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Neutron Science Community Roadmap 2024

Update of Swiss Community Needs for Research Infrastructures 2029–2032

SWISS NEUTRON SCIENCE SOCIETY

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ELABORATION PROCESS
The present document is a community effort, with contributions from 'core communities' across Switzerland represented in the Swiss Neutron Science Society (SNSS), as well as from user communities across various disciplines working with neutron scientists to exploit neutron probes for specific applications.

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LAYOUT
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COVER PHOTO
Nicolas Gauthier
In 2020, an international team led by PSI researcher Romain Sibille established in neutron-scattering studies a fundamentally new state of matter, higher-rank multipole ice (Nat. Phys. 16, 546–552; 2020). The image shows a representation of a liquid of magnetic multipoles, obtained by immersing bar magnets and iron filings in water.

This report can be downloaded free of charges from scnat.ch/en/id/BGqdL

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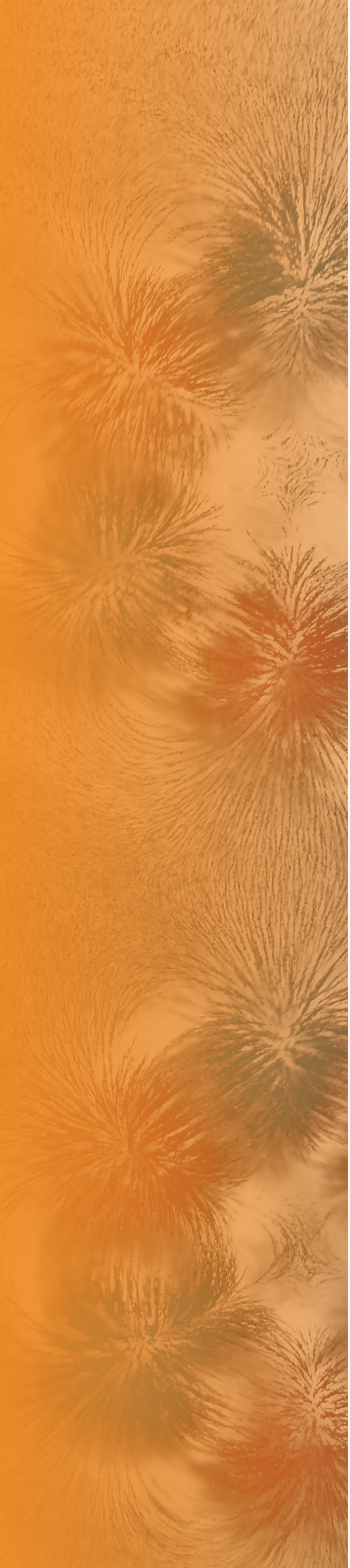


Neutron Science Community Roadmap 2024

Update of Swiss Community Needs for Research Infrastructures 2029–2032

Content

1 Executive summary

Thanks to a well thought out strategy based on competitive Swiss national neutron sources combined with continuous and investment in European flagship facilities serving a vibrant community of Swiss neutron scientists, Swiss neutron science is world-leading. Swiss researchers use neutrons to tackle scientific, technological, and societal challenges across diverse fields ranging from fundamental physics to condensed and quantum matter, to material science to soft matter, biology and medical research. This document reports the status of various large-scale projects designed to further Swiss leadership in neutron science.

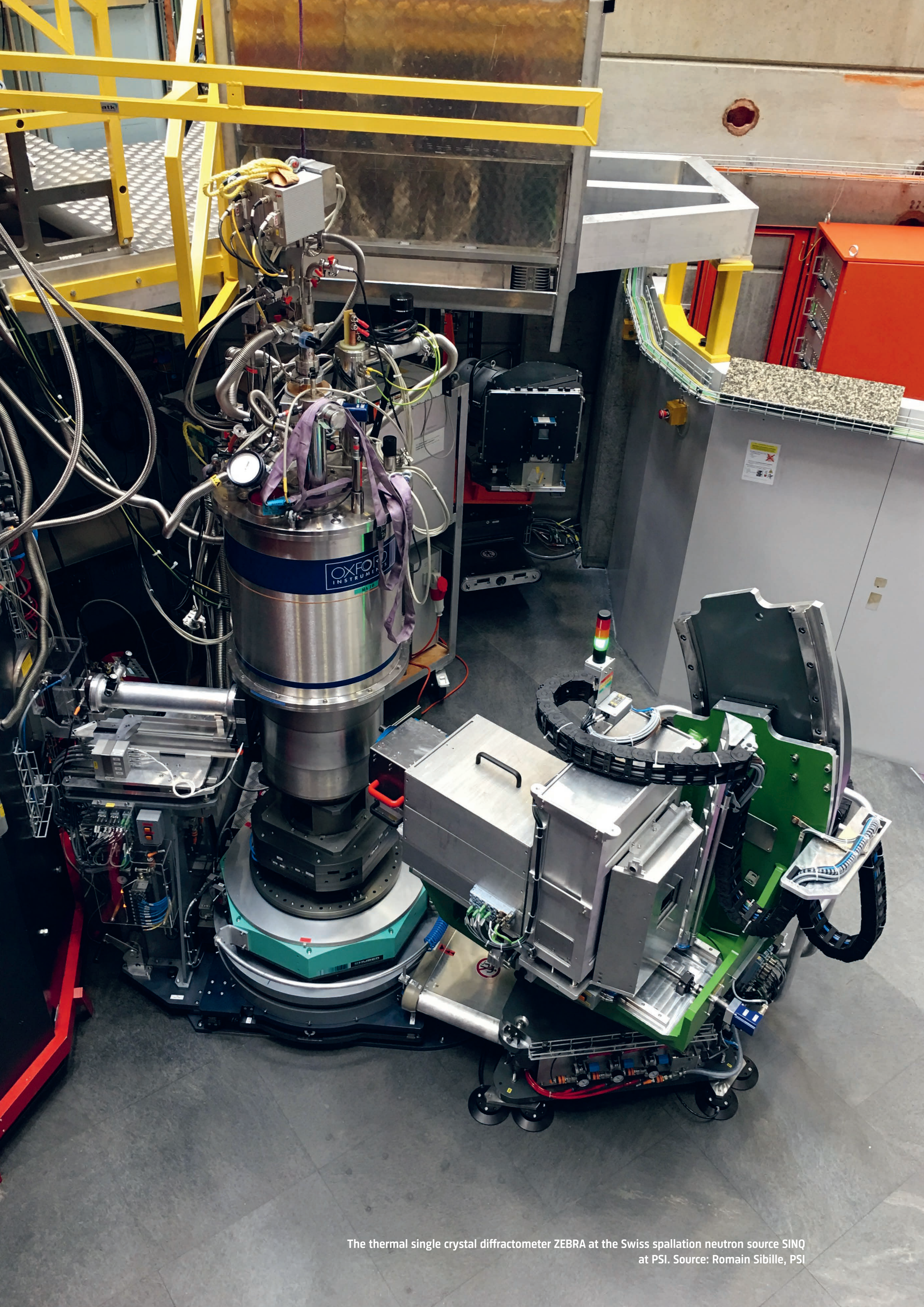
Despite this continued success, there are early signs of future threats due to challenges in the provisioning of neutrons in Europe. In this document we assess this situation in detail and provide recommendations for mitigation. A key recommendation is to continue work on the conceptional design report for the **SINQ++** project to upgrade the Swiss spallation neutron source SINQ. We show that this project has the potential to substantially improve the existing instrumentation as well as to create new neutron instruments that are designed to address emerging scientific questions. At the same time **SINQ++** offers unique opportunities to exploit neutrons for topics of strategic relevance to Switzerland. These are the production of medical isotopes for cancer treatment and diagnosis, the testing of advanced nuclear materials for next generation fission reactors, fusion reactors and transmutation, as well as development of electronics required for the exploration of space.

The feeder optic and collimator for the neutron reflectometer Estia developed and build by PSI for the European Spallation Source. Source: Mahir Dzambegovic, PSI

2 Foreword

This document is an update to the Neutron Science Community Roadmap published in 2021. It presents the needs of the Swiss neutron 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 the Federal Council. The role of 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 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.



The thermal single crystal diffractometer ZEBRA at the Swiss spallation neutron source SINQ at PSI. Source: Romain Sibille, PSI

3 Introduction

The main purpose of this document is to provide an update with regard to the Neutron Science Roadmap published in 2021,[1] which gave a broad overview of the status of neutron science in Switzerland at that time. Notably, it identified the unique contributions that neutron probes provide across a broad set of scientific and technological fields and disciplines, and showed that Switzerland has a continuously growing and broadening neutron science community. However, the Neutron Science Roadmap also identified some early signs of challenges in the provisioning of neutrons.

Further, the 2021 roadmap was written and published just after the neutron guide upgrade program of Switzerland's national neutron source SINQ at the Paul Scherrer Institute (PSI) was completed, and just before the rebaselining of the construction effort of the new European neutron flagship, the European Spallation Source (ESS) in Lund Sweden was carried out. Thus, this update of the roadmap document in 2024 comes at an ideal moment in time to take stock of the progress of these key projects that will benefit the Swiss neutron science community. Our survey of these key projects shows that:

- The SINQ guide upgrade program and related instrument upgrades were successful, leading to impressive performance gains enabling the community to address new challenges.

- Although, the ESS is not operational yet, it is set to produce its first neutrons by the end of 2025. Crucially, the Swiss contributions to ESS's instrument suite are making excellent progress and will soon allow Swiss scientists to carry out novel types of neutron studies.

- An additional upgrade of Switzerland's world-leading ultra cold neutron (UCN) source at PSI has been started in the meantime and will ensure continued and improved operation of UCN to carry out fundamental physics experiments.

We also have resurveyed key aspects of the neutron science community. Here we emphasise that because the need for neutrons to address scientific, technological and societal challenges remains unprecedentedly urgent, we have focused on assessing the impact of Swiss neutron scientists in the context of the international community, and the size and needs of the community. We find that the Swiss neutron science community is verifiably and quantifiably among the most successful neutron communities in Europe and world-wide. We are also able to report that over the last few years, the community continues to grow.

We further identify that the community has a strong demand for carrying out neutron experiments with increasing complexity that drives a constant need for improving the available instrumentation. This interplay between excellent science and the ability to develop state-of-the-art neutron instrumentation is a key component of Switzerland's leadership in neutron science.

Due to concerns that the provisioning of neutron access in Europe is facing increasing challenges, we have also investigated this aspect in detail and provide a quantitative outlook on the neutron access for the next two decades. We find that the severity of this situation has increased and, if not mitigated in time, has the potential for long-term detrimental effects on our community. In particular, we fear that it will have negative impact on educating the next generation of neutron experts, which will erode the Swiss leadership in neutron science. However, based on this assessment, we also offer a mitigation strategy with various scenarios that may be considered.

Finally, following the recommendation of the last neutron science roadmap, we make progress on defining a strategy to continuously upgrade the Swiss national facility SINQ and its suite of instruments. Based on a pre-project carried out over the last two years at PSI, we show that there is a realistic path to an upgraded **SINQ++** facility with a new cold source that would provide an increase in brightness of at least a factor two across all instruments. Further, the extension of the current target Hall would allow the construction of five additional state-of-the-art instruments while improving two existing ones by a factor 20 and 200, respectively. Moreover, this upgrade would further increase the use of neutrons for the production of medical isotopes, the testing of advanced nuclear materials (for next generation fission reactors, fusion reactors and transmutation), as well as development of electronics required for the exploration of space. These are topics of strategic relevance to Switzerland.

The vacuum tank for the detector of the SANS-LLB instrument at the Swiss spallation neutron source SINQ at PSI. Source: Viviane Lütz Bueno, PSI

4 Findings and recommendations

Key findings

- The Swiss neutron science community is verifiably and quantifiably the most successful neutron science community world-wide as identified by an independent study.[2] This is the result of an effective strategy combining competitive national neutron sources with a strong development program and the investment in international flagship facilities.

- The Swiss neutron science community continues to grow and broaden.

- The recent SINQ neutron guide upgrade and related neutron instruments upgrades were successful and provide a path for further instrument upgrades. We also find that the enhanced flux is mostly exploited to carry out more complex experiments, and only results in a moderate decrease in experimental times (about 10%). In short, improved instruments are used to tackle new scientific challenges and not to simply repeat the same type of experiments faster, as desirable for advancing science, technology and society.

- The entire European ecosystem of neutron sources is experiencing a 'neutron drought', where currently only about 50% of previously provisioned neutron beam days are available. While measures such as the possible extension of the operation of the reactor at the Institute Laue Langevin (ILL) in France up to 2033, as well as the imminent start-up of the European Spallation Source, will mitigate this in the short term, our analysis shows that if no further actions are taken, the long-term availability of neutrons will only be about 60% of previous capacity. If this remains unmitigated it will harm the output and the size of our community in the long-term, because the education of new neutron experts will be hampered.

- This also entails that the key role of Switzerland's national neutron source SINQ will be even more prominent in the future. At the same time, the Swiss neutron science community is part of the European ecosystem, and we rely on the availability of additional neutron facilities for neutron provisioning, training of students and technological synergies.

- The community has an ever-increasing demand for experiments with increasing complexity that require advanced and optimised instrumentation.

- A proposed upgrade of the SINQ facility in 2033–2036, currently code-named **SINQ++**, would not only allow to vastly improve its cold-source and instrumentation with substantial gain factors of up to 200, but also extend the already immensely broad use of neutrons in Switzerland to even more areas of research and development. These are the exploitation of neutrons for the production of medical isotopes, the testing of advanced nuclear materials (for next generation fission reactors, fusion reactors, mobile compact reactors and transmutation) as well as the development of electronics required for the exploration of space. We note that all these are scientific and technological areas that are currently rapidly growing and also well-aligned with the priorities of the ETH domain and Switzerland.

Recommendations

1. To accommodate the scientific needs of the Swiss user base, ensure access to neutron beams in Switzerland beyond the next decade, maintain Swiss leadership in neutron science, and also widen the exploitation of neutrons, we propose to further pursue the promising proposal of the **SINQ++** upgrade project and provision a detailed conceptual design report over the next ERI period.
2. A series of workshops with the community should be organised to define the exact instrument suite to be part of the SINQ++ scope so that the project ideally meets the needs of our community beyond 2030. Here new instrumentation should aim to strengthen soft matter and applied research and to address current and future societal challenges. Moreover, researchers concerned with the use of medical isotopes, advanced nuclear materials, and space exploration should participate in defining the specifications for experimental stations at **SINQ++** to cater to these growing fields.
3. Given the current situation that there will only be four major neutron sources in Europe after 2033, we will experience an ongoing 'neutron drought' with about 60% of the previously available neutron capacity. Thus, Switzerland should strongly engage in increasing the number of instruments at ESS from currently 15 to the maximum of 35.
4. Currently, ESS has no possibility for carrying out fundamental physics experiments yet. For the particle physics community working with neutrons, it is therefore crucial to implement options that allow conducting a rich fundamental physics research program, e.g. realizing a dedicated cold neutron fundamental physics beamline, as well as exploiting the installation of a future second moderator.
5. Similarly, options should be evaluated, collaborating with other European countries, to operate the ILL reactor as long as possible. This would not only strongly offset the challenge in the provision of neutron time, but also conserve the ILL as strong provider of neutron technology and expertise for the European ecosystem. The ILL remains a leading neutron center with 45 instruments that in many cases are complementary to the advanced capabilities at the ESS. In particular for fundamental physics and the provisioning of radioisotopes the ILL represents an extremely strong partner of Switzerland.

5 Updates on existing infrastructures and user community

In this section we will first review recent upgrades to the Swiss neutron sources SINQ and UCN at PSI. We will also provide an update on the European Spallation Source (ESS) in Lund highlighting the status of the Swiss contributions to ESS. Finally, we will survey the current situation of the Swiss neutron science community.

5.1 Updates on national neutron science facilities at PSI

5.1.1 Performance gains due to the SINQ guide upgrade

The Swiss spallation neutron source SINQ at PSI went through an extensive upgrade program of its neutron guides between 2019 and 2021. In turn, the facility has been in user operation over the last three years, which roughly corresponds to the period since the last Neutron Science Roadmap[1] was published. Measurements of the neutron flux at the instruments' positions serviced by the new guides after the upgrade show substantial improvements ranging from at least a factor 2 up to 30 (see Fig. 1), demonstrating that the SINQ guide upgrade project was highly successful.[3]

Following the neutron guide upgrade, several of the instruments have been upgraded to take advantage of both the increased neutron intensity but also to improve the neutron counting efficiency. Among the recently upgraded instruments that are either already in full user operation or in the hot commissioning phase are:

- **DMC** is a cold neutron powder diffractometer optimised for magnetic scattering, which previously was operated with a one-dimensional detector. Recently, in collaboration with the detector group at the FRM II reactor in Munich, Germany, a new detector has been developed that allows for two-dimensional detection of neutron events over a large area. Notably, the new detector covers 120 degrees within the scattering plane (instead of 80) and 15 degrees in the vertical direction (instead of three). This larger coverage has been realised by employing an array of vertical anode wires and horizontal cathode strips with an angular separation of 0.125° in both dimensions. Although the exact gains depend on the required resolution and wavelength for powder diffraction experiments, the detector alone will achieve an increase of detection efficiency of about nine. Together with a factor two due to the guide upgrade, a total gain of about 18 was achieved. Finally, the two-dimensional detector also allows the mapping of large regions of reciprocal space in single crystal experiments, opening the instrument to new science cases for the exploration of quantum materials.

- **AMOR-Selene:** Selene is a new scheme for high-intensity specular reflectometry. Instead of a highly collimated beam one uses a convergent beam covering a large angular range. The key development is a new type of focusing neutron optics, the so-called Selene guide.[4] This guide system is made of two subsequent planar-elliptical reflectors which share the long axis and one focal point. This leads to an imaging system where coma aberration, which is inherent to elliptical mirrors, is corrected to first order. This means that the geometrical properties of the beam at the sample position can be defined at the initial focal point, here referred to as the virtual source. When this concept is applied in the horizontal and vertical direction normal to the beam, a three-dimensional image of the virtual source is projected onto the sample. This upgrade resulted in a total gain factor of 30 compared to the old instrument. Here, a factor of ten is a result of the increased neutron flux, and an additional factor of three comes from a large reduction of background, and thus a better signal-over-noise ratio, which is a key figure-of-merit for reflectometry. In addition to the new guide system the instrument was also equipped with a new ^{10}B multiblade detector developed by the detector group of the European Spallation Source. The instrument is currently in the hot commissioning phase.

- **SANS-LLB:** The shutdown of the Orphée reactor at LLB (Saclay, France) and the upgrade of the SINQ neutron guide system at PSI (Villigen, Switzerland) in 2019 were the beginning of a long-term collaboration between PSI and LLB. The SANS-LLB instrument, formerly known as PA20 has been installed at SINQ/PSI as a collaborative effort between PSI and LLB. This modern SANS instrument will predominately cater to the soft matter neutron scattering community at SINQ. We note that the oversubscription for SANS beamtime is currently the highest among all instruments at SINQ. Considering the combination of the modern instrument with the ninefold increase of the neutron flux, thanks to the SINQ neutron guide upgrade, the SANS-LLB instrument will be key to satisfying this high demand. The instrument is currently in the hot commissioning phase.

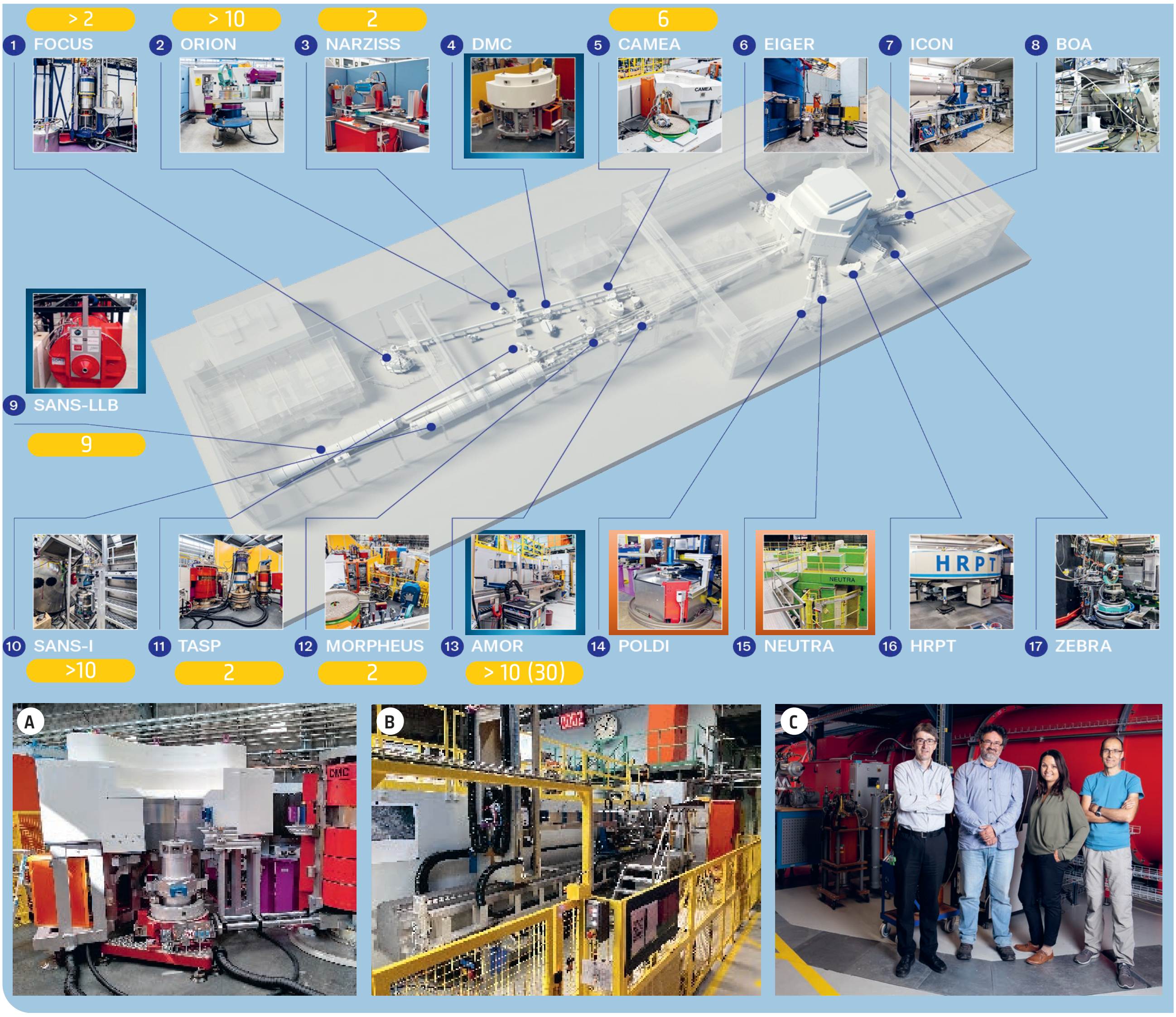


Figure 1: Results of the SINQ guide upgrade at the Paul Scherrer Institute. The upper panel shows an overview of all instruments operated at the SINQ neutron source. The instruments, which are situated at a neutron guide replaced during the SINQ guide upgrade project are denoted with a yellow bar, where the number provided highlights the neutron flux gain at the instrument as a result of the upgrade. The instruments, whose pictures are framed in dark blue recently received additional upgrades (see text for details). The instruments denoted with an orange frame are currently being upgrade. The lower three panels show photographs of the upgraded instruments A) DMC, B) AMOR and C) SANS-LLB.
Source (photos): Lukas Keller, Jochen Stahn, Markus Fischer

In addition to the instrument upgrades, which have already been carried out, three more upgrades are currently in preparation or being implemented. Projects that are already in the execution phase (meaning that either parts are being procured, manufactured or even installed) are:

- **NEUTRA 2.0:** Major upgrade of the thermal imaging workhorse instrument NEUTRA to enable more versatile and complex *operando* measurements (cf. section 4.1).

- **POLDI:** Upgrade of the engineering diffractometer POLDI with two state-of-the-art ^{10}B jalousie detectors allowing for an increase in neutron counting efficiency of more than two, and better resolution, and a new guide system resulting in a gain factor eight. This entails that the overall improvement of Poldi is a factor 16.

- **FALCON:** A novel neutron Laue diffractometer that was transferred from the Helmholtz Zentrum Berlin after the BERII reactor was shut down. The FALCON experimental station will be very flexible and is also foreseen to host experiments by the fundamental physics community, for instance the Beam EDM and QNeutron projects led by the University of Bern.[5] It will also offer unique possibilities to test novel instrument developments/concepts.

We note that the Neutra and Poldi upgrades are carried out in collaboration with ANAXAM and the Norwegian Institute for Energy Technology (IFE). In addition, there are three more upgrade projects for the instruments TASP, FOCUS and EIGER, which are currently in the design phase. Notably, for the two latter instruments funding for the planned upgrades is already secured via the intensifying collaboration with IFE. The instrument TASP will be replaced by WARP, the **W**ide-**A**ngle high-**R**esolution **P**rismatic spectrometer, which will combine the new technology of bent silicon single-crystals developed at the ILL with the CAMEA concept developed at PSI. Together this enables focussing on smaller samples while increasing energy resolution to reach large coverage of parameter space. The WARP instrument will provide three times higher resolution compared to CAMEA in combination with polarisation analysis. The WARP instrument will be carried out in collaboration with the EPFL and the ILL and is partially funded by an SNF R'Equip proposal. These three instrument upgrades are dedicated to spectroscopy of quantum and soft matter, both key topics for the Swiss community.

5.1.2 SINQ++ project

As proposed in the Swiss Neutron Science roadmap published in 2021,[1] at SINQ a unique opportunity exists to build new instrumentation catering to new emerging user communities in an affordable fashion. Notably, the existing guide hall shown in Fig. 1 points towards the South serving a total of ten instruments, whereas currently there are only two cold-neutron instruments that take advantage of the neutrons scattered towards the North (the cold-neutron imaging instrument ICON, and BOA, which serves both as a polarised imaging instrument, test instrument for neutron optical concepts and for fundamental physics measurements). By extending the existing SINQ target hall north – where space is available on the PSI site – it becomes possible to add several new cold neutron instruments to the facility. At the time of the last roadmap, a first estimate showed that up to six new instruments may be built in a cost-effective way to cater to these new communities and expand neutron access for the corresponding Swiss and collaborating European researchers.

In 2027, SINQ will be reaching 30 years of successful user operation. SINQ is a continuous neutron source where a proton beam impinging on a lead target produces spallation neutrons. A key component for the success of SINQ is the so-called cold source, which consists of a liquid deuterium moderator cooled to 25 K, and serves to slow down neutrons required for high-resolution experiments. The last upgrade of the cold source of SINQ was realised in 2001 and implemented an early attempt of a reentrant hole (REH) geometry. A REH pursues the goal to remove

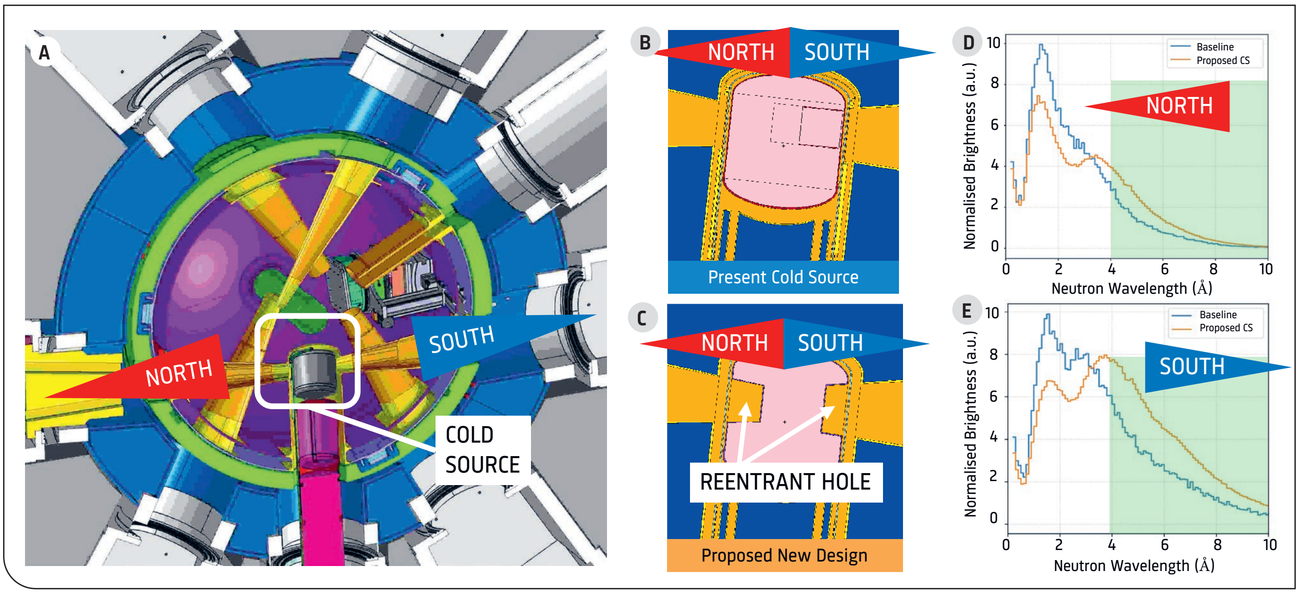


Figure 2: Preliminary design of the new SINQ cold source. A) The area of the SINQ target hosting the cold source (denoted by a white rectangle) is shown. The blue and red arrows denote the neutron extraction channels towards the South and North of the SINQ target, respectively. B) The present design of the SINQ cold source is shown. The red light rectangle denotes the current reentrant hole solution on the South sector, which relies on radiation-induced evaporation of the liquid deuterium moderator. The proposed new design illustrated in C) is instead based on mechanical generation of two reentrant holes for both the extraction of neutrons to the South and the North. Panels D) and E) show simulations of the normalised neutron brightness for extraction of neutrons to the North and South, respectively. Here the result for the current cold source design ('baseline') is shown in blue, whereas the new design is denoted in orange. The green shaded area marks the cold neutron spectrum which is improved for the new design for both directions. Source: Nicola Rizzi and Uwe Filges (PSI)

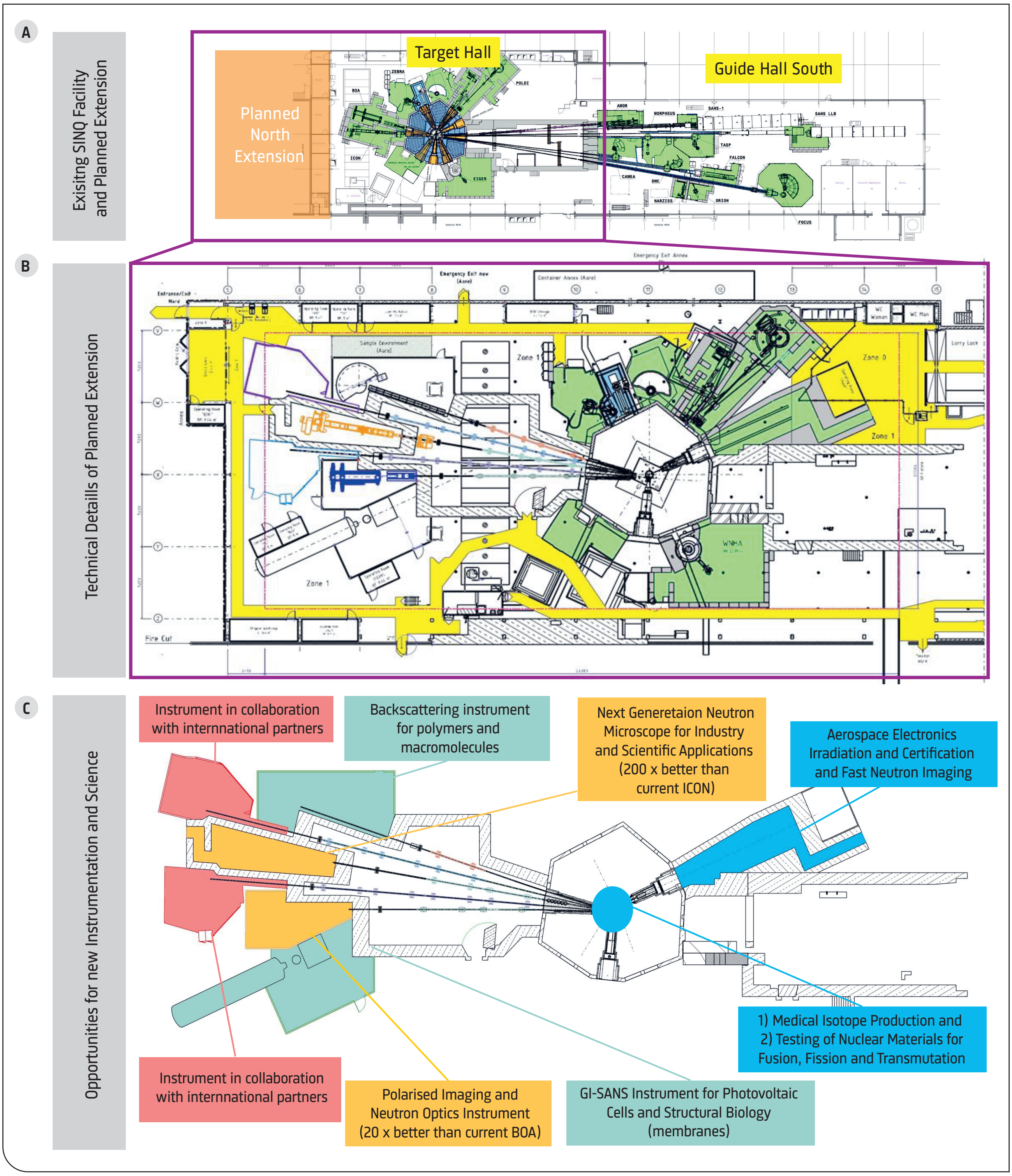


Figure 3: Proposed layout of the SINQ++ upgrade. A) Map with the current layout of the SINQ facility at PSI is shown. It consists of a Target Hall on left side and a Guide Hall, which extends to the South of the Target Hall. For the SINQ++ Project, the Target Hall would be extended to the North as indicated by the light orange area. B) This panel is an enlarged version of the area in panel a framed in purple and shows the details of the technical implementation of the extension to the North. C) A possible layout of the six instruments to be included in the new extension to the North is shown (red, orange, green areas, see text for details). In addition, three more experimental stations would be created in existing target Hall for the production of medical isotopes, the testing of nuclear materials and the testing of electronics for aerospace applications (blue, see text for details). All instruments facing the cold source would benefit from the improved fluxof the SINQ++ neutron source highlighted in Figure 2. Source: Uwe Filges and Jonathan White (PSI)

material, which scatters and absorbs desired neutrons, between the spot with the maximum cold neutron flux (the center of the cold source) and the direction in which neutrons are extracted. However, it is now understood that the used technology for the implementation of the REH was not as effective as thought at the time.[7] In addition, in the last 20 years the understanding of neutron moderators has improved enormously, where additional technologies such as neutron reflectors and low dimensional moderator geometries have been shown to vastly improve the brilliance of a cold neutron source. These are exactly the developments that will make the ESS cold source very performant. At the same time, it needs to be taken into consideration that the cold source vessel is close to the lead spallation target and therefore exposed to a very high flux of fast and thermal neutrons. This is known to result in corrosion and radiation damage after an operation time of approximately 30 years. This highlights that the cold source of SINQ needs to be replaced within the next decade to ensure continued operation of SINQ well beyond the mid 2030s, however, with the attractive prospect of a substantial improvement in performance at the same time. Most notably, the performance of the cold source could also be tailored to optimally serve the potential new instruments towards the North side of the source while at the same time increasing the flux for the existing instruments to the South even further.

To validate the potential of both the extension of the facility to the North to host more instruments, as well as of a new cold source, PSI has performed a pre-study that started at the beginning of 2023. Here two aspects were investigated: 1) using current knowledge to improve the cold source, the potential gain factor enabled through such an upgrade was evaluated; and 2) given the space constraints existing towards the North of SINQ (existing buildings and the proximity to the river Aare), the number of instruments that may fit into an extended instrument hall was evaluated. This pre-project has been labelled as the **SINQ++** project.

Concerning 1), the study finds that replacing the original REH solution with a mechanical approach, which avoids radiation-induced boiling of deuterium, significantly improves the cold neutron flux, particularly for neutron wavelengths over four Å. This results in an approximate increase in brilliance of 80% for both the existing ten instruments to the South of SINQ and the potential new instruments to the North (see Fig. 2). We note that further improvements are expected from a complete overhaul of the source improving isotopic purity, temperature, geometry (including low dimensional moderators such as used at ESS) and use of better reflector materials. Additional gains will be achieved thanks to improvements of the High-Intensity Proton Accelerator (HIPA) at PSI that drives the SINQ neutron source. Here both increasing the proton current as well as the focusing and positioning of the proton beam would allow further gains of 30 to 50%. Finally, the existing SINQ lead target can also be optimised in this process to further increase the neutron flux. Compounded together, gains in the cold neutron spectrum of SINQ of well over a factor two can be expected from these improvements. We note that this is also true for the existing instruments, where this gain needs to be multiplied with the flux gains already achieved with the newly installed neutron guides. For example, an instrument already seeing ten times higher flux will achieve an overall gain of larger than 20.

In a second step, PSI also verified how many instruments can be accommodated in the extension of the existing SINQ target hall, as shown in Fig. 3. Here, the neutron spectrum that would be delivered to each instrument position was also taken into account to ideally match instrument requirements and performance. Based on the available space, the maximum extension of the target hall is illustrated via the orange shaded area shown in Fig. 3a. Fig. 3b shows the currently envisioned technical layout of the guide extraction system and possible instrument areas. A PSI working group, comprising experts in instrument design and neutron source simulations, have proposed several types of world-class instruments that could take full advantage of this new arrangement. These new instruments are shown in Fig. 3c.

The instruments marked in light orange are upgraded versions of the existing instruments ICON and BOA. We note that both instruments are heavily oversubscribed where the oversubscription factors (the ratio of requested and available experimental days) is larger than four. Thus, due to this high demand, the upgrade of these instruments will be a strategic investment for the user community. Combining the improved performance of the cold source with upgrades of the instrument, the pre-study shows that BOA would be about 20 times more performant compared to its current form. With a novel neutron optics system based on nested mirrors (known as Wolter optics, see Reference[8]), the ICON beamline could achieve a spatial resolution of approximately one micrometer while simultaneously enhancing the flux by two orders of magnitude. Remarkably, this increase does not yet factor in the additional gains from the improved cold source, bringing the total potential gain to around 200-fold. This would allow the operation of a true neutron microscope featuring a condenser instead of the currently used pinhole geometry and would enable the community to perform *operando* imaging at micrometer length scales as routine experiments (see also section 4.1 below).

The instruments highlighted in green in Fig. 3c are entirely new instrument concepts optimised for the novel cold source design proposed by PSI scientists. Here two current proposals are scattering instruments, notably a new grazing incidence small angle scattering instrument (GISANS) and a multiplexing backscattering instrument. These instrument concepts are dedicated to studies of biological membranes, energy materials, polymers and macromolecules, which are emergent scientific fields as highlighted in the 2021 roadmap.[1] Finally, two more instruments highlighted in red in Figure 3c have not been designed yet. Currently, PSI and SNSS are going through a selection process, where in a first step PSI scientists (Deadline October 31, 2024) have submitted new instrument concepts, and now in a second step proposals by international neutron scientists are solicited. In the fall of 2025, a workshop organised jointly by PSI and SNSS will take place where all instrument concepts will be presented, discussed and reviewed by an external panel of experts in neutron instrumentation before the final selection of the instrument suite to be part of **SINQ++** will be made.

Finally, we note that Fig. 3c highlights three more experimental stations that are not part of the extension to the guide Hall but are envisioned as part of the **SINQ+**+ project. They are denoted in blue and are dedicated to applications in isotope production, nuclear materials and aerospace electronics and primarily use the neutron spectrum of SINQ for irradiation (see also section 4.2). These stations are highly relevant for societal progress and have a large relevance for medical and industrial exploitation of neutrons. The first beamline will be exploited for exposing electronics and chips designed for aerospace applications (airplanes, satellites, rockets) to the neutron spectrum they will experience during flight conditions. While the profile of the neutron energy spectrum will correspond exactly to that of cosmic neutron radiation, its flux will be several orders of magnitude higher, allowing both the testing and certification of these components and avoid costly and fatal failures during actual flight. Close to the actual neutron source two more irradiation stations are proposed: 1) The first will be dedicated to the production of radioisotopes by exposing suitable target materials to the intense flux close to the neutron source for an appropriate time. Here the station will be designed in a way to optimise the spectrum for this purpose. 2) A second station will provide infrastructure for testing of advanced nuclear materials. This includes materials for fourth generation fission reactors, materials used as blanket materials in fusion reactors, as well as materials for transmutation facilities.

In summary, the **SINQ++** pre-study shows that an upgrade of the cold source will result in substantial performance

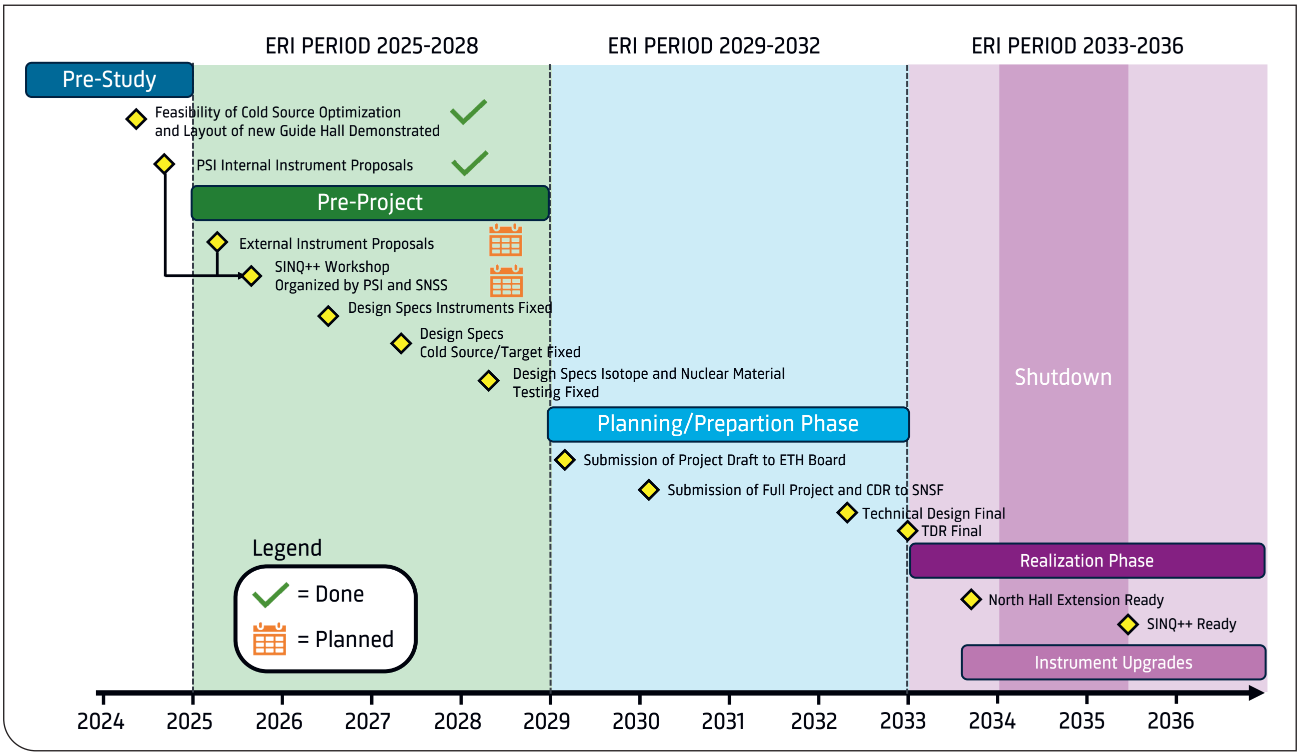


Figure 4: Possible timeline for the SINQ++ project. The pre-study has already been carried out at PSI, and its outcomes are presented in Figure 2 and 3. Currently next steps to define the project scope are underway. It would be feasible to implement **SINQ++** in ERI dispatch period 2033–2036.

gains of SINQ while at the same extending its lifetime. We envision that this upgrade would be carried out in the early to mid 2030ies, extending the ability to operate SINQ well beyond 2050. A possible timeline for the project is shown in Fig. 4. The instrumentation proposed for S**INQ++** would address the emerging needs of the neutron science community and is also well-aligned with Swiss national priorities as well as the missions of the Horizon Europe program. In turn, **SINQ++** will be an important project to address emergent scientific and societal challenges in the following areas:

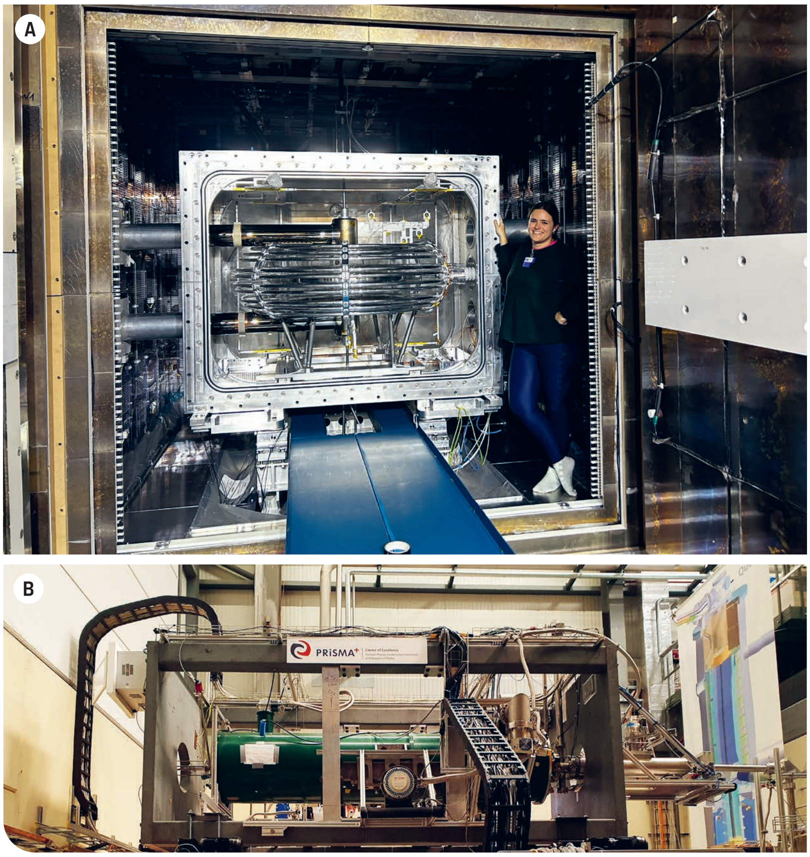


Figure 5: Current experiments at PSI's ultra-cold neutron (UCN) source.
A) The new and upgraded n2EDM experiment and B) the τSPECT experiment are shown.
Source: Viktoria Kletzl/Martin Fertl

- testing of advanced materials for fusion, transmutation and fission materials
- advanced isotope production for radiochemistry and medical purposes.
- fast neutron irradiation for aerospace applications
- *in-situ* and *operando* studies of active/energy materials
- applied materials and engineering
- understanding of biological systems such as cell membranes and proteins
- hydrogenated materials or other materials with functional light elements (i.e. lithium)
- soft matter: medicine, smart coatings, switching devices, food science
- fundamental neutron particle physics (at the upgraded BOA beamline)
- multimodal imaging of hierarchical architectures
- cultural heritage studies
- quantum materials: coherence, entanglement, devices, dynamics

5.1.3 UCN

The ultra-cold neutron source (UCN) at PSI provides world-leading high intensity of storable ultra-cold neutrons for fundamental physics experiments. Most notably, UCN has allowed leading experiments for the search of the neutron electric dipole moment (nEDM) and the precision determination of neutron lifetime, which are important quantities to either search for physics beyond the Standard Model or to understand the early stages of our universe (Bigbang nucleosynthesis). Currently there are two active experiments at UCN (details in the last roadmap). The next generation of instrumentation to search for the neutron electric dipole moment, the n2EDM experiment has been set up and commissioned by the international nEDM collaboration at PSI's UCN source (see Fig. 5). It will start data taking in 2025 to reach $\sim 1 \times 10^{-27}$ *ecm* sensitivity already in the baseline setup. Design and preparations for the upgrade phase 'n2EDMagic' with $\sim 1 \times 10^{-28}$ *ecm* sensitivity goal has already started.

Additionally, together with Gutenberg University Mainz the τSPECT experiment (see Fig. 4) was installed at the PSI UCN source and is at the brink of data taking. Based on the magnetic storage of UCNs, a precision measurement of the neutron lifetime with better than 0.3 s uncertainty in phase one is targeted, with the final goal to exploit the high available UCN intensity to achieve higher precision.

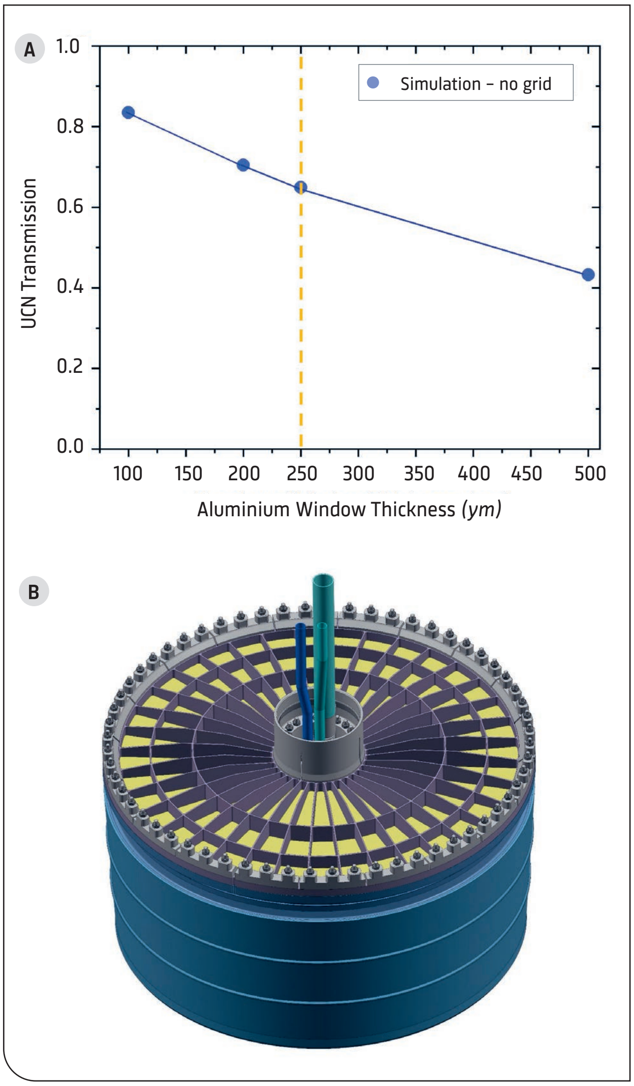


Figure 6: The UCN-EZE project. A) Simulations of the UCN transmission as a function of the thickness of the aluminum moderator window are shown (simulations by Bernhard Lauss, PSI). B) Technical drawing of the current design of the new solid deuterium moderator vessel is shown. The moderator vessel has a diameter of 510 mm and is cooled to five Kelvin to maintain the solid deuterium. The aluminum window needs to maintain a maximal internal pressure of up to three bar and maximum external pressure of one bar. The grid seen on top is to support an aluminum window (shown in yellow) of about 250 *μm* thickness that is clamped between the upper and lower halfs of the grid. The simulations show that compared to the previous window thickness of 500 *μm* the UCN transmission should be improved about 50%, however, due to the supporting grid, only 30% are expected. Source: Jörg Welte/Bertrand Blau

5.1.4 UCN-EZE project

UCN has been in regular user operation since 2011 and achieves the highest intensities of UCNs by exploiting the high intensity proton beam of the HIPA proton cycloctron at PSI in combination with the high UCN yield in solid deuterium at a temperature of five kelvin. Capitalizing on the vast experience gained over more than ten years of operation, a project called UCN-EZE ('UCN-Ersatz Zentral Einschub', German for replace of central insert) was started in 2023 and planned to be completed in 2027 in order to guarantee the long-term availability of UCN and at the same time improve its intensity. The project aims to replace UCN's central, cryogenic insert. Notably, the aluminum window separating the solid deuterium moderator from the UCN storage volume, which distributes UCNs to various experiments, will be half as thick as previously, which is expected to improve the UCN yield by about 30% (see Figure 6). Both the n2EDM experiments as well as the new τSPECT experiment will naturally benefit from this upgrade.

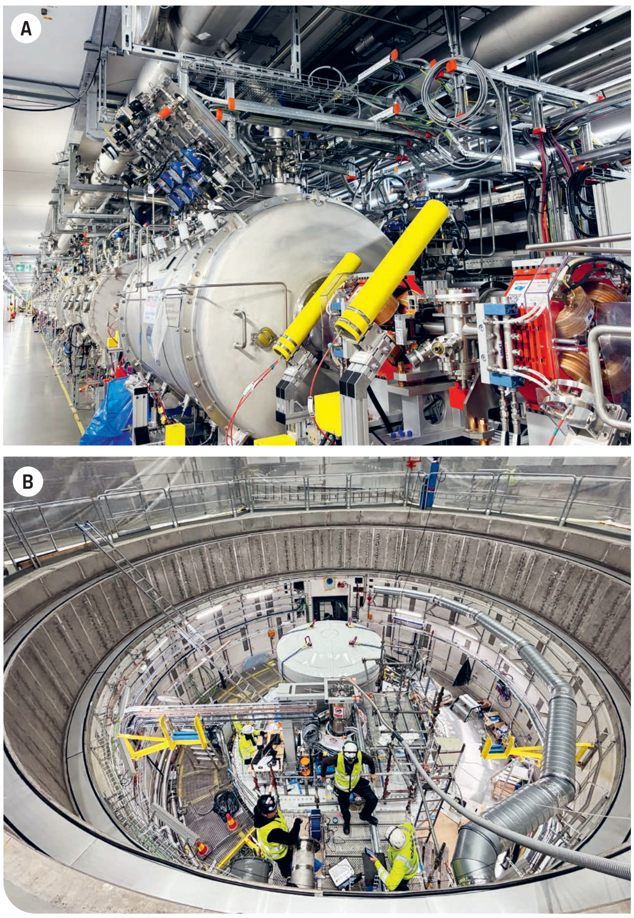


Figure 7: Progress at the European Spallation Source (ESS). A) Completed superconducting section of ESS's linear proton accelerator. B) Last work being down on the ESS target block, where in the center the drive shaft for its rotating tungsten target can be seen. Source: ESS

5.2 European spallation source

Switzerland is a member of the European Spallation Source (ESS) under construction in Sweden, which will be the world's premier neutron source for the decades to come. ESS construction is financed via in-kind contributions from its 13 member countries.

Switzerland is investing a total of 155 million CHF and significant intellectual resources in the construction and initial operation phase of ESS. Most of the Swiss in-kind contributions are managed by PSI, contributing additional unique human skills and technical resources to ESS. As a result, PSI is a partner in no less than five of the 15 instruments currently under construction at ESS. These instruments are the multiplexing spectrometer BIFROST that is based on CAMEA technology from SINQ (Swiss contribution 35%), the advanced Selene-type reflectometer ESTIA that is based on technology of AMOR (Swiss contribution 100%), the diffractometers HEIMDAL (Swiss contribution 35%) and MAGIC (Swiss contribution 15%), and the imaging instrument ODIN (Swiss contribution 35%).

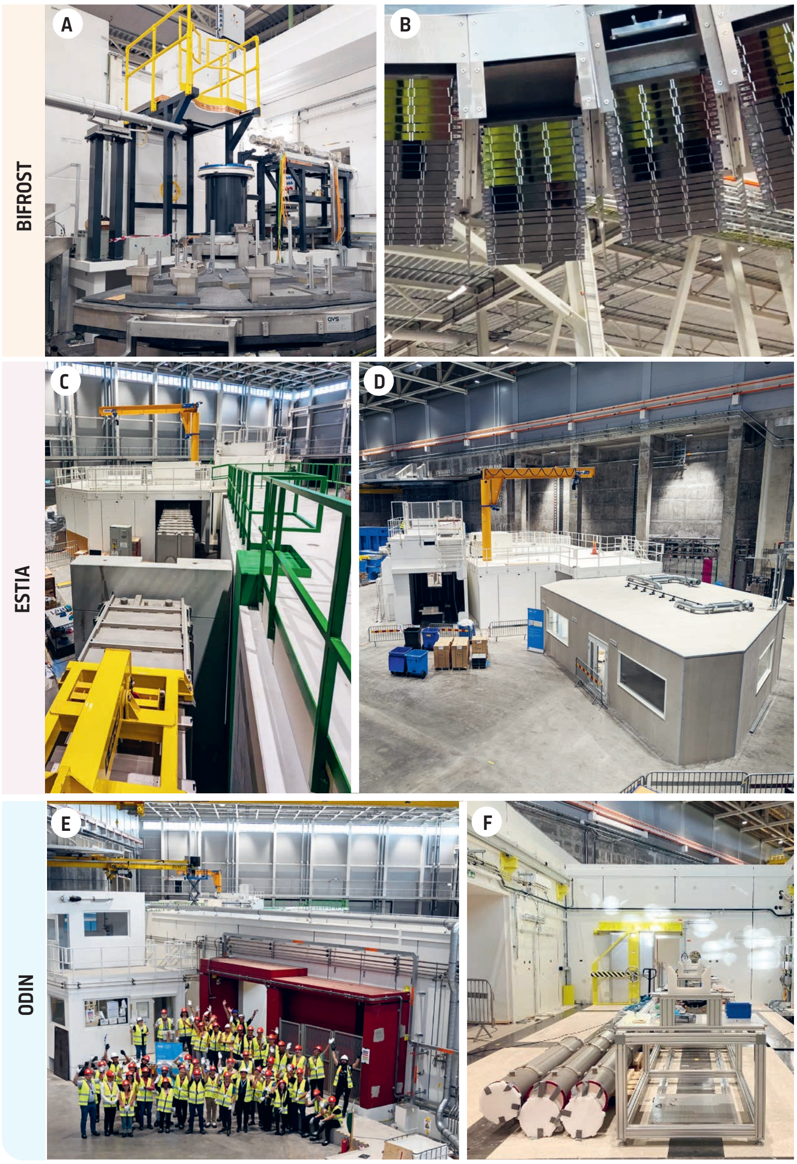


Figure 8: Progress of the three ESS Instruments BIFROST, ESTIA and ODIN. For all three instruments PSI has provided major contributions. ESTIA was solely designed and built by PSI. A) BIFROST Cave Interior with Optics, B) BIFROST Analyzer Array, C) SELENE Neutron Optics, D) ESTIA Cave and Control Hutch, E) ODIN Cave and Control Hutch and F) ODIN Cave Interior Source: Rasmus Toft-Petersen, Jos Cooper, Robin Woracek, ESS

ESS is currently in the so-called initial-operation phase during which the facility is not in full user operation yet, but components of the facility are brought into operation step-by-step. Notably, the ESS linear proton accelerator is nearly complete and the first beam through the completed accelerator onto the beam dump is planned to occur in February 2025 (see Fig. 7). Similarly, the target station is nearing completion, and the first beam on completed target is as of writing of this roadmap expected in the last quarter of 2025 (see Fig. 7). This milestone is known as BOT (beam on target) at ESS. Full user operation with the completed suite of instruments is currently foreseen for 2028. Out of the five instruments with Swiss contributions, the instruments BIFROST, ESTIA and ODIN are expected to be completed by the end of next year, and they will be available to receive first neutrons at BOT or shortly after. The current state of BIFROST, ESTIA and ODIN is shown in Fig. 8, illustrating that all three instruments are close to completion.

5.3 Updates on the Swiss neutron science community

In the first neutron science roadmap published in 2021,[1] we showed that the Swiss Neutron Science community has not only continuously been growing with a rate of at least 5% per year, but also provides a substantial fraction of the neutron science output in Europe. Notably, a bibliometric study based on a machine-learning-assisted analysis of around 46,000 manuscripts published between 1956 and 2020, which is now publicly available,[9] showed that 10% of all European neutron science articles are generated with Swiss contribution (see Fig. 13 in Ref.[1]). Given that Europe remains the most productive neutron science region world-wide, already at this time, we argued that normalised to its population, Switzerland may be considered the leading neutron science nation worldwide.

Indeed, this has now been confirmed by an independent study carried out by LINXS,[2] the Swedish Institute of Advanced Neutron and X-ray Science. This study defines the expression participation, i.e. the number of publications that a country or world region appears on the author affiliations. With 73% participation to the global output of neutron scattering between 2012 and 2021, Europe remains the most productive region world-wide. Among all countries Switzerland sits on the 8th place (and 5th in Europe) with 9% participation, only preceded by countries with larger population (Fig. 9a). However, when the size of the country is accounted for by normalizing the findings per 10,000 capita, Switzerland squarely sits on the top spot with a normalised participation of three (see Fig. 9b). Apart from the second- and third placed countries Netherlands and Sweden, all subsequent countries have a normalised participation that is one third or less of the Swiss participation.

The trend of a growing Swiss neutron science community is also reflected in the usage statistics for Switzerland's national neutron facility SINQ. Fig. 10a shows the total submitted proposals for each year over the last 15 years and illustrates that the number of user requests have been continuously increasing. This is similarly true for the number of requests from Swiss user groups (red line), for which the current growth rate corresponds to about 8%, which is even stronger compared to 2021 when the last roadmap was published. In Fig. 10b, we show the average oversubscription of SINQ as a function of year that is defined as the number of proposals requested divided by the number of proposals receiving experimental time averaged over all instruments. It can be seen that before the SINQ guide upgrade that was carried out during the years 2019 and 2020 the average oversubscription was around two, which is generally considered as healthy for user facilities because this value ensures that proposals receiving beam time are of high scientific quality. However, since 2020, the oversubscription has now risen towards three, with some of the SINQ instruments having an oversubscription of up to six. The origin of this increase is two-fold: on the one hand, it is a symptom of several European neutron sources (HZB, JEEP-II, Orphée at Saclay) having been shut down permanently, while others are either in a prolongated temporary shutdown for maintenance (FRM-II) or have not started user operation yet (ESS). Thus, the access to neutrons in Europe (and actually world-wide) has become increasingly more difficult in the last decade. On the other hand, the SINQ guide upgrade has also increased the efficiency of the neutron instrumentation at SINQ, and some instruments have seen increased popularity and new user communities from outside of Europe such as the United States. At the same time new user communities such as the Swedish community have been emerging in preparation of the European Spallation Source (ESS) anticipated to come online for user operation in 2027/2028. We also note that the improvement of SINQ instruments since the guide upgrade is visible in Fig. 10c, which shows the average number of days required for each experiment granted. Notably, the average number of days per experiments has only decreased by 10% in the ten years prior to the upgrade but increased by another 10% within three years of completion of the upgrade.

A further sign of a growing community is that the Swiss Neutron Science Society has also seen strong increase of its membership numbers. Over the last two years the number of SNSS members has grown by over 60%, after being stable at about 200 members for many years (see Fig. 11). There are several reasons for the strong growth. First, the increased capabilities available at SINQ and UCN have attracted new members. In addition, the anticipation of new capabilities that will become available at the European Spallation Source also is attracting interest. However, equally important, the society has recently extended its scope to include all scientists and industry users using neutrons whereas previously the society was predominantly focused on neutron scattering. Over the last few years, we have reached out to the various user communities of neutrons and have successfully integrated them in the society. Next to neutron imaging and fundamental physics, this includes scientists in radiochemistry and medical use of neutron-rich radioisotopes, as well as scientists working on new generations of fission as well as fusion reactors. Although, this strong growth will eventually reach a saturation point, we foresee that the strong current growth will continue for the foreseeable future.

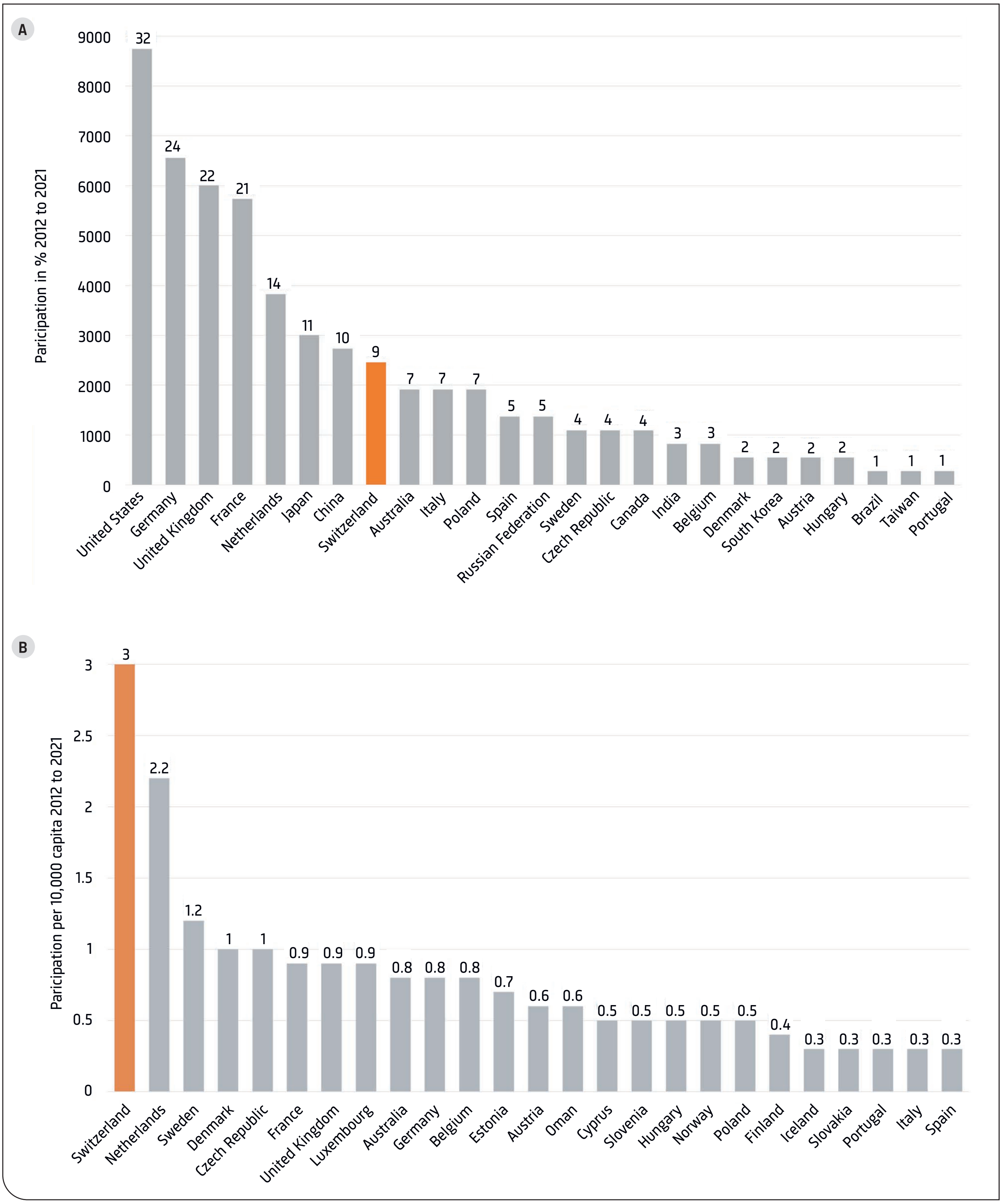


Figure 9: Results of the LINXS Study.[2] This study defines the expression participation, i.e. the number of publications that a country or world region appears on the author affiliations. It finds that between 2012 and 2021 about 46,000 papers have relied on neutron scattering to obtain their results. Panel A) shows both in absolute numbers (vertical axis) and in percent (labels on bars) how high the participation per country to these publications in this period was. B) The same data is shown but this time normalised by 10,000 capita. Switzerland is highlighted in orange in both panels.

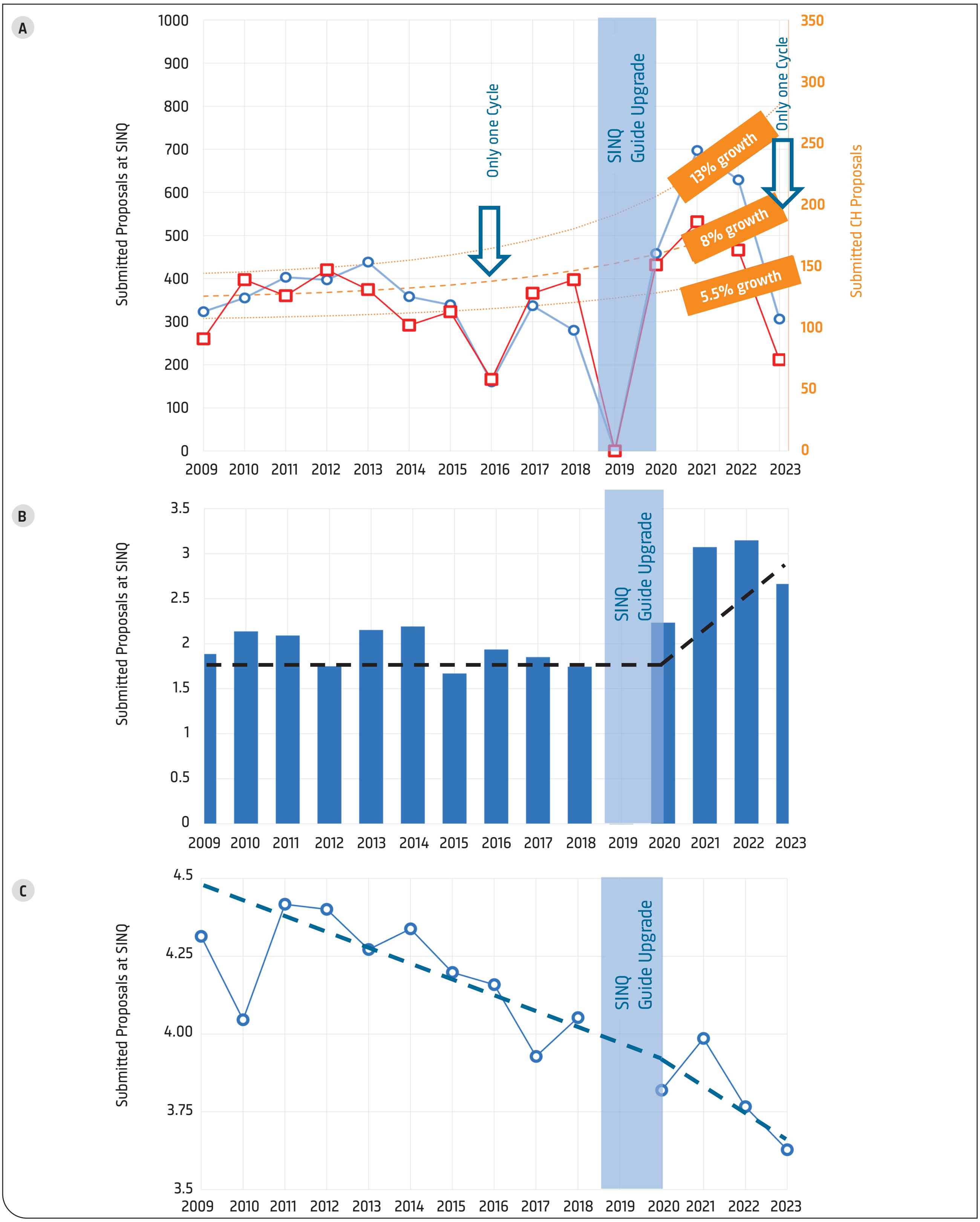


Figure 10: SINQ statistics. We present statistics kindly provided by the PSI User Office. A) The number of proposals submitted each year is shown over the last 15 years. The blue curve is the total number of proposals whereas the red curve denotes the proposal submitted by Swiss scientists. The orange dashed and dotted lines give estimates of the average and minimal/maximal growth of the submitted number of proposals to SINQ, respectively. They were obtained via exponential fits. B) The overall subscription error averaged over all instruments is shown. C) The average number of days per experiment is shown. The blue shaded region in all panels denotes the time when SINQ was shut down for the SINQ Guide Upgrade.

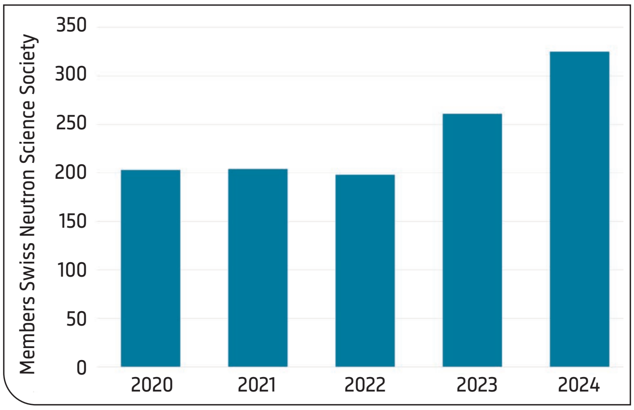


Figure 11: SNSS membership numbers. We show the development of the number of members of the Swiss Neutron Science society over the last few years.

We also note that out of the currently 325 members about 100 are postdocs or students currently being educated as neutron scientists. Therefore, early career scientists keep being added to the community at a healthy rate, suggesting that neutron science will remain an important field of expertise in Switzerland.

A key point is that the strong and successful neutron science community also has resulted in successful Swiss companies such as SwissNeutronics, which delivers neutron optical components to all neutron sources worldwide and ANAXAM, which aides Swiss SMEs to exploit large-scale analytics with neutrons for development of new products.

5.4 Shifts in the European neutron ecosystem and effects on the Swiss community

As showcased above, the European neutron science community remains the most dominant player in terms of output world-wide, and Switzerland is arguably one of the most successful countries in this landscape (see also Fig. 8). This success is based on a solid and well-proven strategy that combines several pillars:

- Competitive national neutron sources: with SINQ and UCN at PSI, Switzerland operates its own neutron sources that serve to satisfy the immediate demand for neutron beam days by the Swiss community, and also allows to train early-career scientists in the use of large-scale neutron user facilities. In particular, UCN remains a world-leading facility for fundamental science experiments with ultra-cold neutrons. SINQ is a medium-flux source with competitive instrumentation. At the same time, with both facilities being situated at PSI, with its leading expertise in developing and innovating large-scale scientific operations, this allows to respond to emerging scientific topics by designing pioneering instrumentation

- Around these successful Swiss facilities, a strong Swiss neutron science community has emerged with scientist not only situated at PSI but at many other Swiss universities and scientific institutions.

- In addition, a commensurate investment in European-scale flagship facilities such as the Institut Laue-Langevin (ILL) for which Switzerland is a member state, allows Swiss scientists access to state-of-the-art instrumentation not available at their national facility. Crucially, this enables Swiss scientists to contribute to novel instrumentation originally invented in Switzerland but then installed at these flagship facilities. Examples are the BIFROST, ESTIA and ODIN instruments at the European Spallation Source to which Switzerland is contributing based on technology invented at PSI for the instruments CAMEA, AMOR and ICON. This also ensures that Swiss neutron scientists are well-embedded in and connected to the surrounding European neutron science community, which for example allows to attract leading neutron scientists to Switzerland.

Although, as evidenced above, this strategy is highly successful, it will face increasing challenges over the next decade. As discussed in the original neutron science roadmap published in 2021, the past European neutron ecosystem consisted of ten low/medium-flux national sources, three medium-flux sources (FRM II, ISIS and SINQ) and the worldwide highest-flux source, ILL. However, of the ten low/medium-flux sources, the two with the strongest user programs, LLB in Paris and BER2 in Berlin (both of which were frequently used by the Swiss scientific community) have already been closed. In the last roadmap, we speculated that by 2025, only five neutron sources with international user programs will remain: ESS, ILL, ISIS, FRM II and SINQ. However, ESS, which was expected to come online in 2023 at the time the last roadmap was published, has faced delays due to the COVID-19 pandemic and the geopolitical situation. ESS is now expected to produce first neutrons only at the end of 2025, with the full start of the user program only foreseen in 2028. At the same time, FRM-II has been temporarily shut down since 2021, and is only foreseen to come back into partial operation during 2025. Here it will initially only deliver thermal neutrons as the replacement of its cold-source remains ongoing for some more time. In conclusion, this situation has presently created a 'neutron drought' in Europe.

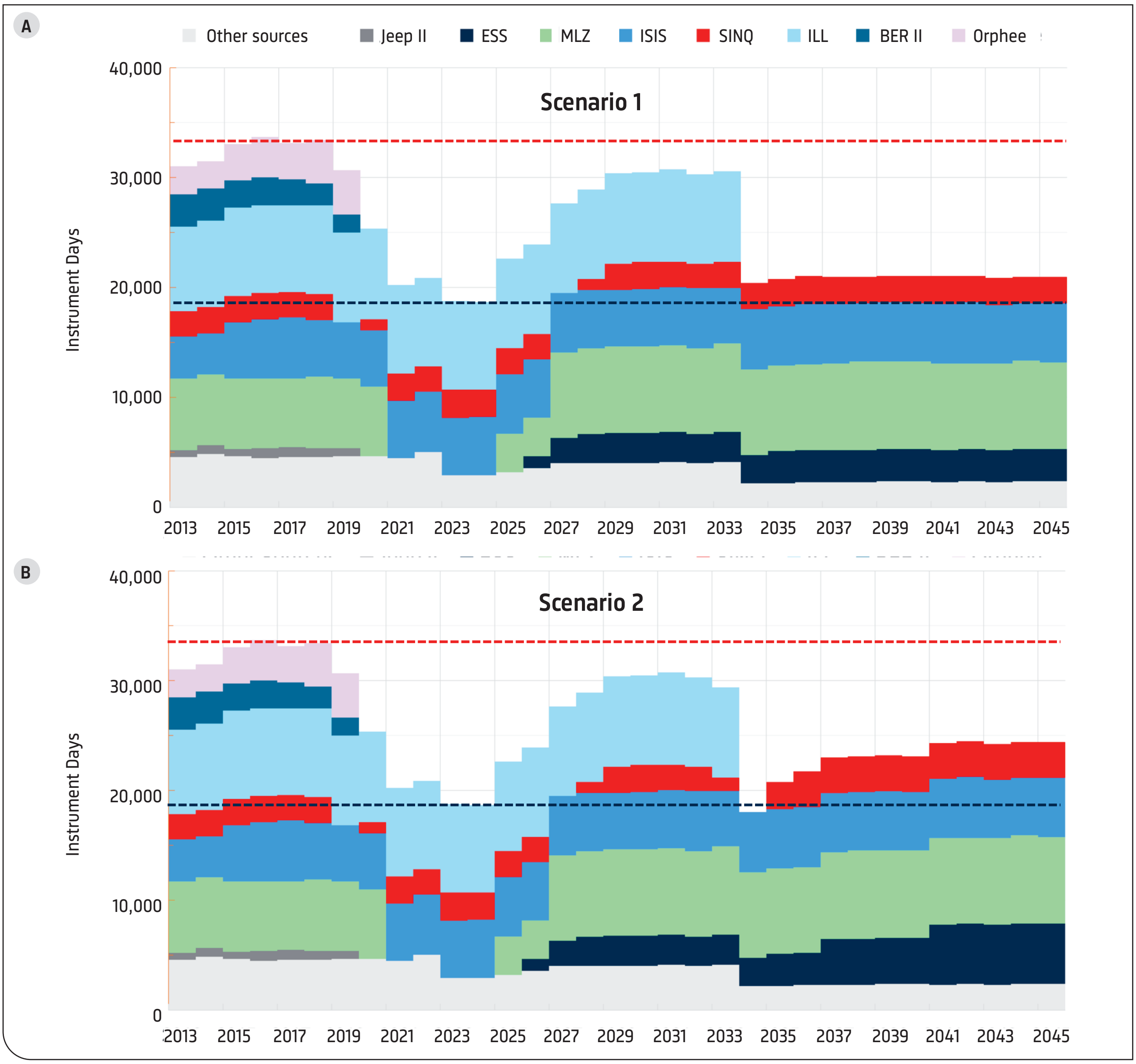


Figure 12: Available neutron beam days in Europe. We show two scenarios, which are based on the numbers provided in the 2016 ESFRI Report and that were updated in the recent report by the League of Advanced European Neutron Sources (LENS). We additionally consider that the FRM II has been shutdown since 2021. Panel A) corresponds to the considered currently established baseline scenario that the MLZ reactor will start up again next year (also with somewhat reduced capacity initially), that the ILL runs until 2033 (which is the most optimistic scenario currently being discussed), and that ESS will start operating by the end of 2025 and will reach a full capacity of 15 instruments in 2028. B) A more optimistic scenario is shown where SINQ will be upgraded with 5 additional instruments available by 2036, and that eight instruments will be added to ESS by 2035 and an additional 7 by 2040. The red and blue dashed lines denote the maximum and minimum number of beam days available in Europe since 2013.

We illustrate this situation in Fig. 12, which shows the number of neutron beam days in Europe as a function time. Due to the temporary shutdown of FRM II, it can currently not deliver any neutron days (see light green curve in Fig. 12a), and as a result the overall access to neutrons has been reduced much more strongly than anticipated. Although, this temporary shutdown of the FRM II reactor is unfortunate for the German and European communities, it also serves to highlight the challenges that we will face in the future. Notably, as can be seen from Fig. 12a, even after FRM II comes back online next year, and additionally ESS will slowly starts to produce neutron from late 2025 on (dark blue), due to the imminent shutdown of ILL currently foreseen in 2033 (best case scenario), the total number of neutron days provisioned starting from 2033 on, will be only ~10% more than in the present ‘neutron drought' (cf. dark blue dashed line in Fig. 12a) and will be about 40% less compared to the maximum of neutron days that were available around 2017 (cf. dark blue dashed line in Fig. 12a).

Before moving on to discussing the effects of this neutron drought onto the Swiss neutron science community, it should be emphasised that this baseline scenario already includes measures to mitigate this situation for Swiss neutron scientists. These measures explained in the following are well appreciated by the community. Switzerland is a long-time member country at the ILL, which was built originally in 1971 as the world's premier neutron source and through a series of extensive upgrade programs both of the reactor itself as well as of its extensive suite of instruments, the facility has remained in a leading position since then. Switzerland has been a member of the ILL since 1988. Due to the delays of the new European flagship facility ESS, in which Switzerland is also deeply invested, the Swiss membership to the ILL has been extended even with increasing financial contributions to at least 2028. Currently, it is certain that ILL will run at least until 2028, and viable options to extend its operations up to either 2030 or 2033 are being considered. Switzerland has already signed a contract with ILL that extends its membership in case either of these options become reality. This, in turn, will help Swiss scientists through the period until ESS is fully operation. For Fig. 12a the most optimistic scenario of the ILL running up to 2033 has been included. In this scenario, as soon as the FRM-II reactor is providing neutrons again, the number of available neutron days will reach 90% of its maximum in 2017. However, as soon as the ILL will be shutdown permanently, the neutron provision will be at about the same level as the current 'neutron drought'.

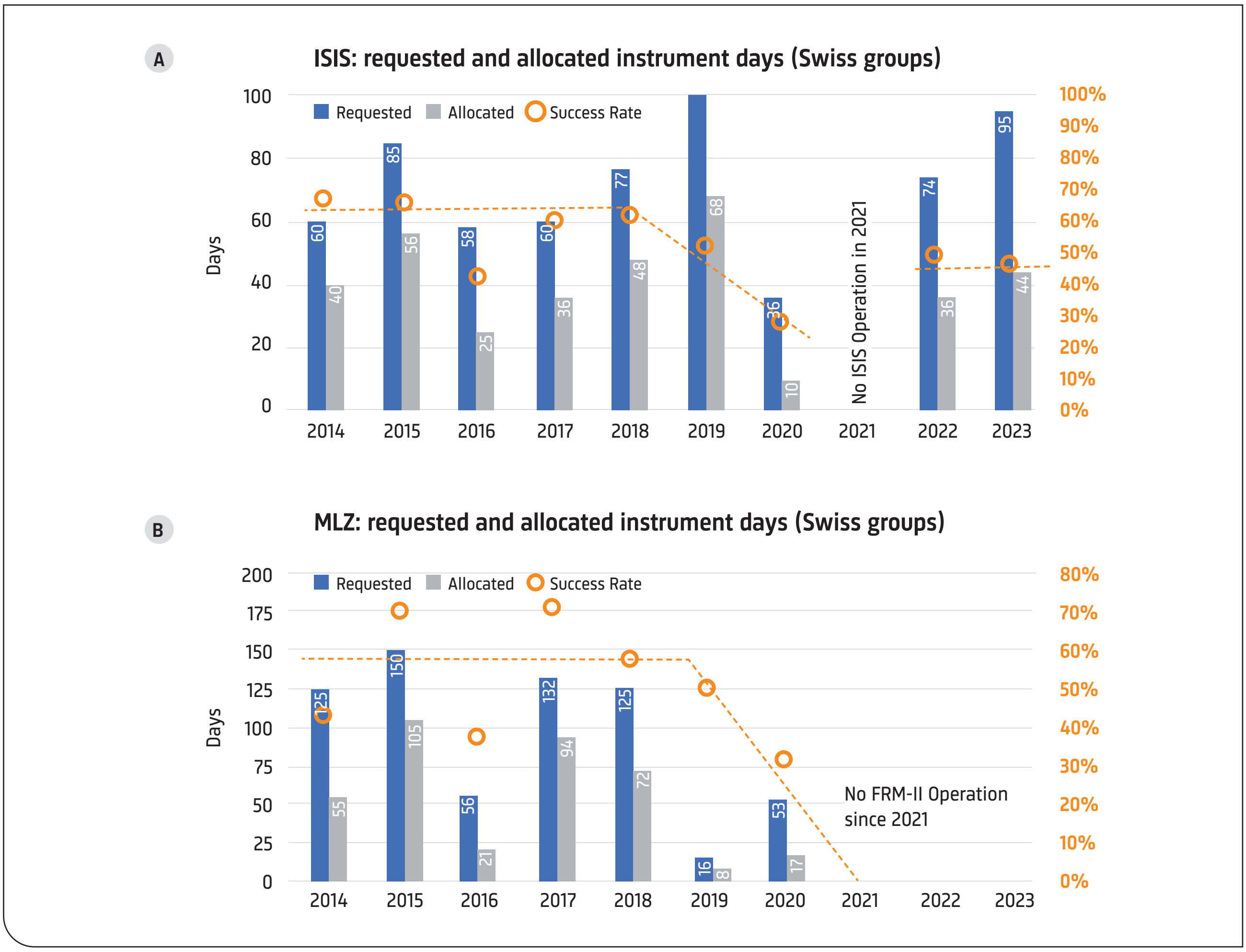


Figure 13: User access of Swiss neutron scientists at other national neutron sources. The graph shows the number of neutron beam days requested by and allocated to Swiss neutron scientists at A) the ISIS neutron source in the UK and B) the FRM-II in Germany, respectively. The orange circles provide the corresponding success rate. The orange dashed lines are guides to the eye. Numbers were provided by the user offices of ISIS and MLZ, respectively.

In Fig. 13, we show the consequences of this neutron drought. It shows the neutron days requested by and allocated to Swiss neutron scientists at FRM-II in Germany and ISIS in the United Kingdom. It is clearly visible that at both sources the access to neutron beam time has become harder for Swiss scientists over the last few years. At the same time, because the entire ecosystem of sources is under pressure, there is also more demand of European neutron scientists to request beam time at SINQ, which has slightly reduced the fraction of Swiss experiments at SINQ. Naturally, in the short-term this is not desirable for Swiss groups; however, it needs to be considered that compensating for currently not running sources elsewhere is in the interest of Switzerland, at least in the mid-term. All European neutron sources form an interconnected ecosystem, where scientists of all sources need to collaborate. Notably, Swiss students frequently carry out their postdoctoral studies at other neutron sources outside of Switzerland, and at the same time, we benefit from international neutron experts being hired at SINQ. Similarly, neutron technology development is often carried out in collaboration and with immense synergies with other sources.

However, we also caution that the situation cannot remain like this in the long-term as it will eventually lead to a stagnation of the very successful Swiss community. In particular, this has detrimental effects on educating the substantial fraction (about one third, see section 3.3) of earlycareer scientist (PhD students and postdocs) who are part of our community. For example, an oversubscription of instruments or facilities of about two is considered healthy. In contrast, at SINQ the average oversubscription is now reaching three (see Fig. 9b) with some instruments seeing oversubscription factors of over five. In other words, statistically speaking, to get beam time on such an instrument, a PhD student has to propose an experiment an average of five times before being granted neutron time. Most facilities have two proposal rounds per year, meaning that this entails a wait of 2.5 years, which is not viable for PhD projects in the long term.

In 2028, the full user program of ESS will start, and the Swiss community who is deeply invested in bringing this new flagship facility operational, is looking forward to using its advanced capabilities. Already based on a pure capacity argument, which contrasts the 45 internationally leading instruments operated at the ILL with 15 advanced instruments at ESS, it is clear that at least initially, and despite its superb suite of instruments, ESS will not replace the capacity offered at the ILL. Apart from capacity, it is crucial that reactor and spallation neutron sources do deliver unique neutron spectra and, in many regards, may be considered as complementary (see for example Ref.[9]). While most experiments can be carried out at both types of sources, each has their unique strength, and ideally a healthy ecosystem should contain both types, even for flagship facilities such as the ESS and the ILL sources. An important example are fundamental physics experiments, for which the ILL currently provides important and unique capacities. Unfortunately, despite a plethora of proposed activities, ESS is not yet optimised for hosting such experiments.[12]

For completeness, we add that Germany, France and Spain are currently working on developing so-called High-Current Accelerator-driven Neutron Sources (Hi-CANS) that eventually may be used as their national neutron sources. Although, this development is important, also because the characteristics in terms of brilliance and resolution will be complementary to existing neutron sources, and therefore will provide access to new scientific challenges, we note that we do not know yet if they will deliver their potential as full-scale facilities. Therefore, we do not consider them in our analysis, as it remains uncertain if and when they may be added to the ecosystem. Finally, we also mention that in the UK the Science and Technology Facilities Council (STFC) is preparing to apply for funding for an upgraded ISIS-2 facility. If funded, which is currently not known, its construction should start in the early 2030s and the project would be finished by 2040.

Concluding, for the foreseeable future, the European and, in turn, also the Swiss ecosystem for provisioning neutron access will remain strained. It is also clear that for Switzerland, the key role of its own national facility SINQ will become even more important. Further, this picture shows that upgrading and continuing to operate existing and proven facilities is the most cost-effective way to increase neutron capacity. For example, in Fig. 12b, we provide a more optimistic scenario compared to the baseline compared in Fig. 12a that is based on increasing the number of instruments at ESS by eight more coming into operation by 2035 and a further seven instruments by 2040. Additionally, it assumes that the **SINQ++** project would be carried out, which would add five additional instruments while increasing the efficiency of existing instruments by a factor two to three. In this scenario, the available amount of neutron days will reach about 75% of the maximum in 2017, even after the ILL shuts down. However, even in this optimistic scenario, either new sources have to come online, or the ILL has to remain operational beyond 2033 so that the European ecosystem of sources reaches full strengths again. In addition, as a premier neutron science facility, ILL is also an important provider and developer of neutron technology, which created many synergies with other facilities in the European ecosystem.

6 Future needs of the neutron science Community

5.1 Increased demand for complex scattering and imaging experiments

The scientific drivers and fields identified in the Neutron Science Roadmap published in 2021[1] remain relevant, even though new directions have naturally emerged in the identified fields. However, instead of discussing nuanced shifts in topics in detail, here we will focus on an overall trend that can be traced in all topics that rely on neutron scattering and imaging experiments. Notably, there is an increased need for more complex experiments. This includes *operando* experiments as well as experiments carried out at extreme conditions of matter. In general, these experiments have high demands in terms of effort but also require increasingly optimised setups. We note that this list is not extensive but rather serves to highlight the general trends observed in the community. An additional factor is that there is an increasing complexity of materials and problems that are investigated. Notably, many key questions require to collect information on several hierarchical levels of length and/or time scales. This entails that to solve the question at hand, neutron users have to request and use a combination of instruments sensitive to different length- and/or time scales in combination with extreme conditions.

6.1.1 *Operando* experiments

Investigating the changes of states or properties of a system or materials as a function of time under real world operational conditions is key to understanding processes, developing new devices and achieving optimal performance. This is particularly true for energy devices for heat storage, electrolysis, fuel cells, batteries and power-to-gas applications. Similarly, time dependent processes in biological systems such as the plant root water uptake, water distribution in building materials such as concrete and wood, or the distribution of adhesives in materials benefit from such *operando* techniques. Another example is the study of additive manufacturing techniques such as the laser powder bed fusion metal additive manufacturing setup available at SINQ, which is shown in Fig. 14. Due to their penetration power, neutrons are an ideal probe for such studies as they can penetrate a device revealing changes of multiple materials and components. This can be achieved both with imaging and scattering studies. The complexity of such *operando* measurements is driven by the requirement that the experiment has sufficient time resolution to map the temporal evolution of a system and provide the details required for understanding the process. Naturally, such experiments require instruments optimised for a high neutron flux allowing fast data acquisition. A further challenge derives from the large amount of experimental data to be transferred, stored and analyzed. Such challenges entail that *operando* experiments are not always possible, but in general the demand for such experiments and, in particular, their speed and complexity, are increasing. This is also driven by novel capabilities at SINQ, which allow higher temporal resolution, more complex sample environments/*operando* devices with an improved infrastructure on the instruments for *operando* studies. Overall, this demonstrates that the gains in flux achieved through the SINQ guide upgrade are mostly used to address new scientific questions and not to perform more experiments of the same kind on average. This means the average time required for experiments has only marginally improved (10% as can be seen in Fig. 9c) despite substantial flux gains. We note that the **SINQ++** project proposed in sections 3.1.2, represents a unique opportunity to build new imaging instruments that receive cold neutrons from a new cold moderator, optimised for *operando* experiments.

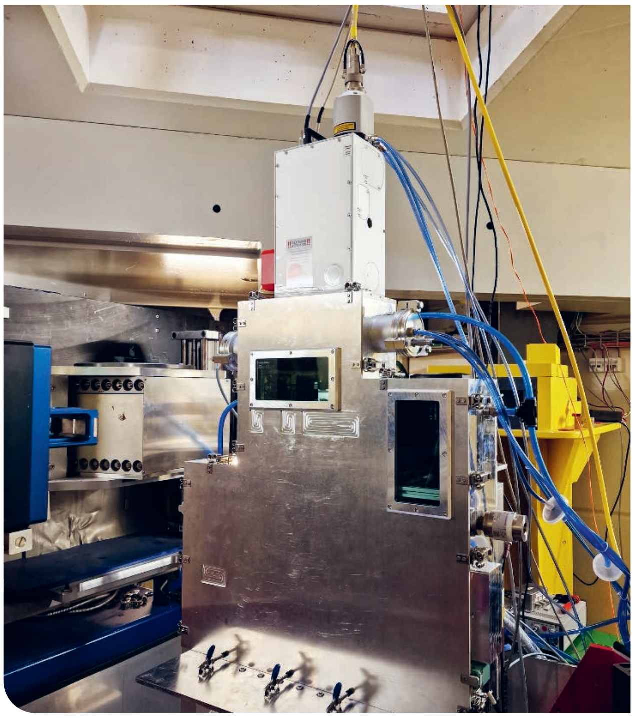


Figure 14: Laser powder bed fusion metal additive manufacturing setup installed at POLDI at PSI. The setup allows *operando* experiments on the understanding of additive manufacturing processes. Source: Shieren Sumarli

Figure 15: Experiments at the extremes of matter at SINQ. A) Gediminas Simutis from the SINQ Sample Environment Team is installing a high-pressure cell into a cryomaget at DMC. B) Users Grace Longbons (University of Notre Dame) and PSI Postdoc Tina Ahr install an uniaxial pressure stick developed at PSI into a cryomagnet at SANS-1. C) The sample installed in the pressure cell is highlighted. Panels D – F show the increased demand for such complex experiments. D) The number of requested proposals with extreme condition sample environment is shown by type. E) The same information but as percentage of the total available beam time is shown. Such experiments are now almost havlf of all experiments. F) The number of requested and allocated experiments relying on high magnetic fields is shown. The demand now outweighs the availability by more than a factor two.
Source: Gediminas Simutis: PSI, data from PSI sample environment group and user office

6.1.2 Experiments at multiple and combined extremes of matter

Neutrons have always been exploited to understand the atomic-scale structure and dynamics of materials when they are exposed to extreme conditions. This entails that the material of choice is subjected to extreme heat, to ultra-low temperatures, high magnetic or electrical fields or high pressures. The key advantage of neutrons is that they exhibit high penetration power, and thus they can travel through the required apparatus (oven, cryostat, magnetic field coils, pressure cells) that is used to expose the material of interest to these extreme conditions, and allow researchers to study the response of materials to in these conditions. Despite the ideal properties, such experiments typically have higher requirements for neutron flux and signal-to-noise ratio as achieving these conditions only allows for smaller samples. Such extreme conditions are relevant for studies in quantum materials, engineering materials or topics such as chemistry or geology.

Thanks to the SINQ guide upgrade and new instruments such as the diffractometer DMC and the spectrometer CAMEA that were designed for this use case (see section 3.1.1), the feasibility of such experiments at PSI has recently been vastly improved. In particular, the ability to carry out high-pressure experiments at SINQ is increasing due to the development of new pressure cells but also advances in neutron optics using focusing guides and 3D-printed collimation and shielding developed at PSI. Thanks to these improvements the demand for such experiments has exploded over the recent years, where it has become common to carry out experiments that include the combination of up to three extreme parameters such as a combination of low temperature, high magnetic field and high pressure all at the same time (see Fig. 15 a–c).

In Figs. 15d–f, we show that the demand for experiments requiring high magnetic field, ultra-low temperatures, and high pressures, respectively, has dramatically increased. In Fig. 15d we show that the number of experiments that require either high magnetic field, ultra-low temperatures, or high pressures has doubled in the last few years. Fig. 15e shows the same information but as a percentage of the total experiments carried out any given year. This shows that about half of all experiments now require extreme conditions, which is a massive increase compared to times before the SINQ guide upgrade. In Fig. 15f, we show that the number of requests of high-field experiments outweighs the number of experiments that can be accepted by more than a factor two. This is similar for the other types of extreme conditions experiments. We note that the capability to carry out experiments relying on extreme sample environments at SINQ remains approximately the same because the number of cryostats and magnets remains identical. Only the number of optimised high-pressure devices has been improved. This highlights that despite the improvements in instrumentation at SINQ, it remains challenging to meet the demand for these experiments and the need for advanced instrumentation able to handle experiments at extreme conditions remains. As we show in section 3.1.2 the **SINQ++** project combined with other developments is a valid path forward to address this challenge.

Finally, we note that while the capability to reach the extremes of low-temperature and high-pressure is very similar or some cases better to what can be achieved with other methods, the capability to reach high-magnetic fields using neutrons is currently limited to 15 T with static fields and around 40 T for pulsed fields. However, the latter can currently be only used at the ILL and is only of relevance for specific cases. In turn, Swiss activities to develop new superconducting solenoids based on high-temperature superconducting (HTS) tapes such as pursued in CHART are highly relevant to the neutron science community.

6.2 Additional opportunities for Swiss neutron science

6.2.1 Radioisotope production for medical applications

SINQ is already used in the context of radioisotopes for medical applications. The Swiss Center for Radiopharmaceutical Sciences (CRS), together with its partner at ETH Zurich and various Swiss hospitals, plays a central role in the development of innovative radionuclides and radiopharmaceuticals with the aim of clinical translation in Switzerland. Its bench-to-bedside capacity is based on radiopharmaceutical expertise and know-how in radiochemistry (in collaboration with the Laboratory of Radiochemistry at PSI), preclinical research and Good Manufacturing Practice (GMP). CRS/LRC operates the neutron irradiation stations NIS at SINQ, which has been fundamental in the development of Tb-161,[11] regarded as a very most promising therapeutic radionuclide of the future.[12, 13] Currently, SINQ is mostly exploited to identify potential radionuclide production routes in preparation of reactor irradiations, as well as for the manufacture of radioactive tracers for benchmark separation experiments. However, the NIS station is currently not equipped to produce the quantities that are needed e.g. for large-scale clinical trials.

To ensure access of Swiss researchers to such larger-scale productions, Switzerland has invested in the radionuclide production facility at the ILL in Grenoble. In many cases, such as for the production of Sc-47, the use of ILL's high-flux of thermal neutrons is vital. In addition, a new

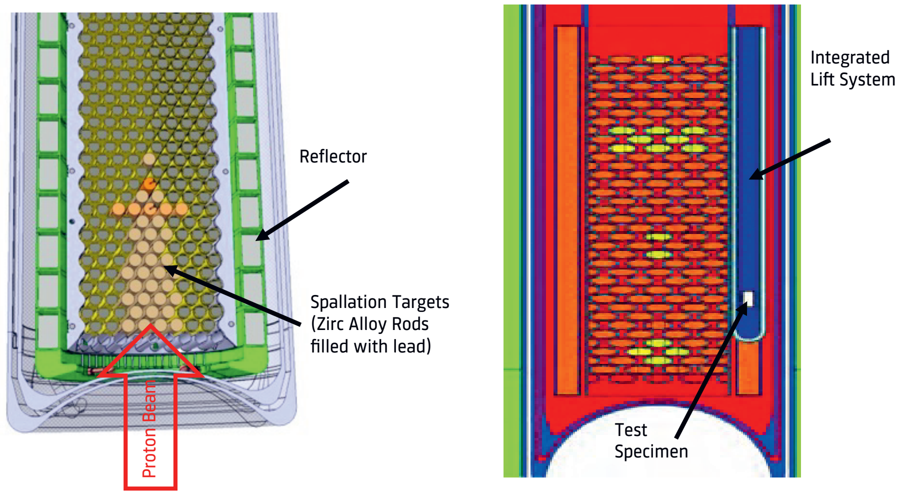


Figure 16: Proposed flexible material irradiation facility at SINQ. Left: The current design of the SINQ lead spallation target is shown. Spallation neutrons are produced when the protons hit the lead in the zirc alloy rods. Right: Simulations have shown that the ideal position for fast neutron irradiation would be in the reflector tube surrounding the spallation targets. A sketch of a possible lift system to lower specimen into the region of the highest flux is shown. Source: Jörg Welte (PSI) and Luca Zanini (formerly PSI and now ESS)

project called IMPACT (Isotope and Muon Production using Advanced Cyclotron and Target technology) at PSI if funded for the ERI dispatch 2025-28, will realise the new facility for proton irridiation of targets of high atomic number, namely, tantalum and uranium carbide for radionuclide development. The facility will rely on the 50-fold higher proton beam intensity of the HIPA accelerator at PSI (100 µA will be used for this new facility) compared to existing facilities.

However, we note that irradiation capabilities relying on thermal neutrons remain crucial as they provide viable routes to neutron-rich radionuclides, complementary to neutron-deficient spallation products for ongoing preclinical studies and clinical trials (for example Tb-161, Er-169, Dy-166) as well as established treatment routes through, for example, Lu-177. In turn, the **SINQ++** project presented in section 3.1.2 presents an opportunity to also optimise the thermal flux to increase this capacity in Switzerland. The corresponding irradiation facility will need an optimised spectrum, which avoids the fast neutron background characteristic of spallation targets. This should become possible through recent progress at PSI with 3D-printed shielding solutions. We note that this becomes particularly relevant when the ILL reactor will shutdown, which is currently foreseen at the end of this decade.

6.2.2 Validation of advanced nuclear and energy materials

Switzerland remains a competence center for nuclear applications where in particular the PSI Center for Nuclear Engineering and Sciences (NES) is concerned with the safety of currently operating light-water reactors, safety characteristics of future reactor concepts, such as fourth generation reactors and compact reactors, and long-term safety of deep geological repositories for nuclear wastes. In addition, at EPFL, the Swiss Plasma Center (SPC) is making crucial contributions to the realisation of fusion energy by advancing our understanding of plasma physics and fostering the use of plasmas for industrial applications. The SPC is among other things involved in ITER, the experimental international fusion reactor. The qualification of materials, in particular, for the tritium breeding blanket, which is subject to intense neutron irradiation and immense heat, is of outmost importance for the success of fusion energy altogether. . Finally, Swiss companies such as Transmutex are starting the development of a transmutation plant to transform long-lived nuclear waste into nuclides of shorter life-time, which substantially simplifies the safety case for deep geological disposal, clean energy, and fresh nuclear fuel. For all these developments advanced nuclear materials that can safely handle a substantial flux of fast neutrons are required. At PSI, ETHZ, EPFL and EMPA, researchers are working on using advanced manufacturing techniques to create such materials. Here the uniquely high and continuous flux of fast neutrons produced by the SINQ target at PSI when impinged with protons from the HIPA accelerator provides a unique way to test the response of such novel and advanced materials when they are exposed to neutrons. This could also be highly relevant in the context of nuclear space applications for which the availability of state-of-the-art facilities to characterise long-term irradiation effects on structures, systems and components will be of highest priority. This also connects well to the activities proposed in section 4.2.3

Through the SINQ Target Irradiation Program (STIP), PSI already is able to do such tests. However, for STIP material specimens to be irradiated are installed into the existing target design and can only be taken out when a new SINQ target gets installed, which happens every other year. This means that the irradiation time is fixed by the runtime of the HIPA accelerator, which is controlled by other overriding factors. An alternative would be to modify the SINQ target to include a rabbit system, which would allow to exchange specimens in the target at will, and potentially also improve temperature control of the sample. Such a facility illustrated in Fig. 16, would enable flexible material irradiation with fast neutrons under controlled conditions, and would find immense interest in the global nuclear community and would deliver important contributions to the understanding of radiation damage of innovative materials for Generation-IV reactors, mobile compact reactors, fusion reactors, and transmutation applications. A test target including such a rabbit system is therefore a key interest of the Swiss community working on nuclear materials. The **SINQ++** project detailed in section 3.1.3 would be an ideal opportunity to modify the SINQ target accordingly. Here it is also worth noting that PSI represents an ideal environment for testing irradiated samples. Notably, irradiated samples can be investigated using state-of-the-art analysis techniques, as PSI offers a unique combination of infrastructure, including a Hotlab equipped with a Focused Ion Beam (FIB) for sample downsizing, advanced microscopy, the SLS, and SINQ. This enables highly advanced analysis and facilitates the exchange of samples with ETH, EMPA, and EPFL, expanding the capabilities. This unique environment allows cutting-edge research on irradiation effects, spanning from the underlying fundamental mechanisms to applied investigations with near-term practical implications.

The **SINQ++** upgrade with the irradiation capability would also find strong international support, e.g. through the OECD Nuclear Energy Agency's (NEA) Framework for Irradiation Experiments (FIDES), which supports the material experimental needs of nuclear safety regulators, technical support organisations, research institutions and industry, to safeguard experimental knowledge for the next generations and to investigate the latest material innovations available for future reactors. Through FIDES, a global network of research facilities to perform high-priority experiments through Joint ExpErimental Programmes (JEEPs) has been established, and several FIDES partners have expressed their strong support adding SINQ to the phalanx of these irradiation facilities, in particular due to its uniquely high and clean fast neutron spectrum. This presents a unique opportunity to place SINQ prominently on the map of international facilities supporting Generation-IV and fusion reactor material research.

6.2.3 Opportunities for aerospace applications

On 19 April 2023, the Federal Council adopted the 2023 Space Policy acknowledging the rapid developments and increasing importance of space, where for example satellite-based applications are now essential for our society, help to understand climate change and are also crucial in the context of security. Space is also becoming increasingly accessible due to lower-costs rocket launches. This is further underlined by the establishment of the European Space Deep-Tech Innovation Centre (ESDI) at the PSI as a joint Centre of Excellence with the European Space Agency (ESA) as well as ETH Zurich Space in 2022. In turn, the availability of research tools that drive these missions forward remains crucial for Switzerland.

Neutrons at PSI are already used to secure the safety of the ESA Ariane 5 and Vega rockets (see last roadmap) where neutron imaging is used for the quality control of components that ensure the safe launch of such a vehicle. A further key aspect is the understanding of the radiation environment in space. The radiation environment in space as well as during flights can have detrimental effects on semiconductor components and other materials used in spacecrafts. The ability to simulate this environment on earth allows companies and research teams developing components for airplanes, satellites, spacecrafts or vehicles and rovers for planetary exploration, to make sure that they will safely operate in this environment. Notably, already single event effects (SEEs), caused by single ionizing particles that penetrate sensitive nodes within an electronic device, can lead to anything from faulty system responses to catastrophic system failures. With the Proton Irradiation Facility (PIF) at PSI the effect of SEEs, radiation hardness of products, the properties of radiation monitors for space and similar effects with regard to protons can be investigated. However, the effect of neutron radiation, which travels much further, is equally important. At the ChipIR beamline at the ISIS facility the immense importance of neutron irradiation of electronics for aerospace applications has been recently demonstrated.[14] This beamline offers a neutron spectrum whose profile exactly corresponds to cosmic neutron radiation. Its flux is eight to nine orders of magnitude higher compared to cosmic radiation, allowing to test and certify these components and avoid costly and fatal failures during actual flight. As shown in section 3.1.2 such a beamline could be implemented as part of the **SINQ++** project.

7 Conclusions and maintaining Swiss leadership in neutron science

On the one hand, we have demonstrated in section 3.3 that the Swiss neutron science community is tremendously successful and can be considered a world leader in neutron science and continues to grow. On the other hand, in section 3.4, we showcased that the entire European neutron science ecosystem, including Switzerland, is strained due to the permanent or temporary closure of neutron facilities over the last few years. This entails that to maintain and advance Swiss leadership in neutron science several scenarios as well as opportunities should be considered. In the following we give a list of considerations summarizing the need of the community.

1. As we describe in section 3.3 and 3.4, key ingredients of the success of the Swiss neutron science community are rooted in the dual strategy of a competitive national source and investing in international flagship facilities such as the ESS. However, considering the long-term availability of neutron beam days in Europe (cf. Fig. 12), the key role of the Swiss national neutron sources will become even more prominent. As a baseline scenario, the competitive Swiss national sources SINQ and UCN must therefore be continuously upgraded to ensure their long-term availability well beyond the next decade. For SINQ this requires at least the replacement of its cold source within the next ten years. After the substantial investment of Switzerland into ESS, a commensurate investment in its national source will generate the desired large return on this investment fully in line with the current success strategy.

2. The replacement of SINQ's cold source is a major upgrade, which should be carried out within the next 10 years, but at the same time offers unique opportunities. In the minimal configuration, it can be improved to offer an increase of at least a factor two of cold neutrons to the instruments in the existing guide hall. Further, the spectrum could be optimised to better meet the emerging needs of the community (cf. section 4.1).

3. An optional scenario for the replacement of the cold source is to carry it out as part of a larger project to be realised during the ERI dispatch 2033–2036 (cf. Fig. 4). This project, described in section 3.1.2 and named **SINQ++** would extend the existing target Hall to the North, which would allow to build 5 novel instruments at SINQ while improving two existing ones by a factor 20 and 200 respectively. This is a very cost-effective way to counter the current 'neutron drought' and simultaneously open new scientific horizons.

4. As already illustrated in the neutron science roadmap published in 2021, it is clear that soft matter, life science, investigation of applied and functional materials, as well as industrial use of neutrons are emerging topics in Switzerland, where neutron scattering is becoming increasingly important. These sub-communities would strongly benefit from novel instrumentation optimised for their scientific challenges. These could be realised as part of the **SINQ++** project in a very cost-effective fashion.

5. Similarly, the general challenge of the increasing demand for more complex experiments (cf. section 4.1) would be optimally mitigated by building optimised instrumentation for these tasks as part of the **SINQ++** project.

6. Because Swiss large-scale neutron facilities are part of the larger European ecosystem of such facilities, SINQ is currently compensating for other facilities that are currently temporarily or permanently shut down, or that have not come online yet (see section 3.4). At the same time, Swiss neutron scientists benefit from other national sources when they are running. Currently, SINQ is also financially supported for certain projects by the Danish, French and Norwegian communities, which currently do not have a national neutron source. We therefore recommend expansion of this strategy, where European countries with substantial user communities but without or too little national capacity may invest in upgrades of instruments and their operation for the **SINQ++** project.

7. As we describe in section 4.2, the SINQ++ project also contains important opportunities to widen the reach of neutron science to contribute to new scientific and societal challenges such as advanced nuclear installations like fourth generation reactors, fusion reactors, compact mobile reactors, transmutation, radioisotope production for medical research and therapy, as well as to space exploration. In turn, investment in this new project during the ERI dispatch 2033–2036 would benefit a wide array of strategic topics for Switzerland.

8. The Swiss neutron science community is looking forward to the start of user operation at ESS in 2027. The

novel and advanced capabilities of ESS instruments, in several cases driven by Swiss innovation will allow the Swiss neutron science community to meet current and future challenges. Nevertheless, at the currently foreseen capacity of 15 instruments at ESS the access to neutron beam time will be very challenging for Swiss scientists as soon as the ILL will be permanently shut down. Therefore, it is crucial for the Swiss neutron science community that as a first step the expansion of the ESS instrument suite is pursued in a timely fashion after ESS user operation starts and to reach the foreseen maximum of 35 instruments.

9. At the same time, it would be sensible to consider extending the run time of the ILL beyond 2030/2033, at least up to the moment when ESS is operational with all 35 instruments. According to the make-up of our community presented in section 3.4 about one third of our members are early-career scientists (PhD students/postdocs). To continue and grow our highly successful community, requires sufficient access to neutron beam days to educate these early-career scientists. In addition to the argument of the required capacity to the continued success of the Swiss neutron community, it is important to note that neutron instrumentation at reactor and pulsed spallation sources is complementary (see for example Ref.[10]) and that there are certain capabilities at the ILL that ESS will not be able to replace.

10. Finally, the currently planned ESS instrument suite does not yet include a beamline dedicated to fundamental physics with cold neutrons. However, the ESS, with its pulsed source and high peak brightness, has the intrinsic potential to provide unique and exciting research opportunities for future high-impact particle physics at low energies.[4, 15] Therefore, for Switzerland, it is important to realise such a beamline in the next round of ESS instrument proposals as well as to push for a second moderator optimised with fundamental neutron science experiments in mind.[16]

Part of the detector electronics for the new instrument DMC at the Swiss spallation neutron source SINQ at PSI. Source: Lukas Keller, PSI

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