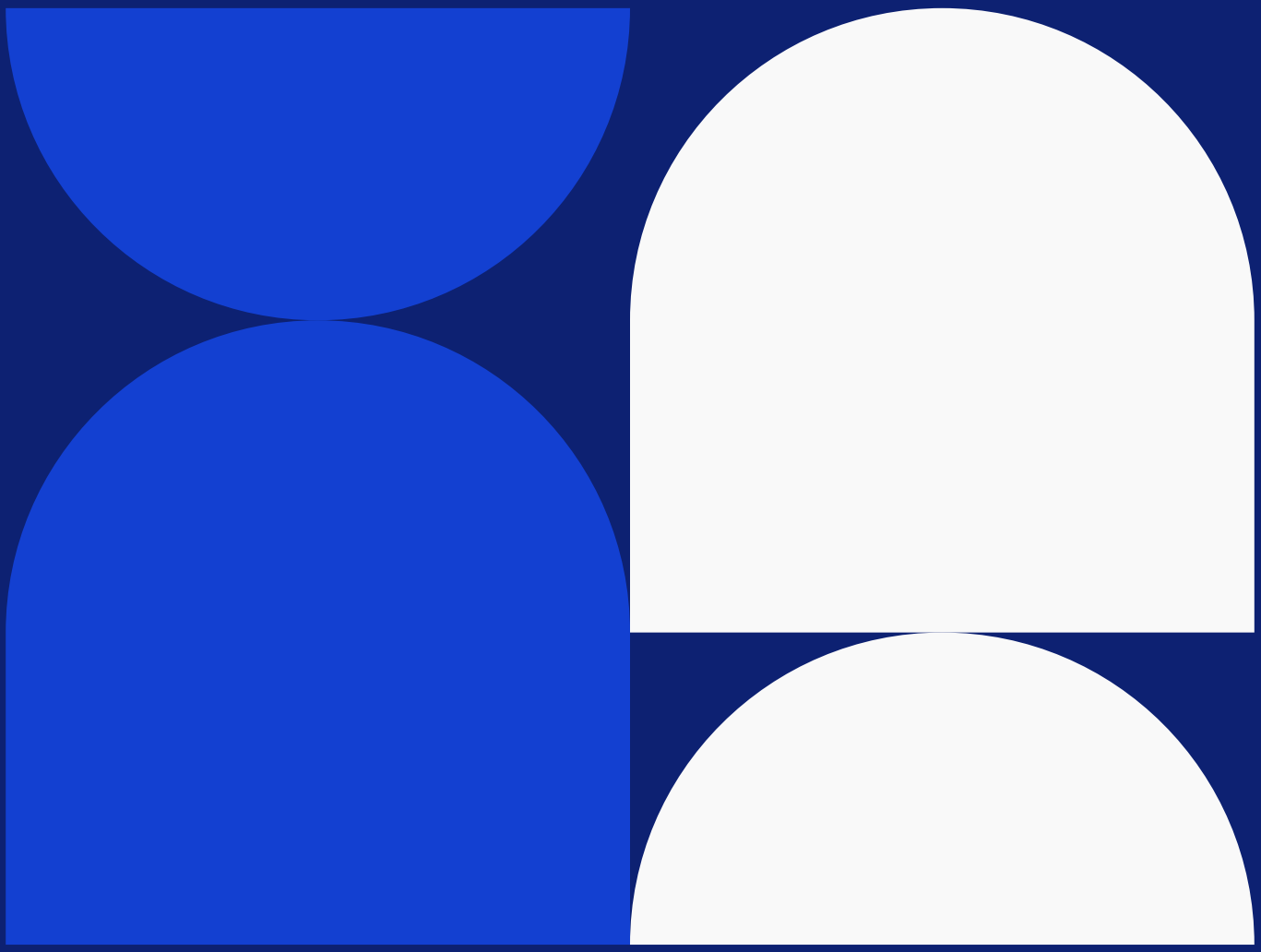
Swedish Needs in Neutron Science 2025

Report from the Swedish Neutron Scattering Society (SNSS) to the Swedish Research Council



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2025

Swedish needs in Neutron Science 2025

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List of abbreviations

AFM	Atomic Force Microscopy, Surface/topography measurement technique
ANSTO	Australian Nuclear Science and Technology Organisation, Australian neutron source and research organization
ARI4SWEDEN	Industrial access/pilot program for neutron methods (formerly SPIRIT; funded by Vinnova)
BAG	Block Allocation Group proposal mode for beamlines
BEER	ESS instrument (engineering materials)
BIFROST	ESS instrument (spectroscopy)
CSPEC	ESS instrument (spectroscopy)
DDLS	Data-Driven Life Science, Wallenberg Foundation program
DREAM	ESS instrument (diffraction)
ESRF	European Synchrotron Radiation Facility, Synchrotron facility, Grenoble
ESS	European Spallation Source, Long-pulse spallation source in Lund, Sweden
ESTIA	ESS instrument (large-scale structures)
FIB-SEM	Focused Ion Beam, Scanning Electron Microscopy – Sample preparation and imaging technique
FRM-2	Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II), Reactor-based source in Garching (MLZ)
GISANS	Grazing-Incidence Small-Angle Neutron Scattering, Grazing-incidence SANS; thin films and interfaces
HEIMDAL	ESS instrument (diffraction)
HIBEAM	High-Intensity Baryon Experiments, Proposed fundamental physics instrument at ESS
HZB	Helmholtz-Zentrum Berlin, Synchrotron BESSY and former reactor source BER II; closed in 2019
Hereon	Helmholtz-Zentrum Hereon, Former reactor source FRG-1 (decommissioned in 2010), German partner institution at MLZ
HiCANS	High-Current Compact Accelerator-based Neutron Sources, Compact accelerator-based neutron sources
ILL	Institut Laue-Langevin, Reactor-based neutron source in Grenoble; broad instrument suite
INS	Inelastic Neutron Scattering, Vibrations, phonons, etc.
ISIS	Pulsed spallation neutron and muon source at STFC RAL, UK
J-PARC	Japan Proton Accelerator Research Complex, Japanese spallation source (Ibaraki)
JCNS	Jülich Centre for Neutron Science, Former reactor source FRJ-2 (closed in 2006), German partner at MLZ, ILL and SNS. Project coordinator for the high brilliance source (HBS)
LINXS	Institute for advanced Neutron and X-ray Science, Lund-based institute for advanced neutron and X-ray science

LOKI	ESS instrument (large-scale structures)
LP3	Lund Protein Production Platform, Protein production and characterization platform at Lund University
MAX IV	Swedish synchrotron facility in Lund
MIRACLES	ESS instrument (spectroscopy)
MLZ	Heinz Maier-Leibnitz Zentrum, Garching; central hub around FRM II
NAISS	National Academic Infrastructure for Supercomputing in Sweden, National high-performance computing infrastructure
NIST	National Institute of Standards and Technology, US neutron research facility (Gaithersburg, USA)
NMX	ESS instrument (diffraction/structural biology)
NORDITA	Nordic Institute for Theoretical Physics, Nordic theoretical physics institute
NPL	Neutron Physics Laboratory, Laboratory near Prague; hosts former Studsvik instruments
NR	Neutron Reflectometry, Surfaces and interfaces
NSC	National Supercomputer Centre, National supercomputing center (Linköping University, Sweden)
NSE	Neutron Spin Echo, High-resolution neutron spectroscopy
ODIN	ESS instrument (engineering/imaging)
ORNL	Oak Ridge National Laboratory, US facility operating the Spallation Neutron Source (SNS)
PSI	Paul Scherrer Institut, Villigen, Switzerland; hosts SINQ and SLS
PhD	Doctor of Philosophy, Doctoral degree
QENS	Quasi-Elastic Neutron Scattering, Diffusion and dynamics studies
R&D	Research and development
RFI	Council for Research Infrastructures, Swedish Research Council's Council for Research Infrastructures (RFI)
SAC	Scientific advisory committee
SAGA	Proposed GISANS instrument at ESS (Swedish involvement)
SANS	Small-Angle Neutron Scattering, Mesoscale; large structures
SAXS	Small-Angle X-ray Scattering, Complementary X-ray scattering technique
SC	Steering committee
SINQ	Swiss Spallation Neutron Source, PSI's neutron source (Switzerland)
SKADI	ESS instrument (large-scale structures)
SNS	Spallation Neutron Source at Oak Ridge National Laboratory (USA)
SNSS	Swedish Neutron Scattering Society
SPIRIT	Former industrial access program (now ARI4SWEDEN)
SSF	Swedish Foundation for Strategic Research
STAP	Scientific and Technical Advisory Panel at facilities
STFC	Science and Technology Facilities Council, UK research council operating RAL/ISIS
SWAXS	Small- and Wide-Angle X-ray Scattering, Combined SAXS/WAXS technique
SWEDNESS	Swedish Neutron Education for Science and Society, Swedish graduate school in neutron science (funded by SSF)

Super-ADAM	Swedish neutron reflectometer at ILL (CRG instrument)
T-RAX	ESS instrument (spectroscopy)
TUM	Technische Universität München, German MLZ/FRM II partner university
VESPA	ESS instrument (spectroscopy)
WISE	Wallenberg Initiative Material Science for Sustainability, Wallenberg Foundation program
XRD	X-ray diffraction technique
cryoEM	Cryogenic electron microscopy

Vetenskapsrådets inledning

Denna rapport, författad av styrelsen i Svenska Neutronspridningssällskapet (SNSS), ger en översikt av överväganden kring forskningsinfrastrukturer för neutronspridning ur perspektivet av svenska användare. Rapporten beställdes av Rådet för forskningens infrastrukturer (RFI) vid Vetenskapsrådet under 2024 för att ge en samlad bild av det svenska neutronforskningslandskapet och för att identifiera framtida behov och möjligheter. Rapporten har författats av SNSS:s styrelse och färdigställdes under 2025.

Rapporten belyser de svenska forskningsbehoven och resursanvändningen inom neutronspridningsområdet samt diskuterar hur Sverige kan ta största möjliga vetenskapliga nytta av den betydande investering som gjorts i European Spallation Source (ESS). Den behandlar också hur man ser på behoven av att fortsatt tillgång till komplementära anläggningar som ILL och ISIS kan säkerställas. Rapporten belyser hur utveckling av instrumentering, metodik, kompetens och nationell samordning kan stärka det svenska ekosystemet för neutronbaserad forskning.

Rapporten utgör en samlad expertbedömning av hur Sverige kan stärka och konsolidera sin position inom europeisk neutronspridningsforskning i en tid av omfattande förändringar i det internationella anläggningslandskapet. Den ger därmed ett underlag för framtida strategiska överväganden om forskningsinfrastruktur på området.

Rapporten är en oberoende expertanalys och speglar författarnas egna bedömningar och slutsatser. Den utgör som sådant ett av flera inspel till Vetenskapsrådets fortsatta strategiska arbete med att utveckla förutsättningarna för svensk forskning med neutroner och maximera forskningsnyttan av investeringar i ESS och andra internationella neutronkällor.

Vetenskapsrådet tackar SNSS:s styrelse för det omfattande och kvalificerade arbete som lagts ned.

Stockholm, november 2025

Lisbeth Olsson

Huvudsekreterare, Rådet för forskningens infrastrukturer, Vetenskapsrådet

Författarnas sammanfattning

Rådet för forskningens infrastruktur (RFI) vid Vetenskapsrådet har gett oss i uppdrag som arbetsgrupp att kartlägga de svenska forskningsbehoven av forskningsinfrastruktur för neutronvetenskap i syfte att ge en översikt av området ur användarperspektiv.

De direktiv (Terms of Reference) som utfärdats av RFI, vilka har definierat och avgränsat vår utredning, finns här med som Bilaga 1. Vårt arbete har särskilt fokuserat på European Spallation Source (ESS), som snart väntas påbörja sitt användarprogram. Sverige står för en betydande del av anläggningens byggbudget och stora insatser har möjliggjort uppbyggnaden av det framtida svenska användarkollektivet. Vår rapport fokuserar på tre områden som rör neutronvetenskapens relevans med målet att möjliggöra excellens inom svensk forskning och säkra bästa möjliga nytta av ESS:

- Förtydliga och rekommendera hur svenska forskningsbehov kan tillgodoses, användarbasen konsolideras och vetenskaplig excellens möjliggöras.
- Undersöka hur framtida svensk excellens inom neutronvetenskap kan möjliggöras genom instrument- och metodutvecklingsprojekt.
- Föreslå mekanismer för att bredda forsknings- och utbildningsprogram kopplade till neutronvetenskap vid svenska lärosäten samt inom industrin.

Genom hela texten utvärderar vi de senaste utvecklingarna inom användargruppen och ger rekommendationer om hur RFI vid Vetenskapsrådet kan prioritera finansieringen av neutronanläggningar och forskning med neutroner. Våra viktigaste slutsatser sammanfattas i avsnitt 6.

Authors' Summary

The Council for Research Infrastructures (RFI) at the Swedish Research Council has tasked us as a working group to investigate the needs of Swedish research for research infrastructures for science using neutrons to provide an overview of the field from the user perspective.

The Terms of Reference issued by RFI, which has defined and limited the scope of our inquiry, are included as Appendix 1. Our work put specific emphasis on the European Spallation Source (ESS) that is expected to start its user program soon. Sweden provides a significant fraction of the construction budget of this facility, and substantial efforts have enabled building up the future Swedish user community. Our report focuses on three areas concerning the relevance of neutron science with the goal to enable excellence in Swedish research and take best benefit from the ESS:

- Clarify and recommend how Swedish research needs can be satisfied, the user base can be consolidated, and scientific excellence can be enabled.
- Investigate how future Swedish excellence in neutron science can be enabled by instrument and method development projects.
- Suggest mechanisms for widening the research and education programmes connected to neutron science at Swedish higher education institutions as well as in industry.

Throughout the text, we evaluate the recent developments of the user community and give recommendations for how the RFI at the Swedish Research Council could prioritise the funding of neutron facilities and research using neutrons. We summarise our most important findings in Section 6.

1 Current status of neutron science in Sweden

Neutron science is a powerful toolbox for a broad range of areas from materials to life science and soft matter. Neutron experiments provide unique information on structure and dynamics complementary to other methods. This capability is related to the ability of neutrons to probe light elements, in particular hydrogen, and to penetrate deep into matter. Other specific advantages are the direct sensitivity of the neutron to magnetic properties as well as the low energy, which allows the study of low energy excitations and molecular diffusion. The low energy of neutrons also prevents radiation damage, and the weak interaction and minimal absorption of neutrons allows the study of samples in complex environments.

Neutrons for all material science and life science are available at dedicated large-scale research facilities and no complementary laboratory sources exist. Such neutron facilities are either international or national, and most of them operate via a user program, where neutron beamtime is allocated after a review process evaluating and ensuring scientific excellence. For academic research, neutron beamtime at all currently existing facilities is free of charge for the user with the commitment that data are public, after a certain embargo time, and will be published. Industrial research can access these facilities through a paid beamtime model if they would like to keep the results confidential. At present, Sweden does not have its own national neutron source for research. The Swedish Research Council directly contributes financially to the Institute Laue-Langevin (ILL, Grenoble, France), where, in addition to the membership, the instrument Super-ADAM is operated as national infrastructure, and to the ISIS Neutron and Muon Source (part of the STFC Rutherford Appleton Laboratory, Didcot, UK). As a response to the international user community's needs, the European Spallation Source (ESS, Lund, Sweden) as the next generation neutron source is coming close to commissioning outside Lund. This facility will offer unprecedent brilliance and open new scientific opportunities. The Swedish Research Council has contributed significantly to the construction budget of ESS, and currently the funding model for operation is being negotiated.

To allow the Swedish user community to take best benefit of the large investment in ESS, several targeted programs have been launched. These resulted in a significant growth of the Swedish neutron community, which is now one of the strongest in the world in researchers per capita. This provides strong opportunities for future impactful research.

To consolidate the Swedish user community and ensure the best return on the strategic investments, in particular with respect to ESS, we recommend:

- To secure sufficient neutron capacity by providing direct access models to neutron beam time[1] to cater for the Swedish neutron scattering community
- To unlock new capabilities by building and maintaining knowledge in neutron methods in the framework of national centres[2] supported by academic and industrial partners
- To enable scientific excellence by consolidating and expanding the user community via collaborations between experienced and new neutron users
- To improve the scientific program of ESS by supporting auxiliary laboratories offering complementary methods for sample preparation, characterization, data analysis and simulations
- To implement education in neutron techniques at university level, through PhD programs and courses, as well as education of Postdoctoral researchers and industrial users.
- To provide decisive input to strategic decisions at neutron facilities to respond to the needs of science in Sweden using neutrons

In this document we describe the current landscape of neutron sources from the viewpoint of the Swedish neutron scattering community, to be used as input for decisions for efficient use of resource to allow Swedish researchers to excel in science using neutrons as a probe.

[1] Sufficient neutron capacity can only be secured by long term funding from Vetenskapsrådet/RFI continuing to contribute to several neutron facilities with sufficient direct access beamtime to cater the needs of the Swedish neutron scattering community.
[2] Like national Swedish research infrastructures, such as Super-ADAM, ideally as parts of a competence centre.

2 Methodology of this report

In this report we evaluate the neutron landscape and infrastructures for material and life science. Neutrons are also used in other fields, mostly nuclear physics and fundamental particle physics. The needs in these fields regarding instrumentation and scientific practices are significantly different. Nuclear physics needs mostly high energetic neutrons and fundamental particle physics instruments are built for a single purpose. However, similar or the same sources can be used. The significant unexploited potential for synergies should be evaluated in the future bringing the communities closer together.

2.1 Bibliometric studies

The bibliometric data shown in figures 2, 3 and 6 are taken from the SNSS bibliometric study that was published in Neutron News: H. Barriga, M. Cardenas, S. Hall, M. Hellsing, M. Karlsson, A. Pavan, R. Peng, N. Strandqvist, M. Wolff, A Bibliometric study on Swedish Neutron Users for the period 2006-2020, Neutron News 32(4), 28 (2021). For details about how the counting was done we refer to the article. We are aware that some articles have not been detected correctly but the trends have proven to be very robust against different ways of counting and verifying, see E. Velichko et al., Rendering the European neutron research landscape, Scientific Reports 15, 5722 (2025).

We also used a specific bibliometric study for the Nordic countries (in particular data for Fig. 1): S. B. Schack, M. K. Lindholm, D. Lomholt Christensen, and K. Lefmann: Nordic and Baltic Neutron Scattering Communities, 2006-2023 - a bibliometric study (pdf), Niels Bohr Institute, University of Copenhagen.

In addition, we used the bibliometric study published by LINXS for international comparisons: M. Stankovski, F. A. P. Khotbehsara, What is the size of the global light- and neutron source research communities? LINXS Institute for advanced Neutron and X-ray Science (May 2024).

All these studies base on the same data set considering publications until 2020. This set is not easily expandable and therefore for more recent dates detailed information is not available. In figure 1 we include user data until 2023 and in figures 4 and 5 publications and beam time statistics from ILL until 2022 and 2023, respectively. These show that the general trends continue. However, neutron science was severely affected by travel bans during the Covid pandemic, which is clearly visible as dips in the usage of ILL during 2021 and 2022. The field is still recovering. Usually, the time between experiment and publication is on the order of two years and bibliometric data from the last five years have to be taken with care.

2.2 Expert interviews

For specific questions, we had open conversations with selected persons with unique knowledge, including Emanuel Larsson (LU, neutron imaging, academy-industry interface), Derek Logan (LU, neutron crystallography, interactions with SSUO), Maria Öhman (activities of Vinnova).

2.3 Community discussion

During the Swedish Neutron Week Meetings 2024 and 2025, we had an interactive session attended by about 70 neutron scientists, which resulted in a good overview of relevant questions for the Swedish neutron community.

2.4 Community survey

A community survey was done online. E-mails have been distributed via the SNSS mailing list. Out of the approx. 230 members of SNSS, 28 replied. Questions asked were:

- What is the level in your scientific career?
- How many neutron experiments have you done?
- What is the average success rate of your proposals (number granted / number submitted)?
- Have you had beamtimes cancelled or postponed due to technical issues at the facilities? If yes, how many?
- Are you using synchrotron radiation as a complementary method?
- Are any of your neutron scattering experiments linked to industry projects? Please comment on you industry connection.
- What reflects your area of research best? Five alternatives were given.
- Which neutron scattering methods/instrument types have you used (select all that apply)? 13 alternatives were given.
- Which of these methods is most relevant for your research? Eight alternatives were given.
- In which techniques do you consider yourself an expert user? 13 alternatives were given.
- Which infrastructures supported by VR have you used? Four alternatives were given.
- Which other research infrastructures have you used? Eight alternatives were given.
- Are the methods you need for your research covered by VR supported infrastructures? Please specify which infrastructures you require are not supported by VR.
- What kind of support/education did you receive in neutron scattering? Eleven alternatives were given.
- Do you have relations with ESS?
- In what way are you involved in ESS?
- Which new types of experiments do you expect to become possible at ESS that are not currently feasible?

- Will your future work be possible with the current ESS instrument suite?
- If not, what is missing?
- Rate each point from least challenging (1) to most challenging (5):
  - Securing sufficient beamtime at competitive instruments
  - Data analysis of complex samples
  - Securing samples for relevant science cases
  - Practical transfer of expertise and knowledge in Sweden
  - Travel costs of beamtimes
- Open comments to SNSS and VR

3 Needs of and resources available to the Swedish user community

We here describe the recent development of the Swedish user community and how its needs are currently addressed. We also detail the use of facilities by Swedish researchers.

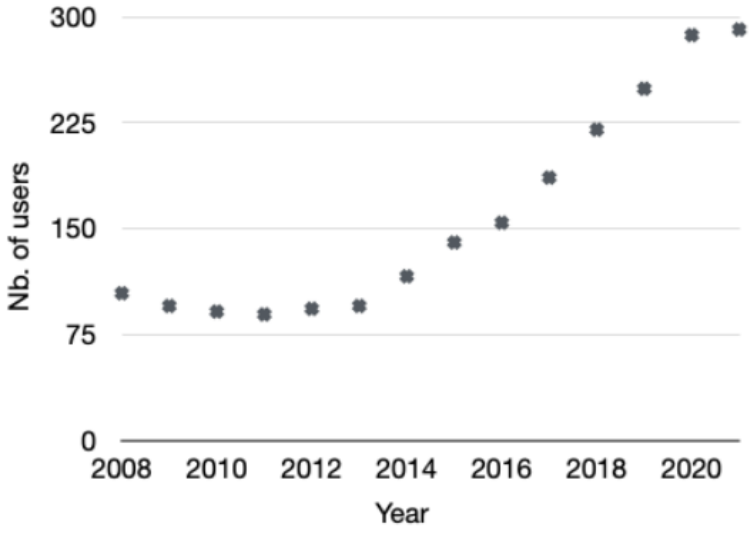
3.1 Development of neutron science in Sweden

Over the last years significant effort has been dedicated to increase the awareness of neutron scattering methods in Sweden, and to grow the user community. Dedicated funding initiatives, like ARI4SWEDEN (industrial use, formerly called SPIRIT, funded by Vinnova), SWEDNESS (PhD school and postdoctoral fellowships for neutron researcher careers, funded by Swedish Foundation for Strategic Research (SSF)), programs of the Swedish Research council (Röntgen-Ångström Cluster, neutron projects, ISIS-ESS collaboration grants, accessibility grants) and Vinnova pilot project calls have resulted in a substantial growth of the user community[3] (see figure 1). This went along with a diversification and now Swedish researchers use all available neutron scattering methods over a large range of scientific areas, including research in sustainability, health, engineering and quantum materials. The Swedish neutron community is now among the largest in the world in terms of publications per capita.[4]

[3] Silas Billeschou Schack, Maja Krüger Lindholm, Daniel Lomholt Christensen, and Kim Lefmann: Nordic and Baltic Neutron Scattering Communities, 2006-2023 - a bibliometric study (pdf), Niels Bohr Institute, University of Copenhagen.

[4] Martin Stankovski, Farhad A. P. Khotbehsara, What is the size of the global light- and neutron source research communities? LINXS Institute for advanced Neutron and X-ray Science.

Figure 1: Swedish neutron users 2008–2020[5].



Numbers are given as sum over five years. Data till 2023 have been included. The x-axis annotation gives the middle of this time period. Users are counted as unique authors of scientific publications, and do not include ESS scientists.

Table 1: Science areas and experimental techniques

Research using neutrons may be divided in different science areas as well as experimental techniques, as summarised in the table below. Note, the spectroscopic methods QENS and INS are flexible and able to probe a number of different processes. A representative example is given in the table.

Technique	Length scales/processes probed
Imaging	mm - m
SANS/Reflectometry	nm - μm
Diffraction	Å
QENS	Diffusion
INS	Vibrations, phonons etc.

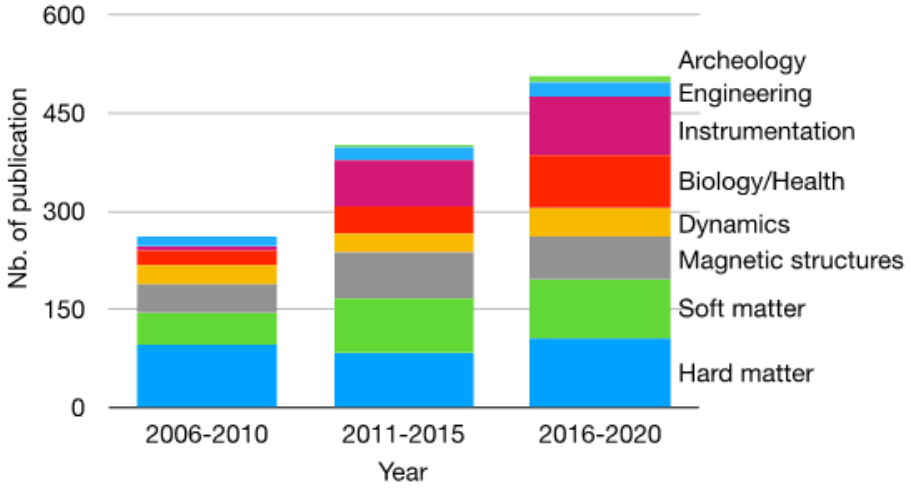
[5] Martin Stankovski, Farhad A. P. Khotbehsara, What is the size of the global light- and neutron source research communities? LINXS Institute for advanced Neutron and X-ray Science.

Traditionally, Sweden was strong in diffraction and research on energy materials. This community has been approximately maintained in size. Strong growth is seen in small-angle neutron scattering (SANS) and neutron reflectometry as well as soft matter and biomaterials. Methods were almost not used by Swedish researchers before 2010, like quasi-elastic neutron scattering (QENS), inelastic neutron scattering (INS) and imaging, now have a visible community.

Currently, the user community is undergoing a renewal, as established neutron researchers come to the end of their tenure. Strategic recruitments of faculty staff have been done at several universities in the last 5 years. These faculty members are either frequent users of neutron methods or have them as their main research tool. Researchers employed at ESS contribute significantly to the Swedish user community, even though their integration in academic and industry research varies from case to case. Given more recruitments are planned once user operation starts, the pool of ESS scientists will provide an important resource to the Swedish neutron community, and measures for increased integration should be evaluated carefully and regularly by ESS and the universities.

The Swedish research community has strong activities in the areas of energy and sustainability, health (biophysics), soft matter, engineering materials, and quantum and magnetic materials (see figure 2[6]). In all these areas neutron scattering methods contribute with unique information, which cannot be acquired by any other method. Depending on the research field different neutron scattering methods are prioritized.

Figure 2: Scientific subjects addressed by Swedish neutron users 2006–2020



The numbers include ESS scientists.

[6] The data for Figures 2, 3 and 6 are replotted from: H. Barriga, M. Cardenas, S. Hall, M. Hellsing, M. Karlsson, A. Pavan, R. Peng, N. Strandqvist, M. Wolff, A Bibliometric study on Swedish Neutron Users for the period 2006-2020, Neutron News 32(4), 28 (2021). The data are extracted from publications of Swedish researchers using neutrons.

In the area of energy and sustainability mostly diffraction, imaging, quasi- and inelastic scattering is used to study the structure and dynamics of compounds containing light elements, such as hydrogen, sodium or lithium. In addition, thin films, as present in fuel cells, photovoltaics, and new coatings, e.g. made from cellulose, or green lubricants are studied by grazing incidence scattering methods.

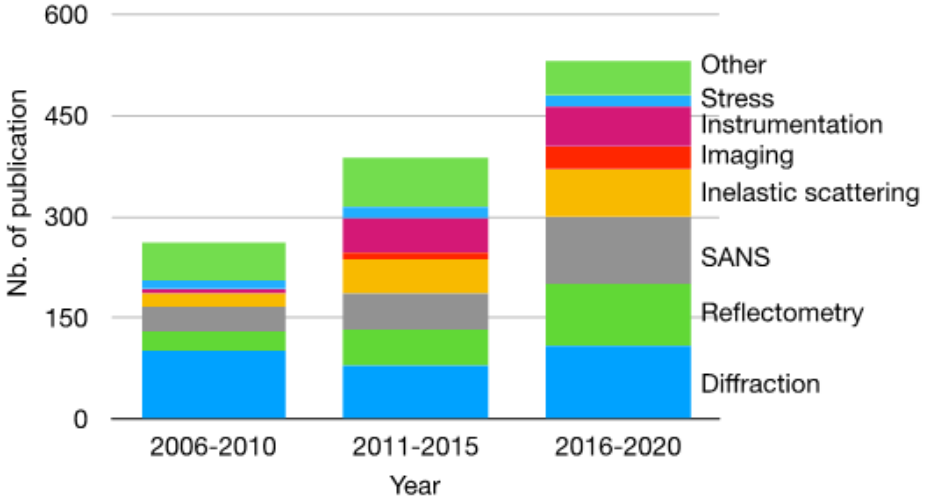
In research focusing on relevant questions in health and the understanding of soft matter and biological processes, mesoscopic length scales need to be studied, and the most relevant methods are SANS, neutron reflectometry (NR) as well as – for the study of dynamics – QENS and INS.

Within the area of engineering materials, typical applications include diffraction-based stress/strain scanning of large complex geometries, utilization of the complementary scattering contrast between X-rays and neutrons for structural studies (diffraction and SANS), and imaging of heterogeneous materials (e.g. using Bragg edge techniques).

For quantum and magnetic materials polarized neutrons are often required, across all instrument classes, as option to resolve the magnitude and direction of the magnetic induction, measure magnetic excitations as well as, in general, outside the area of quantum materials, distinguish coherent and incoherent scattering.

There are strong links of the Swedish neutron community to Swedish industry, such as AstraZeneca, Tetra Pak, SKB, Swerim, etc., including joint research activities and projects using neutron techniques, which promotes engagement of non-academic users. Currently, corporate research is on the order of 3 % of the total research using neutrons.

Figure 3: Experimental methods used by Swedish neutron users 2006–2020



Numbers include ESS scientists.

Swedish researchers nowadays use all available neutron methods, and all techniques are important to the community (see figure 3). While previously the community was dominated by diffraction, over the last years strong growth was seen in imaging, QENS and INS. The strongest growth was in large-scale structures and the corresponding scattering methods of neutron reflectometry and SANS. Some Swedish user groups also depend on the access to neutron spin-echo spectroscopy (NSE). With unexpected shutdowns of some sources[7] and reduced capacity at ILL, access to these instruments has become exceedingly difficult and some of the research is at risk.

Swedish researchers need access to all available neutron scattering methods with sufficient capacity. With the strong growth of the user community, access to sufficient beamtime is starting to become an issue, with the risk that Swedish researchers request significantly more beam time than facilities are willing to allocate. This situation implies that scientifically excellent applications might be turned down, which results in frustration of users and potential shrinking of the community.

3.2 Swedish use of facilities funded by the Swedish Research Council

The Swedish Research Council (SRC) currently contributes directly and financially to two operating facilities, the Institute Laue-Langevin (ILL, Grenoble, France) and the ISIS Neutron and Muon Source (Didcot, UK). In addition, SRC contributes 40 % to the construction budget of the European Spallation Source (ESS, Lund, Sweden). The only neutron infrastructure completely owned and operated by the Swedish community is the instrument Super-ADAM located at the ILL.

3.2.1 ILL

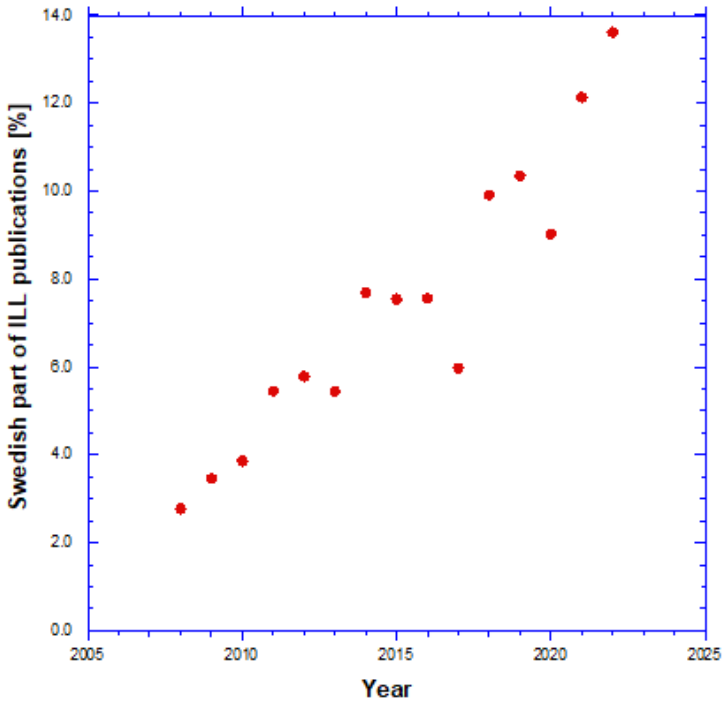
The ILL is operated by three associates - Germany, France and UK - with additional contributions from member countries. The ILL reactor delivers neutrons to more than 40 instruments which cover all methods in neutron science. Swedish researchers have access to SANS, NR, powder and single crystal diffraction, imaging, as well as low- and high-resolution spectroscopy (QENS and INS, including NSE). 10 instruments are operated as Collaborating Research Groups (CRG). CRGs can build and manage instruments at ILL to carry out their own research programs, allowing for specific contributions and research activities for a range of countries beyond the membership share. The SRC national infrastructure Super-ADAM is one of these CRG instruments.

The annual budget of the ILL is close to 1.5 billion SEK, which is spent to operate the neutron source and the ILL instruments for the user program. Sweden is the largest member country of the ILL (after the three associate

[7] The Meier-Leibnitz Center (Garching) has, among others, problems with the cold source and the NIST center for neutron research (Gaithersburg, US) reactor was shut down due to technical problems of the source.

countries) contributing with 6 % to the budget and, in turn, gets access to 6 % of the beamtime in competitive beamtime application calls. At ILL the impact of Swedish research has been significantly increasing over the last 15 years. Currently, about 12 % of the publications from ILL are related to Swedish research (see Fig. 4)[8].

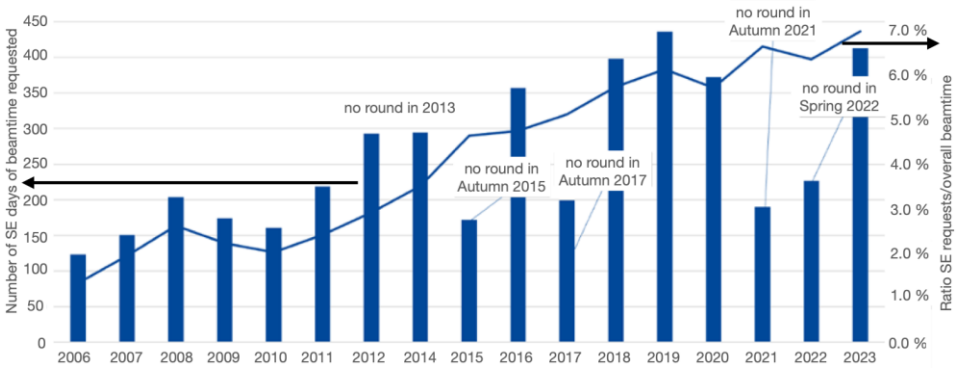
Figure 4. Fraction of ILL publications with Swedish co-authorship 2005–2022



This underlines the success of Swedish researchers at ILL as well as the transnational spirit of research using neutrons. The advantage of the membership at ILL is that Swedish users get access to all neutron methods at the brightest neutron reactor source in the world at relatively low cost. Covering the large range of science areas as offered at ILL would otherwise not be possible. The current agreement for ILL operation extends until 2033, and prolongation of the ILL operation beyond this time would offer opportunities to bridge the ramp up phase until a full instrument suite is available at ESS. However, it should be noted that the ESS instrumentation will not, and is not envisaged to cover all neutron techniques available at the ILL. Moreover, the ILL is essential to provide sufficient capacity for neutron research. Over the last 10 years Swedish use of ILL instruments was constantly growing (see figure 5). Continued access to ILL is therefore critical for the Swedish user community.

[8] The data plotted in Figures 4 and 5 were provided by the ILL user office.

Figure 5: Number of days of beam time requested by Swedish researchers from the ILL 2006–2023



Number of days of beamtime requested by Swedish scientists at the ILL. Total number on the left axis and in staples, percentage on the right axis. Attribution is based on the location of the proposers' laboratory, not their individual nationalities. For a proposal involving laboratories from more than one member country, the total number of days is divided between the collaborating countries and weighed by the number of people from each. Local contacts are not counted as proposers. ESS proposals are divided among the associates and member countries according to their respective contribution.

3.2.2 ISIS

The ISIS Neutron and Muon Source is part of the STFC Rutherford Appleton Laboratory. ISIS operates more than 30 instruments that cover all neutron scattering methods: SANS, NR, diffraction, imaging, low- and high-resolution spectroscopy. In addition, ISIS provides muon spectroscopy and operates an irradiation facility. Beamtime is allocated in competitive proposal calls.

The contribution to ISIS allows some Swedish researchers to participate in instrumentation projects and transfer of knowledge and secures access to beamtime. ISIS is a pulsed spallation source – similarly as the ESS – while ILL is a continuous reactor source. Over the past years a number of common projects were done in the framework of the Swedish Research Council project call for collaborations with ISIS, which would not have been possible otherwise. In this way ISIS offers unique opportunities for the Swedish user community and complements the investment at ILL in an ideal way.

Furthermore, industries have access through specific UK STFC funded initiatives, and this has benefited companies as AstraZeneca with R&D footprint in Sweden and UK.

3.2.3 Super-ADAM

Super-ADAM is a national Swedish infrastructure supported by the Swedish Research Council, via the open calls for national infrastructures, managed by Uppsala University and is the only neutron infrastructure run by the Swedish community. The instrument is a neutron reflectometer situated at the ILL and is run in the framework of the CRG program. The beamtime on the instrument is

distributed following competitive beamtime applications, which are externally reviewed and ranked according to scientific excellence. 50 % of the beamtime is allocated in the ILL user program and available to users from member countries whereas the other 50 % are reserved for Swedish researchers.

Super-ADAM offers neutron reflectometry (polarized as well as unpolarized), off-specular scattering and grazing incidence SANS (GISANS) aimed at tackling surface and interface science, which are areas highly requested by the Swedish user community. The instrument is very flexible and allows instrument and method development projects. It provides unique expertise in the operation, method development, design and construction of neutron instrumentation. It allows the user community to develop new ideas and acquire critical competence for instrument projects at ESS. Super-ADAM complements the access to ILL and the collaboration projects at ISIS in an excellent way by stimulating method development driven fully by the Swedish community.

3.2.4 ESS

As the future world-leading long-pulse spallation source, ESS is still under construction. The accelerator and spallation target are under final commissioning, and first production of neutrons (beam on target) is expected at the beginning of 2026. The construction of 15 instruments in the areas of diffraction (DREAM, HEIMDAL, MAGIC, NMX), engineering (BEER, ODIN), large scale structures (ESTIA, FREIA, LOKI, SKADI) and spectroscopy (BIFROST, CSPEC, MIRACLES, T-RAX, VESPA), is ongoing and covers most instrument classes.

Beyond the 15 instruments under construction the completion of the instrument suite is envisioned by closing identified essential capability gaps (e.g. neutron spin-echo spectroscopy, GISANS, nuclear physics experiments). A call for input on the ESS instrumentation roadmap for the next round of instruments is closing in February 2026, and the financial model for construction will be part of future negotiations among the member states and ESS. Construction of these instruments will likely start from 2028 and be finished in the middle of the next decade.

The funding model for the operation is still under negotiation between the member countries and ESS management. Establishing a well-funded running budget and enabling a fast ramp-up of ESS to a further enlarged suite of instruments is an essential step to maintain the strong landscape of neutron science in Europe with reliable future perspectives for Swedish research. Access to ESS will provide unique opportunities for Swedish researchers due to the geographic proximity and is expected to become one of the most important sources for the Swedish neutron community within the next decade. Considering the limited number of techniques/instruments and low brilliance upon the start of operations it will likely require several years to achieve larger numbers of research results and scientific breakthroughs.

To allow the Swedish user community to take best benefit from ESS as soon as it delivers neutrons, accessibility programs have been started funded by the Swedish Research Council and Vinnova, supporting access to beamtime with an emphasis on new and industrial users. These have increased the interest in neutron scattering methods and strengthened the community, by attracting new users and initiating collaborations between academia and industry through pilot projects. Further, VR has just started a program for first science projects at ESS to allow Swedish researchers to take best benefit of the new facility as soon as it comes online.

3.3 Securing the specific needs of the Swedish neutron community

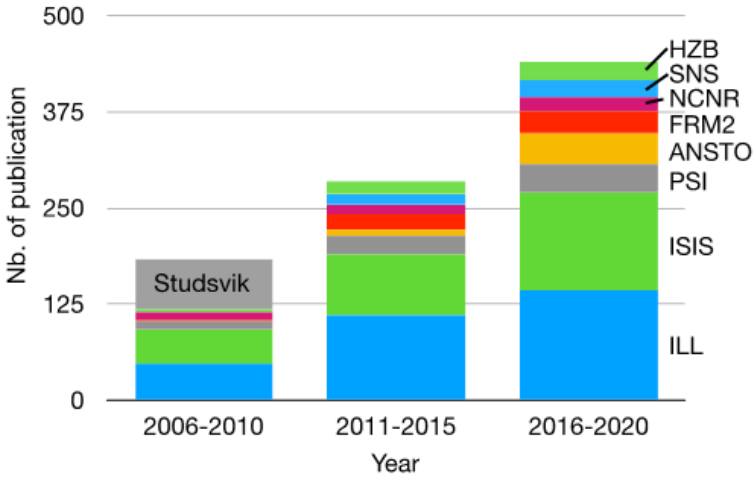
Swedish researchers have limited influence on decisions on instrumentation at the facilities as these are made by the facility management. At the national sources in other countries this is beyond the influence of Swedish researchers. At the international facilities, ILL and ESS, decisions can however be influenced by Swedish representatives in relevant committees, e.g. scientific and technical advisory panels (STAP), scientific advisory committees (SAC) and steering committees (SC), as well as by informal contributions to user workshops, the ongoing call on the ESS instrumentation roadmap, or the operation of instruments in the framework of CRGs, such as Super-ADAM. In this context, the funding from SRC for pilot studies for two Swedish instrument proposals, GISANS (SAGA) and fundamental physics (HiBEAM), as well as strong involvement of Swedish researchers in another proposal for neutron spin echo (NSE) provide examples on ongoing activities in the Swedish community. This needs to be taken into account in discussions and negotiations in the relevant committees to indirectly cater for Swedish needs regarding ESS instrumentation. However, final decision on which instruments will be constructed will only be taken in the future and the funding situation is unclear. Even if not funded, the strong engagement from the Swedish user community builds competence in the country and hopefully allows to steer decisions towards the needs of the Swedish community.

3.4 Other facilities, not funded by the Swedish Research Council

Swedish neutron users use many facilities with no direct Swedish funding. The most relevant facilities are the PSI (Villingen, Switzerland), ANSTO (Lukas heights, Australia), MLZ/FRM-2 (Garching, Germany), and to a smaller but significant extent NIST center for neutron research (Gaithersburg, US), Oak Ridge National Laboratory (Oak Ridge, US) and J-PARC (Ibaraki, Japan). All these facilities cover most of the relevant neutron scattering methods, including SANS, NR, diffraction, imaging, as well as low- and high-resolution spectroscopy. The output from all these sources together is just slightly higher than the Swedish output of either ILL or ISIS. In total approx. 1/3 of Swedish

neutron research is done at sources outside those funded by the Swedish Research Council (see figure 6).

Figure 6: Number of publications of Swedish neutron users resulting from data taken at different neutron facilities.



Note that the former Swedish neutron source in Studsvik was closed in 2005 before the time span of this bibliometric study. HZB closed in 2019. The numbers for ILL include Super-ADAM, which makes about 10 % of the total of Swedish ILL publications.

There are several reasons for the usage of these neutron sources: Some facilities offer special capabilities, like deuteration, specialized instrumentation or sample environments that are not available elsewhere. Other activities build on existing collaborations or tailored user support. The large fraction of used facilities outside the financing of the Swedish Research Council clearly documents the diversity of the needs of the Swedish user community. Currently, the use of neutron sources not supported by the Swedish Research Council is crucial for Swedish research, as they offer unique expertise, capabilities and additional capacity. Even with user operation at ESS, this situation will not change, and international collaborations including but also beyond formal agreements are important to provide sufficient capacity, knowledge exchange and rich capability opportunities for the Swedish neutron community.

We note that the overall number of neutron sources is relatively small and fluctuations in facility operations can have severe consequences. As an example, the unexpected and long shut-downs of the MLZ and NIST are significantly affecting the Swedish user community. The only way to mitigate the related risks is to have access to a healthy ecosystem of sources reducing the dependency on single institutions.

We also note that Swedish users benefit from access to facilities not running large user programs. Diffractometers formerly operated at the Studsvik reactor were transferred to the neutron physics laboratory (NPL) close to Prague. In the framework of collaborations Swedish users benefit from these instruments,

which allow rapid access for experiments not requiring the highest brilliance. Such needs can otherwise not be fulfilled.

3.5 Overview of the international landscape of neutron facilities

3.5.1 Current situation

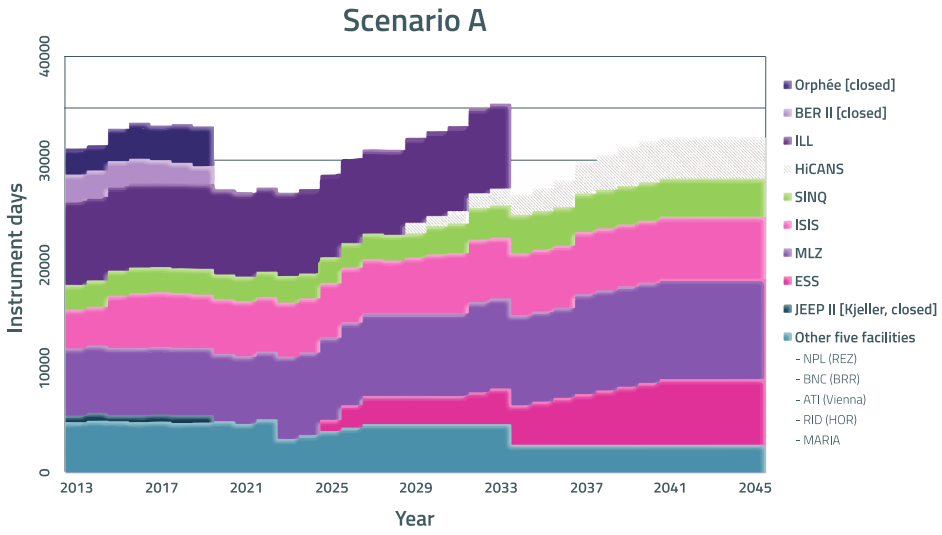
Currently, the field of neutron scattering is undergoing significant changes. Most small national facilities have been closed during the last decade and no replacements will become available in the very near future. At the same time ESS has been delayed by several years now, leading to a lack of neutron beam days and neutrons in general. This situation is even worse as some of national sources have discontinued operation unexpectedly due to technical problems and did not come back online so far.

It may be expected that ESS will start to produce first neutrons at the beginning of 2026. Once neutrons are available, ESS will commission instruments in several instrument tranches, starting with technical validation and first science. The start of user operation on the first instruments is planned for 2027. In parallel to the instrument commissioning, the power of the ESS accelerator will be ramped up within few years. According to plans, ESS will offer an established user program by the end of the decade. In parallel, ESS will continue constructing more instruments to reach the intended number of 22 beamlines. Given the complexity of these instruments, it may be expected that they will come online in the middle of the 2030s.

The future of ILL beyond 2033 is currently unclear and there is a threat that it may shut-down for good. This would result in a severe reduced capacity in the overall neutron facility landscape even after the start of ESS. Note that ILL operates over 40 instruments, whereas currently at ESS only 15 are under construction and the process for decisions on 7 more is just starting. Figure 7 shows the number of beam days available to European users over two decades[9]. Note the timeline may be shifting but the overall scenario implying a significant reduction of experimental opportunities still holds.

[9] ESFRI Scripta Volume I: Neutron scattering facilities in Europe, Present status and future perspectives (pdf), ESFRI Physical Sciences and Engineering Strategy workgroup, Neutron Landscape Group, 2016.

Figure 7: Scenario for the development of neutron beam days available at European neutron sources (created in 2022[10]).



Note that MLZ has been closed for several years now due to technical problems but is expected to come back online in the near future. This is not reflected in the diagram. Note that this scenario is under the assumption that upgrade programs at several facilities, e.g. ESS, SINQ, are realised and HiCANS become available.

3.5.2 Future development

To increase capacity and provide new capabilities several facilities world-wide have plans for upgrade programs. SNS (USA) plans a second target station. ISIS already completed the second target station and is doing feasibility studies for a completely new, more powerful spallation source (ISIS2). This source would have two target stations as well and be built adjacent to the current ISIS facility.

In addition, several countries develop plans on high current compact accelerator driven neutron sources (HiCANS). Major projects are ongoing in Germany and France, and smaller projects exist in other European countries, as well as projects of various scale outside Europe. While such sources are less powerful in the production of neutrons as compared to reactor or spallation sources, they have the advantage that they are scalable, which allows construction and operation at much lower cost. It may be expected that in the longer run such facilities could provide the required capacity for neutron research and replace the closed national reactor sources. The high brilliance source (HBS) project, which is the most developed project of significant size, is now on the German national roadmap for the years 2025-2045. However, given the construction time of approx. 10 years after funding starts, HBS will not become available before 2035. Smaller projects, as the ESS-Bilbao (Spain) and the source constructed by Mirrotron (Hungary), may produce neutrons in the coming years but offer only a very small number of instruments with a limited scope and at a low neutron flux. They will, however, contribute to demonstrate the capabilities and performance

[10] Strengthening world-class research and innovation delivering economic and societal impact (pdf)

of a fully optimised facility. Swedish researchers and funding agencies should closely monitor these developments.

3.6 Summary of the funding strategy of the Swedish Research Council

Currently, the funding from the Swedish Research Council focuses on the sources that are most relevant for the Swedish community. The distribution among different projects, ILL for the user program and scientific excellence, ISIS for scientific excellence and smaller instrumentation projects and Super-ADAM for scientific excellence, method development and instrument operation provides complementarity. However, the fact that a significant fraction of Swedish research with neutrons is done at facilities outside the funding of the Swedish Research Council requires additional consideration, as access to these facilities is critical for the Swedish community. Formalising such collaborations could secure access of Swedish researchers to the unique capabilities offered by these facilities. As these facilities do not have formal memberships, common instrumentation and technical development projects could be a way to increase Swedish impact and strengthen collaborations. Further, such programs would allow knowledge transfer and mitigate the risk of occasional shutdowns and limited access of Swedish researchers to neutrons. PSI has indicated interest in common projects with international partners and at MLZ instruments are operated, installed and maintained by several partners, TU Munich, Jülich Centre for Neutron research, Hereon and the Max-Planck society.

4 Need for methodology development

ESS promises unique capabilities due to the high peak flux realized at the first long-pulse spallation source. These characteristics enable specific instrument concepts optimizing energy resolution and energy range while keeping suitable brilliance. Once reaching the design power, new research opportunities will emerge in several aspects, including time-resolved studies due to faster acquisition, smaller sample sizes due to opportunities for smaller beams with sufficient flux, and swift parameter scans exploiting polychromatic measurement modes. The central shortcoming so far is the limited number of instruments at ESS, which implies inefficient use of the excellent source, and the lack of important instrument types. According to the gap analysis of ESS, these instruments include a nuclear physics instrument (such as HIBEAM) and a neutron spin-echo spectrometer as highest priority. With slightly lower priority ESS demands a GISANS instrument (such as SAGA). Based on our survey, the development of the user community and the expertise available in the national infrastructure Super-ADAM, a GISANS beamline like SAGA is a strong case of instrumentation with clear benefits for the Swedish user community. Such an instrument would offer new capabilities not available elsewhere. Of high relevance for the Swedish community as well is a NSE instrument at ESS. Such instruments are so small in number that there is a risk that Swedish researchers will lose access to high-resolution spectroscopy at some point in the future. Fundamentally different in this context is HIBEAM. This instrument will serve one dedicated purpose in particle physics and not run a user program. HIBEAM will offer unique opportunities to drive the development of neutron instrumentation and technical developments, which is very beneficial for instruments serving the material and life science communities, as it offers ways to improve performance.

Currently, the tools to support neutron instrumentation projects in Sweden are limited. Some opportunities have been implemented in the Röntgen-Ångström Cluster program or the common ISIS-ESS project calls. The planning grants for Swedish-driven instrumentation at the ESS, HIBEAM and SAGA, have been created outside the usual funding schemes. With the ESS coming closer to operation, open calls of similar type to support instrument and method developments with relevance to science at ESS would result in significant impact. In this context, the current funding model at the Council of Research Infrastructures (RFI) and the Scientific Council for Natural and Engineering Sciences (NT) of the Swedish Research Council is suboptimal for neutron science, as typical methodological developments in facility-university collaborations consist in development of sample environments or specific measurements options, which neither qualify as national infrastructure fundable by RFI nor as scientific projects within the NT scheme. Opportunities for such collaborative method development projects will not only be present in the ESS startup phase but continue throughout the entire operation period of ESS. Having

regular funding opportunities for such projects would allow the chance to shape experimental opportunities at ESS for the benefit of Swedish academia and in particular industry, as the latter might require sample environments not established at classical neutron sources. In-kind contributions to the ESS are one potential model that enables instrumentation projects with mutual benefit where the needs of the community and the possibilities at the facility can be matched. The current in-kind program, however, needs some consideration as the decision process involves many steps and ESS-internal evaluation is opaque and does not include enough cost items with clear benefit to the Swedish user community. Tailoring the in-kind program more towards the needs of the Swedish user community would allow significant and relevant contributions to ESS and building of competence in the country.

5 Recommended actions for shaping the future of neutron science in Sweden

After the overview on the Swedish neutron community and its needs, and a description of the landscape of neutron facilities, this section provides an evaluation of recommended action areas where activities from the Swedish Research Council, user community, universities and facilities could create new potentials for Swedish neutron science. In the next section 6, we provide a condensed, prioritized list of recommendations as summary.

5.1 General strategic aspects in the Swedish context

The largest opportunity in the field currently arises from the operation of the ESS at full scope, as the facility will allow the possibility to address scientific questions so far not accessible to neutron methods in Europe or elsewhere. The continued delay of the start of the user program results in frustration and lack of engagement with the ESS activities. In this context contributing to the success of ESS and ensuring rapid implementation of the user program is the highest priority for the neutron user community.

The strongest tool to guarantee sufficient access to neutrons is direct funding. The membership fee at ILL provides access for Swedish researchers to neutron beam time on a wide range of instruments. Once the ESS reaches full capacity a good part of the Swedish research currently done at ILL may become possible at ESS. Care should be taken during the transition period not to suffer from reduced number of beam days and the loss of access to critical methods, e.g. NSE. Membership fees have to be complemented by specific instrumentation projects, such as Super-ADAM, run as a national infrastructure at national or international facilities. These cover very specific capabilities of high relevance for the Swedish community and allow a deep understanding of the respective methods, how to develop them and permit the researchers to be at the forefront of instrumentation. In the future such instrumentation could be run at a Swedish or Nordic neutron source (e.g. employing a cost-effective compact source design as planned in other countries), which would cater to the user community with the most relevant methods and allow instrument developments as well, since it bundles knowledge and expertise.

In addition to formal agreements and direct funding, it is important to keep informal access models as open as possible. This may be secured by collaborative projects with facilities for increased robustness and excellence. The Swedish Research Council can contribute to this open scientific ecosystem by maintaining a significant access of international users at national facilities such as MAX IV, or other national research platforms. Programs such as the ISIS-ESS calls are additional ways to formalize collaborations but require dedicated funding.

To be successful at facilities without formal agreements a strong and healthy user community is mandatory. To consolidate and maintain such a community, direct access models and method developments are very important. Risks of potential losses or damage to the user community should be carefully evaluated and discussed before reductions of funding are decided. In the shorter term, reduced direct access to beam time for Swedish users would increase the load on facilities without formal agreements and may result in access restrictions, such as national quotas for Swedish researchers, to protect local communities. This would further reduce access to neutrons for Swedish researchers and lead to a decline of the user community, eventually loosing competitiveness and endangering the ability to take best benefit of ESS.

5.2 Action area User community – Identification of new users and retention of recent first users

Given the limited capacity of neutron sources, further growing the user community may be challenging, unless new sources beyond ESS become available. Attracting new users should focus on scientific excellence to increase the impact of Swedish research without the need of increased capacity. Moreover, users from fields relevant for applications and industrial users may be attracted to increase the socioeconomic impact. At the same time the recent growth in the community needs to be consolidated by continued funding to provide maturation for increased expertise, and to avoid the loss of excellent researchers, which have been educated over the past years. The neutron user community in Sweden has grown over the last decade, but many of these users are not yet strongly experienced and sustainable long-term experts.

5.2.1 Action U1 - Securing access to neutron beam time

The recently expanded user community in science using neutrons needs to have access to a sufficient number of beam days, as well as a healthy ecosystem of neutron sources. This includes the high-end facilities with highest brilliance, like ESS and ILL, as well as sources offering specific experimental capabilities, e.g. Super-ADAM, deuteration, specific methods such as doping or gamma spectroscopy, and low brilliance sources for method development, tests and long-term experiments.

At ESS, the ramp up to the final specified power of the accelerator to reach the promised brilliance will continue far beyond the start of the user program. From a user perspective, it is most essential to complete the ESS instrument suite based on the capability gap analysis and provide user access at full accelerator power. Stressing these two aspects in the ongoing negotiations of the ESS operational budget is of highest relevance for the Swedish user community.

Access to a sufficient number of neutron beam days needs to be secured by funding agencies (most prominently the Council of Research Infrastructures) covering membership fees, supporting common scientific and instrument programs as well as enabling national research infrastructures.

5.2.2 Action U2 – Developing the community

There is still a large number of potential future users which need to be activated, as well as new users who need to be motivated to continue with neutron research. A regular and systematic review of bibliometric studies and facility statistics as well as regular user surveys are essential to identify potentials and shortcomings. User communities, like SNSS, may collect and summarise such statistics.

Simple entry projects need to stimulate the user community, as e.g. via pilot grants such as the earlier Vinnova scheme. In addition, the relation to industrial networks such as ARI4Sweden can be used to establish new collaboration between academia, industry and large-scale facilities. Programs integrating experienced and less experienced users are an excellent tool to bring together expertise in neutron science with the most impactful science questions, thereby enabling collaborations, allowing experienced users to grow and new users to build competence. Such collaborations can be initiated by centres at universities and directed funding e.g. by Vinnova, SSF, and potentially also the Swedish Research Council.

5.2.3 Action U3 – Representation of the user community

User communities such as SNSS are important multipliers for competence in specific scientific areas and need to be supported in this role. Besides basic support for their activities as provided by the Swedish Research Council, a stronger involvement in strategic development as well as coordination of support for relevant activities can be beneficial, as knowledge in the neutron research is very specific. Relevant actions range from regular discussions on planned actions, support in finding experts for evaluation panels, and feedback on relevant plans for funding schemes.

Strengthening the role of user communities is not only democratizing the research community but also provides a robust situation not relying on personal networks and individuals. The respective communication channels need to be developed on a functional level between funding agencies (in particular the Office for ESS/MAX IV at the Swedish Research Council), universities, SNSS and other stakeholders.

5.2.4 Action U4 – Embedding of ESS researchers

The current model of affiliating ESS scientists to Swedish universities does not always guarantee strong collaborative activities and related competence transfer. An essential problem is the missing research time for ESS scientists at the universities and a travel budget. A possible solution to this would be opportunities to recruit scientists with working time truly distributed between ESS and universities. Respective agreements should be made between universities and ESS. Offering ESS scientists, the option to apply for Swedish research grants at universities strengthens their research activities and facilitates collaborations.

5.2.5 Action U5 – Community-spanning educational and thematic activities

The LINXS Institute for advanced Neutron and X-ray Science located in the immediate neighbourhood of MAX IV and ESS allows Swedish and international researchers opportunities to strengthen research areas in coherent thematic activities integrating neutron and X-ray science, experimental, methodological and theoretical aspects, and academic and industrial perspectives. Extending these activities to an equivalent program on a Swedish or Nordic level as a centre for neutron and X-ray science supported by and uniting all Swedish universities would enable strong topical links and method-driven networks within Swedish academia, Swedish industry, MAX IV and ESS, and couple to international expertise from academia as well as other neutron facilities. Such a centre could host complementary methods and competence in the field of scattering as well as provide a platform for topical collaborations on common interests. The formation of such a centre needs to be initiated as a community initiative anchored at the universities, but would subsequently require political and financial support from funding agencies, similar to support for community centres such as NORDITA, or research consortia such as Treesearch, DDLS or WISE.

5.3 Action area Method development – Development of experienced users to method experts and multiplicators

The Swedish community has experienced neutron users but lacks a strong tradition in development of neutron methodology and instrumentation. This lack of deep expertise limits the opportunities for users to interact with neutron facilities such as ESS, ILL and ISIS with a long-term strategic perspective. Having too few method experts limits not only the ability to educate future knowledgeable users, but also endangers fruitful collaborations between academia and industry, which relies on sufficient time and often geographical proximity. Dedicated funding schemes for method development and building of competence are crucial to allow experienced users to develop into strong method experts which then multiplicate their expertise in future education and collaboration.

5.3.1 Action M1 – National competence centre

As a long-term goal, a national competence centre/network in neutron science as a national infrastructure should be installed to consolidate and drive interactions with ESS, ILL and ISIS on a high-quality level. In this context, extending and combining existing national neutron infrastructure efforts, such as Super-ADAM, SAGA and HIBEAM, may be a good tool to keep and expand method development in Sweden. Such a centre would allow synergies and bundle competence. These activities require a close collaboration of the user community, universities and the Council of Research Infrastructures.

An important consideration concerns lower-level access to beamtime for training and competence development, as this will not be provided by ESS. The planned

national neutron sources in other European countries based on the high current compact accelerator neutron sources (HiCANS) provide a cost-effective option for lower-level access. The respective developments should be followed carefully and evaluated regularly as potential Swedish national or Nordic infrastructure. As a first step towards a national source an evaluation of the needs and opportunities after the adaptation to a Swedish context should be done. Such a study requires limited funding that might be made available by the Swedish Research Council and universities and should be driven by a Sweden-wide or Nordic consortium of neutron experts. Ultimately, such a national source should be the competence centre in the field and host the instrument projects mentioned above.

5.3.2 Action M2 – Strategic funding

A regular dedicated funding scheme for neutron methodology strengthens not only the Swedish neutron competence but also allow the Swedish community to shape experimental opportunities to best cater for strong Swedish research areas and relevant industries. Such funding schemes exist in other countries, e.g. Germany. This scheme has proven to very successfully enable university groups to drive instrument and method development in close collaboration with facilities. The Swedish Research Council should evaluate to what extent, after adaptation to a Swedish context, such a program would enable and activate Swedish University groups to establish method competence and contribute to ESS beyond the current in-kind approach.

Funding initiatives by the Council of Research Infrastructures such as the project call within the Röntgen-Ångström Cluster and the ISIS-ESS collaboration call, provide very valuable opportunities in this context and should be continued with a clear methodology focus and a long-time perspective allowing strategic orientation of the community. Given the upcoming timely opportunities for collaborative projects on method development at ESS with direct benefit for the Swedish community, the success rate of neutron projects in these grant frameworks is expected to increase. The user community (via SNSS) and the Council of Research Infrastructures should regularly discuss and evaluate funding opportunities for neutron science, to follow potential changes of needs when ESS has commissioned the first instruments and defined the full operational model.

5.3.3 Action M3 – Taking benefit of ESS

The involvement of the Swedish user community at ESS currently misses important opportunities to grow and transfer expertise. Development of methodology and instrumentation, such as for specific measurement protocols and sample environments, will continue during the entire lifespan of ESS. A good model in this context are in-kind or collaborative contributions as they allow to tailor investments to the needs of the Swedish community. To allow the most impactful and beneficial developments driven by the Swedish community, the decision process on in-kind projects needs to be with the Swedish Research Council in agreement with the benefits for ESS. Programs currently running outside the in-kind model, such as HIBEAM and SAGA, demonstrate the

potential. In the ongoing process of new instrumentation at ESS, the representatives of Sweden in the scientific advisory committee and council at ESS should be regularly informed about needs of the user support proposals of specific interest for and with involvement from the Swedish user community.

A coherent plan for Swedish involvement taking into consideration the needs of the Swedish user community and ESS is urgently needed. Such a plan has to be developed together by the Swedish user community (represented by SNSS), universities, ESS and the Council of Research Infrastructures to reach consensus on the best way of implementation.

5.4 Action area Education – Involvement in research and education activities on national level

Education of the next generation of neutron users is essential and adequate educational programs need to be developed and maintained.

5.4.1 Action E1 – Courses

The educational program developed in SWEDNESS (PhD graduate school and PostDoc program funded by SSF) should be maintained to take best benefit of the investment. One possibility may be to transfer the curriculum towards a HERCULES-like summer school with a strong combination of lectures and hands-on training strengthening interaction of Swedish universities with ESS. We would like to note that currently several different and independent teaching approaches and schools exist, such as HERCULES, the Oxford School on Neutron Scattering, the JCNS laboratory course on neutron scattering, the ISIS Neutron Scattering School (fees are covered by the Swedish contribution to ISIS), the Röntgen-Ångström Cluster school, to name the most important ones. With ESS and a coherent Swedish national perspective, e.g. coupled to future community-spanning thematic and methodological activities, we see an opportunity to exploit synergies and converge towards a common approach, which needs to be developed together by user communities, facilities and universities.

5.4.2 Action E2 – Programs

To maximize the yield of the investment in ESS, strong and tight collaborations with the facility are ideal. PhD and postdoctoral programs are one relevant tool to foster long-lasting collaborations. Such programs exist elsewhere, e.g. at ILL, and have proven to be successful. An ESS PhD and postdoctoral program needs to follow the Swedish conditions of higher education, allowing e.g. for 4-year duration and time for mandatory PhD courses. The installation of the respective program needs to be initiated by ESS but should be carefully accompanied by Swedish representatives in the scientific advisory committee and council to ensure wide Swedish participation.

5.5 Action area Connections between Neutron and X-ray community

Most neutron users employ X-ray techniques as well. A combined use of neutrons and X-rays provides complementary information often extracted by a common analysis framework. It is highly beneficial to support joint activities to drive the development of experimental methodology as well as interpretation and analysis of data. Opportunities include synchronization and suitable adaptation of sample environments, experimental protocols, as well as data standards and open analysis frameworks.

The interest for complementary use is high e.g. in the field of soft matter, life and material science, since the different contrasts offer obvious benefits for a broad range of techniques such as reflectometry, small-angle and wide-angle scattering as well as diffraction and spectroscopy.

Interactions with the X-ray community are essential for neutron imaging and neutron crystallography. Neutron crystallography is almost exclusively used by X-ray crystallographers for specific systems, in particular, the structural refinement of hydrogen atom locations. The neutron imaging community is growing from the micrometre X-ray imaging and tomography community, including opportunities for industrial use.

In general, strong interactions between the neutron and X-ray community are possible given a similar scientific ecosystem and comparable overall working tradition. Both fields rely on collaborative work involving small groups in academia, large-scale facilities and potentially industry. While neutron and X-ray techniques are based in physics, their applications have a strong interdisciplinary character. The typical project structure involving beamtime proposal, experiment and subsequent data analysis and interpretation without the option to remeasure is specific and shared in both fields. Both fields rely on data analysis of large data sets.

5.5.1 Action C1 – complementary studies exploiting co-localization of MAX IV and ESS

The colocalization of MAX IV and ESS offers unique opportunities for complementing studies. The possibility to swiftly measure samples characterized at ESS and subsequently at MAX IV would offer a strong benefit to both communities. This should include measuring the same sample on comparable instruments (e.g. SAXS/SANS, tomography, diffraction) as well as complementary characterization exploiting probe-specific techniques (QENS, X-ray spectroscopy, small X-ray beams, no radiation damage at neutrons for long exposures).

Despite its high potential for strong impactful science, the combined use of neutron and X-ray facilities has so far been complicated, as e.g. ILL and ESRF did not reach a simple agreement how to handle access and PSI-SINQ and PSI-SLS offered it only for a limited number of techniques and for a short time.

Challenges are related to radiation protection, proposal systems and experimental aspects with respect to sample cells and protocols. It would be desirable to overcome these challenges by a common collaborative action involving ESS and MAX IV, e.g. establishing BAG proposals at MAX IV for ESS samples.

5.5.2 Action C2 – lab-based infrastructure as relevant preparation

Lab-based instruments such as SWAXS, XRD, X-ray reflectometers, and X-ray tomography are an ideal complement to ESS and MAX IV and allow users to build strong science cases. Lab-based facilities are relevant to attract, educate and train new users both from academia and industry. Instrument responsible at lab-based instruments are method experts and can act as facilitators for method development. Strengthening lab-based instrumentation all over Sweden is important to strengthen expertise and pre-characterize samples before use at MAX IV and ESS. This may be enabled by the establishment of a Swedish preparation and characterization lab offering instruments such as SWAXS, XRD, X-ray reflectometer, and X-ray tomographs, as well as confocal microscopy, cryoEM, FIB-SEM, AFM, rheology etc, and advanced preparation opportunities in soft and hard matter (e.g. microtoms, nanoindenter). These experimental opportunities stimulate future Sweden-wide thematic and methodological activities. Such a lab initiated by universities should be coupled to and extended from existing national resources already available at MAX IV and LP3, ESS support labs, as well as MyFab and link to computing facilities as provided by the National Academic Infrastructure for Supercomputing in Sweden (NAISS) or the National Supercomputing Centre (NSC).

5.5.3 Action C3 – common educational activities

It would be desirable to further strengthen interactions between neutron and X-ray communities on the conceptual and educational level. The synergies in theory between neutron and X-ray scattering allows effective common education, in PhD courses as well as in courses on neutron and X-ray science on master level. This action is linked to Action E1 (Courses) and Action U5 (Community-spanning educational and thematic activities).

6 Summary of Central Recommendations

The above actions provide tools to strengthen the Swedish neutron user community. Many of the actions build on existing activities and may be implemented without the need for extra funding. Some others require considerable resources. As central recommendations synthesizing the above actions we identify the following points:

1. **The highest priority is access to sufficient beamtime on all instrument classes.** This can only be ensured by the Council of Research Infrastructures through continued financial contributions and political support for international neutron facilities. A fast ramp up of ESS to full designed power running a competitive user program, as well as swift completion of the instrument suite is of highest priority. During this process Sweden needs to ensure continued access to the ILL by remaining a member country. Any gap in access to neutrons has to be avoided as it would result in a decline of the user community. Furthermore, to be resilient against unexpected facility shutdowns, a diverse portfolio of facility access is needed. ESS may be complemented by ILL and close ties to ISIS. Access to the leading facilities keeps the Swedish user community competitive and allows it to exploit sources not directly funded by Sweden. To enable the best science a close exchange between the user community and the Council of Research Infrastructures is essential. (for more details: Action U1, U3)
2. **Access to neutrons for users' needs to be complemented by the development of neutron instrumentation and methodology.** This allows long-term strategic collaborations between large-scale facilities, Swedish academia and industry by running Swedish-owned neutron instrumentation as national infrastructure, such as Super-ADAM. This may be complemented by regular project-based grants on neutron methodology that allow a meaningful contribution to the instrumentation and operation of ESS. These should build on continued financial and political support for ongoing instrumentation projects at ESS with Swedish involvement and are important to ensure that ESS meets the needs of the Swedish community. The required mechanisms for this effort have to be provided by the Council of Research Infrastructures as well as the representatives of Sweden in ESS panels. (for more details: Actions M2, U2, C1)
3. **Ideally instrument projects may be combined in a newly established national competence centre/network in neutron science.** This is a long-term vision that would allow to strengthen and bundle method expertise and competences in neutron instrumentation, coordinate teaching and thematic activities. Such a centre would provide an arena for consistent interactions with ESS and ILL and offer opportunities to endured community developments attracting new users from academia and industry. It would be the scientific environment inspiring high-impact research in consortia addressing grand challenges. Such a centre should be established from

existing activities such as the national infrastructure Super-ADAM operated by Uppsala, and the LINXS Institute for advanced Neutron and X-ray Science located in Lund and integrate the whole user community. Building on existing activities would allow to establish such a centre exploiting existing resources. SNSS could take a coordinating role in this context, but funding and political support has to be provided by universities and funding agencies. Ideally, such a centre could operate a HiCANS to complement ESS and make the Swedish user community more independent and resilient. The neutron beam days provided by such a source could partially replace access programs to facilities outside Sweden. (for more details: Actions M1, M3, U5, E1, E2, C2, C3)

7 Appendix 1, Terms of references

Terms of Reference för ”Utredning av neutronspridningslandskapet utifrån den svenska forskningens behov”

Finansieringen av neutronspridningsanläggningar upptar en stor del av RFI:s budget. Syftet med utredningen är att kartlägga den svenska forskningens behov inom neutronspridningsområdet och utreda hur detta behov bäst kan tillgodoses i nuläget och strategiskt kan utvecklas för att kunna den framtida utvecklingen på bästa sätt.

Utredningen fortlöper under 2024; en första preliminär, muntlig avrapportering bör ske vid RFI:s möte den 18–20 november 2024. Skriftlig slutrapport bör presenteras på RFI:s möte i mars 2025. Skrivargruppen får kontinuerligt det stöd från VR som krävs för att fullfölja uppdraget.

Frågor som skall belysas:

- Vilka forskningsbehov finns i Sverige som behöver neutronspridning?
  - Vilka av dessa behov täcks upp av instrumenten vid de anläggningar som RFI idag finansierar? Är genomslaget av den svenska forskning som kommer ut från respektive anläggning i paritet med investeringarna (inkl. summa) som görs?
  - Vilka, om några, teknik-/instrumenteringsområden är viktiga för Sverige och hur kan tillräcklig tillgång garanteras?
  - Hur stort är användandet av andra källor än de RFI finansierar och hur viktigt är detta användande för den svenska forskningen? Satsar RFI på de källor i sin finansiering som det finns störst behov av från det svenska forskarsamhället?
  - Görs det idag relevanta satsningar för att öka kunskapen i Sverige om metoderna som används vid neutronspridningsfaciliteter så att nya användargrupperingar kan komma in? Vad behöver göras för att ytterligare öka medvetenheten för dessa resurser?
- Vilka områden inom neutronspridningsfältet är under stark förändring?
  - Hur förändras frontlinjen för tekniker/instrumentering och vilka konsekvenser får detta?
  - Hur förändras det svenska användarlandskapet, t.ex. som en följd av demografiska förändringar (pensioneringar, omförflyttningar etc.), andra strukturella förändringar och uppbyggnaden av ESS? Är nya områden på frammarsch medan andra är på tillbakagång?
  - Hur bör RFI/VR agera för att satsningen på ESS skall ge maximal avkastning för forskning som bedrivs i Sverige?
  - Vad görs idag utomlands som i framtiden bör göras på ESS (inom den idag planerade instrumentuppställningen)?

  - Kräver ett svenskt tillgodogörande av ESS en specifik inriktning vad gäller framtida instrumentering vid anläggningen?
  - Vad kommer att kunna göras vid ESS som vore unikt men som idag inte satsas tillräckligt på? Om dessa områden satsas på, kan då svenska användare tillgodogöra sig dessa på ett tillfredställande sätt?
- Hur skall svenska användarsamhället inom neutronspridningsområdet bäst koordineras/stimuleras så att Sveriges satsningar ger maximal forskningsavkastning?
  - Är det praktiskt möjligt, och i så fall önskvärt, att på ett mer aktivt sätt samordna de svenska neutronspridningsanvändarna med SR/FEL-användarna?
  - Hur kan Sverige på bäst sätt dra nytta av ESS för att långsiktigt bygga upp kompetens inom neutronspridningsområdet?
  - Hur kan kunskapsöverföringen till svenska användare från den utländska expertisen aktiv vid ESS stimuleras?

Vid beaktande av ovanstående frågor bör hänsyn tas ur flera perspektiv:

- Ett stort svenskt framtida användande av ESS är önskvärt.
- Hur kan Sveriges och RFI:s finansieringsstrategi inom neutronspridningsområdet påverka den akademiska forskningen?
- Hur kan finansiering inom neutronspridningsområdet påverka den industriella användningen av dessa källor, främst av ESS?
- Hur bör RFI/Vetenskapsrådet och ESS förhålla sig till internationella neutronkällor?