SLEIPNIR: A High-Capacity Instrument Cluster for ESS

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1. Executive summary

The European Spallation Source (ESS) will become Europe's flagship neutron scattering facility and represents a major long-term investment in advanced research infrastructure. Its success depends not only on world-leading instruments, but also on a strong and active user community with timely and reliable access to beam time across a broad range of applications. Sustaining such a community requires both the **depth** and the **breadth** of the European instrument portfolio. Many scientific workflows benefit from a combination of high-performance instruments (depth) and more accessible ones (breadth); via repeated preparatory trials, long measurement times and fast access to beam time. Indeed, many discoveries and new methods come from trial-and-error tinkering and high risk test measurements.

Yet, over the past decade, several medium-flux neutron sources in Europe have been shut down, reducing overall measurement capacity. With further closures anticipated - the current agreement for operating the Institut Laue-Langevin (ILL) ends in 2033 - the availability of beam time is expected to decline significantly, see Figure 1. This reduction risks constraining the breadth of the user community, by limiting scientific throughput, slowing method development, and constraining the training of new users. The combination of ESS ramp-up and the ongoing reduction in beamtime capacity creates a unique transition period in which capacity gaps and infrastructure opportunities coexist.

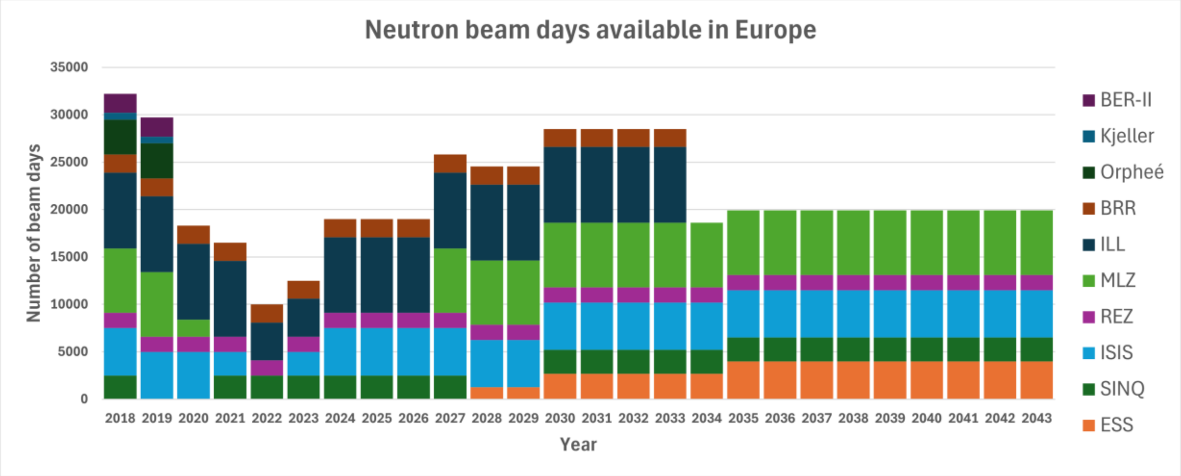

Figure 1: Historical and projected number of neutron beam days in Europe. The shutdowns leading to the neutron drought in 2022-2023 are included. ILL is projected to close in 2033, and both thermal and cold operation of MLZ is included. For ESS, we assume 7 instruments in user operation in 2028, 15 in 2030, and 22 in 2035.

We propose SLEIPNIR, **tailored to utilize space-constrained beam ports, unlocking additional experimental capacity** without impacting flagship performance or requiring major infrastructure expansion. Several beam ports are space constrained by other instruments and their infrastructure (as detailed in Section 3). Yet, instruments can still be built in a limited space by employing vertical scattering geometries, using double-bounce monochromator pairs (see Figure 2, explained in a later section) and with comparatively limited additional cost. The direct beam, otherwise lost in the beam stop, will be used by a compact imaging station. The instruments will be comparable to many productive instruments on medium-flux sources, enabling similar science. This infrastructure represents a unique opportunity to enable more high-demand experiments, without large scale investments.

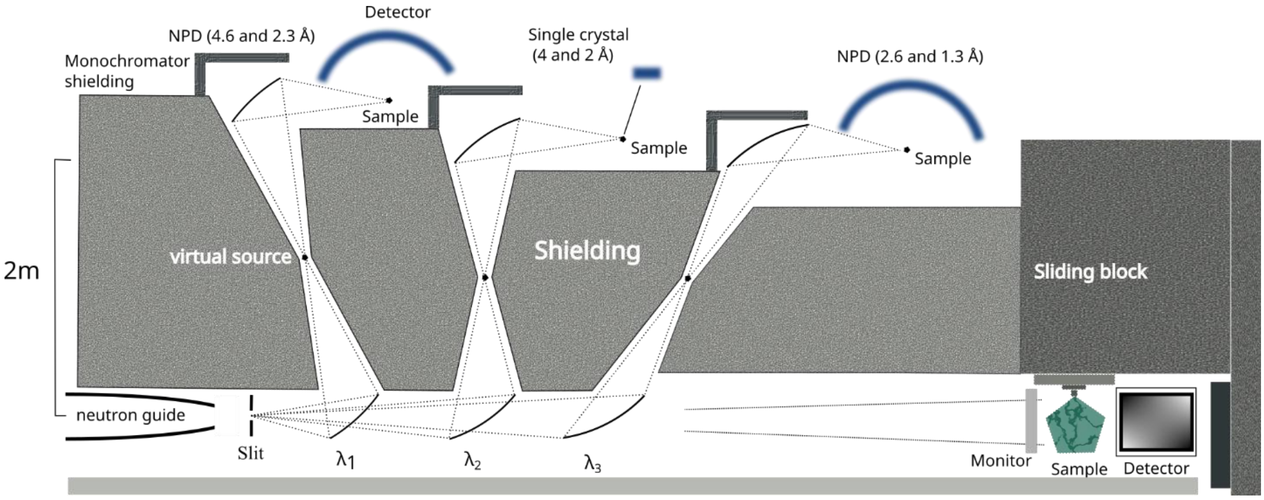

Figure 2: Possible outline of a SLEIPNIR suite. Pairs of monochromators feed small instrument stations with neutrons to be used for powder diffraction and single crystal diffraction, with the direct beam used by a compact imaging station. Exploiting the virtual source delivered by the guide, a compact imaging station can be constructed in the guide plane.

2. Scientific case

A central premise of the instrument suite proposed here is the deliberate acceptance of performance trade-offs for the sake of compactness and increased utilization of the ESS beam ports: Their role is to expand both the volume and diversity of scientific activity that is already being carried out, and to allow a larger fraction of this activity to be hosted at the ESS. By enabling higher experimental throughput, the proposed instruments would lower barriers to access, broaden participation in neutron-based research, and boost the neutron user community on which large-scale facilities such as the ESS ultimately rely.

Many truly groundbreaking experiments require method development and repeated access to test beam time. Other research projects in diffraction and imaging rely on a high throughput of measurements rather than a limited number of uniquely demanding experiments. In cases where the signal strength is high or where experimental parameters evolve on longer timescales than the measurement time, easy access is often preferable to fierce competition for beam time on flagship ESS instruments. The compact symbiotic instruments proposed in the SLEIPNIR suite provide sufficient performance for testing complex sample environment, feasibility verification experiments, method development and alignment.

A suite of instruments is chosen for both feasibility and performance, to target the bulk of diffraction and imaging community of neutron scatterers and industry alike. This choice is indicative rather than prescriptive. Other options are possible, and a full set of options should be explored in future work.

2.1 Key Scientific Drivers

Neutron powder diffraction (NPD)

X-ray and neutron powder diffraction are among the most widely used and important techniques in materials science. The well-established motivations for using neutrons for structure determination include their sensitivity to light elements in the presence of heavy elements, their deep penetration into bulk materials, and their unique sensitivity to magnetic order. For strongly scattering systems, a complete diffraction pattern can be recorded in a few hours at a medium-flux neutron source, whereas on an optimized ESS diffractometer the same measurement may be completed within minutes or even seconds. However, when the experiment in question is limited not by counting statistics but by sample-environment constraints—such as slow electrochemical cycling in batteries, chemically driven transformations in flow cells, or high-temperature processes, sheer beam intensity offers limited advantage. In such scenarios, extended and flexible beam time instead becomes a strength, allowing for careful adjustment of experimental conditions and informed responses to incoming results. Representative examples are outlined in the following paragraphs.

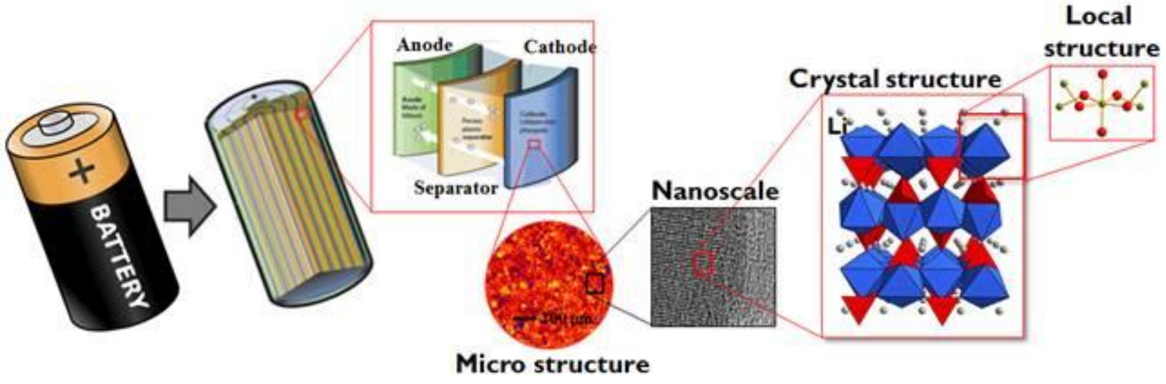

Figure 3: The various structural length scales of a lithium-ion battery – where SLEIPNIR allows for measurements investigating battery materials on the Angstrom and micrometer scales.

In operando studies on batteries and other components

In the quest to understand the ionic structure of battery components, which is the spatial arrangement of the ions that make up the material, X-rays has been the dominant technique for many years. While this technique is powerful, X-rays are relatively insensitive to the light but essential elements, lithium and oxygen. Neutrons famously do not share this limitation. Another equally crucial point is that battery electrodes typically are composed of a mixture of metals with similar atomic weights, which means that they cannot be easily distinguished by use of X-ray techniques. Using neutrons, however, the structural role of these elements can be determined. Lastly, neutrons can probe the bulk, allowing diffraction from complex layered real components. The ability to monitor the structure of the battery components *in situ* when in use is extremely powerful, to probe the structure and electrochemical driven phase transitions of a series of novel cathode materials for Li-ion batteries [1, 2, 3]. Such in-operando powder diffraction studies can be employed on any technological component, like catalysts [4,5], hydrogen storage materials [6] and chemical reaction cells [7]. Thus, a wide range of technologically impactful studies involve timescales of hours and days, in which a medium flux powder diffraction is sufficient, and an advantage in terms of adjusting complex setups. In case a flagship instrument is preferable or necessary for such studies, using compact instruments to demonstrate feasibility, timescale and resolution requirements will improve the chances of success. In addition, detailed studies of charge/discharge effects often require many repetitions and long time scales.

Magnetic nanocomposites

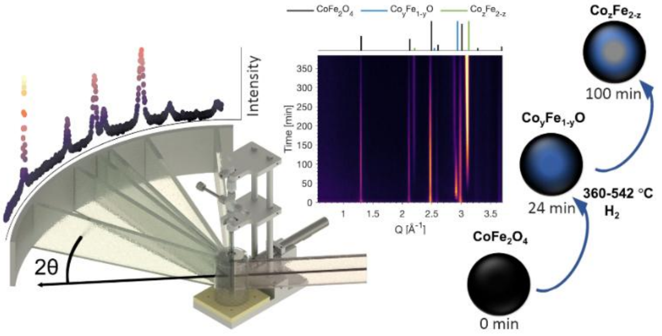

Figure 4: An in-situ neutron powder diffraction experiment, where the Bragg peaks evolve in time, as the nature of the sample changes (from [8]).

Permanent magnets are key to many applications, where electricity is converted into motion and vice versa. Theoretically, intriguing new magnets might be synthesized by mixing hard and soft magnetic materials. Thereby, by combining the right materials, one might be able to obtain magnetic materials that perform better in certain applications, than the sum of the two components. This is achieved by exploiting the quantum mechanical phenomenon of exchange to increase the energy product of the magnet in question. One example is the investigation of the model system, $CoFe_2O_4$. Synthesized powders of $CoFe_2O_4$ can be reduced to $CoFe_2$ by heating up the powder in a flow of hydrogen containing gas, where there is mostly a mix of the two compounds in that process, see figure 4. To understand the workings of the exchange spring magnetic phenomenon, it is important not only to measure the bulk properties of the result, but to measure the structure in-situ. This is exceedingly difficult with X-rays as the furnace and gas flow equipment give complex and high intensity background. Neutron powder diffraction is well suited to working with bulky sample environment. In addition, one can measure the average composition of the entire sample [8, 9]. Studying chemical reactions during slow synthesis does not benefit from diffraction patterns being recorded in seconds, but rather beam times of long duration, allowing reproducibility studies and time to adapt to unforeseen challenges.

Neutron single crystal diffraction

The technique of neutron single crystal diffraction serves the same purpose of structure determination as NPD, albeit with a much better signal-to-noise ratio. It is the preferred technique for detecting weak signals, and in many cases, it is a technique in synergy with single crystal neutron spectroscopy. Single crystal diffraction reveals structural details of the crystal and magnetic structure not evident in powder data. In some cases, these are essential to understand the dynamics and/or the bulk properties of the system under investigation.

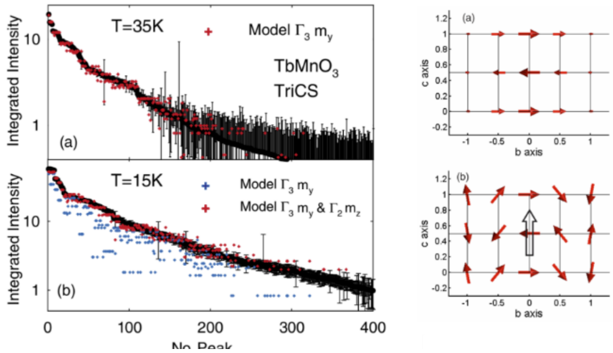

Figure 5: Example of complex magnetic structure refinement of single crystal neutron diffraction data, [10]

Easy access to a single crystal diffraction beamline allows for the plethora of experiments that do not require flagship experiments. This would allow structural details to be investigated, both crystalline and magnetic, without competing for beam time on high-performance instruments.

Functional magnetic materials

The complexity of many magnetic materials is daunting, since the quantum mechanical interaction giving rise to magnetism is in itself complex. The interaction depends not only on the intricate pathway of electron transferal, but also on the crystalline surroundings of the magnetic ions themselves. There are several ways in which this complexity can be put to good use, and one example is the magnetoelectric materials, where the magnetization is switchable with an electrical field, and vice versa. These can be used in the information technology industry, for instance to make 4-state bits and make transistors with very low power dissipation. However, the magnetic materials giving rise to this effect, often have complex magnetic structures, caused by several distinct interactions. To measure such complex magnetic structures, single crystal diffraction is a key tool, as minute details are hard to measure due to the weak signals involved.

Magnetic materials and quantum information

Currently, vast sums are being invested in quantum computing technologies, both in the public and private sector, to facilitate the emergence of useful quantum computers. However, the daunting challenge is that the qubits – necessary for quantum computing – are extremely fragile. Some magnetic materials are proposed as candidates for more ‘protected’ qubits, and the substantial effort is directed towards developing materials of this kind. Synthesis of new magnetic materials involves several magnetic characterization techniques, including bulk magnetization measurements, X-ray diffraction, neutron powder diffraction, and single crystal neutron diffraction. Sufficient access to both neutron diffraction techniques is key to the success of such a challenging project. Determining the magnetic structure of such materials does not necessarily require state-of-the-art instruments. For example, the magnetic structure of α-$RuCl_3$ was determined at HFIR [12]. In addition, the new chiral materials give rise to topologically protected states and dynamics, which have key perspectives in the field of spintronics [13] – the chiral magnetic structures are often too complex to be resolved without single crystal neutron diffraction. With SLEIPNIR, the sheer number of studies can be increased, and the very challenging cases will benefit from preliminary refinements and ordering wavevector determination.

Supporting existing ESS instruments

Single crystal neutron diffraction is ideal for investigating the quality of large single crystals, before using them for neutron spectroscopy. ESS will have considerable interest in giving users access to beamline to screen sample quality, to improve the data quality and reject low quality samples.

This could be especially important for challenging experiments for NMX and MAGIC. When deuterated single crystals are produced, mosaicity and scattering intensity can be checked, before spending a full beamtime on NMX. Similarly, when MAGIC pushes the envelope with polarized single crystal neutron diffraction, a mandatory sample quality check could decrease the failure rate.

Neutron imaging

Neutron imaging has experienced a strong and sustained expansion over the past decade, becoming one of the most rapidly growing neutron scattering technique. Its impact is driven by the ability to probe real objects and operating systems non-destructively, with high sensitivity to light elements, deep penetration into bulk materials, and unique contrast mechanisms that are unavailable to X-rays. As a result, neutron imaging is increasingly demanded across a **wide range of disciplines,** including materials science, energy research, geoscience, biology, food science, heritage science, engineering, and industrial development. [14]

At the same time, neutron imaging is no longer limited to classical attenuation radiography and tomography (where attenuation includes both absorption and scattering). The field has diversified into a **broad portfolio of complementary contrast modalities.** These include diffraction contrast for mapping crystallographic properties such as phase, orientation, and lattice strain [15]; inelastic contrast for studying dynamic processes governed by hydrogen, hydrogen bonding, or temperature variations; polarized contrast for the visualization of magnetic fields [16]; or phase-contrast and dark-field approaches providing sensitivity to microstructure [17]. These advanced techniques continue to open new scientific opportunities and attract new user communities.

A central challenge in the current neutron imaging landscape is that several state-of-the-art instruments are optimized to offer a wide range of advanced contrast mechanisms and specialized capabilities. While this versatility is scientifically powerful, it is also highly resource-intensive and implies that beamlines are frequently operated in a mode of continuous development and reconfiguration. Significant setup effort (often requiring several hours or even days) is needed between experiments, as instrument configurations, sample environments, and analysis workflows must be adapted to fully exploit the available techniques. As a result, valuable beam time is consumed by changeovers, and more routine tomography measurements are increasingly difficult to accommodate on highly specialized instruments.

This creates a strong and growing need for dedicated workhorse imaging capacity, particularly for radiography and tomography. Such measurements form the backbone of many scientific and industrial workflows, including routine 3D tomography of engineering components, screening prior to more specialized experiments, and high-throughput investigations of industrial parts, batteries, hydrogen-related systems, or porous media. For many of these applications, the scientific priority is not maximum performance, but rather reliable, accessible, and reproducible imaging.

The proposed beamline would lower the barrier of entry for new scientific and industrial users. This includes communities from applied engineering, cultural heritage, geoscience, industrial quality control, and emerging technology development, many of whom require robust tomography and screening rather than advanced contrast mechanisms. Enabling access for these communities will stimulate new research questions, unconventional applications, and cross-disciplinary interaction.

Moreover, it is noteworthy that many of the aforementioned advanced contrast modalities originally emerged from medium-flux facilities rather than flagship instruments. A prominent example is the CONRAD beamline at HZB Berlin [18] which delivered much of this innovation without the scale or cost of advanced ToF instruments. This underscores the scientific and methodological potential of the type of imaging beamline proposed here. Representative scientific applications that would benefit from SLEIPNIR include:

Geomaterials and planetary science

Neutron imaging provides unique capabilities for the investigation of geomaterials, particularly where hydrogen-bearing phases play a critical role. The sensitivity of neutrons to hydrogen makes it possible to detect and quantify hydrous phases in rocks and minerals, even when present in lesser amounts or distributed heterogeneously. This is of relevance for planetary science, for example in the study of Martian meteorites and future sample return missions, where the presence, distribution, and state of water are key to understanding planetary formation, alteration processes, and potential habitability (see Figure 6)

Heritage science

Neutron imaging has become a valuable tool in cultural heritage research, where non-invasive investigation of valuable and often unique objects is essential. In this context, the primary limitation is typically not neutron flux, but rather the need for careful preparation, stable experimental conditions, and the avoidance of stress on the object. The use of selected neutron wavelengths by ToF will provide enhanced contrast compared to white-beam imaging at steady state sources.

Enabling statistically meaningful studies

Several recent studies and PhD projects, for example on the hydraulic properties of sandstone [18] or on battery degradation processes [14,19], highlight the importance of investigating larger sample sets, where sample-to-sample variability becomes a key scientific question. SLEIPNIR would directly address this need by providing dedicated workhorse tomography capability and largely automated workflows.

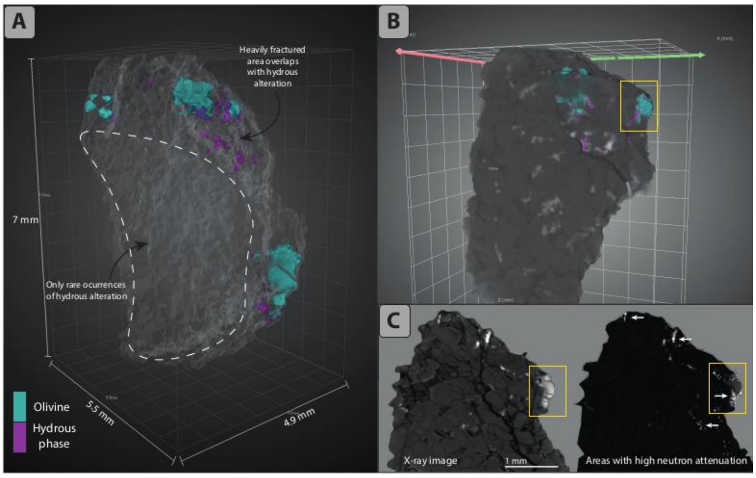

Figure 6: Example of how neutron tomography reveals hydrous constituents inside a Martian meteorite. X-ray CT that can be presumed separately allows for combined image segmentation and to locate olivine volumes [19].

2.1.1 Societal relevance

The potential impact on battery research is substantial. Rechargeable lithium-ion batteries are ubiquitous, powering most portable electronic devices worldwide, and their importance is set to increase dramatically with the ongoing transition from combustion-engine vehicles to battery-electric mobility. At the same time, the practical limitations of current Li-ion technology—restricted energy density, long charging times, capacity degradation, and high replacement costs—are commonly understood. Addressing these challenges requires a detailed, microscopic understanding of battery materials and their operation under realistic conditions. To this end, scientists increasingly rely on state-of-the-art experimental techniques, among which *neutron diffraction and imaging* plays a key and unique role.

Functional magnetic materials have potential to facilitate breakthroughs in the information technology sector, via better storage and information processing. For instance, this can be achieved by making 4-state bits or transistors using spin-polarized currents, which can drastically reduce the current consumption of CPUs. Neutron diffraction plays a key role in understanding the magnetic phases of such functional magnetic materials, and capacity and availability can allow new materials to be studied quickly and frequently.

For geomaterials, planetary and heritage science, imaging already has an immense impact, and easy access to an easy-to-use beamline would increase the sheer output within these areas of fundamental interest.

2.2. New science

SLEIPNIR's primary impact lies in increased beamtime availability, as described in previous sections. However, innovation in neutron scattering often emerges from unexpected use cases, iterative experimentation, and the freedom to explore ideas that do not yet justify flagship-level complexity. By decoupling routine and exploratory experiments from continuously reconfigured state-of-the-art instruments, SLEIPNIR would function as an incubator for new projects, and method development.

2.3. Impact on the user community

The science cases for diffraction and imaging alone represent areas of major scientific and societal importance and are currently experiencing robust growth. In addition, the magnetism community would be a key constituency. From a scientific perspective, the proposed suite therefore offers a broad impact.

Beyond this, the suite addresses a crucial but under-served segment of the neutron scattering community: students. By decoupling training activities from competition with world-leading instruments, it becomes feasible to dedicate more beam time for education and training using only a small fraction of the approximately seven hundred beam days available annually on the suite. Students could spend extended periods on a beamline, gaining hands-on experience with measurements and basic data analysis, with the freedom to explore, learn from mistakes, and develop practical intuition. At the same time, they would be immersed in the wider environment of ESS, embedded in a vibrant and active scientific ecosystem.

Additionally, improved access to neutron instruments can lower barriers for new and interdisciplinary communities that currently have limited opportunities on highly oversubscribed imaging facilities. For industry, straightforward and low cost access to an imaging beamline may increase the use of the technique outside academia.

3. Technical overview of SLEIPNIR

The monolith vessel of the ESS contains 42 beam ports, a significantly higher number than at counterpart facilities J-PARC and SNS. These fixed beam ports set an absolute maximum for the number of beamlines to be installed at the ESS. Nevertheless, constructing 42 large end stations at the ESS – like the current construction projects - is unrealistic. ESS instruments have very large end stations (of the order of 200 m^2), leaving several beam ports essentially blocked for utilization for conventional ESS instruments (see Figure 7). Naively, 6 of these can be identified on Figure 7, which are incompatible with optimized long pulse ToF instruments. These locations provide only a few meters of lateral space, insufficient for standard end-station layouts and shielding. For these reasons, those beam ports were not included in the roadmap call.

Nevertheless, the amount of useful neutrons extractable through this port is just as large as elsewhere at the ESS. Indeed, if the instruments are optimized not for performance, but with the explicit purpose of making them adjustable to these spatial constraints, it is possible to make use of such obstructed beam ports after all. As such, the central premise of this proposal is to limit the **instrument footprint in the experimental hall to within ±0.75 m of the guide axis, thereby avoiding any encroachment on space reserved for large scale instruments**. This approach enables additional capacity to be created without competing with ESS' primary mission of scientific excellence.

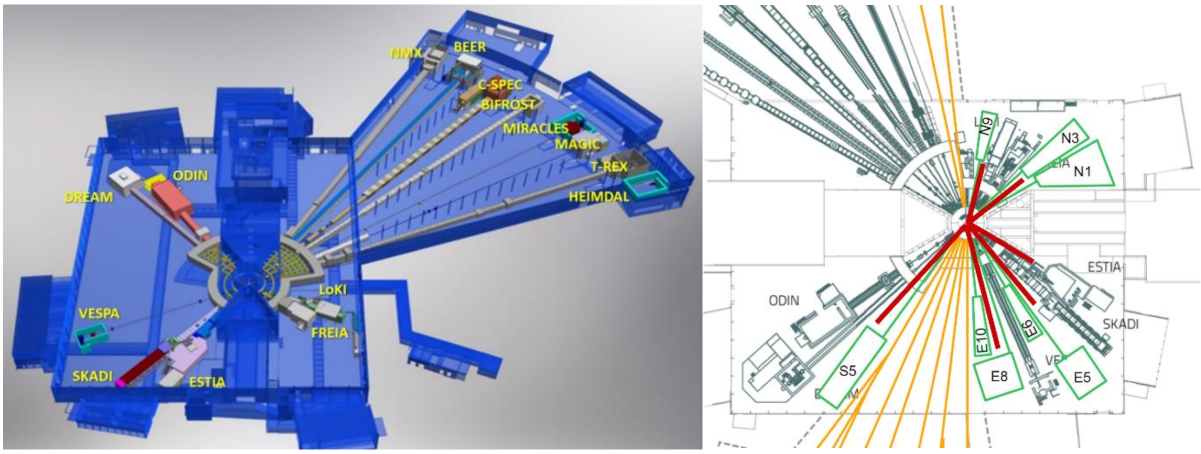

Figure 7: (Left) Layout of the first 15 instruments to be built at the ESS. (Right) Available beam ports in the current call, with potential candidates marked in red, those are N2, N8, E1, E4, E9 and S4.

Using long-flightpath, double-bounce monochromator setups

Compactness can be ensured by utilizing the 2D focusing capabilities of monochromators to create virtual sources, rather than with cascades of neutron beam choppers as on conventional ESS instruments. Since monochromators select single wavelength pairs, rather than polychromatic continuous ranges, this method implies a flux reduction. The advantage is that it allows several monochromators downstream one another, in a stacked fashion. The beam feeding the imaging station would come from a 2 x 2 cm^2 (exchangeable to 1 x 1 cm^2), with a compact frame-overlap chopper in the bunker, and a normalization monitor before the sample. With an approximate pinhole-detector distance of 10 meters (depending on the beam port utilized), the L/D ratio would be 500 (resulting in geometric blur of 20µm at a sample detector distance of 10mm), sufficient for the majority applications envisioned on SLEIPNIR. Higher flux or better spatial resolution configurations will be available at ODIN or the proposed MAGNI beamline. The upstream monochromators will consequently take out wavelength bands from the spectrum; however, this configuration is not expected to change once the monochromators have been aligned and optimized.

By using the monochromators to scatter the beam vertically upwards, building the instruments in the vertical plane, more than one instrument can thus be constructed in a horizontally very slender fashion, adjustable to the strict spatial requirements on the otherwise blocked beam ports. These instruments use two fixed wavelengths, and are much smaller than the ESS instruments. To further ensure compactness of this proposed suite of instruments, the radiation shielding requirements need to be small. This is ensured by using a pair of monochromators, instead of just one, serving to effectively translate the beam vertically, having the instrument built on the shielding blocks. The lower monochromator focuses the neutrons onto a virtual source, which can be aggressively shielded, see figure 1, while the second re-uses the point-to-point focusing to deliver a large neutron current on the sample position.

In this configuration, the scattering geometry effectively functions as a fast-neutron chicane. In addition to the shielding provided by dog-legged neutron flight path, the beam operates at a medium source intensity, resulting in correspondingly modest shielding requirements. The use of a double-monochromator principle is well established and has been implemented previously, for example on the MACS spectrometer at NIST [20] and on 4F1 at Orphée [21]. In the present design, however, this concept is extended through a much larger monochromator separation combined with double-focusing capabilities, explicitly optimized for efficient beam extraction. From both construction and operational perspectives, this approach offers several advantages:

- The shielding costs of such an arrangement, when lifted above the guide plane, will be limited.
- The monochromator setups are fixed and therefore relatively cheap with minimal maintenance.
- The instruments and their data are **simple and manageable for non-expert users in universities and industry**.

- Time-of-flight can be used for fast order separation, and hence, **both λ and λ/2 can be used simultaneously, allowing for structural and magnetic details to be studied in the same experiment**
- Instrument systems from closing reactor sources may be used with subsequent cost reduction.
- **Operating costs will be low**, with very simple setups containing only a few moving parts.
- **Fast neutron background can be filtered out using time-of-flight.**
- **Unutilized neutrons passing through the monochromators are used effectively in the imaging station.**

The double-bounce monochromator results in deliberate flux reduction, to levels one to two orders of magnitude below those of polychromatic ESS instruments. Nevertheless, preliminary Monte Carlo simulations indicate neutron fluxes approaching those of established instruments at the ILL, which sustain high demand and strong publication output. The concept is inherently adaptable to the available space and selected beam port, allowing performance to be enhanced where geometry permits.

Preliminary simulations

Our preliminary simulations focused on the double monochromator setup: the first feasible position of a focusing monochromator would be 12 meters after the beam port, as the instrument needs to be outside the external bunker wall. We use a simple parabolic guide with m = 6, transporting a 2 x 2 cm^2 beam spot and +/- 1.5 degree divergence onto a virtual source just outside the bunker well. As a demonstration, we simulated and optimized a single powder diffractometer with a double-monochromator setup and a first order wavelength of 2.6 Å – enabling direct comparison with existing powder diffractometers.

The monochromators are assumed made of HOPG covering the surface area of the beam at the position in question – using 1x1 cm^2 HOPG tiles, for both monochromators. We used a reflectivity of 80 % for first order and 30 % for second order at this wavelength. The full McStas instrument file can be found in Ref [22].

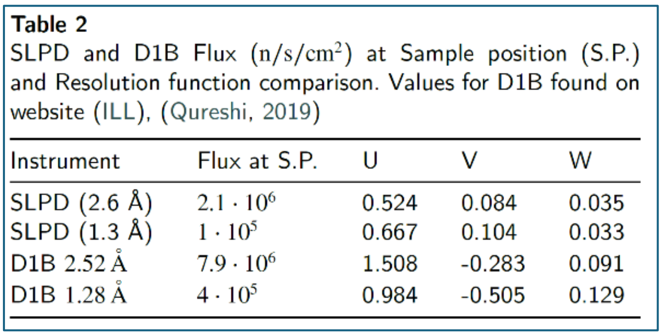

Table 2
SLPD and D1B Flux (n/s/cm^2) at Sample position (S.P.) and Resolution function comparison. Values for D1B found on website (ILL), (Qureshi, 2019)

Instrument	Flux at S.P.	U	V	W
SLPD (2.6 Å)	$2.1 \cdot 10^6$	0.524	0.084	0.035
SLPD (1.3 Å)	$1 \cdot 10^5$	0.667	0.104	0.033
D1B 2.52 Å	$7.9 \cdot 10^6$	1.508	-0.283	0.091
D1B 1.28 Å	$4 \cdot 10^5$	0.984	-0.505	0.129

Figure 8: Flux and resolution numbers compared to D1B

The optimization process led to several distinct instrument setups, of which a medium-flux, medium-resolution version is presented here, with flux and Caglioti resolution function parameters [23] shown in Figure 8. However, it is possible to tune the setup for high flux and low resolution or very-high resolution, depending on the desired use case. Diffraction spectra for a NaCAlF sample of diameter 5 mm, and the angular resolution compared to D1B is shown on Figure 9.

As evident from the simulation, the SLEIPNIR powder diffractometer, operating in a medium-resolution mode, delivers a flux of 25 % that of D1B, the optimized high-performance powder diffractometer at the ILL. The medium-resolution configuration, favored in this preliminary optimization, allows the simultaneous use of two wavelengths via time-of-flight discrimination, effectively enabling near-thermal diffraction with a scientifically useful flux. At 1.3 Å, the flux is lower due to the lower reflectivity of HOPG at higher order, but it is high enough to be comparable to E9 at HZB, and the low fast neutron background would result in a particularly good signal-to-noise ratio

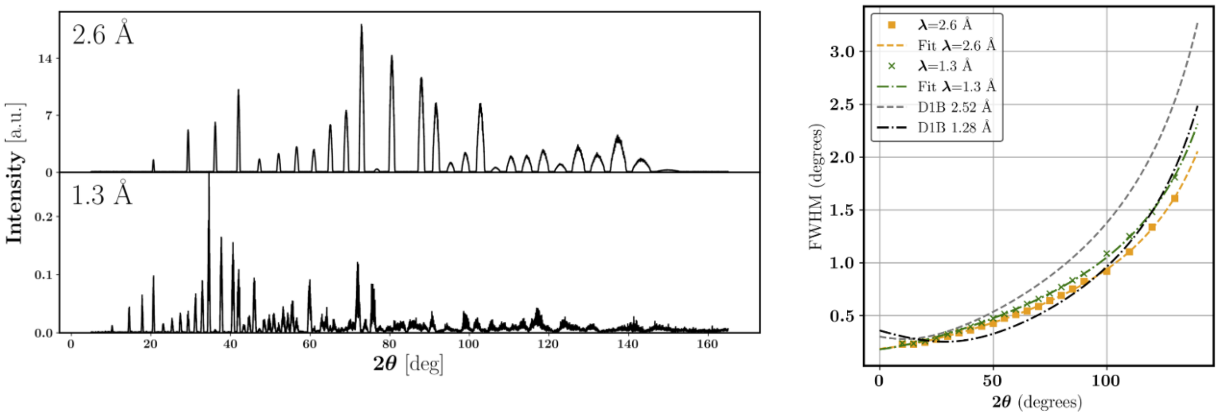

Figure 9: (Right) Diffraction spectra of a NaCaAlF sample, for the medium flux model mentioned in the text (left) Resolution as a function of wavelength of medium flux SLEIPNIR powder diffractometer and D1B @ ILL

Importantly, these simulations represent preliminary estimates based on a conservative starting point for the double-monochromator setup. We expect substantial improvements once the beam port and specific configuration are finalized. With two powder diffractometers, each capable of two wavelengths, there is considerable flexibility to optimize across four wavelengths, enabling high-performance powder diffraction across the full 1.5–4.6 Å range. This will comprehensively support scientific applications spanning magnetism to battery research.

The simulations highlight important considerations for imaging applications, which are straightforward: The relatively short flight path inherently limits the achievable wavelength resolution; however, it enables the use of a broad wavelength band (>10 Å). The presence of upstream monochromators introduces characteristic “dips” in the spectrum, resulting in certain wavelengths missing/underrepresented. This is not expected to be a limiting factor, as quantitative cross-section measurements are not within the scope of the beamline. Instead, the focus lies on white-beam imaging (where all wavelengths are integrated) and on multi-spectral imaging (where thermal and cold neutrons are separated using time-of-flight).

4. Use of the ESS long-pulse source.

This concept exploits the ESS long pulse in an indirect manner by leveraging its exceptionally high integrated brilliance to realize practical monochromatic instruments. At short-pulse sources, comparable approaches would perform poorly, as a monochromator-based configuration without a Fermi chopper relies entirely on integrated brilliance. Because the integrated brilliance of ESS is comparable to that of the ILL, such setups remain performant in this context.

5. Requirements for sample environment

The sample environment suite offered as a standard would be the standard equipment offered elsewhere, barring large cryo-magnets, as these do not operate horizontally. Electromagnets, closed cycle refrigerators and furnaces, Euler cradles for single crystal work, flow cells and most importantly custom equipment for experiments and/or method development.

6. Proposed location of the instrument at the ESS facility

In the previous sections, 6 options for beam ports were outlined. Exactly which ones are to be utilized depends on the interface with other beamlines, the preferred field of view on the moderator and the preferred length of the instrument suite. Most importantly, significant engineering design is necessary to fully evaluate the performance and final configuration of the setup. These include

- Shielding of 3 instruments in proximity. Since the beams are now 2 orders of magnitude less intense than flagship instruments, radiation levels are expected to allow simplified shielding strategies, combining distance mitigation with targeted shielding where required.

- Utilities and sample environment all require infrastructure – which in this case would need to be integrated with the shielding. Access platforms and stairs need to be designed. In that regard, the maximum height of the suite would be a significant parameter for optimization.

In conclusion, significant effort would need to go into establishing practicalities, but none of these fall outside the scope of routine of engineering problems at the ESS.

7. Gap analysis in terms of capacity

Before 2020, HZB operated two powder diffractometers, two single-crystal diffractometers, and two imaging instruments. The LLB hosted three powder diffractometers, three single-crystal diffractometers, and one imaging instrument. The ILL, in turn, operates between 3-5 powder diffractometers and 5-7 single-crystal diffractometers (depending on classification), and is expected to soon operate 4 imaging stations.

By the time SLEIPNIR becomes operational, and assuming the anticipated closure of the ILL, **the European neutron community will have lost of the order of 25 instruments of the type proposed here**, compared to the situation in 2020, when the ESS was originally expected to be fully operational. It is difficult to envisage that three to six ESS flagship instruments alone can compensate for this reduction without compromising their mission of enabling truly groundbreaking science – a choice would have to be made between height and breadth.

8. Comparison other instruments

In the previous section, we compared the powder diffractometer to D1B at the ILL, which is an excellent workhorse. Although not currently simulated, the single crystal diffractometer would be comparable to E4@HZB and ZEBRA@PSI (only the longer wavelengths). For imaging, the proposed setup would be more rigid than most existing instruments, which typically offer a high degree of flexibility. This reduced flexibility is expected to result in improved reproducibility and significantly lower setup overhead between experiments. It should be emphasized that the MAGNI beamline proposed in this roadmap also contributes to addressing capacity; however, its primary focus is on high-flux imaging and advanced operando studies. This is complementary to the SLEIPNIR concept, which explicitly targets simpler, standardized, and workhorse imaging rather than maximum flux or advanced contrast modalities.

9. Construction and operations cost considerations

The individual components of the SLEIPNIR suite will be inexpensive, and the main costs are driven by a short, high m-value guide and detectors, which is this case can be the multiblade detectors for powder diffractometry, He-3 tube for single crystal diffraction and a LumarCam detector for imaging. However, the shielding, integration and project management costs are like those for a conventional instrument. A preliminary cost estimate is provided in Table 1.

Table 1: Estimated costs of the SLEIPNIR suite, judging from previous experience of the proposers.

System	***Estimated cost** (EUR)*
NBOA, Guide	2,100,000
Integration costs: Access platforms, personal safety, motion control, detector infrastructure, electrical infrastructure, piping, racks	2,400,000
Monochromators, sample table and detector for 2 powder diffractometers	2,000,000
Monochromators, sample table and detector for single crystal diffractometer	800,000
Sample table, detector and access system for imaging station	1,500,000
Shielding & simulations	1,000,000
Compact frame overlap chopper	200,000
Design and project management	1,100,000
Total	**11.100.000**

We estimate that the total cost of the SLEIPNIR suite is significantly lower than that of a single ESS flagship instrument, while providing approximately 700 additional beam days per year to the user community. This corresponds to almost an order-of-magnitude increase in beam time per Euro invested.

Operational demands are expected to be modest. The instruments are based on stable configurations with limited complexity in both sample environments and mechanical systems, requiring only minimal reconfiguration between experiments. As a result, the suite is expected to be operable with a small team, on the order of 1–2 full-time staff members in total, rather than dedicated teams per instrument. Synergies with other instruments would allow personnel to be shared between the SLEIPNIR instrument and the flagship instruments.

A range of operational funding models could be considered, including in-kind scientific contributions, guest researchers or postdoctoral programs, and partnerships with industrial users

Key risks and mitigation strategies:

- **Shielding & safety** The concrete outline of the SLEIPNIR suite depends on the radiation environment associated with the double-bounce monochromator configuration and its integration alongside neighboring beamlines. These aspects will require detailed shielding assessments. However, the evaluation of radiation levels and the design of shielding solutions for beamline penetrations and infrastructure are well-established procedures at ESS. The proposed configuration represents an extension of these standard practices.
- **Integration complexity**: The vertically integrated and modular layout introduces additional requirements related to access, infrastructure, and safety systems, including electrical services, personal interlock systems, and sample environment integration. While this adds design complexity, similar multi-layered and space-efficient implementations have been successfully realized at facilities such as PSI and J-PARC. A modular approach will be adopted to ensure maintainability and operational flexibility.
- **Resource drain:** The addition of multiple instruments raises the question of operational and maintenance effort. This risk is mitigated by the deliberately simplified instrument design, characterized by a limited number of moving components and stable configurations. As a result, the operational demands are expected to remain significantly lower than those of a single flagship instrument, allowing efficient use of personnel and resources.

10. Conclusion

The question of beam time capacity within the European neutron landscape has gained increasing prominence as facilities have closed and further reductions are anticipated. While the primary mission of ESS remains the delivery of transformative scientific capability, this evolving landscape invites consideration of how its infrastructure can be used most effectively.

SLEIPNIR does not seek to redefine the role of the ESS, but to extend it in a pragmatic and non-disruptive manner. By making use of beam ports that are not compatible with conventional instrument layouts, it enables additional experimental capacity without constraining flagship instruments. In this way, it complements high-performance instruments by supporting routine measurements, feasibility studies, and training, improving the efficiency of the overall instrument ecosystem.

Taken together, SLEIPNIR provides a concrete and technically grounded basis for assessing such complementary use of ESS infrastructure in practice. The approach allows ESS to contribute to sustaining the European neutron ecosystem without compromising its primary mission of delivering world-leading capability.

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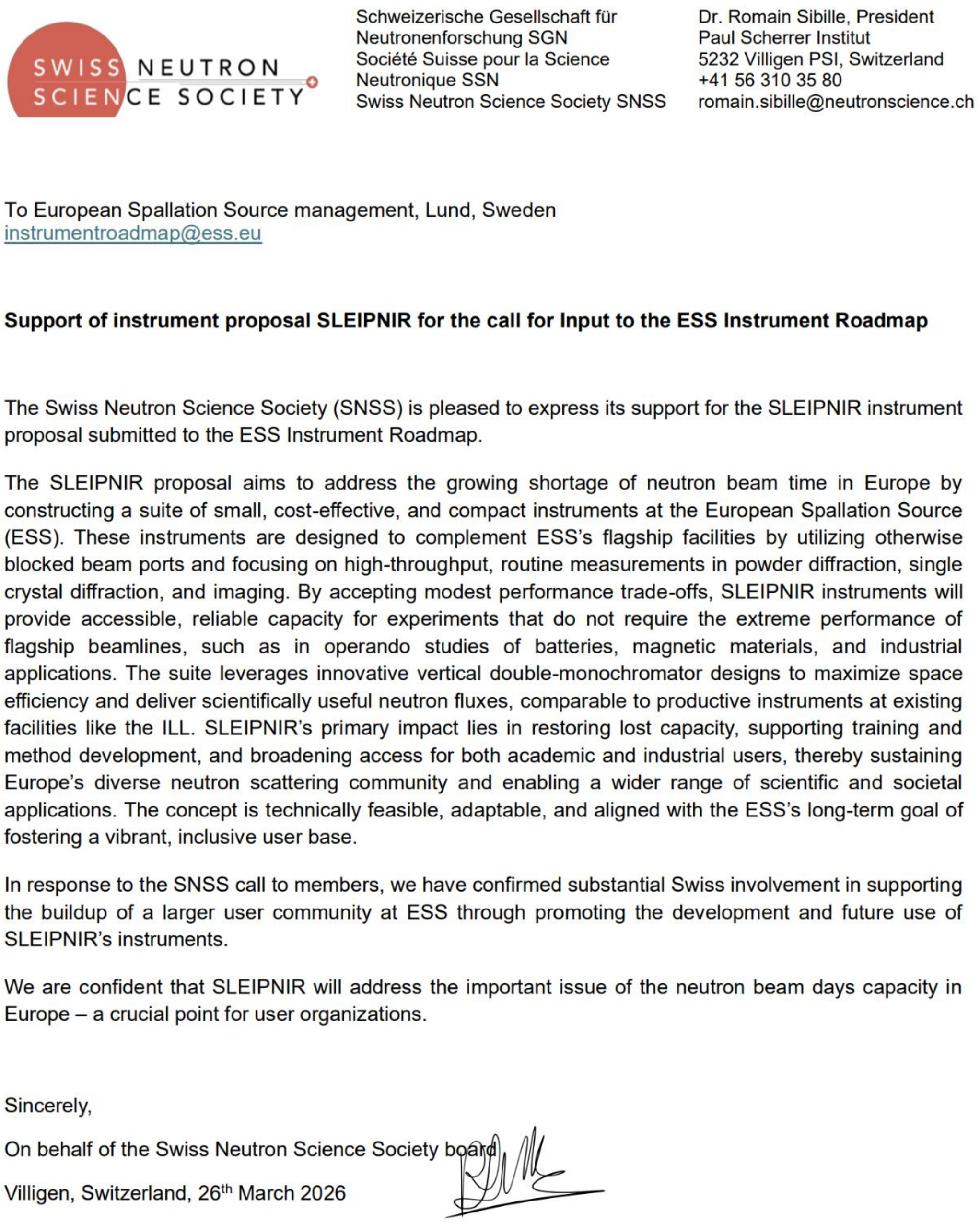
Support letter – Swiss Neutron Science Society



SWISS NEUTRON
SCIENCE SOCIETY

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To European Spallation Source management, Lund, Sweden
instrumentroadmap@ess.eu

Support of instrument proposal SLEIPNIR for the call for Input to the ESS Instrument Roadmap

The Swiss Neutron Science Society (SNSS) is pleased to express its support for the SLEIPNIR instrument proposal submitted to the ESS Instrument Roadmap.

The SLEIPNIR proposal aims to address the growing shortage of neutron beam time in Europe by constructing a suite of small, cost-effective, and compact instruments at the European Spallation Source (ESS). These instruments are designed to complement ESS's flagship facilities by utilizing otherwise blocked beam ports and focusing on high-throughput, routine measurements in powder diffraction, single crystal diffraction, and imaging. By accepting modest performance trade-offs, SLEIPNIR instruments will provide accessible, reliable capacity for experiments that do not require the extreme performance of flagship beamlines, such as in operando studies of batteries, magnetic materials, and industrial applications. The suite leverages innovative vertical double-monochromator designs to maximize space efficiency and deliver scientifically useful neutron fluxes, comparable to productive instruments at existing facilities like the ILL. SLEIPNIR's primary impact lies in restoring lost capacity, supporting training and method development, and broadening access for both academic and industrial users, thereby sustaining Europe's diverse neutron scattering community and enabling a wider range of scientific and societal applications. The concept is technically feasible, adaptable, and aligned with the ESS's long-term goal of fostering a vibrant, inclusive user base.

In response to the SNSS call to members, we have confirmed substantial Swiss involvement in supporting the buildup of a larger user community at ESS through promoting the development and future use of SLEIPNIR's instruments.

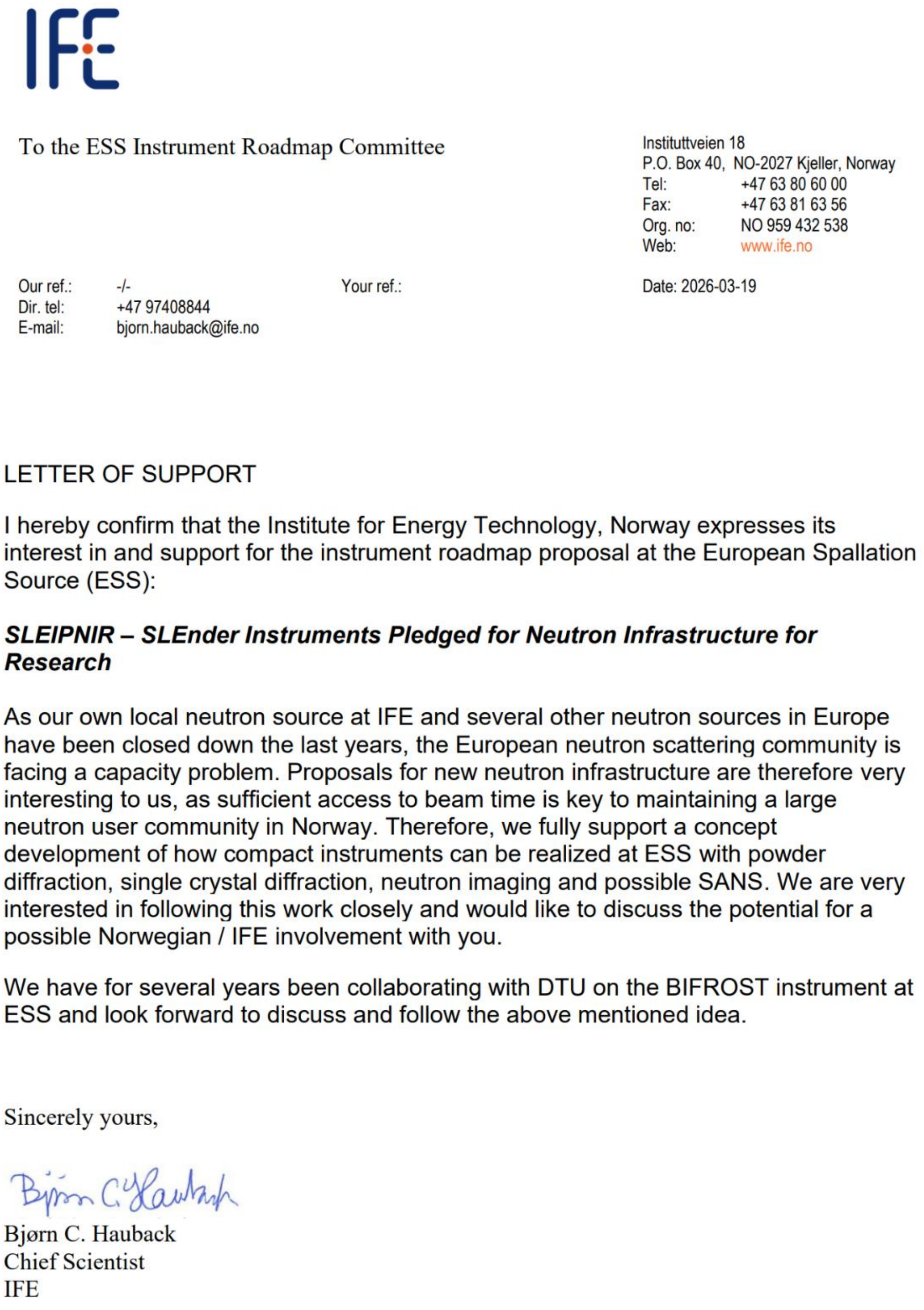
We are confident that SLEIPNIR will address the important issue of the neutron beam days capacity in Europe – a crucial point for user organizations.

Sincerely,

On behalf of the Swiss Neutron Science Society board

Villigen, Switzerland, 26th March 2026

Support letter – Institute for Energy Technology, Norway



IFE

To the ESS Instrument Roadmap Committee

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Date: 2026-03-19

LETTER OF SUPPORT

I hereby confirm that the Institute for Energy Technology, Norway expresses its interest in and support for the instrument roadmap proposal at the European Spallation Source (ESS):

SLEIPNIR – SLEnder Instruments Pledged for Neutron Infrastructure for Research

As our own local neutron source at IFE and several other neutron sources in Europe have been closed down the last years, the European neutron scattering community is facing a capacity problem. Proposals for new neutron infrastructure are therefore very interesting to us, as sufficient access to beam time is key to maintaining a large neutron user community in Norway. Therefore, we fully support a concept development of how compact instruments can be realized at ESS with powder diffraction, single crystal diffraction, neutron imaging and possible SANS. We are very interested in following this work closely and would like to discuss the potential for a possible Norwegian / IFE involvement with you.

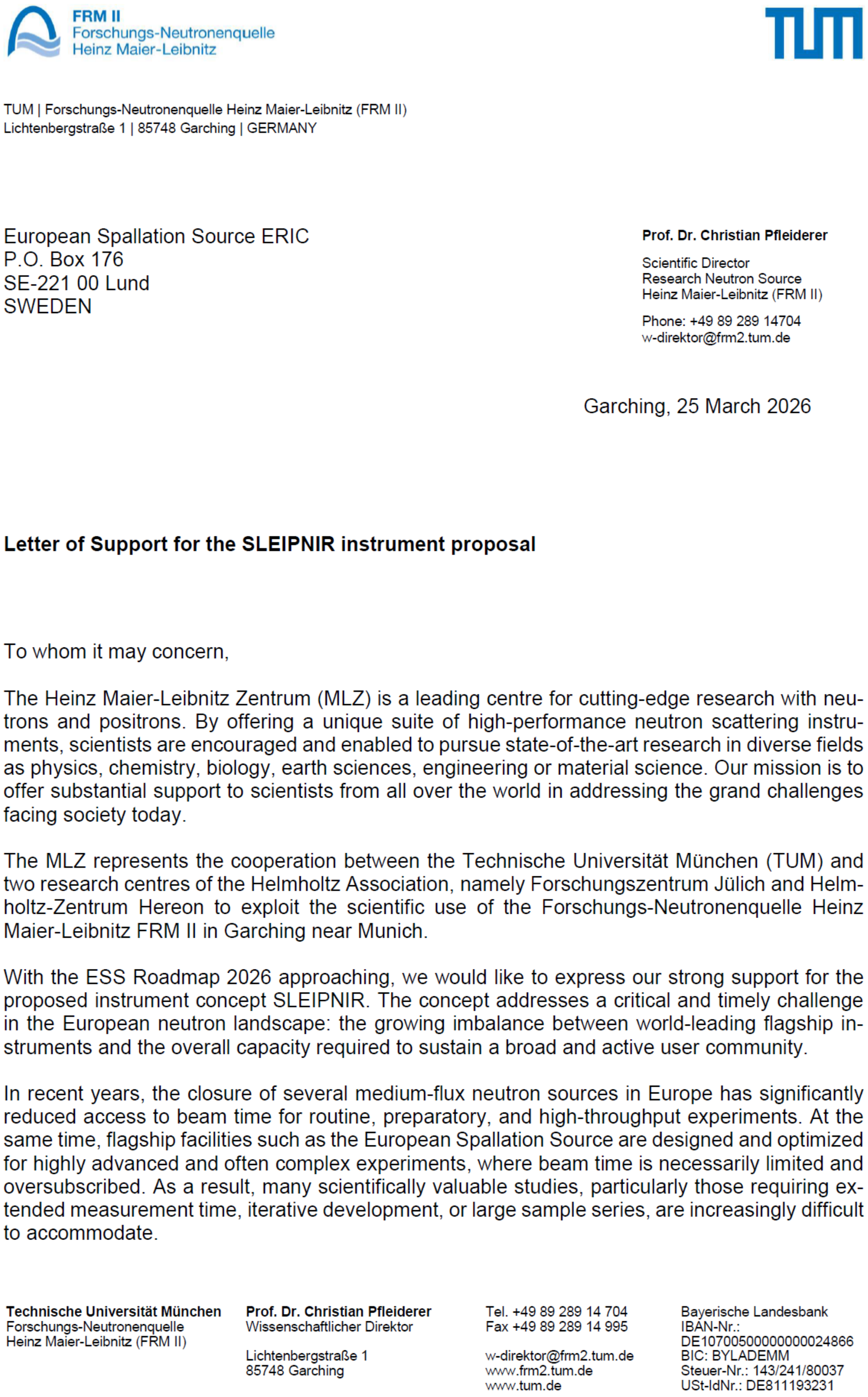
We have for several years been collaborating with DTU on the BIFROST instrument at ESS and look forward to discuss and follow the above mentioned idea.

Sincerely yours,

Bjørn C Hauback

Bjørn C. Hauback
Chief Scientist
IFE

Support letter – FRM II and TUM, Germany



FRM II
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Garching, 25 March 2026

Letter of Support for the SLEIPNIR instrument proposal

To whom it may concern,

The Heinz Maier-Leibnitz Zentrum (MLZ) is a leading centre for cutting-edge research with neutrons and positrons. By offering a unique suite of high-performance neutron scattering instruments, scientists are encouraged and enabled to pursue state-of-the-art research in diverse fields as physics, chemistry, biology, earth sciences, engineering or material science. Our mission is to offer substantial support to scientists from all over the world in addressing the grand challenges facing society today.

The MLZ represents the cooperation between the Technische Universität München (TUM) and two research centres of the Helmholtz Association, namely Forschungszentrum Jülich and Helmholtz-Zentrum Hereon to exploit the scientific use of the Forschungs-Neutronenquelle Heinz Maier-Leibnitz FRM II in Garching near Munich.

With the ESS Roadmap 2026 approaching, we would like to express our strong support for the proposed instrument concept SLEIPNIR. The concept addresses a critical and timely challenge in the European neutron landscape: the growing imbalance between world-leading flagship instruments and the overall capacity required to sustain a broad and active user community.

In recent years, the closure of several medium-flux neutron sources in Europe has significantly reduced access to beam time for routine, preparatory, and high-throughput experiments. At the same time, flagship facilities such as the European Spallation Source are designed and optimized for highly advanced and often complex experiments, where beam time is necessarily limited and oversubscribed. As a result, many scientifically valuable studies, particularly those requiring extended measurement time, iterative development, or large sample series, are increasingly difficult to accommodate.

Technische Universität München
Forschungs-Neutronenquelle
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The SLEIPNIR concept provides a highly compelling and cost-effective solution to this challenge. By enabling compact, non-invasive instruments within the ESS infrastructure, SLEIPNIR would significantly increase available beam time for diffraction and imaging techniques that form the backbone of neutron-based research. In particular, the focus on high-throughput measurements, standardized workflows, and accessible instrumentation aligns closely with the needs of both established and emerging user communities.

From our perspective at FRM II, such complementary capacity is essential. Medium-flux instruments have historically played a crucial role in enabling method development, feasibility studies, student training, and industrial engagement. They also provide the necessary foundation upon which flagship experiments can be built and de-risked. Ensuring that this layer of the ecosystem is maintained at ESS will be key to maximizing the long-term scientific and societal impact of the facility.

We are therefore convinced that the SLEIPNIR instrument suite represents a strategically important addition to the ESS instrument landscape. It has the potential to strengthen the European neutron community, broaden access, and foster innovation by enabling a wider range of experiments and users.

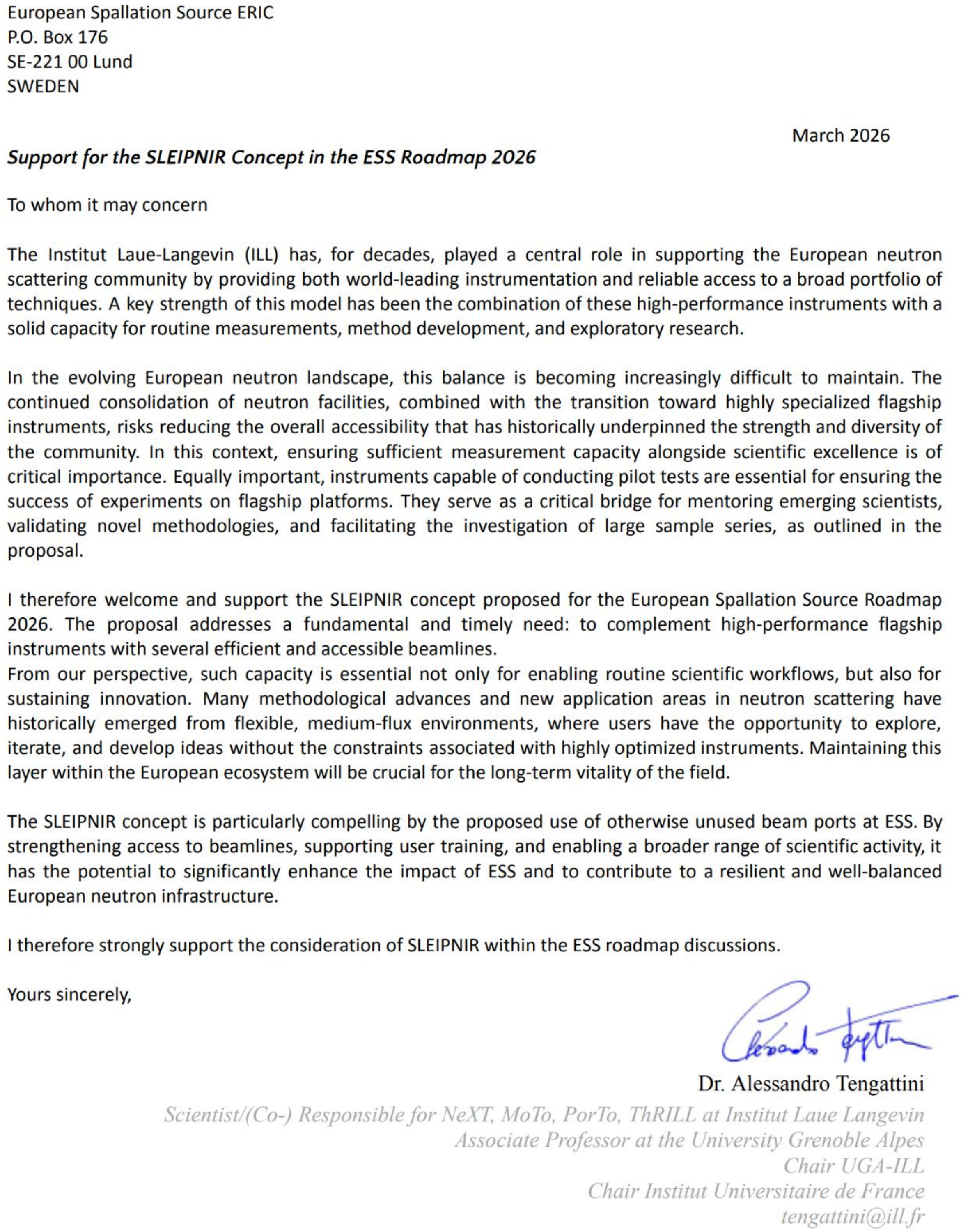
We strongly support the inclusion of the SLEIPNIR concept in the ESS roadmap discussions.

Yours sincerely,

Christian Pfleiderer

Prof. Dr. Christian Pfleiderer
Scientific Director FRM II

Support letter - Alessandro Tengattini



European Spallation Source ERIC
P.O. Box 176
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March 2026

Support for the SLEIPNIR Concept in the ESS Roadmap 2026

To whom it may concern

The Institut Laue-Langevin (ILL) has, for decades, played a central role in supporting the European neutron scattering community by providing both world-leading instrumentation and reliable access to a broad portfolio of techniques. A key strength of this model has been the combination of these high-performance instruments with a solid capacity for routine measurements, method development, and exploratory research.

In the evolving European neutron landscape, this balance is becoming increasingly difficult to maintain. The continued consolidation of neutron facilities, combined with the transition toward highly specialized flagship instruments, risks reducing the overall accessibility that has historically underpinned the strength and diversity of the community. In this context, ensuring sufficient measurement capacity alongside scientific excellence is of critical importance. Equally important, instruments capable of conducting pilot tests are essential for ensuring the success of experiments on flagship platforms. They serve as a critical bridge for mentoring emerging scientists, validating novel methodologies, and facilitating the investigation of large sample series, as outlined in the proposal.

I therefore welcome and support the SLEIPNIR concept proposed for the European Spallation Source Roadmap 2026. The proposal addresses a fundamental and timely need: to complement high-performance flagship instruments with several efficient and accessible beamlines.
From our perspective, such capacity is essential not only for enabling routine scientific workflows, but also for sustaining innovation. Many methodological advances and new application areas in neutron scattering have historically emerged from flexible, medium-flux environments, where users have the opportunity to explore, iterate, and develop ideas without the constraints associated with highly optimized instruments. Maintaining this layer within the European ecosystem will be crucial for the long-term vitality of the field.

The SLEIPNIR concept is particularly compelling by the proposed use of otherwise unused beam ports at ESS. By strengthening access to beamlines, supporting user training, and enabling a broader range of scientific activity, it has the potential to significantly enhance the impact of ESS and to contribute to a resilient and well-balanced European neutron infrastructure.

I therefore strongly support the consideration of SLEIPNIR within the ESS roadmap discussions.

Yours sincerely,

Dr. Alessandro Tengattini
Scientist/(Co-) Responsible for NeXT, MoTo, PorTo, ThRILL at Institut Laue Langevin
Associate Professor at the University Grenoble Alpes
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Support letter – DANSCATT

European Spallation Source management

27 March 2026

Letter of support for instrument proposals SLEIPNER, IDUN, and MAGNI for the call for Input to the ESS Instrument Roadmap

It is with great pleasure that DanScatt, which is the instrument centre for the Danish users of synchrotron and neutron sources as well as free-electron X-ray lasers and funded by the Danish Agency for Higher Education and Science, hereby expresses its strong support for the ESS instrument roadmap proposals SLEIPNER, IDUN, and MAGNI. In the view of that many of the reactor-based neutron sources in Europe have been closed or face an uncertain future during the coming 20 years, it is of utmost importance to DanScatt that capacity-building within neutron scattering and imaging is highly prioritized to be able to support growth of the neutron user community to be able to capitalize fully on the investment in ESS. Despite the considerably higher neutron flux available at ESS when in full operation, DanScatt expects that this will benefit the more complex and time-consuming measurements and therefore not necessarily lead to equivalently more beamtime for different measurements.

The three proposals SLEIPNER, IDUN and MAGNI have been prepared by very experienced consortia of European neutron scientists involving the Technical University of Denmark (DTU) and the Danish Technological Institute (DTI). Besides the excellent science that these proposed instruments will undoubtedly support, DanScatt would like to highlight that they are expected to expand ESS's societal impact considerably within emerging technologies, sustainability, and also the industrial use of neutron scattering and imaging. Further, they will expand the options for educating the next generation of neutron users, thereby supporting the growth of use of neutron methods for analysis at universities as well as in industry.

Best regards

M. Meedom Nielsen

Martin Meedom Nielsen
Chair of DanScatt's Board
Professor, Deputy Head of Department
DTU Physics

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