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A review of selected Swedish contributions to instrumentation at neutron scattering facilities

Thomas Arnold¹ · Jens Birch² · Elizabeth Blackburn³ · Glenn J. Coope⁵ · Reiner Dahint⁴ · Thomas Ederth² · Karen Edler⁵ · Fredrik Eriksson² · Björgvin Hjörvarsson⁶ · Marek Jacewicz⁶ · Sebastian Jaksch¹ · Kenneth Järrendahl² · Victoria Kabanova^{6,8} · Chung-Chuan Lai¹ · Filip Mehler⁶ · Naureen Ghafoor² · Tim Günter⁶ · Maths Karlsson⁷ · Pia Kinhult¹ · Sebastian Köhler^{6,8} · Clara Lopez¹ · David Milstead⁶ · Tommy Nylander⁹ · Adrien Perrichon¹ · Pablo Sanchez Puga⁶ · Felix Roosen-Runge⁹ · Valentina Santoro¹ · Piotr Szaniawski⁶ · Alexey Vorobiev^{6,8} · Max Wolff^{6,10} · Luca Zanini^{1,11}

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Abstract

The European Spallation Source in Lund, Sweden, is the next generation neutron research facility that will provide unprecedented capabilities for particle physics as well as materials and life science research through its high brightness, long-pulse neutron source and advanced instrument suite. To fully benefit from and to contribute to the build up of this facility, Swedish researchers are engaged in a number of instrument and first science projects. This review presents an overview of Swedish involvement in selected projects or proposals of projects and instruments at neutron scattering facilities. The examples highlight the extensive Swedish participation in specific instrument projects, science cases, and supporting technologies. The paper also highlights the larger scientific and strategic impact of this engagement, including capacity building, access to neutron techniques, and the strengthening of Sweden's position within the European neutron science community to take the best advantage of the European Spallation Source.

Keywords Neutron scattering · Instrumentation · European Spallation Source · Sweden

1 Research using neutrons in Sweden

The European Spallation Source (ESS), currently in the final stage of construction in Lund, Sweden, will be the major European research infrastructure for neutron science in the decades to come. It is designed to deliver unprecedented neutron brightness and enable new capabilities across a wide range of scientific disciplines. By combining a high-power proton accelerator with a long-pulse spallation source, ESS will provide advanced instrumentation

Extended author information available on the last page of the article

[6] for studies in materials science, physics, chemistry, life sciences and engineering. The impact of ESS critically depends on the scientific relevance of its instrument suite, which is developed through extensive international collaboration.

Sweden, as the host country, has contributed significantly to the construction budget of the ESS but, so far, has provided only limited input to the neutron instrumentation, which was delivered by other member countries as in-kind contributions. The only existing Swedish national research infrastructure for neutron science is the Super-ADAM [98] neutron reflectometer at the Institut Laue-Langevin (ILL, Grenoble, France). This serves as a platform for instrument and method development, but has also resulted in publications from hard matter to life science that have been acknowledged as highlights at ILL.

The decision to host ESS in Sweden reflects a strategic commitment to build, maintain and advance national competence in neutron science. In response to this a number of targeted funding initiatives have been installed since 2013. The most significant are the Swedish Research Council's Röntgen-Ångström Cluster and ISIS-ESS collaboration grants, for projects with Germany and the UK respectively, as well as funding directly directed to increase the engagement with ESS, namely two instrument pilot projects SAGA and HiBEAM, and the in-kind initiative. In addition targeted initiatives were created to widen the user community as well as promote fundamental and applied research with neutrons. These included specific VR project grants with focus on neutron scattering, the Swedish Foundation for Strategic Research funded Graduate School in Neutron Science (SwedNess), the NordForsk 5-year capacity building project and research school within the Nordic Neutron Science Program, and a NordForsk postdoctoral fellowship program with focus on neutron scattering. Further, Vinnova funded projects for "Increasing capacity and skills of PhD students regarding industrially relevant neutron and synchrotron based analytical methods" and "Industrial utilization of neutron and synchrotron light based technologies in large-scale research infrastructure."

The Swedish neutron science and user community has increased considerably as a consequence of these targeted funding schemes. A bibliometric study published some years ago by the Swedish Neutron Science Society (SNSS) [12] showed that the user community did not only grow but also diversified. Today, applications for beam times from the increasing Swedish user community are very successful for all available instrument methods. The users nowadays come from much more diverse research backgrounds, including engineering, physics, chemistry and life science. More recently another bibliometric study done by the European Neutron Scattering Association [96] confirmed this trend. The Swedish neutron science community has grown and is now among the largest in the world per capita, but to sustain this growth the number of frequent users and experts on instrumentation need to grow at the same pace.

In this review we provide an overview of selected Swedish contributions in instrumentation to neutron facilities, with an emphasis of ESS related projects. We highlight instrument projects, science cases and associated technology developments, focusing on the scope and integration within the wider ESS framework. This work demonstrates how the existing and potential for extending the competence on key neutron methodology benefited from the coordinated national engagement in large-scale research infrastructure. The outcome is both scientific excellence and long-term capacity building in neutron-based research.

2 The reflectometer Super-ADAM at the Institut Laue-Langevin

Super-ADAM, currently, is the only neutron infrastructure completely owned by the Swedish community and provides access for the Swedish research community to neutrons. This monochromatic neutron reflectometer operates at a wavelength of 5.25 Å with a resolution of 0.4 % extracted from the H521 guide of the ILL [34, 97]. It enables high resolution data for a range of scientific questions. The high resolution branch of the instrument was lately complemented by a high flux branch using a shorter wavelength allowing measurements at higher flux and up to larger Q values. The high resolution and high flux branches are visible on the right and left hand side of the photo in Fig. 1.

The operation of the infrastructure is regulated by a Collaborative Research Group (CRG) contract between the ILL and Uppsala University. 50 % of the access to the infrastructure is reserved for the ILL user program and 50 % for Swedish researchers. Super-ADAM has a large experimental area (Fig. 1) and modular design, which allows for a large flexibility that is currently unrivaled by other instruments of this type. One example of this flexibility is the sample to detector and the monochromator to sample distances that can be varied, allowing a flexible resolution for both incident and scattered beams. All instrument components are movable (mounted on air-pads), which allows rapid reconfiguration and test of completely new ideas. One recent example in this context is the development of a GISANS mode flipping the sample by 90° [99]. The selectable outgoing resolution and 2D position sensitive detector make Super-ADAM an ideal tool for experiments on polarised off-specular neutron scattering and GISANS.



Fig. 1 Photograph of the Super-ADAM instrument at the Institut Laue-Langevin. The high flux and high resolution mode are visible on the left and right hand side, respectively

The unique feature of Super-ADAM is its high resolution and polarisation (up to 99.8 % incoming and 99.4 % outgoing) allowing the instrument to excel in reflectivity measurements on magnetic thin films and multilayers. Figure 2 shows a reflectivity curve measured with polarisation analysis of a 100 nm thick layer of vanadium sandwiched between two iron layers of approx. 15 nm thickness [104]. The measurements were performed in saturation. The 100 nm thick layer can easily be resolved from the Kiessig fringes. The spin-flip scattering visible at low Q results from imperfections of the polariser-analyser and spin flippers and demonstrates a flipping ratio of ~ 200 .

Super-ADAMs flexible set-up makes it particularly suitable for method and instrument development in the area of surface scattering using neutrons and also makes it attractive for users from a wide range of science areas and applications. Several specialized experimental techniques are available, which are usually not accessible on reflectometers. These include small angle scattering in transmission mode, alpha and gamma fluorescent polarised neutron reflectometry (PNR), time resolved and time average alternating magnetic field PNR [107]. The excellent polarisation of the instrument and high resolution makes it an indispensable tool for the study of neutron mirrors. For examples in this context we refer to Section 4.1. Further, the development of magnetic reference layers to provide additional contrast for soft matter systems, where selective deuteration is challenging, has been benefited thanks to the polarization capabilities of Super-ADAM [36]. The optimisation of such layers allows to optimise data collection and reduce counting times significantly [106]. Users on Super-ADAM have access to diverse sample environments to allow a wide range of studies with respect to systems and experimental conditions. Directly and dedicated for the instrument are:

- An electromagnet (0.8 T) with He-flow cryostat (1.5–500 K)
- a gas loading system (UHV compatible, with pressure up to 1 Bar and complementary optical characterisation of the sample)

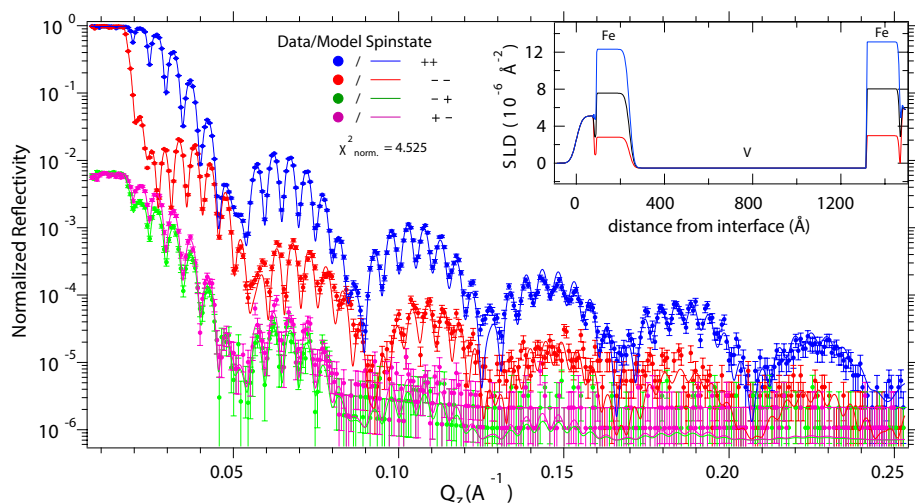


Fig. 2 Specular reflectivity of a 100 nm layer of vanadium sandwiched by iron. Data was taken with full polarisation analysis on the instrument Super-ADAM in high resolution mode. Figure adapted from Ref. [104]

- Cells for the study of solid-liquid interfaces, including a sample changer as well as HPLC and syringe pumps.
- An automated humidity chamber

Requests of experimental needs outside these specifications are enabled by the use of ILL sample environment, offering everything that a large-scale facility may supply, e.g. high magnetic fields, temperatures down to 50 mK and up to almost 2000 K as well as pressures of several hundreds of bars. The capabilities available at Super-ADAM enable high impact research in a wide range of science areas. To give an idea about the diversity of experiments three recent examples of scientific highlights are listed:

2.1 Life science and food

Using Quartz Crystal Microbalance with Dissipation monitoring (QCM-D) and neutron reflectometry (NR) on Super-ADAM it was investigated how the two main pea storage proteins, legumin and vicilin, interact with model phospholipid bilayers. It was shown that legumin has little affinity for lipid interfaces while vicilin actively interacts with and alters them. The results indicate that vicilin can induce structural reorganization and partial removal of lipids—likely forming reversible complexes—highlighting its key role in influencing the interfacial functionality of pea protein [8].

Lipid nanoparticles (LNPs) are increasingly being explored as delivery vehicles in food and pharmaceutical applications. Sponge phase (L_3) LNPs are favorable due to their continuous, highly curved bilayers and large aqueous pores, making them particularly effective for protein encapsulation. Here, the interaction between the encapsulated protein and the lipid bilayer is very important for the efficiency of the encapsulation as well as the lipid matrix. L_3 LNPs were spread on hydrophilic silica surfaces and it was found that they readily form supported lipid bilayers of high coverage on silica deposited on magnetic reference layer as apparent from PNR data [59]. Detailed information on the interactions with Myoglobin (Mb) was obtained from PNR and the interaction could be tuned by the lipid composition (Fig. 3). The gained knowledge of these interactions is needed for the development of lipid systems of relevance for protein delivery.

2.2 Quantum materials

A combination of small angle neutron scattering and polarised reflectometry on Super-ADAM was used to investigate magnetic textures in Pt/CoFeB/Ru multilayers. The presence of stripe domains and skyrmions at room temperature with purely Néel-type domain walls was revealed. Further, it was shown that skyrmions disappear below about 250 K due to increased magnetic anisotropy. This provides important insights for designing skyrmion-based spintronic devices [95].

2.3 Energy materials

NR on Super-ADAM contributes depth resolved structural and compositional information in thin membranes. Such data increase the understanding of interfacial morphology and solvent distribution, which is essential for optimizing membrane performance in fuel

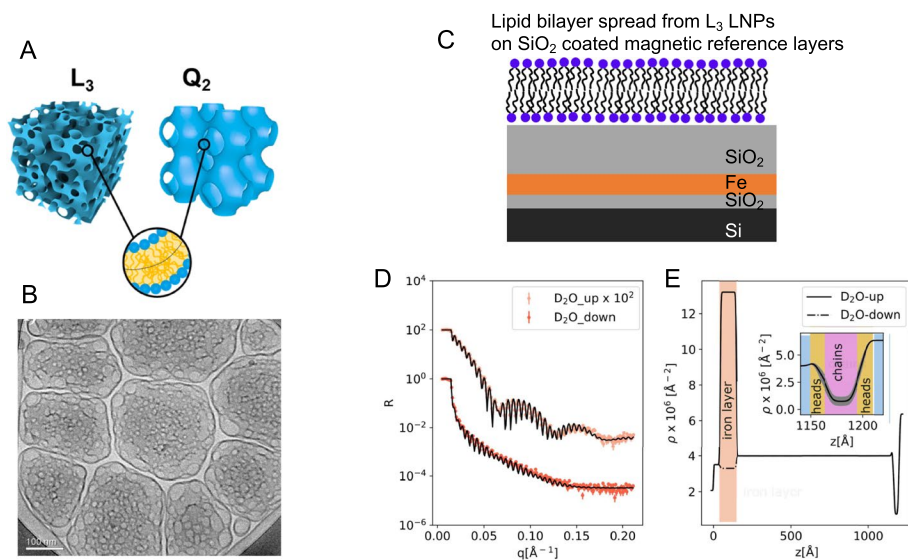


Fig. 3 **A)** Shows schematic figures of related curved bilayer type, sponge (L_3) and reverse cubic (Q_2) phase. **B)** Shows Cryo TEM images of Sponge phase LNPs. **C)** Schematic figure of a bilayer structure formed at magnetic reference layers from L_3 LNPs (note not to scale). **D)** PNR data on a lipid bilayer formed from DGMO/GMO-50/DOPC L_3 LNPs, with the neutron spin polarisation up and down (D_2O up and D_2O down) together with the fitting curves according to model in B. **E)** Shows the corresponding scattering length density profile. Data adapted from [59]

cells. Advanced neutron scattering and imaging techniques enable detailed investigations of structure, water distribution, and ion transport in polymer electrolyte membranes [44]. This provides crucial insights across multiple length and time scales for e.g. energy applications.

3 Beamline concepts for ESS

Recently the ESS has asked for input to the future instrument roadmap of the facility. Swedish researchers are involved in about half of the 22 proposals that have been submitted. In this section we describe four selected instrument projects with very strong Swedish engagement. Two of them, SAGA and FINESSE (developed out of HIBEAM), have received funding from Vetenskapsrådet over the last years to develop the conceptual designs. ECHIR aims for applied science by providing irradiation capabilities and Gersemi proposes the construction of a neutron spin echo instrument at ESS.

3.1 SAGA

The SAGA (Surface Analysis using Grazing Angles) project is deeply rooted in the internationally recognized Swedish competence in surface, colloid and interface sciences, as well as in material and life sciences. The project is a collaboration among several Swedish Universities that proposes a dedicated beam line for time-of-flight grazing incidence small angle scattering (TOF-GISANS) at ESS together with leading international partners. The

ESS technical design report reference suite, under the name "Surface Scattering beamline" and the subsequent capability gap analysis for the ESS instrument suite already identified the need and strong scientific case for such a beamline. The initiative to build a dedicated GISANS instrument, which fully exploits the high source brightness of ESS, is based on the scientific impact from key areas, in which GISANS has proven to be valuable as described in detail in a recent review from the SAGA team [56].

Based on the science drivers design criteria have been developed. The key is to make SAGA optimised for GISANS while remaining flexible enough to serve a wide community. Today GISANS experiments have to be conducted on existing SANS and reflectometry instruments, which strongly reduces the availability and compromises data quality.

TOF-GISANS allows the determination of structure at different distances from an interface, but this requires high wavelength and angular resolution, as shown by several authors [3, 68, 105]. As a consequence SAGA has been designed as a long instrument, 65 m from source to the GISANS detector, resulting in a natural resolution of approx. 2–4% and a decent bandwidth of approx. 4–8 Å. Even better resolution is accessible via wavelength-frame-multiplication to improve the wavelength resolution to 1% for experiments requiring good depth sensitivity. However, this comes at the expense of a factor of about 3 reduction in flux (as determined by McStas simulations).

A significant part of the emerging science cases addresses liquid interfaces, requiring a horizontal sample geometry. Neutrons are an ideal probe for the interface between two liquids, since, unlike for X-rays, the contrast between the two liquids can be tuned using selective deuteration. For this reason SAGA will extract neutrons via a 30x30 mm² guide from the ESS moderator. The guide delivers a natural downturn of $\sim 0.4^\circ$, close to the critical angle of a number of important interfaces such as silicon/D₂O (0.40°), air/silicon (0.27°) or air/D₂O (0.50°) surfaces at 6 Å, the centre of the wavelength band.

For the analysis of GISANS data in the framework of the Distorted Wave Born Approximation (DWBA) the depth profile, extracted from NR, is needed as basis as it provides unperturbed (without diffuse or small angle scattering) depth profiles. This requires a specular NR data set on the same sample and while it may be possible to repeat a measurement on a different (reflectometry) instrument it leads to the risk of perturbing the sample and challenges to account for differences in performance of two different instruments. Some systems are difficult to prepare to be exactly identical and most sample systems that are sensitive to gravity cannot be moved without disturbing their structural organization. For this reason SAGA is designed to provide capabilities to measure NR.

A significant proportion of the science case, particularly studies of quantum materials, requires the provision of full polarisation analysis and space for larger magnets. The incorporation of such components into the design from day one is considered crucial to their successful implementation. To avoid unnecessary losses in neutron flux for unpolarised measurements SAGA is designed in a way that all polarization components are easily removable.

For successful GISANS measurements an excellent signal-to-noise ratio is crucial, since this enables measurements of samples that give weak scattering signals. To minimize instrumental contributions to the background, the SAGA concept includes either an s-bend or periscope guide for a horizontal displacement to break line-of-sight of the moderator twice by the time it exits the bunker.

Figure 4 shows a conceptual and engineering design drawing, top and bottom panel, respectively, of the proposed SAGA instrument at ESS. A proposal to build an instrument based on the above considerations was submitted to the call for input to the ESS instrument roadmap.

3.2 GERSEMI

For the ESS instrumentation roadmap, a community proposal for a neutron spin echo (NSE) spectrometer was submitted with a Swedish spokesperson (Felix Roosen-Runge, Lund University), and significant involvement by several Swedish researchers from Uppsala University, Chalmers, Lund University, and KTH, as well as from other countries. Currently NSE is a unfulfilled capability at ESS. While the proposal focused on the development of the science case and representation of the user community, a brief conceptual outline of the instrument (Fig. 5, left panel) was included along with conceptual calculations and simulations of the primary spectrometer, as detailed technical and conceptual designs are available for the secondary spectrometer at ILL and JCNS.

These conceptual calculations show that an NSE instrument benefits from the time-of-flight mode at the ESS long-pulse source with 14 Hz repetition compared to a reactor source instrument at similar time-averaged flux. A NSE instrument at ESS significantly gains flux due to the broader admissible wave-length band, and at the same time achieves better instantaneous monochromatisation for high Q resolutions (Fig. 5, right panel). Dedicated simulations of the chopper cascade including a pulse-shaping chopper outline the promising opportunities to improve the instantaneous monochromatisation for increased Q resolution relevant for materials with sharp structural features such as Bragg peaks or form factor minima.

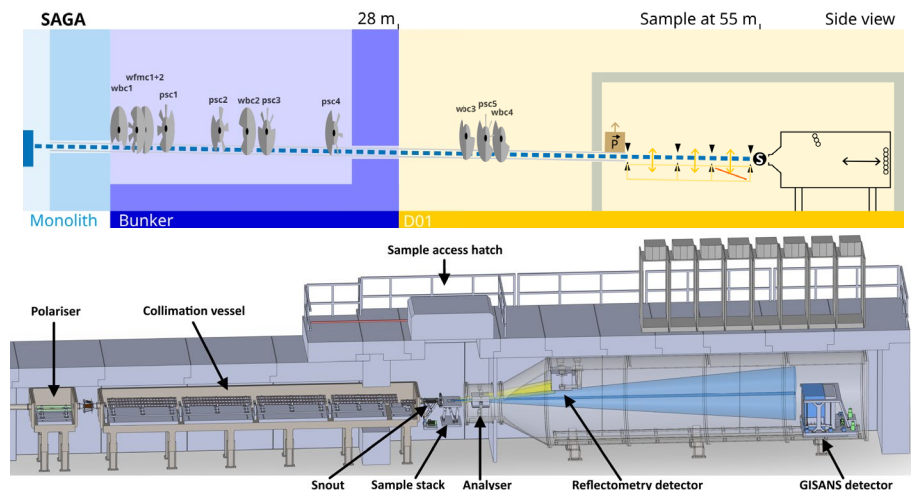


Fig. 4 Top panel: Conceptual design drawing of SAGA. Bottom panel: Engineering design 3D CAD model of SAGA

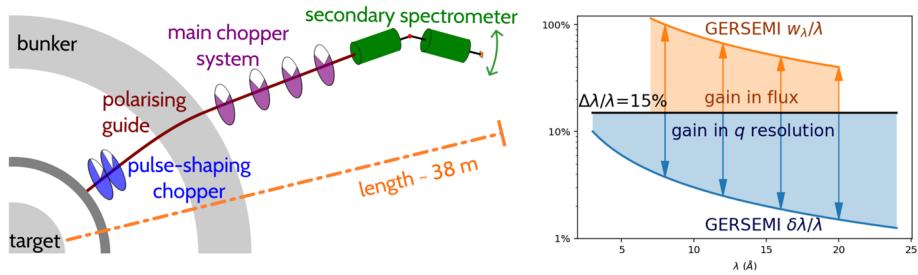


Fig. 5 Left panel: Conceptual sketch of the neutron spin echo (NSE) spectrometer GERSEMI at ESS. Right panel: Conceptual calculations of the beneficial factors of the pulse structure at ESS with a long pulse and only 14Hz repetition for NSE spectroscopy compared to a continuous source with similar time-average flux. While an NSE instrument at a continuous source has a fixed $\Delta\lambda/\lambda$ of $\sim 15\%$, the time-of-flight mode allows to take in a broader wave length band w_λ/λ resulting in higher flux on the sample, and at the same time achieves in lower instantaneous monochromatization $\delta\lambda/\lambda$

3.3 FINESSE

FINESSE (*A Versatile Beamline for Fundamental Interactions with Neutrons at the European Spallation Source*) is a proposed Swedish-led and international general-purpose instrument for particle physics [1, 84]. FINESSE addresses key open questions in particle physics. These include the origin of the matter–antimatter asymmetry of the universe, the nature of dark matter, and the existence of hitherto unseen physical processes beyond the Standard Model [9, 14, 28, 60, 63, 67]. FINESSE fits well within the 2026 European Particle Physics Strategy, offering a unique sensitivity to baryon-number violation, dark-sector searches and precision neutron observables [42].

FINESSE [43] grew out of the HIBEAM [1, 84] program. FINESSE includes a high-flux option, corresponding to the HIBEAM program, and a low-background option which facilitates the ANNI [88] program. FINESSE uses a switchable dual-guide at the E5 location, with a movable section 4.5m in the ESS bunker. Both beam modes can be operated without performance loss compared with that expected from dedicated standalone instruments. Flexibility is a central design principle with FINESSE. It allows greater competition between proposed experiments and keeps the beamline open to new ideas. This is appropriate for an instrument expected to operate over a multi-decadal lifetime. Figure 6 shows the high-flux FINESSE guide geometry and the detailed E5 bunker view of the exchangeable dual-guide system, showing the guide segments, elevator platforms and chopper/shielding integration that allow the high-flux and low-background configurations to share one general-purpose instrument.

High-Flux FINESSE is optimized for those experiments limited by statistical precision such as searches for neutron–antineutron transitions, sterile-neutrons, axion-like-particles and other dark matter candidates [62, 84]. Low-Background FINESSE supports high-sensitivity measurements on which stringent requirements on the neutron beam properties need to be made. Such measurements include neutron decay properties and a search for a non-zero neutron electric dipole moment (EDM) [4, 20, 74, 100].

A flagship High-Flux FINESSE measurement is the first search for free neutron–antineutron conversion, $n \rightarrow \bar{n}$, for more than thirty years and which has a unique physics reach beyond that achievable with bound neutrons [13]. At least an order-of-magnitude improve-

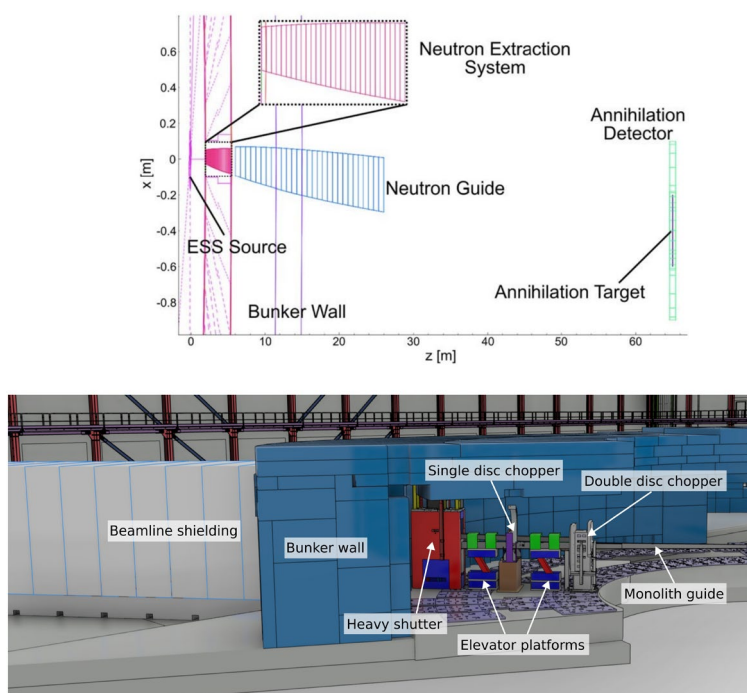


Fig. 6 Top: the high-flux FINESSE guide geometry. Bottom: the detailed E5 bunker view of the exchangeable dual-guide system

ment in discovery sensitivity is expected compared with the last free-neutron search at the ILL [11, 43, 84]. This also aids a longer-term NNBAR program, which can achieve a sensitivity improvement of up to three orders of magnitude [10, 83].

The FINESSE proposal includes 95 researchers from 51 institutes in 18 countries, including Sweden, Finland, Denmark, Germany, Italy, Poland, the United Kingdom, the United States, Brazil, Australia and others [43]. The team comprises expertise on neutron optics, shielding, magnetics, detector systems, computing and simulation as well as the relevant physics areas. The program has been supported by EU Horizon 2020, the Swedish Research Council, the Swedish Foundation for Strategic Research, Crafoord Foundation, and the Olle Engkvist Foundation.

The level of readiness is high. Detailed studies of the physics potential, neutron optics, biological shielding, magnetics and detector solutions have been made. Prototype detector components and magnetic-shielding elements are being developed and tested [40, 81]. It is also important to note that the E5 monolith insert is already installed. This was proposed and designed by the HIBEAM/FINESSE community and enables an early particle-physics beamline at ESS. A short FINESSE beamline has been proposed which provides a cost-effective early physics program with an upgrade path to the full facility [43].

3.4 ECHIR

The ECHIR (ESS Chip Irradiation) project was initiated to evaluate the feasibility of establishing a dedicated fast-neutron irradiation beamline at the ESS [22]. The facility is intended to meet the growing industrial and scientific demand for controlled neutron environments for testing radiation effects in microelectronics, as for example used in aviation [75], power electronics, deep neural networks [82] and board-level integrated systems. A second European high-energy neutron test capability is strategically important to provide redundancy to the ChipIr beamline at ISIS [29] and to strengthen Europe's capacity for cosmic-ray robustness qualification.

The project was carried out in close collaboration between Uppsala University (UU), ESS and Industrial partners. A significant portion of the ECHIR infrastructure is already in place. The fast-neutron channel embedded within the monolith shielding has been constructed, together with additional shielding blocks, a revolver-type shutter system, and the designated beam-dump in the basement. However, no provisions were originally made for the user testing space, the ECHIR experimental room, which now requires dedicated design work to integrate safely with the existing infrastructure. UU and ESS jointly developed a preliminary design for the ECHIR beamline (see Fig. 7, left panel), including shielding concept, collimation, and test-station layout. A design engineer from UU contributed to CAD and engineering integration.

Advanced Monte Carlo simulations were performed by a simulation expert at Technical University of Denmark, and a PhD student at the Helsinki Institute of Physics. The simulations evaluated among others: neutron energy spectrum shaping, achievable high-energy flux at the sample position, shielding performance and dose distributions in adjacent areas (see Fig. 7, right panel) and compliance with ESS radiation-protection constraints. Results confirm that the proposed ECHIR location can achieve the target fast-neutron spectrum and flux levels required for Single Event Effects, Displacement Damage and system-level irradiation studies. Results have been published (or are in course of publication) in [64].

Besides the baseline design located in the basement of the ESS target building, another identified location for a fast-neutron irradiation beamline is the S1 port in the ESS instrument hall, close to the ODIN and DREAM instruments. This location offers several logistical advantages compared with the baseline design. However, it requires a new neutron beam-port insert, potentially tilted toward the target, to extract the high-energy neutrons. This option provides more space for a heavy shutter and collimation system, but it also

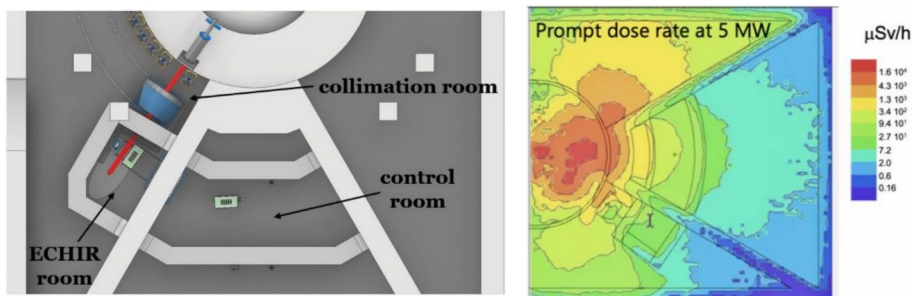


Fig. 7 Left panel: Top view of the proposed ECHIR facility at the ESS. The red line indicates the neutron beam. Right panel: Neutron dose rate map with regular concrete walls between the rooms

requires a careful assessment of the shielding feasibility for the high-energy neutron beam. A neutronics study of this second option is currently being carried out by the University of Helsinki and the Technical University of Denmark (DTU).

Industrial partners made substantial contributions to defining the irradiation needs for both semiconductor devices and system-level electronics. A strong increase in industrial engagement was achieved, documented through letters of intent and formal endorsement signatures from multiple European semiconductor companies and experts. The project produced a complete and well-substantiated proposal for ECHIR, including a detailed business and science case outlining industrial demand, market potential, and the strategic importance for the European semiconductor sector forming a solid foundation for the next phase of establishing ECHIR as a high-flux neutron irradiation facility for European industry and research.

4 Development of components for neutron instruments

Recent advances in neutron instrumentation were facilitated by technical developments allowing to enhance the performance of neutron instruments. In this context two areas are of specific relevance. The first one is beam transport from the source to the sample with minimal loss of neutrons and background scattering. The second one is neutron detectors that go beyond the ^3He technology that was dominating over the past decades. In both these areas thin film technologies, as developed at Linköping University are crucial and described in this section.

4.1 Neutron mirrors

Swedish activities in multilayer neutron optics have mainly been centered on magnetron sputtered thin films and interface engineering at Linköping University. The work has primarily addressed both non-polarising Ni/Ti-based, and polarising Fe-based multilayers and supermirrors, which has formed the basis for three PhD projects. In addition to Ni/Ti, Ni/Ti+ $^{11}\text{B}_4\text{C}$ [25, 41, 90, 91], Fe/Si and Fe/Si+ $^{11}\text{B}_4\text{C}$ [108, 109, 112], related material systems such as Co/Ti and Fe/ $^{11}\text{B}_4\text{C}$ have also been investigated to tune neutron optical contrast, magnetic properties, and interface structure [110, 111]. Moreover, a novel concept for neutron mirrors based on epitaxially grown $\text{CrB}_2/\text{TiB}_2$ superlattices [37–39], which have the potential of forming atomically abrupt interfaces for the benefit of high reflectivity, have been investigated.

A central part of the work has been to understand how deposition conditions, ion assistance and $^{11}\text{B}_4\text{C}$ incorporation affect interface widths, roughness propagation and neutron optical performance. For Ni/Ti multilayers, B_4C incorporation combined with modulated ion assistance was shown to reduce interface widths from the typical value of about 0.7 nm in state-of-the-art Ni/Ti coatings to approximately 0.4 nm. Grazing-incidence small-angle scattering, combined with neutron and X-ray reflectometry, further showed that optimised $^{11}\text{B}_4\text{C}$ -containing Ni/Ti multilayers can reach average interface widths of about 0.27 nm [25, 41, 90]. Material design studies of large-m Ni/Ti-based supermirrors compared pure Ni/Ti multilayers, $^{11}\text{B}_4\text{C}$ co-deposition and interlayer approaches, and identified hybrid designs aimed at maintaining reflectivity at low scattering vectors while reducing interface-related losses at larger scattering vectors [91].

As an example of how these results can be transferred from periodic multilayers to a supermirror design, simulations were performed for a depth-graded Ni/Ti-based supermirror in which the material design was varied through the stack. For multilayer periods larger than about 52 Å, corresponding to the low-Q region, Ni/Ti multilayers with $^{11}\text{B}_4\text{C}$ interlayers were used to preserve optical contrast while reducing interface widths. For thinner periods, co-sputtered Ni/Ti: $^{11}\text{B}_4\text{C}$ was used to minimize the interface width. Using interface widths of approximately 6.2 Å for the interlayer design and 4.6 Å for the co-sputtered design, the calculated hybrid supermirror showed higher reflectivity than a conventional, commercially available, Ni/Ti supermirror with 7.0 Å interface width over the full simulated Q-range. The same design concept also extended the useful range from $m = 7$ to $m = 10$ in the simulation, corresponding to an increase of about 40% in accessible critical angle (Fig. 8). In the high-Q region, the calculated reflectivity gain is typically on the order of 10–20%, while maintaining high reflectivity at lower Q. This illustrates how the materials results can be translated into design rules for large- m supermirrors [91].

For polarising optics, Fe/Si-based multilayers have been modified both by introducing ultrathin $^{11}\text{B}_4\text{C}$ layers and by co-sputtering isotope-enriched $^{11}\text{B}_4\text{C}$ into the multilayer structure. The interlayer approach reduced the interface width from about 0.95 nm to 0.52

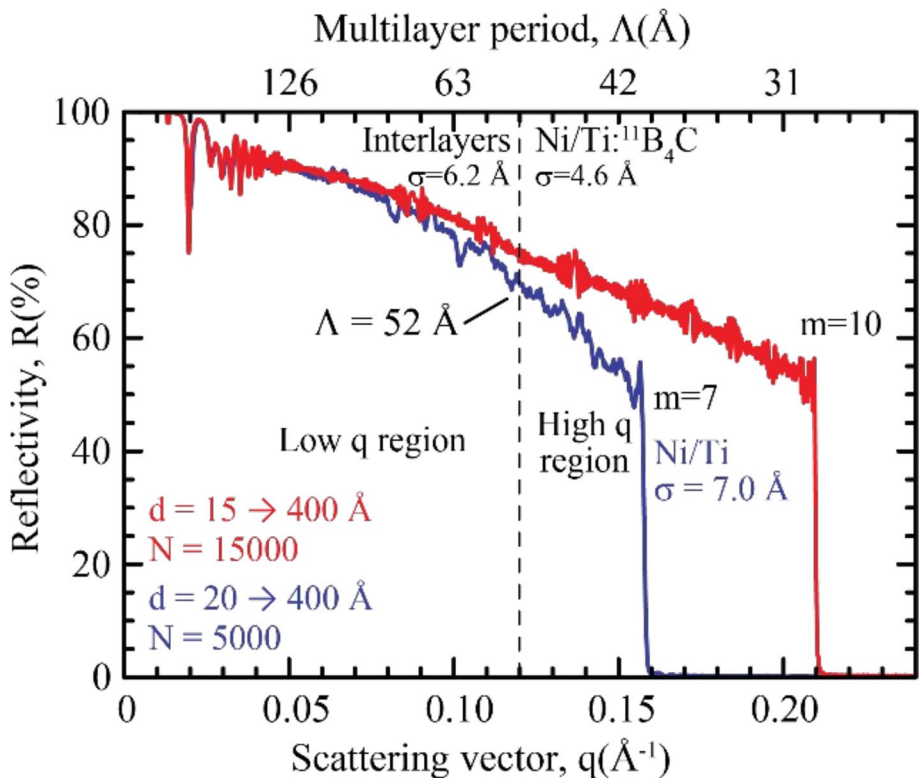


Fig. 8 The calculated performance of a hybrid supermirror design compared to that of a conventional Ni/Ti supermirror. The blue curve shows a conventional Ni/Ti multilayer with an interface width of $\sigma = 7.0$ Å. The red curve shows the simulated reflectivity from a hybrid multilayer design with $^{11}\text{B}_4\text{C}$ interlayers with an interface width of $\sigma = 6.2$ Å for periods thicker than 52 Å, and Ni/Ti: $^{11}\text{B}_4\text{C}$ with an interface width of $\sigma = 4.6$ Å for periods thinner than 52 Å

nm in short-period Fe/Si multilayers, giving a reported 125% increase in reflectivity and 15% higher polarisation [108, 112]. Co-sputtering of $^{11}\text{B}_4\text{C}$ into Fe/Si multilayers led to smoother and more amorphous interfaces, reduced diffuse scattering, improved reflectivity and polarization, and magnetically softer Fe-layers [112]. In stacked Fe/Si multilayers with varying period thicknesses, $^{11}\text{B}_4\text{C}$ incorporation also reduced the internal stress by about 50% and suppressed spin-flip scattering [109, 112]. Related work on Fe/ $^{11}\text{B}_4\text{C}$ multilayers demonstrated scattering length density tuning of the non-magnetic layer as an additional route to improve polarisation performance [110].

As an example for polarising multilayers, Figure 9, panel to the left, compares the reflectivity of Fe/Si and Fe/Si+ $^{11}\text{B}_4\text{C}$ multilayers and summarizes the polarization obtained for co-sputtered Fe/Si multilayers with different $^{11}\text{B}_4\text{C}$ concentrations. The comparison of the spin-dependent reflectivity for Fe/Si and Fe/Si+ $^{11}\text{B}_4\text{C}$ multilayers in a), shows that the reflectivity is improved by 125% for spin-up neutrons with $^{11}\text{B}_4\text{C}$ in the multilayers. Figure 9, panel to the right, shows the polarization as a function of $^{11}\text{B}_4\text{C}$ concentration for co-sputtered Fe/Si multilayers, demonstrating that the polarization can be controlled giving an optimal concentration of about 14 at.%, corresponding to an improvement of about 20% in polarization compared to Fe/Si [112]. This provides a direct experimental example of how interface engineering in Fe/Si multilayers can be used to improve the performance of polarising neutron optics.

Epitaxial $\text{CrB}_2/\text{TiB}_2$ superlattice neutron mirrors, which may have their application in supermirror-based Fermi choppers, were developed using Magnetron Sputter Epitaxy (MSE). Issues with boron segregation in the TiB_2 layers [37] were solved by utilizing an under-stoichiometric TiB target [38]. By tailoring the ion energy as well as the temporal variation of ion assistance flux during growth of each layer, high quality $\text{CrB}_2/\text{TiB}_2$ superlattices suitable as neutron mirrors were achieved, with interface widths of 1 unit cell for TiB_2 -on- CrB_2 and 2 unit cells for CrB_2 -on- TiB_2 , as determined by coupled X-ray and NR analyses.

The coating studies combine thin film synthesis with X-ray reflectometry, X-ray diffraction, grazing incidence small angle scattering, electron microscopy, ion-beam analysis, magnetic measurements and NR. In addition to specular reflectometry, diffuse NR and spin-resolved off-specular scattering have been used to investigate lateral structural and magnetic correlations in the multilayers. These measurements provide information on roughness, magnetic domains and spin-flip scattering channels that are not accessible from specular data alone [90, 109, 112].

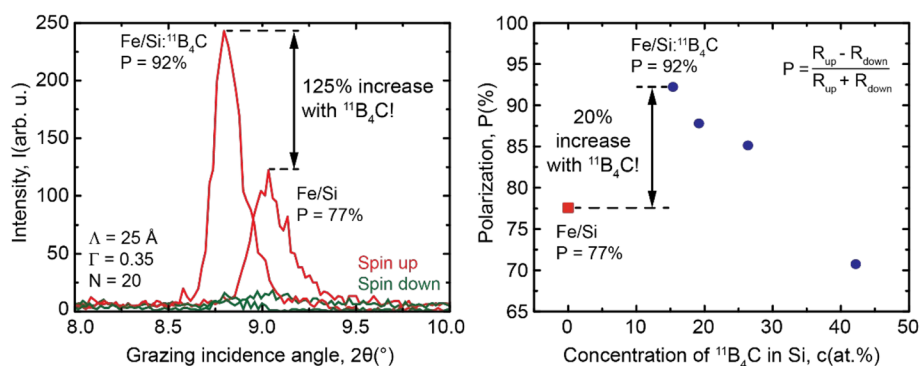


Fig. 9 Example of the effect of $^{11}\text{B}_4\text{C}$ incorporation in Fe/Si multilayers for polarising neutron optics

The results are not tied to a single ESS instrument, but provide materials knowledge and design rules for multilayer coatings used in guides, focusing optics, polarising mirrors, and analysers. This is relevant both for the initial ESS instrument suite and for future instruments in the ESS roadmap, where high transport efficiency, low background and reliable polarisation optics will remain important requirements. The work also contributes to maintaining national competence in neutron-optical thin film coatings, which is needed for future specification, testing and development of neutron optical components.

4.2 Detectors

In 2008, by the time of the conception of the European Spallation Source (ESS), the world faced a decreasing stockpile of ^3He , the main neutron converter used in large area detectors, and it was realized that its limited supply might not meet the demands required by the ESS. ^{10}B in the form of thin solid films was discussed as one alternative to gaseous ^3He as neutron converter material in detectors for future instruments at ESS. By serendipity, Christian Vettier, ESS' Science Director, and Jens Birch, professor in Thin Film Physics at Linköping University (LiU), met during a coffee break at MAX IV's user meeting in Lund, 2009. During the small talk, Vettier asked; "Can you make boron coatings in Linköping?" Based on Birch's previous experience of successfully making good B_4C coatings for X-ray mirrors (and unsuccessfully making stable coatings of pure B), he responded; "- No, but I can make something much better! - Boron carbide!". 2 months later an initial 2-year PostDoc project, jointly funded by ESS and LiU, was started to investigate $^{10}\text{B}_4\text{C}$ thin films as an alternative neutron converter for future ESS detectors. Within the first year 2010, a robust sputter deposition process for thin coatings of $^{10}\text{B}_4\text{C}$ was developed [47]. The coatings, grown in an industrial CemeCon CC800/9 DC magnetron sputtering system, were shown to be dense, amorphous, adherent, and exhibiting a smooth surface, as seen by Scanning Electron Microscopy and Elastic Recoil Detection Analysis measurements showed a very low level of impurities and approximately 80% composition of ^{10}B , demonstrating high quality layers with few impurities, see Fig. 10.

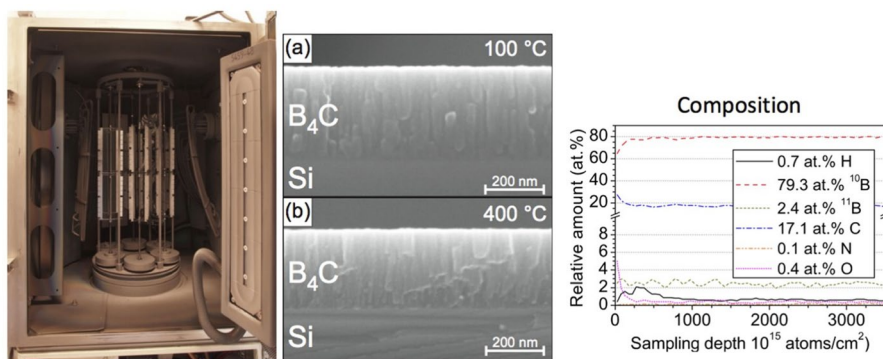


Fig. 10 Left: The LiU industrial thin film magnetron sputter system. Middle: Typical cross-sectional SEM images, showing boron carbide thin films deposited onto silicon at substrate temperatures of 100 °C and 400 °C. Right: ERDA measurement of elemental composition of the $^{10}\text{B}_4\text{C}$ thin films. (from ESS Technical Design Report)

Sub- μm thin $^{10}\text{B}_4\text{C}$ films on 1 mm thin Al blades were demonstrated as suitable for solid neutron converters in e.g. the Multi Grid detector being developed at ILL, see Fig. 11. Together with ILL, the first proof-of-principle $^{10}\text{B}_4\text{C}$ -based Multi-Grid detector prototypes were manufactured and tested in 2011 [15] and 2012 [19], confirming the detector principle and it was practically demonstrated by substituting a section of the ^3He -detector with $^{10}\text{B}_4\text{C}$ Multi Grid stacks in the IN6 spectrometer at ILL [18].

It was shown that ultra pure Al-substrates are needed to avoid internal background due to trace levels of radioactive isotopes such as Th, U, Pb and Po [17]. The stability of the detector coatings in a high-neutron flux environment, was confirmed by placing 1 μm thick $^{10}\text{B}_4\text{C}$ thin films in a cold neutron beam with fluences of $>10^{14} \text{ cm}^{-2}$ (corresponding to more than 1000 years of typical detector operation at a neutron instrument) upon which the coatings did not exhibit any detectable change in structure, composition, or stress [48]. Also scalability of the $^{10}\text{B}_4\text{C}$ deposition process was demonstrated early on by coating 7 m^2 of Al-blades for a 2 m $\times$ 10 cm (active area) Multi-Grid detector [16] prototype [5] in just 10 days. These results, combined with the ^3He crisis, made the ESS to take a strategic decision to promote $^{10}\text{B}_4\text{C}$ -based detectors and to build their own large-scale $^{10}\text{B}_4\text{C}$ deposition facility to meet the demand of $^{10}\text{B}_4\text{C}$ coatings for ESS detectors which was estimated to more than 6000 m^2 , if all detectors should be ^{10}B -based.

In 2014, LiU assisted ESS with building their own large-scale detector coating deposition facility off-campus in Linköping, where a similar industrial CemeCon DC sputtering system was installed. In 2024, the facility was relocated and reintegrated into ESS facilities in Lund after the construction of the main site was finished. The first operational detector based on the LiU-ESS $^{10}\text{B}_4\text{C}$ -coatings, delivered by the coating facility, is a Multi-Blade detector [53, 76] deployed at the AMOR neutron reflectometer at the Swiss Neutron Source. At ESS, more than half of the instruments under construction have chosen detectors with $^{10}\text{B}_4\text{C}$ -based technologies [89]. The SANS instruments ESTIA and FREIA have been assembled with Multi-Blade detectors with $^{10}\text{B}_4\text{C}$ -converter coatings delivered by the ESS coating facility in 2023, while the large bispectral chopper spectrometer T-REX will be equipped with Multi-Grid detectors with $^{10}\text{B}_4\text{C}$ converter layers under production in the facility at the time of writing. Diffraction instruments MAGIC, DREAM, and HEIMDAL use $^{10}\text{B}_4\text{C}$ -based detectors of JALOUSIE technology developed by

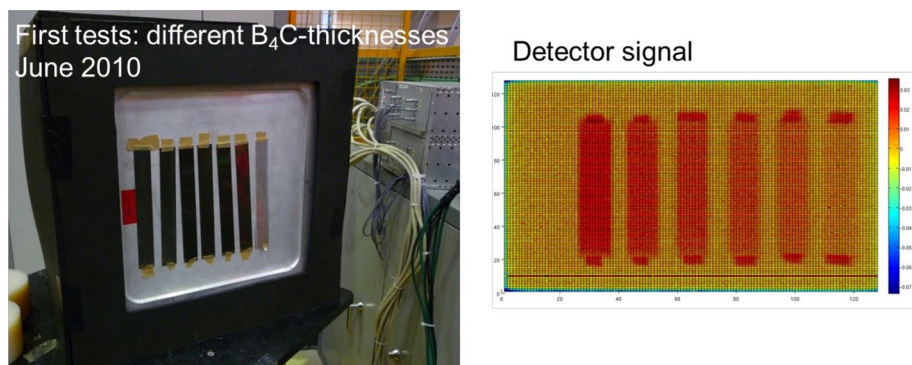


Fig. 11 The first crude radiography tests at the Institute Laue-Langevin in 2010, demonstrating the neutron conversion in five differently thin sub- μm thick coatings of natB_4C on Al-substrates. B_4C thickness decreases from left to right and the right most sample is a bare Al-substrate

Cascade Detector Technologies GmbH in Heidelberg, Germany. The $^{10}\text{B}_4\text{C}$ -converter coatings done by the coating facility have also been delivered to the in-kind partners for assembly of a large part of the detectors in the MAGIC instrument (2020) and all End-Cap and High-Resolution detectors for backward- and forward-scattering in the DREAM instrument (2020–2022) [89].

In addition to the detectors, ESS coating facility has produced $^{10}\text{B}_4\text{C}$ -converter coatings to the in-kind partner from CEA Saclay for the delivery of neutron beam loss monitors (nBLM) [69, 87] deployed at the ESS' accelerator tunnel. The coating facility is also developing other ^{10}B -enriched and non- ^{10}B -enriched B_4C -converter coatings, based on the LiU-ESS $^{10}\text{B}_4\text{C}$ coating process, for CERN and CEA Saclay collaborated on the development of B_4C -based beam monitors to be deployed at ESS instruments.

A solid neutron converter like $^{10}\text{B}_4\text{C}$ may be incorporated in solid state semiconductor neutron detectors which have the prospect of much higher spatial resolution than gas-filled detectors. To achieve high neutron conversion efficiency the neutrons must traverse at least $30\text{ }\mu\text{m}$ of $^{10}\text{B}_4\text{C}$ while the charged neutron conversion products (He^{4+} and Li^{7+}) must originate within a few μm from a semiconductor PN junction in order not to be trapped inside the $^{10}\text{B}_4\text{C}$ converter. This requires deposition of $^{10}\text{B}_4\text{C}$ into a 3D micropattern in the surface of the device, see Fig. 12 [80].

Magnetron sputter deposition, being a line-of-sight deposition method, typically cannot produce coatings conformally covering topographically structured surfaces due to geometric shadowing effects. Therefore, the Thin Film Physics and Chemistry divisions at LiU developed several CVD methods, based on thermal decomposition of triethylboron (TEB), to produce conformal coatings of B_4C . Coatings with step coverage ~ 0.71 in structures with depth/width aspect ratios of 8 were developed at LiU [30] and implemented in a prototype 2D detector chip, based on the principle shown in the center panel of Fig. 12, in a collaboration with ESS and SINTEF in Norway. SEM cross-sections showing the conformally coated structures are shown in the right panels of Fig. 12. The 2D structured test detector showed the expected response to neutrons in a test performed at the Swiss Neutron Source. The process has been further developed utilizing Xe as a heavy diffusion additive [31], which shows great promise of achieving 100% step coverage in structures with aspect ratios >100 which would be ideal for highly efficient solid state neutron detectors with potential spatial resolution of $<10\text{ }\mu\text{m}$.

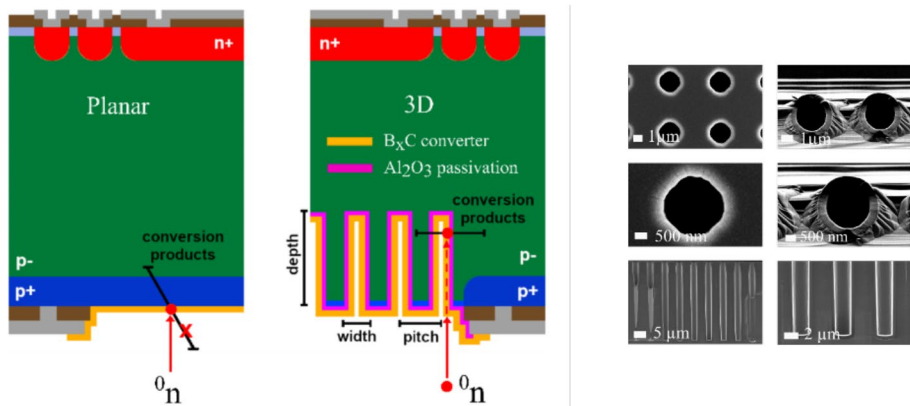


Fig. 12 Schematic of a planar (left) and a 3D (middle) solid state neutron detector architecture, showing the mechanism for higher efficiency in neutron conversion and collection of the conversion products when using $^{10}\text{B}_4\text{C}$ on a 3D structured surface. To the right is shown top view and cross section SEM micrographs of conformal B_4C in a prototype neutron detector chip

5 Sample environment and complementary methods

To enable a wide range of science, specialized sample environment is required for neutron instruments. This includes well controlled experimental conditions, with respect to, e.g. temperature, magnetic field or pressure, as well as the availability of complementary experimental capabilities providing additional information on the sample in parallel to the neutron data. Below we describe Swedish projects which contribute with optical methods complementing neutron measurements as well as a project planning to widen the accessible temperature range down to the sub K regime.

5.1 Ellipsometry and IR spectroscopy

NR offers unique opportunities in resolving structure-function relationships of interfacial layers in soft matter science, biophysics and biomedicine [101]. It is a non-destructive technique for detailed analysis of layered structures on molecular length scales, providing thickness, density, roughness and composition of individual layers or components of adsorbed films. However, chemical information is not available, which would significantly help to derive a complete picture of interfacial properties. Moreover, NR cannot determine large layer thicknesses, and although time-resolution is steadily improving, for many experiments accurate time-resolved data acquisition is a challenge, even for reflectometry experiments in soft matter where resolution can be kept moderate to increase flux. These issues were addressed by Ederth and Dahint [26] by designing a modular and portable sample environment for *in-situ* characterization at reflectometry beamlines, integrating i) infrared spectroscopy (IR) under attenuated total reflection (IR-ATR) for determination of molecular entities and their conformation, and ii) spectroscopic ellipsometry (SE) for rapid and independent measurement of layer thicknesses and refractive indices of adsorbed layers.

IR spectroscopy allows identification of specific molecular entities, as well as molecular conformation and orientation. As IR radiation is strongly absorbed by water, analysis of soft matter films in contact with aqueous solutions is usually performed in total internal reflection geometry (IR-ATR) [54]. The penetration depth of the electric field into the fluid phase is typically of the order of micrometers, thus avoiding excessive intensity losses. The used mid-IR regime corresponds to approximately 500 to 3500 cm^{-1} . Setups for simultaneous *in-situ* NR and IR analysis have been implemented before, for example in the design of BioRef [94], a versatile time-of-flight reflectometer dedicated to soft matter characterization at solid/liquid interfaces at the neutron source BER II of the Helmholtz Zentrum Berlin (HZB).

The basis of ellipsometry is the measurement of the change in polarization upon reflection at an interface. This is quantified by the amplitude ratio and the phase difference, which routinely yield information about layers ranging from a few Å to several μm. SE is widely used for quantitative characterization of thin films and adsorption onto solid interfaces [77], permitting rapid determination of thicknesses and the complex refractive indices of surface films, and further allows determination of parameters such as roughness, anisotropy, and volume fraction changes. As such, it is widely used for *in-situ* and *in-operando* studies.

5.1.1 Implementation

The integrated setup includes independent facilities for IR-ATR and SE experiments, where each technique accesses the sample-supporting block from different directions, see Fig. 13. The design was kept modular to permit easy adaptation to spatial constraints and sample orientations at different reflectometry beamlines. That IR and SE access the sample from different directions permits considerable flexibility in both the overall setup as well as the design of liquid flow cells and optical components for illumination.

The original setup by Busch *et al.* [26] was further developed to accommodate a more compact IR spectrometer, and permitting all optical components to be mounted on a single 0.5 m rail, forming a self-contained optical system where IR and SE could be pre-aligned against a common sample plane (Fig. 14). For use at the ESS reflectometers, this optical unit will be inserted into dedicated beamline sample changers, or used offline for preparatory work. The simplified handling, installation and transfer between beamlines and offline use, will considerably lower the barriers for users to adopt these new complementary methods into their experiments. Although the IR-ATR feature requires trapezoidal sample blocks, the SE feature can be used with rectangular 50x50 mm² sample blocks of a type that is already in widespread use.

The potential of such a combination was demonstrated in investigations of the impact of nanoparticles on lipid membranes and membrane proteins, to identify potential mechanisms of nanotoxicity, and in the pH-dependent swelling and reorganization of polyelectrolyte layers [26].

5.2 NUrF: UVvis absorption, Raman and Fluorescence spectroscopy combined with SANS

A sample environment for simultaneous access to complementary information on structure on bulk solution samples was constructed. The concept of the so-called NUrF setup combines SANS, UVvis absorption, Raman and Fluorescence spectroscopy from the same sample cell volume [35]. The development was driven by a Swedish consortium between

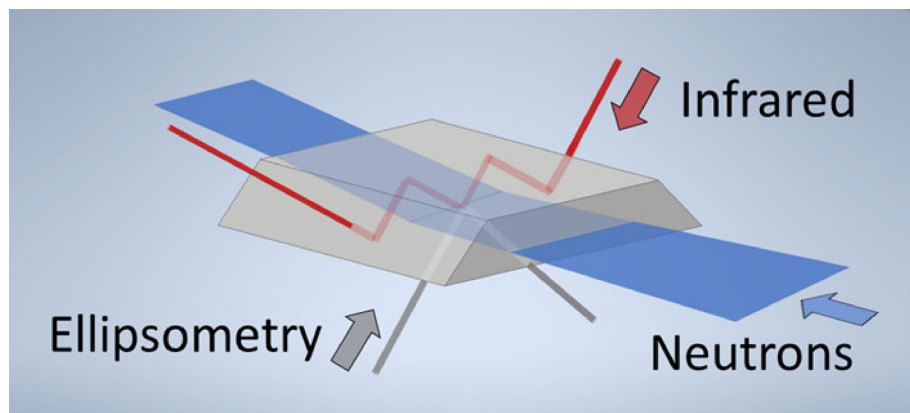


Fig. 13 Schematic view of the optical arrangement around a sample silicon block (sample on the underside in the figure). The IR and ellipsometric optics share the same incidence plane, but access the prism from opposite sides, and the neutron beam is perpendicular to this incidence plane

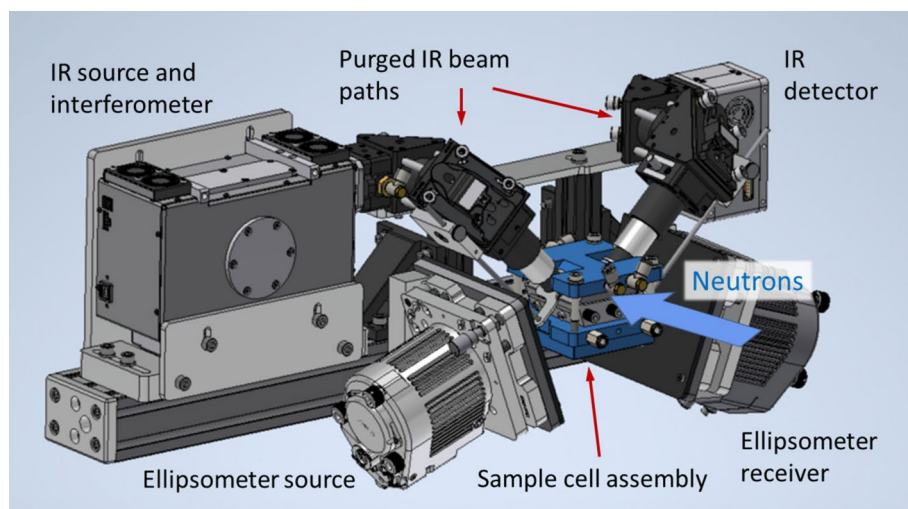


Fig. 14 A compact optical unit containing the optical components for IR and SE. Additional system components are connected via cables or optical fibers (for the SE system)

Lund and Uppsala Universities in collaboration with ESS, ILL, and ISIS. The NUrF cell can be operated both in static and in flow-through conditions, and is supposed to become one of the standard sample environments for liquid solutions at the SANS instrument LOKI at ESS. Similar developments are also on their way for synchrotron radiation and SAXS developing the future standard sample environment at the COSAXS beamline at MAX-IV. Both projects allow for strong cross-technique collaboration and benchmarking.

As a proof of principle of the technique and development of multi-modal comprehensive data analysis, the NUrF cell was used by a Swedish collaboration around a Swedness PhD student for time-resolved monitoring of silk assembly: to combine geometric structure from SANS with thermodynamic characteristics and secondary protein structure from optical spectroscopy, a data-driven analysis integrating batch curve fitting and machine learning was developed which allows to identify precursor structures during molecular processes [45].

5.3 Dilution refrigeration at ESS: cooler, better, faster

Low temperature work at neutron facilities has long had certain particularities, primarily because the beam has to get to the sample without being attenuated or scattered too much, and secondarily because sample change must be rapid and simple to maximise neutron beam use. The Orange cryostat, developed at the Institut Laue-Langevin in 1975, solved these problems elegantly with a base temperature of 1.5 K. Dilution refrigerator inserts were then developed that could be installed instead of standard sample mounting sticks, making it (relatively) routine to reach 50 mK. These inserts have a cooling power of 25–40 μ W at 100 mK. However, the entire insert has to be warmed up for each sample change, and this typically takes 24 hours and requires about two days of effort from cryogenic experts at the facilities. This can easily lead to 1 day in every 4 being spent on sample exchange rather than direct measurement, which is a clear limiting factor.

Lower temperatures were achievable with specially built cryostats, which were not typically a part of the user program. For example studies of solid ^3He below 1 mK [23] required a nuclear demagnetization stage [85], both to reach the very low temperatures, and to deal with sample heating due to neutron absorption.

The recent boom in quantum computing research has accelerated the development of commercial dilution refrigerators to the point where push-button operation of a 10 mK platform is an industry norm. The advent of the dry pulse-tube cryocooler-enabled dilution refrigerator manufacturers to pursue larger and more powerful experimental platforms without the need to worry about a difficult to manage liquid ^4He bath. In combination with the latest computer control, this provides a high performance and automated platform that is safely and simply used by a novice operator.

The extra space afforded by pulse-tube based systems, along with the need for only one vacuum tight radiation shield at room temperature, has led to the development of systems that can rapidly change samples without requiring a full warm-up of the dilution refrigerator. Indeed, some manufacturers have reduced the cold-to-cold sample exchange time to below 3.5 hours [78] in the best case scenario of a bottom-loaded sample and small sample puck. This ease of use and rapid sample exchange makes the new generation of dilution refrigerators ideally suited to user facilities like ISIS and the ESS. Although turnaround times of 3.5 hours will not be reached as samples have to be top-loaded given typical instrument design, even a turnaround time of 10 hours with push-button operation would be a game changer, permitting users to study multiple samples in one experimental beamtime allocation.

In addition to the time-saving potential, basic commercial models offering base temperatures below 10 mK and cooling powers at 100 mK of 300 μW – an order of magnitude better than the dilution inserts presently in use for neutron scattering, thus permitting experiments that are currently not possible at most neutron facilities.

In this project, Lund University in collaboration with ISIS and ESS intends to purchase one of these systems and adapt it for specific neutron use. It will be tested and commissioned at ISIS, for use on experiments at LET, and then will be transferred to ESS for use at BIFROST, although it will be usable at other ESS instruments like CSPEC, DREAM, T-REX, HEIMDAL and MAGIC.

6 Instrument components and method development

An improved performance of neutron instruments strongly depends on the development of instrument components, method development and optimized procedures for sample handling and experimental protocols. Below we describe Swedish projects contributing in this context with a diverse set of developments. These range from beam shaping optics over shutter developments, sample handling and polarisation capabilities to new approaches for data processing and mining.

6.1 Polarized neutron capabilities

Polarized neutron scattering is based on the extraction of one of the two spin states of the neutron to polarize the neutron beam. With a polarized neutron beam, the spin degree of freedom of the neutron can be fully exploited to distinguish nuclear, magnetic and incoher-

ent contributions to the scattered signal. This has been widely used in many studies, ranging from magnetism to soft condensed matter. In this context, 12 of the 15 approved ESS instruments aim to provide polarized neutrons [57]. While neutron polarization comes with a significant reduction of flux, as at least half of the neutrons are rejected in the spin filtering step, this cost is often worthwhile. An often cited example in this area is the use of polarized neutrons by Arbe *et al.* [7] to show that the incoherent component in the dynamics of heavy water (D_2O) is similar to the coherent at mesoscopic length scales, and not dominantly coherent over all length scales as was often assumed.

However, to fully exploit polarized neutrons, one needs to first polarize neutrons before they hit the sample and then analyze the changes in the polarization after. A particular bottleneck to routine use of polarization analysis particularly at spallation sources has been the technical difficulty in analyzing polarization of wide scattering angles and broad wavelength bands. A consortium of Swedish Universities worked on developing components for this using both polarizing supermirrors and 3He -based neutron spin filters for use at both ISIS and ESS.

To address this, a novel supermirror geometry initially proposed by Böni *et al.* [21] has been tested and developed, and work was done on developing the 3He -based neutron spin filter infrastructure at both ISIS and ESS.

6.1.1 Wide angle polarising supermirrors

In a transmission-based neutron polarization analyzer, a neutron that has been scattered by the sample enters one of the channels of the analyzer. The neutron's spin determines whether or not it is reflected or transmitted (see Figure 15). In 2020, Böni *et al.* [21] proposed a novel supermirror geometry, with the mirrors bent in a logarithmic spiral profile, also known as an equiangular spiral. This has the advantage that when neutrons with a given wavelength λ are scattered at different angles, they will reach the mirror at different points but will all hit the mirror surface at the same angle θ . The analyzing efficiency depends on the ratio θ/λ and so all neutrons of the same wavelength should then be analyzed with the same efficiency. This was predicted to both improve the transmission and reduce the cost by cutting the number of supermirrors required.

A prototype containing three channels with pairs of supermirrors in a 'V' formation in each channel, separated by absorbing walls (shown in Fig. 15), was initially tested at Larmor and IMAT. Following the results of these tests, a full-size 25-channel device was purchased from Swiss Neutronics. Each channel consisted of two double-coated supermirrors following a logarithmic spiral profile, arranged back-to-back. The supermirrors were Fe/Si with $m = 4.8$, on 0.3 mm thick silicon wafers. The channels were separated by collimating blades made of borosilicate glass (MEMpax[®]) coated with $2 \mu m$ of Gd on both sides. The prototype contains double-coated supermirrors, with an angular range of 25° in the horizontal plane and a vertical opening angle of 8° . The device was delivered in a housing that can hold a second 25-channel device an additional 25 supermirror channels to eventually provide 25° to 50° coverage in the horizontal plane.

The magnetic housing for the device, required to provide the necessary guide field to polarize the supermirrors, was constructed at ISIS. The device was tested at Larmor in March 2026 (Fig. 16, with a total polarization efficiency, including the performance of the polarizer and flipper of 90%, in good agreement with simulations and consistent with an

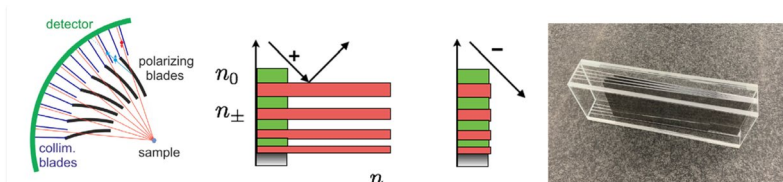


Fig. 15 (left) A cartoon of the logarithmic spiral polarizing analyzer, showing the placement of the device between sample and detector. The polarizing blades are the supermirrors. Adapted from Ref. [21]. (centre) An illustration of the working principle of a transmission-based neutron polarization analyzer. A neutron scatters from the sample and enters one channel of the analyzer. Reflection occurs if the neutron spin state is parallel (+ = spin up) to the magnetization of the magnetic layer (red), giving high contrast. Reflected neutrons are absorbed by the collimators, while the transmitted neutrons (- = spin down) are detected. (right) A photograph of a test device containing three channels



Fig. 16 The wide-angle polarization analyzer installed on Larmor, surrounded by a 3D coil set for XYZ polarization control. Photo: Oskar Štepančić

analyzing efficiency of around 95%~90% polarization efficiency and a transmission > 30%. It will be tested in place at WISH in September 2026, and will then be a part of the user program first at Larmor, then when the polarizer and flipper have been installed, at WISH.

A V-cavity supermirror polarizer is also in the process of being constructed for use on BIFROST.

6.1.2 ^3He -based neutron spin filters

^3He -based neutron spin filters are now commonly used to polarize neutrons. They consist of a cell containing hyperpolarized (> 70 %) ^3He gas. The polarized ^3He absorbs neutrons of one spin state and lets most of neutrons in the other spin state pass through. With suit-

able cell design, a large solid-angle coverage can be achieved, with uniform efficiency over angle and area; this was first done at the ILL [92]. They also operate well over a wide range of wavelengths and a cell can be used at different instruments. The main operating issue is that the ^3He polarization decays exponentially with time and so a given cell has a restricted operational lifetime before the gas needs repolarizing.

Cells are typically made of silica, and Swedish Universities have supplied a number of cells to the ESS. To increase the lifetime, the cell should operate in a highly uniform magnetic field. This field is produced by using 3D field coils so that the polarization direction can be selected at will [86]. These coils require supports that may block parts of the scattered beam; coil setups that significantly reduce the blocking of the scattered beam have been modeled, designed and constructed (see Ref. [57] for some additional details).

6.2 Upgrade of the OSIRIS spectrometer

This collaborative research project between ESS, ISIS, Chalmers and Uppsala University aimed to (1) perform cutting-edge research focused on studies of hydrogen dynamics in proton conducting oxides and metal hydrides, with a view towards their application in, e.g., fuel cells and hydrogen storage, using inelastic and quasielastic neutron scattering (INS and QENS, respectively), and (2) to contribute to the upgrades of the primary and secondary spectrometer of the QENS instrument OSIRIS at the ISIS Pulsed Neutron and Muon Source. With regards to the former, a key result from the performed research was the unravelling of the mechanism of proton conductivity in brownmillerite structured proton conductors [65, 73], as well as in acceptor-doped proton conducting oxides based on the perovskite structure [66]. With regards to the latter, an extensive ray-tracing simulation study of a new supermirror guide [71] and silicon analyser [70] for OSIRIS has been carried out, demonstrating that a five-fold increase in flux could be achieved by replacing the guide, and that the energy resolution could be improved by a factor 2.5, with respect to the existing graphite analyser, by adding a silicon analyser to the secondary spectrometer. These simulation studies were a decisive factor in the decision of the ISIS Facility to implement both proposed upgrades, with the OSIRIS guide being selected in the “Endeavour” instrument upgrade program of ISIS (due 2030), and the silicon analyser being completed in 2026 (see Fig. 17) and to be shortly available to the user community.

6.2.1 Neutron resonators for inelastic scattering from thin films

Further to pave the road towards the study of surface dynamics with neutron scattering methods the current limitations of QENS studies of surface/interface dynamics have been evaluated. In surface scattering generally sample volumes are small, which imposes challenges for the study of dynamics. The reason for this is that as compared to diffractometers typically the flux on neutron spectrometers is significantly lower. Still it has been shown that the incoherent scattering of hydrogen from a 100 nm thin film of $\text{VH}_{0.5}$ could be detected and actually ~25% of the neutrons got scattered incoherently [104]. Building on this the hydrogen uptake in a vanadium thin film was studied exploring signal enhancement using quantum well resonators [72]. It is shown that the hydrogen concentration can be extracted from measuring below the critical angle of total external reflection by just using the position and depth of the resonance in Q. This significantly speeds up such type of measurements and

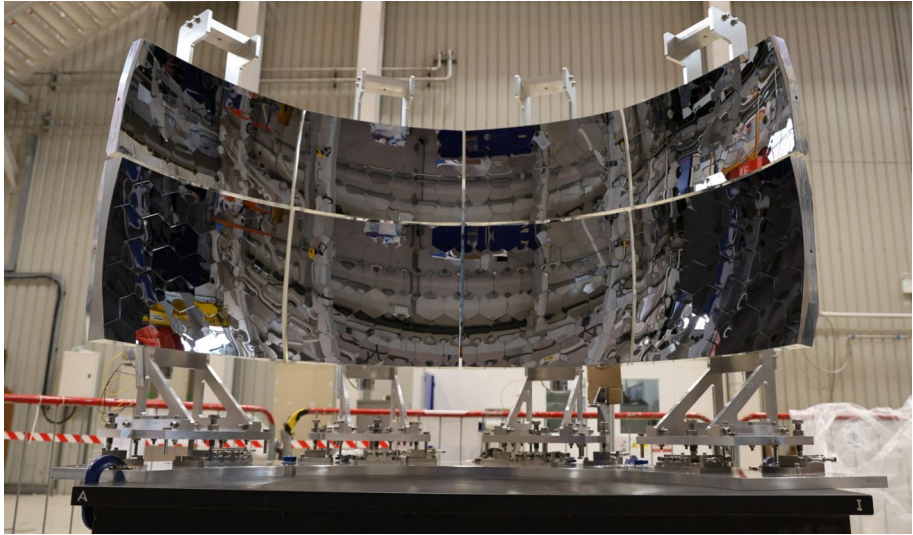


Fig. 17 Picture of the Silicon Analyser of OSIRIS, completed in 2026. The Silicon Analyser is made of 8 spherically curved panels, which are covered by thin elastically-deformed single-crystals of Si(111)

indicates that measurements of proton dynamics in thin films may come in reach with the increased brilliance of spectrometers at the ESS, in particular CSPEC [33].

6.3 Port-GISANS

The Röntgen-Ångström project is a collaboration between Uppsala and Malmö Universities and the German partners at the Ludwig Maximilian University in Munich and the Jülich Center for Neutron Science. The idea roots on initial experiments done at Super-ADAM [99].

Port-GISANS is a nested 1D-focusing device for enhanced GISANS (see Fig. 18) [61]. By utilizing parabolic supermirrors in a nested configuration the device preserves the lateral resolution along an interface and relaxes the resolution out-of-plane, sacrificing depth-resolution.

To demonstrate the performance ray tracing simulations have been combined with the distorted wave Born approximation to demonstrate that Port-GISANS significantly increases the flux on the sample on any SANS instrument available for GISANS studies. The output of the ray tracing simulations was used as input for grazing incidence scattering simulations in BornAgain [79] together with a python code package [55]. A model for a monolayer of hexagonally packed nanoparticles with 74 nm diameter at a D_2O /silicon interface was created and simulated using a sample-detector distance of 20 m and a nominal source-to-sample distance of 38.43 m which is comparable to the dimensions of the SKADI instrument. The simulations were performed in the Mcstas package [102, 103] for the SKADI instrument [51, 52] for one pulse of the ESS source at a power of 2 MW, a collimation of 4 m and a bandwidth between 3 and 8 Å. The ray tracing simulations reveal that Port-GISANS increases the flux available at a sample by at least a factor of 12 compared to a conventional GISANS geometry at the expense of depth resolution and smearing of the data along the vertical, Q_z direction (see Fig. 18).

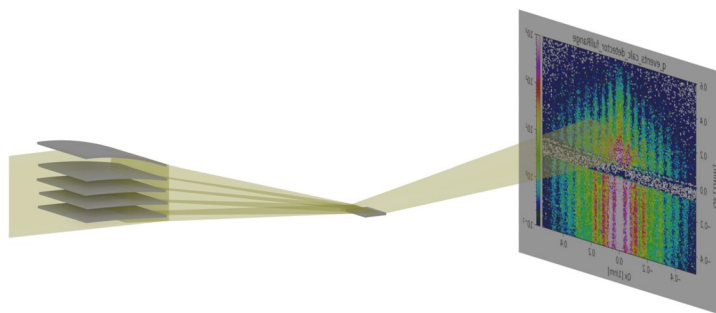


Fig. 18 Graphical representation of the nested focusing device in use

Based on the simulation results Port-GISANS was manufactured by Swiss Neutronics. To verify the performance an experiment at the SANS beamline of the Reactor institute at Delft university has been performed. Figure 19 shows the GISANS scattering pattern of a mesoporous Al_2O_3 sample, with iron filled pores ordered in a 2D hexagonal lattice oriented perpendicular to the substrate. Measurements were done with the optics installed (left panel) and without (right panel). Both measurements were done overnight with a measurement time of 16 h. In the left panel clearly GISANS peaks are visible, while in the right panel they can only be vaguely imagined. This clearly demonstrates the performance of Port-GISANS enhancing the signal and significantly improving the signal to noise ratio, which is crucial for successful GISANS measurements.

6.4 FREIA fast shutter and detector

The Fast Shutter System, designed and manufactured at the FREIA laboratory at Uppsala University, is a planned upgrade of the FREIA reflectometer that will enable time-resolved NR for soft condensed matter and life-science research. A key feature of the FREIA instrument concept focuses on capturing rapid structural and kinetic changes at liquid and solid interfaces, and its optical design uses a wide-divergence elliptical neutron guide to deliver a broad range of incident angles to a fixed horizontal sample.

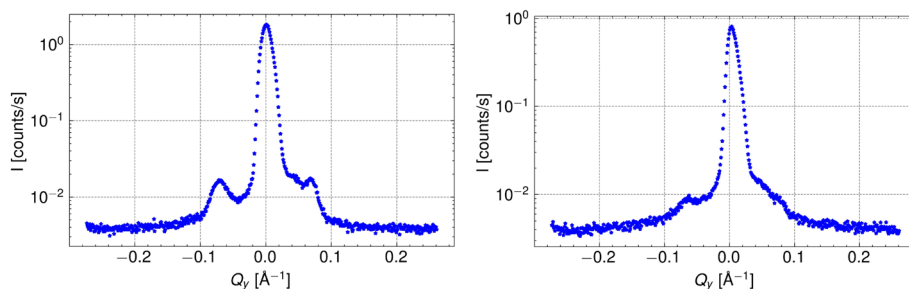


Fig. 19 a) Left and right panel, integrated, along Q_z , GISANS intensity with the focusing optics installed and without, respectively. Data is plotted versus in-plane momentum transfer Q_y and measured at the SANS instrument at the DELFT reactor on an in-plane structured Al_2O_3 sample

The upgrade concept was developed together with ISIS as part of a VR funded project which also demonstrated the limitations of existing instrumentation using an example scientific case: the lipolysis process at the triglyceride/aqueous interface [49]. This work demonstrated the need to be able to follow the structure evolution over the whole Q-range with high time resolution not only at low Q as possible with traditional reflectometry. Such information provides insight not only in physiological processes associated with food digestability and uptake but also for a range of other applications.

The FREIA concept for fast measurements requires the capability to sequentially select one of three predefined incident-angles that are each directed towards a fixed sample position. Fast reflectometry over a broad Q-range without moving the sample is then enabled by changing this angle at speeds compatible with the 14Hz ESS source pulse.

This defines the core function of the Fast Shutter System, which selectively absorbs neutrons in one of three collimated beam paths associated with the instrument's multi-aperture slit configuration. The system is made up of three independently operated shutters, each positioned to correspond to one of the angular beam ranges defined by the rest of FREIA's collimation system (see Fig. 20) [50]. Instead of moving the sample, the shutters allow one beam path at a time to reach the sample while fully absorbing the others. To support FREIA's time-resolved science, the shutters must operate on millisecond timescales. Tests show that the system can transition between open and closed states in about 13.5 ms, meeting the requirement to complete each angle change within 15 ms and remain stable for the rest of the 72 ms pulse interval.

This design is crucial for experiments on delicate or free-liquid surfaces, where mechanical motion would disturb the interface. Since FREIA strives to observe structural changes in films and interfaces on millisecond-to-second timescales, the pairing of ESS's high neutron flux with fast shutter operation opens up experimental capabilities that were not attainable with previous instruments. This fast switching makes it possible to record structural changes in thin films, membranes, and other interfacial systems almost in real time, enabling studies of processes such as assembly, diffusion, chemical reactions, and material responses to external stimuli.

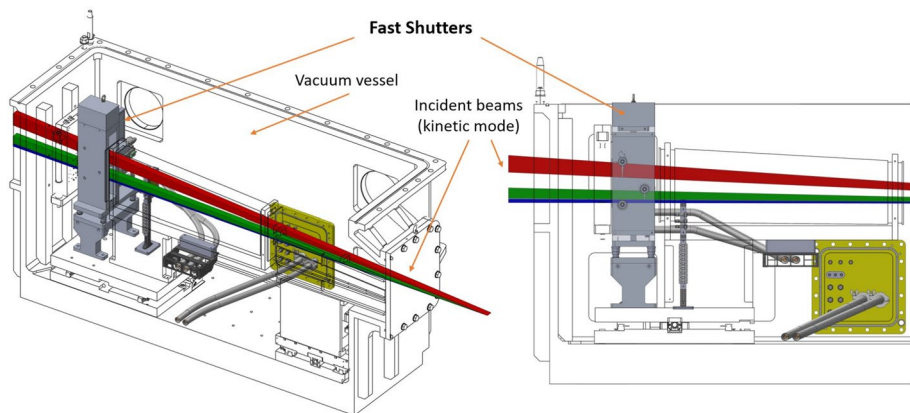


Fig. 20 Schematics and positioning of the FREIA fast shutter designed and constructed at Uppsala University

6.5 Entangled neutrons for the study of mesoscopic length scales

In a collaboration between the ISIS neutron source, ESS, Lund and Uppsala Universities the spin-birefringent properties of Wollaston prisms will be exploited. This birefringence can be used in neutron optics to create separate pathways for neutrons of different spin. Such different pathways can be applied in experiments such as small-angle neutron scattering to create an interference pattern for objects which would otherwise be too large for such experiments or to create dark field imaging conditions, where unscattered neutrons are not propagated to the detector. A schematic image is shown in Fig.21.

The goal is to develop and produce Wollaston-prisms which can be directly integrated into neutron instruments at the ESS. There they will be used to enhance the resolution of SANS (to larger length-scales) and imaging (down to lower length scales) instruments. This will allow an overlap of instrumental resolution between the two instruments in the range between several hundred nanometers to several micrometers.

Similar setups have already been in use, but they have not yet been perfected to be in the commonly available user program of any large-scale neutron facility, which will be a significant break-through in neutron scattering technology in Sweden and it will increase the accessible length scales in both instrument classes, SANS and imaging, considerably. This will improve possibilities in research in areas such as superconducting vortices, fusion processes on large cell-analogue vesicle structures as well as microstructure transformations during phase transitions in nano-structured cellulose.

6.6 Sub millisecond time resolution

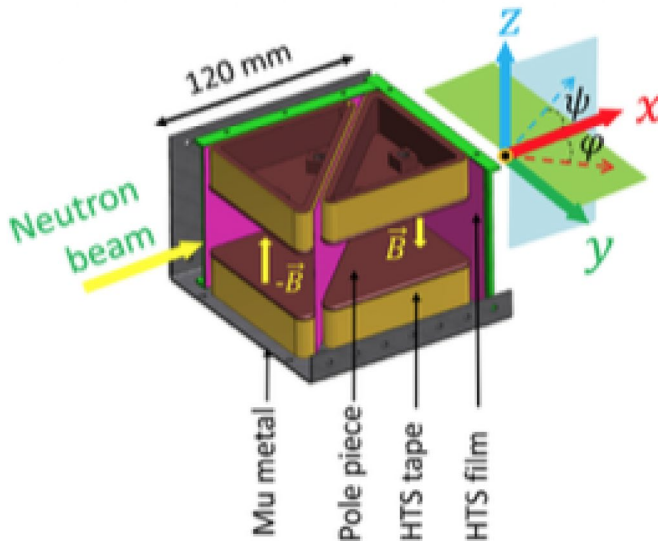
The project to push the limits for time resolution in kinetic studies by stroboscopic reintegration is a collaboration project between the ESS, ISIS and Uppsala University aiming for the user friendly implementation of the method in Scipp [46].

6.6.1 Stroboscopic reintegration

The project concerns the development of a time-resolved neutron scattering methodology tailored for next-generation neutron instrumentation at the ESS. By using event-mode data acquisition with absolute time stamping, neutron detector events can be synchronized with periodic external perturbations at the sample, enabling stroboscopic reconstruction of scattering patterns with sub-millisecond time resolution [2, 32, 58]. This approach overcomes conventional limitations in neutron time resolution while preserving beam intensity and experimental performance. The associated data acquisition and analysis framework has been developed in Scipp [46] and is designed for implementation at large-scale neutron facilities and specifically for ESS.

Different strategies can be applied to detect the duration of a period. If the shape of the triggering signal is known deterministically, it can be fitted to its functional form; otherwise, strategies based on detecting crossings of given threshold values or peaks/valleys (triggers) can be applied. Rolling up the period duration into phase allows all the repeated periods to be folded (collapsed) into a single one. The period phase can then be binned, and the neutron events are histogrammed into the different bins. For binning the period obtained from folding multiple cycles, time bins of a chosen width can be defined within a single period. The selection of bin width sets a trade-off between the statistical noise and the frequency range

a)



b)

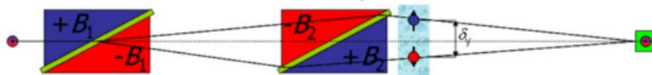


Fig. 21 **a)** Schematics of a Wollaston Prism. The incoming neutron is deflected depending on its spin as shown in **b)** [24] The mu-metal will allow for magnetic shielding, while the conducting HTS tape will create the magnetic field inside the pole pieces. Since the deflection, depending on the current is on the order of micrometers, this assembly has to be very accurate and will have to be custom made

that can be resolved. A good compromise must be found to reduce statistical noise without losing information within each bin. The use of sliding windows [27] allows an increase in temporal discretization by introducing additional sampling points within each bin width. The underlying signal can be reconstructed by deconvolution using a boxcar kernel. However, due to numerical stability issues associated with certain deconvolution operations, it is generally required to apply a low-pass filter to suppress high-frequency components, thereby improving the robustness of the extracted material response from the recorded scattering events. On the other hand, correlation between consecutive bins is introduced.

The method is validated using time-of-flight NR combined with *in-situ* oscillatory rheology on P127 micellar tri-block copolymer solution. The results reveal fast and reversible structural changes with high temporal resolution. Figure 22 shows the reconstructed integrated intensity of the (111) Bragg peak observed in the specular region for a micellar polymer solution in an, fcc (ccp), face centered cubic close packing at an interface. The signal reveals twice the frequency of the applied perturbation, as expected. An asymmetry between loading and unloading, as well as higher-order harmonics, appear to modulate the signal, suggesting the effect of strong non-linearities in the material.

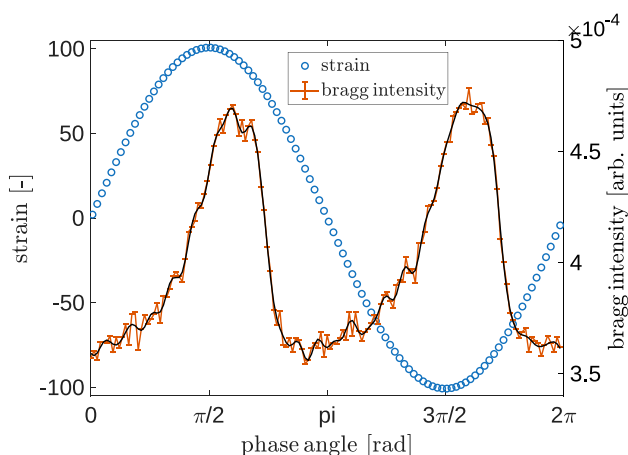


Fig. 22 Integrated intensity of the Bragg peak (111) at the specular ridge for 1 Hz and 10000% strain amplitude using 150 bins. Integrated intensity of the Bragg peak at the specular region after low-pass filtering is represented as solid black line

6.6.2 Limit in time resolution

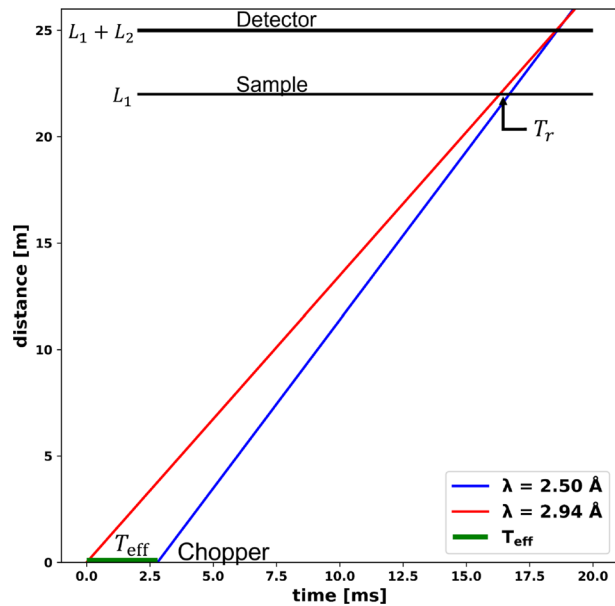
The best possible time resolution T_r that can be achieved with stroboscopic reintegration is limited by the ability to determine when a neutron captured on the detector at a specific time has interacted with the sample. Since the sample state changes constantly over a periodic cycle and since neutrons of different wavelengths require different travel times to cover the sample-detector-distance L_2 , it is possible to determine the interaction time to an accuracy that is limited by the effective neutron pulse time uncertainty T_{eff} [2]. The pulse time uncertainty can in a first approximation be estimated to be equal to the pulse length as determined by the pulse shaping chopper system. Using the chopper-sample, L_1 , and sample-detector-distance, L_2 , one can geometrically (see Fig. 23) calculate the limit in time resolution:

$$T_r = T_{eff} \frac{L_2}{L_2 + L_1} \quad (1)$$

It is worth noting that the size of the sample may limit the time resolution further. In reflective geometry typically samples have a length along the beam of around 40 mm. Since it is unknown whether a neutron scattered from the front or the back of the sample an uncertainty is introduced. For wavelengths between 2.5 and 10 Å, the neutrons require between 25 and 101 μs to cover 40 mm which introduces a corresponding wavelength-dependent uncertainty. Advanced techniques like wavelength frame multiplication (WFM) may be used to shorten T_{eff} and thus improve resolution [93] further.

It should be emphasized that the distinct advantage of our method is that the rebinning is done in the post processing. This allows to choose time resolutions after the experiment is finished and adapt it to the response of the sample as well as to the desired statistics. In particular for strongly non-linear or quickly changing sample structures or dynamics this allows a detailed analysis. Further, our method enables data mining and the use of AI tools to detect patterns.

Fig. 23 Time-distance diagram illustrating the limit in time resolution. Two neutron events captured at the same time at the detector may origin from neutrons of different wavelengths emitted at either end of the pulse. This leads to a uncertainty T_r at the sample position

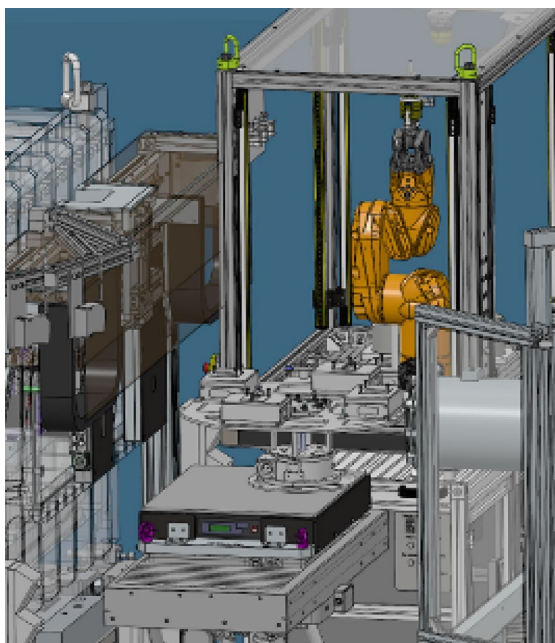


6.7 Sample handling

The UPaRALS project, lead by Lund University, is primarily focused on development of design concepts for automated sample changers to facilitate liquid-air reflectometry experiments. Such automated systems aim to improve sample throughput and reproducibility of measurements, at high flux sources, where measurement times are increasingly short. Two sample environments are being considered; a robotic sample-changer for adsorption troughs, and Langmuir troughs with sub-phase exchange and control.

With the time taken to measure a reflectivity curve taking 15 minutes or less at both Synchrotron sources and at ESS (when it reaches full power) the need for automated and reproducible sample changing will be increasingly important. For air-liquid samples this is particularly challenging because of their size and the need for reliable liquid handling for a range of sample types. In the case of the Langmuir trough, filling/emptying the trough and subphase exchange are target processes. For the adsorption troughs, a number of automated steps are required: movement of clean troughs from a storage space, filling the trough with a liquid sample, placing a lid to allow controlled atmosphere above the trough, and emptying and removing troughs after the measurement is finished. For the adsorption troughs, a robot arm (Fig. 24), and liquid handling system that can handle viscous liquids are being designed, with a science case, based on surfactant self-assembly in deep eutectic solvents in mind. The sample changer design concepts are also transferrable, for use at the FREIA instrument at the ESS neutron source, and also compatible with the LISA instrument on the P08 beamline at the DESY synchrotron.

Fig. 24 Conceptual design of a robot arm to enable automated liquid-air reflectometry experiments on FREIA



7 A bright future for neutron science in Sweden

In this review, we highlight the breadth and depth of Swedish engagement in neutron instrumentation, by summarizing contributions that span from conceptual instrument design to enabling technologies, advanced components, and methodological innovation. As illustrated, Swedish efforts are no longer peripheral but increasingly embedded across the neutron facilities and, in particular, the ESS. Swedish researchers participate in roughly half of the instruments proposed for the roadmap of future instrumentation at the ESS and have a strong involvement in key enabling technologies such as neutron optics, detectors, and sample environments. This evolution reflects a transition from a primarily user-based community toward a more balanced ecosystem that includes instrument builders, engineers, and methodological innovators.

A central outcome of these coordinated activities is the emergence of a more integrated national capability, building on existing expertise at the national infrastructure Super-ADAM. The combination of targeted funding instruments, graduate schools, international partnerships and strategic in-kind contributions has significantly strengthened Sweden's scientific and technical base in neutron science. Importantly, this growth has not only increased the number of users, but also diversified the scientific domains engaged, ranging from soft matter and life sciences to quantum materials, energy technology, and particle physics. This diversification is critical to ensure broad exploitation of the ESS and to maintain a resilient and adaptable user community.

The projects highlighted in this review, such as Super-ADAM, SAGA, FINESSE, GERSEMI and ECHIR, illustrate how Swedish-led initiatives directly contribute to expanding the scientific reach of neutron facilities. They address both fundamental science questions and emerging societal and industrial challenges, including quantum technologies,

energy materials, and radiation effects in microelectronics. At the same time, developments in neutron optics, detector technologies, and data analysis frameworks provide cross-cutting benefits that enhance performance across entire instrument suites. These advances are particularly important in the context of ESS, where the unprecedented source brightness demands equally advanced instrumentation and data handling capabilities to fully realize its potential.

Looking ahead, several key challenges and opportunities can be identified:

- From participation to leadership: While Swedish involvement in instrumentation has grown significantly, a next step will be to consolidate leadership roles in major instrument projects and long-term facility development. This includes not only hardware contributions but also software, data infrastructure, and experimental methodologies.
- Capacity building in instrumentation and data science: The continued success of ESS will depend on a critical mass of experts capable of designing, operating, and exploiting complex instruments. This includes strengthening expertise in areas such as neutron optics, detector systems, simulation, and increasingly, data-intensive approaches including machine learning and real-time analysis.
- Integration of complementary techniques: The future of neutron science lies in multi-modal approaches. Continued development of integrated sample environments combining neutron scattering with complementary methods, such as optical, spectroscopic, and imaging techniques will enable more comprehensive insights into complex systems and kinetic processes.
- Spectroscopic rebinning for time-resolved and operando science: The methodological advances described here, particularly in time-resolved measurements and stroboscopic data reconstruction, point toward a future where neutron experiments routinely probe kinetics on millisecond to sub-millisecond timescales. Exploiting this capability will not only open new frontiers in soft matter, biological systems, and functional materials but also enable data mining and reanalysis of complex data sets, supported by machine learning, to use the limited neutron data sets in an optimised way.
- Industrial engagement and societal impact: Initiatives such as ECHIR demonstrate the growing relevance of neutron facilities beyond academia. Strengthening collaborations with industry will be essential to translate neutron capabilities into technological innovation, particularly in areas such as semiconductors, energy, and advanced materials.
- Sustainability of expertise and infrastructure: Long-term success will require sustained investment not only in new instruments but also in maintaining and upgrading existing capabilities, including the national infrastructure Super-ADAM, which enables scientific excellence and continues to play a crucial role in method development and training.

In a broader European context, Sweden is uniquely positioned as host country of ESS to shape the future direction of neutron science. The combination of local infrastructure, strong academic networks, and increasing international collaboration provides a solid foundation for long-term impact. However, realizing this potential will require continued strategic commitment, coordination across funding bodies, and alignment between national priorities and ESS development.

In conclusion, Swedish contributions to neutron instrumentation have evolved into a coherent and strategically significant effort that bridges scientific ambition, technical innovation, and capacity building. As ESS transitions into full operation, these efforts bring Sweden into a position of not only benefiting from the facility but to actively shaping its scientific agenda. The coming decade will be decisive: it offers the opportunity to transform current momentum into sustained leadership in neutron science and to fully exploit the transformative capabilities of the ESS.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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Authors and Affiliations

Thomas Arnold¹  · Jens Birch²  · Elizabeth Blackburn³  · Glenn J. Coope⁵  ·
Reiner Dahint⁴  · Thomas Ederth²  · Karen Edler⁵ · Fredrik Eriksson²  ·
Björgvin Hjörvarsson⁶  · Marek Jacewicz⁶  · Sebastian Jaksch¹  ·
Kenneth Järrendahl²  · Victoria Kabanova^{6,8}  · Chung-Chuan Lai¹  ·
Filip Mehler⁶  · Naureen Ghafoor²  · Tim Günter⁶  · Maths Karlsson⁷  ·
Pia Kinhult¹ · Sebastian Köhler^{6,8}  · Clara Lopez¹ · David Milstead⁶ ·
Tommy Nylander⁹  · Adrien Perrichon¹  · Pablo Sanchez Puga⁶  ·
Felix Roosen-Runge⁹  · Valentina Santoro¹  · Piotr Szaniawski⁶  ·
Alexey Vorobiev^{6,8}  · Max Wolff^{6,10}  · Luca Zanini^{1,11}

✉ Max Wolff
max.wolff@physics.uu.se

¹ European Spallation Source, Partikelgatan 2, 224 84 Lund, Sweden

² Department of Physics, Chemistry and Biology (IFM), Linköping University, SE-58183 Linköping, Sweden

³ Division of Synchrotron Radiation Research, Lund University, 22100 Lund, Sweden

⁴ Applied Physical Chemistry, Institute for Physical Chemistry, Heidelberg University, Im Neuenheimer Feld 253, 69120 Heidelberg, Germany

⁵ Centre for Analysis and Synthesis, Department of Chemistry, Lund University, Naturvetarvägen 22, 223 62 Lund, Sweden

⁶ Department for Physics and Astronomy, Uppsala University, Box 512, 75120 Uppsala, Sweden

⁷ Department of Chemistry and Chemical Engineering, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

⁸ Institut Laue-Langevin, 38042 Grenoble cedex 9, France

⁹ Division of Physical Chemistry, Lund University, 221 00 Lund, Sweden

¹⁰ Center for Neutron Science, Uppsala University, Box 512, 75120 Uppsala, Sweden

¹¹ Technical University of Denmark, Department of Environmental and Resource Engineering, DK-4000 Roskilde, Denmark