THE 1ST WORKSHOP ON EFFICIENT NEUTRON SOURCES ENS2019

Sponsored by ARIES

Organized by PSI and ESS

In memory of John M. “Jack” Carpenter
(1935-2020)

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TABLE OF CONTENTS

INTRODUCTION

A workshop with European and international participation was held on Efficiency of Neutron Sources at the Paul Scherrer Institut, 2019 September 2-5. The workshop was a deliverable of the ARIES Work Package 4 on “Efficient Energy Management”, task “Increasing energy efficiency of the spallation target station”. The focus was on neutron sources driven by particle accelerators, from the powerful spallation neutron sources like, for example, SNS and PSI to smaller, compact neutron sources, which are nowadays under intense research, but reactor sources were treated as well.

The workshop, with a duration of three and a half days, was hosted by PSI, the Paul Scherrer Institut in Villigen, Switzerland, located between Zürich and Basel. PSI hosts among other facilities, the most powerful continuous spallation neutron source in the world, SINQ, which was undergoing an upgrade of its cold neutron guide system at the time of the workshop. The workshop was co-organized by ESS, the European Spallation Source, which will become in the near future the most powerful spallation neutron source in the world.

The workshop had 63 participants from 17 countries, mainly from Europe, but also from Asia and the Americas. Thirty-five presentations and three keynote lectures were given during three days. Three discussion sessions of one and a half hours each were dedicated to the different topical areas. The last half day was used for summaries of the sessions, discussions and considerations for the future.

Neutron sources are used for various applications, however, the workshop focused on sources for neutron scattering for condensed matter research and fundamental physics, although a small amount of fusion research was covered as well. The demand for efficient neutron sources is strongly felt by the community, which is struggling to make better sources available and to come up with ways to face the current world-wide reduction in neutron instrumentation for these various applications. The participants came from a wide range of research areas, from target and reactor source developers to instrument scientists, and plentiful informal discussions across those different areas were held; the absence of parallel sessions afforded opportunities to attend presentations that might have been skipped at a larger conference. The moderators of the discussion sessions did an excellent job in structuring and leading the discussions. All these factors together lead to a very successful workshop.

The present volume contains the outcome of the workshop. In the introductory article we tried to record the main ideas, reflections, findings, that came from the talks and were extensively treated in the discussion sessions, related in various ways to the concept of efficient neutron sources. As such, it should be considered as representing the ideas and contributions from all the workshop participants. In some paragraphs we mentioned in parenthesis the names of participants, referring either to parts of their presentations, which can be looked up in more depth in the extended abstracts, or to underline a particularly relevant comment or idea. The introduction is followed by extended abstracts for most of the presentations. Together, they contain a record of the scientific content of the workshop to keep track of the main ideas that were discussed for increasing the efficiency of present and future neutron sources.

We received at the time of writing the sad news of the passing of Jack Carpenter. Jack’s contribution to the development of neutron sources across several decades is invaluable. All of us will fondly remember him, also for his gentle manner and his always lively contributions; this book is dedicated to his memory.

The editors

THE WORKSHOP ON EFFICIENT NEUTRON SOURCES

The goal of the workshop was to convene experts in the neutron source community to discuss the state of the art in neutron sources, with a focus on their efficiency, to share new developments, concepts and ideas, with the purpose to improve the current sources or design better future neutron sources. The workshop was structured into three topical areas: neutron production; moderators and reflectors; guides, instruments and detectors. The topical areas were introduced by three keynote presentations held by Jack Carpenter, Rolando Granada, and Feri Mezei, respectively. Scientific presentations by participants were followed by extensive discussion sessions.

NEUTRON PRODUCTION

The session on neutron production was introduced by a keynote lecture by Jack Carpenter, who gave an overview of the different types of neutron sources: fission, fusion, spallation, photoneutron, low-energy charged particles, with a brief mention of exotic schemes. Under the topic of neutron production there were several talks covering different neutron sources in the world, in operation (SINQ, IBR-II, ISIS, SNS, CSNS, J-PARC), in construction (ESS), under study (HBS, SONATE), or upgrade (SINQ, SNS, J-PARC, IBR-II). Talks were also dedicated to the Ultra Cold Neutron (UCN) source at PSI, and to a new idea of an intense UCN source in reverse geometry. The discussion session started with trying to find out what we mean by efficiency.

What is efficiency?

There are many definitions of efficiency, depending on what we are looking at; the list includes, but is not exhaustive to efficiency defined as number of useful neutrons:

- per unit energy deposited on the target;
- per number of fast neutrons produced in the target;
- per number of primary particles on the target;
- per energy put on the grid;
- per cost of the facility (funding perspective).

By *useful* neutrons, we mean the neutrons within the right energy spectrum, typically cold or thermal neutrons from the moderators, that may reach the sample. Thus, there are several approaches to design or improve a neutron source, which can be done at different stages, such as planning, designing, or upgrading of a facility. The validity, or relevance, of the definition of choice for efficiency depends on the target audience, e.g. funding agencies, staff maintaining the facility, or end users.

From the point of view of increasing the efficiency of an existing neutron source, the neutron production part is perhaps not the area that can offer the greatest improvements, at least when compared to other areas such as neutron optics. For a neutron producing target, the increase in the number of neutrons might come from an increase of the accelerator current, or from an improvement of the target itself. The first choice is often not allowed by budget constraints for the accelerator upgrade, or by engineering problems related to the cooling of the target. Nevertheless, significant improvements in the target designs have been achieved in the past, one notable example being the SINQ target, with an increase of neutron flux of about a factor of 2 in the latest spallation targets, compared to the early ones.

Upgradeability

An important aspect to be considered for an efficient source is upgradeability. The ESS case is an example of a facility designed with several upgrade paths, including the possibility of a second moderator source. ESS was designed with a grid of 42 beamports for neutron extraction (many more than the number of instruments in the full scope of the project), and the flexibility for each beamport to look at different moderators, above and below the spallation target. It is therefore possible to add instruments, but also a second source: for the first 15 instruments, water and hydrogen moderators placed above the spallation target will be used, leaving available the place below the target for future upgrades.

Second target stations are planned at SNS and J-PARC, with careful design of the target-reflector-moderator system for optimized neutronic performance. Masahide Harada discussed the proposed second target station of J-PARC. The second target station "TS2" will also have a muon source with muon intensity 50 times higher than the one of the first target station "TS1". The moderator height will be of 6 cm, compared to the 10 cm height of the TS1 moderator. This choice is a good compromise as some experiments need higher brightness, while others higher total intensity.

At SNS, a second target station (STS) project is now established, with expected start of operations within 8-10 years. The power of the STS will be of 700 kW, with a repetition rate of 15 Hz, compared to the 2 MW and 45 Hz for the first target station (FTS). This new facility is intended to be complementary to the existing HFIR reactor and FTS, by delivering the highest peak brightness for cold neutron beams towards small samples. The STS moderators will be low-dimensional. The target will be a rotating tungsten with tantalum cladding, water cooled. The expected peak brightness will be 25 times higher than for FTS (Franz Gallmeier).

From the reactor side, the upgrade of the research reactor IBR-2 with the NEPTUNE project is a very promising initiative. The upgrade is based on a new design utilizing ^{237}Np as fuel. This upgrade is expected to give an order of magnitude higher flux than IBR-2M, and the neutron background between pulses will decrease by 3-4 times. When realized, NEPTUNE (IBR-3) will allow maintaining a leading position among world neutron facilities for research on extracted neutron beams (Sergey Kulikov).

Another example is the SINQ upgrade. The overall upgrade of the SINQ facility happened in different phases. In the past years, significant upgrades were done on the accelerator and the target; more recently, the attention was focused to the rest of the chain, with significant gain estimates: cold moderator, up to factor 2; guides, up to factor 5; shielding (by reduction of the background), up to factor of 10; instruments, up to factor of 10. The SINQ was shut down in 2019 to change guides, add shielding for background reduction, and upgrade some instruments. According to schedule, SINQ restarted in 2020 (Marc Janoschek).

Importance of background reduction

A concept that was stressed by many participants was that for an efficient neutron source, to reduce the background is equally important as increasing the flux: a good signal/noise (S/N) ratio allows performing measurements of high quality. Although this is well recognized, it has happened in the past during the construction of new facilities that when problems with the budget arise, the first cut is on the shielding, resulting in an increase in background. Steven Lilley showed a comparison between ISIS Target Station 2 (TS2) and Target Station 1 (TS1). TS2 is a factor 4 lower in power, but its background is orders of magnitude lower than TS1.

Several factors have been identified as contributors to the better performance of TS2: *i*) TS2 has no muon target: in TS1, several instruments close to the muon target do not have good shielding, with a clear effect on the background; *ii*) in the target/moderator area, TS1 has a relatively large empty space around, while TS2 has more shielding closer to the target; *iii*) the shielding material for TS2 was carefully chosen: TS1 was built with a lot of recycled shielding material, as at the time it was necessary to use cheaper steel to save on the cost; *iv*) for the instruments shielding, the same design of TS1 was used, however, in the case of TS2 there is often more space around the sample area, with less room for backscattering. The identification of the various contributors to the better S/N performance of TS2 is extremely important for the design of new facilities. Despite the considerable progress, there is a broad consensus that we still do not completely understand neutron sources, and that there is much to be gained from a deeper understanding. The gains are perhaps most opportune in the pursuit of background reduction in the instruments. Here the progress in available computer power and more advanced and detailed Monte Carlo simulations will certainly help.

It is of interest to try to optimize the S/N in the design phase via Monte Carlo calculations. Computationally, this is a very difficult task: ideally, one should perform the simulation from source to instrument in one go, but we are currently far away from achieving this. A good start is what a software package like MCViNE does, namely to mark off processes like scattering from sample environment. Because of the challenges in performing simulations from target to sample, it was suggested the opposite approach, i.e. to start from the sample and try to understand the sources of background reaching it, and find measures to reduce it. This is also a difficult task, which could be addressed using deterministic adjoint calculations, knowing the physics principles of a system and having an idea of the sources of the background. Alternatively, it is possible to use advanced features of Monte Carlo codes to study where the neutrons are coming from. Applications on source optimization with particle flagging using the Monte Carlo code FLUKA were shown by Lina Quintieri.

Compact sources to face the decrease in source availability

Europe is entering a phase of reduction of infrastructure availability for neutron scattering experiments. This is due to the recent closure of several research reactors (three in 2019: Orphée at Saclay, BER-II in Berlin, and Jeep II reactor at Kjeller). When ILL will shut down, between 2030 and 2040, the overall beam time in Europe will drop by approximately 40% (Loïc Thulliez). A good source of information on the situation of neutron scattering facilities and on possible scenarios to face such reduction is given in the ESFRI volume on Neutron Scattering Facilities in Europe[1].

This issue is one of the main drivers for the recent studies and projects aimed at replacing research reactors with Compact Accelerator Neutron Sources (CANS). The possibility to run accelerators at power levels of 100 kW may allow the design of CANS with performances comparable to medium flux reactors. Due to the much lower neutron yield per incoming proton, compared to the spallation reaction, the CANS need to be optimized for efficiency to deliver as many neutrons as possible to the instruments. A compact source based on low-energy protons in the energy range of tens of MeV has a fast neutron yield, per joule deposited on the target (energy efficiency), two-three orders of magnitude lower than spallation. It is therefore crucial to optimize the extraction of the highest number of neutrons from a compact source. The last few years have seen extensive studies of this problem, and key parameters for an efficient

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[1] ESFRI Scripta Volume 1, Scientific editors C. Carlile and C. Petrillo, 2016.

CANS, in particular the beam energy and the target material, have been investigated. There is not a single solution and other factors, such as the cost, need to be taken into account.

The proposed CANS to replace the Orphée reactor is SONATE, with the following parameters: 20 MeV proton beam on a Be target, 100 mA average current, and 4% duty cycle. The facility uses the IPHI accelerators and there is an extensive development program, testing targets at 50 kW power in 2020. A strong performance (as good as Orphée) is estimated for SANS and reflectivity instruments. Spectrometers are expected to be better than at Orphée (Alain Menelle, Loïc Thulliez). Furthermore, the cost of such facility is lower than for a reactor. With this promising expected performance, one could envisage a solution of having many small neutron sources to increase the user base.

For the High Brilliance Source (HBS) project, the current proposed design foresees the use of tantalum targets impinged by proton beam of 70 MeV energy. The power of the proton beam is at the level of 100 kW, which forces the investigation of clever solutions for the cooling of the targets (Paul Zakalek). The present design of the HBS foresees at least three different target stations with different frequencies (24 Hz, 96 Hz, and 386 Hz), with frequencies and duty cycles chosen to avoid pulse overlaps. While this could be seen superficially as a decrease in efficiency for a given instrument, as compared with the option of having a single target, in fact such a choice adds flexibility of changing the repetition rate and thus adapting to different instruments. Additionally, moderators can be shaped differently, according to the instrument needs (Thomas Gutberlet).

The CANS have several advantages over spallation sources: lower cost, more flexible design, possibility to place samples closer to the source, and expected lower cost per instrument. The main disadvantages, besides the lower flux, is that a lower number of instruments can be placed per target (Alain Menelle). This is especially true if low-dimensional moderators are used, in particular tube-shaped moderators, which provide maximum brightness, but are very directional: a tube moderator will deliver maximum brightness in the direction of its axis, and only a few (up to three-five) beamlines could be built in each direction of extraction. This disadvantage could however be turned into an advantage, by bringing the concept to the extreme and design one source for one instrument, while adapting the source pulse and repetition length to the particular instrument. This approach is encouraging since, as it was noted, with prices of small accelerators going down, we are approaching the situation where the cost of the source might be lower than the cost of the instrument.

Concerning CANS feasibility, it was noted that the development of relatively high-power sources like HBS will take years, but for the smaller sources the proof of principle is fully demonstrated by facilities like LENS in USA and various compact sources in Japan.

MODERATORS AND REFLECTORS

The moderator and reflector session was dedicated to several interesting topics including the discussion on state-of-the-art and novel materials, on new designs for the upcoming second target stations of SNS and J-PARC, and on possible moderators for very cold neutrons.

New moderator and reflector materials

Rolando Granada gave a keynote talk introducing the state of the art in moderator and reflector research. Concerning moderators, a promising new material is ethane, which has a spectrum that can be changed by varying its temperature. It can be very convenient to shape the neutron spectrum according to the needed application. There is however an increase in emission time compared to methane moderators, which is a disadvantage for pulsed sources. Ethane has the same problem of radiolysis as methane; it is therefore probably not usable in a high-power spallation source, but it could be used in a compact source. Concerning reflectors, a very promising material currently under study is magnesium hydride (MgH_2), which could be used to reflect cold neutrons. The reflector material that has however reached the most attention in recent years are diamond nanoparticles, which have been studied both experimentally and theoretically in several places.

Moderators for Very Cold Neutrons (VCN)

For at least 15-20 years an interest has been expressed by various communities in having neutron beams in the very cold range (20-40 Å). Applications have been identified for SANS, reflectometry, TOF-INS, and spin echo. Colder neutrons are also optimal for fundamental physics, such as neutron-antineutron oscillation studies. So far, however, a suitable moderator or converter for the production of VCNs has not been realized.

One possibility was discussed at the workshop, from an idea of Oliver Zimmer, to use magnetic scattering in a cascaded cooling, using paramagnetic materials. The most promising material is ^{16}O molecules which have a spin triplet with zero-field splitting, thus allowing possible moderation in the absence of an external magnetic field. This material must be encaged in clathrates to keep the oxygen molecules separated. Worth to mention is the initiative to establish a database of $S(\boldsymbol{Q},\omega)$, for various candidate clathrates. Some measurements have been performed at ILL and more is expected to come within the EU CREMLINplus program and the recently approved HighNESS project.

Moderator test facilities

There is the need of facilities to test new moderator concepts. Construction of a moderator test facility is now planned at SNS (Erik Iverson). The development of low-dimensional moderators in the last decade has brought a change in neutron sources towards high-brightness moderators. While the physics principles have been proven, for example, at J-PARC, a test facility will allow to study these moderators more in depth. It is important to have a facility that can test moderators placed in wing configuration, which is the chosen configuration for all the latest neutron sources, both spallation and CANS, and cannot be tested at the existing LENS facility in Indiana. In discussing the capabilities of the moderator test facility, it was suggested to have enough space available to place a large reflector, and the possibility to test novel reflector materials such as nanodiamonds in the beam extraction channel.

Codes and cross sections

The availability of neutron cross section data for the design of neutron sources is essential. Scattering kernels are critical for the correct simulations of neutron sources. Several topics were discussed at the workshop, concerning codes and cross sections. From the theoretical side, expertise in calculating cross sections is lacking. There are occasional workshops dedicated to scattering kernels, but no events or schools where experts can teach us to generate them. It was mentioned that events such as scattering kernel schools could be organized, funded by institutes or via EU grants[2].

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[2] It is worth noting that in the recently approved HighNESS EU-project N° 951782 for the design of the ESS source upgrade, a school on scattering kernels is foreseen.

Concerning measurements of cross sections, there are several places where good kernel measurements can be done. Such measurements are very important to validate or complement the model calculations. Total cross sections can be measured at several places, such as Vesuvio at ISIS. There are, however, not many places to verify the angular distributions.

At HBS it was realized that different codes need to be used for different calculations, as some codes are better than others for some specific tasks. The cross section databases for the reactions in the energy range and for the materials of interest for compact sources show large differences, indicating that these cross sections are not very well known. It was suggested to consider creating a platform of information exchange on codes, where benchmarks of codes and cross sections are available.

GUIDES, INSTRUMENTS AND DETECTORS

Efficiency improvements of the last two decades

In his keynote presentation, Ferenc Mezei discussed the many past advances in the combined moderator and beam efficiency systems, that led to more efficient neutron sources. Confirming the general theme of the workshop, that the various systems should be considered in connection to each other, the link between the moderator and the beam delivery was emphasized: major gains are obtained by considering the two as a unified system. One of the reasons is the realization that, for the optimization of the number of neutrons at the sample, what matters is the brightness at the moderator surface, rather than the total number of neutrons emitted from the source. This realization, which came out of a unified study of source and guide systems, led to the introduction of low-dimensional moderators which give a factor of three increase in moderator efficiency, compared to conventional volume moderators, with respect to the initially produced fast neutrons.

The time structure of the neutron source influences its efficiency in beam delivery. The most obvious difference is between steady state pulses such as reactors and pulsed neutron sources. Pulsed neutron sources have an efficiency gain equal to the inverse of the pulse duty factor. There are some additional gains that can be obtained using recently developed multiplexing chopper systems to shape the length of slow neutron pulses.

The efficiency gain in the last two decades, considering the combination of these different factors, and including the use of supermirrors discussed below, is estimated to be of about three orders of magnitude. Additional gains of about two orders of magnitude can be expected from improving the instruments and the data collection systems.

Development of small samples and small moderators go in parallel. The physical size of the source and the size of a sample to which the beam can be optimally transported are correlated through the conservation of the phase-space density in any conservative beam transport system. For both, the current trend is that these dimensions become smaller.

The matching of moderator type, repetition rate of the source, and type of instrument was discussed. For spallation sources, the following has been identified (Georg Ehlers): *i*) direct geometry spectroscopy instruments favor a pulse with a maximum brightness within a finite width, a coupled moderator for cold neutrons and a decoupled poisoned water moderator for thermal neutrons. The frequency should be variable and high, 180 Hz for cold neutrons and at least 600 Hz for thermal neutrons (the frequency takes into account the increase given by repetition rate multiplication (RRM)); *ii*) indirect geometry spectroscopy instruments favor a short pulse, poisoned decoupled moderator. The frequency should be lower, 20–60 Hz; *iii*) spin echo spectroscopy instruments can afford the pulse to be longer. Considering that new instruments should be long, to be in a low magnetic noise environment, to achieve the desired bandwidth the frequencies should be even lower, in the range of 10 Hz. We have seen that for HBS, at present the best solution envisaged is of three sources at different repetition rates, all using the low-dimensional moderators for increased brightness.

The time structure of the pulsed sources was further explored, and valuable insights regarding avenues for improvement can be obtained from the comparison of the long and short pulse sources (Masa Arai). The comparison between ESS and J-PARC instruments was discussed. J-PARC has a short pulse, 1 MW power, 25 Hz repetition rate, using volume moderator for cold neutron production. ESS is a 5 MW power long pulse (2.87 ms) source. The following points are worth noting: *i*) the ESS source gives an order of magnitude brightness gain at 5 Å, the combined effect of higher power of ESS, and use of low-dimensional moderators; *ii*) the bi-spectral opportunity of ESS is really unique. This will increase the performance of the instruments; *iii*) the performance of spectrometers at ESS and J-PARC is found to be comparable.

The impressive gains reached in beam delivery in the last two decades can now be adapted for compact sources allowing them to replace research reactors, at much lower price than reactors. CANS can additionally have some gains from being much more compact than high power spallation sources. For example, pulse shaping choppers work well if the pulse is long enough; in a compact source the chopper can be placed closer to the source, and this will make the multiplexing easier; this should be considered in the design of compact sources.

Developments in neutron optics

The development of supermirrors has been of paramount importance for the increase in efficiency of the transport of neutrons, and this is an area where additional improvements are still possible and should be pursued. The systematic use of supermirrors can give an increase in beam delivery efficiency by a factor of 10-40, additionally offering the possibility to simultaneously accept neutrons from two different moderators of different spectral energy (bi-spectral extraction).

A new interesting guide concept from Oliver Zimmer was presented, the nested mirror concept, originally designed for 9 Å neutron transport for UCN sources. The nested mirror concept gives single reflections with well-defined reflection angles, and has the advantage of no contamination by fast neutrons; this results in pure spectra adaptable to the needs of instruments. Nested mirror optics give also other advantages: being far away from the source there will be less radiation damage; furthermore, such optics are independent of the geometry of the inserts around the moderators, giving more flexibility to reshape the mirror system when the necessities of the experiment change.

To reduce background issues, the use of elliptic parabolic shapes was discussed. The idea is to only extract the beam being used at the instrument, thus getting rid of all the unwanted neutrons, as in the SELENE concept. The development of optics and use of supermirrors improve the brilliance transfer and lead to a better signal-to-noise ratio, because mainly useful neutrons are transported to the sample. Supermirrors can be optimized for large m, polarization capabilities, and radiation resistance. For optimal beam extraction, it is generally better to extend guides closer to the moderator. It is also of importance to maintain a dense phase space to optimize the brilliance transfer (Peter Böni).

As already mentioned, from the point of view of the background, a recommendation for future beamline designs is to design beamlines *backwards*, using physics principles from sample to neutron source. This approach was discussed extensively and could be seen as a new paradigm in designing of neutron sources, where one starts from the sample and designs the facility backwards. Such approach stresses the importance of having a very high-quality neutron beam at the sample with a low background. One possibility to reduce the background at the sample position at existing instruments is by carefully focusing the beam. At the same time, the source of "good neutrons", i.e. the moderator, is designed to match the beam reaching the sample. Sources of background must be understood experimentally, or by using Monte Carlo or deterministic codes, in order to minimize them at the sample position. Such approach is expected to work particularly well with CANS.

BUDGET CONSIDERATIONS

Budget considerations were discussed at the workshop, with a good part of the discussion focusing on CANS. Budget and prices for CANS are scalable, from 1 kW low power sources designed for universities, to ~100 kW full-fledged national facilities. The top price is for HBS or SONATE, which are national facilities; the full cost of a source of the size of HBS with 15 instruments is of 300 million euros. With a tenth of that cost, one can afford to make one target and two-three instruments. Tandem accelerators can be bought off the shelf for 2 million euros. A small CANS built with this limited investment can be used for the education of the user community.

The role of universities was discussed. It was noted that there are reactors operated by universities. There are examples in Japan and China, where the small sources are completely operated by universities, and the initial investment is compared to areas like NMR or electron microscopy. Such approach is very promising. In Germany, there are universities strongly involved in building instruments: at the Munich reactor, half of the instruments were built by universities. In Japan, many compact sources are in universities. In the USA, the LENS facility is at a university (Indiana University, Bloomington).

For the financing of CANS, more involvement of the industry can be considered. The HUNS facility in Sapporo, Japan, has been particularly successful in this regard, with applications ranging from radiography and single-event effects in electronics, to SANS/SAXS analysis of steels. One should convince producers, for example, of batteries, that they need imaging for improving their products, which would give a case to build these small sources. In Japan, they have staff members to train the industry. At PSI, for the Swiss Light Source, there is a company that helps industries to use the beamlines.

Finally, for cost optimization, it should be considered that most of the neutrons to an instrument end at the beam dump; this could suggest to use the remaining neutrons, by placing a second instrument after the main one. Such additional instrument could be used for education, and it should not disturb the primary instrument (Masa Arai).

WORKSHOP AGENDA

2019 September 2 **Monday**

08:00-09:00	Registration
09:00-09:10	Michel Kenzelmann, Welcome Address
09:10-09:30	Yoann Charles et al, Workshop Goals and Details
09:30-10:00	Michel Kenzelmann, Neutron scattering at SINQ
10:00-10:30	Coffee Break
10:30-11:30	John M. Carpenter, Neutron production, &C
11:30-11:40	Break
11:40-12:10	Sergey Kulikov, High-intensity pulsed neutron source “NEPTUNE” (IBR-3)
12:10-12:30	Masahide Harada, Neutronic optimization for new neutron source in J-PARC
12:30-12:50	Bernhard Lauss, The solid-deuterium-moderator-based ultracold neutron source at PSI
12:50-14:00	Lunch
14:00-14:30	Thomas Gutberlet, Neutrons for today and tomorrow – The HBS project for compact accelerator based neutron sources
14:30-14:50	Loïc Thulliez, First steps toward the development of SONATE, a compact accelerator driven neutron source
14:50-15:10	Guenter Muhrer, A next-generation inverse-geometry spallation-driven ultracold neutron source
15:10-15:30	Yongjoong Lee, Tungsten as spallation neutron production target material
15:30-16:00	Coffee Break
16:00-16:20	Elena Protsenko, Assessment of the effect of burnout in the pulse research neptunium reactor
16:20-16:40	Lina Quintieri, Simulating neutron tracks in the new TS1-TRAM at ISIS with FLUKA code: some insights towards an optimised and more efficient target-moderator-reflector assembly for high power spallation sources
16:40-17:00	Michael Wohlmuther, Target development at PSI
17:00-17:10	Break
17:10-18:40	Discussion Session, Moderator: S. Lilley

(cont.)

2019 September 3 **Tuesday**

08:30-09:30	Ferenc Mezei, Combined efficiency of moderation and beam delivery
09:30-10:00	Coffee Break
10:00-10:30	Peter Böni, Development and applications of supermirror
10:30-10:50	Oliver Zimmer, Imaging nested-mirror assemblies for efficient beam transport with tailored spectra
10:50-11:10	Marc Janoschek, SINQ neutron guide upgrade
11:10-11:30	Yutaka Yamagata, Ultrahigh precision machining of neutron focusing mirrors using metallic substrate
11:30-11:50	Marek Bartkowiak, Neutron optics inside sample environment
11:50-12:00	Break
12:00-12:30	Georg Ehlers, Spectroscopy requirements for new neutron sources
12:30-12:50	Salvatore Fiore, On-target neutron production monitoring with self powered neutron detectors
12:50-14:00	Lunch
14:00-14:30	Alain Menelle, Neutron scattering on compact neutron sources
14:30-14:50	Steven Lilley, Neutron noise and delayed neutron backgrounds at spallation facilities
14:50-15:10	Alexander Backis, Boron-10 based neutron detectors at ESS
15:10-15:20	Workshop Photo
15:20-15:50	Coffee Break
15:50-16:10	Wen Yin, Physical design and progress of multi-purpose physics neutron diffractometer of CSNS
16:10-16:30	Thomas Huegle, Large scale data analysis for the operations side of neutron scattering
16:30-16:50	Paul Zakalek, High performance target for an accelerator driven neutron source
19:00-20:30	Workshop Dinner

(cont.)

2019 September 4 **Wednesday**

08:30-09:00	Masa Arai, The performance of ESS spectrometers in comparison with instruments at a short pulse source
09:00-09:20	Mihails Birjukovs, Neutron radiography imaging of argon bubble flow in liquid gallium in external horizontal magnetic field
09:20-09:40	Roberto Coppola, Experimental needs for neutron scattering methods in the characterization of nuclear materials and components
09:40-10:10	Coffee Break
10:10-11:40	Discussion Session, Moderators: M. Janoschek, C. Niedermeyer
11:40-11:50	Break
11:50-12:50	Rolando Granada, Cold neutron moderators and reflectors: some recent problems and results
12:50-14:00	Lunch
14:00-14:30	Franz Gallmeier, Moderator choices for SNS Second Target Station (STS)
14:30-15:00	Oliver Zimmer, Deuterated clathrate hydrates for neutron moderation and reflection in future high-flux sources of very cold neutrons
15:00-15:20	Konstantin Mukhin, Technical parameters of exploitation a cold neutron source on mesitylene beads on IBR-2 nuclear research facility
15:20-15:50	Coffee Break
15:50-16:10	Mostafa Jamalipour, Nanodiamond application for cold neutron enhancement in compact neutron sources
16:10-16:30	Tianjiao Liang, Neutronics performance measurement of CSNS moderators
16:30-16:50	Erik Iverson, The SNS moderator test station
16:50-17:10	Alan Takibayev, ESS moderators: current status and upgrade options
17:10-17:30	Alexander Wolfertz, Overview over Fast Neutron Lab activities

(cont.)

2019 September 5 **Thursday**

08:30-10:00	Discussion Session, Moderator: F. Gallmeier
10:00-10:30	Coffee Break
10:30-10:45	Steven Lilley, Neutron Production Session Summary
10:45-11:00	Christof Niedermeyer, Guides, Instruments and Detectors Session Summary
11:00-11:15	Franz Gallmeier, Moderators and Reflectors Session Summary
11:15-11:30	Luca Zanini, Workshop Closeout, part 1
11:30-11:45	Michael Wohlmuther, Workshop Closeout, part 2
11:45-12:00	Yoann Charles, Workshop Closeout, part 3
12:00-13:00	Take-Out Lunch

EXTENDED ABSTRACTS

NEUTRON PRODUCTION, &C

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Efficient means "Producing more from fewer resources." To us, "more" means more science, more neutrons, more instruments, higher neutron yield, etc. Our resources are many. Not to be forgotten are abandoned good stuff, infrastructure, buildings, instruments, space, shielding materials, detectors, components, computers and software, and so on.

Important laws to obey 3rd law: entropy only increases. Liouville's Theorem: the particle phase-space distribution function is constant along the trajectory of the system. We often say that the theorem states that we cannot increase the phase-space density of neutrons. But then we go about actually doing this, for example, by cooling, by H^- stripping injection, or other means. We must look into the admitted limitations of the theorem to understand what we are doing right.

Neutron production. What we do is only to release them from bound states in nuclei where they are constituent parts. We still call the process "production."

Primary neutron sources

Fission (in research reactors) and **Spallation** (in GeV accelerator-driven spallation neutron sources). **Low-energy nuclear reactions** (low-energy charged-particle accelerators) and electron-driven **bremsstrahlung photoneutron** sources. **Fusion** reactions may someday become practical as grid-scale energy sources and before that as sources for neutron research applications, but not yet. Several **exotic schemes** have recently been suggested which may someday provide high fluxes of neutrons.

Fission occurs when a fissile nucleus, usually ^{235}U, but a few others (^{233}U, ^{237}Np, ^{239}Pu), captures a neutron, then splits into a great variety of charged fragments and promptly yields an excess of neutrons, about 2.5 neutrons per fission, born with energies around 2 MeV. Fission-fragment and neutron KE, gamma rays, and beta particles deposit about 190 MeV of energy in the fuel material. Neutrons propagate the nuclear chain reaction. Delayed neutrons are most famously those emitted by radioactive fission fragments that decay slowly by beta emission to states that further decay into neutron emitters; decay times range from microseconds to tens of seconds. The delayed fraction of the total neutron yield from ^{235}U is about 0.6%, which is important for reactor control and in pulsed sources is an important, effectively steady background. Other delayed neutrons: Energetic gamma rays emitted following (slow) beta decay of activated nuclei can produce photoneutrons neutrons in Be and D near the source. Source designers need to avoid these sources of backgrounds.

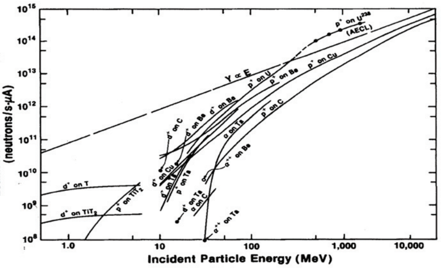
In **spallation** sources, the number of neutrons produced per incident particle from spallation reactions varies strongly with the particle energy and the mass number of the target nuclei. A function that reasonably well correlates the data is

$$Y(E,A),\ \text{n/p} = \begin{cases} 0.1(E_{GeV} - 0.12)(A+20) \text{ except for fissionable materials;} \\ 50.(E_{GeV} - 0.12) \text{ for } {}^{238}U. \end{cases}$$

For example, a tungsten target irradiated with 1 GeV protons produces about 18 neutrons per proton, and about 60% of the proton beam energy appears as heat. For proton energies above 1.0 GeV, the yield varies approximately as $E^{0.8}$. The spallation-neutron spectrum exhibits an isotropic evaporation (~ 1 MeV) spectrum similar to that of prompt fission neutrons, with a strongly angle-dependent component of higher-energy direct-collision ("cascade") neutrons, different for different angles of emergence. In principle, there should be no high-energy neutrons at angles greater than 90°, but multiple collisions produce some at larger angles.

Bremsstrahlung photoneutrons. Energetic electrons striking target materials slow down to emit *bremsstrahlung (e,g)* photons. Photons proceed to interact with target nuclei to produce *(γ,n)* photoneutrons. Heavy-element targets are best. The yields plateau at high electron energies (*Swanson, 1958*). The neutrons are emitted in an evaporation spectrum with average energies 1-2 MeV. Most of the electron energy dissipates as heat, so the process is rather inefficient; energy (heat) per neutron E/Y exceeds ~ 2800 MeV/n on the plateau, (yield = 2.23×10^{12} n/kw-s) for W. In practice, target heat transfer limitations constrain the power on targets a few centimeters in diameter to about 50 kW. (It is easy to melt even refractory target materials.) Electron accelerators (usually linacs) are relatively inexpensive, small and simple, and many electron-bremsstrahlung photoneutron sources are in use in moderate-flux applications.

Low-energy charged-particle-induced neutrons. Prospects are good for proliferation of this class of neutron facilities because of the availability at tolerable cost of compact, low-energy proton and deuteron accelerators. Such systems are the basis of low-cost, compact, accelerator-based neutron sources and are the topic matter of the UCANS collaboration, the Union of Compact Accelerator-based Neutron Sources, see UCANS websites.



The figure summarizes neutron yields per unit of incident-particle charge data for low-energy charged particle-induced reactions. Below about 30 MeV, proton and deuteron reactions in Li and Be are the most efficient. Above about 30 MeV, proton reactions in heavy elements are more efficient. See *Carpenter and Yelon (1986)*, adapted from *Stevens and Miller (1969)*.

Charged-particle range, blistering. Incident particles slow down in the target material, stopping at the end of range in a rather sharp peak, where they concentrate in solid material, diffuse away if the material allows, are swept away if the material is fluid, or collect to cause swelling and material stresses and blistering. This is a famous problem in Beryllium targets. Then, the solid target layer should be thinner than the particle range.

Periodically-reactivity-pulsed reactor sources. There is only one of these, IBR-2, a periodically prompt-supercritical-pulsed-reactivity fast reactor operating at the Joint Institute for Nuclear Research (JINR), Dubna, Russia, where it serves a large community of scientists for slow-neutron scattering research. (IBR = Russian for pulsed fast reactor.) A new source, NEPTUN, driven by a proton accelerator with a multiplying target based on ^{237}Np, is currently under consideration (*Shabalin, et al., 2018*).

Exotic schemes. Inverse Compton Scattering (ICS), a process in which a relativistic electron collides more-or-less head-on with a laser photon, producing photons with GeV energies, is a prospect for photonuclear neutron production (*Khaykovitch, et al., 2011*). Laser Fusion. An inertial fusion scheme evaluated by *Taylor, et al. (2007*), might achieve a very powerful neutron source. Laser plasma production of energetic proton beams, recently has yielded beams of 10-to-50 MeV protons, which, directed to heavy-element targets, could produce very short neutron pulses, (See *Zagar, et al., 2005*). Halo nuclei. Nuclear isomers in which the binding energy of the last neutron approaches zero can be produced by ICS. They have half-lives 100 nsec to msec and low neutron separation energy, which could be released by a second, low-energy polarized pulsed photon pulse to provide a low-energy, pulsed polarized neutron beam (*Habs, et al., 2011*).

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HIGH-INTENSITY PULSED NEUTRON SOURCE “NEPTUNE” (IBR-3)

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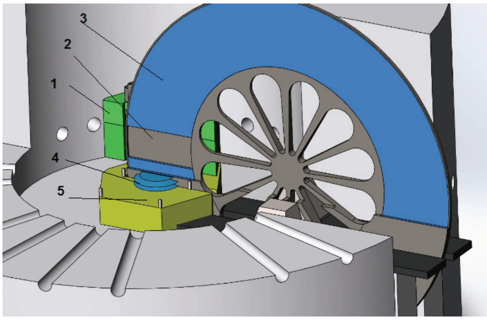
In the course of the first third of the century the IBR-2 reactor, has been and still is the most intense high-flux source of thermal neutrons in the world for investigations on extracted beamlines, providing for the peak density of the neutron flux on the surface of moderators $6{\cdot}10^{15}$ n/cm²/s and for the time average neutron flux up to 10^{13} n/cm²/s. However, the service life of IBR-2M is expected to end in 2032÷2037. The modern science requires neutron fluxes of one order of magnitude higher. Progress in the technics of spallation neutron sources gave opportunity to achieve the peak fluxes of neutrons approximate to 10^{16} n/cm²/s, and the average time fluxes – to 10^{14} n/cm²/s.

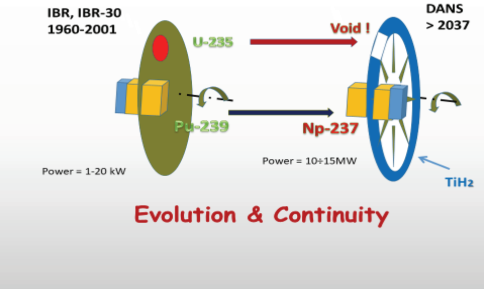
In consequence of a special study, it was proved that the pulsed sources of slow neutrons based on the fission reaction may be competitive with spallation neutron sources and even significantly (by an order of magnitude) exceed them in the peak slow-neutron flux. Principally, such facility is considered to be the pulsed fast reactor like its predecessors IBR, IBR-30 and IBR-2M but with higher power (10-12 MW) and the reactor core based on fissionable isotope Np-237.

The design of the IBR-3 (NEPTUN) facility follows the traditional concept of JINR, which dates back to the construction of IBR in 1960 – a high-intensity pulsed neutron source for physical research on extracted beams. It is a periodic pulsed fast neutron reactor. The pulses of fission power (and, accordingly, fast neutrons) are provided by a *reactivity modulator* and arise in the reactor core in a short period when it is in the supercritical state with respect to instantaneous neutrons. Slow neutrons, as a result of moderation of fast neutrons, are emitted by external *hydrogen-containing moderators*.



1-reactor core, 2-the empty sector of the modulator, 3-titanium hydride in the modulator, 4-moderator, 5-beryllium reflector

Differences of IBR-3 (NEPTUN) from IBR and IBR-2M are as follows:



- Np-237 nitride is proposed as nuclear fuel instead of Pu-239 (IBR) and plutonium oxide (IBR-2M).
- The modulator is a rotating disk with titanium hydride around the entire periphery, except for the empty sector on the arc equal to the size of the core. Supercriticality is created when an empty sector passes between two halves of the core.
- Hydrogen-containing moderators are placed directly at the boundaries of the core and are surrounded by a beryllium reflector.

On the IBR-3 reactor, the flux density of thermal and cold neutrons on the extracted beams will be an order of magnitude higher than on IBR-2M, and the neutron background between pulses will decrease by 3-4 times. This is achieved precisely due to the neptunium loading of the reactor due to the threshold nature of the dependence of the neptunium fission cross section on the neutron energy. On the plutonium reactor, an increase in the neutron flux will lead to an unacceptably long neutron pulse and a high background.

When being realized, NEPTUNE (IBR-3) will preserve a leading position among world neutron facilities for research on extracted neutron beams such as high current linear proton accelerators. Peak neutron flux density expected to be near 10^{17} n/cm^2/s and the time averaged thermal neutron flux – 10^{14} n/cm^2/s. Duration of the thermal neutron pulse 250÷300 μs is consistent to a high degree with experimental needs of neutron spectroscopy physics that use more and more cold moderators and long wave neutrons.

NEUTRONIC OPTIMIZATION FOR NEW NEUTRON SOURCE IN J-PARC

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At Materials and Life science Facility (MLF) in Japan Proton Accelerator Research Complex (J-PARC), 3 GeV and 1 MW proton beam induces a carbon target and a mercury target to provide muon beam and neutron beam, respectively. The first target station of MLF, "TS1", started to operate from 2008 and stably operates with 500 kW as of June 2019. And 1 MW operation for 10 hours was successful in July 2019. On the other hands, as a future plan to upgrade of MLF, the second target station, "TS2", is being planned.

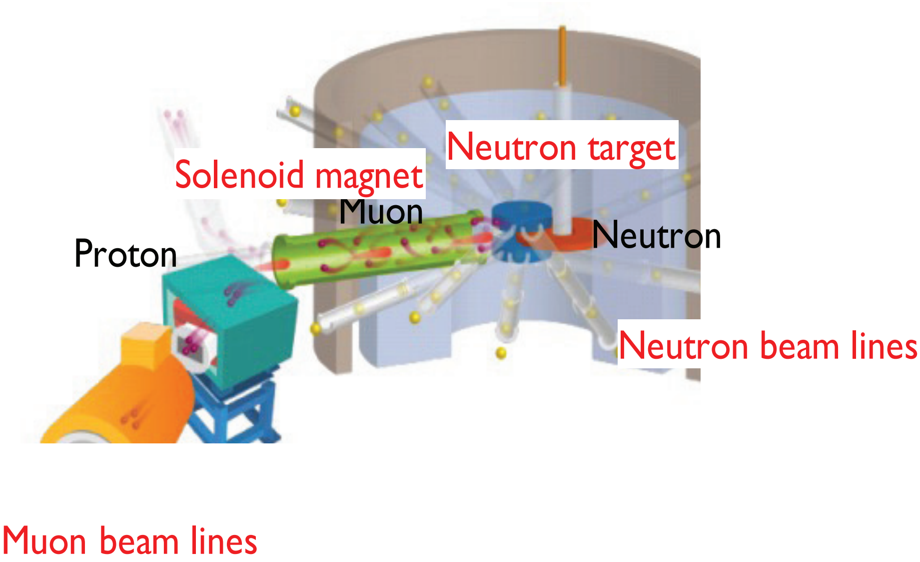

Fig. 1. Schematic three-dimensional view of TS2.

A schematic three-dimensional view of preliminary TS2 is shown in Fig. 1. TS2 is located near TS1 and the proton beam line to TS2 is divided at halfway to the TS1 proton beam line. Total proton beam power supplied by accelerators increases to 1.5 MW. Although the repetition rate is still 25 Hz, 1 of 3 pulses are transported to TS2, resulting in 8.3 Hz and 0.5 MW of proton beam to TS2. TS2 has a tungsten rotating target to provide both neutron and muon, and moderators to provide much higher neutron brightness by adopting higher current density of proton beam, a closer moderator position to the target, a flatter (smaller height) moderator and so on. Beryllium and Iron are chosen as reflector materials. The rotating target cooled by helium gas is also expected to increase neutron and muon intensities with a coexistence of them. Details of TS2 plan are summarized in Ref. [1].

In order to provide high intensity neutrons, optimization studies of TS2 were performed by the simulation code PHITS[2] and MCNPX[3]. It was confirmed that a tungsten rotating target could provide 1.2 times higher neutrons. As results of optimization for target, it was obtained that target thickness was 4 cm and its diameter was 120 cm. Also as results of the optimization for moderators, it was good choice that moderator position was 9 cm from the target head, premoderator thickness was 1 cm and reflector radius was 50 cm. A moderator height was the most important factor to decide neutron brightness. The moderator of 2 cm in height provided 2 times higher neutron brightness than that of 10 cm with sacrificing total neutron intensity. From a viewpoint of brightness and total intensity, 6 cm in height was chosen as the moderator height. For a moderator to provide shape pulses, one poisoned decoupled moderator was considered. Finally results of optimization are shown in Fig. 2. The coupled moderator of TS2 can provide 4 times higher intensity than that of TS1. If smaller height of moderator is chosen, brightness increases to 8 times compared with TS1. Decoupled moderators of TS2 also provide 3 time higher than that of TS1.

As the results, the optimization of TS2 could be performed by the simulations. To realize TS2, engineering designs are very necessary. Because TS2 looks like European Spallation Neutron Source (ESS), J-PARC would like to collaborate target and moderator developments for TS2 with ESS.

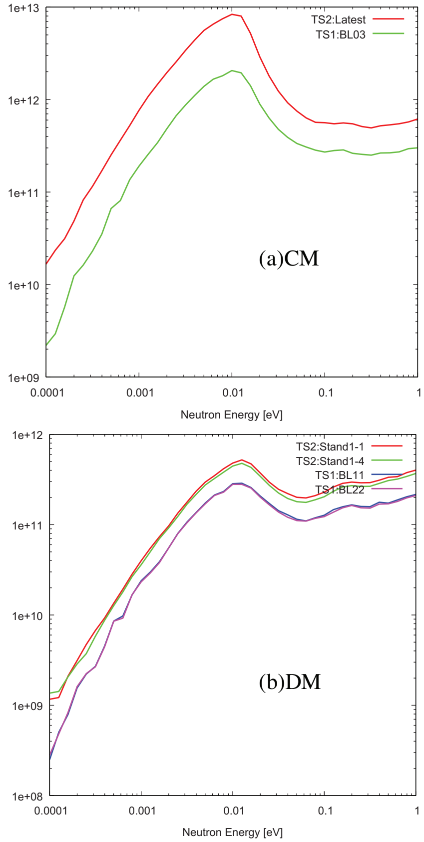

Fig. 2. Neutron spectral intensities
at each port compared with several TS1 ports:
(a) CM case (for high intensity), and
(b) DM case (for sharp pulse).

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THE SOLID-DEUTERIUM-MODERATOR-BASED ULTRACOLD NEUTRON SOURCE AT PSI

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Neutrons at the lowest end of the energy scale are called ultracold neutrons (UCN). They are totally reflected from suitable materials under any angle of incidence and can therefore be stored in material bottles and manipulated via gravitational or magnetic interaction. This makes them unique to study fundamental properties of the neutron itself. Over the last 8 years the Paul Scherrer Institute (PSI) has been operating a UCN facility [1] for up to 8 months each year. Three beam ports provide UCN to experiments with a priority on maximizing the UCN intensity for the search for a permanent neutron electric dipole moment (nEDM and n2EDM [2]). The nEDM experiment recorded data with world-record sensitivity in 2015/16, n2EDM is presently being assembled.

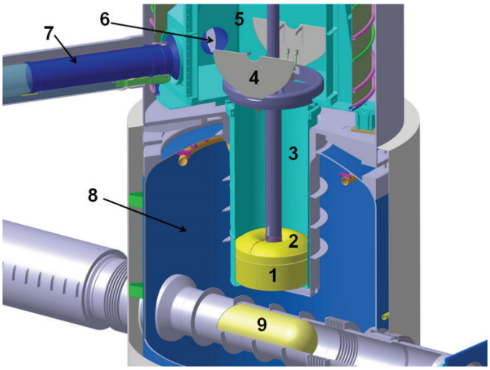

Fig. 1: Main components of the PSI UCN source tank: 1: Solid deuterium vessel; 2: vessel lid; 3: vertical UCN guide; 4: storage vessel shutter; 5: UCN storage vessel; 6: guide port; 7: UCN guide; 8: D_2O thermal moderator tank; 9: lead spallation target.

In order to provide maximum intensity to experiments at three available beamports, most components of the source installation were characterized in recent years, and operating parameters and procedures improved and optimized. UCN production is achieved in the following way: PSI's 590 MeV proton beam with currents of up to 2.4 mA impinges for a duration of up to 8 s on the UCN lead spallation target [3], where slightly more than 7 neutrons per incident proton are created [4] every 300 s. The neutrons are thermalized in room-temperature heavy water, and further cooled and finally down-scattered to UCN in the solid deuterium (sD_2) at 5 K their energy being converted into phonons. Figure 1 illustrates the important parts of the UCN source's vacuum tank. The distance between the sD_2 vessel at 5 K and the 1.4 MW beam on the target is only 40 cm and a technical challenge. After production, UCN can exit the sD_2 on the top and then have to pass a 0.5 mm thin AlMg3 safety lid. Subsequently they are guided vertically to an intermediate storage vessel, and then horizontally distributed to the three beamports. All UCN guides were tested for UCN transmission before installation using the prestorage method [5] and have proved to be excellent.

In order to achieve a thorough understanding of the UCN production and transport, a requisite for an improved UCN intensity, all components of the source contributing to neutron production or neutron transport have been individually checked. Measurements to test the neutron production and thermalization were reported in [4]. Tritium production via neutron capture is inversely proportional to the neutron velocity. Measurement of the tritium activation yield confirmed our understanding of the neutron moderation in the sD_2 [6]. The UCN transmission from the moderator vessel to the beamport was checked in various ways and reported in [7, 8]. UCN production and extraction from the sD_2 has been subject of intense studies (e.g. in [6, 9, 10, 11]). Energy deposition due to the irradiation of the moderator vessel region causes the appearance of surface degradation decreasing UCN intensity with operating time. The time dependent UCN output is shown in Fig. 2 for a standard data taking week in 2017. PSI has invented and optimized an 'sD_2-conditioning' procedure, which lasts around 2 hours and consists of a special warm-up and cool-down sequence. By applying this procedure, the initial UCN intensity is fully restored. Figure 2 shows the UCN output over a week as monitored on the West-2 beamport. Recently [12] we have interpreted this behavior with formation of a frost-like layer on the sD_2 surface which is caused by the heat impact during beam pulsing, giving rise to sublimation and amorphous refreezing of D_2 on the surface. Even extremely thin layers of frost can already generate a relevant decrease of UCN intensity due to back-scattering effects, as has been shown in simulations [13].

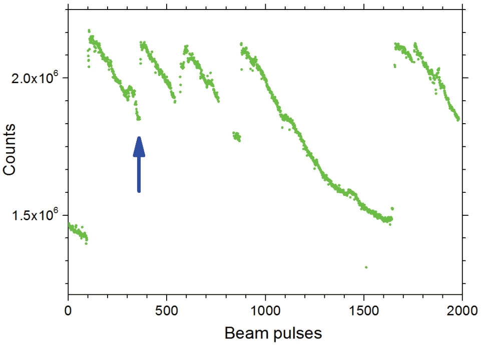

Fig. 2: UCN intensity per proton pulse in Sept. 2017 as monitored at beamport West-2 over 7 days. The intensity decrease within a day and the full intensity restoration after conditioning, indicated one time with a blue arrow, are obvious. The longest decreasing slope corresponds to a weekend with almost 3 days without conditioning.

Operating parameters and procedures were improved over the last years and a significant increase of the UCN output was observed and could be provided to experiments. The maximum UCN intensity observed from a single proton pulse at beamport West-1 is shown in Fig. 3 for the given years. The production pulse length was increased over the years from 6 s to 8 s length. The shown counts were normalized to the standard 2.2 mA operating current of the PSI cyclotron.

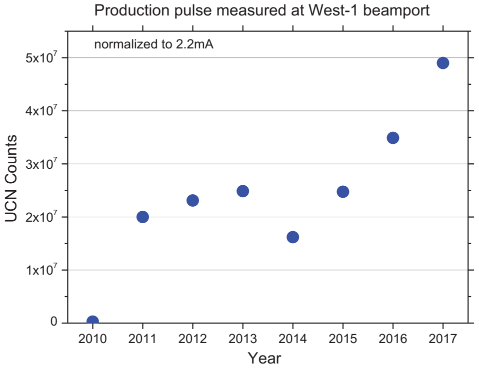

Fig.3: Maximum intensity of UCN observed at beamport West-1 in a given year with maximum allowed pulse length and full available proton beam current scaled to 2.2 mA [8].

Understanding the process of D_2 solidification and the behavior of sD_2 under pulsed heat input is of major importance for further increasing the UCN output of the source. Raman spectroscopy [14] is used to monitor the ortho-D_2 concentration which was always well above 98% [6]. Raman spectroscopy was also used to measure and monitor the contributions from isotopic impurities, present dominantly as HD molecules. Results were below significant levels [6].

In addition to measurements at the PSI UCN source we have initiated a standardization of UCN density measurements with a 'travelling' UCN storage bottle and detector system [15]. This allowed us to compare UCN source densities at various operating UCN sources around the world [16] with the same device, thus avoiding ambiguity from locally very different measurement methods or detectors. Some of the sources have been upgraded since the publication and thus increased their UCN output, as did the PSI source, where an increase of the maximum UCN density of 60% was observed.

Acknowledgments

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NEUTRONS FOR TODAY AND TOMORROW – THE HBS PROJECT FOR COMPACT ACCELERATOR BASED NEUTRON SOURCES

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Accelerator driven neutron sources with high brilliance neutron provision present an efficient and cost-effective alternative to classical neutron sources of fission reactors and spallation sources to provide scientist with neutrons to probe structure and dynamics of matter. The Jülich Centre for Neutron Science has started a project to develop, design and demonstrate such a compact accelerator driven high-brilliance neutron sources (HBS) [1,2]. The HBS will consist of a high current proton accelerator, a compact neutron production and moderator unit and an optimized neutron transport system to provide thermal and cold neutrons with high brilliance. Being a scalable neutron source, the performance level can vary from a low power pulsed neutron source designed for universities and industry with an average power at the target of around 1 kW to a high-performance neutron source with ~100 kW average power designed as a full-fledged national facility. Embedded within international collaboration with partners from Germany, Europe and Japan the Jülich HBS project will offer flexible solutions to the scientific challenges.

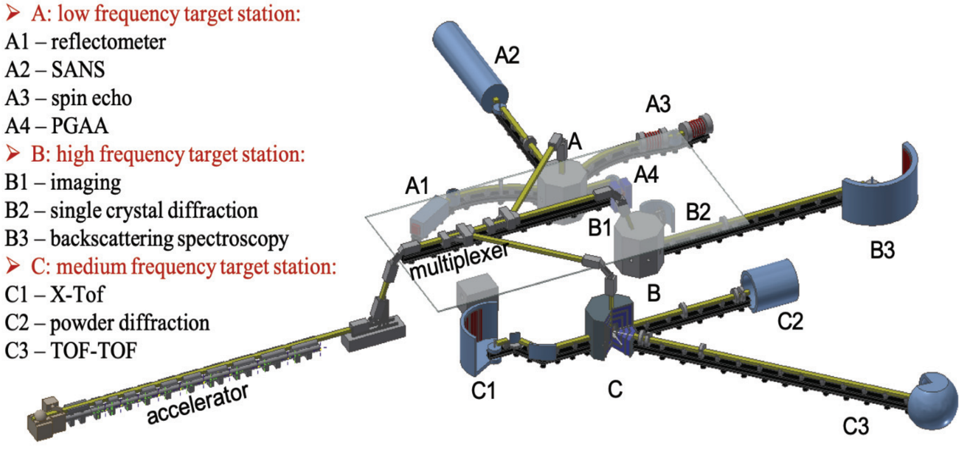

Fig. 1. Outline of a multipurpose high brilliance accelerator driven neutron source

The basic design of a CANS is shown in Figure 1. It consists of a pulsed proton linear accelerator, a multiplexer distributing the protons to different target stations each consisting of a target / moderator / shielding assembly and neutron experiments. The basic components of such a facility are described briefly.

Accelerator

The protons used for the nuclear reaction need to be accelerated to an energy between 10 MeV and 100 MeV. Various types of particle accelerators are available for this purpose, e.g. a tandem accelerator, a cyclotron or a linear accelerator. For the large scale CANS facility, a linear accelerator with dedicated radio frequency quadrupoles (RFQ) and a drift tube linac (DTL) is used which delivers a proton peak beam current of up to 100 mA with energies up to 70 MeV. The accelerator has to provide a pulsed proton beam for at least three target stations with an average beam power of 100 kW each resulting in an average beam power of 300 kW and a total duty cycle of ~4.3%.

Instruments at the different target stations are optimized to use a pulsed proton beam with different frequencies of 24 Hz, 96 Hz and 386 Hz. The frequencies and duty cycles are chosen in a way that the pulses do not overlap and that the maximal depositable power can be delivered to a dedicated target. A particle beam multiplexer will be used to distribute three particle beam pulse structures to different target stations.

Target / Moderator / Shielding Assembly

The target / moderator / shielding assembly presented consists of the target which is surrounded by a thermal moderator like polyethylene (PE) moderating the fast neutrons with MeV energy to thermal energies between 10 meV and 500 meV. A reflector like beryllium, lead or graphite increases the thermal neutron flux inside the moderator due to backscattering. Everything is surrounded by the shielding consisting of borated PE and lead. Extraction channels directing the thermalized neutrons to the experiments are inserted into this assembly. Their location is optimized in such a way that they extract the neutrons from the maximum of the thermal neutron flux inside the moderator. Into these extraction channels cryogenic one-dimensional finger moderators [3] can be inserted further shifting the thermalized neutron spectrum to cold energies between 1 meV and 10 meV.

The advantage of the compact design is the possibility to place the first optical elements like neutron guides, filters and choppers close to the target / moderator. Therefore, a large neutron phase space volume can be transferred to the instruments increasing the flux at the sample position. Less neutrons are produced with the nuclear reaction in comparison to spallation or fission, but with this compact design this is compensated by the improved coupling of the moderator and extraction system making the source competitive to modern research reactors. As the whole target / moderator / shielding assembly is optimized to the needs of the instrument and especially as each instrument can have its own optimized cryogenic source.

The neutrons are produced by nuclear reaction in a suitable target material. For energies below 30 MeV, low Z materials are preferable like beryllium or lithium. For energies above 50 MeV, high Z materials like tungsten or tantalum are preferable regarding the neutron yield. As the power depends directly on the energy, a low power CANS will therefore use a beryllium target and the large scale facility will utilize a high Z material like tantalum. The target design for the large scale facility at a power level of 100 kW and a tantalum target needs to comply with a power density deposition of 1 kW/cm^2 with a target area of 100 cm^2. In order to cool such a power density μ-channels can be applied which can remove up to 3.5 kW/cm^2 [4].

Instruments

The instruments built at a pulsed CANS are designed in a time-of-flight (TOF) setup and can be mainly distinguish by the bandwidth they can use and the resolution they need. The bandwidth and the resolution can be defined by choppers which in most cases results in a loss in neutron flux at the sample position or by adjusting the beam frequency and the target / moderator / reflector to the instrument requirements. For a large scale facility we distinguish at least three different repetition rates, e.g. 24 Hz, 96 Hz and 384 Hz. Instruments using these repetition rates are grouped together at the same target station.

Conclusion

CANS come at a much smaller price tag then research reactors or spallation sources, avoid the problem with nuclear licensing and the nuclear fuel cycle, and allow one to construct instruments fitting to the particular problem at hand, e.g. smaller samples. The approach of the scalable accelerator driven neutron source enables one to develop a network of large and small neutron sources throughout Europe improving the access to neutrons.

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FIRST STEPS TOWARD THE DEVELOPMENT OF SONATE, A COMPACT ACCELERATOR DRIVEN NEUTRON SOURCE

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Facilities providing thermal neutron beams are important for condensed matter researches, neutron-imaging or medical applications. Currently these are mainly spallation sources and nuclear reactors. However, these later facilities are aging and in Europe the political context does not favor the building of new ones. In Europe, after the ILL nuclear reactor shutdown foreseen in 2030-2040 (optimistic scenario from [1]), the neutron beam time will drop roughly by 40 %. In this context, new small facilities affordable by one country are necessary to support the large neutron community to develop new experimental techniques and train new scientists. Compact accelerator driven neutron sources (CANS), based on (p/d,n) reactions can now be competitive with nuclear reactors in term of neutron brightness because of the recent developments of high intensity accelerators, for less than 200 MEuros. In France at CEA-Saclay, since the Orphée reactor will shutdown in October 2019, a CANS is expected to be developed taking advantage of the IPHI proton accelerator able to deliver a 3 MeV proton beam with an intensity up to 100 mA, in continuous or pulsed mode. In the future, SONATE is foreseen to operate with 20 MeV protons. In addition to the difficulties to operate such high intensity accelerators, the other challenges regard the target-moderator-reflector (TMR) design. Several experiments were performed between 2016 and 2019 and ANSYS and Geant4 simulations are developed to demonstrate the feasibility and find the best TMR configuration for the future SONATE facility.

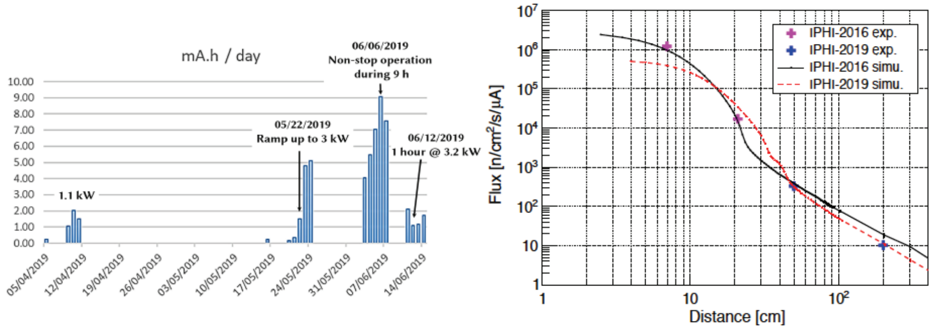
The high intensity proton injector IPHI commissioning has started in 2015. It is made of an ion source, SILHI, providing protons at 95 keV up to 100 mA. Then the beam goes through a low energy beam transport line to optimize its injection into the Radio-Frequency-Quadrupole (RFQ). This latter is designed to accelerate the protons to 3 MeV. It operates with an 352 MHz RF signal and requires stringent material tolerance (~ 30 μm). Then with the help of a dipole magnet the beam can be sent to two diagnostic lines. In 2016 IPHI delivered its first beam with a 60 mA intensity with a 0.4 % duty cycle. In 2018, the beam power increased to 7 kW. Then in 2019, IPHI has demonstrated its ability to provide a sustainable 3 kW beam (Figure 1a) and the beam power has recently successfully increased to 60 kW. Since 2016 the proton beam regularly impinges on a target to produce neutrons.

To maximize the neutron flux at the sample location, the target has to maximize the primary neutron yield and to handle the heat load deposited by the beam. In the SONATE project, a solid beryllium target sustaining 50 kW is studied in priority because of its high (p,n) reaction cross-section from 3 MeV to 20 MeV incident protons [2] and its good thermal properties. A first step was to design a beryllium target able to handle a 7 kW beam power with a power density limit set to 500 $W{\cdot}cm^{-2}$ in order to keep the target surface around 500 °C. At this temperature beryllium has a high elongation parameter and also a high hydrogen diffusion coefficient. The proton blistering effect can be then avoided. ANSYS thermo-hydraulics simulations (ANSYS Workbench V19R2) show that these requirements are fulfilled with a beryllium target screwed on a copper alloy heat sink having sixteen Inconel mini-channels (1.4 mm inner diameter) in which liquid water is running with a 20 bar inlet pressure at an estimated

19 m·s^{-1} velocity. In 2019, as Figure 1a shows, the beryllium target was successfully irradiated for 56.2 mA·h total integrated current and no blistering effect has been seen so far. This validates the target design as well as the numerical design approach implemented in ANSYS.

To maximize the thermal neutron flux (T=300 K), Geant4 [3] Monte-Carlo simulations are performed to find the best TMR configuration. The neutron source term is built as explained in [4]. Figure 1b shows that the simulations have been benchmarked, with an accuracy better than 20 %, against two TMR configurations with different accelerator, target and polyethylene moderator sizes. In the 2016 and 2019 TMR configuration the moderator dimensions are respectively equal to 30×30×40 cm^3 and 50×50×60 cm^3. The simulation has also been successfully benchmarked against MCNP6 [5]. This validates the neutron transportation process in Geant4. Simulations show that the thermal neutron flux (T=300 K) can be increased by a factor 2 with a TMR made of a 100×100×100 cm^3 beryllium reflector in which a small 10 cm thick polyethylene moderator touches the target, compared to a TMR only made of polyethylene moderator. The beryllium lateral dimension is higher than three time the thermal neutron diffusion length in beryllium to reach its asymptotic albedo parameter (reflection coefficient) value. The polyethylene size is kept small to avoid loosing neutron by absorption but big enough to well thermalize the neutron.

In 2020, the average beam intensity will be increased from 1 mA to 17 mA. The deposited power in the target will be around 50 kW. Therefore the target has been redesigned and studies are ongoing to find the best TMR configuration. In a near future, cold moderators will be investigated.



(a) Timeline of the 2019 beryllium target irradiation with a 3 MeV proton beam. At 3kW 1 hour running time is equal to 1mA·h.

(b) Thermal neutron flux (E_n<400 meV) as a function of the distance, for the 2016 and 2019 TMR configurations. Geant4 simulation results are compared with experimental data.

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NEPTUNIUM-BASED PULSED RESEARCH REACTOR: POSITIVE REACTIVITY EFFECT OF BURN-UP

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Since modernization in 2011, the IBR-2 pulsed reactor at the Joint Institute for Nuclear Research has been successfully used by researchers from dozens of countries to carry out experiments on extracted neutron beams in solid state physics. However, the capability of reactor operation is limited by the lifetime from 2032 to 2035. In order to maintenance this area of research, it is necessary to create a new world level neutron source by the mid-2030s.

The new pulsed neutron source, the IBR-3 facility (NEPTUN), which is currently developed by the Joint Institute for Nuclear Research (JINR), follows the traditional concept of JINR, originating from the construction of IBR in 1960: a high-intensity pulsed neutron source for physical research on the extracted beams on the basis of a periodically pulsed fast-neutron nuclear reactor. Fission power pulses (and, correspondingly, fast neutron pulses) are produced by modulation of reactivity of the reactor during a short period of time, when the reactor is supercritical on prompt neutrons. External hydrogen containing moderators are used to slow down fast neutrons. The IBR-3 will be charged with Np-237 nitride fuel instead of Pu-239 (IBR) and plutonium oxide (IBR-2M). It would allow to reduce the duration of power pulse and the neutron background between the pulses significantly (3-4 times lower than at IBR-2) due to the threshold nature of the energy dependence of the Np fission cross section. High thermal power of 12-15 MW and the modified geometry of moderator placement will provide the time averaged neutron flux density up to 10^{14} n/cm^2/s.

The modulator of reactivity is a rotating disk with titanium hydride filler over the entire periphery, except for an empty sector matching to the size of the reactor core. The supercriticality is created when the empty sector passes between the two halves of the reactor core. This method of modulation of reactivity is much more efficient than the movable reflector at IBR-2M.

Hydrogen-containing moderators are placed directly at the boundaries of the core and are surrounded by the beryllium reflector.

One of the characteristics determining the capability of reactor operation is the reactivity effect of fuel burn up. The change of reactivity in the neptunium charged reactor is summarized from the negative effect of neutron absorption by the neptunium nucleus and the positive effect of plutonium-238 accumulation as a result of neutron capture by the neptunium nucleus. Assessment of the effect of the burn-up has been carried out analytically for several of the most used databases (ENDF/B-VII.1, JEFF-3.2, JENDL-4.0, CENDL-3.1) with an energy spectrum of neutron flux density in the neptunium reactor core, calculated via the Monte Carlo software package. The analytical calculation method is based on the use of the simplest approximate expression for the neutron multiplication factor:

$$k_{eff} = \frac{\gamma\Sigma_f}{\Sigma_a} P_{out} \tag{1}$$

where Σ_f, Σ_a – macroscopic fission and absorption cross sections for core material, γ – the average number of neutrons emitted per fission, P_{out} – probability to avoid neutron leakage.

All the values in equation (1) are assumed to be averaged over the neutron energy spectrum and the reactor core volume. Assuming that both the energy spectrum and the spatial distribution of the flux do not change drastically during the burn-up process, one can obtain the simple equation for the burn-up reactivity effect:

$$\Delta k_{eff} \approx C(\overline{\gamma\sigma}_{f8} - \overline{\gamma\sigma}_{f7}\delta) \tag{2}$$

The value δ in (2) is the ratio of the number of disappeared (fission + capture) neptunium nuclei to a single plutonium nucleus accumulated: $\delta = \sigma_{a7}/\sigma_{c7}$, where the absorption and the capture microscopic cross sections for neptunium are averaged over the spectrum and volume. Indexes 7 and 8 refer to Np-237 and Pu-238 respectively. The factor C is proportional to Np burn-up and equals to $1.268 \cdot 10^{-3}$ at 1% of heavy nuclei burn-up.

The results of estimation are presented in Table 1.

Table 1. Estimated reactivity effect after 3% of heavy nuclei burn-up

	ENDF/B-VII.1	JEFF-3.2	CENDL-3.1	JENDL-4.0
$\overline{\gamma\sigma}_{f238}$	4.51	4.18	4.11	4.16
$\overline{\gamma\sigma}_{f237}$	1.85	1.84	1.89	1.86
δ	2.04	2.03	2.11	2.09
Δk_{eff}	0.00280	0.00162	0.000428	0.00103

For all of the databases considered the reactivity effect is appeared to be positive.

SIMULATING NEUTRON TRACKS IN THE NEW TS1-TRAM AT ISIS WITH FLUKA CODE: SOME INSIGHTS TOWARDS AN OPTIMISED AND MORE EFFICIENT TARGET-MODERATOR- REFLECTOR ASSEMBLY FOR HIGH POWER SPALLATION SOURCES

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In 2020 the ISIS Target Reflector and Moderator assembly (TRAM) at target station 1 (TS1) will be replaced with a new design incorporating lessons learnt from the design of the ISIS 2nd target station with a particular focus on maintainability. The new TRAM will be made up of a 10 plate Tantalum clad Tungsten target, 2 water moderators in the upper part, 2 cryogenic moderators (liquid Methane and liquid Hydrogen respectively) in the lower part and a solid Beryllium reflector. A detailed FLUKA model of the new TS1 TRAM at ISIS has been built and used to get both scientific and engineering relevant information, such as: neutron and other secondary particle production, energy deposition profile, particle fluence energy spectrum, decay heat, overall radionuclide inventory.

The comparison between the FLUKA predictions and the corresponding MCNPX simulations has been performed for several physical quantities (i.e. spatial profile of energy deposition in each TRAM region, decay heat, moderators brightness), showing a generally good agreement (within the statistical accuracy) with only few exceptions.

Exploiting an advanced use of the FLUKA code, it has been possible to track the TRAM escaping neutrons in such a way to assess quantitatively the contribution of the different target plates to the overall neutron leakage as well as the effective contribution of the water moderators to a couple of ISIS-TS1 instrument beam lines. The results of these calculations provide some useful hints that could help to address a more efficient design of the whole target-moderator-reflector assembly for high power spallation source.

1 Introduction

The total yield of neutrons escaping the upgraded TS1 target has been estimated by using the FLUKA code [1] and this prediction is in good agreement (within 5% in the worst case) with the value derived by well known and widely used semi-empirical correlations in literature over all the investigated energy range (protons from 600 MeV up to 2 GeV) [2], [3] (in the specific case of 800 MeV impinging protons, the value predicted by FLUKA for the neutron leakage from the upgraded TS1 target is 14.2 neutron/proton). This agreement has been considered a sort of indirect validation of the FLUKA model for the target, making us confident also in the reliability of the estimated neutron leakage from the whole TRAM (target embedded in the reflector together with the moderators). The escaping neutron current (in neutron/primary), derived integrating the neutron flux over all the solid angle, energy spectrum and surface area of a virtual sphere enclosing the whole TRAM, is about 60% less of the yield escaping the only bare target: i.e only 5.3 neutron/primary escaping from TRAM against 14.2 escaping the bare target. Moreover most of the neutrons escaping have still energy around 1 MeV and less than 18% of the total leakage has energy lower than 1 eV as shown in Figure 1.

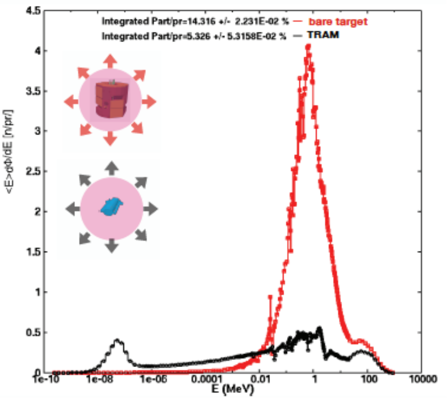

Figure 1. Escaping neutron energy spectrum: from bare target (red-curve); form the whole TRAM module (black-curve)

These results highlight the inefficiency of the TRAM design in terms of total yield of neutron delivered and quality of the neutron spectrum (since the fast neutron component is still dominant) and suggest to investigate alternative or innovative TRAM design.

In this context, exploiting an advanced use of the FLUKA code, it has been possible to track the TRAM escaping neutrons in such a way to assess quantitatively the contribution of the different target plates to the overall neutron leakage, as well as the effective contribution of the water and cryogenic moderators to several ISIS-TS1 instrument beam lines.

The results of these calculations could provide useful hints to address a more efficient, integrated and synergic design of the whole target-moderator-reflector assembly and the beam lines layout at the same time. In this paper a general overview of the methodological approach applied to track neutrons is given and some preliminary results for an ISIS TS1 instrument beam line (POLARIS) are discussed.

2 Fluka model of the upgraded TS1 TRAM

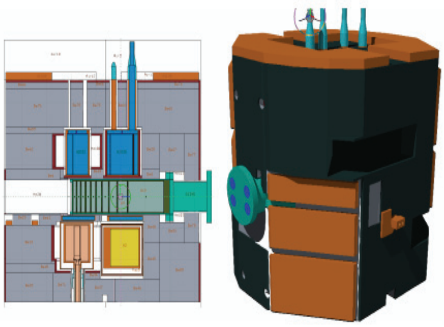

Figure 2. Fluka model of the upgraded TS1 TRAM

A very accurate model has been built with FLUKA code aimed at providing a valuable support both to the engineers and the instrument scientists (see Figure 2) [4]. The comparison between the FLUKA predictions and the corresponding MCNPX [5] simulations has been performed for several physical quantities (i.e. spatial profile of energy deposition in each TRAM region, decay heat, moderators brightness), showing a generally good agreement (within the statistical accuracy) with only few exceptions. In particular, the total energy deposited in the target is about 14% larger in case of the FLUKA model than in the MCNPX one. This is considered not a negligible difference and a more extensive analysis is ongoing in order to identify the main factors that could explain this difference (i.e. different geometrical details implemented, material and nuclear data used, physics models used at high energy).

3 Tracking neutrons for a more efficient TRAM design: the "latching" and "flagging" methods

The information about the origin (specific region and material inside the TRAM) of the channeled neutrons in each beam-line could help to have a better understanding of the efficiency of the moderator and reflector assembly in terms of both intensity of neutrons delivered to the instruments and quality of the neutron spectrum at the instruments. So that a systematic work is ongoing with Fluka in order to record the place of origin and other relevant information (i.e. if the channeled neutrons have effectively passed across moderators, the last TRAM region visited, etc) that can help to figure out the way the TS1 TRAM is feeding each instrument.

A record of specific details of the previous history in the TRAM is stored for and assigned to each neutron escaping the TRAM: technically, this is possible by exploiting advanced FLUKA scoring features, as LATCHING and FLAGGING techniques, respectively.

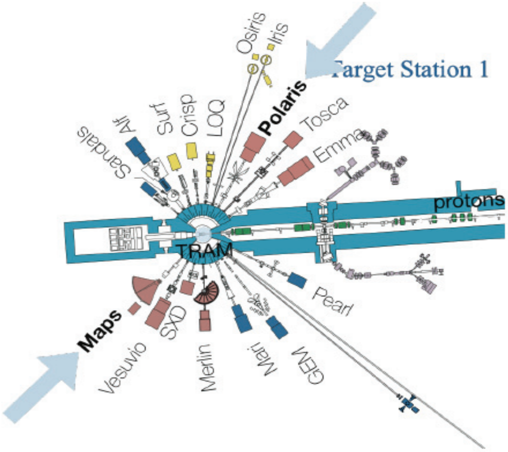

Figure 3. ISIS TS1: instruments layout

The recorded details could be used in a profitable way to discriminate the signal against the noise and eventually contributing to enhance the signal to noise ratio by applying suitable related software techniques.

4 Discussion of preliminary results

A detailed analysis of the different materials and target plates contribution to the escaping neutrons has been carried out:

- 67.8% of the escaping neutrons are born (we use this expression referring to neutrons made free from nuclei) in Tungsten
- 14.6% is born in the Tantalum cladding
- 13% is born in Beryllium reflector
- 2.5% is born in Stainless Steel vessel
- 2.1% in other auxiliary materials inside the TRAM

A first preliminary analysis to reconstruct the history of the neutrons arriving and channeling in the instrument beam lines has been already done for a couple of TS1 instruments: Polaris and Maps (Figure 3). The preliminary results obtained for the Polaris Instrument are discusses hereafter.

4.1 Polaris

Neutrons at the inlet port

- 0.04% is the fraction of the TRAM escaping neutrons actually impinging on the Polaris inlet window;
- Among those neutrons: 36.6% are below 1 keV; 63.4% above 1keV;
- 16.25% of all the impinging neutrons on Polaris are flagged 131, that is they have been actually in the moderator designed to feed the instrument itself.

Channeled neutrons

- 340 cm far away from the inlet port, 82% of transmitted neutrons have actually been in the asymmetrically poisoned water moderator (flagged 131)
- The channeled neutrons have been generated mainly by direct spallation in the central target plates (any contribution has been recorded from plates n.8, 9 and 10, these latter being the plates in the opposite location with respect to the impinging surface of the target);
- 72% of the channeled neutrons in Polaris have been produced in Tungsten. Anyway a not negligible contribution comes from Beryllium and it is slightly higher than the contribution coming from Tantalum cladding.

Moreover, our preliminary predictions reveal that all the channeled neutrons in Polaris have passed by Beryllium and Boral made regions after visiting the asymmetric poisoned water moderator and before leaving the TRAM. Further investigation could notify if those neutrons have experienced any interaction and the nature of the interaction itself (elastic or inelastic one) in those regions. Finally, the last TRAM region visited by all channeled neutrons in the instrument beam-line can be identified.

5 Conclusion and future plan

Exploiting high performance computing resources and advanced Monte Carlo code skills, it is possible to track the escaping neutrons by transporting relevant information of their history (i.e. ancestors, origin region, last TRAM region crossed before leaving the TRAM module, moderators in which they stayed, etc).

Some preliminary estimations have been provided for the total TRAM leakage and for couple of instrument beam lines (Polaris and Maps). A more systematic and complete analysis is ongoing for all the instruments of ISIS-TS1: recording the neutron history and identifying the origin of neutrons that are in the delivered pulse at the instrument could be a valuable support to improve the signal to noise discrimination and eventually enhance the signal to noise ratio. Obviously a more dedicated study is needed before arriving to produce a suitable applicable software tool with this purpose.

Finally the results of calculations based on latching and flagging neutrons could provide useful hints to address a more efficient design of the whole target-moderator-reflector assembly with respect to the effective beam lines layout and promise to be a valid tool to possibly identify and test innovative TRAM solutions.

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COMBINED EFFICIENCY OF FAST NEUTRON MODERATION AND SLOW NEUTRON BEAM DELIVERY TO THE EXPERIMENTS

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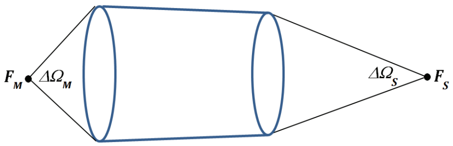
In order to obtain slow neutrons with energies << 1 keV for beam experiments at neutron sources, fast neutrons with energies >> 1 keV are initially produced by nuclear reactions and subsequently slowed down in moderators to the desired energy range. The moderation involves thermalization in moderators with adequate temperatures, usually referred to as cold, thermal and hot, respectively, for moderator temperatures much lower, about equal and much higher than room temperature. The production of the initial fast neutrons involves considerable amount of energy, which at the end dominates the technical challenges and costs of their production. In view of these one cannot expect that the rate of initial fast neutron generation in a neutron source for beam research will ever substantially exceed the highest rates achieved by now, i.e. about 2×10^{18} neutrons/s. Actually, this number applies today to the highest power beam reactors: ILL, HIFR and the planned PIK. Rather independently of the method of fast neutron generation, whether it is fission in reactors or various kinds of nuclear reactions in sources based on accelerators of a large variety of bombarding particle energies between a few MeV and few GeV, the most important part of the initially created fast neutron spectra falls between about 100 keV and 10 MeV. Therefore, largely the same type of moderators can be used for many types of neutron sources, with rather similar efficiency of turning the fast neutrons into slow ones. Exceptions are the very compact layouts of < 15 kW low power sources with ~4 higher moderation efficiencies, and fusion based neutron sources to the contrary, where the moderation of the 14 MeV energy fusion neutrons is a lot less efficient. It is a good absolute measure of the slow neutron production efficiency at any source to relate the neutron beam brightness delivered to the beam experiments to the total number of fast neutrons initially produced in the source.

Thinking in terms of the number of slow neutrons delivered to the incoming beam window of the neutron beam experimental stations, the global combined moderation and beam delivery efficiency at the continuous beam reactors was about 20 years ago typically 1 in the range of 10^{-8}. A variety of new approaches (partly already implemented, partly developed in all details for use in the next future) offer improvement potentials ranging from a factor of 500 to 10000 in the combined efficiency of neutron moderation and delivery. (An additional factor of about 10 to 100 improvement in total data collection rate can also be achieved by modern instrument design aimed at enhanced probability of detection of the neutrons scattered from the examined samples and advanced beam modulation patterns for information collection.)

In recent years, substantial progress has been accomplished in our skills to slow down the initial fast neutrons. One basic ingredient of this development is the realization that what primarily matters, similarly to other beam optical systems, is the brightness of the slow neutron beam emerging from the utilized moderator emission surface, and not the total number of neutrons originating in a large emission area. The brightness (i.e. the number of neutrons crossing in unit time a unit area within unit solid angle divergence and unit neutron energy window) is a constant of motion in particle beams in a conservative force field. In neutron beam experiments, the delivered beam has to provide best intensity traversing a surface area (sample window) within a required (usually anisotropic) angular divergence and at given beam monochromaticity. The product of these parameters is the called the beam "phase space volume" and the beam intensity is simply determined as the product of beam brightness and the phase space volume. Most often, the beam monochromaticity can be considered independently from the other two (spatial) phase space parameters.

In optical beam delivery systems, typically represented by the condenser lens ensemble in microscopes, the design is governed by assuring that the phase space volume needed for the illumination of the sample area is captured from the emitted phase space volume from the source of radiation, and transmitted with moderate losses to the sample area. With neutrons by the use of supermirror optical systems (variously shaped neutron guides) this also can by now be systematically achieved as the rule, with the only specific restriction, that the beam divergence in all directions (typically vertically and horizontally around the average beam direction) cannot or only marginally exceed the wavelength dependent cut-off reflection angle of the supermirrors used. In neutron scattering experiments the typical spatial phase space volume required at the sample is usually ≤ 4 °cm both in the vertical and horizontal directions (e.g. 2 cm sample dimension and 2° FW required beam divergence), but small angle scattering work it can be as small as 0.001-1 °cm.



This principle is illustrated in the figure. The entrance and exit windows of an optical (neutron guide) system are represented by the two ellipses, and their dimensions determine the incoming and outgoing beam divergences, $\Delta\Omega_M$ and $\Delta\Omega_S$, respectively. Thus, the number of neutrons entering the optical system will be given by the product $\Phi F_M \Delta\Omega_M$, where Φ is the brightness of the moderator with beam emitting area F_M. The number of neutrons reaching the sample window of area F_S will be similarly given as $\eta\Phi F_S\Delta\Omega_S$, where η is the beam transmission efficiency of the neutron optical system. If we make sure, that the incoming phase space volume is larger than the phase space volume intercepted by the sample, i.e. $F_M\Delta\Omega_M > F_S\Delta\Omega_S$, well designed, state-of-the-art supermirror optical systems can deliver transmission efficiencies $\eta > 60\%$.

The opportunity of designing brighter moderators with smaller beam emitting surfaces adjusted to the phase space volumes really used in the experiments, allows us today to envisage ~3-fold gain in the moderation efficiency of the initially produced fast neutrons. The systematic use of supermirrors optics in neutron guides accounts for 10-40-fold gain in beam delivery efficiency from the moderator to the samples, depending on neutron wavelengths and including the potential of expanding the delivered wavelength band by simultaneously accepting neutrons from two moderators of different thermal spectra. An additional, most fundamental gain in the efficiency of beam delivery is offered by pulsed neutron sources compared to steady state ones. At a continuous source, neutrons of all velocities arrive at the same time to the sample (without extra measures for eliminating all but those with the "right" velocity). At a pulsed source, neutrons emitted with different velocities in the quasi Maxwellian spectra of a moderator arrive at different times, and can be all used one after the others, i.e. a gain in the efficiency equal to the inverse of the source pulse duty factor. On the other hand, the pulse length of the source imposes an upper limit on the neutron velocity spread that can be excessive for a number of experiments. This limitation is avoided by the so-called long pulse neutron sources (duty factor 3-5%), with the use of newly developed, general methods for flexible mechanical shaping the length of the slow neutron pulses.

DEVELOPMENT AND APPLICATIONS OF SUPERMIRROR

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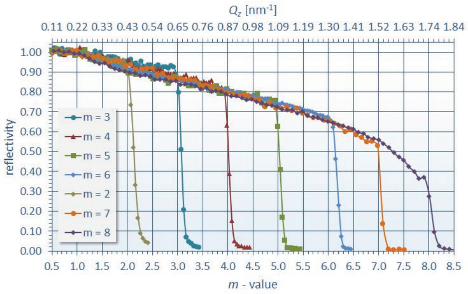

Fig. 1: Reflectivity profiles of large-*m* supermirror. The reflectivity decreases almost linearly with increasing *m*. The dip near $m = 7.8$ of the supermirror with $m = 8$ was caused by a plasma failure (after Ref. [3]).

The introduction of the concept of supermirror in 1967 [1] and its technological realization [2] laid the foundation for increasing the efficiency of the transport of neutrons and of polarization analysis techniques due to the large increase of the maximal angle of reflection by a factor of m when compared with the angle of total reflection of Ni. **Fig. 1** shows the present state of the art of the reflectivity *R* of supermirror $2 \leq m \leq 8$. The linear decrease of *R* with increasing *m* demonstrates that the roughness does not deteriorate with an increasing number of layers from 120 for $m = 2$ to approximately 16'700 for $m = 8$ [3].

A complete guide system based on supermirror technology was implemented for the first time at the Swiss spallation neutron source SINQ at PSI in 1994 using mostly mirrors with $m = 2$ [4]. The following years witnessed enormous increases in the performance of beamlines for neutron scattering thanks to the combination of new guide concepts, e.g. linearly tapered [5] and non-linearly tapered parabolic and elliptic guides [6,7] with supermirror technology. One of the first large elliptic guides was installed at the spallation neutron source ISIS in 2007 feeding the high-resolution powder diffractometer HRPD with neutrons. The neutron flux was increased by up to two orders of magnitude [8].

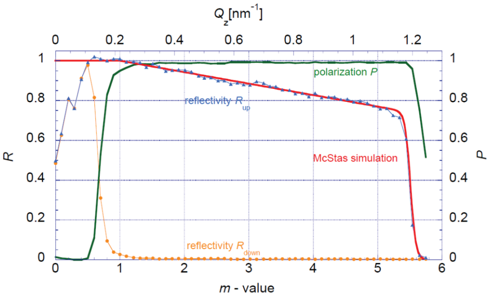

Fig. 2: Reflectivity *R* and polarization *P* of Fe/Si supermirror with $m = 5.5$ [9]. Polarizing supermirror with large *m* and high *R* and *P* are the basis for wide-angle polarization analysis.

Similar progress has been achieved with polarizing supermirror. For wide-angle polarization analysis, SANS, and PNR, there is an increasing demand for mirrors with large *m* and a high polarization. In order to analyze the polarization of thermal neutrons, mirrors with large *m* are required. Using supermirror with $m = 5.5$ (**Fig. 2**), a wide-angle analyzer was recently realized for the beamline POLANO at J-PARC that can cover an angular range of 400 and accepts neutrons with an energy up to 40 meV [9]. Most recent developments demonstrate that *m* can be extended to $m > 7$ while maintaining a polarization of the reflected beams above 99%. The large increase of *m* allows the extraction of beams with a high divergence. Therefore, large moderators are required to warrant a full illumination of the neutron guides because the entrance of the guides is typically a couple of meters away from the moderator. For example, the small height of 30 mm of the moderators foreseen for ESS leads to an under-illumination if neutrons with a divergence of approximately 10 or larger are supposed to be extracted.

Here, Montel optics or nested-mirror assemblies may provide the required high extraction efficiency. In contrast to Montel mirrors [10], nested mirrors (**Fig. 3**) provide a proper optical imaging of the source [11]. Moreover, the mirrors can be placed further away from the moderator, i.e. outside the biological shielding. Using parabolic or elliptic mirror geometries, parallel or focused beams can be extracted. A crossed arrangement of nested-mirrors provides 2-dimensional beam handling.

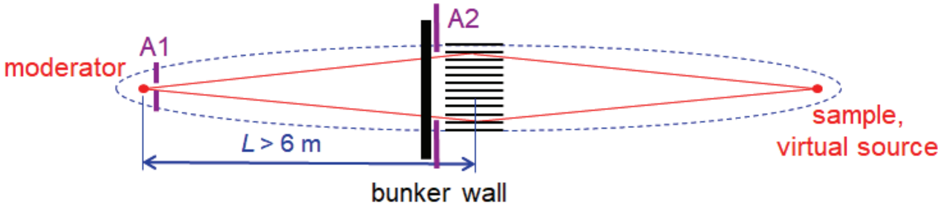

Fig. 3: Replacement of a long elliptic guide by nested elliptic mirrors allows the imaging of the neutrons from the moderator to the sample thus minimizing illumination losses. The size and the divergence of the beam at the sample position is defined by apertures close to the moderator (A1) and close to the entrance of the mirror optics (A2), respectively.

In conclusion, the combination of advanced neutron optics with supermirror technology will enhance the brilliance transfer of neutron beams and leads to an improved signal-to-noise ratio because most neutrons that are not going to illuminate the sample will be sorted out already near the moderator. In addition, costs for shielding are minimized.

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IMAGING NESTED-MIRROR ASSEMBLIES FOR EFFICIENT NEUTRON BEAM TRANSPORT WITH TAILORED SPECTRA

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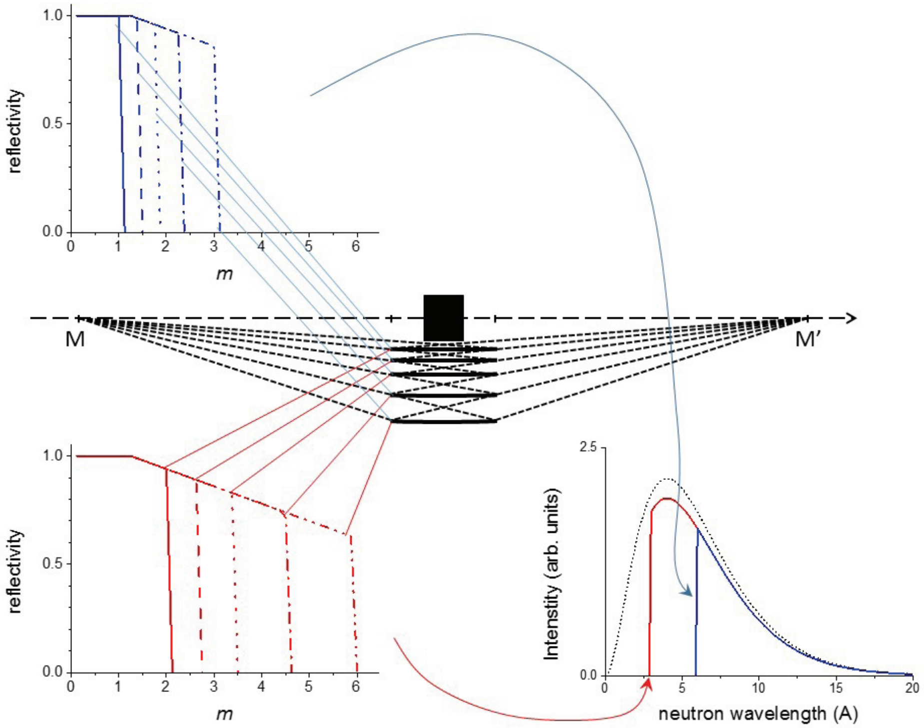
Imaging assemblies of nested mirrors offer interesting possibilities to improve neutron beam transport to instruments. Such systems allow not only to almost conserve the flux density of neutrons emitted from a source under large solid angle, but also to match the brilliance transfer exactly to the beam phase space needed in neutron instruments. While nested-mirror optics were already demonstrated experimentally for neutron microscopy [1] and recently also for focusing SANS [2], the advantages for neutron delivery due to the optical properties of such devices still need to be fully appreciated by the community.



The figure shows an implementation (see Refs. [3, 4] for the geometric construction and more details), which is conceptually even simpler than the different variants of Wolter optics [5]. Nested short elliptical (or very short flat) mirrors located halfway between two common focal points M and M' image cold neutrons by single reflections from an area around M onto an area of similar size at M'. An absorber on the straight line MM' blocks the direct view onto the source, with little impact on the transported solid angle. Multiple reflections as common in long elliptical neutron guides do not occur, resulting in lower transport losses. As there are no garland reflections the transported beam is not contaminated by a tail of short-wavelength neutrons.

This simple geometry with well-defined, non-grazing angles of reflection off the individual mirrors opens up attractive possibilities for enhancing the spectral quality of primary beams, while simultaneously lowering radiation backgrounds at the instrument. It becomes indeed possible to tailor the beam characteristics, including size, divergence, wavelength spectrum and polarization, to match instrumental needs. These opportunities are all consequences of rather well-defined reflection angles from the mirrors.

A common small-wavelength cut-off in the spectrum to be transported can be set by proper choice of the m values of the individual supermirrors, as indicated in the figure for two different sets. Bandpass supermirrors, delivering almost monochromatic neutrons in the extreme case, may be used for further tailoring of the spectrum. The advantage of such mirrors is a higher reflectivity than available for full-bandwidth supermirrors, and lower backgrounds due to unwanted neutrons which in a neutron guide cannot be filtered out. One may also imagine to choose mirror coatings to provide modulated beams with different wavelength spectra in different fractions of solid angle. Adjustable apertures far away from the instrument can define the size and the divergence, or q-resolution for an experiment in a precise manner, while keeping radiation backgrounds due to unnecessarily high divergence far away from the instrument.

Neutron optical imaging systems in various circumstances also have a number of practical advantages as compared to neutron guides. In particular, no delicate high-m mirrors need to be installed in the harsh radiation environment close to an intense source. This not only increases mirror lifetimes but also simplifies the maintenance of beam tubes. Due to the imaging property of the assembly, neutrons can be transported with only little dilution in beam phase space density, whereas notably for a small source it becomes difficult if not impossible to fill the transportable beam phase space of a neutron guide. Imaging systems of nested mirrors should therefore be considered in particular for the European Spallation Source, but they might also be an asset for reactor neutron sources and compact neutron sources.

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SPECTROSCOPY REQUIREMENTS FOR NEW NEUTRON SOURCES

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In the recent past, new ideas and concepts have emerged for new types of neutron sources and moderators. A short list of such ideas includes small scale accelerators [1,2] and dimensionally reduced moderators with much increased surface brightness [3,4,5]. As the physical characteristics of a source will always have to be optimized to the needs of the instruments that receive its neutrons, it is worthwhile from time to time to review what these needs are.

Neutron scattering science happens in an environment where sources and instruments are long standing installations, but the underlying technologies (such as neutron generation, optical transport and detection) see continuous advancements over time. At the same time, sample synthesis, data collection and analysis strategies also evolve with time. All these factors directly or indirectly affect what the best source should look like.

This contribution specifically looked at the modern-day scientific requirements for sources from the perspective of spectrometers for quasi-elastic and inelastic scattering. We considered the physical size, frequency and time structure (pulse length) of pulsed sources.

One can identify a few general trends in the current development of neutron scattering instrumentation. One is the general desire to bring more useful neutrons to the sample. This can be achieved with new ideas for neutron optical transport systems (ballistic guides, elliptical mirrors, parabolic focusing, to name a few examples) as well as with new ideas for chopper systems such as repetition rate multiplication (RRM) [6,7]. Another trend is to enable the detection of scattered neutrons in larger areas through bigger detector arrays, larger crystal analyzer arrays and multiplexed back-ends [8]. Finally, one aims today for more flexibility with the beam size and beam divergence at the sample position. All these developments aim to increase the scattering signal and to push the feasibility for experiments towards smaller samples.

Modern neutron optical transport methods lead to a correlation between the physical size of the source and the size of a sample to which the beam can be optimally transported [3]. This will hold as long as smaller surface moderators will have a higher brightness than larger ones. Specifically, for instruments using natural collimation, a coupled moderator should be about the same size as a typical sample, and a decoupled moderator should be about twice the size of the sample. In instruments that employ neutron guide systems the source dimension should match the guide entrance, and the optics system will allow one to magnify/demagnify the source image at the sample position by trading beam divergence correspondingly.

Regarding the repetition frequency and pulse length of pulsed sources, we arrived at the following conclusions.

Direct geometry spectroscopy will prefer a pulse with a maximal brightness *within a finite width*, a coupled liquid hydrogen moderator for cold neutrons or a decoupled poisoned water moderator for thermal neutrons. The appropriate pulse width will follow from the desired energy resolution and instrument length. Optimizing a moderator for peak brightness alone will in general not lead to an overall best source for such a spectrometer. The effective source frequency should be variable and high, at least 180 Hz for cold neutrons and at least 600 Hz for thermal neutrons. Here, "effective" means to include an increase of the actual source frequency by using a chopper system that enables RRM.

Indirect geometry spectroscopy requires a short source pulse to match the energy resolution of the analyzer bank (commonly Si-111 or HOPG-002). The pulse would have to be delivered by a poisoned decoupled moderator, or by a longer source pulse that is to be cut short by a chopper system. The frequency should be lower than with direct geometry, 20 Hz – 60 Hz.

Spin echo spectroscopy can afford the source pulse to be longer, as the energy resolution is achieved with homogeneous magnetic fields and not with time of flight. Assuming that new instruments will be long to distance themselves from others (to be in a low magnetic noise environment), the source frequency should be even lower, not more than 10 Hz, to achieve the desired bandwidth.

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ON-TARGET NEUTRON FLUX MONITORING WITH SELF POWERED NEUTRON DETECTORS

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The Roadmap to Fusion Energy poses several technological challenges, many of them related to neutrons generated in the fusion reactions. A high intensity fast neutron flux ($>10^{14}$ n/cm^{2}s) is expected to hit the inner walls of the tokamak. ITER will be the first fusion reactor to be built in which neutron fluxes of the order of 10^{14} n/cm^{2}s will be reached on the first wall surface, decreasing with depth. Monitoring this neutron flux is one of the key diagnostics to understand plasma burning conditions, and with such flux intensity this is a challenging task, also considering the environment conditions such as high temperatures above 200 °C. DEMO is the ITER's successor, and it will be the first prototype of a fusion power plant. In order to evaluate the damage to structural materials in DEMO, the Roadmap to Fusion Energy has foreseen the construction of a dedicated test facility, IFMIF-DONES, which is planned to be built in Escuzar, 30 km far from Granada (Spain).

DONES is based on the acceleration of a deuteron beam up to 40 MeV, 125 mA current in continuous wave mode, with 5 MW beam average power. The rectangular beam (approximately 20 cm × 5 cm) hits a liquid lithium target flowing at 15 m/s to dissipate the beam power. A neutron flux of 10^{14} n/cm^{2}s, with a broad peak at 14 MeV, is produced by stripping nuclear reactions, reproducing the expected conditions in DEMO [1]. The neutron flux in the test cell must be monitored. The detectors to be used to this purpose must withstand the high incident neutron flux at high temperatures (between 200 °C and 500 °C), working consecutively for almost one year without the possibility to access the irradiation cell. Almost any neutron detector currently available would not work in these conditions for such long time, therefore new ad-hoc detectors must be developed.

Self Powered Neutron Detectors (SPNDs) seem one of the most suitable option for the DONES sample irradiation cell. SPNDs are electronic devices that exploit the neutron-induced activation of specific materials, which then decay through electron emission: in an SPND, the activated material acts as a first electrode called emitter. A second electrode (collector) placed at close distance from the emitter catches the beta electrons. These two electrodes, connected in a circuit, act as a current generator whose current is proportional to the emitter activation, which is in turn proportional to the incoming neutron flux (Fig. 1). SPNDs are used for in-core neutron flux measurements in fission reactors, exploiting thermal neutron induced activation. The typical time response ranges from milliseconds to seconds, and the sensitivity is around 10^{-21} A/(n/cm^{2}s); the assembly is coaxial with an outer diameter of 3 mm and few cm length. Due to the low current over neutron flux ratio, SPNDs are used for the measurement of neutron fluxes above 10^{10} n/cm^{2}s. Their use can be extended over several orders of magnitude above, where other kind of detectors fail due to radiation effects (NIEL, SEE, DDD) especially when exposed for long periods of time. As an SPND does not require bias voltage to work, these detectors are easy to operate.

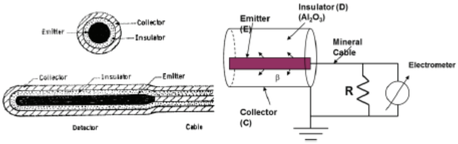

Fig. 1. Schematic view of an SPND (left) and simplified readout scheme (right)

The operation of SPNDs in fusion environments like DONES imposes some constraints on the choice of the materials (operating temperature, burnup, time response). In light of these considerations two prototypes of SPNDs were produced: one with a rhodium emitter (a common material used in fission reactors neutron flux monitoring) and one with an aluminum alloy emitter. Also one dummy SPND with no emitter material was produced to study the electronic background noise. Rhodium has a neutron radiative capture cross section of ~10^{-1}-10^{-3} barn between 100 keV and 15 MeV, while the cross section for aluminum in the same energy region is roughly constant, with a value of the order of 10^{-3} barn [3]. Both chosen elements would produce a delayed response in the SPNDs due to the beta decay of ^{104}Rh and ^{28}Al.

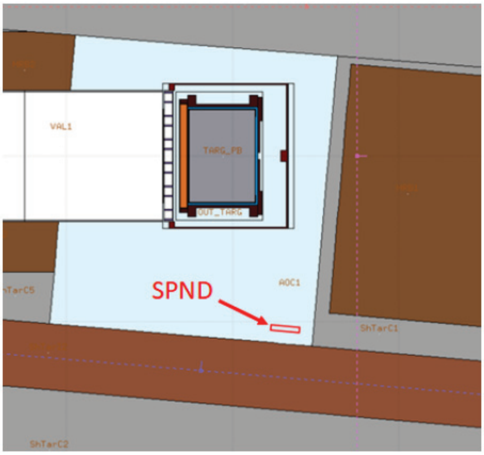

Fig. 2. FLUKA Monte Carlo model of the target area at n_TOF. The SPNDs were installed in the area showed in the red box.

The SPNDs had to be tested in an environment similar to the one expected in DONES, that is a mixed neutron and gamma field, with a neutron spectrum up to 40 MeV, in an accelerator-driven neutron source with a similar background radiation conditions: a set of SPNDs have been installed at the n_TOF facility at the European Laboratory for Particle Physics (CERN). n_TOF is part of the fixed target experimental program at the CERN accelerator complex. The neutrons are produced by the spallation of 20 GeV/c protons coming from the Proton Synchrotron (PS) on a pure lead target. The high intensity neutron pulses are produced by 7 ns (1 sigma) wide proton bunches of 7×10^{12} p every 1.2 seconds (or multiples of this interval). The neutrons have a wide energy spectrum ranging from 10 meV up to several GeV [5]. In order to get a neutron flux of about ~10^{11} n/cm^{2}s with the main component in the energy range between 1 MeV and 10 MeV, it was decided to install the SPNDs in the area surrounding the target, inside the concrete shielding (Fig. 2).

The SPNDs were connected to the readout system through three cables 100 m long. Two readout systems were used: one with the Keithley picoammeters employed in the GELINA run, and one with a 4-channel CAENels picoammeter (model AH401D).

The test beam lasted over 50 days in 2018. During this time the detector response under different beam conditions was tested, including Machine Development stops, technical stops and short beam interruptions, as well as different proton pulse intensities, that have resulted in a wide range of average neutron production rates.

The 10 ms time resolution of the CAENels picoammeter allowed us to resolve the individual current peaks produced by the prompt emission of the target following the proton pulses. In such conditions it was possible to distinguish the prompt and the delayed components of the SPNDs signal.

The rhodium SPND signal is the superposition of a prompt and a delayed component (Fig. 3). The prompt component is represented by the sharp current peaks corresponding to a proton pulse hitting the target, which are produced by the detection of prompt emission of photons and charged particles. The delayed component is visible as a slow variation of the baseline current with the change of the average neutron flux, due to the different sequence of proton pulses on the target. The delayed component is entirely due to neutron activation, and it was therefore isolated from the prompt current peaks in order to study the neutron response of the rhodium SPND.

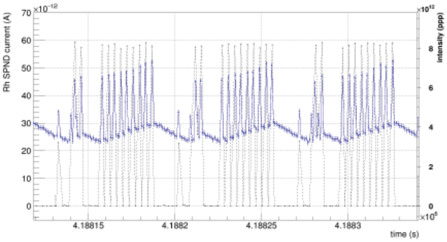

Fig. 3. Rhodium SPND signal shape at n_TOF. The proton pulse intensity is shown with black points connected by a dashed line, the Rh SPND current is shown with blue points. The superposition of a prompt and a delayed signal component is clearly visible.

The time response of the detectors was studied in the time windows in which the beam is switched off. The baseline current decays exponentially, consistently with the hypothesis of the beta activation of ^{103}Rh. Because of the particular position of the detectors, no reference value of the neutron flux was available. The only measurable quantity which is proportional to the neutron flux is the average proton current on the target. In order to study the linearity of the signal, the rhodium SPND baseline current was put in relation with the corresponding average proton current, and a linear relation was found. The measured current is also consistent with the analytical calculations based on the Warren model [6], [7], that predict a delayed component of the order of 10^{-11} A in the simulated flux conditions.

According to the Warren model the prompt component of the signal of the aluminum SPND is one order of magnitude lower than the rhodium SPND current, as it was confirmed by the data. Also, the expected delayed component is of the order of 10^{-15} A, much lower than the noise level. This is consistent with the measurements, that show sharp current peaks corresponding to the proton pulses, and no visible change in the baseline current. This could be explained by the low cross section for neutron capture on aluminum in the energy region of the actual neutron spectrum around n_TOF target, which was simulated with FLUKA.

The performances of the SPNDs and the experience of the first on-target experiment at n_TOF will open new scenarios. SPNDs are planned to be installed near the third generation n_TOF spallation target to monitor the neutron production independently from the detectors in the experimental areas for 10 years operation. This installation will be interesting also for the fusion community, since it will give the chance to perform a long-term test of the detectors before the installation of SPNDs in the DONES test cell. Additional short- and long- term SPNDs tests at accelerator-based neutron sources could also be set up to complement these studies in different mixed-field environment.

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NEUTRON NOISE AND DELAYED NEUTRON BACKGROUNDS AT SPALLATION FACILITIES

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Any discussion on neutron source efficiency should not only consider how to maximise the number of ‘useful neutrons’ at the sample but also how to minimize ‘useless neutrons’. In this work we will discuss background sources and outline recent work on ISIS Target Station 2 to measure delayed neutrons and photons after it was found they may be limiting some low contrast reflectivity measurements.

Introduction

It is well known that the lower power and thick shielding on ISIS Target Station 2 (TS2) results in very low backgrounds. This is one of several factors that allows a wide variety of instruments to produce world class science despite the relatively weak source strength. Background ‘noise’ can come from a large number of sources, such as sky-shine, target shine, instrument to instrument & sample environment etc. As a result of the effective shielding on ISIS TS2 some of these backgrounds are reduced to extremely low levels and the dominant and limiting backgrounds for some experiments becomes lesser considered backgrounds such as atmospheric neutrons or delayed neutrons. The main cause of delayed neutrons is likely to be photo neutrons as a result of high energy gamma ray interactions in the target reflector and moderator. The beryllium reflector in particular has a low threshold for photo nuclear interactions. The work includes neutron and gamma measurements as well as neutronics simulations to both attempt to measure and explain the delayed neutrons at ISIS.

Sources of Background

There are several sources of backgrounds at spallation facilities, this includes:

- Internal instrument noise sources – sample environment, in beam scatter, prompt gamma and block house scatter.
- Target noise – direct fast neutrons, delayed neutrons, target prompt gamma, target decay gamma.
- External noise – target sky/ground shine, instrument to instrument scatter, accelerator shield, cosmic.

The relative magnitudes and effect of the different background sources depend on the instrument, neutron scattering technique and the signal strength from the sample. In many cases it is the sample environment that dominates but in some cases such as low contrast reflectometry at short pulse sources it is any constant signal such as the delayed neutrons which are important.

It is widely known that ISIS TS2 has a low background which means that despite the low power target (only 40 kW), it is able to perform world class science. There are several reasons for this firstly there is more shielding close to the Target, Reflector and Moderators (TRAM) than on Target Station 1 (TS1), secondly the instruments are shielded to the same or higher specification then on TS1 and thirdly all the shielding was custom designed from the start considering background issues. In practice this means over 100× the shielding performance but only ¼ the power compared to ISIS TS1.

Measurement of TRAM background at ISIS

A result of the low background is that for some experiments background sources that would normally be low priority can be important an example of which is the 50 Hz signal seen on the LET instrument. This is likely to be from the accelerator. In the case of low contrast reflectometry measurements on the POLREF instrument a constant noise signal was detected. Initial investigations suggested this was possibly a gamma noise issue from the target so gamma spectrometry was performed. The results of the measurement are shown in Figure 1, the identified gamma lines are most likely from neutron activated components of the TRAM.

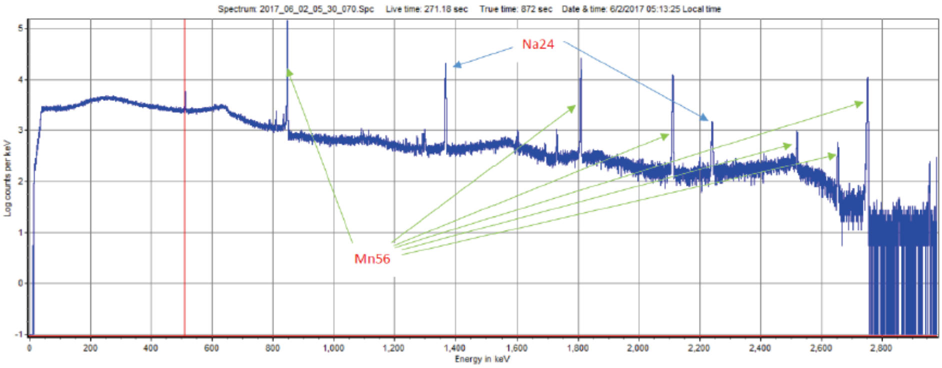

Figure 1 Gamma spectrum at POLREF sample position with shutter open and no proton beam, red line defines the 511 keV peak used for calibration

Figure 2 Delayed neutron detectors set up on ChipIR.

This allowed some discrimination to be added to the detector system but did not fully solve the problem, after further investigation it was thought to be a constant neutron source independent of the proton pulse i.e. "delayed neutrons" from activation gamma induced photo-neutrons. In order to establish if this was correct a measurement has been performed using CHIPIR after the proton beam was switched off to measure the delayed neutrons as a function of time. Measurements were taken using 3 different detectors including a 'Bonner cylinder' and a spectrometer as shown in Figure 2. Preliminary results suggest that the delayed neutron count rate over the 1-24 hours' time period is linked to the Mn-56 half life.

Conclusions

Background noise is an important aspect when considering efficiency of sources, there are many sources of background noise many of which can be reduced with good design. Several measurements of background at ISIS have been reported and work is on going to isolate and measure more detailed backgrounds for each instrument.

BORON-BASED NEUTRON DETECTORS AT ESS

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In Lund, Sweden, the European Spallation Source (ESS) is currently under construction [1]. In order to cope with the expected high neutron fluxes at ESS and to reduce the dependence on Helium-3 gas, whose future availability is uncertain [2], alternative neutron detector technologies are being developed. Here we present an overview of the most recent developments from the ESS Detector Group and Collaborators, concerning a new generation of neutron detectors for neutron scattering experiments. The detectors use thin $^{10}B_4C$ films coated on Aluminum and Titanium. The coating technology of the thin films has been a core part of the development program [3]. Neutrons are detected using the neutron capture reaction in Boron-10 coupled with a Multi-Wire Proportional Chamber (MWPC). The focus in this abstract will be on two Boron-10 based detector designs, the Multi-Grid and Multi-Blade detectors, explaining their working principles and presenting the most recent update on their performance.

The Multi-Grid detector is a large area detector designed for neutron spectroscopy, first introduced at ILL, and jointly developed with ESS thereafter. The design specifications are based on the requirements for the upcoming CSPEC (Cold Neutron Spectroscopy) and T-REX (Thermal Neutron Spectroscopy) instruments at ESS, where a large area coverage and a high count rate capability are needed. The detector is modular in design, where the basic building block is a *grid*. This unit consists of a stack of $^{10}B_4C$ coated aluminum sheets, arranged perpendicular with respect to the incoming neutrons, as well as aluminum sheets placed in parallel, forming a solid grid. These grids are then stacked in a column, and wires are drawn between cells in the grids. This forms a 3D detection system, where the neutron position is found from coincidences between wires and grids. To optimize for neutron detection efficiency, within each grid the coating thickness varies from layer to layer, where the coating is thinner at the front and thicker at the back. The exact distribution of thicknesses is optimized for the average energy expected upon the detector. For T-REX, this is optimized for thermal neutron energies, while for CSPEC the optimisation is done for cold energies. The multilayer design has an additional advantage in terms of enhanced count rate capabilities, as the incident flux is distributed along the depth of the detector. To further increase the count rate capabilities, the charge gain in the MWPC is kept at a low value, reducing charge build up effects. The detector technology has been characterized from test measurements at several world leading neutron scattering facilities. The most recent measurements were conducted at the Spallation Neutron Source (SNS) at the Oakridge National Laboratory in the USA, where the detector was used in the CNCS, a cold neutron spectroscopy instrument, and SEQUOIA, a thermal neutron spectroscopy instrument. There the Multi-Grid detector was installed in the instrument tank, alongside the permanent ensemble of He-3 tubes, allowing for a direct performance comparison. The results obtained with the Multi-Grid detector from the CNCS measurements [4] showed a good agreement with the theoretical efficiency calculation and matched the energy resolution of He-3 tubes for the entire measured energy range. Comparing the energy transfer spectra, all of the elastic and in-elastic features seen in the He-3 tubes were reproduced by the Multi-Grid detector. Furthermore, the detector was operated continuously for over 6 months with only remote access to the data, successfully demonstrating long term detector operation. During the SEQUOIA measurements, the vacuum tight vessel of the Multi-Grid detector was tested for the first time, which was a success. The analysis of the SEQUOIA data is ongoing, with a publication expected by the end of the year.

The Multi-Blade detector is a small area detector developed for neutron reflectometry, with the detailed designed done in a collaboration between ESS, Lund University, Perugia University and the Wigner Institute. The detector is designed to have a high count rate capability and fine position resolution, as required by the upcoming ESTIA and FREIA reflectometry instruments at ESS. Similar to the Multi-Grid detector, the Multi-Blade detector is modular in design. The basic building block is a *cassette*. A cassette consists of a $^{10}B_4C$ coated Titanium substrate, equipped with a 2D read-out system of wires and strips, arranged perpendicular to each other. The cassettes are placed in a circumference around the sample, keeping a constant five degree incident angle with respect to the scattered neutrons. As cassettes are placed in an inclined geometry, a third coordinate can be obtained, resulting in a 3D position sensitive detector. The inclined geometry leads to: better detection efficiency, higher count rate capability and finer position resolution. The increased detection efficiency, as compared to neutrons incident perpendicular to the cassette, result from a longer neutron travel path through the coating film, increasing the neutron absorption probability, while keeping the perpendicular escape distance for the conversion products unchanged. The count rate capability is increased, because with such an inclination incident neutrons are distributed on a larger physical detector area, reducing neutron flux per unit area on each cassette. Furthermore, similar to the Multi-Grid detector, the charge gain in the MWPC is kept low. Finally, the increased position resolution comes from the inclination of the wire plane, resulting in a smaller wire pitch as seen from the perspective of the incoming neutrons. The Multi-Blade detector has also been characterized at several research facilities. The most recent ones being at ISIS [5, 6] in the UK and the Paul Scherrer Institut (PSI) in Switzerland. From the ISIS measurements, the theoretical efficiency curve was well reproduced by measurement data, and the spatial resolution was measured to be 3-4 times finer than current state-of-the-art neutron detectors. Furthermore, by performing a reflectometry measurement on a thin Iridium layer coated on a Silicon substrate, and fitting the data, the correct thickness of the coating could be obtained. This demonstrates the capabilities of the detector to be used in a reflectometry instrument. The PSI data is still being analysed, but preliminary results already indicate a factor of 40 higher count rate capability than current state-of-the-art neutron detectors.

It was found that the detector performance of the Multi-Grid and Multi-Blade detectors matches or outperforms Helium-3 tubes. Furthermore, by demonstrating the technology at current state-of-the-art instruments, the scientific performance of the detectors could be evaluated. This showed that the detectors can fulfill the ESS instruments requirements, while at the same time reducing Helium-3 dependence and cost. Finally, the development shows that Boron-10 based neutron detectors are good options for future efficient neutron sources, as well as enabling future performance gains from this new development path for neutron detectors.

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LARGE SCALE DATA ANALYSIS
FOR THE OPERATIONS SIDE OF NEUTRON SCATTERING

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This research used resources at the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

Recording neutron data on an event base is current state of the art, as is recording the data produced by the many sensors and probes (temperatures, pressures, voltages, etc.) distributed throughout both the neutron scattering instruments and the wider facility. The enormous archives of data present a great opportunity to apply large scale data analysis techniques to verify expected correlations and explore unexpected ones.

During beam characterization measurements at SNS over the years, suspicion rose that some moderators might exhibit beam power dependent effects. Therefore, a campaign of dedicated measurements was arranged in collaboration between beam line scientists and accelerator operators, overseen by the neutronics team. The neutron scattering instruments would take continuous data without any changes to the instrument conditions, while the accelerator operators slowly increased beam power in varying patterns. An analysis of the neutron yield (neutrons detected/proton charge delivered) over time showed that while most moderators deliver constant neutron yield, the decoupled poisoned liquid hydrogen moderator shows significant aberration from this behaviour. Furthermore, a detailed analysis of instrument detector data showed that these changes are wavelength dependent, significantly impacting instrument operations. [1]

Using the analysis scripts developed for these measurements, we thereafter drastically increased the scope of the analysis. Instead of focusing on the high-quality data delivered by instrument detectors during a dedicated measurement, we analyzed the usually less detailed data delivered by beam monitors over long timespans. Beam monitors have the advantage in this that they are usually not influenced by everyday instrument operations (e.g. samples, temperatures, sample environment). This allowed us to pinpoint the time that the poison/decoupler burnup in the SNS' target-moderator system reached critical levels and warn the instrument scientists of the impending changes in moderator performance in time.

Other interesting findings included a time when the accelerator suddenly shut off while instruments were still taking data. Surprisingly, the instrument count rates did not immediately fall to zero, but instead slowly decreased over the course of about half an hour. Analysis of the rate of count rate decrease showed a half life constant consistent with that of Al-28, suggesting that the neutrons observed might be a result of beta-delayed neutron production in the Beryllium reflector assembly.

Up to this point, analysis was done by analyzing individual Nexus files provided by the instruments, and correlating the data extracted from these to Process Variable (PV) data provided by SNS operations (e.g. beam power). This often involved loading thousands of experiment files (usually larger than 1 GB), a rather tedious and fragile process that could take weeks. Therefore, new pathways were developed: Starting with the latest iteration of EPICS, basic instrument data (e.g. beam monitor count rates) are continuously saved as PVs and accessible in parallel to operations data using the Control System Studio (CSS) software. At the same time, beam monitor event data from several beam lines is written into dedicated files once per day, allowing highly detailed data analysis (theoretically down to individual pulses) in a data stream that is completely separate from the scientific user program.

In mid-2019 these new systems were put to the test: The cryostat servicing the liquid hydrogen moderators at SNS developed a vacuum problem, leading to a rise in the hydrogen temperature by ~1.5K, with the potential to change moderator characteristics. Since the hydrogen temperature is also saved as a PV, we were able to monitor the correlation between instrument count rates and hydrogen temperature in real time with very little effort. Furthermore, using the event data files, we were also able to analyze temperature induced changes to the neutron spectrum.

While the change from dedicated measurements to continuous monitoring of moderator characteristics has been a great success so far, it should be considered as only the first step. As of now, the method is still largely reactive (we know roughly what we expect to see) and has not yet gone beyond rather simple correlations. Developing advanced statistical methods of data analysis and possibly even venturing into machine learning has the potential to uncover correlation patterns of higher complexity, which might fundamentally change how neutron scattering facilities are operated and maintained.

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HIGH PERFORMANCE TARGET FOR AN ACCELERATOR DRIVEN NEUTRON SOURCE

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Today's research neutron sources typically utilize fission or spallation in order to provide neutrons for neutron scattering or analytic experiments. As in both processes large energies are involved, these sources are very expensive. An alternative is a Compact Accelerator driven Neutron Source (CANS) with ion beams operating at low energy (below the spallation threshold) and high current using nuclear reactions for the neutron production. Such sources, as developed in the High-Brilliance neutron Source project (HBS), are very effective and cost efficient due to their lower energy with respect to spallation [1].

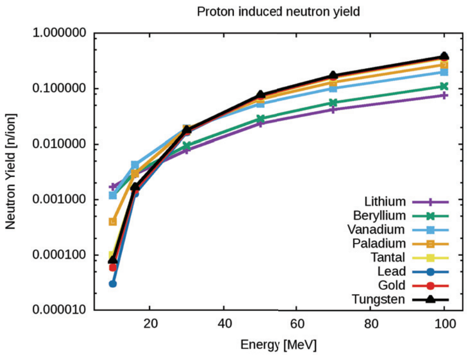

Figure 1: Analytically calculated neutron yield for selected elements at different proton energies using the TENDL 2017 nuclear data library.

The neutrons are produced in a CANS by nuclear reactions of light ions like protons or deuterons in the low MeV range impinging on a suitable target material. The cross sections for the neutron production depend on the particle energy, the particle type and the target material. For energies in the 10 MeV range, low Z materials like lithium or beryllium are generally used due to the high neutron yield. However, by increasing the ion energy above 30 MeV, the performance of high Z materials is improving, and other target materials are becoming more favourable i.e. tungsten or tantalum. The neutrons yield per incident proton as a function of the initial proton energy is presented in Figure 1.

As the neutron output scales approximately quadratic with the primary ion energy but linearly with the ion current, we started to develop a CANS using a 70 MeV proton beam to maximize the neutron yield. With a high peak ion beam current of 100 mA, the risk of blistering inside the target material due to hydrogen accumulation is one of the main reasons for a potential target failure. Tantalum as a target material was chosen considering the high neutron yield, good thermo-mechanical properties and especially a high blistering threshold [2].

To further reduce the risk of hydrogen embrittlement, the target thickness should be smaller than the ion stopping range to move the Bragg-peak outside the target. For the high-power CANS, we are aiming for an average ion beam power at the target of 100 kW at a surface area of 100 cm^2 in order to increase the brilliance further to maximize the neutron flux at the sample position. This power density cannot be cooled with conventional methods. Thus, new concepts like a μ-channel cooling need to be utilized showing a cooling capacity of up to 3.5 kW/cm^2 [3].

A geometry optimization for such a target concept showed that 0.4 mm thick μ-channels are needed as well as elongated μ-channel geometry to increase the heat exchange for an efficient target cooling. In order to prevent that the μ-channels act as guiding channels for the protons, these channels are tilted and the probability that a proton can pass through the target material with a high energy is minimized.

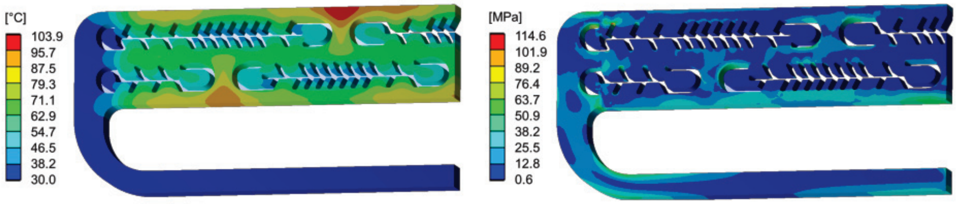

Figure 2: ANSYS simulation of the temperature distribution and the mechanical and temperature induced stress inside the target.

The ANSYS simulations of the target geometry presented in Figure 2 show that with the concept of the μ-channel cooling the temperature inside the tantalum target can be reduced to around 100 °C at an average power deposition of 100 kW with a power density of 1 kW/cm^2. Due to the efficient cooling, and therefore the small temperature gradients, the maximum stress inside the target is about 115 MPa, well below the yield strength of tantalum which lies above 300 MPa.

Such a target concept can be utilized for a high-performance target with can be operated safely at 100 kW average beam power. The average neutron output of such a target with a 70 MeV proton beam and a peak current of 100 mA is according to MCNP simulations using the TENDL 2017 database in the order of 10^{15} s^{-1}. This allows the operation of demanding elastic and inelastic neutron scattering experiments.

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EXPECTED PERFORMANCE OF ESS INSTRUMENTS IN COMPARISON WITH THOSE AT A SHORT PULSE SOURCE OF J-PARC

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ESS will be the first long pulse spallation source to be built. The power is an unprecedented 5MW with a pulse width of 2.9 ms (precisely 2.857 ms) and a repetition rate of 14 Hz. Spallation sources, so far, have been using short proton pulse to produce sharp neutron pulses, which is suitable to analyse the energy by the time-of-flight (TOF) method.

Since the situation on the requirement for TOF is the same at ESS, therefore, shorter neutron pulses are often cut out from the long pulse by a pulse shaping chopper (PSC), resulting in a significant sacrifice of the flux at the instrument. Repetition rate multiplication (RRM) may compensate this drawback [1].

In this report the performance of ESS instruments is estimated in comparison with existing short-pulse instruments at J-PARC, operating at 1 MW and 25 Hz.

A significant reduction of the neutron cross-section of para-hydrogen below 30 meV [2] hinted a thin moderator concept at ESS, which gives a gain factor 2.5 with 3 cm thickness [3]. Hybridization of ambient water moderator together with the thin hydrogen cold moderator would give a great advantage to instrument performance. Together with the higher proton power in the accelerator and the advanced moderator concept, the estimated source performance in comparison to that of J-PARC coupled moderator could be generally a factor 10 as illustrated in Fig. 1 [4]. In addition to this, the gain at the thermal region is remarkably to be 60 in comparison to that of J-PARC.

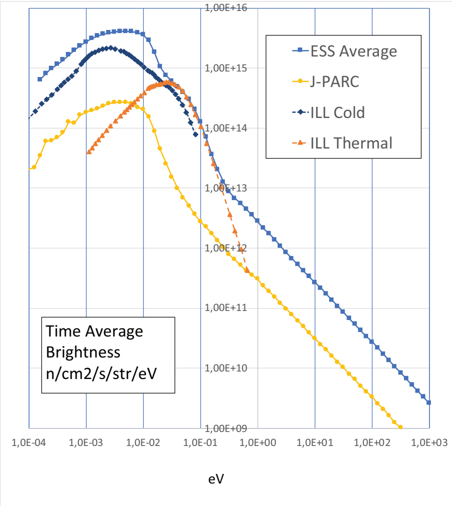

Figure 1. Time-averaged brightness of ESS, J-PARC and ILL.

Since spectrometers uses either monochromatic incident beam or energy analyzed neurons after sample, we can easily estimate the performance of those class of spectrometers in comparison to similar counter partners at J-PARC. In case for the direct geometry instrument, the chopper opening time of monochromating chopper can directly give the estimate by considering the time width of at the moderator. The resolution is dominated by the secondary spectrometers for this class of instrument, the performance of CSPEC against AMATERAS [5] for a single mode could be almost equivalent each other. However, in case for the indirect geometry instrument such as MIRACLES [6] and DNA [7], we estimate a fairly good gain enhancement of a factor 20 to MIRACLES, even for the equivalent secondary spectrometer. This enhancement mainly

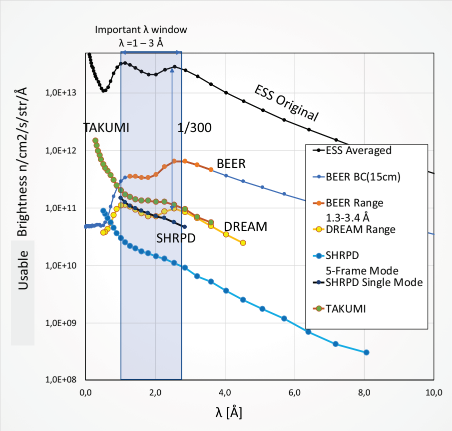

Figure 2. Performances of diffractometers. BEER, DREAM are ESS instruments. TAKUMI and SHRPD are J-PARC instruments.

comes from the nature of the long pulse of ESS [4], and we have realized that performance enhancement could highly depend on the class of instruments.

On the other hand the performance of diffractometers would highly depend on the design concept of PSC to sharpen the time width of incident beam. Figure 2 summarizes the brightness at the sample of diffractometers. BEER [8] and TAKUMI [9] are engineering diffractometers. DREAM [10] and SHRPD [11] are high resolution powder diffractometers. Those pairs of instruments are aiming at a similar resolution each other. BEER adopts a blind chopper concept [12] to realize the resolution of Δd/d is constant, whose character is naturally realized at the sharp pulsed source because of the intrinsic nature of moderation time in the moderator. BEER would fairly well perform in the typical wave-length rage between 1 Å and 3 Å in comparison to TAKUMI. On the other hand DREAM adopts a conventional fixed time window opening of PSC so to realize a high resolution. Because of slow repetition rate at ESS, its single flame gives wide wave-length range to DREAM. SHRPD often takes the five-frame mode by sacrificing 4 out of 5 frames so as to have a really wide wave-length range. However, the brightness of SHRPD for the single frame mode is almost comparable with that of DREAM at the important wave-length range.

Here, we saw the instrument design concept is quite important to extract the full potential of the source, and we hope the report will be useful for those designing activities.

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ARGON BUBBLE FLOW IN LIQUID GALLIUM IN EXTERNAL MAGNETIC FIELD

Mihails Birjukovs, Valters Dzelme, Andris Jakovics, Knud Thomsen and Pavel Trtik

This work is dedicated to neutron imaging of two-phase liquid metal systems with relevance to theoretical and applied magnetohydrodynamics, as well as computational fluid dynamics. Specifically, argon bubble flow in liquid gallium in with and without the presence of external magnetic field is studied using high frame rate neutron beam transmission signal recordings obtained at the NEUTRA beamline, SINQ, PSI.

This is motivated by the fact that, among other non-invasive measurement methods available for liquid systems, optical measurements are impossible due to metal opacity [1], ultrasound Doppler velocimetry and transit time technique yield no information regarding bubble shapes and are imprecise in case of oscillating bubbles [2,3], while X-ray transmission methods are limited to thin liquid metal samples [4], which may not be representative of systems to which the probed small scale system is later upscaled. Neutron radiography allows one to potentially sidestep these issues and perform direct observations of phase distributions within metal flow [4-8].

Detailed data from such experiments would prove very useful in understanding the physics of multiphase flows, magnetohydrodynamic of otherwise, as well as for verification of numerical models. As such, the end goal of the study, a part of which this work represents, is to produce the tools that would enable as detailed and direct comparisons as possible between experiment and simulation. The objective of the present work is to construct a robust image processing pipeline capable of extracting as much physical information as possible out of two-phase flow snapshot series. The caveat is that, due to high bubble velocities and the required large field of view, the signal-to-noise ratio within the obtained images is inherently low. As a result, generating usable results is much less trivial and requires special considerations.

The first version of the developed neutron image processing routine is shown be sufficiently robust and capable of reliable recognition of bubble shapes and free surface of metal, performing velocimetry and analyzing data. This is verified by numerical simulations that reproduced the experimental setup in silico, where results are in good agreement with what is seen from the experiment and is expected from theoretical considerations.

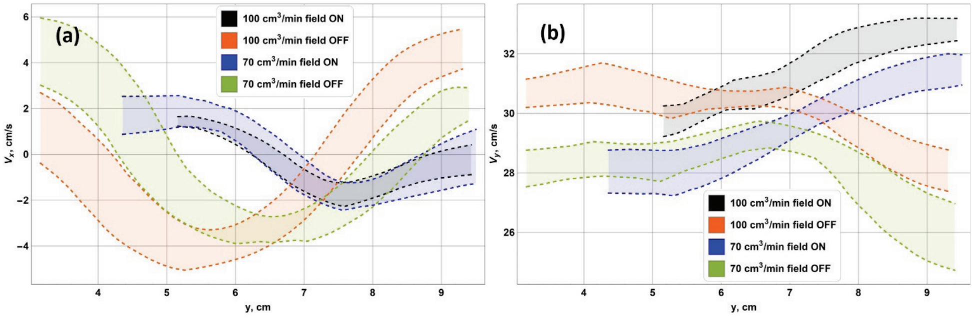

Figure 1. Experimentally determined averaged (a) horizontal and (b) vertical velocity components of ascending bubbles at different elevations above the inlet, for different gas flow rates, without and with (~ 0.3 *T*) applied magnetic field. Colored bands represent averaged curves plus their local errors.

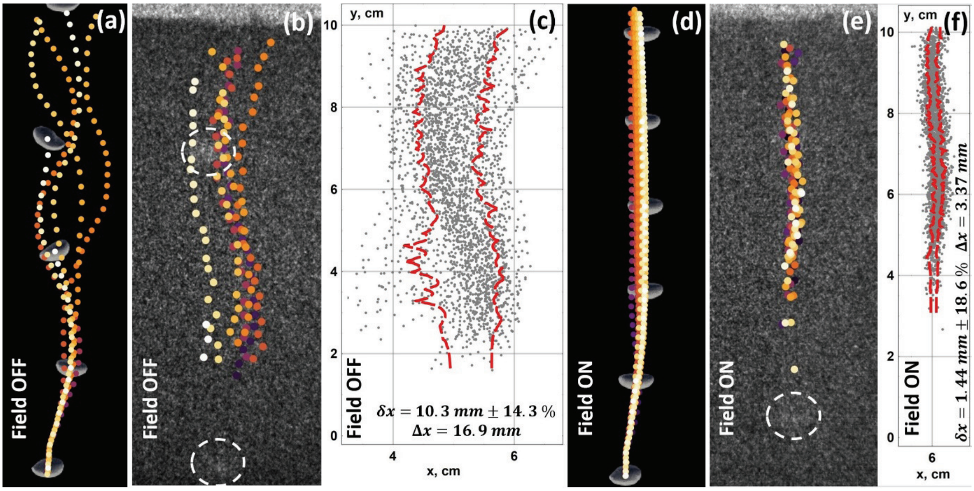

Figure 2. Several initial bubble trajectories for a 100 cm^3/min flow rate derived from simulations (a,d) and experiments (b,e). In cases (a,b) there is no magnetic field, and in (d,e) the field (~ 0.3 T) is applied. Simulation frame rate matches that of the experiment. Bubble detection points are color coded by order or appearance, dark purple to white. Inlet and free surface are located right beneath and above vertical boundaries of images, respectively. Bubbles are highlighted in experimental images (b,e) by dashed white circles. In (c,f), entire sets of detected bubbles over all frames are shown, without (c) and with (f) horizontal magnetic field. Dashed red lines indicate bubble set envelopes, derived using the statistics-sensitive nonlinear iterative peak-clipping (SNIP) algorithm. δx and Δx in (c,f) stand for mean bubble set envelope thickness and maximum horizontal bubble spread, respectively. Distance scales in (c,f) are identical.

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EXPERIMENTAL NEEDS FOR NEUTRON SCATTERING METHODS IN THE CHARACTERIZATION OF NUCLEAR MATERIALS AND COMPONENTS

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Advanced materials and related technologies are a key issue in the development of GenIV reactors and of the future fusion reactors like DEMO [1]. In fact, severe and unprecedented radiation damage effects are expected in fusion materials: the exposure to 14 MeV neutron fluxes will produce helium concentrations and damage levels (dpa, displacement per atom) one order of magnitude higher with respect to the fission reactors. Furthermore, complex welding and joining techniques must be developed for the so called “plasma facing components”, directly exposed to plasma disruptions and submitted to cyclic thermo-mechanical stresses due to the pulsed operation mode of the *tokamak*. Neutron sources provide a powerful experimental tool to investigate in the bulk the effects of such service conditions and to provide the experimental data needed to validate numerical predictions.

SANS is particularly useful for studying irradiated ferritic/martensitic steels currently considered as the prime option for the “first-wall” of the future *tokamaks* [2, 3]. The available samples are usually very small (typically 3 mm × 4 mm × 1 mm in size) and very radioactive (10-20 mSv/h contact dose), therefore the following is first of all required to the instrument: high flux, adequate shielding, well developed equipment and procedures for sample transportation and handling. As discussed in [3], samples irradiated under different conditions may not be available at the same time and have to be measured in separate SANS experiments: since understanding micro-structural evolution as a function of irradiation parameters is the main goal of such studies, an excellent reproducibility of SANS cross-section is mandatory (taking also into account the complexity and the costs of such experiments). Furthermore, the utilization of polarized beams for studying these magnetic steels can provide unique micro-structural information by the nuclear-magnetic interference [4, 5]. Also from this viewpoint, high flux is the first requirement. However, it is interesting to note how the high quality polarized SANS measurements of ref. [4] could be obtained even without high flux, but with an excellent efficiency of the utilized instrument, originally designed also for this type of application. This work, as well as ref. [2], show also how important a Q range as wide as possible is to properly understand the complex micro-structure of these materials.

An important development of the SANS application in this area might concern in the future the characterization of samples irradiated at the International Fusion Materials Irradiation Facility [6], providing fluxes of 14 MeV neutrons concentrated in very small volumes. The sizes of such miniaturized samples may be almost one order of magnitude smaller than the ordinary ones, so very high neutron fluxes and accurate experimental layouts will be needed to this task. Irradiation effects in materials may also be studied by implantation techniques (see for instance ref. [7]): in this case the surface of the samples is large, but their thickness usually limited to a few microns, so GISANS and reflectometry should probably be considered to characterize them. The scientific interest is very high also to understand the fundamental differences in micro-structural effects produced by neutron irradiation or ion implantation.

Neutron diffraction is indispensable for stress measurements in nuclear welds and for monitoring crystallographic phase changes under thermo-mechanical treatments or irradiation. The utilization of these techniques in such complex fields is challenging, both concerning instrument development and needed flux. High spatial resolution is first of all needed for stress measurements in nuclear welds, since the most critical stress gradients, next to the weld or in the heat affected zones, may often develop over distances smaller than 1 mm; adequate neutron flux is also mandatory for obtaining bulk averaged results and comparing both with mechanical testing and with numerical predictions. A recent example is provided in ref. [8], referring to the neutron diffraction characterization of a sample developed for the so called "divertor", one of the most critical plasma-facing components: it consists in an assembly of CuCrZr cooling pipes coated with a W armor brazed by a thin Cu interlayer. Despite the complexity of this prototype component, made up by 3 different materials (one of them quite absorbing), the neutron diffraction experiment has provided an accurate mapping of the stress field, contributing to check the numerical predictions. However, the interlayer region, the most critical one particularly in view of radiation resistance, requires much sharper gauge volumes and higher flux (or longer counting times) to be properly mapped and understood.

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STUDIES ON REFLECTOR MATERIALS FOR COLD NEUTRONS

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The tremendous potential of neutrons as a probe of matter or as a research object by itself is limited by the relatively low-flux intensity of the neutron sources, as compared with photon sources. In addition, the different processes (production, slowing-down) and devices (moderators, transport systems, collimators, energy-selectors, detectors, etc.) reduce by several orders of magnitude the actual neutron intensity that eventually conveys the experimental information of interest. One of the research lines devoted to minimize those loses has been oriented to the search for efficient reflector materials, that may improve the efficiency of guiding surfaces or the actual reflection of neutrons on a containment walls to reduce their leakage. A large body of work has been done in the past, particularly concerning the interaction of slow neutrons with diamond nanoparticles. It has been demonstrated the high reflectivity of this material for UCN and VCN on the basis of calculations for ideal systems as well as by scattering experiments, and proposed that such capacity may extend to higher neutron energies, thus bridging the "reflectivity gap" in the neutron spectrum [1, 2].

Diamond Nanopowders

The description of the neutron cross sections of nanodiamond (ND) over the thermal and cold energy regions demands a proper account of the bulk diamond properties, as their contribution will be significant for thermal neutrons.

In order to evaluate the elastic and inelastic components of the cross sections, we first calculated the phonon density of states (PDOS) of diamond, using *ab initio* algorithms [3]. We then developed a scattering kernel and generated cross section libraries over the thermal and cold neutron energy ranges, using the codes NJOY [4] for the inelastic contributions and NCrystal [5] for the elastic ones.

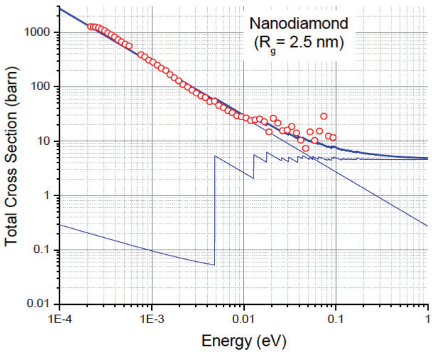

Fig. 1: Total cross section of nanodiamond, comparing our calculated curve (heavy line) with experimental data from Ref. [7].

The characteristics of the diamond nanopowder and the interactions of slow neutrons with such system are given in [6]. The diffraction of the neutron wave on structural and density inhomogeneities gives rise to coherent elastic effects that superimpose upon the bulk crystal cross sections.

In order to produce a library corresponding to a real material, we used the experimental SANS results obtained by Teshigawara and coworkers [7], and fit them using the unified exponential/power-law approximation [8] as expressed in Eq. 3 of Ref. [9]. This structure factor can be integrated to give the scattering total cross section corresponding to the coherent elastic effects caused by the

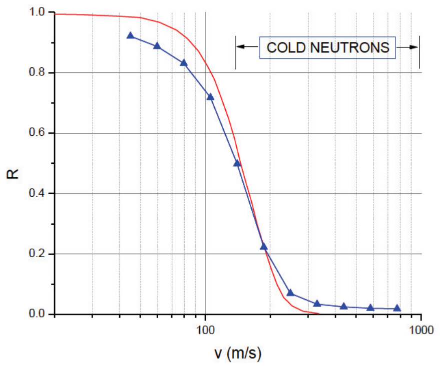

Fig. 2: Reflectivity vs. neutron velocity, for a 10 mm thick ND sample. The continuous line (red) is the result from Ref. [11], while the curve with symbols (blue) corresponds to our calculation (density = 0.6 g/cm^3).

nanopowder which, when added to the nanospheres' bulk diamond contributions produces the total scattering cross section for this system with apparent radius of gyration of 2.5 nm. Those calculated contributions together with the experimental points [7] are shown in Fig.1.

The scattering kernel, including small angle scattering effects, was implemented in the Monte Carlo program OpenMC [10], and this tool was used to study the reflective properties of nanodiamond layers.

We modeled the experiments performed by Nesvizhevsky et al. [11], with a monoenergetic beam of neutrons impinging on a plate of variable thickness. The results (Fig. 2) show a good agreement with experimental results, showing a good reflectivity for very cold neutrons that falls sharply for energies above 0.1 meV. Calculation of thicker ND slabs and removal of impurities allowed a modest increase of the energy at which the reflectivity decreases, but none of the calculations showed high reflectivities above 0.5 meV.

Magnesium Hydride

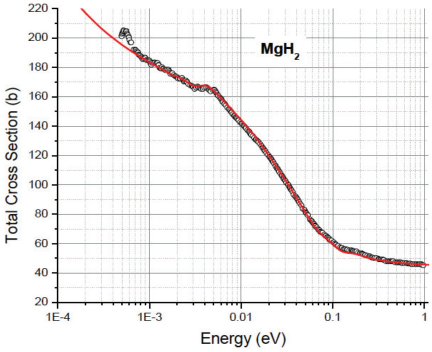

Fig. 3: Calculated total cross section of room temperature MgH_2 (solid line) and the experimental points of Ref. [14].

At neutron energies where coherent elastic interaction with the scattering system cannot produce an intensity much larger than the bound-atom coherent cross section value, other kind of interactions should be explored as mechanisms to produce a significant reflection capacity. To drive our search for a material with such property, we must look for: a) large scattering cross section, b) large elastic cross section, c) highly isotropic angular cross section, d) small inelastic cross section, and e) small absorption cross section. Several years ago we proposed that a material with these properties is Magnesium Hydride (MgH_2) at a low temperature [12].

The structure and dynamics of the material are the necessary pieces of information to generate a scattering kernel and a cross section library. We developed a new frequency spectrum for MgH_2, and then calculated the components due to the metallic lattice and the hydrogen, employing again NJOY [4] and CRIPO [13]. As a first validation test we compared the calculated total cross section with experimental data at room temperature [14], obtaining an excellent agreement as shown in Fig. 3.

OpenMC was used to simulate the configuration used by Nesvizhevsky [11] to compare the reflectivity of nanodiamonds and magnesium hydride. The scattering kernel calculated with NJOY and formatted into a standard ACE library was used to model the material.

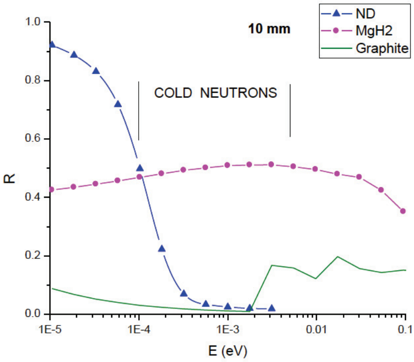

Fig. 4: Reflectivity profile of MgH_2. Comparative with known moderators/reflectors shows constant performance for a wide energy range.

The results (Fig. 4) show a reflectivity profile which remains almost constant at all energies, with a value of ~50% for 10 mm thickness with an apparent density of 1.0 g/cm^3. For very cold neutron energies the absorption of hydrogen reduces the reflectivity, but the large and almost constant elastic scattering cross section of hydrogen maintains a high reflectivity from very cold to thermal energies.

Conclusions

We have developed a new scattering kernel to describe the interaction of slow neutrons with diamond, with special reference to nanopowders, and generated a cross section library that includes both the bulk contribution as well as the elastic coherent one due to the nanostructure. Reflectivity calculations using our library confirmed the excellent performance of that material for ultra-cold and very-cold neutrons.

On the other hand, to deeply explore a proposal we made few years ago concerning a potential good cold neutron reflector, we produced a new scattering kernel for MgH_2 which was validated against available transmission experiments.

A cross section library for this material at low temperatures was generated and used to perform reflectivity calculations that confirm its expected good performance as reflector of cold and thermal neutrons.

We expect that this new reflector system could help to improve the efficiency of advanced cold neutron sources, at pulsed or stationary facilities.

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MODERATOR CHOICES FOR SNS SECOND TARGET STATION

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Oak Ridge National Laboratory has initiated the project for building a second target station (STS) co-located at the Spallation Neutron Source (SNS) to provide 22 more beams to the neutrons scattering mission of Department of Energy [1]. At 700 kW power and 15 Hz repetition rate, STS will utilize every fourth pulse served by the SNS accelerator, which is presently being upgraded from 1.0 GeV proton energy and 1.4 MW power to 1.3 GeV and 2.8 MW [2]. Geared to produce the highest intensity cold neutron beams into small samples, STS is complementary to the other ORNL neutron sources, with HFIR providing high intensity continuous beams of thermal and cold neutrons, and with the SNS First Target Station (FTS) serving thermal and cold neutron beams for high-resolution instruments.

The core components will be a water-cooled rotating-wheel tungsten target with two coupled moderators positioned on top and bottom of the target to provide the best feed-in from the compact neutron production zone obtained by a proton beam footprint of 60 cm^2 and the high neutron yield zone obtained from the high-Z and high density provided by the target material choice.

Moderator performance is impacted by the choice of moderator materials, the moderator size and temperature, position with regard to the neutron production zone, the moderator environment including pre-moderator and reflector material choices and sizing. As a short-pulse source striving for high intensity cold neutron beams, STS was decided to be best served by liquid para-hydrogen moderators pre-moderated with ambient temperature light water and surrounded by beryllium reflector. Moderator geometries have been identified that provide the highest brightness of cold neutrons to the neutron scattering as depicted in Figure 1: a cylinder moderator of 8 cm hydrogen diameter and 3 cm height, and a tube moderator in triangular arrangement with 3 cm diameter and 14-16 cm length hydrogen tubes premoderated with approx. 2-2.5 cm thick ambient temperature water. Both concepts live from the facts that the water premoderator/hydrogen interface zones are most productive for the brightness at the emission ports first utilized at J-PARC [3], and that extraction ports of 3-cm linear dimension are sufficient to map neutrons efficiently on to the instrument samples of sub-centimeter sizes [4]. The moderator designs were the outcome of numerous optimization studies via Monte Carlo simulations with MCNPX [5] using a pulse-integrated cold-flux figure-of-merit metric for the cylinder moderator and a peak-pulse cold flux figure-of-merit metric for the tube moderator.

These two optimization metrics mostly drive the viewed moderator depth (i.e. cylinder diameter or tube length) and favor by a factor of two narrower pulse width using the peak-pulse metric or broader pulses at some cost to pulse height and bracket the possible extremes in moderator shapes. Optimization of the moderator sizes applying instrument-specific metrics is foreseen as STS instrument concepts are maturing. With the cylinder moderator being optimized towards cold peak-pulse metric, and the tube moderator towards cold pulse-integral metric, the two STS moderators provide a factor of 25 higher peak-brightness compared to the FTS coupled moderator of today (operated at 60 Hz, 1.4 MW with 30/70 ortho/para ratio), and factors of 5 and 9 higher time-averaged brightness for the cylinder and tube moderators, respectively.

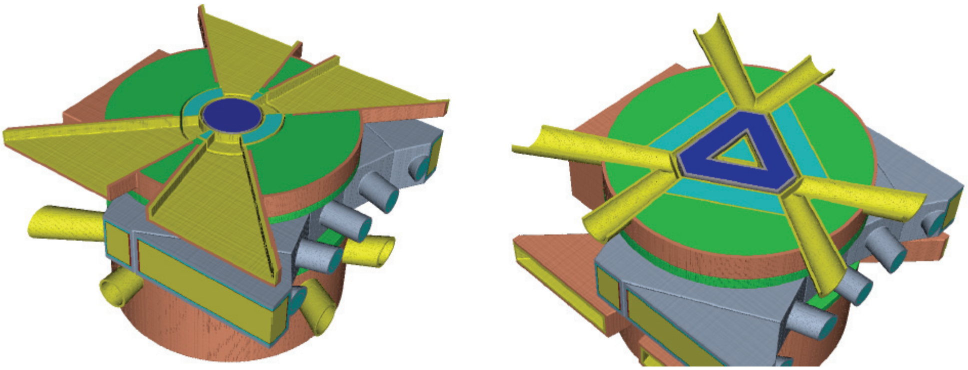

Figure 1: Cylinder moderator (left) and tube moderator (right) placed on top and bottom of target. The color notation is blue – para-hydrogen, light-blue – water, green – beryllium, yellow – aluminum, lightbrown – tungsten, grey – steel.

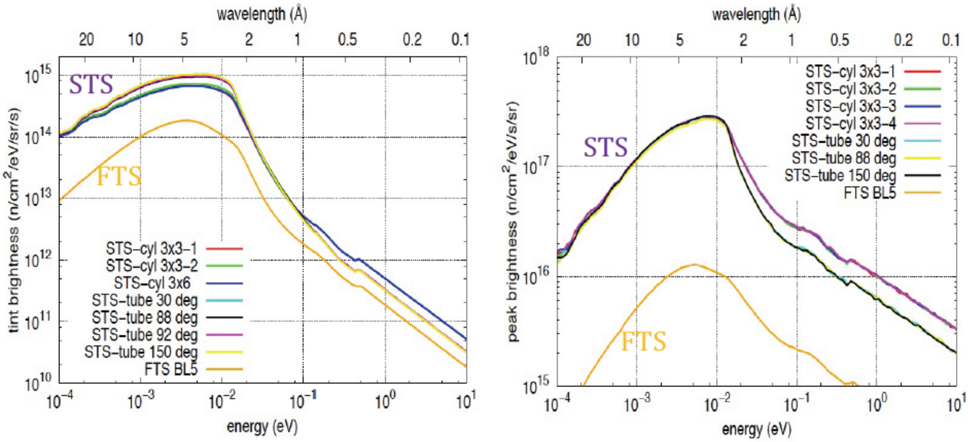

Figure 2: Comparison of time-averaged brightness (left) and peak brightness (right) of STS moderators and the FTS coupled hydrogen moderator with SNS operating at 60 Hz / 1.4 MW.

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DEUTERATED CLATHRATE HYDRATES AS NEUTRON MODERATOR AND REFLECTOR IN HIGH-FLUX SOURCES OF COLD AND VERY COLD NEUTRONS

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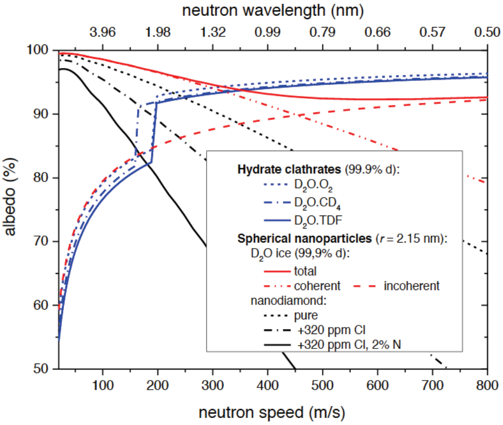
Sources of Very Cold Neutrons (VCN), providing large yields in the long-wavelength tail of existing cold sources, are a current topic of interest for the community of neutron users. They would enhance the capabilities of major neutron scattering techniques and the scientific reach of particle physics experiments using beams of slow neutrons. Necessary requirements for VCN moderator materials include weak absorption, and availability of low-energy modes with large inelastic scattering cross sections for efficient slowdown of pre-moderated neutrons. Deuterated clathrate hydrates seem particularly promising for this. These inclusion compounds consist of a network of water molecules that form cages able to host small guest molecules. Inelastic incoherent neutron scattering by local modes of the latter can remove energy from the neutrons without kinematic restrictions due to a phonon or magnon dispersion relation. A concrete proposal presented at this workshop employs a cooling cascade mechanism in fully deuterated O_2-clathrate hydrate, exploiting the zero-field splitting of the magnetic triplet ground state of the oxygen guest molecules [1]. It is also interesting to investigate the effectiveness of rotational and local librational modes of alternative, non-magnetic guest molecules in the water lattice. For instance, Tetrahydrofuran (THF) clathrate hydrate ($17H_2O{\cdot}C_4H_8O$) was already shown experimentally to offer a broad band of low-energy incoherent excitations [2]. However, still missing is a determination of $S(q,\omega)$ of clathrate hydrates in absolute units, which is a key input for choosing among moderator material candidates. Like the O_2 hydrate, the THF hydrate crystallizes in the clathrate structure CS-II with 8 large and 16 small cages in an fcc unit cell, wherein the THF molecules fill only the large cages. The properties of this material are particularly interesting from a practical point of view. First, it can be produced directly from a stoichiometric THF/water mixture at ambient pressure allowing for simple preparation of large quantities. If the moderator turns out to degrade in the harsh radiation environment of a high-flux source, annealing by melting and refreezing seems a possibility. Moreover, THF is known to promote migration of gas molecules like oxygen into the empty small cages, resulting in strongly relaxed pressure conditions to form the binary clathrate as compared to a simple gas hydrate without THF [3]. Planned inelastic neutron scattering experiments have the primary goal to establish a database of $S(q,\omega)$ for promising materials, thus enabling realistic model calculations for optimisation of moderators. The scope of application might be limited by the radiation hardness of these materials, which also needs to be determined. In strong radiation fields, Buckminster fullerenes [4] or other carbon nano-materials intercalated with oxygen might be a viable alternative to the hydrates [5], however with larger absorption due to the carbon nuclei and with lower abundance of the guest molecules.

Clathrate hydrates are also interesting as reflectors for neutrons from standard cold sources. Besides atypically weak neutron absorption they possess unusually large crystallographic unit cells, leading to Bragg scattering below large cut-off wavelengths of 2 nm and 2.4 nm for the most common hydrates CS-II and CS-I, respectively. Even neglecting the latter, the 2 barn spin-incoherent scattering cross section of the heavy-water deuterons generates a high albedo of 90% at $\lambda \sim 1$ nm for a thick diffusive wall. This type of scattering (occurring in any standard liquid heavy-water reflector) covers the entire cold-neutron range 0.6 nm $< \lambda <$ 2 nm, where the authors of Ref. [6] claim the existence of a “reflectivity gap”. The Bragg scattering further



enhances the albedo, which is visible as a step in the figure, which compares albedos of different materials (no further Bragg edges appear in the figure, as the coherent cross section has been approximated by the sum of the nuclear cross sections without interferences). The clathrates thus seem able to enhance the output of a standard liquid-D_2 if used as a reflector, notably when cooled to low temperature to avoid re-thermalization. As incoherent scattering by carbon is negligible, diffuse reflection by nanodiamonds on the other hand relies solely on coherent inhomogeneity scattering [7], which rapidly falls off with decreasing λ. Hence, even unrealistically pure nanodiamonds become inefficient for cold neutrons. However, this type of reflector is interesting for reflection of VCN with $\lambda > 2$ nm, with performances depending on the achievable level of impurities (see the figure, where one also notes an even better performance of aerosols of D_2O ice, which have lower absorption than the best possible nanodiamond powder, and which can be abundantly produced with suitable particle sizes).

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NANODIAMOND APPLICATION FOR COLD NEUTRON FLUX ENHANCEMENT IN COMPACT NEUTRON SOURCES

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Nanodiamond Particles (NDP) are new candidates for neutron reflection. They have a large scattering and low absorption cross-section for low-energy neutrons due to their high optical potential [1]. Very Cold Neutrons (VCN) are reflected in NDP with large scattering angles while Cold Neutrons (CN) have a quasi-specular reflection at small incident angles [2, 3]. NDP surface is surrounded by impurities consisting of carbon, oxygen, nitrogen, and traces of metals. These sphere-like shape particles are made by explosive shocks dating back to some decades ago. They are produced in the scale of nanometers. CN have a quasi-specular reflection if they are irradiated with small incident angles on NDP while they penetrate deep through and do not come back to the surface if they have large incident angles. VCN, on the other hand, can be scattered in large angles for any incident angles. NDP cross-sections are calculated based on Born approximation.

A new scattering process has been added in Geant4 in order to model the low-energy neutron interaction in nano-dispersed media [4]. A new discrete process is implemented along with predefined processes to examine the directional reflection of CN in an extraction beam made of NDP layers. Impurities in NDP are responsible for the up-scattered neutrons, especially hydrogen which has a large cross-section. Other impurities are also considered as a normal material in Geant4 in order to produce a more accurate model for low-energy neutron scattering in NDP powder. A case study of Compact Neutron Source (CNS) is introduced for the production of CN. Geant4 is used to model the possible configurations of Target-Moderator-Reflector (TMR) in the CNS. A typical beam of 13 MeV proton is bombarded on a beryllium target with the thickness of 2 mm in order to produce the fast neutrons from (p,xn) reaction. Liquid parahydrogen is placed as a cold moderator in front of the target in order to slow down fast neutrons to cold ones. The length of cold moderator is optimized to 14 cm while its diameter is kept constant with the value of 3 cm. NDP are placed around the extraction beam for scattering the CN toward the exit of the beam. The extraction beam is made of a cone with the thickness of 3 mm and length of 1 m starting from the center of moderator. **Fig. 1** shows the CNS implemented in Geant4. CN with small incident angles entering the extraction beam and making an interaction with the NDP layer are going to have a quasi-specular reflection and are going to be directed toward the exit. The results show that CN exiting the extraction beam can be increased thanks to the implemented NDP layer. The results are shown in **Fig 2**. Two sizes of NDP with 5 and 10 nm are compared with aluminum, and carbon. Moreover, the angle distribution of neutrons exiting the extraction beam is increased not only for small incident angles but also in large angles. Fig 2 shows the CN angle distribution. In addition, since the number of neutrons with larger angles arriving at exit increases, this can be useful in order to place another neutron convertor in order to produce Very Cold Neutrons (VCN).

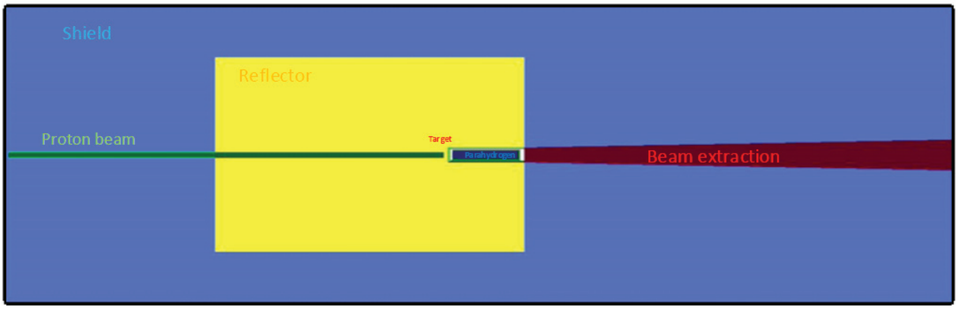

Fig 1. CNS implemented in Geant4.

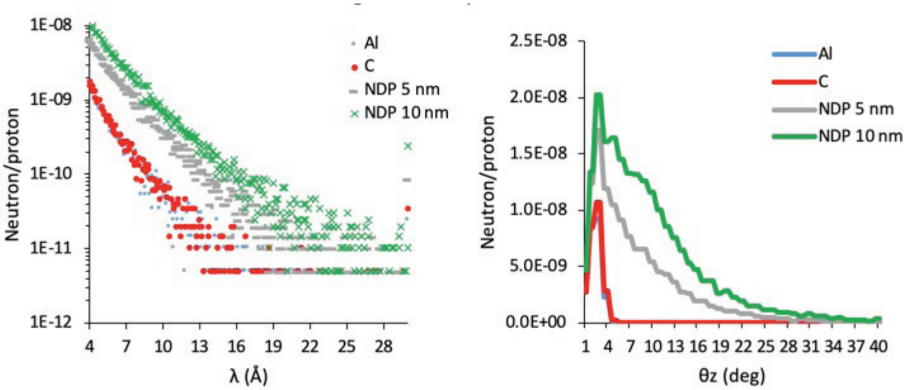

Fig 2. CN spectrum at the exit of CNS.

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ESS MODERATORS: CURRENT STATUS AND UPGRADE OPTIONS

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Figure 1. ESS construction site, 2019 April

The European Spallation Source (ESS), under construction in Lund, Sweden (Fig. 1), will be the most powerful neutron source in the world for neutron scattering experiments. The design of ESS moderator system to produce both cold and thermal neutrons was based on the novel concept of a high-brightness moderator developed at ESS – the so-called quasi-low-dimensional moderator [1, 2].

After an intense design and optimization effort, a single flat moderator system placed on top of the spallation target in wing configuration was selected. The moderator-reflector assembly consists of a cryogenic liquid para-hydrogen tank of 3 cm height and a pair of water moderators surrounded by layers of water pre-moderators and capped by Be reflector (Fig. 2). All 15 instruments of the initial instrument suite, plus the test beam line, will point to the top moderator.

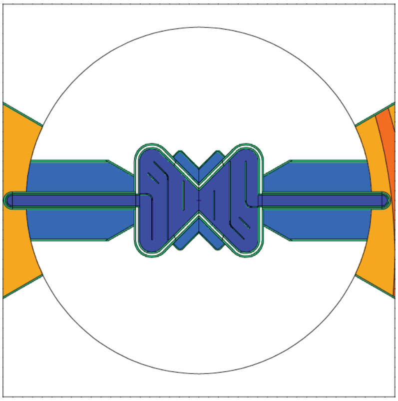

Figure 2. ESS butterfly moderator

Being the most powerful spallation neutron source in the world, the unique capabilities of ESS can be accommodated for a variety of applications beyond neutron scattering experiments: material testing, isotope production for medical use, neutrino beams, muon beams, even a Higgs factory [3], to name a few. However, ESS is a neutron scattering facility first and foremost: its main upgradeability path is to produce more (useful) neutrons for more neutron scattering experiments.

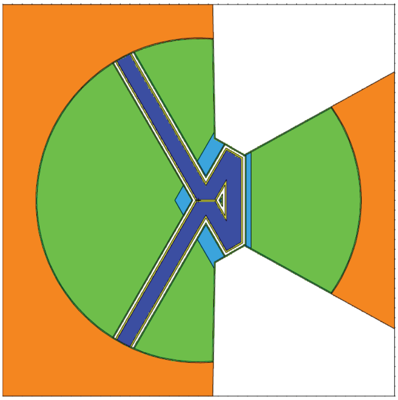

Figure 3. Extreme-brightness moderator: a possible configuration

In this respect, three design features of ESS are particularly remarkable: (1) 42 beamports placed around the spallation target in uniformly spaced grid, leaving upgrade areas available for future instruments beyond the initial suite; (2) the freedom of choice of placing the instruments, since, contrary to other facilities, all the beamports have the same neutron spectral characteristics (bi-spectral cold-thermal); (3) beam extraction system, which allows for neutron extraction from below the target, where another moderator system can be installed in the future. Thus, a moderator system placed in the pre-allocated space below the spallation target will in essence constitute an equivalent of an upgrade to the second target station, but without the necessity to build a second target station or to modify the accelerator.

Currently, the possibilities for the bottom moderator system are under intense investigation. The research is aligned along the following options:

- Directional extreme-brightness moderators,
- High-intensity moderators,
- Very cold neutron (VCN) and ultra-cold neutron (UCN) sources.

The concept of the directional extreme-brightness moderator is based on quasi-1-dimensional tube-like moderators capable to serve a number of dedicated beamports (Fig. 3).

Another option is to develop a high-intensity moderator to maximize the total number of neutrons delivered in order to complement the high-brightness moderator system above the spallation target. In this case, the different phase space region would emphasize applications such as fundamental physics, imaging, and spin-echo. A promising candidate for high-intensity moderator is a large liquid deuterium moderator (Fig. 4), which is expected to deliver about 3-4 times the intensity of the top high-brightness moderator [4].

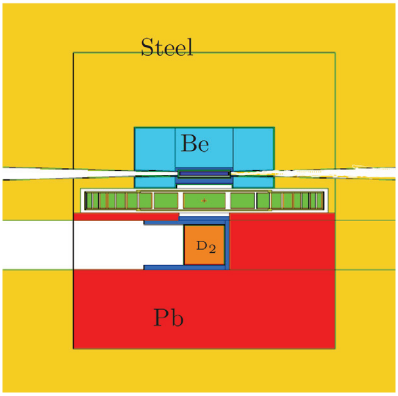

Figure 4. High-intensity liquid deuterium moderator [4]

Comparing with the top moderator designed for bi-spectral neutron extraction, neutron spectrum delivered by the liquid deuterium moderator is colder. The neutrons emitted can then be either used directly for experiments, or be further cooled down to VCN (10-40 Å) and UCN (several 100 Å) energy ranges in secondary sources placed either near the bottom moderator (in-pile), or in a dedicated beamline (in-beam) for fundamental physics research.

The design study of the ESS second neutron source, including the research and development on new emerging materials, nuclear data and software, will be of impact and carry innovative potential both for neutron user community and for the design of other neutron sources all over the world.

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OVERVIEW OVER PSI FAST NEUTRON LAB ACTIVITIES

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1 D-D Fast Neutron Generator

The core of the Paul Scherrer Institut (PSI) Fast Neutron Lab is a neutron generator which is based on the ${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{2}He + {}^{1}_{0}n$ (2.5 MeV) fusion reaction. One of the main features of this generator is its small emission spot. The neutrons are generated in a disc with a diameter of ~2 mm. The neutron generation process starts by injecting deuterium gas into a ionization chamber where it is transformed into a plasma by radio frequency (RF) radiation. The ionization chamber has a small hole facing a titanium target which is kept at a negative voltage of about –100 kV (relative to the ionization chamber). This accelerates the ion beam towards the target. There, some of these ions are implanted into the titanium matrix of the target and some of the ions undergo a fusion reaction with one of the ions previously incorporated, releasing a fast neutron. Figure 1a shows a schematic of this process and Figure 1b shows a picture of the neutron generator and a 3D rendering of the part where the neutrons are generated. [1]

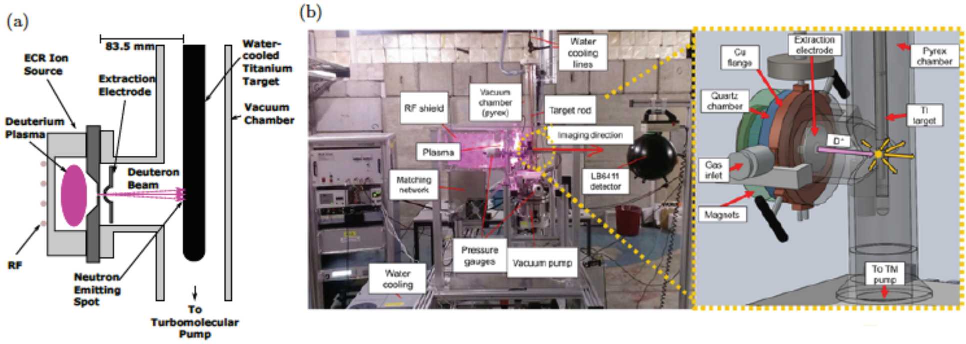

Figure 1: (a): A schematic of the working principle of the D-D fast neutron generator. The deuterium ions are depicted in pink and the titanium target in black. (b): A picture and a 3D rendering of the neutron generator with the most important components labeled.

2 Target Improvements

An option for increasing the neutron output of the generator is to increase the deuterium beam power. However, this also increases the target temperature and at about 200 °C the titanium loses its ability to efficiently store deuterium. Therefore, methods of improving the cooling of the target were developed. The main change is the switch to a rotating target in order to distribute the generated heat without increasing the emission spot size. To improve the heat removal further, the diameter of the target was increased and its composition changed from solid titanium to titanium coated copper. Figure 2a shows a picture of the neutron generator with the improved target. The beam power was increased by a factor of 2.8 with the new target in place. In total, the improved cooling and higher beam power lead to an increase in the neutron output by a factor of 4.4, as shown in Figure 2b. The acceleration voltage had to be reduced with the new target due to electrical breakdowns. Eliminating this issue is one of the ongoing developments. [2]

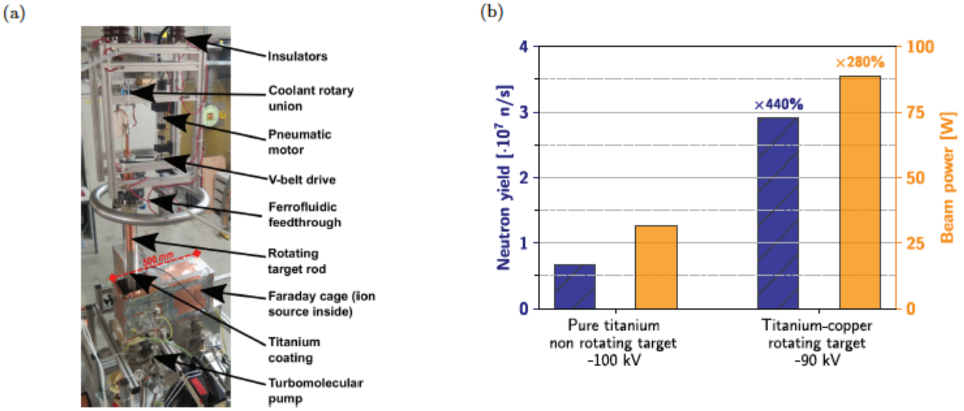

Figure 2: (a): A picture of the neutron generator with the new target. The different parts related to the new target are labeled. (b): A visualization of the beam power and neutron production improvements when using the new target.

3 Energy Dependent Fast Neutron Tomography

Due to the fact that the center of mass of the D-D fusion reaction is moving, neutrons emitted in the direction of the deuterium beam have an energy of about 2.8 MeV. Neutrons emitted at other angles have lower energies, down to about 2.2 MeV at 180° from the deuterium beam direction. The exact energies are dependent on the acceleration voltage. Since the neutron cross-sections are very element- and energy-specific, (unlike for photons) it is in principle possible to discriminate one element from the other by making attenuation measurements at different energies. As an example, the cross section of Al_2O_3 is show in Figure 3b. The energy dependent cross section can be measured by moving the detector and the sample on an arc around the neutron generator. A picture of this setup is shown in Figure 3a and the results of such a measurement are shown in Figure 3b. [3]

Currently, a tomography setup is being tested which will enable the mapping of the distribution of the neutron cross-section inside objects. Ultimately this mapping can then be used to calculate the distribution of elements inside unknown samples.

4 Gamma Blind Fast Neutron Detection

The PSI Hot-Laboratory plans to measure the fast neutron emission of spent nuclear fuel rods and its axial distribution. The gathered data should later be used for example to help validating reactor core simulations or designing transport containers for spent fuel. A measurement system for this task is being designed at the Fast Neutron Lab. The core problem of this project is to construct a detector which can efficiently measure the relatively few neutrons emitted by spent fuel while ignoring the large amount of gamma rays which are emitted as well. For this, a custom detector using silver activated ZnS (ZnS:Ag) and wavelength-shifting fibers (WLSFs) is being developed, based on a thermal neutron detector which was designed at PSI [4]. A picture of four of the prototypes which were built so far is shown in Figure 4a.

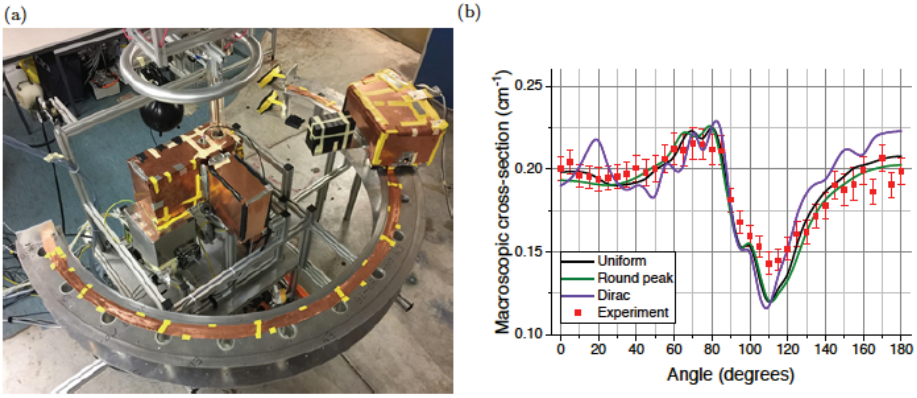

Figure 3: (a): A picture of the neutron generator with the arc and movable detection unit for energy dependent measurements. (b): A graph showing experimentally determined energy dependent cross-section of Al_2O_3, as well as theoretical curves assuming different energy spread functions.

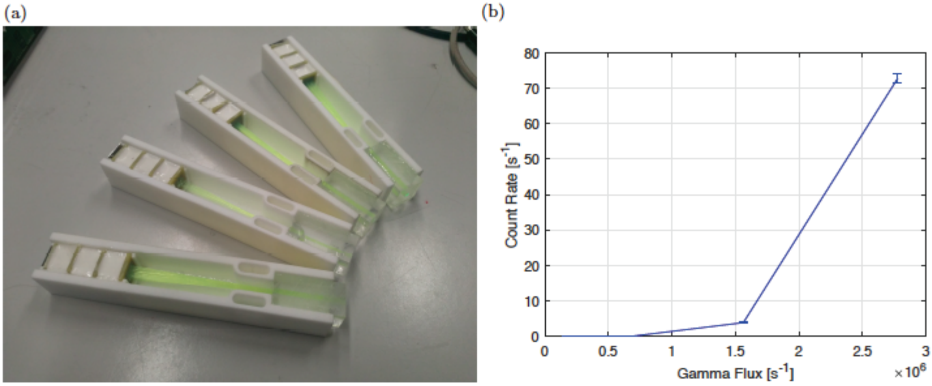

Figure 4: (a): Four prototype detectors. The volume containing the ZnS:Ag where the fast neutrons interact with the detector are visible as 3 white squares on the left side of each detector. The green wavelength shifting fibers which come out of these volumes are visible as well. (b): The count rate of one of the prototypes when exposed to gamma radiation from a ^{60}Co source.

The neutron detection efficiency of the prototypes was measured using a Cf-252 source. It was shown that efficiencies of about 3% are possible. The sensitivity to gamma radiation was ascertained using a ^{60}Co source. The result for one of the prototypes is shown in Figure 4b. The gamma blindness of the detector is good enough for measuring samples which emit relatively few gamma rays, however the count rate of the detector increases over-proportionally for higher gamma fluxes. This is an indication of pile-up (events which are caused by multiple gamma rays hitting the detector simultaneously). A possible solution to the pile-up problem is to segment the detector into multiple smaller ones. This is currently being investigated. [5]

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The workshop participants. Photo by Markus Fischer.

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