LENS Report

Low Energy Accelerator-driven Neutron Sources

LENS Ad-hoc Working Group CANS
Nov. 2020

LEAGUE OF ADVANCED EUROPEAN NEUTRON SOURCES

Table of Content

1 Foreword 6
2 Executive summary 8
3 Neutrons for science and industry 12
4 Neutron production and landscape of neutron Infrastructures in Europe 16
4.1 Neutron production 16
4.2 Situation in Europe 16
4.3 Situation outside Europe 18
5 Capabilities of CANS 22
5.1 What is a CANS ? 22
5.2 What are the different types of facilities that can be considered? 22
5.3 What performances can be achieved on a CANS for neutron scattering 23
6 Advantages / limitations of CANS 26
7 Operation and Costs 30
7.1 Investment costs 30
7.1.1 Proton accelerator 30
7.1.2 Target – Moderator – Reflector (TMR) monolith 30
7.1.3 Instruments 31
7.1.4 Building 31
7.2 Operation costs 32
7.3 Economic returns 33
8 Communities and business case 36
8.1 Scientific research 36
8.1.1 Scientific fields with direct use of CANS 36
8.1.2 Typical measuring times 38
8.1.3 Instrumentation 39
8.2 Industry 39
8.2.1 Quality assurance screening 39
8.2.2 Ad-hoc problems, e.g., related to quality issue 39
8.2.3 Joint research and development 40
8.3 Other applications 40
8.3.1 Fast neutron irradiation 40
9 CANS within a future landscape of neutron infrastructures in Europe 44
10 Conclusions and Recommendations 50

LENS LEAGUE OF ADVANCED EUROPEAN NEUTRON SOURCES

Annexes

11 Technical requirements for CANS 52
11.1 Accelerator system 52
11.1.1 Ion source 52
11.1.2 Radio-Frequency Quadrupole (RFQ) 53
11.1.3 Accelerator 53
11.2 Target 53
11.3 Moderator 55
11.4 Reflector 57
11.5 Neutron yield 58
11.6 Instrumentation 60
11.6.1 Neutron scattering instruments 60
11.6.2 Neutron radio-tomography 61
11.6.3 Analytical tools 61
11.6.4 Instrument performances 62
11.7 Operational considerations 63
11.7.1 Radiological safety 63
11.7.2 Waste Management 64
11.7.3 Decommissioning 64
12 State of the art across the world 66
12.1 CANS across the world 66
12.2 Examples of analytical studies using CANS 68
12.2.1 Small Angle Neutron Scattering on CANS 68
12.2.2 Powder Diffraction on CANS 69
12.2.3 Neutron Texture on CANS 69
12.2.4 Neutron radiography on CANS 70
12.2.5 Other analytical methods 71
12.3 Current CANS projects in Europe 72
13 References on CANS 76
List of participants in the editorial group of the Report 77

1

Foreword

1 Foreword

As Chairs of the League of European Neutron Sources (LENS) we would like to thank the working group for producing this report on the potential of low-energy accelerator driven neutron sources.

The European landscape of research infrastructures for neutron scattering has changed considerably in recent years. Much of the capability was originally developed through ‘parasitic’ use of materials testing reactors for the development of nuclear power through the 1950’s and 60’s. This led on to the construction from the 1970’s of reactors dedicated for neutron scattering research, such as the Institut Laue Langevin (France). Together with the construction of the major accelerator based sources ISIS (UK, 1980’s) and SINQ (Switzerland, 1990’s), and the research reactor FRM-II (Germany, 2000’s), this created a powerful ecosystem of small, medium and large, national and international facilities that supported a world leading community of European researchers. However, many of the national reactor based sources have come to the natural end of their operation at around the same time leading to a significant reduction in support capacity. The European Spallation Source, currently under construction in Sweden, will offer enhanced capabilities but these will be exploited effectively only if the supporting ecosystem has sufficient strength and depth.

Much of the development of neutron scattering capabilities has been through the development of instrument technologies, such as neutron optics and detectors, rather than through the enhancement of the neutron sources themselves. Low-energy accelerator driven neutron sources have existed for decades, but have had relatively limited performance and small numbers of users. However, as the report shows the combination of technology developments, including accelerators, targets and moderators, now offers the possibility to construct and operate such neutron scattering facilities with much enhanced performance and considerable flexibility in terms of cost, capacity and capability. These could play a critical role in re-creating the European neutron scattering ecosystem that has been so successful.

This report provides a detailed overview of low-energy accelerator based neutron sources. There is clearly great potential, but the technical feasibility and predicted performance now need to be demonstrated through the construction of prototype facilities. Based on the results, and given the flexibility of these sources, individual countries or partnerships could then consider the business case for the construction and operation of such national sources depending on their particular academic or industrial research requirements. LENS eagerly anticipates and will support such developments.

Helmut Schober
LENS Chair

Robert L. McGreevy
LENS Vice Chair

2

Executive summary

2 Executive summary

Progress in high current, high intensity accelerator development, cold neutron moderation and long pulse neutron scattering instrumentation have opened the perspective to construct neutron sources using low energy accelerators with performances on par with medium power nuclear reactors or medium power spallation sources. Such sources are usually referred to as Compact Accelerator-driven Neutron Sources (CANS) or Low Energy accelerator-driven Neutron Sources (LENS).

Low power CANS (~1 kW) have been in operation since the late 70s. The LENS facility at Indiana University, Bloomington, USA, is a nominal 4 kW CANS. Currently there is no high power CANS (>10 kW) in operation. Nevertheless, numerical simulations on target and moderator performances together with experimental validation at low beam power are encouraging for such sources.

This new technological approach has the potential to contribute to a more widespread use of neutron scattering and analytical techniques. Such sources can be tailored and scaled to specific needs and can thus allow scientific communities either at a university level, at a regional level or at a national level to engage locally in neutron techniques and develop local scientific programs and the associated skills. Depending on the requirements (power, number of instruments), the cost can be scaled from about 10 to 400 M€ for CANS or LENS like facilities.

The success of the European neutron scattering communities during the previous decades has been built on a rich ecosystem of small, medium and high neutron flux sources. This eco-system allows users to access facilities fitting their needs (from the first contact with neutron scattering techniques, to routine experiments, and eventually higher-end experiments)[1]. This hierarchy of neutron sources is vanishing as it is currently expected that only a handful of higher end facilities may remain in operation in Europe in the next decade (2030+). CANS and LENS are a potential answer to maintain a rich ecosystem in Europe after the closure of the aging nuclear research reactors.

Although CANS or LENS are unlikely to beat higher end facilities in raw neutron flux at the sample position, they can ideally complement flagship facilities, such as the future ESS, due to their scalability. They offer unique and specific advantages, especially with respect to other “soft capabilities” to make such sources efficient in terms of scientific and economic capabilities:

- Establish a strong local expertise in some specific field to reach a critical mass possibly with the local academic community. Develop advanced sample environments dedicated to focused topics.
- Favor strong collaborations between instruments scientists and local users. This shall be the easier when the source is installed in a large university campus and is able to establish strong links with the local research communities.
- Access agility. This is in particular important for material science screening experiments or for industrialists.
- Open possibilities to develop innovative instrumentation.
- Training capabilities, possibly using dedicated instruments to minimize overlap with the scientific capabilities but making it possible to accommodate a continuous flow of master students for hands-on experiments.

Furthermore, when pushed to the current technological limits, CANS and LENS type of sources have the potential to provide the basis for the next generation of new national neutron facilities. They will

[1] In comparison for X-rays this has been the case for decades.

offer capabilities at neutron beam instruments prospectively even surpassing present-day performance of instruments at the existing national facilities. LENS and CANS type of sources will require no nuclear licensing and the related security measures, which allows much easy access. The facilities will produce less radioactive waste, being more economic both in initial investment and decommissioning as in operation, and offering enhanced flexibility for upgrades due to relatively low cost of adding more target stations.

3

Neutrons for science and industry

3 Neutrons for science and industry

The neutron is a subatomic particle with unique abilities which allows scientists to probe and understand matter at the atomic and molecular level, in a non-destructive way. This makes the interaction and the scattering of neutrons with matter a highly useful analytical technique used across numerous science and technology disciplines. During the second half of the 20th century, the use of neutrons to probe and explore matter was developed continuously and neutrons became one of the important analytical tools in the scientist's toolbox.

More than 4,000 scientific publications using neutron scattering techniques are produced every year. Thanks to a versatile and broad network of neutron sources, Europe has led the field for 40 years in scientific studies using neutrons and contributes to about half the neutron scientific works worldwide.

Due to the characteristics of neutrons – suited to investigate magnetic properties, light elements or big samples – they contribute to areas ranging from fundamental research in elementary particle and nuclear physics to condensed matter physics and chemistry, soft matter science, life science, geo-science and engineering material scienc to health, environment, food and cultural heritage. Neutrons participated in the development of modern theories of condensed matter and fundamental physics, for example by highlighting the concept of topology or broken symmetry as a motor for phase transitions or by revealing new states of matter. They contribute to the characterization of almost any new material issued from modern research.

The unique properties of neutrons to probe and interact with matter coincide with nearly all scientific and societal issues including energy, transportation, information technology, environment and health. The knowledge gained by neutrons provide the basis for innovation, new and better products and, in result, societal well-being. Figure 1 illustrates the demands for neutron beam time according to different societal challenges.

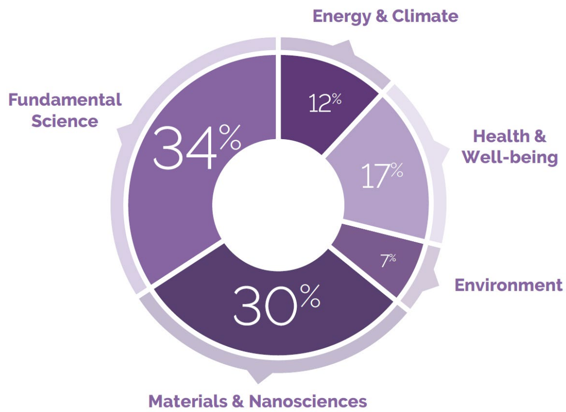


Figure 1: Share of the beam-time use between the main societal challenges. Average over the ILL, the LLB and ISIS (adapted from [2]).

While fundamental research is being performed at neutron facilities with roughly one third the major fraction of the research is devoted to directly and indirectly tackle societal challenges. Hence, the knowledge gained by neutrons support direct and indirect innovation, new and better materials for

---

[2] ILL Associates, Strategy for Neutrons, 2013 http://www.ill.eu/fileadmin/users_files/documents/news_and_events/news/2013/20130704-Report-ILL-Associates-including-scientific-case.pdf

products and environment, new drugs and materials in health care and leads to a continuous better societal well-being.

Materials and Nanosciences. Science and industry rely strongly on neutrons in the characterization of novel materials. Thanks to diffraction and small angle scattering techniques, neutrons are well suited to examine new metallurgical alloys (ODS type alloys with oxide or nitride inclusions, new titanium alloys, shape memory alloys…). They are also extensively used to check the integrity of materials constituting structures such as landing gear, aircraft side members, train wheels, nuclear tanks, cladding of nuclear fuel in zircalloy and many more.

Due to the high penetration depth of neutrons, their use is attractive in a large range of applications in industry, from revealing points of weakness in materials, controlling production processes, visualizing hidden components or developing new technologies. It is also possible to study new manufacturing methods such as stir welding, shot peening, rolling, hot compaction or 3D printing. The identification and engineering of the best materials and components for new innovative devices and systems can be enhanced tremendously.

Neutrons also make it possible to study materials under extreme conditions of pressure or temperature as well as defects or disorder in glasses or liquids. Neutron diffraction allow following chemical reactions and catalysis in-situ or even operando.

Tracking material changes under simulated production conditions (in situ) or at extreme pressures and temperatures are performed with neutrons. Structural changes in situ as a function of stress and/or changing environmental conditions or failure mechanisms in composite materials and stress-transfer in fiber-reinforced composites during in situ deformation are investigated.

Health and Well-being. In life sciences, neutron scattering techniques are applied in fundamental studies of the adsorption of water molecules around proteins, conformation and flexibility of proteins or adsorption of membrane proteins and virus interaction. Location of active hydrogen in enzymatic reactions are resolved by neutron protein crystallography. The interaction of peptides and drug molecules with biomembranes is probed using neutron reflectometry. Deuterated molecules highlight macromolecular interactions or interaction of drugs and peptides with bio-membranes. Small angle neutron scattering is applied to study nanoparticles as drug delivery systems.

Neutron scattering helps to solve problems in food industry for example to study freeze-drying processes, cooking of meat, cooking of bread, preservation of dehydrated powders (eg milk powders), stability of foams and emulsions in food processing.

Environment. Neutron scattering is helping scientists to fight pollution and develop environmentally friendly processes that generate and release fewer contaminants into the environment. Prompt and delayed gamma neutron activation analysis can provide information about rare elements and serve as a way to detect contaminants, eg in soil. Neutron diffraction can help identifying the structure of particles and modifications due to interactions with contaminants.

Neutron diffraction and neutron activation analysis are important methods for the study of geological materials due to the possibility of localizing hydrogen, an important and common element in minerals. Diffraction experiments yield large and more exact information when analyzing complex low-symmetric crystal structures of many minerals. Prompt gamma neutron activation analysis (PGNAA) provides information on the composition of the sample including light elements.

Energy and Climate. Extensive work with neutrons is done in the study of batteries and fuel cells for the characterization of new electrode materials and new electrolytes by diffraction. New ion exchange membranes are characterized by small angle neutron scattering (SANS). Formation of water in operating fuel cells is followed in situ by neutron radiography.

Thermoelectric materials are studied via the characterization of the phononic spectrum or magneto-caloric materials by the characterization of magnetic properties.

Many questions arising in polymer physics dealing with adhesion, friction or mechanical reinforcement of polymers and nano-composites are tackled by neutron scattering techniques. Problems in the petroleum industry can be optimized such as the origin of clogging of pipelines by asphaltenes (problems of stability of emulsions), optimization of the recovery of hydrocarbons in shale rocks (problems of diffusion in porous media) or to understand lubrication at oil-metal interfaces.

Cultural Heritage. Being a non-destructive probe, neutrons can penetrate deeply into cultural artefacts or beneath the surface of paintings to reveal structures at the microscopic scale, chemical composition, or provide 3D images of the inner parts of the artefacts. For heritage science purposes, whole artefacts can be placed in the neutron beam and analyzed at ambient conditions without tedious sample preparation. Measurements at neutron imaging stations are made in real time, which can be useful for testing conservation materials and methods.

Information, Communication and the second Quantum Revolution. Strong activities using neutrons are centered on the characterization of “quantum materials” and “topological materials” that have potential uses for information processing and fo the second quantum revolution. Novel topological quantum states in magnetic and electronic materials are a new and exciting frontier of science. It is possible to probe magnetism at interfaces by neutron reflectivity, new magnetic structures (e.g. skyrmions) by diffraction or SANS or to study the effects of order or magnetic dynamics in different types of crystals (topological insulators, spin glasses …) by diffraction or neutron spectroscopy. Neutron imaging can visualize magnetic domains and nanostructures.

Fundamental Science. Neutrons answer fundamental questions about our existence through extreme precision measurements. They (i) strive to solve the riddle why we exist by searching for an electric dipole moment (EDM) in an attempt to explain the disequilibrium of matter to antimatter, (ii) provide stringent tests of the standard model of physics via high precision measurements of the neutron‘s lifetime or (iii) test Newton’s law on otherwise inaccessible length scales through the observation of quantum states in the earth’s gravitational field.

As the demand in non-destructive methods to probe, develop and manipulate materials and devices is constantly increasing, access to neutrons becomes increasingly important for industry. Upstream industrial research mainly carried out in collaboration with academic laboratories through research contracts is estimated to represent up to 25% of beam time at some neutron facilities. A small fraction of this access is performed via “proprietory access” though. Simplified and easy access for analytical services including chemical and structural analysis, visualization techniques, advanced modeling and reliable protocols, are attractive for further applications by industry with neutrons.

Hence, service to industry has become an evolving part of neutron facilities activities including dedicated industry services, special industry access programs (e.g. ISIS Collaborative R&D Program) and national, regional or European funding of activities to foster industrial use of neutron analysis techniques (e.g. SINE2020).

4

Neutron production and landscape of neutron Infrastructures in Europe

4 Neutron production and landscape of neutron Infrastructures in Europe

4.1 Neutron production

To produce neutrons, the most efficient processes are i) nuclear fission in nuclear reactors, ii) spallation using high-energy proton accelerators, and iii) nuclear reactions with low-energy proton accelerators.

The high flux research reactors such of the ILL (Grenoble, France) or of the MLZ (Garching, Germany) produce about 10^{18} neutrons/second. These facilities are using highly enriched uranium (>90% ^{235}U). They currently offer the highest neutron flux for science and technology studies. In addition to these high-end facilities, a number of medium flux reactors sources using highly or low enriched uranium are operating at different institutions in Europe: BNC (Budapest, Hungary), TUD (Delft, The Netherlands), NPI (Rez, Czech Republic), NCBJ (Swierk, Poland).

Spallation neutron sources such as ISIS (Didcot, England) or SINQ (Villigen, Switzerland) use proton beams in the $E_{proton} > 500$ MeV range to hit a heavy metal target (e.g. lead, tantalum), where about 20 neutrons are produced per incident proton. The high neutron yield combined with the relatively small heat release per produced neutron makes spallation an ideal choice for high intensity sources.

Bombarding materials such as lithium, beryllium or tantalum with low or medium energy protons or deuterons in the range of 2 to 70 MeV produces neutrons via nuclear reactions. Existing sources of this type reach a neutron yield in the range of $10^{12\text{-}13}$ neutrons/second (e.g. LENS, Indiana Univ. in the USA or RANS, Riken, Tokyo in Japan) while only using modest power (up to 1 kW).

4.2 Situation in Europe

In Europe there are currently 9 neutron facilities in operation (ILL, MLZ, ISIS, PSI, BNC, NPI, TUD, MARIA, ATI) among which 7 are research reactors. Within these facilities, about 160 instruments are operated to serve up to 3,200 experiments per year by about 4,700 unique users according to a recent survey of the BrightnESS project[3]. Thanks to the broad network of neutron sources, Europe has led the field of neutron scattering for 40 years. More than 2,000 publications are produced every year. However, except FRM II at MLZ in Garching, all research reactors in use started operation in the previous century and the question of their future operation is critical.

The world leading centre for the research with neutrons is the Institut Laue Langevin (ILL) in Grenoble with a research reactor of highest flux (1.5×10^{15} $n_{therm}/cm^2.s$) and the broadest instrumentation suite (about 40 instruments). Compared to ILL, the FRM II is nearly in the same league with a nominal flux of 8×10^{14} $n_{therm}/cm^2.s$ and a very modern instrumentation with 27 running instruments and six more under construction.

In addition to these two high flux reactors in Europe, the UK operates ISIS, a short-pulse neutron spallation source, with two target stations well equipped with highly efficient instruments. At PSI in Switzerland, the neutron spallation source SINQ is operating 22 instruments and is currently undergoing an ambitious upgrade program to improve its performances.

[3] https://europeanspallationsource.se/sites/default/files/files/document/2018-06/NEUTRON USERS IN EUROPE-Facility-Based Insights and Scientific Trends.pdf

The medium flux reactor-based neutron sources at Saclay (Orphée, France) and Berlin (BER II, Germany) offered a very productive suite of neutron instruments but both facilities were shut down in 2019. The facility in Kjeller (JEEP II, Norway) was also stopped in 2019. Several smaller neutron sources are located in Europe in Rez (NPI, Czech Republic), Budapest (BNC, Hungary), Delft (TUD, The Netherlands), and Swierk (MARIA, Poland). In Austria, the Atominstitut (ATI) operates a small TRIGA reactor.

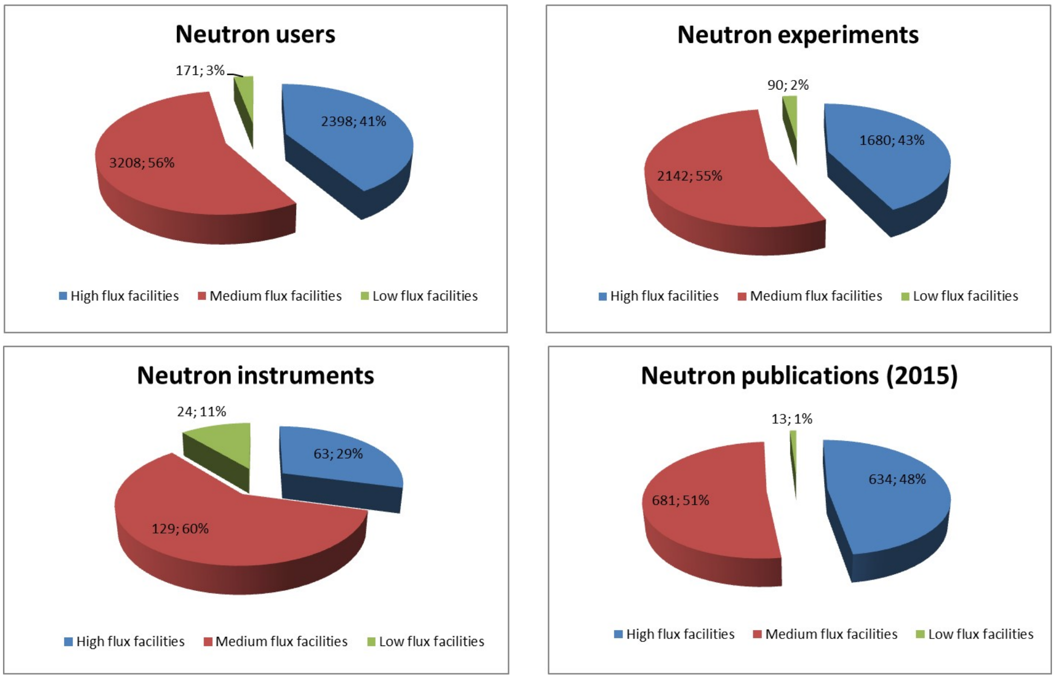


Figure 2: Distribution of neutron users, experiments, instruments and publication between the neutron facilities in Europe[3]. High flux facilities: ILL, MLZ; Medium flux facilities ISIS, LLB, SINQ, BER II, BNC, NPI, MARIA, TUD; Low flux facilities[4]: JGU, JEEP II, JSI, RPI, ATI.

Based on a survey performed in 2016[3] within the suite of European neutron sources, about 40% of the scientists use the high flux sources ILL and MLZ, more than 50% make use of the middle flux facilities (ISIS, LLB, SINQ, BER II, BNC, NPI, MARIA, TUD), a few percent work with the low flux sources (see Fig. 2). The number of experiments performed is distributed similarly between the facilities, despite the fact that only 29% of instruments are operated by the two high flux sources, 60% by the medium flux sources and the remaining 11% by the low flux sources. The number of publications is comparable between the high flux and medium flux facilities.

With the closure of the neutron facilities in France (LLB), Germany (BER II) and Norway (JEEP II), a reduction of available neutron instruments and experiments performed per year of 21% and 30%, respectively, has affected the European neutron landscape[1].

The ILL aims for another decade of operation with a prolongation of the current contract with its associates until 2032. MLZ is also negotiating a prolongation of its current funding for the scientific operation from 2021 to 2030. ISIS is currently about to refurbish its first target station to ensure operation well beyond 2030, and preparing plans for a future new facility beyond this.

The European Spallation Source (ESS) in Sweden plans to see the first protons on the target in 2023. ESS will be the worldwide most intense pulsed neutron source with a prospect to become the world's

[4] JGU: TRIGA reactor University Mainz, Germany; JEEP II: IFE Kjeller, Norway, JSI: TRIGA Reactor Ljubljana University, Slovenia; RPI: CTN Bobadela, Portugal; ATI: Atominstitut Vienna, Austria

foremost source for basic and application-oriented research. The goal is to propose 15 instruments to external users in 2026 and add 7 additional instruments in a further upgrade.

In the European part of Russia there is one facility in operation and one in construction: the JINR facility in Dubna near Moscow, a recently refurbished pulsed high flux neutron research reactor and the PIK reactor in Gatchina, near St. Petersburg, which is planned to become operational soon, offering a state-of-the-art neutron source which aims to reach neutron flux comparable to the ones at MLZ and at ILL.

4.3 Situation outside Europe

Outside of Europe, a few world-class user facilities are operated: the megawatt spallation sources SNS in the USA and J-PARC in Japan, the NIST reactor close to Washington (4 x 10^{14} $n_{therm}/cm^2.s$) and the HIFR reactor in Oak Ridge (2.5 x 10^{15} $n_{therm}/cm^2.s$). These facilities operate about 110 neutron instruments allowing for 1500 to 1700 experiments per year.

At SNS in Oak Ridge, USA, due to the high demand for beam time, the construction of a second target station is planned. The NIST neutron source is also planning major upgrades to improve the beam delivery systems and their suite of instruments and considers options for a new reactor.

In Canada, the Chalk River facility was closed in 2018, leaving Canada with only the university-based research reactor at the McMaster University in Hamilton. Recently, in Canada a project for a compact accelerator based neutron source is discussed. In Argentina, the new RA-10 reactor is under construction.

In the Pacific region, South Korea operates the HANARO reactor (3.2 x 10^{14} $n_{therm}/cm^2.s$) with a 18 neutron instruments suite. Japan is operating the JRR3M reactor in Tokai (2.7 x 10^{14} $n_{therm}/cm^2.s$). The operation of these reactors is at current however suspended since the Fukushima accident in 2011. South Korea is considering accelerator based provision[5]. Japan is establishing a dense network of small accelerator-based neutrons sources[6].

China is strongly investing in the research with neutrons and intends to start operation of its CARR reactor close to Beijing (8 x 10^{14} $n_{therm}/cm^2.s$), which can host 17 instruments. It has also started operation of the CSNS neutron spallation source in Dongguan which eventually aims at performances comparable to ISIS. Furthermore, it operates the China Mianyang Research Reactor (CMRR) with 11 neutron instruments located at the NP campus of the Institute of Nuclear Physics and Chemistry in Mianyang. China develops also a few accelerator-based neutrons sources[7].

In Australia ANSTO started the operation of the new OPAL reactor (2 x 10^{14} $n_{therm}/cm^2.s$) in 2007 with 15 instruments in operation.

Overall, the mentioned 11 neutron facilities outside of Europe host in total about 180 neutron instruments, similar to the number of instruments in operation in Europe in the last decade. Due to the non-operation or recent closure of several reactor-based neutron facilities (JRR3M, CARR, HANARO, Chalk River) only about 110 instruments offer access to users which provides an estimated capacity of about 1700 experiments per year outside of Europe providing an overall capacity comparable to the capacity offered to European users.

[5] KCANS, Korea Collaboration on Accelerator-driven Neutron Sources (KOMAC)
[6] JCANS, Japan Collaboration on Accelerator-driven Neutron Sources
[7] C-CANS, Chinese Collaboration on Compact Accelerator-driven Neutron Sources

Because of the mix of small, medium and large facilities and a large capacity offered, Europe has had the clear lead in neutron science till now but this is at risk of disappearing in the future by the ongoing reduction of European sources. To maintain that lead, actions have to be taken. CANS and LENS provide a strategy for this.

5

Capabilities of CANS

5 Capabilities of CANS

5.1 What is a CANS ?

Compact Accelerator-based Neutron Sources (CANS) or Low Energy accelerator-based Neutron Sources (LENS)[8] refer to sources where the proton (or deuteron or electron) energy is in the range 2–70 MeV and where the main neutron production nuclear process is not spallation but rather lower energy nuclear reactions.

The key components of a proton CANS are:

- A pulsed proton accelerator with a duty cycle in the range 1–4 % and peak currents as high as possible, in the mA range and eventually in the ~100 mA range for higher performance CANS.
- A target sustaining a beam power in the range 1–100 kW from which fast neutrons are released through nuclear reactions when bombarded by protons.
- A neutron moderator which is reducing the neutron energy to thermal energies and wavelengths suitable for studies in condensed and soft matter.
- A suite of neutron scattering, radio-tomography instruments, analytical tools (e.g. PGNAA[9]) or a BNCT facility.

This technology based on high current proton accelerators has the potential to provide a more widespread use of neutron scattering as such sources can be tailored and scaled to specific needs. Thus they can be made affordable to countries who would not consider investing in research reactors or spallation sources. Depending on the requirements (power, number of instruments), the cost for the investment into CANS can be scaled from lower ten millions to several hundred million Euros.

5.2 What are the different types of facilities that can be considered?

The power and the neutron flux of CANS can be adjusted and scaled depending on the applications aimed for. CANS facilities may be divided into three main categories: i) low flux, low power CANS (up to 1 kW), ii) medium flux, medium power CANS (1 to 10 kW), and iii) high flux, high power CANS (beyond 10 kW) (see figure below).

The low and medium power CANS are usually small, laboratory based accelerator installations with small linear proton accelerators, tandetrons or cyclotrons in the low energy range of below 10 MeV and small protons current below 1 mA. There are also a number of electron accelerator based CANS. These systems can be operated for low cost at universities (e.g. HUNS @ Hokaido University) or research institutes (e.g. RANS @ RIKEN). They are flexible and allow basic experiments with variable setups.

Beyond 1 kW, only the LENS facility at Indiana University is currently operated at a maximum power on the order of 4 kW using a 13 MeV, 25 mA proton accelerator and serving three experimental stations, a SANS, an irradiation and a radiography facility and a SESAME instrument. An upgrade of the CPHS facility at Tsinghua University should eventually reach a final beam power of 16 kW and the facility aims at operating a SANS and an imaging station as its first 2 instruments. Such kind of facilities are in the range of small low flux research reactors as the reactor at TU Delft or the TRIGA reactor at

[8] In the following only the abbreviation CANS will be used for low energy accelerator driven neutron sources.

[9] Prompt Gamma Neutron Activation Analysis

Atominstitut Vienna. The investment of such a medium power CANS can be up to a few 10 M€ depending on available infrastructure.

Higher power CANS with the possibility to achieve performances comparable to current medium flux reactor or spallation neutron sources have not been realized till now. For a basic facility with a power above 10 kW an accelerator system, target and moderator unit and the option for 5–10 neutron instruments the investment can be calculated in the order of 50–150 M€. The scalable implementation and nature of such CANS allows for continuous upgrade and adjustment to the demand and requirements of the user community by additional target stations to the existing accelerator system and corresponding instrument and experimental stations. Such a facility could be considered as a full fledge user facility within the landscape of neutron sources in Europe.

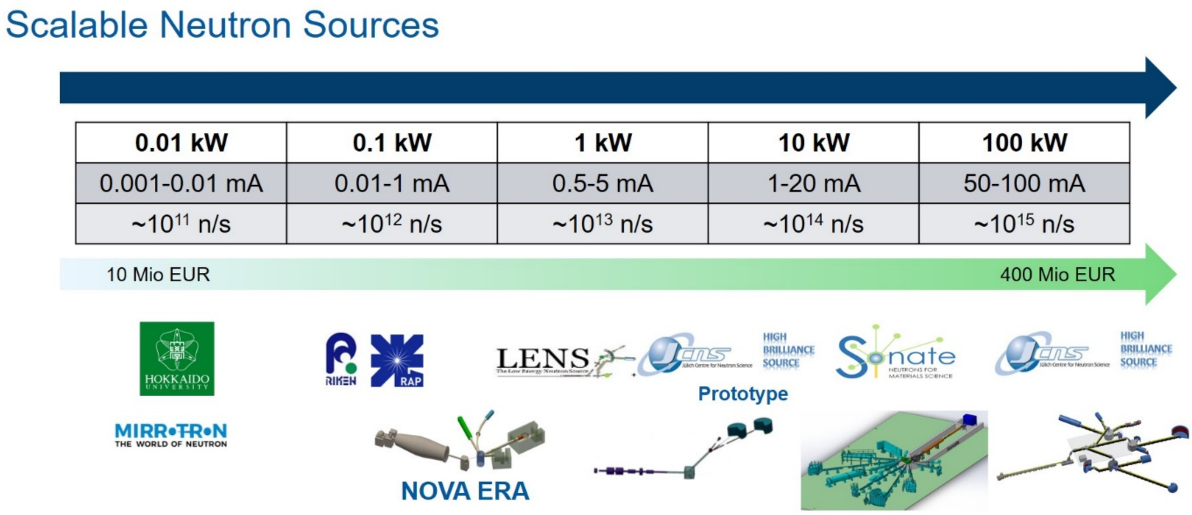


Figure 3: Comparison of proton beam power, proton current and neutron peak flux for CANS systems and existing or projected sources.

Based on this intrinsic scalability of CANS specialized small CANS are affordable as well as high power facility leading to a versatile network of such neutron sources. A concept which is difficult to achieve by comparable investment with reactor based or spallation neutron sources.

5.3 What performances can be achieved on a CANS for neutron scattering

Due to the high energy release per produced neutron, the primary neutron production of a CANS is technically limited. Hence, low energy accelerator driven neutron sources will not achieve neutron source strength on par with flagship facilities such as the future ESS. However, the important figure of merit of a source is given by the neutron flux at the sample position. CANS offer opportunities to maximize this flux due to various specific features.

One key feature of CANS is that the flexible design of the source allows adapting the time structure (pulse length and repetition rate) to specific applications. For neutron scattering, the operation in pulsed mode is strongly preferred so as to maximize the use of the produced neutrons by using time-of-flight measurement techniques. Combining several targets on the same accelerator allows filling the phase space of specific scattering techniques in an optimal way without having to adapt the instruments to the source but by adapting the source to the instruments.

On CANS due to the compactness of the target – moderator – reflector (TMR) assembly (due to the small size of the target), only a limited number of beamlines can be extracted from a TMR assembly. This can be turned into an advantage by providing each instrument with a dedicated optimized moderator. Advanced moderation concepts such as one-dimensional tube moderators can thus be implemented.

All these strategies are not specific to CANS, but they can be realized more easily on CANS for the following reasons (i) the relatively low cost of the target station which allows one to realize several target stations for different pulse structures; (ii) the compactness of the TMR assembly which allows one to place choppers and other optical elements very close to the source; and (iii) the relatively low radiation level that makes the installation of individual one dimensional cold tube moderators possible for every single beam port due to the low cooling power requirements. The outcome of these different incremental progress is that optimized instruments on high power CANS (~50–100 kW per target station) could achieve performances equivalent to current existing instruments (see Appendix Section 10.5). Thus, it should be possible to perform excellent scientific research with high value reward. Topics requiring more flux than routinely available, will still need to apply for beam time on flagship facilities such as ESS, ILL or ISIS.

There are however currently no high brilliance CANS in routine operation across the world. The operation of a relatively high-power target (50kW) even at a low proton energy has still to be demonstrated. First steps have been made with tests of a bonded Be-target at 21 kW[10], bulk metal target[11] and liquid metal targets[12].

A further step would be the construction a full fledge demonstrator (e.g. PRELUDE, HBS-P) featuring a high-power target, a high-performance moderator and a few full fledge neutron instruments to demonstrate all the concepts underlying the construction of high brilliance CANS. Full scale neutron scattering platforms or facilities, such as SONATE or HBS, could then be confidently built.

[10] T. Kurihara, H. Kobayashi, EPJ Web of Conf., 231, 03001 (2020). Diffusion bonded Be neutron target using 8 MeV proton beam
[11] IPHI – Neutron project
[12] M. Paul et al., EPJ Web of Conf., 231, 03004 (2020). A 50 kW Liquid-Lithium Target for BNCT and Material Science Applications

6

Advantages/limitations of CANS

6 Advantages / limitations of CANS

Compared to classical neutron sources, CANS offer the following advantages:

- They are relying on a low energy accelerator (E_p ~ 10–70 MeV) so that the investment costs and the operation costs are reduced compared to a spallation source (E_p ~ 1–2 GeV).
  - Possible scales of investment: NOVA-ERA ~10 M€[13] - HBS ~400 M€[14]
  - A single accelerator can serve a number of target stations.
- The production of secondary particles is limited. The gamma radiation as well as the fast neutron energies are limited at energies on the order of E_{proton} (~10–70 MeV) to be compared to spallation where particles with energies on the order of 1 GeV are produced.
  - The volume of shielding is thus reduced (about 20–100 tons compared to about 6000 tons at ESS).
  - The background noise on the instruments is reduced.
- The facility (if E_p<30 MeV) is not an Installation Nucléaire de Base (INB)[15] in the French legislation.
  - The administrative and security costs are reduced.
  - The access rules are simplified.
  - This specific point needs to be quantitatively assessed for the different European countries since the legislation varies from one EU country to the other.
- The low activation of the target material (e.g. Be, V, Ta) during operation simplifies waste management and decommissioning.
  - Administrative, operational and security costs are reduced.
  - Safety operation of the facility and maintenance is simplified.
- The low gamma radiation allows the construction of low cost cold sources.
  - The cooling power is reduced to ~10–20 W to be compared to ~3–7 kW on a reactor or a spallation source.
- The Target – Moderator – Shielding assembly is not an element as critical and complex as on a spallation source.
  - Its construction and maintenance costs are reduced.
  - This opens the possibility to build several target stations (2–3) with limited cost overheads but major benefits for instruments performances.
  - It may be modified and upgraded rather easily during the lifetime of the source. Some « small » CANS are for example used to test moderators for J-PARC or SNS.
- The performances of the instruments on a CANS can be tuned to the defined needs.
  - It is possible to build a small scale CANS for specific industrial uses or a full fledge facility with ~20 high performance neutron scattering instruments.
- Owing to the smaller scale of the accelerator, complex time structures may be implemented.
  - It is in principle possible to propose interlaced long pulses and short pulses at different frequencies on different targets.
  - While ISIS has demonstrated that a single accelerator could provide protons beam to several targets (50 Hz on TS1 and 10 Hz on TS2) it was not possible to change the pulse length on TS2 which would have been advantageous.
- A CANS may be upgraded during its lifetime

[13] Conceptual Design Report NOVA ERA, General / Volume 7 ISBN 978-3-95806-280-1
[14] Conceptual Design Report Jülich High Brilliance Neutron Source (HBS), General / Volume 8 ISBN 978-3-95806-501-7.
[15] The quantity and variety of the produced radionuclides increases with the proton energy due to the opening of new activation channels. The experience on other facilities shows that proton energies lower than 30 MeV allow reducing activation issues.

- The proton beam energy can be increased to higher energies to increase the neutron yield on the target if some provision in space and power was made in the initial design (as will be the case at ESS where the proton energy should eventually double to E_p = 2 GeV).
- New target stations may be built without changing much of the accelerator system as was done at ISIS (without performance penalty if the accelerator duty cycle can be increased).

- Owing to the lower costs, facilities can be specialized for special purposes to respond to specific needs or requests.
  - The company Phoenix[16] has for example opened in 2019 a neutron imaging facility offering 10 imaging beam ports with thermal and fast neutrons to industrial users.

There are however also limitations for CANS:

- There is currently no example of high peak current accelerators (I_{peak} ~100 mA) and high duty cycle in routine operation in Europe or elsewhere in the world. However, several light ion accelerators with intensities ranging from 5 mA to more than 100 mA are currently being built or under commissioning: e.g. IFMIF/Lipac in Japan, Spiral2 at Caen, SARAF 2 in Israel, ESS in Sweden. Their operation will allow demonstrating the mature possibility to build and operate such accelerators routinely.
- Progress in peak current in proton accelerators are very slow. While there are developments to push the peak current at 125 mA (at IFMIF/EVEDA for example), the possibility to operate an accelerator at currents of 200 mA is still very remote.
- There are currently no « high brilliance CANS » in the world.
  - The new neutron moderation concepts have not yet been implemented.
  - There is no demonstration of a target sustaining routinely a power above 10 kW.
  - The operation of scattering instruments at long pulse sources still needs to be demonstrated (the return of experience from ESS is eagerly awaited).
- The number of beamlines which can be accommodated on a single Target – Moderator assembly is limited (probably to about 5–8), while the number of instruments which can be fed by a TMR depends on an intelligent neutron guide system layout.
- As the number of instruments is increasing, the cost of the accelerator becomes marginal with respect to the instrument construction and operation so that the economics becomes less advantageous relative to comparable higher power sources (spallation, reactor).

Recent progress using ultra-intense lasers have demonstrated the capability for short bursts of neutrons suited to fast time high energy neutron tomography and neutron resonance spectroscopy. In the long-term future, when high power lasers become more reliable and efficient, also for higher repetition rates, one might be able to realize compact and less expensive short pulse laser driven neutron sources as user facilities[17].

[16] https://phoenixwi.com/neutron-radiography/neutron-imaging-services/
[17] see e.g. M. Roth et al; PRL 110 (2013), 044802; S.R. Mirfayzi et al., APL 111 (2017) 044101

7

Operation and Costs

7 Operation and Costs

7.1 Investment costs

The key investment costs mainly comprise of the

- Proton accelerator
- Target – Moderator – Reflector (TMR) monolith
- Set of neutron instruments
- Building and Infrastructure

7.1.1 Proton accelerator

One of the key element of an accelerator-based neutron source is the proton accelerator. There are a few commercially available proton accelerator technologies which can provide continuous proton beams: either cyclotrons[18] or electro-static tandem accelerators[19]. These accelerators have the drawback that they operate in continuous mode and with rather low peak current and are thus not ideally suited for neutron scattering instruments.

On the basis of the ESS accelerator, it is possible to extrapolate the costs of a high peak current, pulsed proton beam accelerator with a beam energy of 25 MeV. The cost scales more or less linearly with the proton energy. However, the cost does not scale linearly with the accelerator current. A high power accelerator / high peak current is technically more challenging to build than a low current accelerator. As a rule of thumb, the cost of a proton Linac is on the order of 1–1.5 M€ per MeV.

7.1.2 Target – Moderator – Reflector (TMR) monolith

The core of the neutron experimental facility is the target / moderator / reflector unit as it is shown below. It consists of the target which is surrounded by a thermal moderator (ex. polyethylene, PE) moderating the fast neutrons with MeV energy to thermal energies between 10 meV and 500 meV. A reflector of lead, graphite or beryllium increases the thermal neutron flux inside the moderator due to backscattering. This assembly is surrounded by a biological shielding consisting of usually borated PE and lead. The whole target / moderator / shielding assembly is optimized to the needs of the experiments to be performed at a CANS and the instruments to be operated.

The neutrons are produced by a nuclear reaction in a suitable target material. Here the neutron yield depends on the cross section, the stopping power of the target material, the primary particle energy and particle type. Various target materials are considered or used, in most cases lithium and beryllium but also lead, tungsten or tantalum are discussed. Depending on the used material and the power of the proton beam, cooling is required which will have to neutralize an average power of up to 100 kW on the target as in the HBS concept.

Depending on the total power of the target and the required shielding, the costing of a Target / Moderator / Reflector unit can vary between a few 100 k€ up to 2–3 M€.

[18] IBA Radiopharma Solutions
[19] High Voltage Engineering Europa B.V., D-PACE

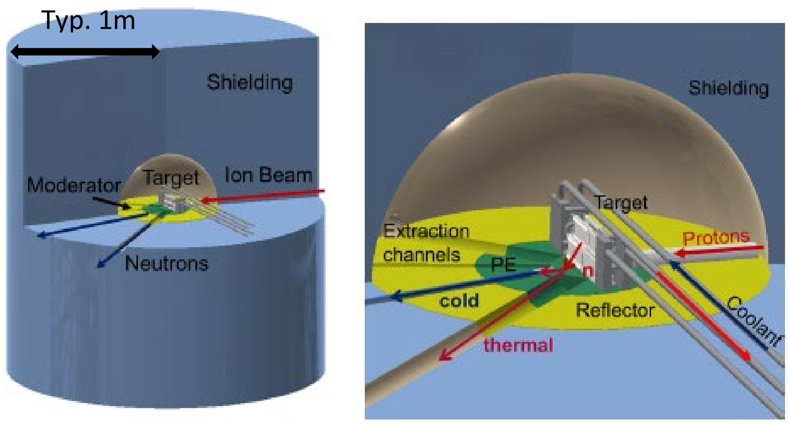


Figure 4: Sketch of target / moderator / reflector unit for CANS

7.1.3 Instruments

Instruments on CANS will mostly follow designs similar to instrument designs at ISIS or at ESS. In terms of costs, one advantage is that the required shielding will be reduced even though these aspects needs thorough calculations.

A more clear-cut advantage of CANS is that the source will be tuned to the instruments needs. Hence the need of T_0 and pulse shaping choppers will be reduced. Besides, the length of the instruments can also be reduced if the source is adapted to the instrument resolution. This will lead to savings in optics and shielding costs.

Unfortunately, the efficiency of a number of instruments will still scale with the surface of the detectors (except for SANS, reflectivity, radiography). Little progress has been made in reducing the cost of neutron detectors during the last 20 years. However, once the Boron detector technology developed for ESS will have been industrialized, the costs of neutron detectors may eventually be reduced, but probably not by a large amount due to the intrinsic complexity of these detectors.

As a rule of thumb, the cost of a neutron scattering instrument on a CANS should be lower than on other pulsed neutron sources but only by a factor 30–50% at best. Additional savings could be made by focussing the purpose of the instruments on CANS with the possible benefit of improved performances (though with a more narrow range of capabilities, lesser resolution, no polarization…).

The cost of an instrument may range from 0.5 M€ to 7 M€[20] depending on its complexity.

7.1.4 Building

The building requirements can be divided on 4 main parts

- Proton accelerator
- Radiofrequency platform
- Target – Moderator – Shielding assembly
- Instrument hall
- Space for pumps, electronic bays, control rooms, cooling tower…

The required surfaces depend hugely on the machine being built.

[20] Conceptual Design Report Jülich High Brilliance Neutron Source (HBS), General / Volume 8 ISBN 978-3-95806-501-7.

The proton accelerator requires roughly (as a rule of thumb) 1–2 meter length per MeV. It also needs a cave for shielding purposes. A 20 MeV accelerator is thus typically occupying a surface on the order of 2–300 m².

The Target – Moderator – Shielding assembly may occupy a typical space ranging from a few to about 100 m², depending on the quantity of neutrons produced in the target.

It is very difficult to estimate the space used by instruments since it may vary by an order of magnitude (see the example of the ESS instruments). A radiography station or a reflectometer are rather short instruments which may only need 30–50 m² while very long instruments such as high resolution powder diffractometers may require 300–400 m².

Typically, the footprint for a group of 5 instruments around a single target will be in the range of ~600–1200 m² [21]. Additional space for laboratories, workshops and work space have to be added.

Special requirements have to be taken into account regarding radiation shielding and safety at the buildings in particular for the housing of the accelerator system and the TMS. For handling of activated components during operation, special rooms and equipment will have to be foreseen. To handle shielding components or other parts of higher weight appropriate cranes and storage areas will have to be taken into account.

7.2 Operation costs

The estimation of operation costs is very difficult since the perimeter of the cost may be fuzzy and it may vary from one country to the other.

As a tool to estimate the operation costs, we will base our calculation from the figures of the operation costs of existing sources[22]. From these figures, it can be estimated that the operation costs of a facility are on the order of 4% of the initial investment for the source operation and an additional 0.2% for each instrument. For example, for a neutron facility operating 20 instruments, this leads to typical operation costs on the order of 8%, half of the cost being dedicated to the source operation and half of the cost used to run instruments. It can be considered that on medium flux source providing services to users, the support consists of 2 instruments scientists, 1 technician and 2–3 person-year from the general support (radio-safety, administration, electronics, computing, sample environment …).

As the amortization costs are not considered in the cost of operating neutron facilities, we focus only on operation costs irrespective of the initial investment so that the figures may be compared to existing figures[23]. The yearly operating costs can be modelled as $C_{year} = I_0 * (0.04 + N_i * 0.002)$ where I_0 is the initial investment and N_i is the number of instruments around the facility.

Figure 5 below provides the cost of a neutron instrument day as a function of the initial investment and as the number of instruments around the source (assuming an operation of 180 days per year). The cost of operating an instrument on a source decreases as the number of instruments around the source is increased. When building a new source, a careful balance should be made between the source cost and the number of instruments the institute will be able to operate.

[21] The MLZ guide hall is hosting 16 instruments in a space of about 1200m² but this is a very crammed configuration.
[22] Report from the ILL Associates' Working group on *Neutrons in Europe for 2025*.
[23] The initial investment usually represents roughly 1/3 of the total costs over the lifetime of most facilities.

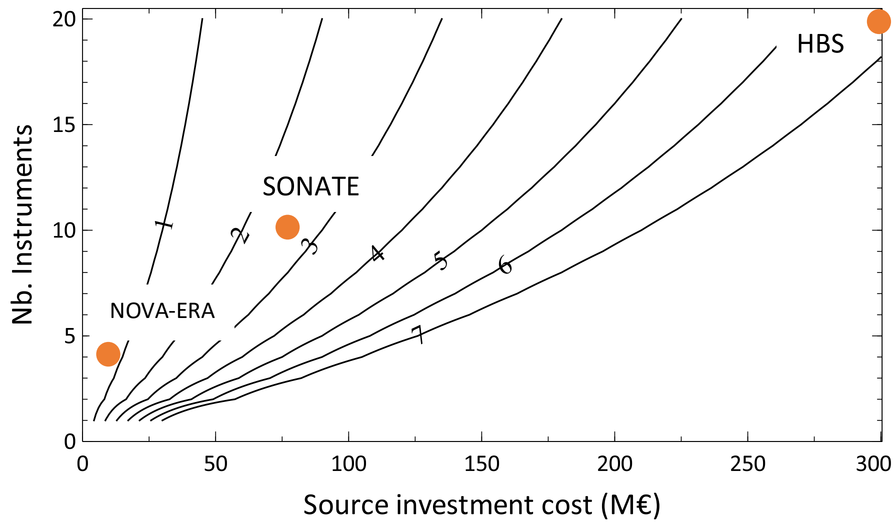


Figure 5: Dependency of the cost of an instrument-day in k€ as a function of the initial investment and the number of instruments attached to the source. The initial investment scales with the proton beam power of the source (see Fig. 3).

7.3 Economic returns

Apart from the initial investment costs and ongoing operational costs, a research infrastructure exhibit a direct impact on the economic strength of the local host region via highly qualified jobs, users visiting and staying for experiments, training sessions and education and regular orders to local companies and infrastructures. With operation times of several decades, a research infrastructure generates substantial long-term economic impact over its lifetime.

8

Communities and business case

8 Communities and business case

8.1 Scientific research

8.1.1 Scientific fields with direct use of CANS

The performance of CANS depends extremely on their realization. Low- to medium-power CANS can provide useful to remarkable performances for neutron scattering while high end CANS facilities are highly competitive, only surpassed by flag-ship facilities such as the future ESS. High power CANS offer the opportunity to realize the next generation of national neutron facilities.

Smaller CANS will focus on rewarding experiments, such as urgently needed e.g. for material characterization. Quite often these are both rather simple to perform but provide a good scientific value. Typical examples of such experiments are SANS measurements and powder diffraction measurements for which there are often no problem of sample size or availability (contrary to single crystals or thin films for example).

Table 1 below lists scientific topics that can be dealt with rather plain instruments. Instruments such as SANS or powder diffractometers will remain important in the foreseeable future and while the scientific topics will shift over the decades, these instruments will still be needed in materials science. Figure 8 shows the interconnection of keywords placed in neutron scattering related publications highlighting the strong interdependency in the scientific areas and topics[23].

Following the overall requirements by the scientific community, smaller to medium sized CANS should offer:

- Workhorse instruments with performances on par with current operational instruments.
    - Instrument which are easy to use both in operation and data processing: SANS, powder diffraction, reflectivity, radio-tomography. These techniques will remain essential as long as material development is needed for the solution of grand societal challenges, so at least for the coming decades. A lot of excellent scientific output can be expected there.
- A significant fraction of the time should be open « on-the-fly » so that neutron characterizations can be performed in parallel with other characterizations techniques. This is essential e.g. for feed-back loops to optimize synthesis or device production.
    - The operation assumes a « right to failure » (measurements providing data from which expected physical properties cannot be extracted).
    - « Screening » measurements would be welcome.
- Long term projects with guaranteed beam time should be made possible. In many cases, PhD projects cannot rely on access to flagship facilities like ESS, when only a very limited amount of beam time per year will be granted. Continuous reliable access to neutron beam time is essential for universities to continue to invest in PhD projects based on neutron scattering techniques. Without such a possibility, the strong European neutron scattering community will cease to exist due to lack of young academics.
- The possibility to develop a specific instrumentation by an external laboratory.
    - Possible access to a dedicated beam tube for a scientific topic with a lifetime on the order of a decade (Batteries – hydrogen – clathrates – metallurgy – catalysts).

Table 1 : Scientific topics which could be studied on CANS.

Scientific field	Instruments
Soft matter	
nanocomposites, mesoporous, nanoparticles colloidal suspensions, clays, self-organized systems of surfactants, polymer melts, stimulables systems, complexes in solution, coacervates, hydrogels, emulsions, foams, nanostructured materials based on cellulose nanocrystals, copolymers vesicles, biopolymers, ionic poly-liquids, conducting polymers for batteries, nanometric pores membranes, inclusions in recrystallized glasses, polymers, colloids, nano-composites, nanoparticles, structures-properties relations, mixed and associative systems, self-organization	SANS Reflectometry Spectroscopy
Multi-scale confinement	
geometric confinement, simple liquids, polymers and biomimetic systems, ionic transport properties, diffusion in porous media (rocks, mesoporous), metal-organic frameworks (MOFs)	SANS Radio / Tomography
Interfaces	
stimulable polymer thin films, adhesion at the molecular scale, Langmuir monolayers	Reflectometry
Bio-Physics	
cellular et macromolecular crowding, membrane interactions and nanopores, stability and folding of proteins, aggregation and diffusion, thermodynamic and transport properties, amyloids assembly, nucléo-proteic complexes	SANS Spin-Echo spectroscopy Reflectometry
Metallurgy	
nuclear alloys (local order and segregation mechanisms), hydruration processes, mechanical properties	SANS Spin-Echo spectroscopy Reflectometry Engineering Diffraction
Multi-scale magnetism	
structure of novel magnetic materials, shape memory alloys, hybrid materials, thin films, nanoparticles, self-organization, molecular magnets, photo-magnetism	SANS Diffraction
Functional materials	
materials for energy (photovoltaics, thermos-electrics, batteries, hydrogen storage), materials for information storage and processing	SANS Powder Diffraction Radio / Tomography
Quantum magnetism	
reduced dimension magnetic systems, non-conventional magnetic systems, geometric et magnetic frustrations, topological defects (vortices, skyrmions magnetic monopoles, magnetic fluids (spin liquids/ices/glasses)	SANS Powder Diffraction Radio / Tomography ToF Spectroscopy

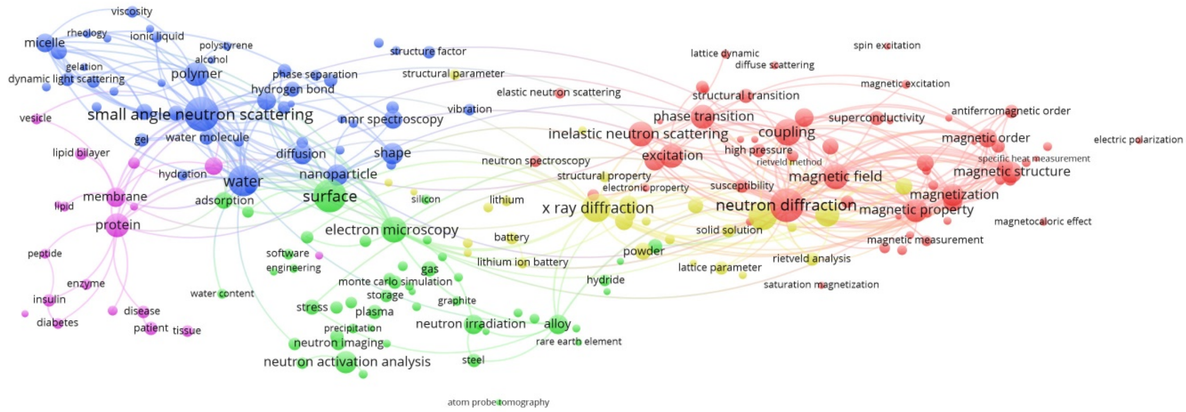


Figure 6: Connectivity map of keywords in neutron scattering based on publication abstracts[24]. The size of the circles around a keyword shows how often the keyword has been found. The lines and the strength of the lines express the connectivity of a keyword with other keywords

- Original instrumental developments.
  - In the future, it may be difficult to perform original instrumental developments around ESS due to the costs and constrains of the source.
  - Examples: Very Cold Neutrons, Spin-Echo, Polarimetry experiments
- Put efforts on education.
  - Make the source access easy.
  - Have simple instruments dedicated for training.
- Allow users to prepare ESS experiments, which would make them more competitive to obtain time at ESS.

8.1.2 Typical measuring times

Depending on the experimental techniques, the duration of an experiment can greatly vary. A reasonable estimate at a potential high power CANS facility with 10 instruments is summarized below.

Table 2 : Number of experiments which could be performed on a CANS operating 180 days with an availability for scientific experiments of 160 days per year.

Instrument	***Typical run duration***	***Nr. Run / year***
SANS (soft matter)	3.5 days	45
SANS2 (hard matter)	7 days	23
Reflectometer	7 days	23
Radiography	5 days	32
Powder diffraction (structure)	3.5 days	45
Powder diff (phase transitions)	3.5 days	45
Powder diff. (high resolution)	7 days	23
Powder diff. (large scale structures)	5 days	32
Spin-Echo	16 days	10
Direct TOF	7 days	23
TOTAL		**301**

[24] T. Gutberlet et al., Neutron News, 29 (2018) 18, Do neutrons publish? A neutron publication survey, 2005-2015.

Around a 10 instruments CANS, about 300 experimental runs could be performed every year, which is comparable to medium flux neutron facilities. Assuming an average of 2 runs per scientific publication, such a facility could produce about 150 publications per year. Again, this estimate holds for a specific choice of facility. Numbers can vary largely, depending on the size of the facility, i.e. power on target, number of target stations, number of instruments.

8.1.3 Instrumentation

Depending on the nominal power and accessible neutron flux, the suite of instruments at CANS will vary. At low and medium power CANS, elastic instruments such as SANS, reflectometry, diffraction, radiography and neutron analytical instruments should be preferred. At high power CANS, neutron spectroscopy spectrometers should be sufficiently performing.

In parallel, the more flexible access to CANS would make them ideal test beds for original instrumental developments. In the future, it will be impossible to perform original instrumental developments around ESS due to the costs and constrains of the source. On CANS, very innovative idea could be pursued. As examples, one could mention the production of Very Cold Neutrons or the implementation of advanced Spin-Echo techniques.

The rather easy access to beam tubes could make it possible for a University group to implement a dedicated instrument to a specific scientific problem. Such an instrument being focused on a specific topic, it could be optimized and costs made affordable.

8.2 Industry

Industry is involved in the use of neutron techniques at several levels:

1. Quality assurance screening
2. Ad-hoc problems, e.g. related to quality issues
3. Joint research and development

These levels can be tackled by neutron facilities by different approaches.

8.2.1 Quality assurance screening

In this case, a beam line at the facility is dedicated to the screening of industrial pieces. This is typically the case for the screening of pyrotechnical elements, metallurgical pieces, nuclear elements… or irradiations for soft or hard error qualification of electronic systems.

These stations are operated as “industrial” facilities and are not occupied with a scientific use. The measurements are provided as a service. The cost of these neutron measurements limit the use of these techniques to technical objects of high value. CANS can offer here flexible, timely and cost efficient access.

8.2.2 Ad-hoc problems, e.g., related to quality issue

During running industry production, it can happen that outcome deteriorates and the number of rejected parts increases beyond the usual / accepted level. In this case, there is a well-defined and urgent need to identify where the problem results from and what to do to remedy it. Just the fact that industry is asking for additional diagnosis, from techniques that they do not regularly employ, tells that the issue is urgent. As an order of magnitude, results are required in one- or two-weeks’ time. Such requests come intermittently and unforeseen. This means that tremendous flexibility and fast response is asked from the facility’s side and its administration.

8.2.3 Joint research and development

Common projects with industry for the development of new goods or services using neutrons are often linked to a certain minimum size of company (-branch). Such projects can be better planned for as they stretch over longer periods of typically a year or two, and there is (at least in the beginning) no direct time pressure to achieve a certain result.

However, upstream industrial research is mainly carried out in collaboration with academic laboratories through research contracts (e.g. ANR in France) who then apply for beam time at facilities. Hence it is very difficult to estimate and quantify the use of neutron scattering by industrialists via academic channels.

The Institut Laue Langevin estimates that experiments directly linked to private companies (via funding, staff, the supply of samples …) represent around 4 % of the proposals over the period 2012-2017. However, the information is often hidden, so this is a minimum figure.

At LLB, a study conducted over the period 2012-2014 suggested that a fraction of 11% of the beam time requested was linked to industrial applications. The manufacturers with which there are links are for example: Solvay, L'Oréal, Essilor, Thalès, Nestlé, IFP, TOTAL, EDF, CEA, Michelin, Dassault, PyroAlliance, SDH, Swiss Neutronics, NOB.

If we stick to a minimum value of 10% of the beam time contributing to upstream research by manufacturers, this represents an investment (beam time only) of the order of 30 M€ / year in Europe. The beam time sold directly to manufacturers relates only to 1.2% of the beam time available in Europe at an average cost of 9.7 k € / day. This represents an annual income of 4 M€. As these figures combined represent less than 0.01% of the R&D effort in Europe new opportunities could allow a lot of improvement.

One possibility CANS can provide easily here is to offer a dedicated target station for industrial research with very flexible and timely access scheme. As the target station could only being deserved with protons if experiments are ongoing there, additional operational costs are little as the “public” target stations receive the full proton power continuously.

An important issue with respect to industry is the handling of intellectual property rights. Here a somewhat contradictory culture and requirements have to be melded. Whereas researchers at an institute aim for publication, industry has no interest in making their findings openly accessibly. Appropriate access schemes and industry liaison offices provide solutions for this issue.

8.3 Other applications

8.3.1 Fast neutron irradiation

A wide range of different fields are interested in understanding and quantifying the effects of fast neutron (E_n > 1 MeV) irradiation: semiconductor electronics, commercial information technology electronics, avionics, application specific systems for space, nuclear and high-energy physics, bio-medical and bio-hazard applications such as in oncology, secondary neutron dose effects at hadron therapy facilities or the development of new fast neutron detectors and methods. Other potential applications of fast neutrons might be found in the evolving field of fast neutron imaging. Last but not least, more knowledge of fast neutron production and interaction cross-sections as a function of energy and angle is required for the development of precise Monte Carlo simulation codes, crucial in many technological applications of nuclear physics.

8.3.1.1 Electronics

Fast neutrons are ubiquitous, naturally found at flight altitudes and sea-level, as they are an important part of cosmic-ray air showers. Industry cannot risk releasing products on the market that are too sensitive to these so-called atmospheric neutrons, especially those used for critical applications that could lead to severe loss of revenue, if not worse. For instance, in digital telecommunications electronics, neutron induced Soft Errors (SE) already dominate the observable failure rate of electronic systems.

In general, industry relies on accelerator-based test facilities where fast neutron beams are used to test and validate new commercial products and systems[25]. Military and aerospace have long traditions of neutron testing and well established standards. Standards for commercial electronics industry have been more recently established too, with the intention of defining requirements for benchmark atmospheric neutron SEE tests. Such tests are performed around specialized beam tubes around nuclear research reactors. In Europe Chip-IR, a new test irradiation facility at ISIS, is dedicated to address the need of the industry to test for atmospheric neutron effects in industrial products[26].

Compact lower energy proton accelerators, capable of producing fast neutrons in the low to medium energy range, from a few MeV up to tens of MeV, can clearly play an important role: being numerous and distributed, they would be easily used by local academic research and industrial users to quickly probe novel test structures and electronic products and for unexpected SEE sensitivity to lower energy neutrons, before committing to expensive tests at the highest-energy facilities. For example, in Japan a CANS dedicated to such test facility supported by the NTT company was recently commissioned.

8.3.1.2 Space Neutron Shielding

The health risks due to cosmic radiation are the major showstopper for safe space exploration and colonization. Fast neutron beams can be used to test physical (active and passive shielding materials) and biomedical (hibernation) countermeasures for human space exploration. New materials are being considered for various applications. Monte Carlo codes are used to predict the performance, but space agencies require validation tests: code predictions may have high uncertainties or may be completely lacking for novel shielding materials, based on composites and nanomaterials, or even made of complex in-situ available planetary resources. In these cases, accelerator-based benchmark measurements are an essential tool to correctly characterize the shielding capabilities of various solutions.

Collaborations, contracts, and letters of agreement with European space agencies are a reality; an example is the SPARE (Space Radiation Shielding) project: a joint INFN, ASI and the Centro Fermi collaboration that deals with health risks due to cosmic radiation.

8.3.1.3 Nuclear Medicine

Fast neutrons can undergo nuclear collisions with the nuclei in human tissue and generate charged particles that will ionize surrounding atoms and molecules and perturb the normal biochemical activity of living cell or damage the DNA. Fast neutrons are present in accelerator-based radiotherapy setups. They increase the risk of secondary malignant neoplasms. New tracking systems are being developed to detect and monitor these secondary fast neutrons at hadron therapy centers[27].

[25] W. Yang et al., Atmospheric neutron single event effect test on Xilinx 28 nm system on chip at CSNS-BL09 Microelectron. Reliab. 99 (2019) pp. 119-124.
[26] https://www.isis.stfc.ac.uk/Pages/ChipIR.aspx
[27] S.M. Valle and et al. The MONDO project: A secondary neutron tracker detector for particle therapy. Nucl. Instr. Meth. A: 845, 2017.

8.3.1.4 Detectors and Dosimetry

Threshold reactions are widely used in activation measurements, both for mapping neutron fields and for dosimetry. As for neutron dosimetry, the new IRDFF2 database for the dosimetry of fusion and fission reactors was released less than two years ago by the IAEA[28]. For the evaluation of the cross sections, Coordinate Research Projects (CRP) were activated; these involve the most important facilities for fast neutrons in the world, with important contributions from European, Chinese, Japanese and USA laboratories. The energy range that must be covered for dosimetry and reactors (both fusion and fission) is from thermal up to about 20 MeV.

Moreover, all the dosimetric instruments used by nuclear facilities must be periodically checked and certified. Certification is done using standards at National Institutes, but the access to these institutions is not easy and the costs are very high. It is therefore appropriate to check the dosimetry before sending them to be certified and this can be easily done in laboratories where there is a well characterized energetic neutron beam. The scarcity of facilities of this type in Europe is particularly evident when looking at Germany, where the standard is kept at the national metrology institute (PTB). Measurements are made on site for the low energy part (as they have their own structures), while for fast neutrons (up to 70 MeV), the reference laboratory for Germany is iThemba-LABS in South Africa.

8.3.1.5 Nuclear Physics

Quality cross-section data are necessary to study new fission (IV generation and accelerator driven systems) and fusion reactors, but also for developing radioisotope production: the closure of reactors in Europe and the Chalk River reactor in Canada poses serious problems for the production of radioisotopes for medicine. Many countries and the IAEA are considering accelerator driven production [29-30].

Knowledge of neutron interaction cross-sections are important for background studies, such as in is the development of dark matter detectors: neutrons are always present (even in underground laboratories) and, as they are not charged, the signals they can leave in detectors are similar to those of dark matter particles. Other examples come from homeland security systems used to detect fissile material that must be able to distinguish the fast fission neutrons from background atmospheric neutrons, mostly produced by atmospheric muons.

Cross-sections as a function of neutron energy can be measured with the TOF technique or by scanning with adjustable quasi mono-energetic neutron (QMN) beams. An example of these measurements are the systematic study of (n,p) cross-sections at high neutrons energies as this is the easiest reaction to exploit for monitoring and measuring neutron fluxes.

---

[28] https://www-nds.iaea.org/IRDFF/

[29] J.Esposito et al, LARAMED: A Laboratory for Radioisotopes of Medical Interest, Molecules. 2019 Jan, 24(1):20.

[30] A.Vidal et al, ARRONAX Cyclotron: Setting up of In-House Hospital Radiopharmacy, BioMed Research International Volume 2020, Article ID 1572841.

9

CANS within a future landscape of neutron infrastructures in Europe

9 CANS within a future landscape of neutron infrastructures in Europe

The European neutron scattering landscape consists of a hierarchy of sources with different capabilities. In the recent BrightnESS report on Neutron Users in Europe[31], it was proposed to categorize the facilities in (A) Large-scale facilities with a large user base comprising of 450–1600 unique users, (B) Medium-scale facilities with 50–350 unique users, (C) Small-scale facilities with less than 50 unique users. The figure below presents the landscape as of May 2018. In 2019 alone, three research reactors stopped their operation: Orphée in France, BER II in Germany and JEEP II, in Norway. The situation will further evolve in the coming decade. In the worst-case scenario, in the 2030', if most of the aging reactors (>50–60 years old) are shut down, the landscape will have completely changed with only a handful of remaining sources (MLZ, ISIS, PSI and ESS).

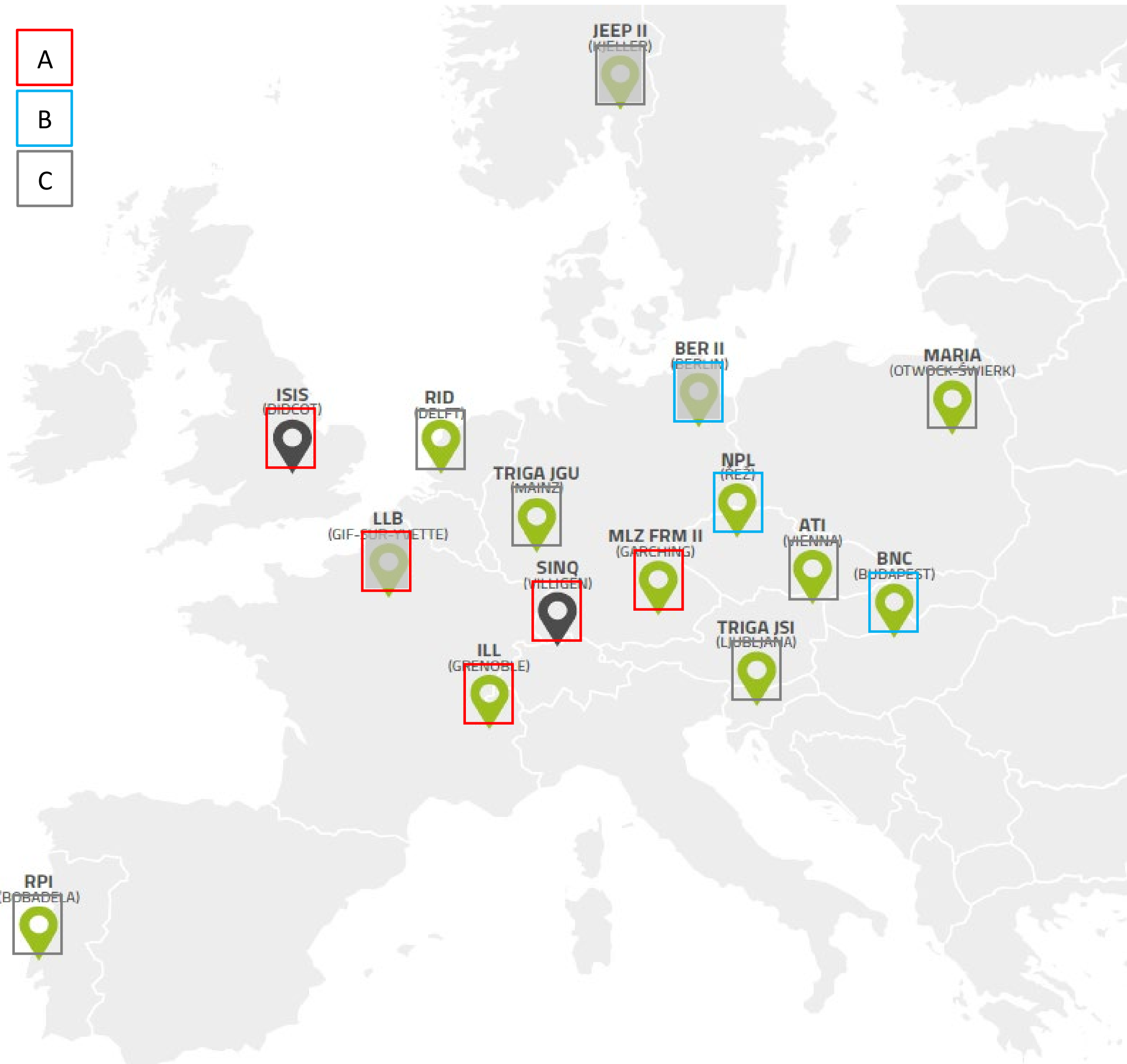


Figure 7: Adapted from NEUTRON USERS IN EUROPE: Facility-Based Insights and Scientific Trends, BrightnESS, 2018

[31] NEUTRON USERS IN EUROPE: Facility-Based Insights and Scientific Trends, BrightnESS (May 2018).

While the remaining sources will be highly performing sources, such a concentration would not be healthy to maintain a European user community beyond the 4 countries who would maintain operational neutron sources.

It is rather obvious that the presence of a neutron source in some geographical area is a key factor to generate a neutron user community. In France, the ILL reactor and the Orphée reactors where key assets to develop the French neutron scattering community both regionally with neighboring laboratories investing strongly in neutron techniques (Institut Néel, CEA) and nationally. In Germany, the FRM 1 seeded the TUM campus and the research reactors in Jülich, Geesthacht and Berlin shaped the German neutron research. ISIS and SINQ are successors of successful research reactor facilities in both countries.

Direct contacts between potential users and neutron experts are the first step to involve users (both academic and industrial) into neutron techniques. Without facilities where users can learn to use neutron scattering and get help for the exploitation of the data via strong scientific collaborations with the personnel of the institute hosting the facility, the neutron user community is at risk of shrinking to specialized users and hence making its impact to the broader scientific community decrease. This will also affect innovation and competitiveness within the society.

CANS sources are ideal candidates to fulfill the role of building a hierarchy of sources to maintain a thriving user community[32].

CANS could potentially offer “capabilities” which are sometimes difficult to accommodate at high performance sources. In particular, CANS can better integrate in the existing local scientific fabric by focusing on specific topic and creating privileged links with existing institutes. Among the potential capabilities of CANS, most to mention are:

- Setting up long term projects with guaranteed beam time for local institutes.
- The possibility to develop a specific instrumentation by an external laboratory with potentially access to a dedicated beam tube for scientific topics with a lifetime on the order of up to one decade (e.g. batteries, hydrogen storage, clathrates, metallurgy, catalysts).
- Providing a significant fraction of the time « on-the-fly » so that neutron characterizations can be performed in parallel with other techniques.
- The possibility to perform « screening » measurements.
- Original instrumental developments.
- Opportunities for the formation and training of students and users by making the source access easy and having simple instruments dedicated for this purpose.
- Helping users to develop and test experiments foreseen to work at e.g. ESS, ILL etc..
- Creation of a reservoir of technical know-how on accelerator based neutron source around each CANS.

Beyond these capabilities, higher-end CANS offering a full suite of neutron scattering instruments could also be built. While these instruments would provide performances as reached at medium flux reactor or spallation sources, they would not be in the same league as ESS instruments. Hence the focus should not be put on the raw performances of the instruments in terms of flux but rather on “soft” aspects such as advanced sample environments, close cooperation between the “external users” and the “neutron scattering expert”, ease of access and long term collaborations.

Workhorse instruments which are easy to use both in operation and data processing such as SANS, powder diffraction, reflectivity, radio-tomography should be privileged. These techniques will not turn obsolete for the coming decades and in a large fraction of the experiments the neutron flux is not a limitation.

[32] In the field of x-ray scattering, this hierarchy was never an issue since users are usually acquainted with experiments on laboratory spectrometers and can end up performing experiments on X-FEL sources

Overall CANS would open a flexible strategy to distribute and concentrate tasks and serve general as well as specialized requirements with a network of CANS facilities embedded in the European ecosystem of neutron sources.

Figure 8: Ecosystem of European neutron sources

The ESFRI scenario is projecting that by 2035, the reduction in beam-time capacity would be about 40% (+/- 10%). It could be argued that ESS would provide vastly more efficient instruments and thus compensate for this loss of capacity. While it is true that the average duration of neutron experimental runs has decreased over the last decades, it does not scale with the raw performances in terms of neutrons flux at the sample position. The average run times at the ILL are 4 days and it is projected that the average run time at ESS will be 3 days. Hence the capacity loss would mechanically lead to a drop in scientific output.

It could be argued that that the remaining facilities could be better exploited by third party countries or institutes. It should thus be reminded that existing national sources are already welcoming a significant share of foreign users (35–40%) and it is unlikely that this share could be further increased. Besides the possibility of installing new instruments at existing facilities has become a more demanding task in previous years[33]. In many cases new instruments were installed mainly by replacement of operating ones following scientific demand.

At the European level, the construction of CANS could partially remedy this capacity loss. If one makes the assumption that 3 national or regional sources are built in the next decade and start operation in the 2030' and assuming on average 10 instruments per source (e.g. 5 + 10 + 15), about 30 new instruments could enter the pool of European neutron scattering instruments. If these instruments operate for 160 days per year, an extra 5000 instrument days could be provided. In terms of raw

[33] The installation of new LLB CRGs at the ILL has proven to be very difficult due to a lack of available experimental positions. Only parts of a few HZB instruments will be moved to MLZ for similar reasons.

capacity, this supply would improve strongly the resilience of the landscape although it would only represent an extra 25% of beam capacity in Europe.

Some countries will be in a precarious situation to maintain a healthy user community after the ILL shutdown. For example, in the case of France, the capacity in terms of [instrument-days] will be reduced by 90% even including the French share at the ESS. A French CANS operating 10 instruments and providing 1600 instrument days would allow maintaining a French community.

Spain and Italy could similarly build sources to support their national communities and improve their international positioning.

10

Conclusions and Recommendations

10 Conclusions and Recommendations

To keep a sustainable access and use of neutrons in science and industry, a **hierarchy of neutron sources** is necessary to maintain a healthy neutron scattering ecosystem. It offers users access to facilities fitting their needs (from the first contact with neutron scattering techniques, to routine experiments, and eventually higher-end experiments)[34]. CANS are well suited to fulfill a critical part of this need due to their flexibility and scalability.

Ultimate capability, usually considered in terms of neutron flux, is not the only figure of merit of a neutron source. Other capabilities can be considered:

- Strong collaboration between instruments scientists and users.
- Advanced sample environments, which may be achieved via specialization.
- Possibility to develop innovative instrumentation.
- Access agility which is important for material science screening experiments or for industrialists.
- Training capabilities, ideally not overlapping with scientific capabilities.

CANS should be tightly integrated within a local scientific tissue to maximize external inputs. This leverage may be enhanced by specializing in scientific fields of direct interest with the local scientific community.

CANS are within the scope of **"national level fundings"**. For national projects, the scope of a source should be oriented to answer specific national needs thus providing good investment for innovation and a knowledge driven society.

CANS are also be suited for a concept of a **distributed facility** (even by self-organization) with sharing users on a European scale by specialization but this is too early to assess prior the demonstration of the operation and performances of a high power high brilliance CANS.

Research and development need to be pursued to **assess the technical feasibility** of suitable high power CANS in Europe. A significant amount of R&D developments undertaken during the previous decades for projects such as ESS, SARAF, MYRRHA on accelerators, targets and moderators may directly be reused, which limits the remaining extra R&D effort.

Detailed costing has to be performed combined with a survey on user needs.

A **prototype of a high brilliance CANS** needs to be built to validate the technical feasibility, the actual costs and the performances.

[34] This has been the case for X-rays for decades

Annexes

11

Technical requirements for CANS

11 Technical requirements for CANS

11.1 Accelerator system

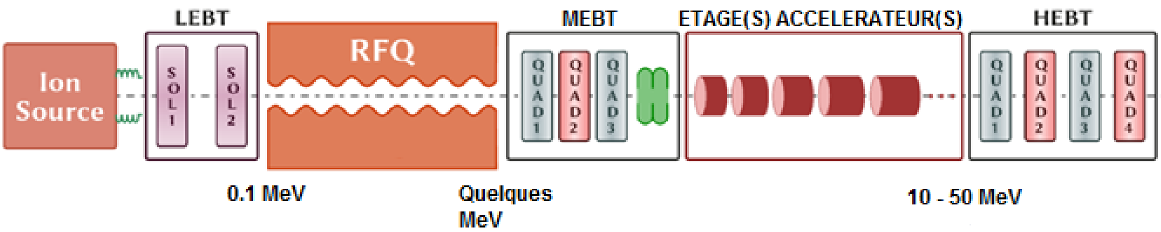
There are several accelerator technologies allowing accelerating protons in the 2–70 MeV region.

In the continuous accelerators, one finds electrostatic accelerators and cyclotrons. The accelerator are commercially available from industrial companies: High Voltage Engineering, D-PACE for electrostatic accelerators and IBA, GE Healthcare, Advanced Cyclotron Systems, Sumitomo Heavy Industries… for cyclotrons.

These accelerators are operating in continuous mode with limited peak currents (~1 mA) and are thus not ideally suited for neutron scattering applications. Note that D-PACE is proposing a high current electrostatic accelerators (30mA) but with a low proton energy (2.6 MeV).

If pulsed proton beams are to be produced, Linear Accelerators (LINACs) are the preferred choice. A LINAC system comprises of the following elements:

- An ion source whose role is to produce a high intensity proton beam with energies in the range 50-100 keV.
- A Low Energy Beam Transport (LEBT) whose role is to guide the beam and create an appropriate time structure.
- A Radio-Frequency Quadrupole whose role is to accelerate the low energy proton beam and to shape the beam into packets
- A Medium Energy Beam Transfer section (MEBT)
- A Drift Tube Linac (DTL) to accelerate the protons up to their final energy
- A High Energy Beam Transfer section (HEBT)



11.1.1 Ion source

The ion source is the component whose role is to provide an intense source of proton current. Such sources are nowadays routinely able to provide tens of mA of proton current. The ESS ion source was built by the Laboratori Nazionali del Sud (LNS) in Catania and should provide proton currents on the order of 70 mA. The ion source of FAIR is providing a pulsed proton beam (DC 4%) with a peak intensity of 100 mA. Around IFMIF/EVEDA, continuous beams of 125 mA have been produced. High current proton sources can almost be considered as off-the-shelf components as a few commercial companies are proposing high current ion sources.

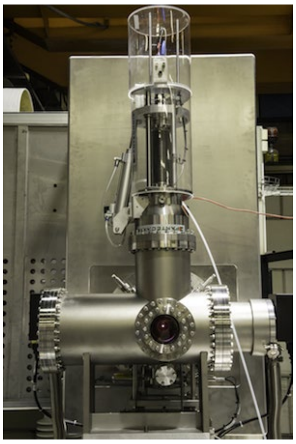


Figure A1: The ESS ion source

11.1.2 Radio-Frequency Quadrupole (RFQ)

A Radio-Frequency Quadrupolar cavity is an element requiring very demanding mechanical specifications and stability. During the last decade, several such equipment have been built and commissioned in Europe: LINAC4 (I_{peak} = 80 mA), IPHI (I_{peak} = 100 mA), ESS (I_{peak} = 70 mA).

11.1.3 Accelerator

The accelerator can be either normal conducting or super-conducting. The second option is usually preferred for high duty cycle machines. At ESS for the section E_p = 3.6 to 90 MeV, the choice of a normal conducting Linac has been made. Other machines are using cryomodules: SPIRAL2, SARAF, IFMIF.

There are currently very few industrial providers of LINACs. The Accsys Technology Inc. company claims to be able to provide a 11 MeV proton accelerator with a peak current of 40 mA and a maximum power of 11 kW (LANSAR PL-11).

11.2 Target

In a compact accelerator-driven neutron source, the production of neutrons is using the interaction of light ions such as protons with the atomic nuclei of a target material in the low energy range (2–70 MeV). The neutron yield depends on the particle type, the particle energy, and the target material.

In the low energy range, below 5 MeV, lithium is showing a high neutron production cross section and is used as a target material at low energy CANS[35]. As the melting point of lithium is very low, it is feasible to build a liquid metal target. The LiLiT prototype was operated at 2.3 kW beam power and studies indicate that a liquid metal target can withstand a power of 200 kW[36]. The IFMIF/DONES aims at operating a liquid lithium target at powers up to 10 MW. Due to the low beam energy and a beam current limit of around 100 mA, such sources are mostly operated in CW to maximize the neutron yield. This is viable for applications which are not using time-of-flight techniques such as BCNT or irradiation but not efficient for a neutron scattering facility.

While liquid lithium targets look as a good choice for low energy beams (<10 MeV) due to the high neutron yield and the low penetration depth (<<1mm), at higher energies (tens of MeV), the neutron yield becomes less favourable compared to other materials and a thick jet becomes necessary (1–2 cm). Hence, for the operation of a 40 MeV target, a liquid gallium jet is being considered.

[35] https://iopscience.iop.org/article/10.1088/0031-9155/52/3/008/meta
[36] https://doi.org/10.1140/epja/i2018-12526-2

In the intermediate proton energy range, between 5 MeV and 50 MeV, Beryllium has a high neutron production cross section and is used as a target material at existing sources like LENS in Indiana[37], RANS at RIKEN[38] or iBNCT at the Tsukuba university[39]. To prevent the deposition of the protons inside the beryllium material, the target layer is reduced in thickness so that the Bragg peak lies either in the cooling medium (LENS) or inside a hydrogen mitigation material (RANS, iBNCT). The neutron yield using a Beryllium target is limited by the heat removal capacity and could be improved recently (RANS: 700 W, LENS: 4 kW, iBNCT: 20 kW[40].)

In the energy range above 50 MeV, heavy target materials like Tungsten, Tantalum or Lead become preferable because more reaction channels with multiple neutron emissions are opening. Such targets are commonly used in spallation neutron sources at high proton energies and are being considered as targets for higher proton energy CANS[41].

The development and the operation of targets face two main challenges concerning the target integrity and stability over long periods of time (thousands of hours),

i) the hydrogen embrittlement by the deposition and accumulation of protons inside the target
ii) the heat removal capacity for a large power deposition of up to 100 kW creating large temperature gradients and a temperature induced stress.

Depending on the particle energy, the target material and the beam current, different solutions are used. For a peak proton beam current of up to 100 mA, the hydrogen embrittlement caused by proton deposition is a limiting factor regarding the lifetime of the target. A target which has a high blistering threshold like Tantalum can be used. For beryllium, increasing the hydrogen diffusion coefficient by operating at elevated temperatures or minimizing the proton deposition inside the target by reducing the target thickness can be used. By employing these techniques, a target can be constructed which can withstand a year of operation.

Due to the relatively small stopping range in the order of a few mm to some cm of the protons at energies below 100 MeV and an aimed average power of up to 100 kW at the target position[42], the power density is rather large and needs to be removed efficiently. A neutronics analysis shows that the coupling in the target-moderator-reflector system is not significantly affected up to ~200 cm² of target footprint[43] thus defining a minimum power density of 500 W/cm². Reaching the desired 100 kW requires a sophisticated cooling mechanism.

Another possibility is to use advanced cooling techniques like a micro-channel cooling allowing to remove up to 3.5 kW/cm²[44]. With this cooling technique it is possible to create a compact target with a surface area of around 30 cm² and thus increase the brilliance. There exist even more advanced concepts that could remove heat up to 10 kW/cm² as demonstrated using divertor devices in fusion technology[45]. The last possibility to dissipate the heat is to use a rotary target wheel[46] reducing the deposited power density significantly but preventing a compact design.

---

[37] T. Rinkel et al, Target Performance at the Low Energy Neutron Source, Physics Procedia, 26 (012) 168-177.
[38] Y. Ikeda et al., Prospect for application of compact accelerator-based neutron source to neutron engineering diffraction, Nucl. Instr. Meth. A, 833 (2016), 61-67.
[39] H. Kumada et al., Development of beryllium-based neutron target system with three-layer structure for accelerator-based neutron source for boron neutron capture therapy, Appl. Radiation Isotopes, 106 (2015) 78-83.
[40] T. Kurihara, H. Kobayashi, EPJ Web Conf., 231 (2020) 03001
[41] P. Zakalek et al., High-Brilliance Neutron Source Project in Proc. HIAT 18, Lanzhou, China, Oct. 2018, pp. 117-121. doi:10.18429/JACoW-HIAT2018-WEZAA01
[42] A. Marchix et al., Saclay Compact Accelerator-driven Neutron Sources (SCANS), J.Phys: Conf. Ser., 1046, (2018) 01009.
[43] S. Terron et al., Conceptual design of the beryllium rotating target for the ESS-Bilbao facility, Nucl. Instr. Meth. A, 724 (2013) 34-40. .
[44] P. Mastinu et al., Status of the LEgnaro NeutrOn Source facility (LENOS), Physics Procedia, 26 (2012) 261-273.
[45] F. Escourbiac et al., Fusion Engin. Design, 75-79 (2005) 387-390.
[46] S. Terron et al., Conceptual design of the beryllium rotating target for the ESS-Bilbao facility, Nucl. Instr. Meth. A, 724 (2013) 34-40.

The SONATE project develops a Beryllium target working at 20 MeV proton energy and a beam current of 100 mA with an average power deposition of 80 kW. The beryllium target is mounted on a cooling plate which is optimized to remove the 80 kW but keeps the beryllium at elevated temperatures. This increases the hydrogen diffusion coefficient and allows the protons to diffuse out of the target allowing stable target conditions.

The HBS projects develops a tantalum target working at 70 MeV proton energy and a beam current of 100 mA with an average power deposition of 100 kW. To remove the heat density of 1 kW/cm^2, it uses a microchannel cooling with channel thicknesses of 0.3 mm directly inside the Tantalum target. The protons are stopped inside a water beam stop at the backside of the target preventing an accumulation of hydrogen. Mechanical simulations show that the target can be cooled efficiently and is stable in a pulsed operation mode.

With a power deposition of around 100 kW, the estimated neutron yield inside the target is in the order of 10^{15} s^{-1} allowing to feed instruments with neutron fluxes comparable to medium power research reactors. The power of 100 kW at the target position is challenging but possible to solve with recent developments.

11.3 Moderator

For neutron scattering applications, it is necessary to slow down neutrons to thermal (26 meV) or colder energies (typ. 4 meV). Hydrogenous materials are effective moderators since hydrogen has the highest scattering cross section and the highest moderation performance. These characteristics lead to higher intensity and shorter emission times. As a thermal neutron moderator, water or polyethylene can be used. Metal hydride may be considered as a candidate, but its molecular dynamics has no effective slowing down modes at thermal energy region, and the neutron spectrum forms a Maxwell distribution with a much higher peak energy than the moderator temperature. Hydrogen number density, operation temperature, melting point, boiling point are summarized in Table A1 for thermal and cold moderator materials. Polyethylene has a higher hydrogen number density than water and the neutron intensity from a polyethylene moderator is a little bit higher than water. However, polyethylene is sensitive to radiation damages. Therefore, it is required to exchange the polyethylene moderator at some intervals.

Large deuterated moderators vessels cannot be used on a pulsed source due to the requirement of keeping rather short pulses. Partly deuterated moderators may be considered but at a pulse source they will only be beneficial if the pulses are long enough."

Table A1. Characteristics of cold and thermal moderator materials.

	H/cm^3	Operation Temperature	Melting point	Boiling point
H_2O	6.7×10^{22}	Ambient Temp.	273K	373K
$(CH_2)n$	8.2×10^{22}	Ambient Temp.		
CH_4	7.8×10^{22}	20K,105K	99.6K	112K
H_2	4.5×10^{22}	~15K	20.4K	14.7K
C_9H_{12}	5.2×10^{22}	Ambient~20K	229K	437K

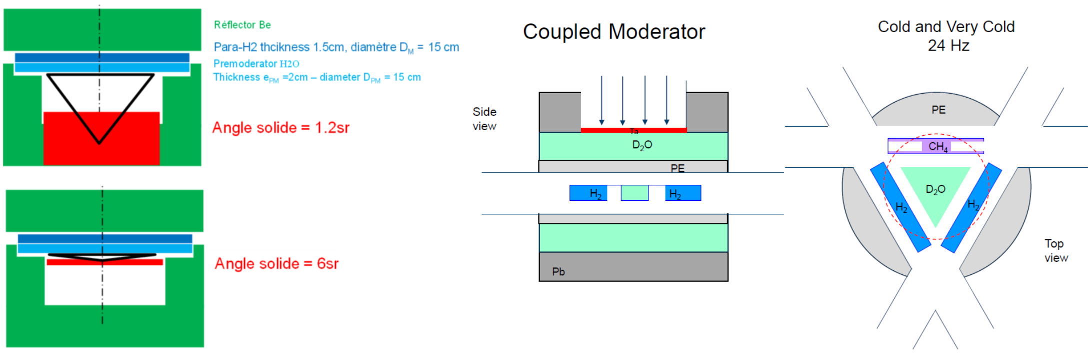


Fig. A2: Possible moderator arrangements in CANS. Left: SONATE, Right: HBS.

In order to keep a high brilliance, a small and compact moderator is needed. Maximization of the flux is also achieved by almost fully coupling the moderator to the target. At ESS, the target will see the moderator under a solid angle of 1sr while on a CANS a coupling of 6sr should be possible.

A large number of neutrons techniques are more efficient with cold neutrons (SANS, reflectometry, radiography, spin-echo, high-resolution spectroscopy). Thus, a cold moderator is a key component of any neutron scattering facility.

Candidate materials for cold moderators are solid methane (CH_4), liquid hydrogen (H_2) and mesitylene (C_9H_{12}). A solid methane cold moderator was developed at Hokkaido University Neutron Source (HUNS)[47-48]. Methane has high hydrogen number density and low energy rotation level (~1.3 meV). The low energy level works very effectively to reduce the neutron energy and the high number density contribute to increase the neutron intensity. A methane moderator gives the highest intensity in the cold neutron region (few meV region). Para-hydrogen provides a slightly warmer spectrum.

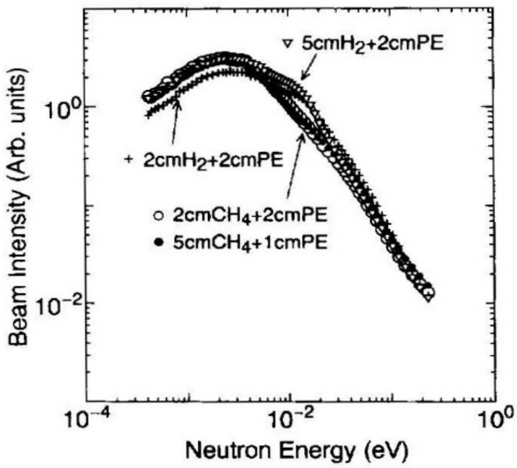
Methane is a low radiation-resistant material and even at low power sources it is required to exchange methane gas after some irradiation time, for example, twice a year at a 10^{12}n/sec class photo-neutron source.

Coupled hydrogen moderators were developed to increase the intensity from the hydrogen moderator since at high power spallation neutron sources the solid methane moderator cannot be used[49]. The energy spectrum of coupled moderators of liquid hydrogen and solid methane are shown in Fig. A3. Each includes a pre-moderator of polyethylene (PE). It was found the cold neutron intensity of the coupled methane moderator was almost the same as the coupled liquid hydrogen moderator and the pulse shape was narrower than that of the coupled hydrogen moderator[50]. As a cold moderator, solid methane is the best material.

Methane is explosive material and so handling and regulation are rather severe. Therefore, a mesitylene cold moderator has been used at compact neutron sources [51-52] but the intensity is not so high in the cold neutron region compared with methane.

---

[47] K. Inoue, N. Otomo, H. Iwasa and Y. Kiyanagi: Slow Neutron Spectra in Cold Moderators, J. Nucl. Sci. Tech., 11, 228-229 (1974).
[48] K. Inoue, Y. Kiyanagi and H. Iwasa, An Accelerator-Based Cold Neutron Source, Nucl. Instr. Meth. in Physics Research, 192, 129-136 (1982).
[49] Y. Kiyanagi, N. Watanabe and H. Iwasa, Experimental Studies on Neutronic Performance of Coupled Liquid-Hydrogen Moderator for Pulsed Spallation Neutron Sources, Nucl. Instr. Meth. in Physics Research, A312, 561-570 (1992).
[50] Y. Kiyanagi, Effect of Reflector on Intensity of Thermal Neutrons Emitted from Moderator for Pulsed Neutron Source, J. Nucl. Sci. Tech., 24, 6, 490-497 (1987).
[51] M. Utsuro and M. Sugimoto, Pulsed Cold Neutron Source of Solid Methylbenzene, J. Nucl. Sci. Tech., 14, 390-392 (1977).
[52] T. Cronert, J.P. Dabruck, M.Klaus, C.Lange, P.Zakalek, P.-E.Doege, J.Baggemann, Y.Beßler, M.Butzek, U.Rücker, T.Gutberlet, R.Nabbi, T.Brückel, Compact and easy to use mesitylene cold neutron moderator for CANS, Physica B: Condensed Matter, 551, 377-380 (2018).



New moderation concepts[53] using low dimensional (1D or 2D) moderators have recently been proposed to increase the brilliance. A flat "butterfly" moderator (2D) is planned for ESS. Higher brilliances are expected for tube (1D) moderators.

Fig. A3: Comparison of neutron energy spectra from coupled moderators of liquid hydrogen and solid methane [39].

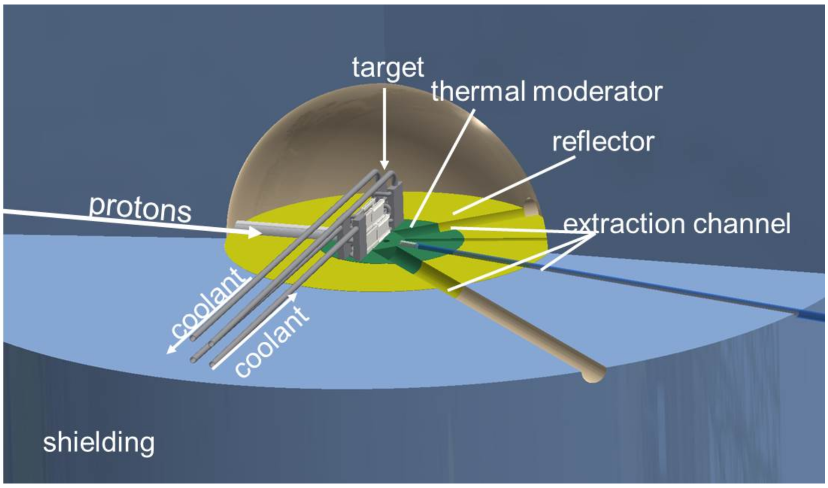


Figure A4: A possible target-moderator-reflector unit on a CANS. (green) polyethylene thermal moderator, (yellow) lead reflector.

11.4 Reflector

The reflector is one of the important components. Various materials have been considered as a candidate[54]. Be and Graphite are effective materials for neutron sources for neutron scattering experiments. Be provide better performances than graphite but graphite is much cheaper than Be.

[53] L. Zanini et al, EPJ Web Conf. **231**, 2020, *Low-dimensional moderators at ESS and compact neutron sources*. DOI: https://doi.org/10.1051/epjconf/202023104006. L. Zanini, F. Mezei, K. Batkov. E. Klinkby, A, Takibayev, IOP Conf. Series: Journal of Physics: Conf. Series 1021, 012009 (2019).

[54] Y. Kiyanagi, Effect of Reflector on Intensity of Thermal Neutrons Emitted from Moderator for Pulsed Neutron Source, J. Nucl. Sci. Tech., 24, 6, 490-497 (1987).

Recently nano-diamond has been studies since it increases the intensity in the very cold neutron region[55-56]. In BNCT systems, Pb is used since the energy of the required neutrons is epithermal[57-58].

11.5 Neutron yield

To rationalize how low neutron yield nuclear processes may allow achieving performances on par with neutron sources using the very efficient spallation process, one has to take into account a number of specific parameters as proton beam current, peak brightness, time structure and TMR design. The raw fast neutron production of the HBS source is estimated at 1.2 x 10^{15} n_{fast}/s while the one at the ISIS Target Station 2 (TS2) is 5 x 10^{15} n_{fast}/s. These figures are rather close because the HBS source is using a high average proton current of 2 mA while the ISIS TS2 is using only 50 µA. The highest current compensates a large fraction of lower neutron yield of low energy nuclear reactions. A further significant gain is achieved in the moderator design which is fully coupled to the source. As a consequence, the HBS cold neutron peak flux is expected to be very close to the peak flux at ISIS TS2.

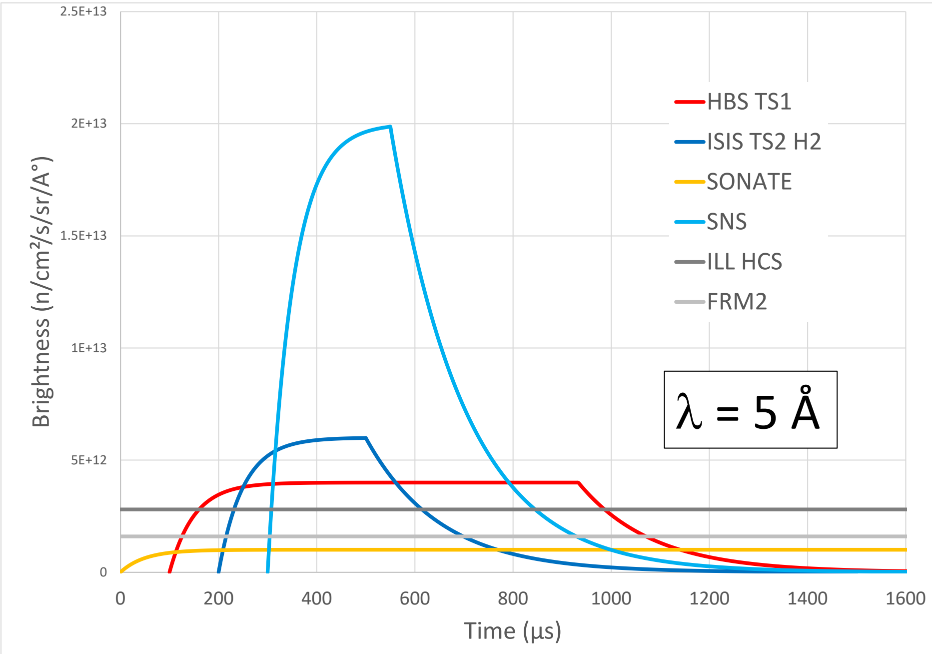


Figure A5. Single-pulse peak brightness as a function of time at a wavelength of 5 Å at HBS TS1, ISIS TS2, SNS, and brightness of ILL and FRMII cold sources. The SONATE pulse width of 2 ms is proposed to be very close to the ESS pulse structure. The starting points of the pulses have been shifted for clarity.

A comparison of the peak brightness of different accelerator-based spallation and low energy neutron sources is presented on Figure A5. The ILL and FRM2 cold moderators brightness are quoted as

[55] V. Nesvizhevsky, U. Koester, M. Dubois, N. Batisse, L. Frezet,A. Bosak, L. Ginesdan, O. Williams, Fluorinated nanodiamonds as unique neutron reflector, J. Neutron Research, 20, 81–82 ((2018). DOI 10.3233/JNR-180090

[56] M. Teshigawara, Y. Tsuchikawa, G. Ichikawa, et al., Measurement of neutron scattering cross section of nano-diamond with particle diameter of approximately 5 nm in energy range of 0.2 meV to 100 meV, Nucl. Instr. Meth. in Physics Research, A929, 113-120 (2019).

[57] H. Tanaka et al., Measurement of the Thermal Neutron Distribution in a Water Phantom Using a Cyclotron Based Neutron Source for Boron Neutron Capture Therapy. IEEE Nuclear Science Symposium Conference Record 2009, Article number 5402230, Pages 2355-2357.

[58] H. Kumada et al., Development of LINAC-Based Neutron Source for Boron Neutron Capture Therapy in University of Tsukuba. Plasma and Fusion Research: Regular Articles 2018; 13: 2406006

reference points. The ESS peak brightness is expected to be on the order of $5x10^{13}$ n/cm²/s/sr/Å (not represented on Figure A5).

Beyond the peak brightness, it was mentioned before that the time structure could be optimized for different techniques. The HBS project is thus proposing to build up to 3 target stations to optimize the use of neutrons. The SONATE project is proposing to build a long pulse target station well suited to low resolution techniques (duty cycle ~4%). Figure A6 illustrates the various time structure at different facilities.

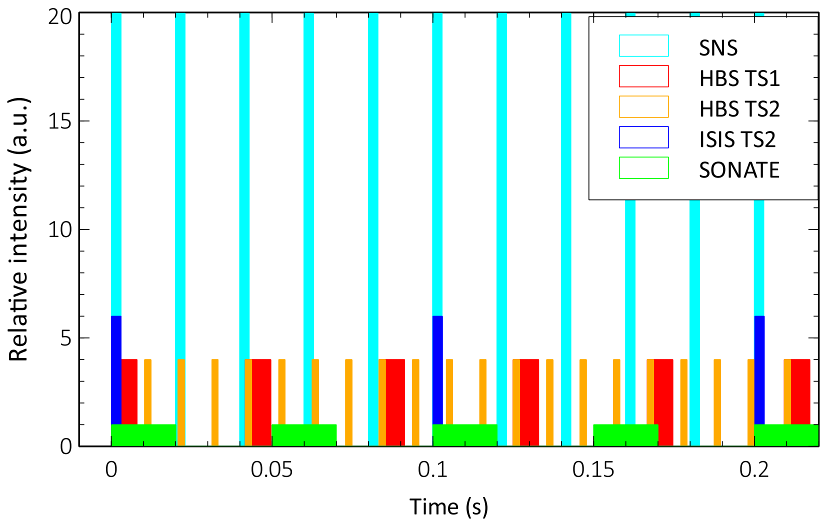


Figure A6. Pulse time structures at various facilities. The different target stations at HBS TS1 (red) and HBS TS2 (orange) would operate at different repetition rates and pulse lengths. A long pulse structure is proposed to be used on the SONATE facility (green). For technical reasons, the ISIS TS2 target station has a low repetition rate (10Hz) as it is using a small fraction (1/5th) of the pulses produced by the accelerator. For visualization purposes, the pulses widths have been enlarged by a factor 10.

Figure A7 gives a summary of the peak and average brightness of several accelerator-based neutron sources and CANS projects. For comparison, the reactor source ILL is included.

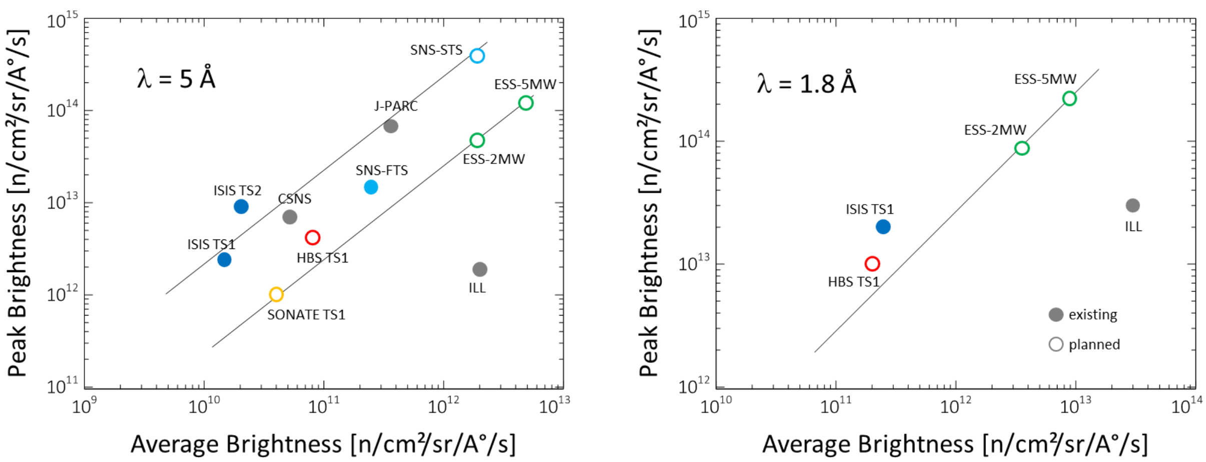


Figure A7: Peak brightness and average brightness (cold and thermal) of existing and planned sources. Adapted from Paul Kangan[59].

[59] Paul Kangan, Proton Power Upgrade and Second Target Station for the Spallation Neutron Source (Rockville, 2019)

11.6 Instrumentation

11.6.1 Neutron scattering instruments

11.6.1.1 Large-scale structure instruments

Small angle neutron scattering (SANS) instruments and neutron reflectometers (NR) require a highly collimated neutron beam in 1D (reflectometry) or 2D (SANS), but can accept a very relaxed wavelength resolution $\Delta\lambda/\lambda$ ~10% (that can be relaxed to 20% in some cases, like for instance in reflectivity measurements for very thin films). Therefore, these instruments are best served by a long neutron pulse > 500 µs and a low repetition rate < 50 Hz providing a broad band width covering a large momentum transfer range. The low requirements on the chopper system and the large scattering cross sections at low angles make these types of instrument very attractive for low power CANS.

The small source size from a quasi 1D para-hydrogen moderator matches well with the requirements of a narrow beam collimation. Also, novel focusing concepts, such as SELENE guides or Wolter Optics benefit from a small source size.

11.6.1.2 Diffractometers

Diffractometers need a high wavelength resolution to resolve Bragg peaks or Debye-Scherrer rings with very close d-spacings. The necessary $\Delta\lambda/\lambda$ < 1% resolution can be efficiently achieved with the pulse structure provided by a double disk chopper. Typically, diffractometers are equipped with area detectors that cover a large range of scattering angles, so that the wavelength band used can be relatively narrow.

Implementation of bi-spectral extraction improves the versatility and flexibility of the diffractometer. Short wavelength neutrons (λ ~0.5 Å) can be used for PDF measurements. Longer wavelengths (λ ~ 3–4 Å) can be used for high-resolution experiments on samples with small unit cells. In this case, a para-H_2 vessel can be implemented attached to the cold extraction guide segment to improve the neutron flux.

11.6.1.3 Spectroscopy instruments

CANS will provide neutron pulses with a pulse length > 100 µs. For compact and versatile instruments, pulse shaping choppers will therefore be employed to achieve a high initial neutron energy resolution. Such chopper assemblies can be placed at a rather short distance from the moderator, limiting the bandwidth for broad band applications only modestly. On the other hand, the availability of high frequency target stations is ideal for narrow band applications. Repetition rates between 100 Hz and 400 Hz are well suited for direct geometry cold and thermal spectrometers or backscattering instruments.

Not only choppers, but also the neutron optics can be brought very close to the source. That will allow the transport of large phase space volumes to the sample to provide high intensity on the sample with relaxed momentum transfer resolution. The lighter shielding will allow instruments close to the target using focusing crystal monochromators for very compact direct geometry spectrometers.

11.6.1.4 Spin Echo

A spin-echo instrument on a pulsed source could benefit from the very large divergence accessible by neutron optics at very short distance from the source. It can use a long pulse and a broad band width to achieve a high intensity on the sample. In particular, spin echo instruments would benefit from dedicated moderator developments or slow neutron reflectors based on fluorinated nanodiamonds to increase the delivery of very long wavelength neutrons.

A solution for the anticipated low neutron flux on detectors would be the multichannel concept of the Multi-MUSES project (boosting the efficiency of the MUSES spin-echo instrument by a factor 70), outperforming existing state of the art spin-echo instruments but at the expense of a complex instrument.

11.6.2 Neutron radio-tomography

Neutron imaging instruments at a CANS profit in particular from very compact designs. Small area moderators, e.g. 1D para-hydrogen moderator or the thermal extraction channels, provide a suitable source even without mandatory pinhole, which optionally could be used to tailor the sample flux and resolution. Sample can be placed at distances shorter than 5 m, with a reasonable field of view. The lighter shielding provides a flexible instrument setup with different sample positions to match the resolution requirements perfectly.

Table A2. Instrument parameters at current CANS Projects (SONATE, HBS, ESS-Bilbao).

Instrument	Pulse length	Frequency	Beam size	Divergence	Source (λ range)	Δλ/λ
Imaging & PGAA			10x10 cm^2	0.2°	Bispectral (0.6-4 Å)	1
Single crystal Diffractometer	20-200 μs	100-300 Hz	< 5x5 mm^2	0.5°x1°	Bispectral (0.6-4 Å)	0.01-0.02
Powder Diffractometer	20-200 μs	100-300 Hz	1x1 cm^2	0.5°x1-2°	Bispectral (0.6-4 Å)	0.01-0.02
TOF (direct) Spectrometer	50-500 μs	100-300 Hz	< 3x3 cm^2	5°	Thermal or cold	> 0.01
Crystal TOF Spectrometer	20-2000 μs	20-300 Hz	< 3x3 cm^2	5°	Cold (2-6 Å)	> 0.01
TOF-BS Spectrometer	20-2000 μs	20-300 Hz	< 3x3 cm^2	5°	Cold (~3-10 Å)	< 0.005
NSE	~1-2 ms	20-48 Hz	<3x3 cm^2	5°	Cold (5-10 Å)	0.2
SANS	~1-2 ms	20-48 Hz	1x1 cm^2	0,4°	Cold (3-16 Å)	0.1
Reflectometry	~1-2 ms	20-48 Hz	< 1x30 mm^2	0.2°x2-4°	Cold (2-6 Å)	0.1

Imaging instruments are suitable for both high power and low power CANS, providing complementary capabilities in terms of spatial and time resolution and sample size. Novel detectors using micro-channel plates (MCP) are now commercially available and offer an increased detection efficiency by a factor 5 to 10 with high spatial resolution while possibly providing additional time resolution.

11.6.3 Analytical tools

Additional neutron analysis techniques, like prompt-gamma activation analysis (PGAA), neutron depth profiling (NDP), etc. profit from the high neutron flux that is available at very short distance to the sample. On sample stages at larger distance one can use the time-of-flight to increase the information content of an experiment, e.g. about the spatial distribution of a specific element inside the sample. At a pulsed source one can expect to achieve very good signal to noise ratio and hence improve the element sensitivity.

11.6.4 Instrument performances

On CANS, the neutron source can be built to match specific instruments requirements. However, due to the wide range of neutron scattering techniques, it is challenging to have “one source fits all needs”. Hence, the time structure should be adapted by building several target stations with different time structures ([long pulse – low repetition rate] and [short pulse – high repetition rate] for example). A further possible refinement is to fit each instrument with a dedicated optimized moderator[60]. Assuming this versatility, Monte-Carlo simulations (MCNP – GEANT4 – McStas) show that the flux at the sample position on a high brilliance CANS should be comparable to the flux on a medium power reactor (such as Orphée) or a medium power spallation source (such as ISIS)[61]. This approach is also attractive comparing the relatively low cost of a target station in comparison to the surrounding instrumentation.

The performances of a wide range of neutron scattering instruments and a few analytical methods was estimated by calculating the neutron flux at the sample position for the HBS design[62]. The performances of these instruments assume that they benefit from an optimized moderator spectrum and an optimized time structure, which requires 3 different time structures and thus 3 different targets. The possibility to perfectly match the source phase-space with the neutron scattering instruments phase-space allows building instruments which make use of most of the produced neutrons. The outcome of these calculations represents the potential performances of a high-end CANS.

Table A3: Basic parameters of instruments at the different target stations of HBS and calculated neutron flux at the sample position. Based on[61].

	Length [m]	Resolution	Bandwidth	Flux [cm^{-2} s^{-1}]	Frequency [Hz]
SANS	20.0	5% $\Delta\lambda/\lambda$	2.0-9.0 Å	9.4×10^7	24
Reflectometer	22.0	4% $\Delta\lambda/\lambda$	1.3-8.0 Å	1.7×10^7	24
Thermal powder diffr.	100.8	0.0061-0.014 $\Delta\, d/d$	0.75-2.4 Å	1.5×10^8	24
Cold neutron imaging I	6.0	2.0-10.0%	1.0-15.0 Å	3.0×10^8	96
Disordered material diffr.	61.0	0.016-0.028 $\Delta\, d/d$	0.5-1.2 Å	1.9×10^7	96
Macromolecular diffr.	12.5		2.0-4.0 Å	4.0×10^7	96
Cold chopper spectr.	18.5		1.6-10.0 Å	3.4×10^5	96
Backscattering spectr.	102.5	3.0-20.0 μeV	6.05-6.0 Å	7.0×10^6	96
Epithermal neutron imaging	37.0		25-80 meV	5.0×10^9	384
High energy chopper spectr.	28.5	4% ΔE/E	0.5-2.5 Å	9.0×10^4	384
PDGNAA-2	21.0	50%	0.6 eV - 10 MeV	2.7×10^7	384

Figure A8 compares the specific case of the performances of existing instruments around the Orphée reactor and equivalent instruments on a source with the SONATE design. It can be seen that for

[60] Workshop on instrumentation at CANS (Gif sur Yvette, 2017); HAL-CEA

[61] F. Ott et al, J. Phys.: Conf. Ser. 1021 (2018) 012007. Performances of Neutron Scattering Spectrometers on a Compact Neutron Source. J. Voigt et al., Nucl. Instr. Meth. A, 884, 59 (2018). Spectrometers for compact neutron sources.

[62] Conceptual Design Report Jülich High Brilliance Neutron Source (HBS), General / Volume 8 ISBN 978-3-95806-501-7. The HBS source design assumes a 70 MeV accelerator with a 100 mA peak current.

scattering techniques which can benefit from the pulsed beam structures (SANS, reflectivity, diffraction), the performances of the instruments would be equivalent, allowing conducting a high-level scientific program. For the techniques which cannot benefit from the pulsed beam structure (white beam radiography or spin-echo), the performances would be reduced. However, these comparisons are based on the flux at the sample position and with the current state of the technology. In the case of radiography, fast progress is taking place in detector technology with the use of detectors using micro-channel plates which achieve detection efficiencies 5 times higher than scintillator technologies. This would raise the performances of radiography measurements on SONATE at the current level of performances around Orphée. In the case of resonant Spin-Echo, the LLB has developed the necessary technology to build a wide-angle instrument (Multi-MUSES) which would increase the performance of the existing instrument by a factor 70. In the case of powder diffraction, the flux at the sample position is also not the only figure of merit. The PRESTO powder diffractometer design on SONATE[63] would achieve performances 10 to 30 times higher just on increasing the detector surface compared to the current instruments.

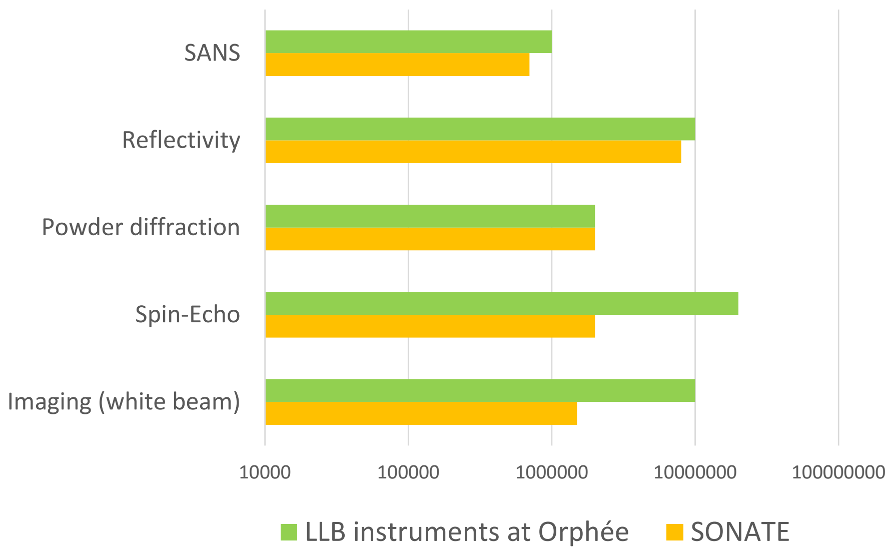


Figure A8: Comparison of the performances of different neutron scattering instruments in terms of neutron flux (n/cm²/s) at the sample position for LLB instruments around Orphée (green) and equivalent instruments around SONATE (yellow).

11.7 Operational considerations

11.7.1 Radiological safety

The sources of radiation are numerous in a CANS. Gamma radiation is induced by the interaction of protons and neutrons with the target as well as by the interaction of neutrons with the moderator, reflector, shielding and further structural materials. Neutrons and gamma radiation are also produced when protons escape the beam and hit the vacuum chamber. Small sources of X-ray radiation are the radio-frequency generators (klystrons).

[63] X. Fabrèges, Un spectromètre de diffraction de poudre sur une source compacte. Séminaire 2FDN sur les sources de neutrons compactes (Paris, 2018).

The design and construction of a CANS must be performed taking into account regulatory requirements in order to guarantee a high level of radiological safety during the operation, maintenance and handling of radioactive materials. A general concept for radiological safety can be provided for a CANS. The details and realization of the safety procedures, including risk management, must be discussed with the national or local licensing authorities.

The objectives of radiation safety at a CANS are to ensure that during normal operation, the maintenance and handling of radioactive components, the radiation dose to personnel, users and population is kept below the limit values defined by the authorities. These objectives are generally met by maintaining safety features which comprises: appropriate shielding, safety interlocks, access to control systems, switches, and alert and caution systems. A sufficient number of qualified radiation protection officers is required for its safe operation.

In order to keep radiation exposure as low as possible, radiation shielding will be built in different parts of the facility such as along the whole proton beam line, around the beam dump, the neutron targets, the neutron guides and the instruments. If necessary, systems for airborne particulate radioactivity monitoring will be installed. Safety procedures including beam safety interlocks, real-time beam diagnostics, and vacuum control will ensure that the average beam power at a target station does not exceed the operation value.

All systems for radiological safety will be monitored during operation of the CANS and their functionalities periodically inspected according to a maintenance plan.

11.7.2 Waste Management

Radionuclides are produced by proton and neutron activation of the target and by neutron activation of the components of the target monolith such as the moderator, reflector, biological shielding and further structural materials. They are also generated in the accelerator components, beam dump and associated shielding by the proton beam itself and induced secondary particles. The produced radioactive materials will be considered as radioactive waste or released via clearance measurements.

11.7.3 Decommissioning

The decommissioning costs should be included in the investment costs of facilities.

In the case of ESS, while this facility will most likely produce significantly more waste than CANS facilities due to the operation at very high proton energies, the decommissioning costs have been estimated as about 10% of the construction costs (M€ 177 for a construction budget of M€ 1843).

In France, for the synchrotron SOLEIL and ESRF, decommissioning costs on the order of 5-10% have also been provisioned. Note that synchrotron facilities are however technically different from neutron sources (use of electrons instead of protons and no neutron transmutation).

12

State of the art across the world

12 State of the art across the world

12.1 CANS across the world

The first "accelerator-based compact neutron sources" were built in the 1960s and used electron accelerators and photofission reactions to produce neutrons. Among the “historical” sources, one can cite Harwell in the UK[64], HUNS (Hokkaido University Neutron Source)[65] and CNS (Compact Neutron Source of Bariloche, Argentina)[66]. The Harwell facility operated 10 instruments and had an external user program.

After a long period without major developments, Bloomington University in the USA, Indiana proposed the construction of a CANS for neutron scattering (based on an existing accelerator). This source called LENS began operating in 2010[67]. In the 2010 decade, projects have multiplied. Figures A6 show the developments around compact sources for neutron production in Japan[68] and China. Compact sources are under construction in several other countries (USA, Korea, KCANS network; SARAF in Israel; in Canada, India, Hungary, Italy…). In France the NFS platform (1kW) at GANIL has been installed[69] and the SAPHIR accelerator for the production of fast neutrons and the radiography of nuclear waste drums.

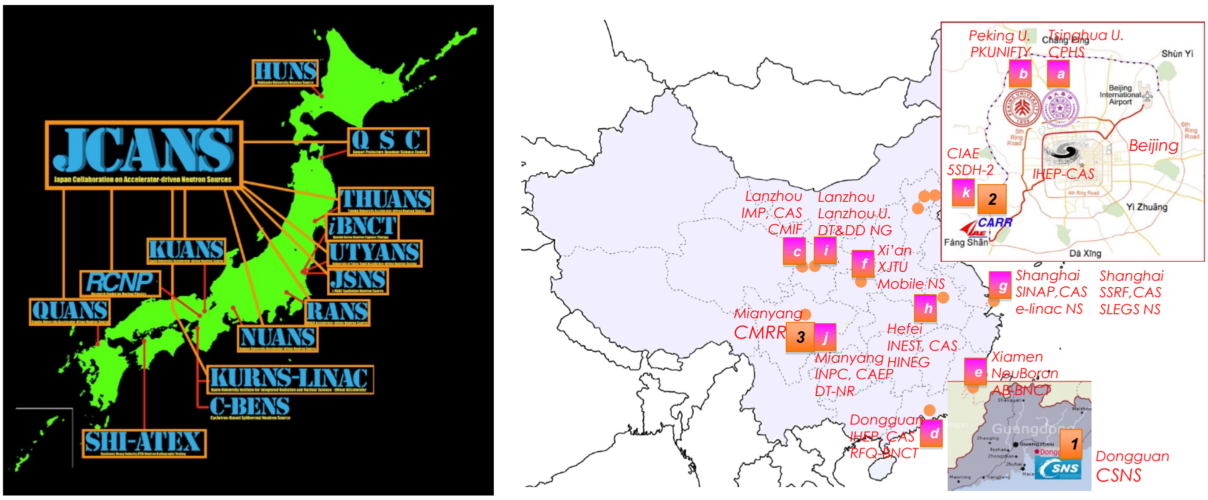


Figure A9: Left: JCANS Network (Japanese CANS). A number of these neutron sources are still in commissioning or in projects. Right: Network of compact sources in China. Beyond the 3 major sources (CNS, CARR, CMRR), China has a dense network of compact sources of lower performance for various applications.

It is however necessary to moderate this abundance aspect by the fact that these installations, built or in commissioning, have a reduced experimental program. It is usually limited to 1-3 experimental stations, the powers of the sources are limited, the scientific objective is very specific (nuclear physics, BNCT, industry). These sources cannot be considered as "platforms". The investment in such equipment, however, demonstrates the motivation of many countries for the production and use of neutron techniques. An overview on existing and planned CANS system is given in Table A4-6

[64] J.P. Scanlon, Proc. 5th Int. Cyclotron Conf., 1969
[65] M. Furusaka et al., Phys. Procedia, 60, 167, 2014
[66] J.R. Granada et al., Eur. Phys. J. Plus, 131, 216, 2016
[67] D.V. Baxter, Eur. Phys. J. Plus, 131, 83, 2016
[68] http://www.jcans.net/
[69] https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/nfs/

below[70,71]. The table refers to facilities with relevant neutron yield (>10^{11} n/cm^2/sec) and is grouped in installations used for neutron scattering applications, nuclear physics based on proton beams and facilities based on electron beams.

Table A4: Proton accelerator-based neutrons sources with primary neutron flux above 10^{11} n/s.

Facilities producing neutrons as analytical tool for solid state physics (neutron scattering, radio-tomography, PGAA…)	**Country**	**Proton Accelerator type**	**Energy (MeV)/ Current (mA)**	**Target**	**Neutron flux**	**Methods**	**Status**
LENS (Low-Energy Neutron Source)	USA	Proton RFQ + linacs	13 MeV / 20 mA	Be		SANS, imaging	Operational since 2005
KUANS (Kyoto University Accelerator-driven Neutron Source)	Japan	Proton RFQ	3.5 MeV / 100 μA	Be	10^{11} n/cm^2/s		Operational
RANS (RIKEN Accelerator-driven Neutron Source)	Japan	Proton RFQ + linac	7 MeV / 70-100 μA	Be	10^{12} n/cm^2/s	SANS, PGAA, diffraction, imaging	Operational since 2013
CPHS (Compact Pulsed Hadron Source of Tsinghua University)	PR China	Proton linac					Operational since 2013
PKUNIFTY	PR China	RFQ linac					Operational
NUANS (Nagoya University Accelerator-driven Neutron Source)	Japan	Proton DC accelerator (Dynamitron)	2.8 MeV / 15 mA	Li, Be			Under construction
ESS Bilbao Project	Spain	Proton linac	50 MeV / 75 mA	Be	2.9 10^{15} n/cm^2 eV Sr s MW		Under study or ongoing development
LENOS (Legnaro Neutron Source)	Italy	Proton RFQ	5 MeV / 50 mA	Li	10^{14} n/cm^2/s		Under study or ongoing development
NEPIR facility at the SPES source of Laboratori Nazionali di Legnaro	Italy	Proton cyclotron	35-70 MeV /	Li, Be		nuclear physics, irradiation	Under study or under construction
SARAF	Israel	Proton RFQ	40 MeV / 5 mA	liq. Li, liq. Ga		mostly nuclear physics	Under construction

NOTA: There several dozen proton accelerator-based neutron sources with lower flux used in the field of nuclear science.

Table A5: Proton accelerator-based neutrons sources with primary neutron flux above 10^{11} n/s in the field of nuclear science.

Facilities producing neutrons as analytical tool for nuclear physics	**Country**	**Proton Accelerator type**	**Energy (MeV)/ Current (mA)**	**Target**	**Neutron flux**	**Methods**	**Status**
ASP Neutron Generator	UK		14 MeV	3H	2.5 10^{11} s^{-1}	nuclear physics, irradiation	Operational
TSL Svedberg Laboratory	Sweden	Cyclotron	20-180 MeV / 10 μA	Li		nuclear physics, irradiation	Operational
IGISOL	Sweden	Cyclotron	18-30 MeV / 100 μA	Be		nuclear physics, irradiation	
NPI cyclotron	Czech Republic	Cyclotron	38 MeV / 20 μA	Li		nuclear physics, irradiation	
IPPE (Institute of Physics and Power Engineering)	Russia	Tandem Van-de-Graaf accelerator	0.3-15 MeV			nuclear physics, irradiation	Operational
FRS / JAEA Pelletron accelerator	Japan	Tandem Pelletron accelerator	4 MeV	Li		nuclear physics, irradiation	Operational
Tokyo Tech Research Laboratory for Nuclear Reactors	Japan	Pelletron accelerator	3 MeV	Li		irradition	Operational
RCNP cyclotron facility	Japan	Cyclotron	100-400 MeV / 1 μA	Li		nuclear physics, irradiation	Operational
JAEA tandem facility at the Tokai	Japan	Tandem Pelletron accelerator	2.5-18 MeV	Th, U		nuclear physics, irradiation	Operational
KOMAC-NST, KIRAMS-MC-50	Korea	Tandem accelerator, cyclotron					Operational since 2000
University of Kentucky Accelerator Laboratory	USA	Van-de-Graaf accelerator	5.5 MeV			nuclear physics, irradiation	

[70] IAEA TECDOC 174 2014
[71] I.A. Anderson et al., Phys. Rep. 654, 1, 2016

Table A6: Electron accelerator-based neutrons sources with primary neutron flux above 10^{11} n/s.

Facilities producing neutrons as analytical tool for nuclear physics	Country	Electron Accelerator type	Energy (MeV)/ Current (mA)	Target	Neutron flux	Methods	Status
GELINA (Geel Electron Linear Accelerator Facility)	Belgium	Electron linac	150 MeV	U, Mo	3.4 10^{13} n/s	nuclear physics, irradiation	Operational
nELBE (Time-of-flight facility at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR))	Germany	Electron linac, superconducting	40 MeV / 1.6 mA	liq. Pb	10^{13} n/s	nuclear physics, irradiation	Under study or ongoing development
n@BTF (Frascati electron-driven source)	Italy	Electron linac				nuclear physics	Under upgrade
HUNS (Hokkaido University Neutron Source)	Japan	Electron linac	45 MeV / 140 μA	Pb	1.6 10^{12} n/s	SANS, Imaging	Operational since 1974
KURRI-LINAC (Kyoto University Research Reactor Institute, Electron Linear Accelerator)	Japan	Electron linac	0-46 MeV /	Ta	8 10^{12} n/s		Operational
UTCANS (University of Tokyo CANS)	Japan	Electron linac					Under study or ongoing development
PAL-PNF	Korea	Electron linac	40-100 MeV / 30-100 mA	Ta	1.9 10^{12} n/s	nuclear physics, irradiation	Operational since 2000
Gaerttner linear accelerator at Rensselaer Polytechnic Institute	USA	Electron linac				nuclear physics, irradiation	Operational
Bariloche Linac	Argentina	Electron linac	25 MeV	U	2 10^{13} n/s	nuclear physics, irradiation	Operation stopped 2018
NFS SPIRAL2	France	Proton linac	33-40 MeV / 50 μA	Be, C	5 10^{11} n/cm²/s	nuclear physics, irradiation	Under commissioning
FRANZ (Frankfurt Neutron Source at the Stern-Gerlach-Zentrum)	Germany	Proton linac	1.8-2.2 MeV / 20 mA	Li	10^{12} n/cm²/s	nuclear physics, astrophysics	Under construction or ongoing development

NOTA: There are several dozen proton accelerator-based neutron sources with lower flux used in the field of nuclear science.

12.2 Examples of analytical studies using CANS

12.2.1 Small Angle Neutron Scattering on CANS

The ratio of neutron flux at large facilities to the one at CANS is quite large, of the order of 10^3-10^5. Despite this fact, CANS can be competitive in many important areas, for example in case of metallurgical materials development. Small-angle X-ray and neutron scattering methods are inherently strong in the area where TEM is not appropriate. The *Q*-range necessary for this kind of measurement is centered around 1 nm^{-1} region. Concentration in measuring this region, gives an intensity gain compared with measuring conventional SANS region around 10^{-2}-10^{-3}.

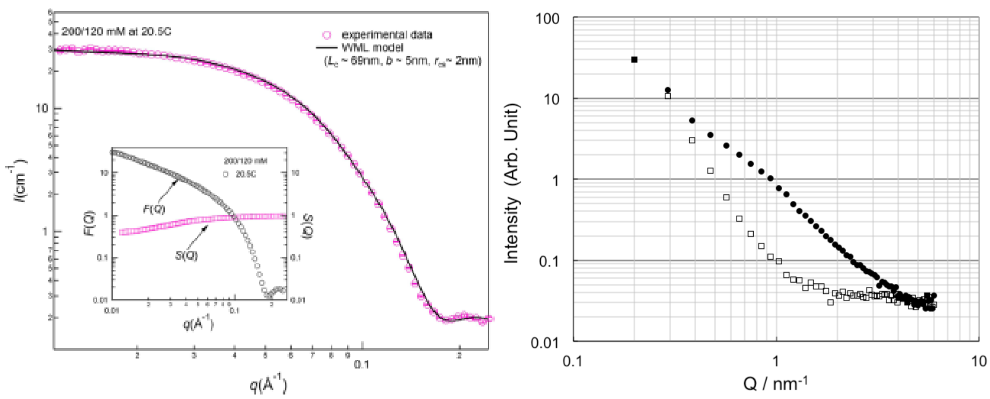


Figure A10: (left) SANS data. CTAB (200mM) micelles with 120 mM NaCl. Measured at LENS@13MeV; 20mA; 20Hz, 600µs; I_{av} = 0.24mA ; P = 3kW (Das et al, Langmuir 2014). (right) SANS in steel samples with (filled markers) and without (open markers) nanoscopic precipitates.[72]

[72] M. Furusaka et al, Physics Procedia 60 (2014) 167-174. Activity of Hokkaido University Neutron Source, HUNS.

The Intermediate-Angle Neutron Scattering instrument, iANS, at HUNS is one such instrument. It focuses to the nanoscopic structure studies in metal materials. In Fig. A10 right, SANS in steel samples with and without nanoscopic precipitates are shown. Small/medium-angle neutron scattering was measured with good enough statistics in the Q-range of 0.2 to 5 nm^{-1} with a measuring time of about 6 hours.

12.2.2 Powder Diffraction on CANS

HUNS is a compact accelerator-based short-pulsed cold neutron source. It is relatively easy to observe shape change of a Bragg-edge transmission spectrum caused by change of crystal orientation distribution (texture), and also increase of transmission intensities due to the primary extinction effect (multiple diffraction inside a crystallite) caused by coarse crystallites. Fig. A11 shows Bragg-edge transmission spectra of various α-irons measured at HUNS, and the profile fitting curves obtained by the RITS code. The changes of shape/intensity due to texture/crystallite size are experimentally observed. Transmission spectra calculated by the RITS code follow experimental data with good agreement. Through such profile fitting analyses with the RITS code, successfully material parameters on texture (preferred orientation and degree of crystallographic anisotropy) and microstructure (crystallite size) could be evaluated at HUNS.

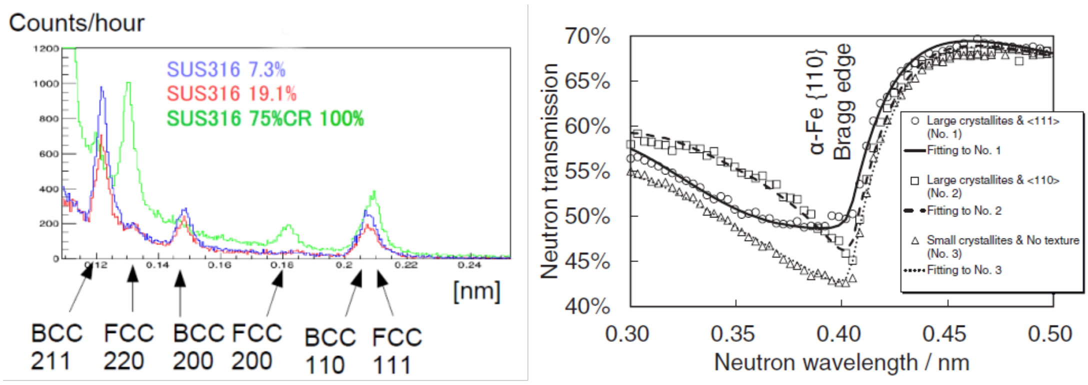


Figure A11: (left) Powder diffraction patterns on steel samples providing the austenite – martensite ratios[73]. (right) Bragg-edge transmission spectra measured at HUNS, and the profile fitting curves obtained by RITS.[72]

12.2.3 Neutron Texture on CANS

The figure below (Fig. A12) shows texture measurements on rolled steel performed at different sources (i) RANS @ RIKEN operating at a power of 700 W (proton power on the target), (ii) TAKUMI @ J-PARC spectrometer, the Japanese spallation source, (iii) HIPPO @ LANSCE spectrometer, on a spallation source in the USA.

The "raw" neutron flux at the sample level on RANS was 0.4% that of TAKUMI and 0.2% that of HIPPO. However, thanks to an optimization of the instrumentation and of the measurement protocol, it is possible to obtain data equivalent to that of the instruments on spallation sources with "reasonable" acquisition times (5 hours per sample). In 3 days of experiments, it is therefore potentially possible to

[73] R. Oishi et al, NIM A 600 (2009) 94-96. Rietveld analysis software for J-PARC;
Ikeda, Yoshimasa; Takamura, Masato; Hakoyama, Tomoyuki; et al. TETSU TO HAGANE-JOURNAL OF THE IRON AND STEEL INSTITUTE OF JAPAN 104 (2018) 138-144. Development of On-site Measurement Technique of Retained Austenite Volume Fraction by Compact Neutron Source RANS.

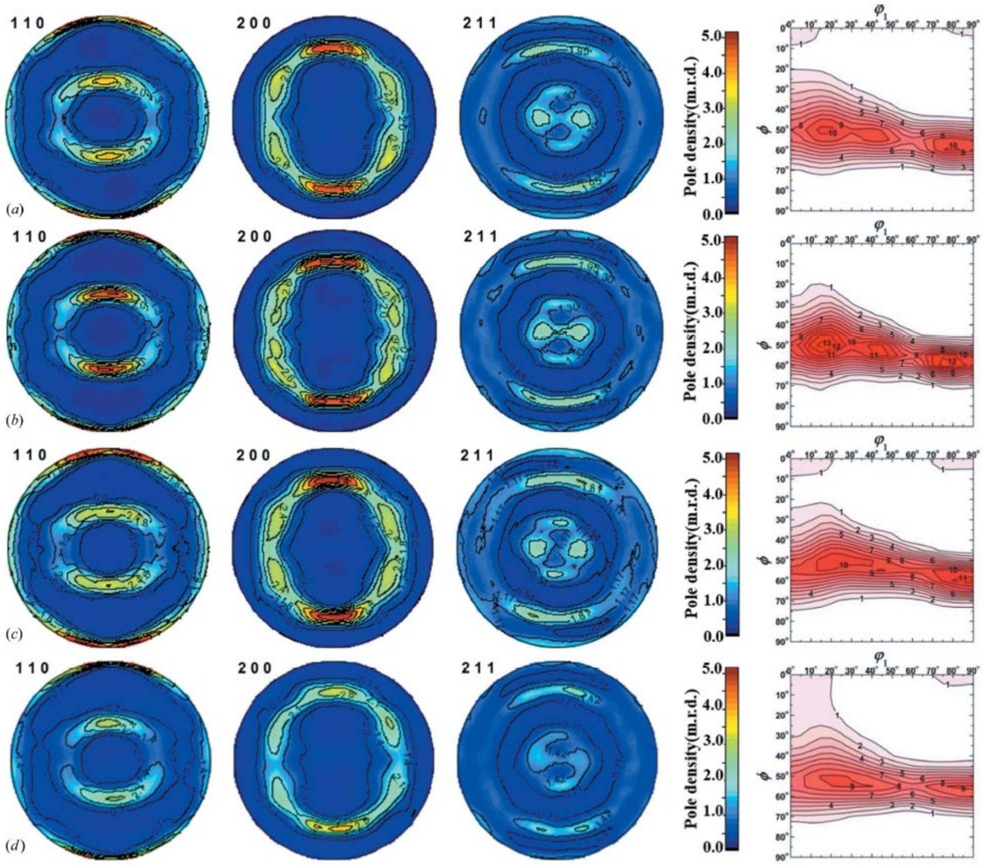


Figure A12: Example of measurements of pole figures[74]. (a) - (b) On RANS, with 2 different assumptions on the modelling parameters ("unequal d-range" and "" equal d-range); (c) Measurement on TAKUMI @ JPARC; (d) Measurement on HIPPO @ LANSCE.

characterize a dozen different grades of steel. Other examples were given during the seminar on compact neutron sources - April 13, 2018 organized by the 2FDN[75].

12.2.4 Neutron radiography on CANS

Using high-performance neutron radiography, nondestructive quantitative observation of localized water movement in corroded painted steel during the drying process can be visualized. The approach to visualizing the water drying process in such devices was demonstrated at RANS, a compact neutron source.

The accumulation of water in a specific area due to the progression of wet corrosion is strongly correlated with the product of the amount of water and the wetness duration[76]. Figure A13 left shows the two-dimensional spatial distributions of water. X and Y describe the position in the unit of mm. The color indicates the water content, where red indicates a high and blue indicates a low water content. This water distribution indicates that water remains for a long time along the edge. This is consistent with the observation of no significant change in the width of the water distribution after prolonged time drying.

[74] Pingguang Xu, Yoshimasa Ikeda, Tomoyuki Hakoyama, Masato Takamura, Yoshie Otake and Hiroshi Suzuki, J. Appl. Cryst. (2020). 53, 444-454. https://doi.org/10.1107/S1600576720002551. In-house texture measurement using a compact neutron source.

[75] Séminaire sur les sources de neutrons compactes (Paris, Avril 2018). http://2fdn.neel.cnrs.fr/IMG/pdf/Worshop_Cans/Menelle_CANS_existantes.pdf

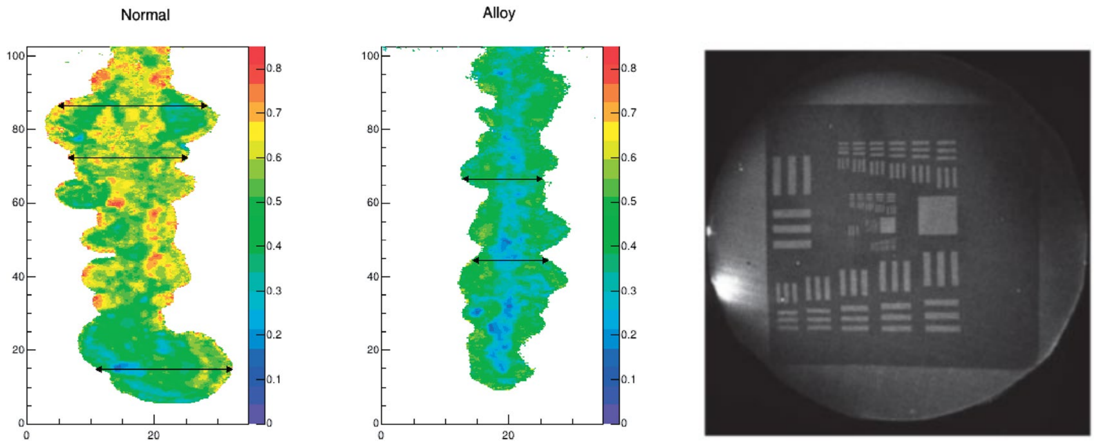


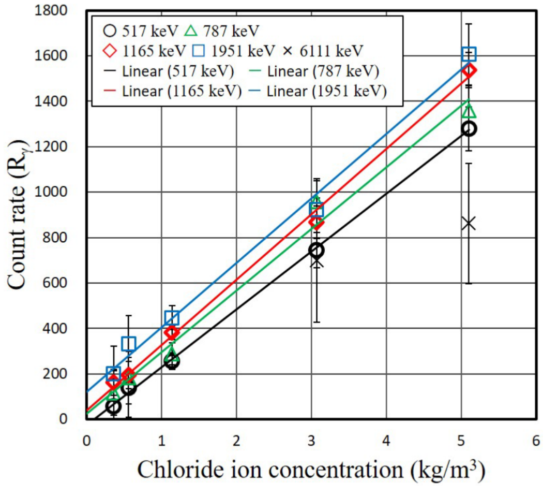
Figure A13: (left) Radiography of corroded steel plates and humidity up-take as a function of time. Pixel Size 0.8x0.8mm² ; Measured at RANS; 5 minutes exposure time; E_p = 7 MeV ; I_{av} = 15µA ; P = 100W[76]. (right) MCP image of a USAF-1951 Gd-mask measured with the beam line of CPHS at 3MeV.

12.2.5 Other analytical methods

The chloride ion distribution in concrete is important from the viewpoint of preventive maintenance against chloride attack causing deterioration of many concrete structures. As a non-destructive measurement, neutron-captured prompt gamma-ray analysis (PGA) can be applied as a diagnostic technique of a non-destructive measurement method. Recently, the γ-ray sensitivities of mortar samples with different chloride ion concentrations were determined experimentally by PGA using the RIKEN accelerator-driven compact neutron source. The time of flight measurement technique with pulsed neutrons was applied to determine the depth profile of chloride ion distribution in concrete. The results showed that the present detection system was sensitive to a chloride ion concentration of 1 kg/m^3, which is lower than the marginal chloride ion concentration of 1.2 - 2.5 kg/m^3 to incur corrosion (Fig. A14 left).

One of the key elements of preventive maintenance for such infrastructures is to conduct effective and efficient nondestructive inspections. However, effective methods have yet to be established, especially for deep within sections of concrete. A new transmission imaging method for bulk concrete structures using fast neutrons at the accelerator driven compact neutron source RANS has been applied. Successfully embedded steel bars could be identified, a void hole, and water with 300-mm-thick concrete blocks via the RIKEN Accelerator-driven compact Neutron Source (RANS). In Fig. A14 right the transmission images of the quartz cell without water obtained for the second column is given.

[76] Taketani, Atsushi; Wakabayashi, Yasuo; Otake, Yoshie; et al., MATERIALS TRANSACTIONS 59 (2018) 976-983. Quantification of Localized Water Image in Under-Film Corroded Steel with High Spatial Resolution, High Time Resolution, and Wide View by Neutron Radiography



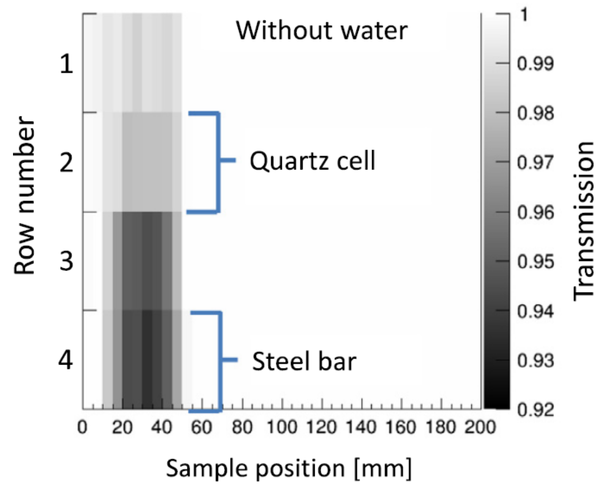


Figure A14: (left) Quantification of the chlorine content in concrete by PGA measured at RANS[77]. (right) Observation of water in concrete using fast neutrons[78].

12.3 Current CANS projects in Europe

In Europe several institutes are considering various CANS facilities using the latest available technologies. They include smaller facilities comparable to existing CANS as well as projects to achieve high brilliance and competitive neutron fluxes.

12.3.1.1 The ESS-B reference design

The ESS-Bilbao institute is in charge of the Spanish contribution to the ESS construction. It has put together a detailed technical design study of a CANS design which could provide neutrons as a user facility[79]. The ARGITU reference design is based on a 31.5 MeV proton accelerator and a power on the target of about 50 kW. It will be using a rotating Beryllium target.

12.3.1.2 The HBS reference design

The Jülich Center for Neutron Scattering at the Forschung Zentrum Jülich is proposing the design of a High Brilliance Source (HBS) with the following parameters, E_p = 70 MeV, I_{peak} = 100 mA, P = 100 kW, fixed Ta target[80].

12.3.1.3 The SONATE reference design

The CEA is considering a reference design SONATE with the following parameters: E_p = 20 MeV, I_{peak} = 100 mA, duty cycle = 4%, P = 80 kW, fixed Be target[81].
These parameters were chosen partly because they correspond to the first 20 m of the ESS Linac (out of 600 m). Hence the components (Source, RFQ and DTL) are available with no R&D developments.

---

[77] Wakabayashi, Yasuo; Yoshimura, Yuichi; Mizuta, Maki; et al., JOURNAL OF ADVANCED CONCRETE TECHNOLOGY **17** (2019) 571-578. Feasibility Study of Nondestructive Diagnostic Method for Chlorine in Concrete by Compact Neutron Source and PGA
[78] Seki, Yoshichika; Taketani, Atsushi; Hashiguchi, Takao; et al. NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 870 (2017) 148-155. Fast neutron transmission imaging of the interior of large-scale concrete structures using a newly developed pixel-type detector.
[79] de Vicente, J.P.; Fernandez-Alonso, F.; Sordo, F.; Bermejo, F.J, RAL-TR-2013-016 Technical Report (2013). Neutrons at ESS-Bilbao: From Production to Utilisation.
[80] Conceptual Design Report Jülich High Brilliance Neutron Source (HBS) General / Volume 8 ISBN 978-3-95806-501-7
[81] http://iramis.cea.fr/llb/Phocea/Vie_des_labos/Ast/ast_sstechnique.php?id_ast=2755

12.3.1.4 The LENOS design

The LNL Laboratori Nazionali di Legnaro is developing the LENOS facility (LEgnaro NeutrOn Source facility)[82]. The design parameters are E_p = 70 MeV, I_{av} = 750 µA, Lithium target. This facility is close to completion but is not oriented towards neutron scattering but rather towards nuclear physics.

12.3.1.5 The NOVA-ERA reference design

The Jülich Center for Neutron Scattering at the Forschung Zentrum Jülich is also considering the construction of a “laboratory” source with modest performances NOVA-ERA: Neutrons Obtained Via Accelerator for Education and Research Activities.[83]
The design parameters are E_p = 10 MeV, I_{peak} = 1 mA, P = 1 kW, Be target, duty cycle 4-10%. Such a source can be built using off-the-shelf commercial proton accelerators.

12.3.1.6 The LvB design

The Hungarian company Mirrotron Ltd. has started to build a low energy CANS (LvB) which will use a low energy accelerator (3 MeV)[84].

[82] P. Mastinu et al., Physics Procedia, 26 (2012) 261, Status of the LEgnaro NeutrOn Source facility (LENOS)
[83] Conceptual Design Report NOVA ERA, General / Volume 7 ISBN 978-3-95806-280-1
[84] https://mirrotron.com/en/about/news-hirek

13

References on CANS

13 References on CANS

Reviews

I.S. Anderson et al., Research opportunities with compact accelerator-driven neutron sources, Physics Reports, 654 (2016) 1-58.

C. Andreani, C,-K. Loong, G. Prete (Eds.) EPJ Plus Focus Point on Compact accelerator-driven neutron sources, 131 (2016) 217

J. Carpenter, The development of compact neutron sources, Nature Rev. Phys., 1 (2019) 177-179

F. Ott, A. Menelle, C. Alba-Simionesco (Eds.) 8th International Meeting of Union for Compact Accelerator-Driven Neutron Sources (UCANS-8), EPJ Web Conf., 231 (2020)

Projects

J.P. de Vincente et al, Neutrons at ESS Bilbao: From Production to Utilisation, STFC Technical Report RAL-TR-2013-016 (2013)

F. Sordo et al., Baseline design of a low energy neutron source at ESS Bilbao, J Phys.:Conf. Ser. 549 (2014) 012001

U. Rücker et al., The Jülich high-brilliance neutron source project, Eur. Phys. J. Plus 131 (2016) 19

L. Silvestrin et al., SPES and the neutron facilities at laboratory Nazionali Legnaro, Eur. Phys. J. Plus 131 (2016) 72

D. Baxter, Materials and neutronic research at the Low Energy Neutron Source, Eur. Phys. J. Plus 131 (2016) 83

S. Alzubaidi et al., The Frankfurt neutron source FRANZ, Eur. Phys. J. Plus 131 (2016) 124

Y. Kiyanagi, JCANS network of compact neutron facilities in Japan, Eur. Phys. J. Plus 131 (2016) 132

S. Böhm et al., Neutron Scattering Instrumentation at Compact Neutron Sources. Workshop on ”Neutron Scattering Instrumentation at Compact Neutron Sources”, Gif-sur-Yvette, France, Juillet 2017, Gif sur Yvette, France. cea-01870227 (2017)

P. Zakalek et al., High-Brilliance Neutron Source Project, 14th Int. Conf. Heavy Ion Accelerator Tech. HIAT2018, Lanzhou, China, JACoW-HIAT2018-WEZAA (2019) 117-121

F. Ott et al., The SONATE project, a French CANS for Materials Sciences Research, EPJ Web Conf., 231 (2020) 01004. *http://iramis.cea.fr/llb/Phocea/Vie_des_labos/Ast/ast_sstechnique.php?id_ast=2755*

Y. Otake, RIKEN Accelerator-driven compact neutron systems, EPJ Web Conf., 231 (2020) 01009

T. Brückel, T. Gutberlet (Eds.), Conceptual Design Report, Jülich High Brilliance Neutron Source (HBS), Schriften des Forschungszentrums Jülich, General / Volume 8 (2020), ISBN 978-3-95806-501-7. *https://www.fz-juelich.de/jcns/jcns-2/EN/Forschung/High-Brilliance-Neutron-Source/_node.html*

List of participants in the editorial group of the Report

Editors:

- Thomas Brückel (FZJ)
- Eric Eliot (LLB)
- Thomas Gutberlet (FZJ)
- Alain Menelle (LLB)
- Frederic Ott (LLB)

Participants:

- Fernando Sordo (ESS Bilbao)
- Felix Villacorta (ESS Bilbao)
- Ibon Bustinduy (ESS Bilbao)
- Pierfrancesco Mastinu (LNL)
- Gianfranco Prete (LNL)
- Luca Silvestrin (INFN Padua)
- Jeffrey Wyss (INFN Padua)
- Philip King (ISIS)
- Robert McGreevy (ISIS)
- Michael Jentschel (ILL)
- Yoann Calzavara (ILL)
- Knud Thomsen (PSI)
- Jerome Schwindling (IRFU)
- Holger Podlech (Uni Frankfurt)
- Henrik Ronnow (EPFL)
- Eric Mauerhofer (FZJ)
- Ulrich Rücker (FZJ)
- Jörg Voigt (FZJ)
- Paul Zakalek (FZJ)

Mailing list:

t.brueckel@fz-juelich.de;
eric.eliot@cea.fr;
t.gutberlet@fz-juelich.de;
alain.menelle@cea.fr;
frederic.ott@cea.fr;
fernando.sordo@essbilbao.org;
fjimenez@essbilbao.org;
ibustinduy@essbilbao.org;
pierfrancesco.mastinu@lnl.infn.it;
gianfranco.prete@lnl.infn.it
luca.silvestrin@pd.infn.it
wyss@pd.infn.it
philip.king@stfc.ac.uk;
robert.mcgreevy@stfc.ac.uk;
jentsch@ill.fr;
calzavara@ill.fr;
knud.thomsen@psi.ch;
jerome.schwindling@cea.fr;
h.podlech@iap.uni-frankfurt.de;
henrik.ronnow@epfl.ch;
e.mauerhofer@fz-juelich.de;
u.ruecker@fz-juelich.de;
j.voigt@fz-juelich.de;
p.zakalek@fz-juelich.de;