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Low energy accelerator-driven neutron facilities—A prospect for a brighter future for research with neutrons

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Introduction

The major grand challenges of humankind in the decades to come are (i) the energy and climate transformation of our societies, (ii) maintaining the physical and psychical health of an aging population, and (iii) creating a digital world beneficial to everyone. One of the key methods to approach these global objectives is materials research of natural and artificial matter. Success depends critically on the availability of all possible kinds of powerful methods able to unravel the structure and function of matter at different length and time scales. Each method adds its own specific and unique set of properties to a global approach of understanding and designing future high performance materials.

From the outstanding scientific advances achieved with neutron research during the pioneering years to solutions to the grand scientific and technological challenges of the future, neutrons are microscopic probes that are irreplaceable and are becoming more and more essential in an ever-increasing number of disciplines. The success of the neutron as an analytical tool is based on a hierarchical network of neutron facilities. Low flux sources with a limited number of instruments at universities provide the foundation by educating the next generation of neutron users and offering a platform for methods development. This aspect is particularly important as standard laboratory-size instruments available for research with photons or electrons, for example, are missing for research with neutrons. Medium flux sources with more extensive instrumentation cover similar aspects, but also provide capacity and capability, e.g. by specializing on certain aspects like advanced sample environment or by addressing a specific local or regional user group. Finally, the flagship facilities are essential for the most demanding flux-hungry experiments.

Three world regions feature flagship facilities: Europe hosts the Institute Laue-Langevin (ILL) with its High Flux Reactor (HFR) in Grenoble, France; North America is home of the first Mega Watt spallation source (SNS) in Oak Ridge National Laboratory, USA; and in Asia, Japan operates the JSNS at J-Parc. In Europe, we are looking forward to the commissioning of the European Spallation Source (ESS), which aims to become the world-leading neutron facility in the medium term. User demand for beamtime is extremely high at these facilities and a healthy ecosystem can only be maintained through a network of regional, national and global sources. This is where the field of research with neutrons runs into a very serious problem: most of the medium flux facilities are based on research reactors which were constructed in the previous century and are approaching, or have already reached, the end of their lifetime. This is particularly true for Europe, which over the years produced about one-half of the scientific output in the field [1] through its well-developed neutron landscape.

Just last year, three important research reactors were permanently shut down in Europe: JEEP II in Kjeller, Norway, Orphée in Saclay, France and BER II in Berlin, Germany. Similar trends are observed in other world regions: in 2018 the National Research Universal (NRU) reactor, operated by the Canadian Nuclear Laboratories (CNL) at Chalk River, Ontario, was taken out of service. We could go on with many more examples during the past decade. With this slow phasing out of older research reactors, the neutron community loses significant capacity and capability. For Europe, this has been analyzed in detail by a working group of the European Strategy Forum on Research Infrastructures on the neutron landscape in Europe [2], which in different scenarios predicts a dramatic loss of instrument beam days. But this problematic situation can also be considered a unique opportunity to develop new concepts for sources with problem-tailored performance and societal acceptance. Therefore, it does not come as a surprise that, worldwide, several projects to design and eventually build new neutron facilities have appeared. Many of them are based on Low Energy accelerator-driven Neutron Sources (LENS[1]).

In what follows, we will introduce the concept of such sources, give examples of existing facilities and ongoing projects, highlight their potential and discuss their possible function within a future neutron landscape. Details on the present-day usage of such facilities and the design parameters of ongoing projects can be found in the subsequent articles.

Processes producing beams of free neutrons

Table 1 gives an overview of different nuclear processes to release neutrons from atomic nuclei [3]. Since the total neutron yield is mainly limited by the ability to remove the heat released during the nuclear processes, it becomes immediately clear that spallation is the method of choice if one aims at the highest source strength, immediately followed by fission in nuclear reactors. All other processes are orders of magnitude less efficient in terms of neutron yield and heat release. Therefore, it is natural that flagship facilities are based on spallation (e.g. SNS, JSNS or ESS) or fission (ILL, MLZ). Nevertheless, the alternative processes have found applications. Nuclear fusion is employed in neutron generators for laboratory application or as portable devices e.g. for oil well logging. Nuclear reactions induced by low energy (some 10 MeV) particle (electron, proton, deuteron) impact are employed in so-called Compact Accelerator-driven Neutron Sources (CANS, e.g. SARAF, HUNS, n-ELBE, RANS, LENS-Indiana, GELINA). Some of these sources serve specific purposes, from nuclear physics applications measuring high energy neutron cross-sections (e.g. [4]), via portable sources for the non-destructive inspection of road infrastructures such as bridges, tunnels, and elevated roadways [5], to medical applications in hospitals for Boron Neutron Capture Therapy (BNCT) [6]. In what follows we will restrict ourselves to neutron scattering, imaging and neutron analytics facilities.

[1]Note that in this article the acronym LENS is being used with several meanings: 1) the specific neutron facility LENS in Bloomington, Indiana; 2) Low Energy accelerator-driven Neutron Sources in general; and 3) the League of advanced European Neutron Sources. When necessary to avoid confusion, we will designate case 1 as LENS-Indiana.

Concept of high-brilliance LENS

For a neutron facility, it seems natural at first sight to maximize the source strength, i.e. the raw number of fast neutrons released per second. This will lead to the highest neutron flux in the surrounding thermal moderator, which is undoubtedly important for applications such as the production of certain radioisotopes for medicine and technology or homogeneous doping of silicon for the semiconductor industry. However, one can question whether the source strength is the correct factor of merit for neutron beam applications. High flux reactors produce on the order of 10^{18} n/s (neutrons per second), while, after beam preparation, typical scattering instruments at these facilities have a neutron flux of some 10^6 to 10^8 n/s·cm^2 at the sample position, i.e. most (on the order of 10^{18} n/s) neutrons end up in the biological shielding and produce background radiation. In fact, for neutron beam applications, the brilliance of the source,

$$B = \frac{neutrons}{A\Omega(1\%\Delta\lambda/\lambda)\Delta t} \tag{1}$$

i.e. the number of neutrons emitted from the source surface with an area of A into a solid angle Ω inside a wavelength band $\Delta\lambda$ at a mean wavelength λ within a time Δt is the decisive quality parameter, since according to Liouville's theorem

$$\prod_{i=1}^{3}(\Delta q_i \cdot \Delta p_i) = const \tag{2}$$

the volume in phase space is constant for conservative optics. This means that for loss-less devices the brilliance of the beam at the sample position of the instrument is identical to the brilliance of the source.

If we chose brilliance as the quality parameter of a neutron beam research facility and employ the latest developments in accelerator, target, moderator and beam extraction technologies, Low Energy accelerator-driven Neutron Sources (LENS) become extremely competitive

Table 1. Compilation of different nuclear processes to release neutrons from atomic nuclei with examples for the corresponding neutron yield and facilities using the respective processes. The table is based on reference [3].

Nuclear Process	Example	Neutron Yield	Heat Release (MeV/n)	Facilities (examples)
D-T in solid target	400 keV d on T in Ti	4×10^{-5} n/d	10000	Neutron generators
Deuteron stripping	40 MeV d on liq. Li	7×10^{-2} n/d	3500	SARAF
Nuclear photo effect from e-Bremsstrahlung	100 MeV e– on ^{238}U	5×10^{-2} n/e$^-$	2000	HUNS, n-ELBE
^{9}Be(d,n)^{10}Be	15 MeV d on Be	1.5×10^{-2} n/d	1000	
^{9}Be(p,n:p,pn)	11 MeV p on Be	5×10^{-3} n/p	2000	RANS, LENS
Nuclear fission	Fission of ^{235}U by thermal neutrons	1n/fission	180	MLZ, ILL
Spallation	800 MeV p on ^{238}U or Pb	27 n/p or 17 n/p	55 or 30	SNS, JSNS, ESS

with existing medium flux reactor or spallation sources in terms of instrument performance. This has been shown within the SONATE [7] and HBS [8] projects, which are described in detail in other contributions to this special edition of *Neutron News*.

To understand in a hand-waving argument how a much less efficient nuclear reaction can compete with the most efficient process of spallation in terms of beam brilliance, one has to consider three aspects: 1) the proton beam current, 2) a solid angle effect due to an exceptionally compact arrangement and 3) extremely efficient neutron beam extraction:

1. Spallation requires proton beams with energies in the GeV range, say 1 GeV, reaching a beam power of several 100 kW to 1 MW or more at the target. An accelerator delivering the same beam power on target, but designed for 10 MeV protons, has a proton beam current which is 100 times higher. This induces correspondingly more nuclear reactions, partly compensating for the lower cross section of the individual nuclear reaction to reach an appropriate neutron yield.
2. Another factor comes from the extreme compactness of the target-moderator-reflector assembly, which avoids losses due to solid angle effects (see Figure 1). Note that for spallation sources, the neutron production takes place within several 10 cm in the depth of the target material, while for the low energy accelerator-driven sources, the target has a thickness of only a few mm, allowing significantly better coupling between target and moderator.
3. The radiation level around the target is orders of magnitude smaller for LENS compared to spallation sources, where high energy particles up to the energy of the impinging protons and an extremely high level of gamma radiation are produced. As a result, at low energy accelerator-driven neutron sources, optical elements such as neutron guides or neutron lenses can be placed in close proximity to the moderator, resulting in extremely efficient neutron beam extraction.

Given these three factors and pushing modern technologies to the limit, these types of neutron facilities can become highly competitive to existing medium flux fission- or spallation-based neutron sources. Such high-end versions are distinctly different from the already existing CANS—with accelerator lengths approaching 100 m and a full suite of instruments, they are no longer "compact", see e.g. the HBS or SONATE projects. But focusing on brilliance instead of the source strength, these facility projects mark a change of paradigm in the sense "produce less and use more". This novel approach reduces the cost of installation and operation while maximizing the brilliance for research on small samples.

Moreover, with the concept of several target stations and one-dimensional finger moderators, the neutron moderator becomes an integral part of the instrument. Compromises in pulse structure and moderator design are no longer necessary, opening another change of paradigm: the neutron source becomes an integral part of the instrument instead of the present-day compromise of "one source has to fit all instruments". Another beauty of these type of sources is the fact that they are scal-

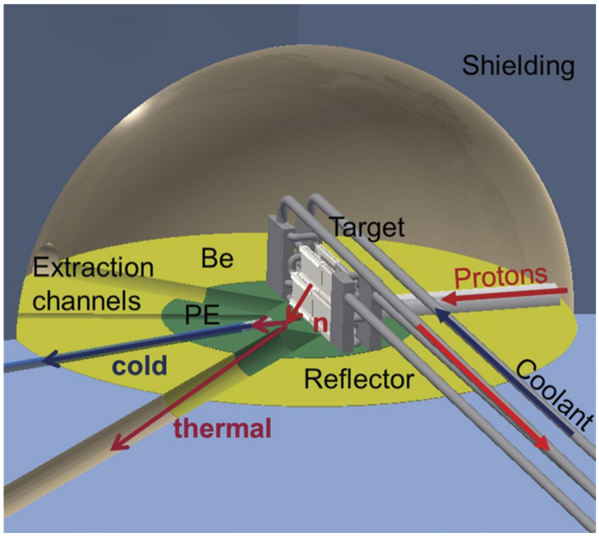

Figure 1. Schematic drawing of a possible target-moderator-reflector-shielding assembly of a Low Energy accelerator-driven Neutron Source LENS. The proton beam power on the target can be on the order of 100 kW (see SONATE and HBS projects) with target dimensions of approximately 10x10x1 cm^2. The target is entirely surrounded by the thermal moderator covering close to 4π in solid angle. The moderator in turn is encased by the reflector. Such an arrangement minimizes the loss of neutrons released within the target. In the extraction channels for thermal neutrons, one-dimensional cold finger moderators can be inserted, which are optimized for the specific application and become integral part of the instrument.

able from large laboratory size to full-fledged user facility since they do not depend on the high proton beam energy necessary to induce spallation processes. This aspect can help to spread research with neutrons to universities, research institutions or industrial companies if they are only interested in some specific neutron beam instruments.

CANS and projects for Low Energy accelerator-driven Neutron Sources (LENS)

The concept of CANS is not new. A review of their history, existing facilities and their applications is given in [9]. What is novel is the idea to apply all recent technological advances and the above-mentioned paradigm changes to make LENS facilities highly competitive. Here we just introduce a few examples for existing facilities and projects, some of which are described in more detail in separate articles in this issue.

Probably the most well-known CANS facility is operated by Indiana University in Bloomington, Indiana. LENS(-Indiana) [10] features a 13 MeV proton LINAC, two water-cooled Be target stations and a solid-methane cold moderator at one target station. This facility has demonstrated the potential of CANS for method development, e.g. for neutron moderators or Larmor precession techniques.

The neutron community in Japan has realized early on that the JSNS flagship facility needs to be underpinned by a network of smaller sources. They have created the Japan Collaboration on Accelerator-driven Neutron Sources (JCANS) [11]. Some of these sources are driven by electron LINACs, some by proton LINACs. The RIKEN Accelerator-driven compact Neutron Source (RANS) [12] is based on a proton LINAC with 7 *MeV* energy and 100 µA maximum beam current. While these parameters seem not very impressive compared to the parameters of some ambitious recent projects, the neutron research group at RIKEN has convincingly demonstrated the potential of even a relatively small CANS for industrial research in materials science (see corresponding article by Y. Otake in this issue).

In Europe, no LENS facility for condensed matter application exists yet, but several projects are underway at ESS-Bilbao in Spain, LNL-Legnaro in Italy, LLB-Saclay in France and JCNS-Forschungszentrum Jülich in Germany (see corresponding contributions in this issue) or in a conceptual phase, ACDC at Helmholtz-Zentrum Dresden-Rossendorf. The most ambitious project for a High Brilliance neutron Source HBS [8, 13] features a 70 MeV, 100 mA proton accelerator, three target stations with different pulse structures (different pulse length and frequencies), and Ta targets sustaining a beam power of 100 kW each. The reference design includes a full suite of 13 scattering, imaging and analytics instruments. Each single one of these instruments compares well with existing leading instruments at present day sources, see e.g. [14] for spectrometers. A schematic drawing of the layout of the experimental areas and target stations of the HBS in its reference design is depicted in Figure 2.

In addition, JCNS has developed the concept of a smaller facility NOVA ERA [15], which is based on an easy to operate electrostatic tandedron accelerator. Such a source could be operated as a central facility at major universities or companies. Workhorse instruments for small angle scattering, reflectometry or powder diffraction would have very reasonable performances at such a pulsed source operating with 400 W average accelerator power [16]. In Hungary, the company Mirrotron is building a small CANS specifically for industrial applications.

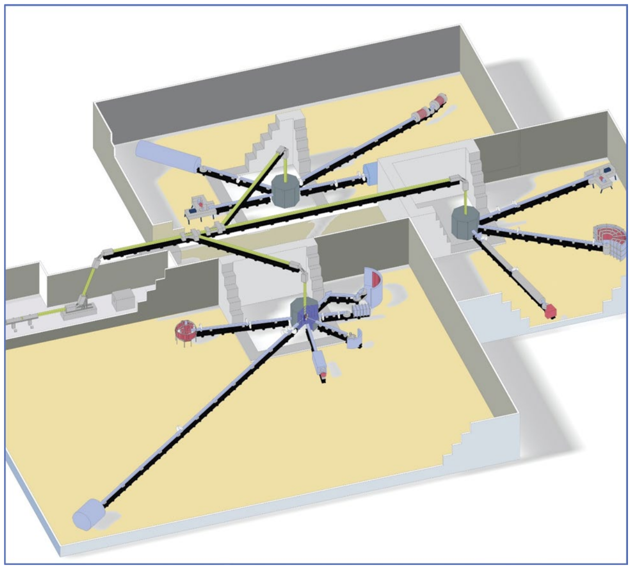

Figure 2. Schematic drawing of the three experimental areas surrounding the three target stations of the HBS in its reference design. Protons from the LINAC (only the last section shown to the left) are guided towards an upper level, distributed by a beam multiplexer and fed from above into three target stations operating at 24, 96 and 384 Hz. The target stations are surrounded by concrete walls as biological shielding. Instruments fitting to the respective pulse structure are grouped around the individual target stations. The reference design includes one instrument of each common type, but more instruments can be added or the instrument suite adapted to the needs of the respective user community. As an example, a dedicated target station for industrial research could be added.

Major projects outside Europe exist at the University of Windsor/TRIUMF in Canada, at CIEA in China and at SOREQ in Israel.

Reflecting on the list of existing CANS and LENS projects, one particular aspect of these type of neutron facilities becomes clear: their scalability. This is illustrated in Figure 3. Low Energy accelerator-driven Neutron Sources (LENS) range from very compact CANS for very specific applications for industry or material science via university based local sources all the way to highly competitive facilities with the potential to replace ageing research reactor sources for applications in scattering, imaging and analytics.

Conclusion and outlook

With the ongoing slow phasing out of older research reactors, the neutron research community must turn to alternatives to underpin the flagship facilities. Small- to medium-sized local, regional and national sources are needed to maintain a healthy ecosystem and support a diverse user community with the influx of new ideas from young scientists coming from universities. Low Energy accelerator-driven Neutron Sources (LENS) are scalable in price and performance and can fill the gap which is currently showing up in the neutron landscape. Smaller Compact Accelerator-driven Neutron Sources (CANS) have already demonstrated their usefulness for specific applications, from education, via method development to material science studies for industry.

By focusing on beam brilliance and pushing recent technological developments to their limits, LENS facilities are no longer "compact". They will in future be able to compete favorably in instrument performance with medium to high flux reactor- or spallation-based facilities. This is evidenced by the two ambitious European projects, SONATE and HBS (see corresponding articles by F. Ott and T. Gutberlet, et al. in this issue). While these types of sources do not aim at covering applications of research reactors which require a high flux of thermal neutrons within the moderator, they will be highly competitive for most neutron beam applications. Their clear advantage is that they are highly flexible, can easily be adapted to the needs of the respective neutron user community, do not need a nuclear license and come at significantly lower price-tag for installation and operation compared to research reactors or spallation sources. While at present, the necessary high reliability required for user facilities can only be achieved with conventional

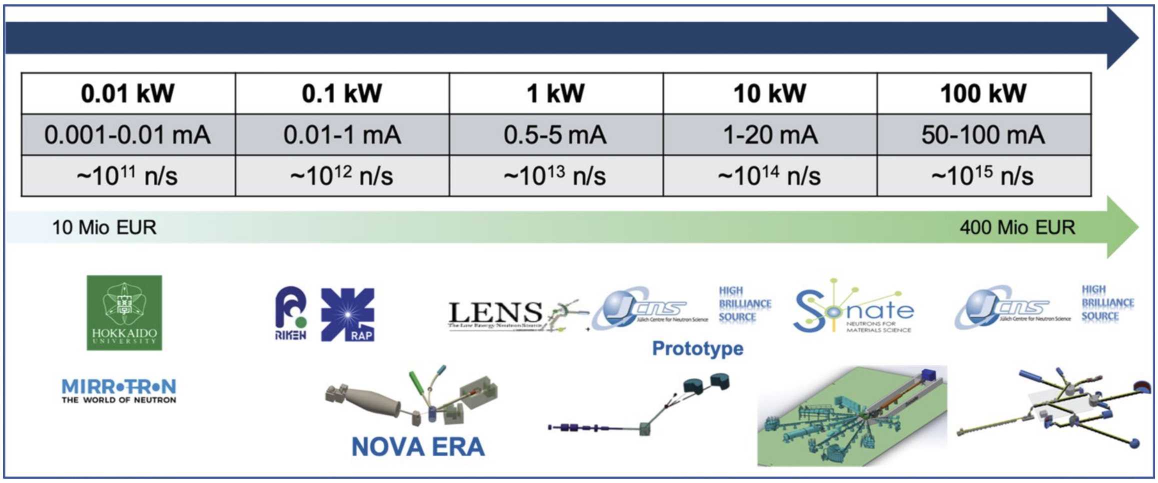

Figure 3. Schematic illustration of the scalability of CANS LENS in terms of proton beam power, proton beam current, source strength and required investment budget. At the bottom of the figure, examples of corresponding facilities or projects are depicted.

particle accelerators, laser-driven acceleration of protons or deuterons [17] might offer a prospective for further cost reduction in the future.

The realization of the ambitious ongoing projects for LENS will help to realize a brighter future for research with neutrons. The potential impact of these sources has been realized by the League of advanced European Neutron Sources [18], which has mandated an ad-hoc working group to write a white paper on Low Energy accelerator-based Neutron Sources.

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