Union of Compact Accelerator-Driven Neutron Sources (UCANS) I & II

Calculations for ESS-Bilbao low energy target

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Abstract

ESS Bilbao is a research facility already in the initial construction stages that will host an accelerator-driven neutron source. It consists on a phased approach and its first phase considers the operation of proton beams accelerated up to 40 MeV, currents within 25–75 mA, and 20 Hz repetition rate with a 1.5 ms pulse length. Such accelerator parameters will allow a low intensity neutron-source to be configured with a power in the 30–90 kW range, and a neutron production close to 0.05 n/p. With these conditions, two rotatory target configurations are presented, one for low energy (30kW) and one for mid energy (90kW).

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Keywords: Beryllium, Neutrons, Cooling of target

1. Introduction

The strategy of building a MW-range, accelerator-based spallation neutron source as the next generation neutron facility for Europe is at present under scrutiny on the basis of experience gained during commissioning of the SNS in the US and the JPARC facility in Japan as well as from current operational experience achieved by high throughput installations such as the ISIS source at the U.K. The underlying technology has however advanced since the time when previous generation facilities reached final design stages and therefore time is now ripe to learn from ongoing experience and define the development areas which would allow the ESS to benefit from recent advances in technology while maintaining a reliable, low risk, design.

Within the current European context, ESS-Bilbao (ESSB) has entered a new endeavor within which while being a partner of the ESS project aims to develop significant in-house capabilities needed to support the country participation in a good number of accelerator projects worldwide (IFMIF/EVEDA, LINAC4, FAIR, XFEL, ESRF upgrades, ISIS-FETS etc.). On such grounds ESSB has started the construction of a modular, multipurpose research accelerator which should serve as a benchmark for components and subsystems relevant for the ESS project as well as to provide the Spanish science and technology network with hands-on experience on power accelerators science and technology, a task long overdue.

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The present document reports on the development of ongoing projects which basically comprise the construction of the room temperature accelerating structures plus some prototyping of a first demonstration cryomodule comprising two superconducting spoke resonators, as well as some foreseen applications of the generated proton and neutron beams. The current concept entirely deals with a proton / H- accelerator facility, being the possibility of using a common low-energy injector for protons and low-energy deuteron beams under detailed study at present. The current parameter values are to be considered as a basis for a feasibility assessment of the ESS linac components and consist in 75 mA of proton current, 20 Hz repetition rate using 1.5 ms proton pulses and two 352/704 MHz bunch frequencies with a single frequency jump. The accelerator structures either planned or under development at present are meant to satisfy such stringent demands. A number of applications of proton and neutron beams have already been envisaged. Here we report on the state of our conceptual design for the proton/neutron converter which basically consists on a rotating beryllium target.

2. Neutron Source

Neutron yield angular distribution is one of the critical issues in low energy targets due to the low efficiency of the process (around 1 neutron every 20 protons), and the neutron performance optimization will be critical. Suitable candidates as target materials are light ones such as Lithium, Beryllium or Carbon; all of them could produce neutrons, but the most efficient in total and forward direction is beryllium (table 1), as consequence, it is the natural election as target material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Neutron yield [n/p]</th>
<th>Neutron at 1 m on forward direction [n/cm-p]</th>
<th>Neutron yield (Average energy spectra)[MeV/n]</th>
<th>Neutron flux at 1 m on forward direction (Average energy spectra) [MeV/n]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium</td>
<td>3.98E-2</td>
<td>1.07E-6</td>
<td>7.3</td>
<td>14.3</td>
</tr>
<tr>
<td>Beryllium</td>
<td>4.96E-2</td>
<td>1.28E-6</td>
<td>8.37</td>
<td>13.9</td>
</tr>
<tr>
<td>Carbon</td>
<td>2.33E-3</td>
<td>5.19E-8</td>
<td>5.42</td>
<td>6.84</td>
</tr>
</tbody>
</table>

Table 1: Neutron production of different target materials, estimated with MCNPX & ENDEF-VII

Total neutron production could be an adequate figure of merit for the material efficiency as target when dealing with experimental lines needing a moderator-reflector system, because these elements will homogenize the cold neutron angular distribution reducing the importance of the initial angular distribution. However, there are other possible experimental lines in which a clean direct view of the target is needed, and therefore source angular distribution is critical.

Our study of the neutron angular distribution was performed in a two step simulation with MCNPX code [1]. First we have calculated and registered the surface particle flux produced by the interaction between 40 MeV protons and small radius beryllium cylinder using ENDF-B-VII cross section data library [2], which produces neutron yield results similar to the experimental ones in the energy range of our interest [3], with the aim of obtaining an equivalent cylindrical surface source. Regarding the angular distribution, the conclusion of the experiments of Iwamoto [3] performed with 10 MeV protons is that the library ENDEF-VII adequately reproduces the angular distribution of the neutron source so that we can qualify the estimates in this document as appropriate and reliable for a preliminary study. Nevertheless it will be convenient for subsequent phases of this study to confirm the results based on experiments performed with protons in our energy level.

Second we use that cylindrical surface source to calculate time and energy distribution on 5 point detector angularly distributed at a distance of 1 m (Figure 1). This procedure is required because of the vast amount of protons (and its corresponding calculation time) needed to obtain a good statistic in the results, due to the low neutron production rate, and it allows performing multiple geometry calculations with reasonable computational cost.

In addition to this, MCNPX point detectors by default consider surface sources as emitting an isotropic distribution, and this standard configuration can only be modified to introduce a limited anisotropy. That anisotropy is bound to the geometry of the surface source (and its local directing vectors), rather than to the actual trajectory of
the particles emitted, given by an actual physical process, which has previously been simulated in the first step. This means every particle is statistically contributing to the tallying despite its anisotropic generation; the estimation with this technique is not correct if the source is angular dependent. In order to solve this problem we have modified the angular probability distribution to account only for the direct contribution of the source if the trajectory of the particle intersects the point detector sphere. This modification does not provide a significant reduction of the computational time for the isolated target, but, since it only affects unperturbed particles coming directly from the source, it will allow point detectors to perform a good background estimation while scoring a right direct source contribution to their tally when, in a second phase of these studies, neutrons might be scattered by auxiliary elements introduced where there is only vacuum now.

Figure 1: Point detectors position. 1 m far from beryllium target.

Total neutron yield is close to \(5 \times 10^{-2}\) neutrons per proton with an average neutron energy of 8,4 MeV. Figure 2 shows energy spectra of neutrons emitted in all directions. This energy distribution shows a significant neutron production in the fast (high energy) range that could be of interest if time distribution is right for TOF (time of flight) experiments. Figure 2 shows time distribution for neutron energies between 8 and 10 MeV with a pulse width of 2-2.5 ns, with this width for the neutron pulse it will be possible to use a kicker to select 10-20 bunches of each pulse of our beam of protons (the working frequency of the accelerator will be 352.2 Mhz, so that the width of each bunch will be 0.5 ns, therefore, selecting groups of 10-20 bunches per pulse of protons we will have a pulse with a width of 7-12 ns) for a neutron pulse with a length slightly over 10 micro-s. If TOF line length is enough (15-20 m) it should be possible to make measurements of scattering cross sections over the fast neutron regime; however, a direct view of the target is needed in order not to disturb neutron energy spectra.

In order to summarize neutron source analysis we can conclude that we have two different types of possible experiments:

Time of flight (TOF): In these experiments we make direct use of the unmoderated high-energy neutrons. We need a direct view of the target without any light material in the visual line (0.5 mm of water will reduce source brightness by 30%) and we are going to use only several bunches of the beam so total energy will be around 10% of the total power (~9 – 10kW).

Low energy neutrons (LEN): In these experiments we employ a moderator-reflector system to generate slow neutrons from the full power (90kW) proton beam on the Be target. Moreover, a direct view of the source should be avoided in order to reduce the fast neutron flux over low energy instruments.
3. Thermomechanical conditions

Target requirements for both type of experiments TOF an LEN are not compatible due to conditions of direct view and total energy deposition. In the case of TOF, the target cannot be cooled using a layer of water between the target and the beam lines as in the LENS design [4]. In LEN experiments we need to moderate neutrons and its layer of water does not have any negative effect. Both target designs have to be implemented on common layout in order to design a flexible installation that could be useful in both experimental areas.

3.1. Thermomechanical conditions: Conduction target for TOF

The penetration length of 40 MeV protons over beryllium is around 1-1.3 cm and that is the minimum thickness needed to be able to guarantee interaction of all protons. The energy deposition profile of this protons has a very intense Bragg peak with a sharp thermal gradient, which is associated to a high thermal stress. In order to reduce the stress we introduce thermal expansion gaps to allow deformation of the beryllium slab. Figure 3 shows the final configuration of the target element with 3 beryllium slabs, each of 3 mm thickness, with 2 expansion gaps in between slabs and aluminum casing. Cooling of the system is achieved via heat conduction to the water cooled bottom surface of the beryllium slabs, as is shown in Figure 3.
These beryllium elements can withstand an average beam intensity of 12.5 μA for 4 cm beam radius (2 Gaussian distribution inside beam radius and 0.5 kW of heat deposited). This average intensity matches 25 mA of peak intensity, a repetition rate of 0.5 Hz and 1 ms pulse length. As we can see on Figure 4 the temperature remains very low and thermal stress is below 1/3 of beryllium yield stress limit so fatigue should not be a problem.

In order to distribute the energy of the beam we need 40 elements moving in a rotating geometry, as shown in Figure 5. This rotating design will allocate total beam power distributed in a large volume. The structural integrity of the elements is guaranteed and hydrogen can be implanted along this volume, resulting in an expected lifetime of several months until failure. Moreover, the absence of any coolant (e.g., water) in contact with the beryllium will eliminate the radiolysis-induced corrosion of the target, and the neutron emission spectrum in the forward direction will be close to that of pure $^9\text{Be}(p, x\nu)$ reaction. Radius of the wheel is 80 cm and maximum total power is 20 kW, enough for TOF experiments beam configuration.

3.2. Thermomechanical conditions: cooled by water to LEN

The previously shown configuration is not enough to support all nominal beam power (90 kW) that is needed on LEN experiments. Increasing the number of elements is not possible without increasing the complexity and size of the
installation layout. We propose a second cooling scheme for the elements, which is shown in Figure 6. In this scheme we have a layer of water cooling a single beryllium slab on the side opposite to the beam incidence. LEN experiments need to include a moderator so this layer of water will have a premoderation effect that can be compensated in the moderator design.

In order to maintain the common layout for both type of experiments we implement a rotating design with 40 of this elements so each one will support 75mA@0.5Hz@1.5ms. Temperature and thermal stress under beam conditions is shown on Figure 7. It is clear that these elements will operate in very safe conditions at low temperature and far from 1/3 of the beryllium maximum yield stress, so mechanical integrity is guaranteed. In fact, as it is shown in these figures, a frequency of up to 1.5 Hz could be withstood without mechanical threats.

As before, the rotating design will allow to distribute hydrogen implantation in a large volume and also it will mitigate corrosion effects. We can expect several months of full operation power before the failure.
4. Conclusions

This initial study for a low energy target in ESS-BILBAO facility defines two different configurations that could allow neutron experimental applications on high energy ($\sim MeV$) and thermal-cold range. We have proposed experimental layout configurations, shown in Figs. 11 and 12, that share all external elements (cooling system, engines, bearings) however target elements of the wheel, moderator and maybe several parts of the deflector will need to be removed for the TOF experiments in order to have a direct view of the target on forward direction.

Additional studies are needed in order to determine lifetime of the target elements due to hydrogen implantation and water corrosion effects reported by LENS[5] before starting the engineering and prototyping process, but the present propose constitutes an adequate baseline design for ESS-BILBAO target system.
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References


