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Baseline design of a low energy neutron source at ESS-Bilbao

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Abstract. This article briefly describes the basic design of the ESS-Bilbao neutron target station as well as its expected neutronic performance. The baseline engineering design, associated ancillary systems, and plant layout for the facility is now complete. A rotating target composed of twenty beryllium plates has been selected as the best choice in terms of both neutron yield and engineering complexity. It will provide neutron beams with a source term of 10^{15} n s^{-1} resulting from the direct ${}^9\text{Be}(p, xn)$ reaction using a 75 mA proton beam at 50 MeV. The design envisages a target station equipped with two fully optimized moderators capable of withstanding a proton-beam power of 112 kW. This design is flexible enough to accommodate future upgrades in final proton energy. The envisaged neutron-beam brightness will enable several applications, including the use of cold and thermal neutrons for condensed matter research as well as fast-neutron irradiation studies. We close by discussing the role that this facility may play once the European Spallation Source becomes operational in Lund, Sweden.

1. Introduction

The design, construction, and optimization of last-generation neutron facilities such as the Spallation Neutron Source (SNS) at the Oakridge National Laboratory (ORNL, USA) and the Materials and Life Sciences Facility at the Japan-Proton-Accelerator-Complex (MLSF-JARC) has involved the activity of smaller research laboratories and/or research units within established national laboratories. The increasingly important role of these smaller institutions has been facilitated by advances in instrumentation technologies enabling the emergence of local facilities within university-scale organizations. These facilities have carried out critical work so as to render the ultimate performance of high-power sources truly competitive. The scientific and technical relevance of these smaller-scale facilities has been emphasized in an International Atomic Energy Agency (IAEA) (report in 2004 [1], highlighting the relatively unexploited synergy between high- and low-to-medium-power neutron sources. As discussed in this report, the rationale behind this synergy stems primarily from the high costs associated with the operation



of high-power sources and the pressing need to deliver intense neutron beams to a wide user base for as many days per year as budgetary constraints allow. These stringent requirements pose a number of difficulties for the development and testing of equipment critically needed to fully exploit their capabilities, as such facilities usually leave little room for ad-hoc tests or fully fledged research and development programmes requiring extensive access to beamtime.

The purpose of the present article is twofold. First and foremost, to describe progress to date in the design of the ESS-Bilbao facility, including its potential to host several applications in neutron science. Second and final, to identify specific areas where ESS-Bilbao will be of direct relevance for the further development of the wider European Spallation Source (ESS) project. We emphasize from the outset that the *raison d'être* of ESS-Bilbao is entirely compatible with current ESS developments in Lund (Sweden), as current efforts at ESS-Bilbao address issues which are geared towards the effective exploitation of ESS by the Spanish neutron user community in the foreseeable future. The Spanish user base has experienced a very significant increase in size over the period 1987-2005, representing a total use of available beam time at the Institut Laue-Langevin (ILL) of approximately 5%. Notwithstanding the above, the development of this user base [2] has not been accompanied by parallel developments in expertise associated with innovative uses of the available techniques or the development of cutting-edge neutron instrumentation. A relatively brief partnership with the ISIS Pulsed Neutron and Muon Source over the period 2004-2010 provided access to $\sim 2\%$ of the available beamtime for the Spanish user community. Cooperation between ISIS and Spain has also represented a veritable quantum jump in the capabilities of the Spanish scientific community and industrial sector to provide state-of-the-art neutron instrumentation. In addition to the delivery of world-class neutron instrumentation including the development of scintillation-detection systems using cutting-edge technologies, this fruitful collaboration has enabled several research groups as well as local companies to develop significant capabilities in accelerator science and technology as well as spallation targets.

On the basis of the above considerations, it seems clear that participation in remotely located large-scale infrastructures such as ESS-Lund without parallel and uninterrupted developments of national capacity in instrument and technique development for subsequent deployment and exploitation at high-power sources risks mimicking the conditions of the 1987-2005 period mentioned above, ultimately leading to the suboptimal use of high-power neutron sources by Spanish scientists in the years to come. It is in this spirit that ESS-Bilbao has progressed the design and construction of a laboratory on the main campus of the University of the Basque Country near Bilbao. The main characteristics and aims of this laboratory are described below.

2. The ESS-Bilbao neutron source

2.1. The ESS-Bilbao Accelerator

The first stages of room-temperature proton and H^- accelerators are currently under construction at ESS-Bilbao. Both designs make extensive use of accelerator structures developed in close collaboration with ongoing projects such as the Accelerator Design Update at ESS-Lund, the Front End Test Stand at ISIS, and the Linac4 project at European Organization for Nuclear Research (CERN) [3]. The main accelerator parameters are listed in Table 1.

2.2. The Rotating Target Concept

Account made of the accelerator parameters listed in Table 1, a neutron target station designed so as to deliver moderated and fast neutron beams with useful fluxes for scientific applications will extend the testing capabilities and remit of ESS-Bilbao. In our case, such a target concept relies upon the neutron-yield properties of the ${}^9\text{Be}(p, n)$ direct reaction. The expected integrated

| | |
|-------------------------|--------------|
| Proton Energy | 50 – 60 MeV |
| Peak Current | 75 mA |
| Repetition Rate | 20 – 50 Hz |
| Pulse Length - variable | 0.1 – 1.5 ms |
| Average Current | 2.25 mA |

Table 1. Main parameters for the ESS-Bilbao accelerator.

neutron flux amounts to $\sim 10^{15} \text{ n s}^{-1}$, an adequate level of particle production for the testing of neutron-instrumentation components (including moderators, neutron guides, and pulse-shaping devices), as well as for the operation of several irradiation and scattering instruments. The rationale behind the development of a facility of these characteristics has been emphasized repeatedly in several IAEA official reports [4] [5]. Moreover, significant research activities and experiments are nowadays being carried out with compact sources delivering fluxes in the range $\sim 10^{13}$ - 10^{14} n s^{-1} in close collaboration with large spallation facilities [6] [7] [8] [9].

The choice of a beryllium target is based on its reasonably high neutron yield of $6.5 \cdot 10^{-2}$ neutrons per proton at a beam energy of 50 MeV [10]. With the expected beam current and duty cycle, the total calculated neutron yield reaches ca. $9.4 \cdot 10^{14} \text{ n s}^{-1}$. Other options such as Li-based targets have been dismissed on the basis of significant engineering complications associated with the handling of these materials.

In the case of low-power spallation sources, targets are typically assembled by lining up a series of tungsten, tantalum, or clad uranium plates with thicknesses increasing from about a millimeter up to one centimeter or so, and with gaps of about 1 mm to allow water flow at moderate rates. Contrary to this situation, the low penetration depth of 50-MeV protons in beryllium (ca. 1.5 cm) rules out the use of such vastly proven target configuration. The use of a single plate as target has also been ruled out because of heat-load considerations. For a proton beam of diameter 10 cm, a single beryllium plate would require an average power flux in the water-cooling channel of roughly $\sim 7 \text{ MW/cm}^2$, a figure that is far beyond the limits of the state-of-the-art for low-pressure water-cooling systems. We note that this value is roughly twice the heat flux estimated for the ESS-2003 Solid Target Project Proposal [12].

The solution proposed by ESS-Bilbao to circumvent these difficulties capitalizes on previous developments in high-power spallation targets. The use of a rotating target wheel with 20 beryllium plates ensures that each plate sees the proton beam at an effective repetition frequency of 1 Hz. In this configuration, the total heat load on each element is limited to 5.6 kW, and the time-averaged heat flux is 0.4 kW/cm^2 . Although the average heat flux may not be a problem, the instantaneous heat flux during the pulse can be considerably higher, and thus the maximum temperature in the water-cooled surface can quickly approach $100 \text{ }^\circ\text{C}$. A water pressure of 5 bar is sufficient to withstand this temperature rise. Using the value for the water pressure just referred to, simulations carried out using the FLUENT-ANSYS packages predict a maximum stress in the range of 80 MPa, a value well below the fatigue limits of beryllium. Figure 1 shows the average temperatures and von Mises stresses on the target.

Figure 2 shows the configuration of the target-moderator-reflector (TMR) assembly. The beryllium plates are embedded in a wheel rotating on the horizontal axis and in contact with the water channels. The proton beam hits the target at a relative angle of incidence with respect to the plates of 45° . On the other side of the target assembly, a methane moderator is placed in order to maximize neutronic performance. Both target and moderator are surrounded by the reflector. Around the reflector, several layers of shielding material are used to minimize dose rates outside the target station.

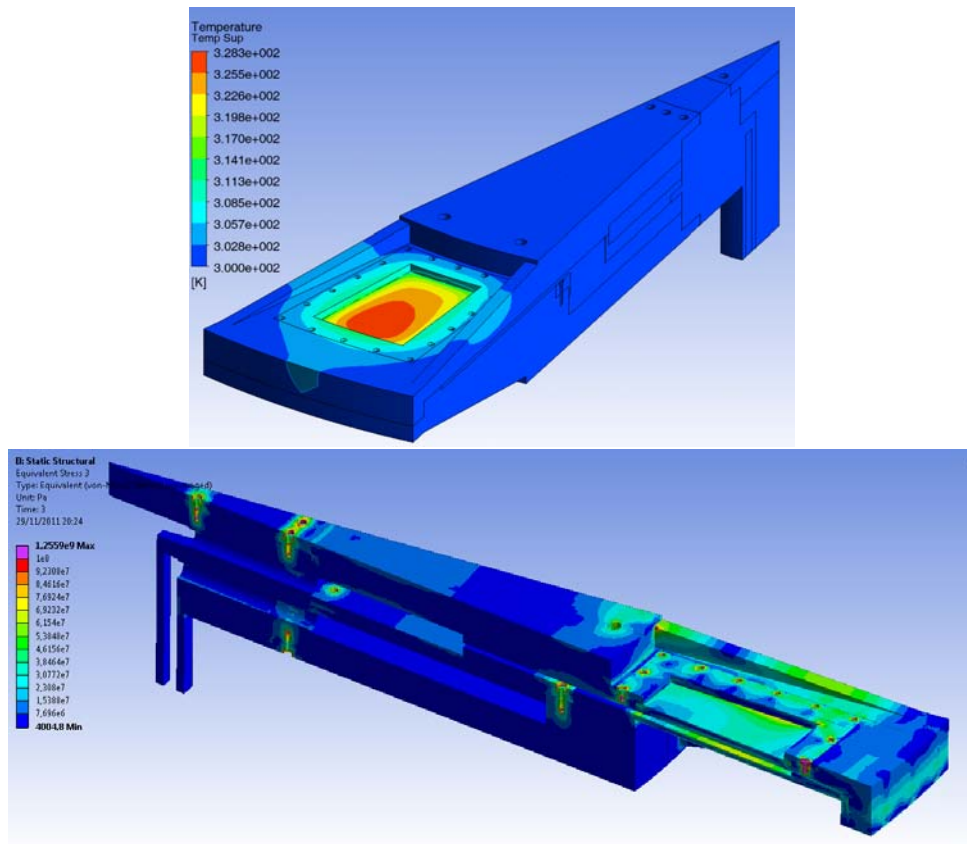


Figure 1. Three-dimensional representation of average temperatures and von Mises stresses in the target assembly.

2.3. Neutronic Performance of the Target Station

Since the ESS-Bilbao source provides moderate neutron intensities, detailed optimization of the moderator-reflector assembly is a must. There are three main configurations for positioning the moderators with respect to the neutron-producing target, namely: WING, SLAB, and Flux TRAP [11]. In general, a WING configuration results in a lower brightness than a SLAB configuration, but since moderators are usually located above and below the target element, this particular geometry precludes the use of neutron-transport devices such as inserts and beam tubes in line of sight with the target through the moderator. The latter limitation is of concern for the SLAB configuration where moderators are located sideways to the target and thus may lead to significant leakage of fast neutrons coming from the direct view of the target. These considerations are of particular relevance for high-power spallation sources since the relevant nuclear reactions display a first step or hadron cascade leading to a highly anisotropic emission of high energy neutrons, while a second step involving fission/evaporation leads to the isotropic emission of high-energy neutrons[13]. For this reason, the majority of high-power sources like ESS [14], ISIS [15], or SNS [16] prefer the use of WING or Flux-TRAP configurations to reduce backgrounds associated with fast-neutron production.

Nevertheless, for ${}^9\text{Be}(p, n)$ reaction at 50 MeV, most of the high energy neutrons are produced in the forward direction [17]. Hence, background neutrons can be controlled by creating a 45° angle between beam and experimental lines. Considering this factor, the slab configuration will maximize neutron production.

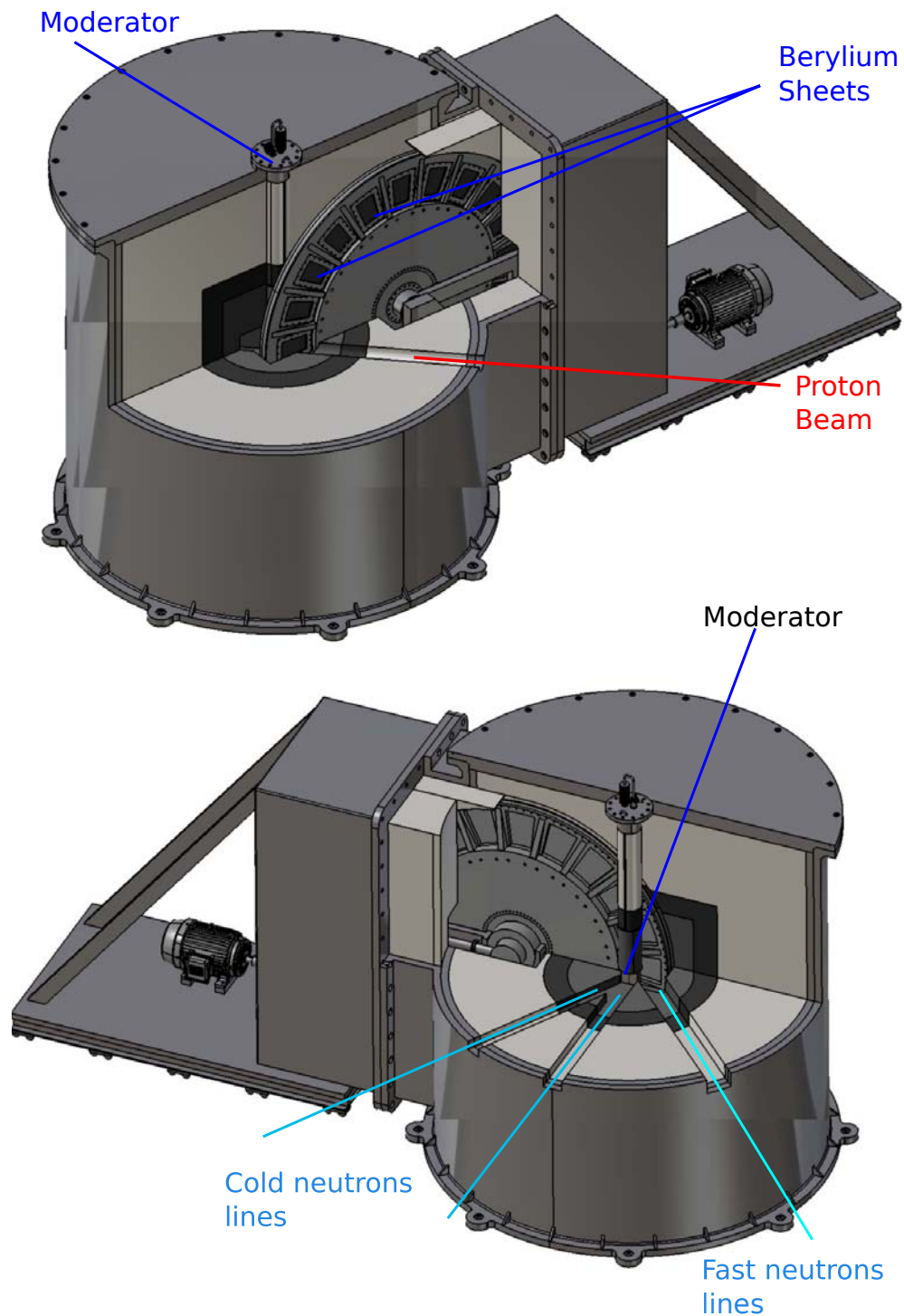


Figure 2. ESS-Bilbao Target-Moderator-Re flector assembly. For further details see the text.

Figure 3 shows the proposed TMR layout with a solid methane moderator in SLAB geometry.

Methane has been selected as moderator material because of its excellent neutronic performance [7] as well as the extensive experience gained from years of operation at existing neutron sources. The long-pulse nature of the installation (maximum pulse length of 1.5 ms) dictates that a coupled moderator represents the best choice [8] to maximise neutron production. The methane moderator and target are also surrounded by a reflector material to increase neutron brightness on the moderator surface. Current estimates of heat load on the moderator under operating conditions are ca. 50 W. Although significantly smaller than the value of 300 W for the ISIS-TS2 coupled moderator [18], it is still not a negligible figure. Some radiation chemistry effects such as radiolysis and polymerization processes are expected to occur, although previous experience has paved the way to solve these problems by means of periodic annealing and thermal cycling protocols. Other options currently under consideration for the second moderator include the use of liquid hydrogen or mesitylene.

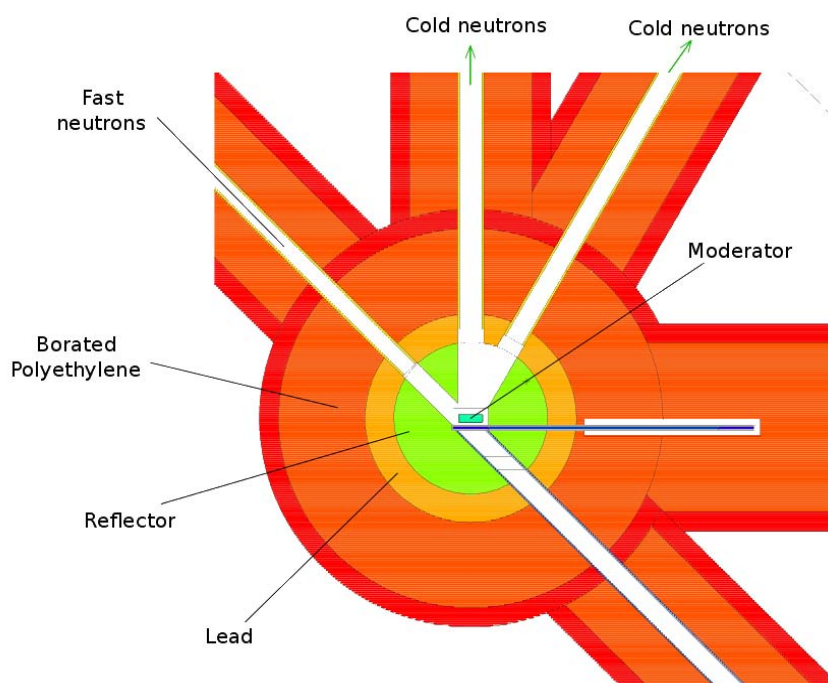


Figure 3. ESS MCNPX model of the TMR assembly with one moderator in SLAB geometry.

Values for the main TMR parameters were obtained via an optimization process to maximize neutronic performance. The Figure 3 shows the MCNPX model develop for the process. Optimal values include a $12 \times 10^{-2.5} \text{cm}^3$ methane moderator, a 40 cm thick beryllium reflector, and a distance of 8 cm from the target surface to the moderator center (mainly needed because of target engineering constraints). The reflector is surrounded by several layers of shielding materials: 15 cm lead, 60 cm of borated polyethylene, and 10 cm of steel. The first layer of lead aims to shield against gamma radiation close to the center while minimizing the total weight of the shielding. The borated polyethylene will moderate and absorb most neutrons. Finally, the steel shielding will absorb gamma radiation resulting from neutron capture in the borated polyethylene. This configuration aims to reduce the activation of the external elements as much as possible with the least amount of shielding.

Several possibilities have been explored for the reflector material and a summary of the

results is shown in Figure 4. This figure shows the distribution at the moderator surface of ~ 5 meV neutrons for long proton pulses (1.5 ms) and different reflector materials. The beryllium reflector introduces significant moderation, has a very low threshold for (n, xn) reactions, and does not have a large capture cross section. The result of this combination is a maximum neutron production associated with a very long tail in the time distribution. Lead has a very high density, not a very high threshold for (n, xn) reactions, and has very poor moderating properties. The combination of these factors results in a much lower neutron yield and a short tail in the time distribution. Alternatively, heavy water provides low neutron absorption and significant scattering cross section but, as a drawback, it has not (n, xn) reactions. Its ultimate performance is therefore low. Finally, a light-water reflector displays a very high scattering and absorption cross sections. As a result, its performance sits right in between lead and beryllium.

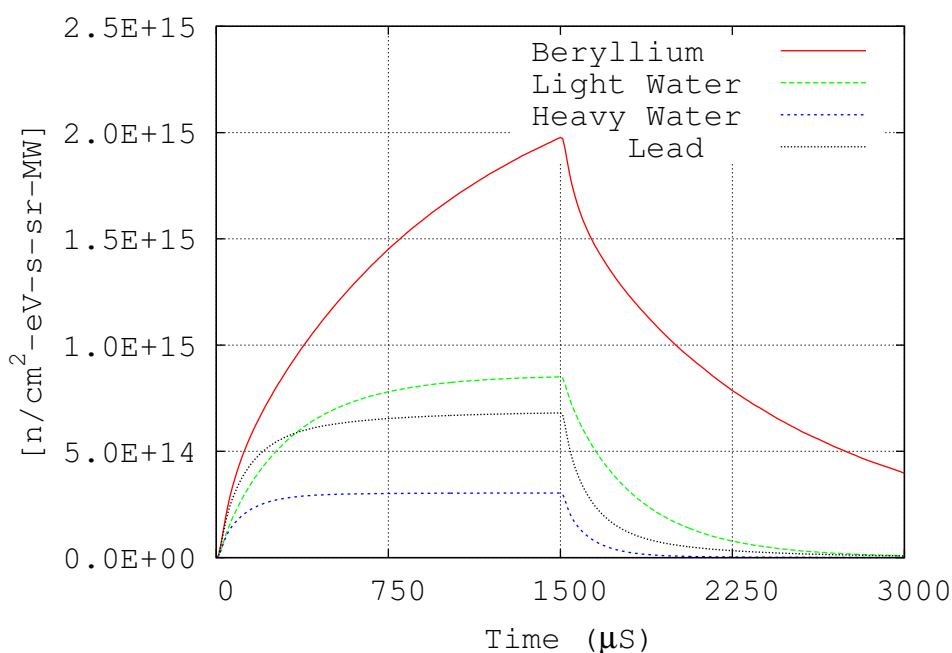


Figure 4. Long pulse for ~ 5 meV neutrons (integration range: 4.4-5.3 meV).

The water reflector exhibits some interesting properties which warrant further discussion. Figure 5 shows the neutron flux on the moderator surface arising from the water reflector compared to a beryllium reflector scaled by a factor of 0.325. These two results are also compared to the predicted ESS time distribution [19] for a 1.5 ms proton pulse. It is rather remarkable that the water reflector on ESS-Bilbao is nearly identical in shape to that predicted for ESS. The scaling factor between these two sources amounts to ~ 800 .

The SLAB configuration for a solid methane moderator and beryllium reflector shows very good neutronic performance. The source term ratio between ESS and ESS-Bilbao differs by a factor of ~ 750 . The average ratio in neutron brightness is close to a factor of $\sim 160/100$ lower without/with beryllium filter. The proposed ESS-Bilbao target station is therefore considerably more efficient per source neutron than ESS.

As reference, this medium-size neutron source will be 20 times more intense than Low Energy Neutron Source (LENS) [20] and ca. 5 times below similar moderators at ISIS-TS2. Table 2.3 shows a comparison between ESS-Bilbao parameters and data from other international facilities [21].

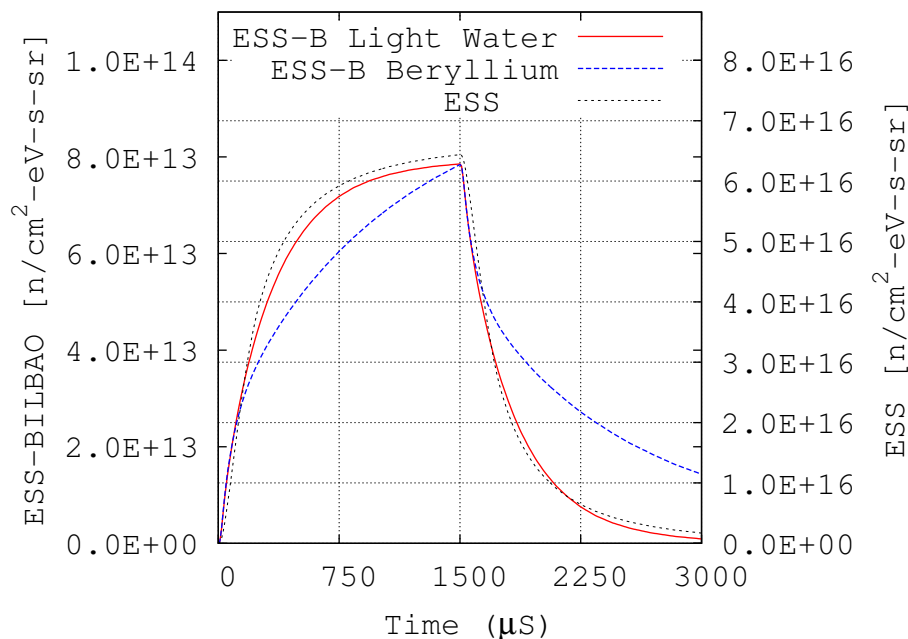


Figure 5. Time distribution of ~ 5 meV neutrons for a long proton pulse (integration range: 4.4-5.3 meV). The beryllium brightness has been scaled by a factor 0.325. For further details, see the text.

| | Power | Rep Rate Hz | Viewed Surface [cm^2] | N. intensity [$n/cm^2 \cdot s \cdot sr$] | N. intensity [$n/cm^2 \cdot pulse \cdot sr$] |
|-----------------------------------|-------|----------------|------------------------------|---|---|
| JSNS C. hydrogen | 300 | 25 | 10 w x 10 h | 1,3E+12 | 5,1E+10 |
| SNS C. hydrogen | 1000 | 25 | 10 w x 10 h | 4,5E+12 | 1,8E+11 |
| | 1400 | 60 | 12 w x 10 h | 2,1E+12 | 3,5E+10 |
| ISIS-TS2 H/CH ₄ , gro. | 48 | 10 | 12 w x 10 h | 3,0E+12 | 4,9E+10 |
| ISIS-TS2 H/CH ₄ , hyd. | 48 | 10 | 12 w x 11 h | 5,0E+11 | 5,4E+10 |
| ESS-B | 112 | 20 | 12 w x 10 h | 3,0E+11 | 3,0E+10 |
| | | | | 1,3E+11 | 6,6E+09 |

Table 2. ESS-Bilbao neutron source compared to other international facilities

With the above figures in mind, we conclude that a mid-intensity neutron source at ESS-Bilbao will enable a sufficient flux of cold and thermal neutrons for component testing, the development of new instrumentation, and the execution of neutron-scattering experiments in condensed matter. At the time of writing, such capabilities are to be found nowhere in Spain.

3. Neutron instrumentation: preliminary considerations

The main parameters for the ESS-Bilbao accelerator given in Table 1 provide lower and upper bounds for the temporal pulse length of the proton beam, where short(long)-pulse operation corresponds to a pulse width of 0.1(1.5) ms and a repetition rate of 50(20) Hz. In what follows, we consider these two limits of operation for the effective use of cold and thermal neutrons in condensed matter research. To provide a realistic assessment of future capabilities at ESS-Bilbao, we shall limit the present discussion to well-established and thoroughly tested instrument

concepts at pulsed (mostly spallation) neutron sources over the past three decades.

Following Windsor [22], we also make a clear distinction between *total* vs. *useful* neutron flux. The efficient use of a pulsed neutron source involves the judicious exploitation of its inherent time structure, enabling the use of a sufficiently wide dynamic range of incident wavelengths (multiplexing advantage) with the requisite instrumental resolution (R). In this situation, R is primarily dictated by the ability to discriminate between neighbouring incident neutron wavelengths in the time domain, that is, $\Delta\lambda/\lambda \propto \Delta t/L$. Δt is the temporal pulse width of the moderated neutron (a wavelength-dependent quantity) and L is the distance between source and sample. Optimal instrument design seeks to match incident and scattered components to the resolution function in order to maximise final detected flux for a given R [22].

In the same spirit as Schober et al. [23], it is convenient to consider several neutron-instrument classes in terms of their resolution characteristics. These categories are briefly described below, along with a summary of specific (yet by no means exhaustive) areas of scientific application:

- Coarse ($R \sim 1$): irradiation studies, activation analysis, boron capture therapy, basic neutronography, neutronics (component testing, moderator studies).
- Low ($R \sim 10^{-1}$): low-angle scattering, reflectometry, spin-echo techniques.
- Medium ($R \sim 10^{-2}$): diffraction, energy-resolved imaging, broadband spectroscopy.
- High ($R \sim 10^{-3}$): high-resolution (e.g., back-scattering) spectroscopy and diffraction.

Figure 6 provides a summary of instrumental characteristics in terms of dynamic range and resolution for ESS-Bilbao as a long- and short-pulse neutron source. We assume thermal and cold neutrons have been produced by the cold methane moderator described in earlier Sections of this paper. Scientific applications requiring coarse ($R \sim 1$) resolution are equally possible in both cases, as all of these do not rely on the use of the temporal structure of the neutron pulse and, if required, energy selection may be performed by some other means (e.g., monochromator, choppers).

As a long-pulse source (1.5 ms at 20 Hz), the data shown in Figure 6 shows that the optimal compromise between resolution and dynamic range requires instrument lengths of ~ 30 -40 m. At these distances, the resulting resolution amounts to $R \sim 10^{-1}$, typical for low-angle and neutron reflectivity instrumentation. To attain medium resolution ($R \sim 10^{-2}$), distances in excess of 100 m are required. These figures are to be contrasted with a maximum attainable instrument length of ~ 50 -60 m imposed by space constraints in the current facility layout for ESS-Bilbao. With these limitations in mind, we conclude that 1.5 ms pulses will enable the exploitation of both coarse and low-resolution instrumentation using well established instrument-design concepts. A significant increase in resolution is also possible via the use of neutron spin-echo techniques [24, 25].

ESS-Bilbao operating as a short-pulse source (0.1 ms at 50 Hz) constitutes a more favorable situation (cf. Fig. 6). Efficient use of the methane moderator spectrum can be achieved at distances of ~ 15 m with medium ($R \sim 10^{-2}$) resolution for cold neutrons. Medium-to-high resolution is also achievable for distances of 40-50 m using well-established instrument concepts. All in all, the use of proton pulses of ~ 0.1 ms represents an optimal combination of dynamic range and resolution for a large proportion of instrumental applications. These pulse widths are also comparable with those typically used in high-resolution spectrometers and diffractometers at short-pulse spallation sources (e.g., the IRIS spectrometer at ISIS [26]), as well as in last-generation coupled moderators [27], an important area for further R&D efforts. Further and significant gains in resolution to reach and cross the $R \sim 10^{-3}$ 'barrier' are also possible via the exploitation of pulsed-shaping choppers (PSC's) placed in the vicinity of the source. This concept has been recognized as the way forward for current and future developments in high-resolution neutron spectroscopy at JPARC [28] and ISIS [29, 30]. The new Biomolecular Dynamics

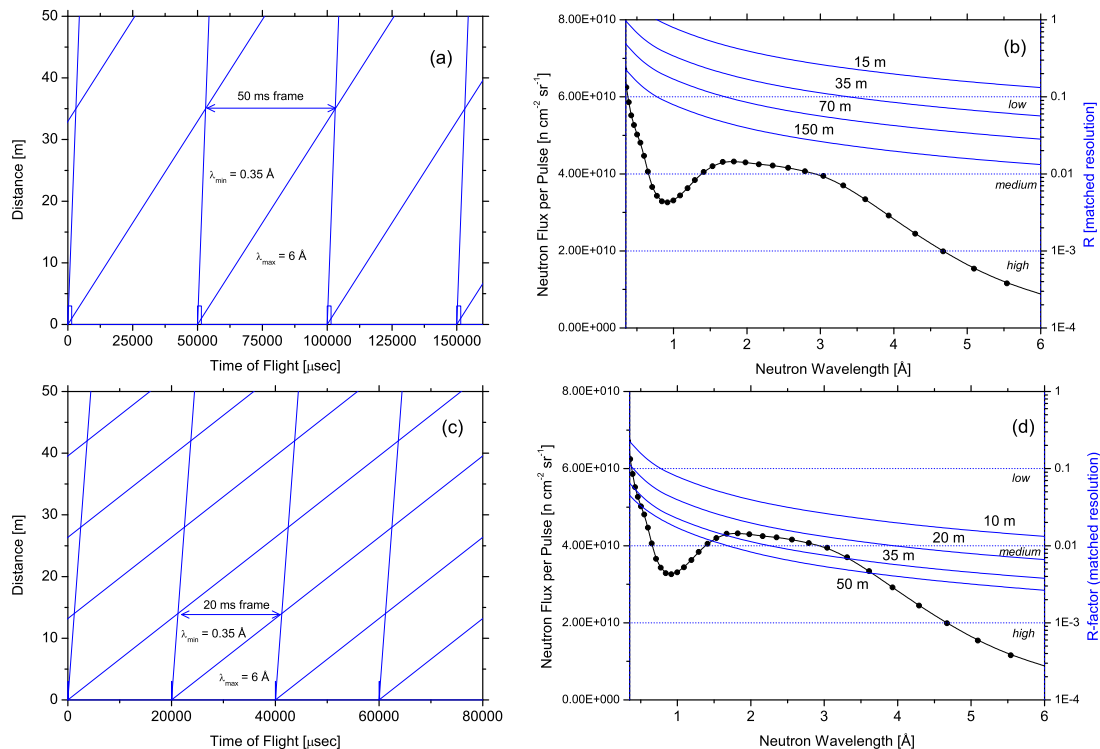


Figure 6. Time-distance diagrams (left) and resolution (right) for long- (panels a,b) vs. short-pulse operation (c,d) at ESS-Bilbao. For reference, the neutron spectrum of the cold methane moderator is also shown in (b) and (d). For further details, see the text.

Spectrometer DNA at J-PARC [31] relies entirely on the use of a PSC in order to reach a resolution of a few μeV with a relatively modest incident path of 42 m. We anticipate that ESS-Bilbao will capitalize extensively from the exploitation of these innovative technologies to tailor flux and resolution in order to meet increasingly demanding scientific requirements.

4. ESS-Bilbao as an experimental support station for ESS.

Finally, we provide a brief outline of the activities envisaged for the ESS-Bilbao site, and highlight their relevance for the full development and exploitation of ESS-Lund. At present, ESS-Bilbao profits from the experience gained through fruitful collaborations with the highest-power spallation sources in operation, namely, SNS at Oak Ridge, as well as with ISIS in the UK and with the reactor source at the Institut Laue Langevin. The rationale behind such efforts stems from the unequivocal realization that further improvements in the efficient use of neutrons is far more cost effective than net increases in neutron production. Therefore, significant efforts should be directed towards improvements in source performance to achieve (quite realistically) order-of-magnitude gains in *useful* neutron flux.

Such previous experience together with the successful symbiosis between university university-based sources serve to envisage clear synergies of issues such as

- *Critical work on components leading to the efficient use of spallation neutrons*, alongside the lines highlighted in recent publications [1, 32] as well as in a number of contributions to meetings of the Union for Compact Accelerator Driven Neutron Sources [33]. UCANS is an alliance between ten neutron laboratories from the Americas, Asia, and Europe. Particular areas where such synergies have already been demonstrated include the development of very cold moderator materials, modelling and measurement of neutronic properties of new cryogenic moderators, R&D of efficient pelletized cold neutron moderators, the development of novel concepts such as directional moderators or, finally, the exploration of new routes for the production of ultracold neutrons by means of novel methods involving solid oxygen or deuterium.
- *Development of new instrumentation for high-power sources*. As a matter of fact, small-to-medium power sources have played an important role in the development and testing of novel neutron instrument concepts and components. New instrumentation enabling new science is typically carried out on test beamlines at lower-power facilities in order not to compromise the tight experimental programmes at high-power sources. In this context, several advantages characteristic of CADNS can be exploited for this purpose, including the reduced shielding requirements owing to lower proton and neutron energies. This feature enables the setting-up of instrument-development stations easily adaptable for testing, development, and training. Contrary to naïve expectation, the inherent time structure of a pulsed source makes CADNS's more suitable for the development of such kind of instrumentation as opposed to continuous (mostly reactor-based) or quasi-continuous sources.
- *Use of ESS-Bilbao for the design and preparation of ESS experiments*, for users aiming to carry out feasibility tests on measurements to be proposed to be carried at ESS. The source will also serve to perform some experiments which do not necessitate the ultra-high fluxes, including those not requiring very high intensities, such as for example a significant fraction of powder-diffraction measurements aiming at materials characterization, or other innovative experiments requiring a feasibility study prior to beam-time allocation on highly oversubscribed instruments.
- *Training new users in neutron-scattering techniques*. There is an inherent difficulty in achieving this goal at large facilities because of the pressure to make the most efficient use of beamtime.

In this respect, it is worth recalling some of the conclusions from the last survey carried out by the European Neutron Scattering Association (ENSA). Specifically, Conclusion 4 states that [34]:

Neutron experiments are planned at appropriate sources. Top-tier sources are extremely important for “demanding experiments, while a large portion of “ordinary research projects can be done at medium flux or sometimes even at low flux sources with an appropriate instrument suite. Our vision is thus fully consistent with such a three-tier structure for neutron science in Europe where, in addition to the top-tier ESS and large sources such as ILL and ISIS, a number of compact national infrastructures should serve to support both the user community and future source developments. The adequacy and timeliness of such a view has already been demonstrated by the ongoing collaboration between university-based facilities and high-power sources in the USA and Japan.

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