Saclay Compact Accelerator-driven Neutron Sources (SCANS)

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Abstract. For next decade, the European neutron scattering community will face of important changes, as many facilities will close, strictly fission-based sources. This statement mainly concerns France with the planned closure of Orphee and ILL. At CEA-Saclay, the project SONATE has been launched in order to provide a high intensity neutron source in Saclay site, this project is based on Compact Accelerator-driven Neutron Sources technology coupled to high-intensity beams. The goal of SONATE is to develop a 50 kW target, aiming to produce at least a neutron yield of $10^{13}$ s$^{-1}$ in pulse mode with a peak current of 100 mA. We have investigated in this document the best combinations of beam/target which would lead to this substantial neutron yields. Further investigations and tests have to be carry out, especially due to sparse data on thick target and such low-energy beams considered in this document. An intermediate step to the SONATE project is under test and development, called IPHI-NEUTRON, which would lead to provide a small-size neutron facility mainly devoted to neutron imagery for industry. This step is based on the existing 3 MeV proton beam, named IPHI. Best target candidates are Lithium and Beryllium, leading respectively to a neutron yield of about $2.10^{13}$ s$^{-1}$ and $4.10^{12}$ s$^{-1}$.

1. Context

Neutron scattering is a very powerful method, widely used for studying materials properties in fundamental physics, materials science, nuclear energy, as well as for industries and societal challenges [1] [2]. Up to now, neutrons are not only produced from fission-based neutron sources (research nuclear reactors), but also from spallation sources. An overview of neutron scattering facilities in Europe is provided in Ref. [3], including their present status and future perspectives. This report brings to light that, for next decade, the European neutron scattering community will face of important changes, as many facilities will close, strictly fission-based sources. Unfortunately, no new project of nuclear reactor is, up to now, launched to replace them. Figure 1 illustrates this, showing a decreasing up to a factor of two on the beam time availability for the neutron scattering community in 2023, according to the baseline and degraded scenario, and 50% of decreasing in case of the enhanced scenario. French community is mainly affected with the closure of the Orphee reactor in Saclay site, which is planned end of 2019, as well as the ILL reactor in Grenoble with an uncertain future after 2023. An opportunity is open for Compact Accelerator-driven Neutron Sources (CANS), as their costs would be affordable for individual country (less than 200 Meuros), compared to the building of a dedicated reactor and they are more flexible in terms of management of targets and wastes, accelerator
upgrading, safety constraints, etc. Those sources would be complementary to spallation and reactor sources in order to develop and test instrumentations, before going to those high-brilliance neutron sources, like ESS [4] for instance.

Figure 1: Scenarios for neutron provision in Europe (from Ref. [2]).

Compact Accelerator-driven Neutron Sources have known a strong interest and a fast-growing, who led in 2009 to the foundation of the community UCANS (Union for Compact Accelerator-driven Neutron Sources) [5]. They are attractive alternative solutions to nuclear research reactors especially in terms of public acceptance as well as for nuclear non-proliferation. Many facilities around the world have already chosen this option but it concerns accelerators with few mA of continuous current. One can cite for instance the facility LENS in the United States [6] : 13 MeV proton beam, a peak current of 25 mA and a duty cycle of 1.8%, leading to an equivalent continuous current of 0.45 mA, i.e. a beam power of 6 kW.

Recent developments in high-intensity accelerators allow us to design high brilliance neutron sources, even with low-energy beams (few tens of MeV). This is for instance the case of the project IFMIF [7] for which the neutron production is induced by two 40 MeV deuteron beams striking on a liquid Lithium target. Note that each accelerator carries a beam current of 125 mA, leading to a total fast neutron yield of $10^{18}$ s$^{-1}$. At CEA/Irfu, 100 mA proton injector has been developed, called IPHI [8], as well as 125 mA deuteron injector, named SILHI [9]. The latter one is now part of the subproject IFMIF/LIPAc, the accelerator prototype of IFMIF. Both injectors may be operated in continuous or in pulse mode. High-intensity beam leads many challenges, especially due to strong space charge that can induce beam halo and consequently beam losses. Another issue concerns heat removal from the target. However, the mixing of concepts of high-intensity accelerator and compact moderator/reflector assembly permits not only to optimize the beam energy, and in consequence to reduce radiological constraints from beam-induced activation, but also to ensure an attractive neutron production.

In the following sections, we present potential neutron production reactions from low-energy beams, and experimental activities for our project. This involves not only the neutron yield, but also angular and energy distributions of emitted neutrons when available. We will also investigate regulatory constraints.

2. Project: objectives, constraints and roadmap

At CEA-Saclay, a project has been launched (SONATE), based on high-intensity accelerator technology and the concept of compact neutron source, using low-energy beam (less than 20 MeV). SONATE expects to provide to the neutron scattering community, as well as to local industries, a
small-scale neutron source with performances similar of a medium-size reactor (2 to 10 MW). Compared to spallation neutron sources, CANS are less efficient in producing neutrons, as the number of neutrons per incident particle is much less important. However, as neutrons produced by CANS are less energetic than those coming from spallation reactions, we may expect to convert them more efficiently into the required energy range and also to direct them more easily towards the required direction. This task would be facilitated as most applications require moderated or cold neutrons, thus a moderator, in association with a reflector, has to be optimized. Validated simulation tools are needed for the optimization of moderator/reflector geometry, taking into account neutronics properties of materials for particle transportation, including neutron diffraction within crystalline structures for thermal energy range, as well as in term of nuclear reaction cross sections.

First of all, our goal is to develop a target which is able to receive and dissipate 50 kW beam, in a compact layout, for the accelerator IPHI. This latter carries 3 MeV proton beam, 100 mA peak current, and is operated both in continuous and pulsed mode. Those developments are opportunity for validating our simulation tools, by measuring neutron flux according to different moderator shape and material [10]. This subproject, named IPHI-NEUTRON, is planned to operate in 2020, and expect to produce thermal neutron beams useful for neutron imagery applications, and small angle neutron scattering experiments. Even with the low neutron production related to 3 MeV protons, this project will be a demonstrator for the next step, SONATE, which could be in operation in 2025. Note that, we are currently limited to a power deposition density of about 0.5 kW/cm² on the target. This means that for a total power deposition of 50 kW, a target area of 100 cm² is needed. This is of importance for optimization studies associated to compact geometry of moderator/reflecter assembly, as we need to concentrate as much as possible the neutron flux density within the moderator, as well as to reduce as much as possible neutron leakages.

| Technique                  | Flux on sample             | Reference spectrometers                     |
|----------------------------|----------------------------|---------------------------------------------|
| Reflectivity               | 0.8 x 10⁶ n/cm²           | HERMES@LLB 1 x 10⁷ n/cm²                   |
|                            |                           | POLREF@ISIS -1 x 10⁷ n/cm²                 |
| SANS                       | 0 7 x 10⁶ n/cm² (low Q)   | PAXE@LLB (low Q) 0.7 x 10⁶ n/cm²           |
|                            | 2.2 x 10⁶ n/cm² (med Q)   | SANS2D@ISIS 1 x 10⁶ n/cm²                  |
|                            | 6.7 x 10⁶ n/cm² (high Q)  |                                             |
| Low resolution powder diffraction | 2 x 10⁶ n/cm²           | G41@LLB 2 x 10⁶ n/cm²                      |
| Imaging (white beam)       | 1.5 x 10⁶ n/cm² (for L/D = 240) | ICON@PSI 1 x 10⁷ n/cm²                |
|                            | 1.3 x 10⁶ n/cm² (for L/D = 80) | CONRAD@PSI 1 x 10⁷ n/cm²         |
| Imaging (time resolved)    | 1 x 10⁶ n/cm² (for L/D = 500) | ANTARES@FRM2 5 x 10⁷ n/cm²                |
|                            | d²l² = 1%                  |                                             |
| Spin-Echo                  | 2 x 10⁶ n/cm²             | MUSES@LLB 2 x 10⁷ n/cm²                   |
|                            | (at 5Å)                    |                                             |
| TOF                        | 6 x 10⁷ n/cm²             | OSIRIS@ISIS 3 x 10⁷ n/cm²/μs              |

Figure 2: SONATE’s reference baseline in term of neutron fluxes and comparison to existing spectrometers.

Figure 2 shows the reference baseline of the project SONATE according to different measuring techniques. To fulfill these requirements, one needs a neutron yield roughly about 10¹⁵ s⁻¹, produced inside the target in continuous mode, and 10¹³ s⁻¹ in pulsed mode by considering a peak current of 100 mA. Indeed, this leads to a neutron density within the moderator quite close to that one obtained from a medium-size reactor (10¹² cm⁻³.s⁻¹), taking into account a volume of 1 dm³ for the compact moderator (instead of 10⁶ cm³ for the moderator volume of a reactor). Compared to the subproject IPHI-NEUTRON, SONATE’s beam energy is higher in order to increase the neutron yield, but the total beam power is still limited to 50 kW. This affects the design of the moderator/reflecter assembly, as the primary neutrons energy is higher as the beam energy increases. In consequence, a larger moderator is needed so as to be as efficient as the one used with 3 MeV protons (in term of neutrons moderation).
3. Neutron production induced by proton and deuteron beams

In this section, an overview of nuclear reactions leading to major neutron yields is presented. A discussion based on each step of the project, namely IPHI-NEUTRON and SONATE, provides the primary neutron characteristics (neutron yields, energy distributions, angular distributions) for these interesting reactions, when available. Only proton and deuteron beams were considered in the following parts based on the high-intensity beams available at CEA-Saclay. Moreover, only energy beams from reaction threshold up to 50 MeV concentrates our attention, as the goal is to take advantages from compact moderator layout. Note that, our discussion will concern thick targets in order to integrate beam reactions all along its range in the target, from incident energies down to the reaction thresholds.

3.1. Neutron production with IPHI-NEUTRON

Based on the accelerator IPHI that is carrying a 3 MeV proton beam, only few nuclear reactions may produce neutrons due to their low reaction thresholds. The reaction threshold strongly depends on the structure of the nucleus, and less bound neutron states (close to Fermi level) will lead to an enhanced microscopic cross section for the reaction (p,n). Indeed, those types of nuclei will emit more easily a neutron when a small excitation occurs. Concerning the neutron yield estimates, other parameters as the atom density of the target, the natural abundance of isotope of interest (if not available in enriched target), the effective range of protons in target, and the microscopic reaction cross section are also important. The effective range of protons means the range through the target for which the proton energy is upper than the reaction threshold, and in consequence leads to a neutron production. This proton range has been evaluated by using SRIM-2008 [11], and has to be as large as possible.

![Experimental cross sections for the reaction (p,n) according to $^7$Li, $^6$Be, $^{48}$Ca, $^{76}$Ge and Tritium targets.](image)

In Figure 3 are shown the experimental cross sections associated to the reaction (p,n), from their thresholds to few MeV, for $^7$Li, $^6$Be, $^{48}$Ca, $^{76}$Ge and Tritium targets. Usually, only light mass targets are considered for such beam energy, according to their low reaction thresholds and high cross sections such as Tritium, $^7$Li and $^6$Be. However, one may observe that higher mass isotopes, which have an excess number of neutrons, may also lead to a substantial neutron production. This is especially the case of $^{48}$Ca which has a microscopic cross section for the (p,n) reaction similar to that one obtained for $^6$Be. Table 1 provides necessary information to estimate roughly the neutron yields obtained for targets made of the specific isotopes considered in Figure 3, including their natural isotopic abundances. Table 1 also contains the energy threshold for the reaction (p,n). Note that Tritium is missing in this table, as that element has to be trapped into another material in order to form a thin layer on its surface [17][18]; Titanium or Scandium are mainly used for instance, especially for
increasing heat deposition on such target, compared to enclosed tritium target. So, the neutron yield of a tritiated target is not so easy to estimate as for the ones considered in Table 1, as it depends on the Tritium concentration and layer thickness which is temperature-dependent. Nevertheless, commercial neutron generators based on the reaction $^7\text{Li}(d,n)^4\text{He}$ are limited to a neutron yield of about $10^{13}$ s$^{-1}$, even if the cross section of this reaction exceeds largely those presented in Figure 3, with a maximum close to 5 barn for 100 keV deuterion beam. So, we may expect a neutron yield less important with 3 MeV protons striking on tritiated target than with 100 keV deuterion beam as its cross section is ten times less than the reaction $^7\text{Li}(d,n)^4\text{He}$.

| Target | $^7\text{Li}$ | $^9\text{Be}$ | $^{48}\text{Ca}$ | $^{76}\text{Ge}$ |
|--------|---------------|---------------|-----------------|-----------------|
| Natural isotopic abundance (%) | 92.5 | 100 | 0.2 | 7.6 |
| Threshold (in MeV) | 1.88 | 2.06 | 0.51 | 1.73 |
| Atom density (cm$^{-3}$) | 4.59E22 | 1.24E23 | 1.93E22 | 4.22E22 |
| Cross section $(p,n)$ at 3 MeV (mb) | 250 | 150 | 100 | 15 |
| Effective range ($\mu$m) | 182 | 46 | 165 | 36 |
| Rough estimated neutron ratio (n/incident) | 2.09E-04 | 4.27E-05 | 1.59E-05 | 1.14E-06 |

*Table 1: Neutron ratio and associated important parameters for specific isotopes, considering 3 MeV incident protons and a thickness corresponding to the effective range.*

First of all, we may observe from Table 1 that a Lithium target provides the highest neutron yield compared to other isotopes. This is due to its larger microscopic cross section for the reaction $(p,n)$, as well as its longer effective range. For this element, we consider that the microscopic cross section at 3 MeV is constant all along the effective range, leading to an underestimation of the neutron yield since the cross section presents a higher value at 2 MeV compared to 3 MeV. On the other hand, according to the microscopic cross section behaviour for $^9\text{Be}$, $^{48}\text{Ca}$ and $^{76}\text{Ge}$, presented in Figure 3, the neutron yield has been estimated assuming a linear interpolation of the cross section along the effective range, starting from 0 up to the threshold. The neutron yield obtained with a target made of $^9\text{Be}$ isotopes is five times lower than for a Lithium target. Even if the cross sections for the reaction $(p,n)$ are similar for $^9\text{Be}$ and $^{48}\text{Ca}$, a target made of $^{48}\text{Ca}$ isotopes leads to a neutron yield which is three times less than a Beryllium target, despite the fact that the effective range in Calcium is four times greater than in Beryllium due to the compact crystalline structure of the Beryllium leading to a higher atom density. Note that an enrichment of 100% in $^{48}\text{Ca}$ isotopes is assumed for the Calcium target. Moreover, it seems difficult to operate a pure Calcium target as this element quickly oxidizes in air, becoming a powder. Nevertheless, for IPHI-NEUTRON, the neutron yield has to be maximized and in the following, only Lithium and Beryllium targets focus our attention.

![Figure 4: Experimental angular distributions for the reaction $(p,n)$ for $^7\text{Li}$ [19], $^9\text{Be}$ [20] and Tritium [21] targets.](image)

In the framework of the IPHI-NEUTRON sub-project, a target is under development that would be able to safely receive a total power deposition of 50 kW, i.e. a maximum beam current of 17 mA for 3
MeV proton beam. Consequently, this leads to a fast neutron yield of about $2.1 \times 10^{13}$ s$^{-1}$ for the Lithium target, and $4.1 \times 10^{12}$ s$^{-1}$ for the Beryllium target, the most favorable targets for the neutron production considering 3 MeV protons. Figure 4 shows the angular distributions of emitted neutrons associated to the Lithium and Beryllium targets for 3 MeV protons, and for the Tritium target for 2.85 MeV protons. In the case of Lithium and Tritium targets, we may observe that neutrons are preferentially emitted in forward direction, while for Beryllium target, the angular distribution is quite flat and favors neutrons in rearward (peak around 120°). This should affect the moderator efficiency and has to be taken into account in optimization studies, especially for defining the best position of the neutron guide. Concerning the energy distribution of the emitted neutrons, data are very sparse. Only one measurement is available for a thick Beryllium target, performed by Howard et al. [22] at two angles (0° and 40°).

Finally, we have also to discuss about the safety constraints of the potential targets (Lithium and Beryllium, and possible even a tritiated target), for 3 MeV protons. Both targets have their advantages and disadvantages. The Lithium target presents the advantage to be operated in a liquid phase, and in consequence to allow to operate at the maximum beam current of the accelerator IPHI, i.e. 100 mA. This option is attractive, as it permits to skip the heat removal issue while at the same time increasing the neutron yield. Such target has been developed by Soreq laboratory for instance that operates the loop LiLiT [23]. Nevertheless, one should notice that a huge production of $^7$Be (about 1 MBq/s) occurs when operating a Lithium target. That element has a half-life of 53 days, and leads to constraints about waste management. Moreover, a liquid target provides more technical constraints associated to the loop, which may lead to potential neutron leakages and a less performance in term of neutron density within the moderator. The operating of a Beryllium target needs to worry about blistering effect that appears when beam is stopped inside the target [6]. To exclude this issue, the target thickness must be set to the effective range estimated in Table 1, i.e. 46 µm, in order to stop protons within a backing material which presents a better hydrogen diffusion coefficient. About tritiated target, the management of Tritium is an issue in case of failure of the target. Moreover, such target has a limited lifetime (about 1000 hours in operation), combining degraded performance during operation due to Tritium release from substrate material.

A Beryllium target seems to be the best choice, for 3 MeV protons, due to a substantial neutron production and less safety constraints. First experiment and test have been performed in 2016 with the accelerator IPHI. All the details can be found in [10][24], including a comparison between nuclear models and data on the primary neutrons emitted. No nuclear model is able to provide a reliable prediction by considering such low-energy beams. Else, a liquid Lithium presents huge advantages concerning the neutron production and also the heat removal issue, and further investigations have to be carry out especially about the optimization of the moderator/reflectors assembly by including neutron leakages due to pipes of the liquid lithium loop (performance reduction).

3.2. Neutron production for SONATE

A brief review is discussed in this section about potential nuclear reactions, induced by proton and deuteron beams, leading to a major neutron production for the project SONATE. We limit our investigations to beam energies less than 50 MeV, as well as to thick targets. To remind, the targeted neutron yield has to be roughly about $10^{15}$ s$^{-1}$ in continuous mode, and $10^{13}$ s$^{-1}$ in pulsed mode with a peak current of 100 mA, in order to fulfil the requirements of the project, whilst the beam power is limited to 50 kW. One has to notice that available data are very sparse and a comparison only based on such data is quite difficult to carry out. So, in this section, neutron yield estimates are obtained from Monte Carlo simulations, as only thick targets are considered. Calculations have been done using the Monte Carlo code MCNPX-2.6 [25], taking into account TENDL-2015 library [26] for proton-induced reactions below 200 MeV.

In Figure 5 are shown the neutron yields obtained for proton-induced reactions, considering 1 mA of beam current, for the following targets: Lithium, Beryllium, Carbon, Lead 208, Calcium 48, Germanium 76 and Tellurium 130. The three last isotopes have been considered because it refers
neutron-rich isotopes. Those isotopes lead to the highest neutron production in the energy range 15 MeV to 30 MeV, according to TENDL-2015 library. Nevertheless, no data are available to confirm those estimates for thick targets. Note that Carbon target is not interesting for the neutron production, because of the reaction threshold of about 18 MeV for $^{12}$C isotope; neutrons produced below 18 MeV only come from the reaction $^{13}$C(p,n)$^{13}$N, while $^{13}$C represents only 1.1% of atoms within the target. Constrained to 50 kW beam power, this leads for instance to an equivalent continuous beam current of 3.33 mA for 15 MeV protons, 2.5 mA for 20 MeV protons and 1.66 mA for 30 MeV protons. Only the duty cycle has to be adjusted to fulfil these beam currents, while considering a peak current of 100 mA. Only neutron yields obtained with a Lithium and Calcium 48 target permit to reach the SONATE’s requirement for a beam energy of 10 MeV ($10^{13}$ s$^{-1}$ in pulsed mode). For instance, a Beryllium or Lead target need a beam energy twice higher for the same performance. Keeping the beam energy as low as possible permits, first, to minimize the cost of the accelerator and the whole facility (safety and radiological constraints), as well as to limit the production of radiological contaminants (waste management and radioprotection).

![Figure 5: Neutron yield (s$^{-1}.mA^{-1}$) as a function of incident proton energy (MeV) obtained with TENDL2015 [26].](image)

![Figure 6: Neutron yield (s$^{-1}.mA^{-1}$) as a function of incident deuteron energy (MeV) obtained with TENDL2015 [26].](image)

About deuteron-induced reactions, Figure 6 shows the neutron yield obtained for the same set of targets previously considered for proton beam. Deuteron beam energy has to be lower than that of protons in order to reach the same performance in term of neutron yield. Moreover, the Beryllium target induces the highest neutron yield for the whole energy range considered. With the Beryllium target, a deuteron energy of 7 MeV is enough to fulfil SONATE’s requirement in term of pulsed neutron yield. This beam energy has to be roughly about 10 MeV for the Lithium and Calcium 48
targets, and around 15 MeV for Carbon. The lead target is only competitive with other studied targets for beam energies larger than 40 MeV. Compared to proton beam, neutrons produced by deuteron-induced reactions are mainly emitted in forward direction, due by part to the break-up of deuterons above 9 MeV, and also they are more energetic. Reference [27] provides the energy distribution and the angular distribution of neutrons produced by proton and deuteron beam, for a thick Beryllium target. More energetic neutrons will affect the geometry of the moderator by increasing its volume. This effect has to be considered for further optimization studies.

Depending on the production of radiological contaminants induced by beam-activation within the target, the best options for the project SONATE would be a proton beam striking on a target made of Calcium 48 isotopes or Lithium for an energy above 10 MeV, or a deuteron beam coupled to a Beryllium target with an energy above 7 MeV.

4. Conclusions and perspectives

Compact Accelerator-driven Neutron Sources are attractive alternatives to medium-size reactors so as to provide a local supply in neutrons for the European neutron scattering community. Those facilities would be affordable for individual country, as their cost depend on the beam energy which is limited as low as possible, first by using high-intensity beams, and also by considering pulse mode. At CEA/Ifru, proton and deuteron beams are able to be operated with high-intensity and in pulse mode. The project SONATE has been launched in order to provide a high intensity neutron source after the final shutdown of Orphee programmed end of 2019. This project is based on CANS technology coupled to high-intensity beams. The goal of SONATE is to develop a 50 kW target, aiming to produce a neutron yield of $10^{15}$ s$^{-1}$ in continuous mode, and $10^{13}$ s$^{-1}$ in pulse mode with a peak current of 100 mA. We have investigated in this document the best combinations of beam/target which would lead to this substantial neutron yields. Best options for the project SONATE would be to consider a deuteron beam bombarding a Beryllium target with an energy larger than 7 MeV, or a proton beam coupled to a Lithium or Calcium 48 target for an energy larger than 10 MeV. Further investigations and tests have to be carry out, especially due to sparse data on thick target and such low-energy beams considered in this document.

An intermediate step to the SONATE project is under test and development, called IPHI-NEUTRON, which would lead to provide a small-size neutron facility mainly devoted to neutron imagery for industry. This step is based on the existing 3 MeV proton beam, named IPHI. Best target candidates are Lithium and Beryllium, leading respectively to a neutron yield of about $2\times10^{13}$ s$^{-1}$ and $4\times10^{12}$ s$^{-1}$. A liquid Lithium target presents huge advantages concerning the neutron production and also the heat removal issue, even if this leads to a huge production of the radionuclide $^7$Be (half-life of 53 days).

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