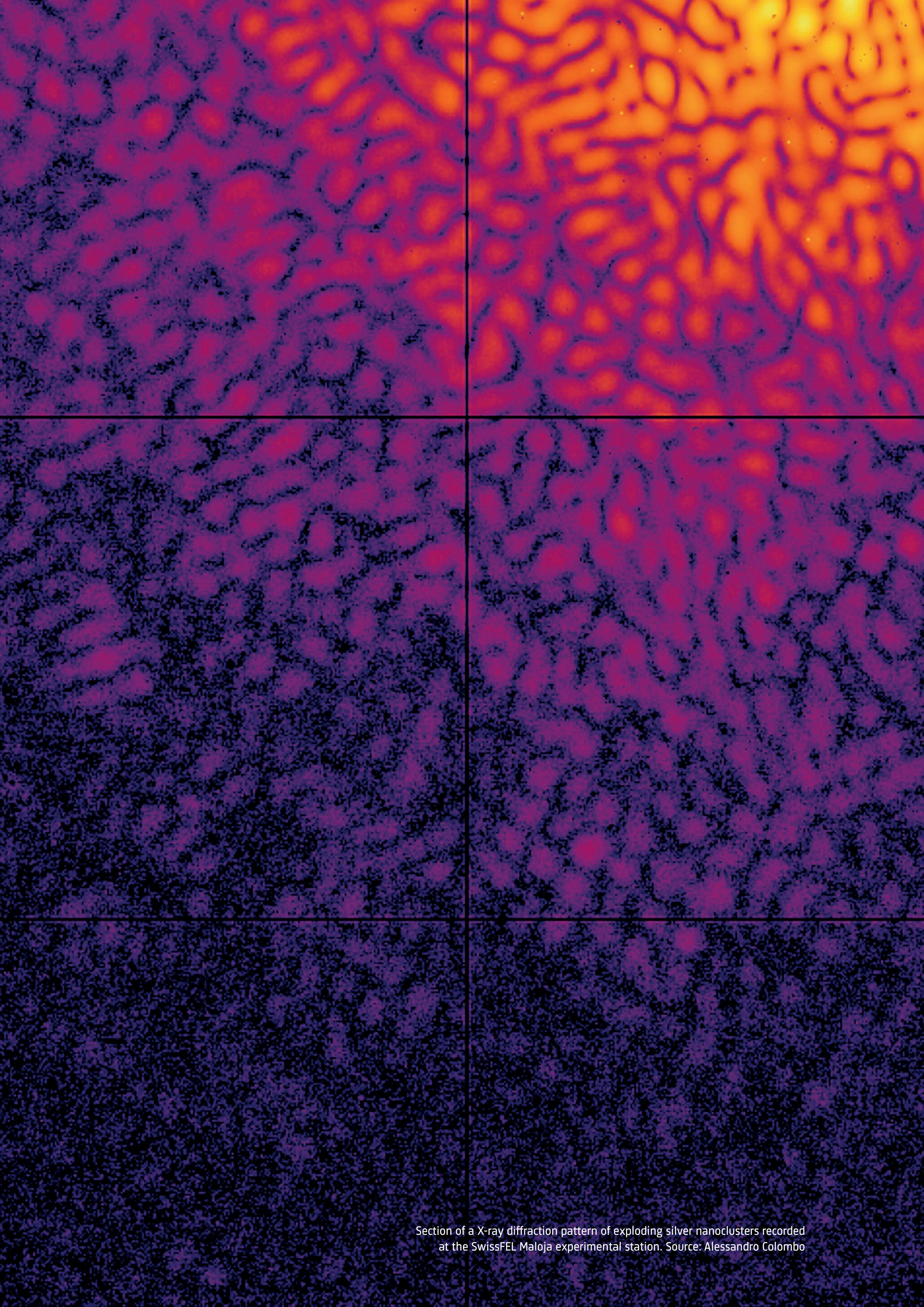
Content

1 Executive summary

Photon science describes the application and development of a range of methods and technologies that produce and use photons for research in a broad spectrum of scientific fields. In the context of this document, photon science refers to research on and with large-scale photon sources, such as synchrotron light sources and free-electron lasers, as well as shared institution-based laser platforms. In Switzerland, the Paul Scherrer Institute (PSI) operates the two large-scale photon sources: the Swiss Light Source (SLS) and the Swiss Free-Electron Laser SwissFEL. Both take internationally leading roles and are heavily used by the Swiss and the international research community. Equally important to the Swiss photon science community is the access to the complementary European Synchrotron Radiation Facility (ESRF) and the European X-ray free-electron laser (EuXFEL). Institution-based shared laser platforms are operational at EPFL, the University of Bern, ETHZ and PSI.

In a consultation of the Swiss photon science community, the authors of this roadmap have identified several findings and recommendations regarding the future research landscape and the needs of the community. The main recommendations are to ensure the international competitiveness of the Swiss infrastructures by upgrading the SLS beamline portfolio to make full use of the capabilities of SLS 2.0, and installing a third undulator line at SwissFEL with concurrent seeding upgrades to the existing lines that provide full control over all relevant pulse parameters for the full available X-ray energy range. Due to the high demand by the Swiss community, it is recommended to maintain support for SLS and SwissFEL as well as the Swiss contributions to ESRF and EuXFEL. In addition, it is recommended to establish a new funding instrument that bridges the financial gap between typical single research group efforts and large-scale facilities. Such an instrument would simplify the establishment of efficient shared laboratories hosted by universities or research institutions and it would also address the demand of the large facilities for smaller upgrades and instrumentation that are typically not covered by the national research infrastructure roadmap process. A general observation is also that data management, i.e. storage, processing, and open access of research data following the FAIR principles, becomes increasingly challenging and needs additional resources.

Photon science operates cross-sectionally across many different research fields, while the development of the underlying technologies and methods represent a research field on its own. Switzerland has traditionally an excellent international standing in photon science. Competitiveness in this rapidly evolving field can only be maintained with strong commitment and support. We are convinced such investments yield massive benefits well beyond the research in this specific domain but also in the broader physics, chemistry, materials, and life science communities which it serves. It should also not be forgotten that the large Swiss photon science facilities are also heavily used by industry and yield direct societal impact, e.g. through essential contributions towards drug discovery.



Section of a X-ray diffraction pattern of exploding silver nanoclusters recorded at the SwissFEL Maloja experimental station. Source: Alessandro Colombo

2 Foreword

This document is an update to the Photon Science Roadmap published in 2021. It presents the needs of the Swiss photon science community in terms of future national and international research infrastructures. Together with similar Community Roadmaps in other disciplines, it is an element of the four-year process leading to the development of the Swiss Roadmap for Research Infrastructures 2027 to be written by the State Secretariat for Education, Research and Innovation (SERI) in view of the ERI Dispatch 2029–2032 to Federal Council. The role for these 'bottom-up' inputs is to serve as an important basis for the strategic planning of the higher education institutions on new or major upgrades to national infrastructures and to inform and support SERI during its decision-making process on Swiss participation in international research infrastructure networks and organisations.

SERI has formally mandated the Swiss Academy of Sciences (SCNAT) to update the seven community roadmaps previously published in the disciplines of biology, chemistry, geosciences, astronomy, particle physics, photon science, and neutron science. SCNAT engaged its network of member societies and commissions to reach out to the scientists willing to get involved. It encouraged diversity of the participating scientists and provided the needed support for the collaborative writing, the layout, the publication and printing of this document.

Close-up of pump beam path of a high-power optical parametric amplifier system.
Source: Pierre-Alexis Chevreuil

3 Introduction

This document provides an update on the infrastructural needs and priorities of the Swiss photon science community for the years 2029–2032. It has been compiled under the leadership of the Swiss Society for Photon Science (SSPh). For this, the SSPh has collected the scientific vision and needs of the community, composed of users of the national institution-based laser platforms, the synchrotron Swiss Light Source (SLS) and the X-ray free-electron laser SwissFEL, as well as Switzerland-based users of the European Synchrotron Radiation Facility (ESRF) and the European X-ray Free-Electron Laser (EuXFEL). This document has undergone an iterative refinement process by circulating drafts and collecting feedback from SSPh members and the broader photon science community.

Photon science in the context of large research infrastructures refers to accelerator based large-scale photon sources, such as synchrotrons and free-electron lasers, as well as to shared laser platforms at research institutions. The research field of photon science is not limited to using these sources; instead, it also drives the development of the next generations of photon-based scientific instrumentation and methods. The development of these research tools enables new types of experiments and insights by pushing the technological boundaries to the benefit of a wide range of scientific disciplines.

Research at large-scale photon sources has a strong interdisciplinary character and addresses a broad range of scientific and societal challenges, spanning key disciplines from medical and life sciences, environmental and material sciences to physics, chemistry and beyond. The sources are used, e.g. for determining the structure of molecules and materials, for high-resolution imaging or for studying complex dynamical processes in matter. These capabilities support developments in key areas such as drug discovery or the search for new materials for energy storage and conversion or for new high-performance electronics for information and communication technology. In addition, this research at large-scale facilities is complemented by major efforts in synthesis, theory and numerical modelling.

Large-scale photon sources also serve as innovation boosters beyond their core purpose since the technical innovations required to realise and continually advance their capabilities bear a large innovation potential for commercial and complementary scientific applications. In addition, large-scale facilities play an important role in conveying the importance of photon science to the public as well as in the training of the next generation of scientists and engineers thanks to the many active research and development programs and diversity of scientific and technological fields.

In the next chapter, we summarise the main findings and recommendations that were obtained in the process of preparing this roadmap update. The background and rationale for the findings and recommendations are presented in more detail in the separate chapters on synchrotrons, XFELs and institution-based laser platforms. For a landscape analysis and a discussion of the broader impact of photon science, the reader is referred to the Photon Science Roadmap 2021. Changes and developments that happened since the last roadmap are specifically highlighted in the present document.

4 Findings and recommendations

All findings and recommendations summarised hereafter are substantiated further in the corresponding chapters. Here, they are grouped in terms of national or international context. Some recommendations relate to what we believe is a gap in the competitive funding landscape, which would help large-scale facilities to develop and use their sources more efficiently and continuously, while facilitating the establishment of complementary smaller-scale shared platforms at the institutions. All recommendations aim to support diverse and scientifically excellent research in photon science within an expanding landscape of large-scale facilities and ever-growing range of scientific use cases.

The main recommendations can be summarised as follows:

- New photon science infrastructure: upgrade of the SLS beamline portfolio to make full use of SLS 2.0 capabilities and installation of third undulator line at SwissFEL that provides full control of pulse parameters in the 2-10 keV photon energy range.

- Funding mechanism for medium-sized instrumentation and infrastructure that enhances impact and flexibility at large-scale facilities and enables smaller-scale shared platforms at the institutions, which support the efficient use of the large-scale photon sources.

- Provide large-scale photon science facilities with funds and support to cope with ever-increasing data management (short- and long-term storage, processing, analysis) requirements and complexity.

- Continued support for SLS and SwissFEL to ensure their long-term competitiveness, acknowledging their important national and international role.

- Continued support for the international European X-ray Free-Electron Laser (EuXFEL) and European Synchrotron Radiation Facility (ESRF), which complement the capabilities of the Swiss sources and are used heavily by the Swiss photon science community.

National context

Photon science at large-scale facilities in Switzerland is performed at the Swiss Light Source synchrotron and the Swiss Free-Electron Laser, both part of the Paul Scherrer Institute. Our findings and recommendations related to the further development and continuous operation of these internationally leading sources are:

1. Continue to develop and upgrade SLS and SwissFEL to keep them at the top level compared to other international facilities.

2. Additional funds are required to ensure that all SLS beamlines can make full use of the upgraded machine capabilities of SLS 2.0.

3. Extend the parameter space of SwissFEL by installing a new undulator branch (Porthos) that enables new classes of experiments by providing full control of pulse parameters (duration, coherence, polarisation, spectral characteristics, phase).

4. With the focus of the Porthos beamline on full pulse control, the demand for higher photon energies at SwissFEL up to 18 keV shall be covered by the Aramis beamline.

5. Seeding strategies shall be pursued at all beamlines to establish SwissFEL as a fully coherent source with the highest level of pulse control from soft to hard X-rays.

6. Data management (processing, analysis, short- and long-term storage) at large-scale research facilities (not limited to photon science) becomes increasingly challenging. Sufficient funding is required to fulfill the needs of the users and improve data accessibility for the research community as a whole.

7. Establish a Center for Operando Synchrotron Studies (COSS) due to the rapidly growing need for in-situ and operando studies in important fields such as energy research, advanced manufacturing, catalysis, biomedical and environmental research.

New funding instrument

A common finding for all types of infrastructure covered in this roadmap is that there is a gap in the funding landscape. We expect that this observation applies to a wide range of disciplines beyond photon science. We propose:

8. Create a new peer-reviewed funding scheme for complex scientific instrumentation and shared technology platforms to bridge the gap between single research group efforts and complex funding for large-scale facilities.

International context

The international ESRF and EuXFEL facilities complement the capabilities of the Swiss photon science infrastructures and beamtime at these sources is in high demand by the Swiss community. Further, SLS and SwissFEL together with ESRF and EuXFEL cover a broad range of techniques and science, but certainly not everything. Thus, it is essential for Swiss researchers to have continued access to international facilities. The current model of international researchers having competitive but free access to Swiss facilities for peer-reviewed research that is published and accessible for the whole community and in turn Swiss researchers having free access to international facilities, not just in Europe but also in Asia and the Americas, is an efficient way to realise this. From this follows our recommendation:

9. Switzerland should maintain its financial contributions to ESRF and EuXFEL.

10. Maintain reciprocity in granting international researchers free access to large-scale facilities.

Links to other roadmaps

The tools provided by photon science are used in a wide range of disciplines. It is therefore not surprising that the needs and recommendations of the photon science community also connect to some of the other roadmaps. In particular, we would like to stress the goal of establishing a Center for Operando Synchrotron Studies that is shared with the Chemistry Community Roadmap but should also be relevant for the fields of biology and life sciences in general. Since the large-scale photon science infrastructures heavily build on accelerator technology, there is also a strong connection to the roadmap for Swiss Accelerator Research and Technology (CHART) which is published at a different time than the seven thematic roadmaps updated now. Common interests lie in the development of new magnet systems for SLS 2.0, the proposed Porthos undulator line of SwissFEL, and the development of a new type of travelling-wave radio-frequency photocathode source. It should be noted that there exist significant synergies between accelerator technologies for large-scale photon sources and other applications of accelerators.

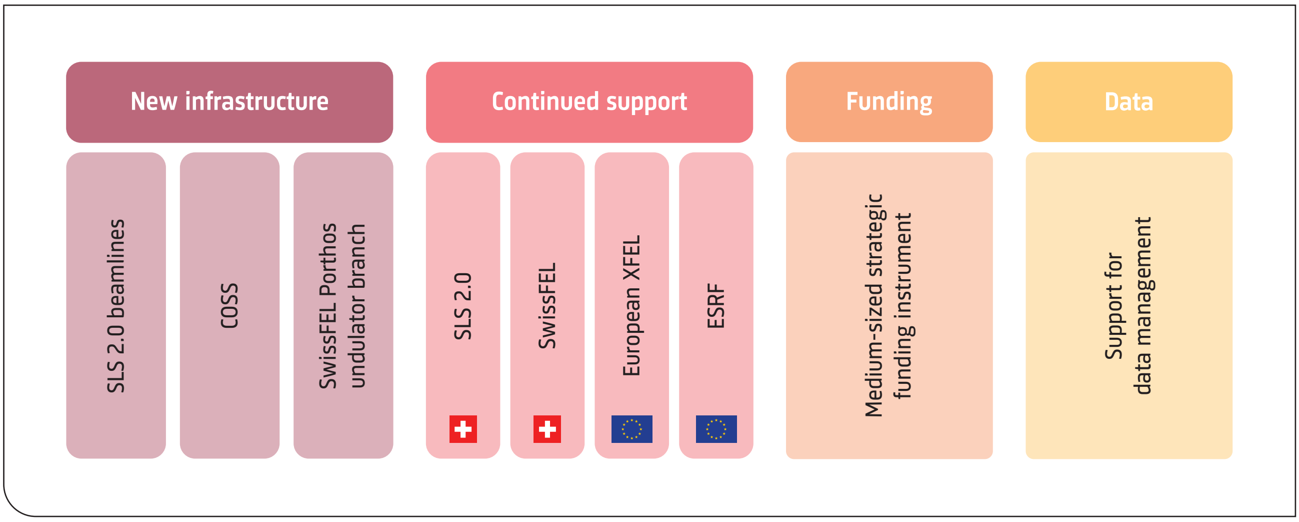


Figure 1: Visualisation of the main needs of the Swiss photon science community.
Details and rationale for the individual items and an explanation of the used acronyms can be found in the text.

View on the upgraded SLS 2.0 storage ring during the installation phase. Source: Paul Scherrer Institute

5 Synchrotrons

5.1 Executive summary

The scientific use of synchrotron radiation remains a corner stone for experimental techniques applied in a broad field of research covering biology, chemistry, geology, physics and is even significantly used by industry. The evaluation of the field and all the recommendations presented in the extended Photon Science Roadmap 2021 in the synchrotron chapter remain fully valid. However, there have been two points that have significantly changed in Switzerland in the last four years, which is of utmost concern to the community. Firstly, the operational costs for the Swiss Light Source (SLS) at PSI outgrew the available budget, leading to significant pressure on running the facility. This resulted in an employment stop, and an effective reduction of manpower available for running the beamlines with strong negative long/middle term impact on the science. In addition, there is clearly insufficient financing available to complete the upgrade program for finishing all beamlines. Secondly, the amount of data (with the SLS upgrade) is exponentially increasing, and will go beyond what the facility or the users can handle with the currently available resources. There is clear need for action.

5.2 Findings and recommendations

SLS

Finding: The SLS is essential for the Swiss and international community. It is recognised worldwide as a facility offering services of high quality with a significant impact on a broad range of research fields, including important branches of industry. The SLS is currently being upgraded to maintain its standing as a leading provider of highly stable photon beams and outstanding instrumentation. It is also of high importance that all the beamlines can benefit from the new source characteristics, and that there are sufficient funds available to modify the beamlines and experimental tools accordingly, which is currently not the case. It is mandatory to realise that this not finished when the SLS 2.0 upgrade project is ending but that a continuous effort is needed to keep the instrumentation on a competitive level.

Recommendation: The SLS should be kept at the top level in comparison to other synchrotron facilities worldwide. Additional funds should be made available to guarantee that the whole SLS beamline portfolio remains competitive and benefits fully from the SLS 2.0 machine upgrade.

ESRF

Finding: The European Synchrotron Radiation Facility remains a very important complementary tool for the Swiss user community, in particular as it offers higher X-ray energies and a broad variety of different experimental techniques compared to the SLS. The allocated beamtime is commensurate with the Swiss financial contribution.

Recommendation: Maintain the contribution to the ESRF facility.

Data management

Finding: Data handling is an important issue in the context of large-scale facilities as they generate enormous amounts of data which is further increasing with the upgrade to SLS 2.0. This involves a series of challenges and topics, from (common) data formats to open accessibility of data (FAIR data) and codes and scripts for data reduction and treatments. Data taken on federal funding must be made available to the public for a prolonged period of time. To this end, the necessary storage capacity and funding thereof must be provided. Furthermore, it is more efficient if the institutions operating the facilities that produce the data also take care of the data management, rather than each user group at university level implementing individual solutions. Therefore, the Petabyte Archive has been established at the Swiss National Supercomputing Center (CSCS) by CSCS and PSI. In addition, PSI established the data catalogue SciCat in a European collaboration. Furthermore, there is a strong need to develop data-driven methods for beamline operation, and smart data reduction methods to make data management more efficient. The opportunities opened up with SLS 2.0 need to be accompanied with additional beamline data scientists, computing power and data analysis tools to reach a broad user community. The use of AI tools like machine-learning based data reduction and analysis could be initiated in collaborative projects with the Swiss Data Science Center (SDSC) and then further developed together with the experimental methods by the beamline scientific staff.

Recommendation: Ensure that the SLS gets sufficient funds and support to cope with this foreseen dramatic increase in data-management complexity and storage capabilities. It is important to fund beamline data science staff for creating tools to bridge the gap between data processing and analysis for the user community. In addition, regulations imposed by funding bodies, such as open access, should go hand in hand with additional funds for the facilities for realizing them and should provide a real practical benefit to the research community.

Strategic funding instrument

Finding: Swiss synchrotron beamlines enable unique scientific experiments that are unattainable elsewhere, employing innovative methods and state-of-the-art instrumentation. This capability allows Swiss researchers to assume a leading role on the international stage. To preserve Switzerland's preeminent standing at the forefront of scientific research, strategic refurbishments and enhancements of beamline instrumentation are crucial.

Recommendation: Establish a dedicated funding mechanism for small to medium-sized scientific instrumentation projects to support a collaborative, science-driven program for synchrotron beamline upgrades.

Center for Operando Synchrotron Studies (COSS)

Finding: The upgrades of both synchrotron facilities with Swiss participation (SLS and ESRF) entail ever increasing complexity in experimental capabilities as well as data structure and data volume for in-situ and operando studies, which is a very important and active development in many research fields. The Center for Operando Synchrotron Studies (COSS), as proposed by the Chemistry CommunityRoadmap, is envisioned to help mature the most widely used operando synchrotron techniques (XAS, XRD, total scattering) for the specific chemistry and catalysis community needs and further push automation and standardisation of both measurements and high-level data analysis. Existing tools can be homogenised, extended with AI and made available to the community. This development step will be planned together with the SDSC and facilities.

Recommendation: COSS aims at supporting optimal operation of Swiss large-scale facilities and creating streamlined and automated data processing infrastructure for the specific needs of the in-situ and operando community. COSS will contribute to the automation of workflows and shares them with the community, to the use of FAIR data principles, data infrastructure, and the training of young researchers. We support the creation of the Center for Operando Synchrotron studies (COSS) for a close collaboration of the community, the SDSC, and the facilities as proposed by the Chemistry Roadmap.

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5.4 Update on existing infrastructure

SLS 2.0 upgrade status

The original Swiss Light Source (SLS) delivered its last photon on 30th September 2023 at 08:00 am. Within 30 minutes of this momentous milestone, the first of the concrete roof shieldings was being lifted away. The entire storage ring (but not the booster, which is being re-used for SLS 2.0) had been removed by late November 2023.

Installation of the new ring is now approaching completion. At the time of writing (23.9.2024) all but one of the 12 arcs have been installed, with the last planned for mid-October. All the planned storage-ring components plus the X-ray sources and front ends required to commission the first phase of beamlines will be in place and the concrete roof shielding remounted by the end of this year, allowing commissioning of the storage ring to commence in January 2025.

The 7-bend achromat arcs that include additional subtle features called 'reverse bends', will result in a reduction in the beam emittance in the horizontal plane (that is, the product of the electron-beam divergence and its cross-section) from 5500 pm·rad to 157 pm·rad. Moreover, implementation of novel insertion-device and X-ray optics developments means that the brilliance of SLS 2.0 will increase at some beamlines by a factor of more than 1000.

The upgrade program has also provided the opportunity to upgrade beamlines and build new ones. Even before the shutdown of the original SLS, an entirely new beamline, 'Debye', was constructed. This is a hard X-ray spectroscopy and scattering beamline for the chemical and materials research community; it is the sister beamline to the already existing SuperXAS beamline. Debye will be served from Spring 2026 by a 3.5 – 5-T superconducting superbend, allowing access to photon energies as high as 60 keV. Furthermore, the PX III beamline was also entirely rebuilt and improved before the shutdown. It was already taking regular users in the weeks before the shutdown.

Another entirely new beamline presently under construction is I-TOMCAT, a beamline conceived to capitalise on the established expertise in multiscale, multimodal dynamic tomographic microscopy. I-TOMCAT will obtain its radiation from a completely novel, ultra-short-period (10.5 mm) high-temperature superconducting undulator, planned to be installed in Spring 2026, which will allow users to access photon energies as high as approximately 60 keV. In the interim, a 1 m U15 type undulator will be installed, thus enabling early commissioning of this beamline beginning in mid 2025. Its sister beamline, S-TOMCAT, is an upgrade of the existing TOMCAT beamline and will provide photon energies up to about 80 keV using the same type of superbend as that for Debye.

Several other beamlines are undergoing significant upgrades – the microXAS beamline will be built anew at a new location to take most advantage of the storage-ring characteristics. The three hard X-ray beamlines of PX I, PX II, and cSAXS also undergo comprehensive upgrades of their sources, optics and endstations. All of these will benefit enormously from the enhanced emittance; PX I and PX II because of the new capability of having both micron-sized X-ray beam spot sizes and low beam diver-

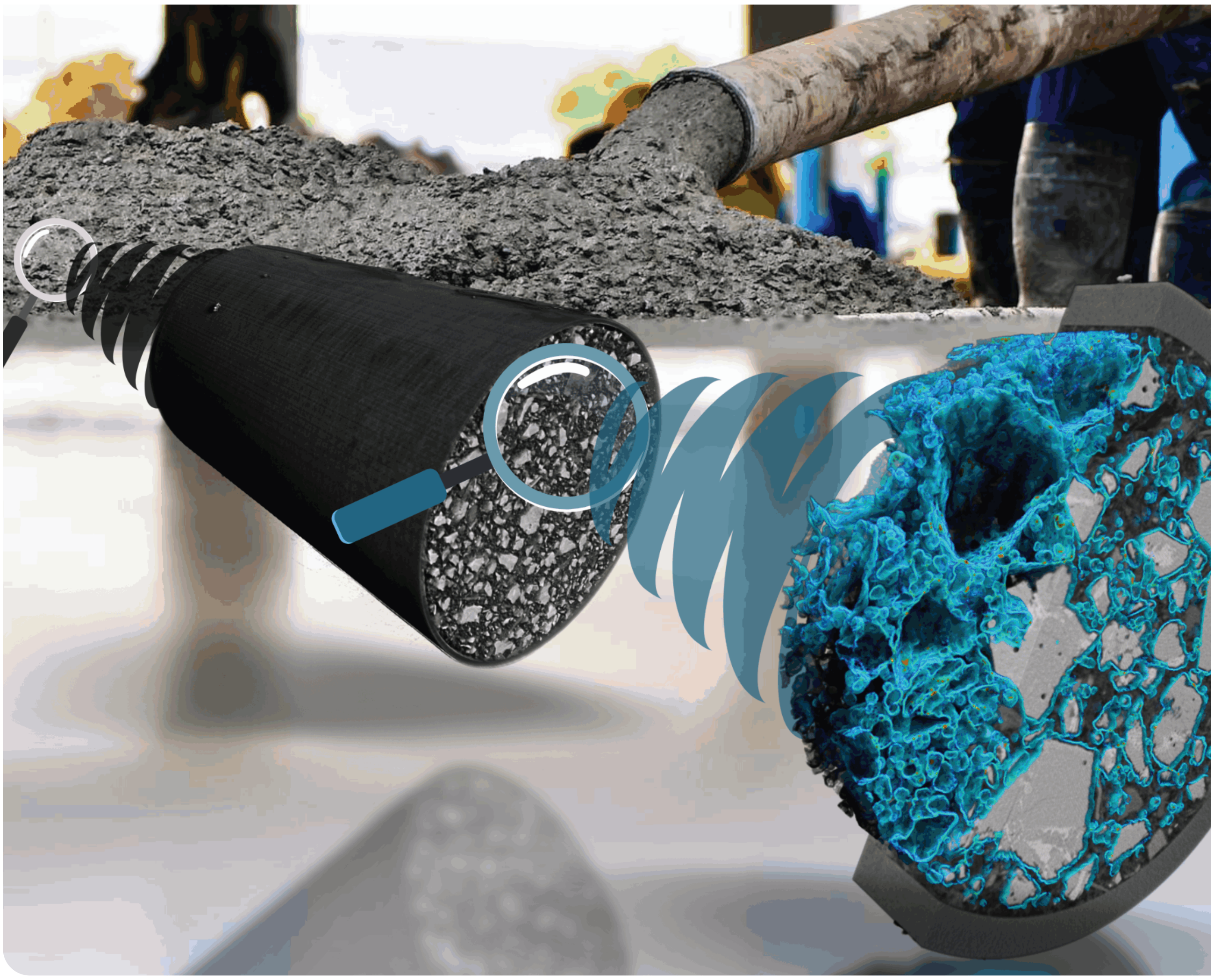

Figure 2: Artistic view of early cement hydration on the micro- and nano-scale. The underlying data was obtained using complementary experimental techniques at the ESRF and SLS. Source: Shiva Shirani, Graphic design: Maziar Moussavi

gence; and cSAXS because of the large increase in coherent fraction and flux.

Commissioning of the storage ring should begin in early January 2025, permitting beamline commissioning of the twelve so-called ‘Phase-1’ beamlines beginning next summer, shortly followed by an expert pilot-user program, which will include external research groups. It is planned that these Phase-1 beamlines will begin to broaden their user access towards the end of 2025 and start regular user operation after the second shutdown. This is required for installation of the Phase-2 beamlines and their sources and is planned for the first three months of 2026.

A second phase of beamline commissioning will thus begin in Spring 2026. It is envisaged that, apart from one or two beamlines that require an extended insertion-device development phase, regular user operation for most other beamlines will start in the second semester of 2026. It is thus planned to announce the first call for regular user operation at SLS 2.0 in February 2026.

To fully realise the potential of SLS 2.0 and secure its future as a global leader in synchrotron science, plans are already under development to continue advancing beamline construction and upgrades beyond mid-2026. However, funding is currently not secured for the beamline Quest (formerly, SIS and PEARL) for enhancing quantum materials research by nano-ARPES, for parts of the upgrade of ADRESS (for high resolution RIXS) and for the beamline microXAS (for chemistry and material science). These cases highlight the pressing need for a new strategic funding instrument as recommended by this Roadmap. Such funding instrument can provide the flexibility to dynamically address evolving technological needs and unforeseen challenges, delivering new tools and benefits to the research community in a timely manner while ensuring Switzerland’s ability to maintain leadership in synchrotron science and innovation.

ESRF

The ESRF is currently supported by 20 countries, consisting of 13 Members and 7 Scientific Associates. It has a capacity of 51 beamlines, including 37 ESRF beamlines and 14 Collaborating Research Groups (CRG) beamlines, as well as two cryogenic electron microscopes (cryo-EM) (1 ESRF, 1 CRG).

In Phase I of the ESRF upgrade program (2009–2015), 15 new beamlines were constructed, and four beamlines were deeply refurbished. Phase II of the ESRF upgrade program (2015–2023) included the construction of a new X-ray source (EBS), the refurbishment and upgrade of existing beamlines, and the construction of four brand new flagship beamlines:

– EBSL1-ID18 (Coherent X-rays dynamics and imaging)

– EBSL2-ID03 (Dark field X-ray microscopy)

– EBSL3-BM18 (High-throughput large-field phase-contrast tomography)

– EBSL8-ID29 (Serial macromolecular crystallography)

Additionally, the program involved the reconstruction of two beamlines (ID14 and ID27) and the deep refurbishment of another four beamlines (ID21, ID24, ID26 and BM23).

Currently, the ESRF operates the equivalent of 32.5 X-ray beamlines and one cryo-electron microscope (cryo-EM), which is operated jointly with the Institut de Biologie Structurale (IBS) and the European Molecular Biology Laboratory (EMBL). The equivalent of 12 CRG beamlines using bending magnet (BM) sources, and one cryo-EM, are operated by the various member states of the ESRF.

Due to various contingent reasons, user operation of the biomedical beamline ID17 was halted, and the EBSL1-ID18 (Coherent X-rays dynamics and imaging) project was put on hold in 2023. Moreover, projects in the Accelerator & Source Division (installation of a 4th harmonic cavity and the injector upgrade) and Technical Infrastructure Division (construction of the data centre and the procurement of hardware for large data management) had to be delayed.

Switzerland contributes 4% of the ESRF running costs and, together with Norway, operates the Swiss Norwegian Beamlines (SNBL) at ESRF (on ports BM01 and BM31), with Switzerland contributing 50% of the running costs. Swiss scientists have had access to ESRF beamlines roughly proportional to Switzerland’s financial contribution.

In 2018, ESRF and PSI established a collaboration agreement to transfer ESRF’s commercial access clients to the SLS at PSI under the same financial conditions during the ESRF-EBS closure. This concept is now applied for PSI-SLS clients during their upgrade closure from September 2023 to July 2025, with a further closure from January 2026 to May 2026. Since October 2023, ESRF has welcomed commercial clients on beamlines offering macromolecular crystallography, X-ray powder diffraction, and X-ray tomography services. An increase in requested and allocated shifts in ESRF’s public user program has been observed, exceeding the nominal share for Switzerland.

5.5 Future needs

Let us first state that the needs expressed in the Photon Science Roadmap 2021 remain all valid. Here, we concentrate on those related to the findings.

The central role is taken by the SLS located at PSI. The SLS is currently being upgraded as a fourth-generation synchrotron with 17 independent beamlines in parallel user operation, with many beamlines having several experimental stations. Most beamlines and experimental stations are directly accessible for Swiss and international users through the peer-reviewed proposal system. There is additional significant use from industry (~10%). The SLS produced in the past and recent years a steady number of publications of approximately six hundred per year.

The current upgrade of the SLS, called SLS 2.0, will result in a diffraction-limited light source, which will provide beams of much higher brightness and coherence. The major costs will come from the rebuilding of the storage ring and many of the undulators to provide the beam. Unfortunately, there are insufficient funds for upgrading all beamlines and building some new key beamlines that optimally use the new beam characteristics (see examples given in the section on SLS 2.0 upgrade status). Therefore, not all beamlines will benefit from the new light-source characteristics.

It is planned to invest in the following years regularly in future optimisation of those beamlines not having benefitted optimally from the upgrade, but funds and manpower will be limited without further strengthening the activities. It will therefore be important to have sufficient/additional funds available for the regular refurbishment program for the beamline portfolio, which necessitates the proposed new infrastructure funding scheme for intermediate-sized projects.

In addition to the SLS, the ESRF remains a very important source for the community and is widely used over different scientific fields, mainly in the fields of material science, biology, chemistry, and physics, with smaller use in several other fields. The Swiss fraction of 4% is very well used and it remains of great importance to the different communities. Note that also other national synchrotron radiation sources within Europe have dedicated users from Switzerland and to a smaller degree this is also valid for the synchrotrons in the USA and Asia.

Data treatment and storage are significant developing challenges. Sufficient resources must be available to the facilities to keep pace with the demands in data management that increased over the past decade significantly faster than capabilities of IT hardware improved ('beyond Moore's law'). Complex data treatment and analysis require computational tools, and method experts will be crucial for enabling the opportunities offered by the upgraded large-scale facilities to reach the broad scientific community.

View along the SwissFEL linear accelerator. Source: Christoph Bostedt (PSI)

6 Free-Electron Lasers

6.1 Executive summary

SwissFEL is still a young and growing facility that has already firmly established itself as a leading X-ray laser on the international XFEL landscape. The flexible accelerator design has allowed novel beam modes including intense attosecond pulses across the full available X-ray spectrum and innovative external seeding schemes in the soft X-ray regime. Concurrently, the user demands have evolved towards enhanced control over the X-ray pulse characteristics including full temporal coherence and phase, duration, spectral content, and polarisation state.

The highest long-term priority remains a third undulator line, Porthos, which is crucial to address oversubscription and essential for responsible utilisation of existing investments in accelerator and building infrastructure. The focus of Porthos has evolved towards the highest level of X-ray pulse control in the tender to hard X-ray regime. On the short- to mid-term, smaller-scale upgrades for the accelerator, undulator, and experimental systems are fundamentally important for SwissFEL to maintain its competitive edge in a globally very dynamic research environment.

6.2 Findings and recommendations

The following findings and recommendations are updates to the corresponding items in the Photon Science Roadmap 2021.

Finding 1 (update): SwissFEL continues to produce high-impact science. SwissFEL remains on a growth trajectory in terms of both experimental capabilities and capacity.

Finding 2 (update): SwissFEL is amongst several leading facilities that deliver tailor-made, user-specified pulses. SwissFEL delivers attosecond pulses across the full energy spectrum. First external laser seeding and X-ray pulse shaping have been demonstrated in the soft X-ray regime.

Finding 3 (update): User demand and community preference have evolved towards enhanced control over the X-ray pulse characteristics including full temporal coherence and phase, duration, spectral content, and polarisation state. Higher photon energies beyond 18 keV are considered less important in view of the international XFEL landscape.

Finding 4 (with addendum): Technological advances enhance the existing infrastructure beyond their initial design envelope. At the same time, they bring new challenges, in particular with respect to data acquisition, storage, management and curation.
Addendum: There is a lack of mid-size funding for critical upgrade and R&D projects to remain internationally competitive, specifically for the electron injector and accelerator, timing and synchronisation systems, seeding schemes, undulator technologies and endstations.

Finding 5 (without change): There exists a strong demand for XFEL beamtime that can currently not be satisfied. Beamtime at SwissFEL is heavily overbooked and the European XFEL in Hamburg is used extensively by the Swiss community.

Recommendation 1 (update): The expansion of SwissFEL with the installation of the third undulator line, Porthos, continues to be strongly supported. The expansion is crucial to address oversubscription and essential for responsible utilisation of existing investments in accelerator and building infrastructure.
The focus for the Porthos project should be full X-ray pulse control from approx. 2 to 10 keV. Higher photon energies up to 18 keV should be accommodated by Aramis. A full program in external seeding at Athos and self-seeding at Aramis should proceed in parallel with the Porthos project, to establish SwissFEL as a fully coherent source with the highest level of pulse control from the soft to hard X-ray regime.

Recommendation 2 (no change): The collaboration within the 'Swiss Acceleration Research and Technology' (CHART) initiative is crucial and should be further intensified.

Recommendation 3 (no change): Switzerland should maintain its EuXFEL participation.

Recommendation 4 (no change): The involvement in initiatives developing data management and analysis tools as well as machine-learning approaches at the national and European level should be further strengthened.

Recommendation 5 (new): A funding instrument for timely small-to-medium sized instrumentation (electron injector and accelerator, timing and synchronisation systems, seeding schemes, undulator technologies, and endstations) should be established.

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6.4 Update on existing infrastructure

Since the publication of the Photon Science Roadmap 2021, SwissFEL has continued to mature, with parallel increases in scientific productivity and corresponding technological advances. User operation has commenced at the Athos soft X-ray branch and new experimental endstations have been established on a nearly annual basis: first the Maloja endstation for atomic, molecular and non-linear X-ray sciences, followed by the Furka endstation for condensed-matter and materials sciences at the Athos soft X-ray branch, and most recently the Cristallina-MX endstation for fixed-target protein crystallography at the Aramis hard X-ray branch. Currently, the Cristallina-Q endstation for quantum science had its first open call for ultra-low temperature scattering experiments, thus completing the current suite of instruments.

Concurrent with facility developments, the experimental program has also been greatly expanded. Here, SwissFEL has benefited from its initial design permitting acceleration and conditioning of two independent electron bunches to drive both soft and hard X-ray undulator lines at the full repetition rate of 100 Hz. Importantly, this concept can be expanded to accommodate three undulator lines in the future to include Porthos.

With many operational advances and inherent flexibility, a broad range of X-ray beam parameters can be realised simultaneously on both the soft and hard X-ray branch, allowing for very efficient operation of the facility greatly benefitting the scientific program. The user operations have constantly expanded and to date SwissFEL serves a diverse community in the biological, chemical, physical, and materials sciences with a strong Swiss user base. It is noteworthy that in particular the biological research community is very active across all three hard X-ray instruments, including the new Cristallina-MX endstation for fixed target and high throughput serial femtosecond crystallography experiments, that also results in a large number of high-impact publications. At the same time, advances in core photon science regularly feed into developments across disciplines, underlining the need to serve a broad community in the rapidly developing field of ultrafast X-ray sciences.

All these factors have contributed to a rapidly increasing number of beamtime proposals for SwissFEL in parallel to the facility expansion. SwissFEL is heavily oversubscribed and cannot satisfy the demand of the Swiss and international research community.

On the X-ray pulse generation side, SwissFEL has made rapid progress in delivering attosecond pulses, which are now available across the entire X-ray spectral range of the facility. Short wavelength, attosecond pulses – with fundamental importance recognised by the 2023 Nobel Prize in Physics – will allow damage-free X-ray experiments with implications in biology, new measures of quantum states, or the observation of chemical reactions on the natural time scale of electron motion. SwissFEL scientists have made further strides in controlling the X-ray generation process with a seed from an external laser in the Athos soft X-ray branch. While this approach is well established at longer wavelengths, SwissFEL has taken a worldwide leading role in transferring the external seeding technology into the soft X-ray spectral wavelength. External seeding of SwissFEL is an important breakthrough towards a fully coherent, i.e. transversally and longitudinally coherent, X-ray laser source with the potential to also deliver phase-locked attosecond pulse trains. The third soft X-ray endstation on the Athos line, Diavolezza, is currently under construction. The endstation will be used to characterise the developing novel X-ray laser emission modes and will offer users unique instrumentation and dedicated diagnostics to take advantage of attosecond and fully coherent X-rays.

The development of new X-ray lasing parameters is closely coupled to progress in accelerator developments. The accelerator technology competences established for the SwissFEL construction now create a new path of synergies between photon science and particle physics. As one of the key activities of the CHART collaboration for accelerator research in Switzerland the PSI accelerator team designs the injector chain for the future CERN FCC-ee collider and prepares crucial hardware demonstrators for the related electron and positron sources. In return the related research infrastructure established for these activities at PSI helps the preparation of Porthos. For example, the electron extraction line for the P3 experiment is designed for later use as an electron beamline for the future Porthos undulator. The P3 experiment aims to demonstrate a novel source for the efficient production of high intensity posi-

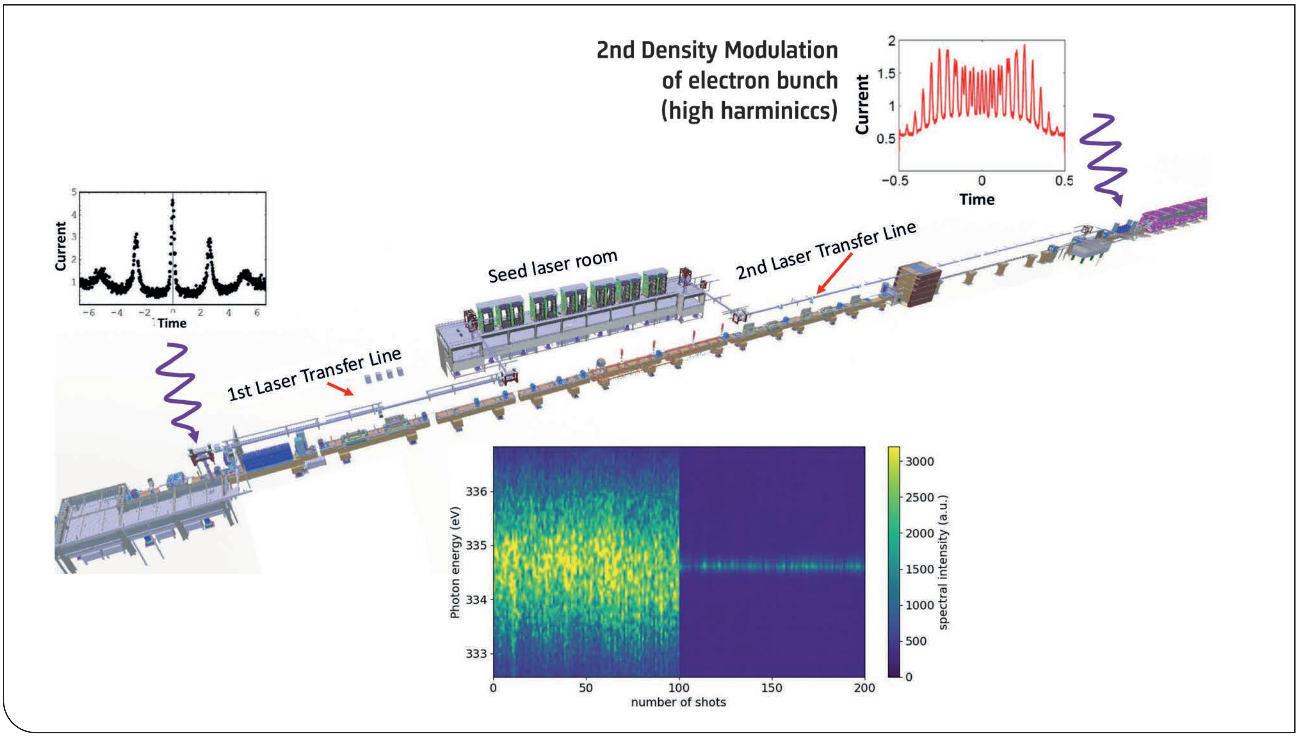


Figure 3: Schematic of the seeding scheme for Echo Enabled Harmonic Generation at the SwissFEL Athos branch. A first optical laser pulse modulates the electron bunch electron density distribution and the beam passes through a chicane. After a second laser pulse modulation and a second chicane, a high harmonic density modulation is achieved in the relativistic electron beam that produces transversally and longitudinally coherent X-ray pulses. The impact on the pulse spectrum is shown in the inset in the lower right corner: Upon seeding, the noisy and broad-bandwidth SASE beam is converted into a fully coherent, narrow-bandwidth beam with stable central photon energy. Source: Romain Ganter, Sven Reiche, Thomas Schietinger (PSI)

tron beams for FCC-ee using the 6 GeV electron beam of SwissFEL. It will be performed in 2026–2027, well before the start of Porthos construction. A new test bench for the FCC-ee electron source demonstrator will also be used for a next generation SwissFEL photo-cathode gun. The latter is an essential ingredient for a comprehensive SwissFEL injector upgrade to meet the challenging electron beam quality demands of Porthos.

On the international landscape, SwissFEL has quickly established itself as an innovative and productive scientific facility. From a technological point of view, SwissFEL is most comparable with the other two 'warm' accelerator facilities SACLA in Japan and PAL in South Korea, with whom there is extensive collaboration on coherent pulse generation. The other two X-ray laser facilities, European XFEL in Germany and LCLS-II in the U.S.A., are based on superconducting ('cold') accelerator technology with a focus on high-repetition rate operation.

The European XFEL pursues a clear hard X-ray strategy towards photon energies far beyond 20 keV that is well suited to the driving accelerator at the facility, which can reach 17.5 GeV of electron beam energy (in comparison, SwissFEL operates at 6 GeV electron beam energy). The European XFEL continues to be heavily used by the Swiss research community: 4% of all experiments in the 2020-2023 period were led by Swiss PIs, thus fully justifying Switzerland's share of 1.5% of the European XFEL. Collaborative ties between Switzerland and the European XFEL have tightened with Prof. Thomas Feurer, the previous president of the Swiss Society for Photon Science, having become their new managing director.

Across the Atlantic, the Linac Coherent Light Source has finished its first upgrade towards a superconducting accelerator (LCLS-II) with 4 GeV beam energy and the aim to reach 1 MHz repetition rate. Continuing upgrade plans exist towards 8 GeV (LCLS-II-HE) and beyond, also pointing to a focus towards hard X-ray sciences. In China, the SHINE project is underway to build the third superconducting hard X-ray laser with a beam energy of 8 GeV and an anticipated photon energy range from 0.25–25 keV. Here the civil infrastructure has been finished and the installation of the accelerator is underway. Additional XFEL projects in China are on the drawing board. In conclusion, the area of XFEL research remains a very dynamic field with currently particularly heavy investments in the USA and China.

A common challenge for all XFEL facilities remains data management, especially as a major cost driver for operations. The sheer amount of raw data, at SwissFEL up to 1 PB per week, requires a combination of revisiting data policies and technical innovation. At SwissFEL, and in close collaboration with the SLS community that will face similar challenges in data management after the SLS 2.0 upgrade, as well as the detector group, leading edge computing technologies for data reduction within the data pipeline are under development. A joint program with the Swiss Data Science Center has been launched to pursue opportunities drawn from machine learning and artificial intelligence for data reduction.

While SwissFEL is currently highly competitive and has proven to exceed its original design parameters, other facilities and countries are investing heavily in their own infrastructure. There is a clear need for SwissFEL to make small and mid-sized upgrades to support newly developing capabilities. SwissFEL has rapidly established itself in the area of attosecond X-ray pulse generation and external laser seeding for fully coherent X-ray pulses and pulse trains. The mandated delay in the Porthos project and cut of the Porthos pre-project, as well as the current employment stop already mentioned in Chap. 5.1 which results in minimal staffing of the existing beamlines, introduces a critical gap in the facility development that can jeopardise the leading position that SwissFEL has achieved over the past years. To remain internationally competitive further upgrades to the SwissFEL injector and accelerator, timing and synchronisation system, seeding schemes, as well as undulator technologies are of critical importance.

6.5 Future needs

The expansion of SwissFEL with the construction and implementation of Porthos, the third undulator line, remains paramount in this updated version of the Photon Science Roadmap. To be consistent with rapid developments made at SwissFEL in XFEL technology, attosecond pulse generation and external laser seeding, and with developments in a rapidly growing international community, Porthos should have a clear focus on full coherence, spectral temporal control, and polarisation. Capabilities pioneered at Athos in the soft X-ray regime should be extended into the tender and hard X-ray regime at the new undulator line. Seeding capabilities that stabilise the central X-ray frequency, increase coherence, and reduce the bandwidth should be implemented across the whole energy spectrum and at all branch lines of SwissFEL. Higher photon energies exceeding 12 keV should be delivered through upgrades at Aramis. For even higher photon energies exceeding 18 keV as originally considered in the Photon Science Roadmap 2021, collaborative access should be considered at European XFEL.

Fully coherent X-ray pulses – with optical laser-like temporal coherence and tunable bandwidth – are expected to revolutionise X-ray spectroscopy and cement the new field of nonlinear X-ray science in the research landscape. This transformative step would be comparable to that achieved in optical spectroscopy with the advent of the optical laser, or in microwave technologies where arbitrary waveforms can be programmed. Broadband attosecond X-ray pulses, shorter than the Auger-Meitner lifetime promise to lead to breakthroughs in non-linear X-ray spectroscopy, including electronic Raman and wave mixing approaches. On the other hand, fully coherent narrowband X-ray pulses will dramatically increase the efficiency of high-resolution X-ray spectroscopy and obviate the need for complex monochromators and X-ray optics. Full control over the X-ray pulse duration and longitudinal phase will also allow relevant dynamics within the respective time-bandwidth limit to be measured with the maximum efficiency, and even via interferometric techniques. Sequences of phase-coherent pulses will open the way for time-domain interferometry of materials, such as the X-ray analogue of Fourier transform infrared spectroscopy and resonant inelastic X-ray scattering, as well as X-ray quantum optics experiments, such as coherent control and readout of prepared states in gases and solids. Optical pump/X-ray probe experiments will naturally remain an important part of the portfolio, and they will benefit from improved source stability for controlled experiments. These experimental breakthroughs will help SwissFEL to maintain a competitive edge, despite its lower repetition rate in comparison with the superconducting facilities.

Access to the polarisation state in the tender to hard X-ray regime will enable the study of molecular transformations that drive ultrafast chirality dynamics in photoexcited biological and chemical processes and energy relevant materials. For example, fully coherent and polarisation-controlled X-ray pulses from the soft to hard X-ray regime promise to deliver unprecedented, site-specific insights into the chiral excited state dynamics and ultrafast polarisation-resolved structural dynamics of molecules. Such experiments could elucidate key mechanistic steps for driving enantioselective catalysis for production of pharmaceuticals. In this context, SwissFEL's tender X-ray capabilities promise to deliver unique local structural information via biologically relevant elements in common amino acids and ligands, such as phosphorus and sulfur. On the other hand, resolving symmetry-breaking in the excited state of emerging solution-processable semiconductors, like chiral or magnetically-doped halide perovskites, semiconductor nanocrystals or polymers, will be

FIgure 4: View along the SwissFEL Aramis and Athos branches towards the switchyard. Source: Mario Sauppe

essential for controlling spin and light polarisation towards future applications ranging from holography to biomedical imaging, and spin-photonic interfaces for quantum information technologies. In atmospheric chemistry, gas-particle reactions at the surface of aerosol particles can exhibit a unique reactivity whose origin is still largely unknown. Light in the tender X-ray regime would provide new insight into the dynamics of such reactions for a number of elements commonly found in aerosol particles (e.g. calcium, sulfur and various transition metals). Paired with coherent imaging using sub-nanometer wavelength light, we would gain insights into reaction systems and structural properties that are otherwise difficult to access.

The capability of X-rays to target individual atomic sites and specific elements (based on core-levels) will be extended to the time domain with pump-probe approaches using the two-color XFEL emission modes that have now been demonstrated on the soft X-ray Athos line. With a pair of X-ray pulses spanning a wide range of photon energies, the first pulse is used to induce a highly localised excitation and the evolution of the system is subsequently probed using the following X-ray pulse with photon energy tuned to probe a secondary location in the system. High time resolution is ensured in this scheme, as both X-ray pulses are generated from the same driving electron bunch. Such pump-probe schemes will be able to follow charge- and energy-transfer mechanisms between specific sites in molecules and materials on electronic time and atomic length scales. Circularly polarised pulses will offer the additional opportunity to locally induce chirality on sub-femtosecond time scales and to study the electronic and structural dynamics induced by such a transformation. They will also enable the creation of photoelectron vortices emitted from selected sites that can be used as an exceptionally chiral-sensitive probe of their dynamically evolving environment.

In materials research, full coherence of femtosecond X-ray pulses at tender to hard X-ray energies offers unique possibilities to study the dynamics of both coherent and incoherent vibrational excitations in nonequilibrium materials across a more complete range of energy and momentum than is currently available, by using Fourier-transform limited pulses to perform time-dependent X-ray scattering. Strengthening the tender and hard X-ray capabilities

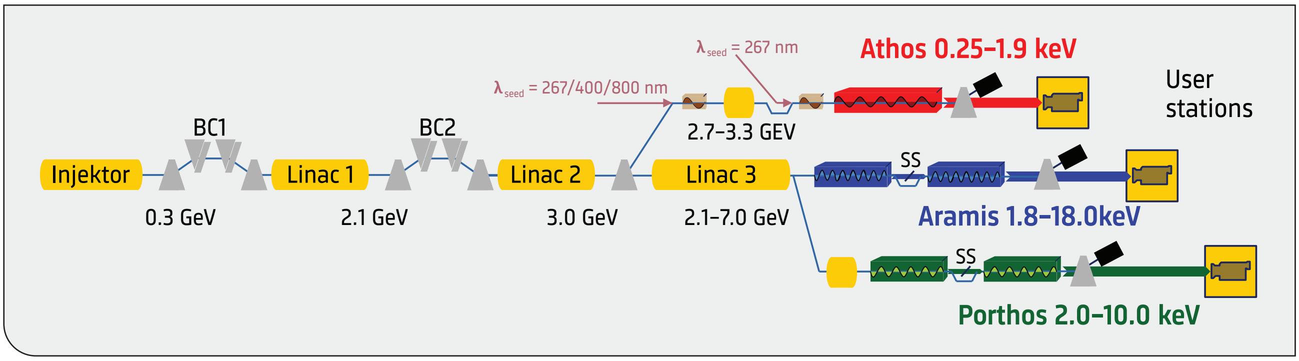


Figure 5: Layout of the envisioned SwissFEL facility including the new Porthos undulator line, an energy upgrade for Aramis, and self-seeding options for both. Athos will be externally seeded. With these upgrades, SwissFEL will remain internationally competitive as a fully coherent source with the highest level of pulse control from the soft to hard X-ray regime. Source: Thomas Schietinger, Christoph Bostedt (PSI)

provides further opportunities in spectroscopy and resonant scattering with access to L- and M-edges of a wide range of compounds, allowing to investigate the ultrafast dynamics of Iridates, Ruthenates, Lanthanides, and Actinides as well as van der Waals materials made of heavy atoms like WSe2 and MoS2, which are highly relevant for the condensed matter community. Novel opportunities also arise for condensed matter systems from the potential of nonlinear processes for enhancing sensitivity to low-probability scattering channels. In addition, full polarisation control of X-rays in this range offers direct ways to probe the nonequilibrium dynamics of chiral excitations in materials, which can serve as reservoirs of angular momentum relevant for magnetic control. An upgrade of the X-ray capabilities in this direction would also enable complementary studies of the magnetic dynamics in such systems. Expanding the capabilities of external seeding at Athos is a crucial next step to enhance its strengths, and opens the way to tackle for the first time the coherent dynamics in quantum materials on the femtosecond, or even sub-femtosecond timescale, with atomic precision. Such a capability will certainly push our understanding and modeling of complex materials beyond the current frontiers.

In the field of ultrafast laser-matter interaction for advanced manufacturing, several questions remain unanswered concerning the dynamics of laser-induced structural modifications. For example, in SiO_2, adjustments of the laser pulse length in the femtosecond regime can make the difference between material densification or the creation of self-organised nanogratings. In other material systems, such as tellurite glass, a single ultrashort pulse can eventually lead to nanocrystallisation. These are just two examples pointing out the current lack of understanding of ultrafast dynamical material restructuration, be it in the form of a certain defect taxonomy or of nano-crystallisation. The proposed upgrades to SwissFEL would provide unique tools to the advanced manufacturing community to understand the formation dynamics of these warm-dense matter states and plasma annealing, a long-standing issue in the field of laser-matter interaction. Coincident ultrafast X-ray scattering and spectroscopy in the tender to hard X-ray regime can provide the electron probes needed to study these processes of highly nonlinear light – matter interaction with micro- to nanoscale spatial resolution and time resolution in the few tens of femtoseconds.

The trend in structural biology is to go beyond the 'structure-is-function' paradigm towards a new frontier: time-resolved structural biology. Biological macromolecules undergo sequential structural rearrangements to perform their functions. Capturing these dynamic movements and advancing the field toward a 'dynamics-are-function' paradigm has been a long-standing goal in structural biology. Time-resolved serial crystallography is currently the most effective method for observing atomistic changes in biological macromolecules. To capture dynamics ranging from microsecond rearrangements of protein secondary structural elements to femtosecond ligand conformational changes and even attosecond electronic rearrangements, XFELs remain the only available experimental tools. To further these advancements, we will capitalise on the key capabilities of the Aramis beamline including the shorter pulse lengths and in the future wider energy range, enabling SwissFEL to remain at the forefront of modern structural biology. The availability of few femto- to attosecond pulses at Aramis further reduces radiation damage and in combination with shorter wavelengths provides higher resolution data. Both, the short pulse modes and the extended energy range at Aramis will significantly enhance the scope and quality of structural biology experiments possible at SwissFEL. These new capabilities will be welcomed by biologists, computational theorists, and chemists with an interest in protein dynamics.

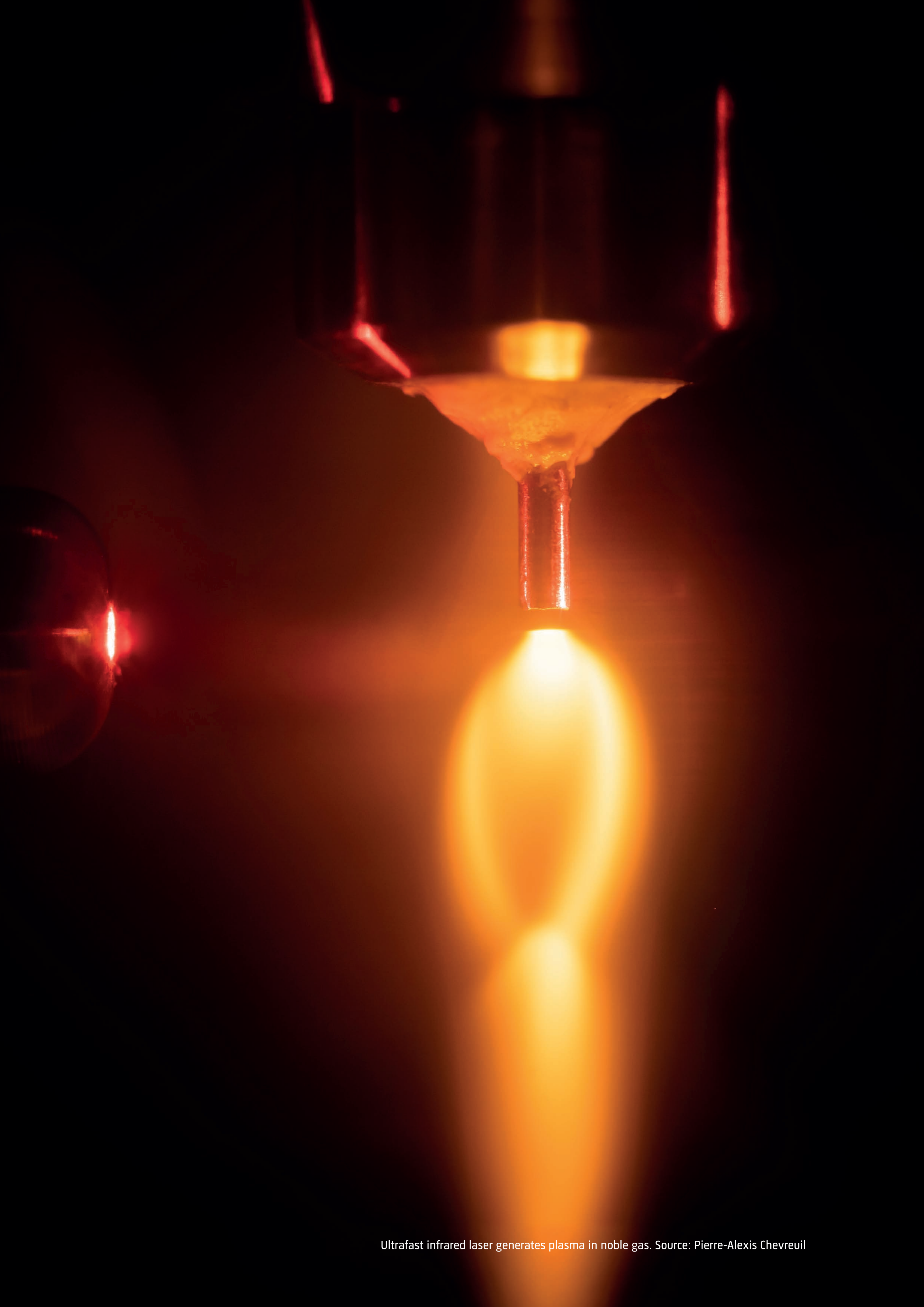
In an overarching theme, the practical needs of the rapidly evolving data analysis must be accommodated, similar to the case made in the chapter on synchrotron radiation. The availability of suitable, reliable, and up to date hardware and software for live data analysis during beamtimes is pivotal for achieving more time-effective experiments and increase the scientific outcome per experiment shift. The short- and long-term storage, processing, and analysis of the data is ever increasing in complexity beyond the abilities of a single user group and the facilities need to continue to fulfill this role.

In parallel to consultation with the Swiss research community conducted by the Swiss Society for Photon Science, an international workshop was held in November 2023 exploring the science opportunities from fully coherent XFEL sources.[1] The workshop results mirror many of the findings of the roadmap process from the SSPh, showing collective excitement about the opportunities of full coherence and potentially even phase stability in the X-ray spectral domain. There was equally strong support for polarisation control, widely spaced two-color X-ray modes, as well as increased stability for optical pump/X-ray probe experiments.

The future needs at SwissFEL reflect evolving demand from the scientific community, recent developments in XFEL sciences and technology, and changes in the worldwide XFEL landscape. The highest priority concerns the third undulator line Porthos, which should be designed for full X-ray pulse control over the energy range from approximately 2 to 10 keV. Crucially, the longer-term Porthos project should be complemented with continuous developments in external laser seeding in the soft X-ray regime at the Athos line, offering similar unique experimental opportunities of phase-coherent pulses as outlined above for Porthos while benefitting from the generally higher scattering cross-sections at soft X-ray energies. The existing hard X-ray Aramis line should be upgraded with self-seeding for temporal coherence and the accelerator should be upgraded to extend the range of photon energies to 18 keV. Experience gained at Athos and Aramis should inform the final design and construction of Porthos so that the advances made at Athos and Aramis can be optimally incorporated in the new Porthos branch. To maximise the scientific impact and for SwissFEL to remain internationally on the leading edge, small to mid-sized investments in existing infrastructure, specifically injector and accelerator, timing and synchronisation system, seeding schemes, as well as undulator technologies and a commensurate investment in endstations should be made to support and enhance the newly developing capabilities (see proposed new funding scheme).

Overall, the developed holistic strategy in response to the future science challenges will serve to distinguish SwissFEL in the worldwide community as a fully coherent source with the highest level of pulse control from the soft to hard X-ray regime.

1 https://indico.psi.ch/event/15311



Ultrafast infrared laser generates plasma in noble gas. Source: Pierre-Alexis Chevreuil

7 Institution-Based Laser Platforms

7.1 Executive summary

Institution based laser platforms consist of laboratories with advanced laser systems and laser-based experimental setups that are shared between different groups within a university or research institute. These are typically complex and costly experimental apparatuses, most commonly based on ultrafast laser systems. The shared nature of these platforms allows to reduce installation and maintenance expenses, guarantees an efficient development and transfer of technical and scientific knowhow as well as an efficient use of equipment, and allows for an optimised development of strategies and goals. While these platforms primarily serve the community within the institution, external user access is possible via collaborations and in some cases via international agreements such as LASERS4EU. Their diverse user base is one of the drivers of innovation for laser platforms: new ideas emerge from the different backgrounds, expertise and goals of the different groups and users involved, which can lead to novel technical developments (e.g. in FastLab Bern, below), new interdisciplinary applications (e.g. the development of new ultrafast laser fusion diagnostics at EPFL) and ideas for new experiments in e.g. X-ray free-electron lasers (cf. chapter 6 of this roadmap).

In light of the numerous advantages presented by institution-based laser platforms, the Swiss photon science community makes two recommendations. First, it is necessary to provide financial support for these platforms. We recommend a new funding scheme for medium level equipment funding on financial scale between single group efforts and the large-scale facilities, which would enable the creation, maintenance and further development of laser platforms and which would also be extremely useful in other fields (cf. chapters 5 and 6 of this roadmap as well as other community roadmaps). Second, we recommend strong strategic support and increased institutional support for these laser platforms, both at the institutional and at the federal level.

7.2 Findings and recommendations

Several institution-based laser platforms have been created in Switzerland over the past ten years: two were already mentioned in the Photon Science Roadmap 2021, two have been created since, and at least one is in a planning stage (cf. section 7.4 for details). Although somewhat recent in Switzerland, institution-based laser platforms are common in other European countries, given their great efficiency – of using equipment, funding, space, personnel, and of preserving and concentrating know-how, etc. – and their unique strength to promote collaborations and generate new ideas and novel research directions.

Findings: Institution-based laser platforms are advantageous since they are highly efficient in many aspects: 1) cost efficiency, since complex and expensive apparatuses are now shared; 2) space efficiency, as laboratory spaces are now shared by different groups; 3) personnel efficiency, since the presence of shared technical staff lightens the burden of the PI, postdocs and PhD students regarding technical developments, planning and maintenance, thereby saving salary costs and freeing up time for research; 4) knowhow efficiency, since the shared technical staff carries this knowledge across generations of PhD students, but also since there is increased communication between members of different groups that can share expertise; 5) use efficiency, as the experimental setups get used more than by a single group, and also since the equipment and knowhow remain in the shared platform even after one of the participating groups leaves the institution (e.g. due to relocation or retirement); 6) innovation efficiency, since shared work, a common technological foundation and strong collaboration promotes innovation and new research directions, and increases the potential for breakthrough ideas.

Laser platforms provide the equipment and know-how that enables several groups to use cutting edge laser technology. This is especially crucial for groups who may not invest in this technology because it is not their main focus, but who work in neighboring fields and could be spearheading the next big ideas. Examples of such innovative synergies already exist in Switzerland, even though institution-based laser platforms remain relatively new (the oldest dates back to 2016): 1) in FastLab Bern, a technological development of combining THz spectroscopy and scanning tunneling microscopy in underway, which arose from a collaboration with the University of Basel; 2) in FastLab Zurich, the collaboration formed around the shared platform led to a variety of novel scientific questions, which extend beyond the field of each individual group; 3) in the LNO laser spectroscopy lab and in LACUS, and to some extent also in the other platforms, the flexible and accessible experimental setups allow for the scientific development of seed ideas, which then serve as a basis for beamtime proposals that are submitted to large scale facilities such as SwissFEL or other X-ray free-electron lasers worldwide (offering many experimental possibilities and modalities, but difficult to access as a user). Platforms also have the potential to lead to technological developments which extend beyond the institution and into industry via start-up companies.

Finally, it is important to note that, despite being relatively new in Switzerland, the importance of resource pooling has made platforms like the ones we describe in this chapter very common and very successful in other countries such as France, Italy, Spain, Sweden, etc. Many scientific and technological achievements have come out of these institution-based laser platforms abroad, including notably the research leading to one third of the 2023 Nobel Prize in Physics, awarded to Prof. Anne L'Huillier from Lund University, in Sweden.

Focusing more specifically on the existing institution-based laser platforms, they are seen to consist mostly of setups based on ultrafast lasers. Indeed, these represent larger investments which can be difficult for a single PI to accommodate. This being said, ultrafast science really is at the forefront of scientific research, spanning several scientific topics and disciplines. Investing in ultrafast science infrastructure is increasingly justified, be it at large scale facilities such as SwissFEL, or at smaller scale shared platforms such as the ones we discuss in this chapter. This new technology is enabling groundbreaking scientific results in many fields such as condensed matter physics, plasma physics, crystallography, biology and femtochemistry. The relevance of ultrafast science is furthermore recognised by two recent Nobel Prizes in Physics, awarded in 2018 'for [a] method of generating high-intensity, ultra-short optical pulses' and in 2023 'for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter'.

In addition to listing the advantages of institution-based laser platforms, this roadmap also identifies issues in this field. One is related to funding, and especially affects institutions with limited PI base funding and less financial flexibility. Notably, 80% of the current and planned institution-based laser platforms in Switzerland are in the ETH Domain and only one at a cantonal university, even though that is where PIs have the least base funding. Also in terms of supporting upgrade costs, funding is an issue: one of the two longest running platforms, FastLab Bern, despite being successful, is struggling with securing funding, both for new equipment and for replacement of permanent staff.

One other issue relates to the lack of permanence of staff, since the platforms do not typically have dedicated funding or long-lasting institutional support. This affects all the platforms described in this chapter, with details given below. Solving this issue relies on increased funding, as well as on institutional support and commitment.

Recommendation 1: A new equipment funding scheme is needed to cover the mid-sized investments required to set up, run and further develop institution-based laser platforms. The institution matches this investment by providing the space and staff beyond the set-up phase.

This funding scheme is essential for institutions where individual setups cannot be established for individual PIs, due to funding and in some cases also space limitations, or where use by a single PI would remain under-critical. Furthermore, a general competitive funding scheme guarantees that all institutions, federal and cantonal, have an equal chance of benefiting from such a shared platform.

More broadly, such a funding scheme fills a gap in the Swiss science funding landscape, for medium sized investments, which has opened up even further with the discontinuation of R'Equip. This new scheme will guarantee that funding opportunities exist at all levels: PI level (project funding, accessible but limited to one million CHF per year), multi-PI level (newly proposed scheme), institutional level (funding for facilities, long application process for large strategic investments).

Finally, this funding scheme finds obvious parallels in other areas of photon science (cf. chapters 5 and 6 of this roadmap) and in other fields.

Recommendation 2: Institution-based laser platforms are an efficient use of funding, personnel, space and equipment. They should therefore receive strong institutional support and be part of strategic planning at the institutional as well as the federal level.

Efficiency regarding funding is particularly essential at a time where budget cuts are a reality, and planning for such scenarios in the future is strategically wise. In addition to being efficient on several fronts, as discussed in detail in this chapter, institution-based laser platforms enable the creation of a community which brings the institution beyond what single PIs can achieve. Furthermore, examples in Switzerland and abroad have demonstrated that such platforms can be a nucleus for innovation, that they are inherently flexible, and that they foster innovation via collaborations and the constant exchange of ideas.

Finally, as for our first recommendation, our second recommendation to guarantee institutional and federal support for these shared platforms naturally expands to other areas of photon science and beyond. Concrete examples of possible institutional support measures include hiring of permanent staff who can run the platform, lessening of administrative hurdles, and support in grant applications.

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7.4 Update on existing infrastructure

FastLab Bern

FastLab Bern is a laser platform run by the Institute of Applied Physics of the University of Bern. A thorough description of the capabilities of FastLab Bern was provided in the Photon Science Roadmap 2021. Since then, some aspects have been upgraded or implemented. Regarding experimental capabilities, the transient absorption and time-resolved fluorescence setups were upgraded to work also in reflection, and a new setup ('SlowLab') for transient absorption at 'slow' timescales (seconds) was built and is in the final stages of optimisation. Furthermore, a THz time-domain spectroscopy (TDS) setup is in the process of being combined with a scanning tunneling microscope (STM) from the University of Basel, in a collaboration which was made possible by FastLab and which will enable THz near-field measurements.

The platform is managed and operated by a permanent scientist, Dr. Hans-Martin Frey. It is funded by the University of Bern (funding for operational costs, under 100k CHF per year; salary funding for the scientist). Users are mainly internal, from the Department of Chemistry of the University of Bern; external users can only be accommodated via collaborations, and pure user lab services are also possible. A significant investment will be needed to maintain this platform in operation beyond the next couple of years, to replace the amplified Ti:sapphire laser system and to purchase an optical parametric amplifier for the 'SlowLab' experiment – this funding is not guaranteed at the moment.

LACUS

Lacus is a laser platform consisting of more than 25 participating groups within EPFL. A thorough description of the capabilities of Lacus was provided in the Photon Science Roadmap 2021. Since then, some aspects have been upgraded or implemented. Regarding experimental capabilities, the time-resolved and angle-resolved photoemission spectroscopy (tr-ARPES) facility was upgraded to include a six-axes cryogenic manipulator, and UHV sample holders were standardised to be compatible with most international laboratories and facilities, such as for example PSI. The ultrafast electron diffraction setup was also upgraded with a direct electron detector. Regarding data management, FAIR data management processes have been implemented, and the NEXUS format was adopted for ARPES data. A collaboration with the Swiss Plasma Center was also established, to explore ultrafast laser diagnostic for nuclear fusion.

The platform is managed by Prof. F. Carbone and operated by one permanent scientist, Dr. M. Puppin, along with PhD students from the participating groups. It is funded by EPFL (budget for equipment maintenance; salary funding for the permanent scientist), while the core facility was funded via SNF and ERC grants of the participants. Internal users come from both the participating groups and collaborators at EPFL. External users can also apply via LASERS4EU, a EU funded initiative (former Laserlab-Europe), which provides central user support, an international review panel and travel allowance for accepted beamtimes. External users come from Swiss universities and from EU countries, and use the platform for 1–2 months per year.

FastLab Zurich

FastLab Zurich has started operation in 2023, with six participating groups from the Department of Physics of ETHZ: Profs. E. Abreu, L. Gallmann (FastLab Director), S. Johnson, C. Rüegg, D. Rupp, and Dr. Y. Acremann. The platform is based on existing infrastructure in the Institute of Quantum Electronics and allows for near-infrared pump – XUV probe spectroscopy experiments with attosecond temporal resolution. Attosecond pulses open tremendous new opportunities in different fields of science, their impact in past and future research having been recognised by the Nobel Prize in Physics 2023, which was awarded ‘for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter’. FastLab Zurich enables several groups at ETHZ to benefit from and contribute to this impactful research field, via technological developments and new research questions. In particular, an extension of the capabilities of the current pump – probe setup is planned, which will allow for THz pulse excitation, cooling down to 10 K and the application of a magnetic field of up to 7 T. This will in turn push the boundaries of the type of systems that can be studied in the platform, to include e.g. quantum materials.

This platform is managed by Prof. L. Gallmann, and operated by Dr. J. Lehmann along with PhD students from the participating groups. It is funded by ETHZ (equipment funding; operational budget; salary funding for the technician and partly for the director), the Department of Physics, and the participating groups. Applications for external funding are ongoing. Currently the users are the members of the groups that participate in FastLab Zurich; external users can be accommodated via collaborations.

LNO Laser Spectroscopy Laboratory (PSI)

PSI

A new platform dedicated to high field THz experiments has been created at PSI in 2022. The goals of this platform are threefold: 1) to allow PSI scientists to test their samples and validate experimental schemes before an allocated beamtime at SwissFEL, as well as to get preliminary measurements that can be included in proposals for SwissFEL beamtime; 2) to provide PSI researchers with an experimental facility where they can test breakthrough ideas and novel physical concepts and potentially validate theoretical assumptions; 3) to serve as an R&D platform for PSI staff on several new topics, such as the development of high-field THz and narrow band THz sources, or the adaptation of the existing THz spectroscopy setups for biological applications.

The optical parameters of this laser platform make it possible to excite the material out of equilibrium using few meV photons. This energy is sub-gap for insulators and for many semiconductors, and furthermore matches the frequency of many vibrational modes in solid state materials. THz pulses therefore enable photoexcitation of materials via controlled resonant processes or via non-resonant pathways which nevertheless limit thermal effects due to electronic excitation. Three experimental setups are in place, enabling THz pump – THz / optical probe experiments in transmission or reflection with different characteristics: 1) very high THz fields amplitudes (up to 5 MV/cm) and broadband THz spectra (~2 THz wide); 2) high THz fields amplitudes (up to 400 kV/cm) and narrowband THz spectra (<1 THz wide); 3) very high THz field amplitudes and broadband THz spectra, with the option to cool down to about 4 K in a cryostat.

The platform is managed by Dr. A. Trisorio and operated by Dr. C. Vicario (20% FTE) and Dr. U. Demirbas (80% FTE), all staff scientists at PSI. It is funded by PSI (equipment funding; salary funding via the staff scientists). It would, however, benefit from additional funding for hiring a dedicated scientific development person and for upgrading the performance of the laser source. The users are PSI scientists who apply for experimental time via an internal call happening once a year. Experiments are selected by a committee, chaired by Prof. T. Lippert and consisting additionally of the three scientists mentioned above plus two PSI staff scientists. 4 – 6 experiments are selected per year, the limit being set by the availability of the staff as well as by the time required for LNO R&D activities and laser maintenance. Experiments so far have focused on solid state samples but other applications, e.g. in biology, are in principle possible, and the setups are being adapted in these directions.

Attosecond and extreme timescales laboratory (PSI)

PSI

An attosecond table-top laser facility is envisioned in the Park Innovaare innovation park next to PSI in conjunction with the construction of the Diavolezza endstation for attosecond X-ray science at SwissFEL. The facility will offer kHz-repetition-rate isolated attosecond XUV pulses with photon energies extending into the so-called water window at approximately 300 eV, which is relevant for biological and aqueous samples. The source will be complementary to the X-ray pulses delivered at SwissFEL, which range from the water window up to 1.8 keV but at a lower repetition rate of 100 Hz and without intrinsic synchronisation. The facility will be used to develop new experimental methodologies, for planning and preparation of user beamtime experiments at Diavolezza, and to sustain additional independent research programs. The facility would be open to PSI scientists, scheduled users at SwissFEL, and the broader Swiss scientific community through collaboration. With sufficient overall funding, the attosecond facility could become operational coincident with the Diavolezza end station by the end of 2027.

7.5 Future needs

In this section we provide additional context to the recommendations made in section 7.2.

Our first recommendation is to create a competitive funding scheme for medium-scale investments, which would allow PIs to set up or further develop a shared platform. While the exact implementation details would naturally have to be worked out keeping in mind also the other potential applications of this new funding scheme (both in photon science and in other fields), features that are important for institution-based laser platforms are: funds for initial infrastructure, possibility to apply again after some period of time for major upgrades of the instrumentation, and support from the institution, namely for employment of staff (ideally permanent, potentially with some partial contribution from the member groups).

Our second recommendation highlights the need for institutional and federal support for institution-based laser platforms. In addition to the matching funds mentioned in the first recommendation, general institutional and administrative support for long-term scientist positions is crucial. As discussed above in this chapter, such a staff scientist position enables long-term management and planning, knowledge transfer and preservation, as well as efficient use of resources. This function is an integral component for the success of laser platforms. Broader support beyond the institutional level provides a policy and structural umbrella which goes beyond funding and administration aspects, and which can be used as a vehicle to share and expand the laser platform model across institutions and user communities.

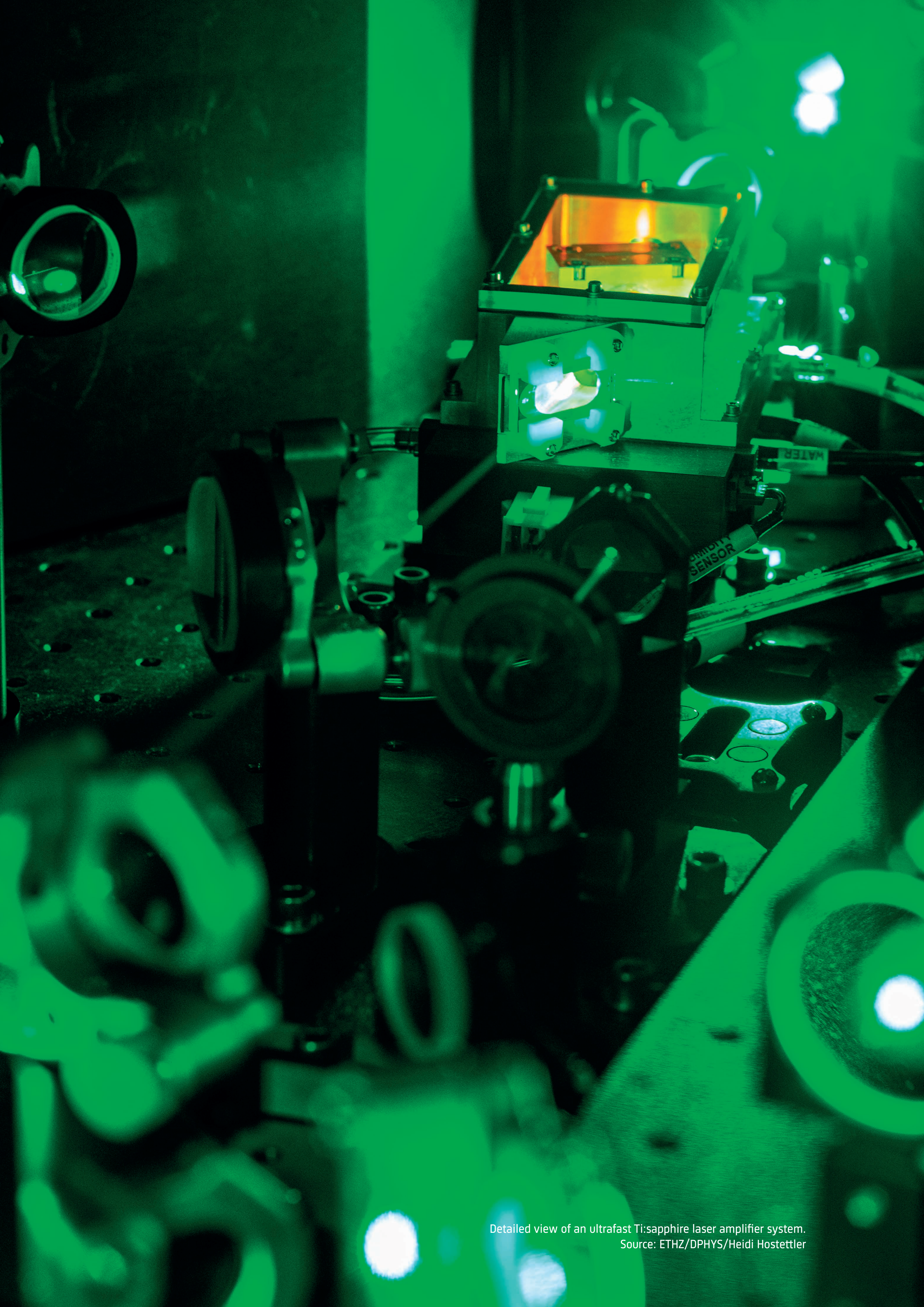
In summary, institution-based laser platforms make laser laboratories accessible to a wide range of researchers, including some who would not be able to afford it individually, creating new opportunities as well as a larger user base for large-scale facilities such as SwissFEL. They foster collaborations within and across departments, interdisciplinarity, and the generation of new ideas. The knowhow of groups with related technical and scientific interests is exchanged and preserved, it accumulates efficiently over time and over generations of PhD students and postdocs with temporary contracts. In addition, shared platforms provide increased opportunities for training of technical experts in Switzerland (semester students, Master's students, etc.), while also serving as a steppingstone for young career researchers (Ambizione grantees, Starting Grant recipients, etc.) who cannot afford to build a laboratory from scratch.

From a broader scientific perspective, institution-based laser platforms widen the access to cutting edge ultrafast laser systems, enabling more scientists to enter this successful and thriving field of research. This type of platform is, however, not limited to ultrafast laser experiments and could easily be extended to other fields, two examples from fields outside photon science being the FIRST-Lab and the Materials Discovery Laboratory at ETHZ.

Off-axis parabolic mirror focusing THz radiation for time-resolved studies of condensed matter.
Source: ETHZ/DPHYS/Heidi Hostettler

8 Acronyms

AI	Artificial Intelligence
ADRESS	Advanced Resonant Spectroscopies (beamline at SLS)
BM	Bending Magnet
CHART	Swiss Accelerator Research and Technology
COSS	Center for Operando Synchrotron Studies
CRG	Collaborating Research Group
Cryo-EM	Cryogenic Electron Microscopy
CSCS	Swiss National Supercomputing Center
EBS	Extremely Brilliant Source (at ESRF)
EMBL	European Molecular Biology Laboratory
EPFL	Federal Institute of Technology Lausanne
ESRF	European Synchrotron Radiation Facility
ETHZ	Federal Institute of Technology Zurich
EuXFEL	European X-ray Free-Electron Laser
FAIR	Findability, Accessibility, Interoperability, and Reuse
FCC-ee	Future Circular Collider, electron-positron collider
FEL	Free-Electron Laser
IBS	Institut de Biologie Structurale
Lasers4EU	Lasers for Europe
PAL	Pohang Accelerator Laboratory
PEARL	Photoemission and Atomic Resolution Laboratory (beamline at SLS)
PSI	Paul Scherrer Institute
R&D	Research and Development
SACLA	SPring-8 Ångström Compact Free-Electron Laser
SASE	Self-Amplified Spontaneous Emission
SAXS	Small-Angle X-ray Scattering
SCNAT	Swiss Academy of Sciences
SDSC	Swiss Data Science Center
SERI	State Secretariat for Education, Research and Innovation
SHINE	Shanghai High Repetition Rate XFEL and Extreme Light Facility
SIS	Surface/Interface Spectroscopy (beamline at SLS)
SLS	Swiss Light Source
SLS 2.0	Upgrade to the Swiss Light Source
SSPh	Swiss Society for Photon Science
SwissFEL	Swiss Free-Electron Laser
TDS	Time-Domain Spectroscopy
TOMCAT	Tomographic X-ray microscopy (beamline at SLS)
US	United States of America
XAS	X-ray Absorption Spectroscopy
XFEL	X-ray Free-Electron Laser
XRD	X-ray Diffraction



Detailed view of an ultrafast Ti:sapphire laser amplifier system.
Source: ETHZ/DPHYS/Heidi Hostettler

SCNAT – network of knowledge for the benefit of society

The **Swiss Academy of Sciences (SCNAT)** and its network of 35,000 experts works at regional, national and international level for the future of science and society. It strengthens the awareness for the sciences as a central pillar of cultural and economic development. The breadth of its support makes it a representative partner for politics. The SCNAT links the sciences, provides expertise, promotes the dialogue between science and society, identifies and evaluates scientific developments and lays the foundation for the next generation of natural scientists. It is part of the association of the Swiss Academies of Arts and Sciences.

The **Swiss Society for Photon Science (SSPh)** was founded in 2019. Its mission is to represent and support scientists active in the many different fields of photon science. It speaks with one voice and provides input to strategic planning of photon science in Switzerland. Through periodic newsletters and events, the Swiss Society for Photon Science aims to advance the science of light and to raise the awareness of photon sciences as being one of the central pillars of our daily life. The SSPh's core values are respect, integrity and inclusivity, and a commitment to excellence and diversity.