Viability of the ESS-Bilbao neutron source for irradiation of nuclear fusion materials

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The ESS-Bilbao neutron source, currently under construction, is conceived as a multipurpose facility. It will offer a fast neutron beam line for materials irradiation. In this paper we discuss the viability of ESS-Bilbao for experimental studies of fusion materials. Making use of the already designed target station we have calculated the neutron spectrum expected in the fast neutron line. Then, we have studied the neutron irradiation effects in two model materials: iron and silica. We have calculated the expected PKA (primary knock-on atom) spectra and light species production as well as the damage production in these materials. Regarding structural materials, we conclude that the ESS-Bilbao neutron irradiation facility will play a minor role due to the resulting low neutron fluxes (about two orders of magnitude lower than in fusion reactors). On the other hand, ESS-Bilbao turns out to be relevant for studies of final lenses in laser fusion power plants. A comparison with the conditions expected for HiPER final lenses shows that the fluxes will be only a factor 5 smaller in ESS-Bilbao and the PKA spectra will be very similar. Taking into account, in addition, that relevant effects on lenses occur from the onset of irradiation, we conclude that an appropriate irradiation cell with in situ characterisation techniques will make ESS-Bilbao very attractive for applied neutron damage studies of laser fusion final lenses. Finally, we compare ESS-Bilbao with other facilities.

1. Introduction

Currently, the National Ignition Facility (NIF) [1] is carrying out the so-called National Ignition Campaign (NIC) to demonstrate the scientific viability of fusion energy. The advances in NIC make us presume that within a few years' time the goal will be reached. This achievement will open the door to further technological developments towards the commercial use of fusion energy. Then, one of the major bottlenecks in the roadmap towards a laser fusion power plant will be the study of materials under neutron irradiation. The lack of facilities able to supply neutron fluxes similar to those expected in future fusion plants constitutes a major drawback for the development and qualification of appropriate materials with different functions.

Most of the efforts regarding the development of facilities for neutron irradiation have been focused towards the development of structural materials for the chamber of magnetic fusion plants. For these chambers, it is necessary to develop structural materials capable of resisting several tens of dpa (displacements per atom). In the line of developing such materials, different possibilities for neutron irradiation have been explored [2–7]. They include in

addition to IFMIF, spallation sources, accelerator driven systems and fission reactors. The major conclusion is that only IFMIF seems appropriate for neutron irradiation studies of structural materials.

On the other hand, the modular nature of the laser fusion power plants allows for the replacement of the chamber periodically, lowering the requirements for the structural materials. However, the operation of these plants depends on the final optical elements, exposed to neutron irradiation. In the case of the European project HiPER (High Power laser Energy Research facility) [8], the final optical elements will be silica lenses located a few metres away from the chamber centre (8–16 m) [9]. Therefore, a detailed qualification of the optical materials with realistic neutron fluxes will be needed to avoid the risk of fatal operation failure.

In this work we study the viability of the ESS-Bilbao facility [10] for fusion materials irradiation. We analyse several neutron irradiation facilities and compare them with the neutron irradiation conditions expected in the HiPER power plant.

2. Neutrons in nuclear fusion and ESS-Bilbao

The future fusion energy power plants will be based on the DT reaction. This reaction produces a fast neutron (14.1 MeV) and an alpha particle (3.5 MeV). Ignoring neutron thermalization, neutrons carry ~80% of the fusion energy. Depending on the

Fig. 1. Model of the ESS-Bilbao neutron target (from the target group of ESS-Bilbao [10]). The irradiation cell is placed near the target (10–20 cm) maximising the damage production. Top: CAD model of the target and its main components; bottom: MCNPX model.

confinement method (magnetic or inertial) and in the latter case depending on the illumination method (direct or indirect), different radiation spectra are produced. At the moment the HiPER project opts for an advanced ignition scheme with direct targets and an evacuated dry wall chamber with silica transmission final lenses. With these conditions, $\sim 70\%$ of the fusion energy will be carried by neutrons and the rest ($\sim 30\%$) by ion pulses. The fusion neutrons cannot be mitigated and thus, they will reach the surrounding materials. In order to study and qualify the material under neutron irradiation, appropriate facilities will be necessary.

The European Spallation Source-Bilbao (ESS-Bilbao) [10] project plans to build an accelerator facility compliant with the ESS-AB requirements. ESS-Bilbao will be able to drive several experimental stations for research purposes. It is based on intense proton beams with up to 75 mA current, 50 MeV proton energy, 0.1–1.5 ms pulse duration and 20–50 Hz repetition rate¹. One of the proposed experimental stations is a compact neutron source for materials irradiation.

In the compact neutron source, the neutrons will be produced through stripping reactions caused by the incident proton beam in a beryllium target (see Fig. 1). The stripping reactions produce neutrons that are biased in the forward direction. To gain advantage from the biased neutron production, the fast neutron line is placed in the forward direction, and moderators for the production of thermal and cold neutrons are placed forming 45° . In the fast neutron line an irradiation cell for materials damage analysis will

be installed. This irradiation cell can be placed at a distance of 10–20 cm from the beryllium target. The position 20 cm away from the target is the most suitable to avoid operational interference between the irradiation cell and other systems of the neutron source (moderators of the cold and thermal neutron lines). However, in order to have higher neutron fluxes, we study the location at 10 cm from the target. This design provides the experimentalists flexibility to meet a broad range of experimental conditions.

In the irradiation cell, the samples could be irradiated to reproduce conditions representative for nuclear fusion reactors. For this purpose the irradiation conditions in ESS-Bilbao and fusion (HiPER) must be compared (see Fig. 2). The comparison shows that although similar, the spectra do not match exactly. The major difference is due to the 14 MeV fusion neutrons that give rise to a marked peak in the HiPER spectrum absent in the ESS-Bilbao spectrum. On the other hand, the ESS-Bilbao spectrum shows a high energy tail absent in HiPER.

What does this imply when irradiating fusion materials? The answer is not straightforward and in the next section the most important aspects are discussed.

3. Viability of ESS-Bilbao as a neutron irradiation facility

In order to evaluate the neutron damage in a neutron facility several aspects have to be considered, such as the flux intensity, flux spectra, PKA spectra, dpa and gas production. In Table 1 the main parameters for HiPER and ESS-Bilbao are summarised.

For structural materials, the average neutron flux expected in the HiPER chamber (6.5 m radius) is $1 \times 10^{18} \text{ m}^{-2} \text{ s}^{-1}$, almost two orders of magnitude higher than the average neutron flux that can be achieved in ESS-Bilbao. In addition, we must take into account that the major motivation for the study of structural materials is to improve the radiation resistance properties. Therefore, experimentalists will be mainly interested in qualifying the materials at fluences far too high to be reached in ESS-Bilbao. The use of ESS-Bilbao as a neutron irradiation facility for structural materials will be limited to certain studies, mainly for academic purposes.

On the other hand, in HiPER the optical final lenses will receive an average neutron flux of $\sim 2 \times 10^{17} \text{ m}^{-2} \text{ s}^{-1}$. The average neutron flux that can be achieved in ESS-Bilbao is $\sim 2\text{--}4 \times 10^{16} \text{ m}^{-2} \text{ s}^{-1}$. The latter is only a factor 5 lower than the neutron flux expected in a

Fig. 2. Neutron spectrum originated in HiPER with the explosion of a direct drive target with a yield of 154 MJ according to LASNEX simulations carried out in the framework of the ARIES project [8] and in the ESS-Bilbao fast neutron line by every proton pulse.

Table 1

Main characteristics of HiPER and ESS-Bilbao.

	HiPER	ESS-Bilbao	
Neutron Yield (n/shot)	5×10^{19}	5×10^{13}	
Average neutron energy (MeV)	11.8	7.7	
Repetition rate (Hz)	10	20	
<i>Damage on iron</i>			
Distance to neutron source (cm)	650	10	20
Average neutron flux ($\text{m}^{-2} \text{ s}^{-1}$)	1×10^{18}	4×10^{16}	2×10^{16}
Damage (dpa/fpy)	7.3	0.14	0.05
H (appm/fpy)	306	7.2	2.2
He (appm/fpy)	97	2.2	0.6
H/dpa	42	51	42
He/dpa	13	15	12
<i>Damage on silica</i>			
Distance to neutron source (cm)	1600	10	20
Average neutron flux ($\text{m}^{-2} \text{ s}^{-1}$)	2×10^{17}	4×10^{16}	2×10^{16}
Damage (DPA/fpy)	0.7	0.08	0.04
H (appm/fpy)	49	5.6	1.6
He (appm/fpy)	83	8.2	2.4
H/dpa	72	66	46
He/dpa	122	97	67

pre-commercial HiPER power plant. Thus, the time required to reach certain neutron fluence in ESS-Bilbao will be close to the time required in HiPER. Since significant phenomena (colouration, compaction, refractive index variation) can be studied in silica at low fluences (minutes to hours of irradiation), the ESS-Bilbao irradiation line appears as an adequate facility to carry out neutron irradiation studies of silica.

The differences in neutron spectra between the ESS-Bilbao irradiation facility and the HiPER power plant must be also considered. Low energy neutrons mainly interact with matter by means of elastic collisions, whereas high energy neutrons produce non-elastic reactions, leading to the generation of light species and gamma emission. The displacement cascades also depend on the neutron energy. Regarding the influence of the neutron spectra in the energy deposition, the first half of the deposited energy occurs for similar neutron energies (10–15 MeV) in both facilities. However, in ESS-Bilbao the energy deposition takes place in a wide energy range (1–50 MeV), whereas in HiPER most of the energy is deposited by neutrons with energies exceeding 10 MeV, and peaking at 14 MeV. In both cases the influence of low energy neutrons (<1 MeV) is low.

An important parameter for the comparison of neutron damage in ESS-Bilbao and HiPER is the PKA spectrum. Following the methods described in Appendix A, we have calculated the PKA spectra generated in iron and silica (see Fig. 3). We observe that the spectra generated in both facilities are similar. Therefore similar neutron damage is expected, although it is produced at a lower rate in ESS-Bilbao. The major differences in the PKA spectra appear at high energies, because of the high energy tail in the neutron spectrum of ESS-Bilbao. This will lead to some high energy recoils absent in HiPER. We discard that they could produce damage by electronic excitation mechanisms [11]. In silica, these mechanisms produce changes in density, stoichiometry, optical properties as well as generation of defects and typically take place above certain stopping power threshold of the order of 2–6 keV/nm depending on the ion velocity [12–18]. Recoiled O atoms can never reach even the lowest threshold value (2 keV/nm), whereas recoiled Si atoms with energy above ~ 3 MeV have an electronic stopping power of ~ 2 keV/nm. Such high Si recoil energies are hardly reached in HiPER and in ESS Bilbao they represent a negligible fraction of the total recoil number. In iron, the threshold for electronic damage exceeds 25 keV/nm [19], which cannot be reached with the Fe recoils expected in both HiPER and ESS Bilbao.

Fig. 3. PKA spectra in iron and silica samples calculated for ESS-Bilbao and HiPER facilities.

In order to estimate the damage level, we have used the NRT model [20]. Although very simple, it is useful for the purpose of comparing different facilities because it provides a meaningful quantity, the number of displacements per atom (dpa) and we can account for the non-linear defect production due to PKAs of different energies. The dpa level expected per year is included in Table 1 for silica and iron in both HiPER and ESS-Bilbao facilities. An analysis of the damage shows, as expected, that the dpa level reached in HiPER will be higher than in ESS-Bilbao due to the higher neutron fluxes. However, the ratios of light species levels to dpa agree quite well in both cases, as expected from the neutron and PKA spectra.

As already mentioned, the main drawback of ESS-Bilbao is its low neutron flux, not enough to reproduce damage at high fluences in structural materials. However, in the next section it is shown that since interesting effects appear in silica at low fluences, ESS-Bilbao can be a useful facility to study them.

4. Damage production in silica

Silica components are expected to be present in future fusion power plants: mirrors, lenses, windows. They will be exposed to severe irradiation conditions in laser fusion facilities where thousands of pulses will be reached in the range of minutes [9]. An important effect is the generation of colour centres. These colour centres produce laser absorption with fatal consequences for the plant operation.

We have calculated the colour centre production in silica making use of the model proposed by Marshall [21] and reviewed by Latkowsky [22]. The implementation of the model is described in Appendix B. For simplicity, only the generation of oxygen defect centres (ODC) by neutron irradiation and their conversion into E'-centres upon gamma absorption are taken into account. The reason is that these are the defects that contribute to the optical absorption of the most important bands in laser fusion, the third and fourth harmonics (351 nm and 262 nm, respectively) of solid state lasers using Nd-glass.

Using this model we have estimated the colour centre concentrations and absorption coefficient in HiPER and ESS-Bilbao at different temperatures (see Fig. 4). Regarding the defect evolution, the steady state is reached in ~ 60 s at 850 K and in ~ 1000 s at 750 K. Associated to ODC concentration, a large peak centred at 248 nm appears in the absorption coefficient. It turns out to be a

Fig. 4. Top: time evolution of the ODC and E' defects until the stationary regime is attained. Bottom: Comparison of the absorption coefficient in stationary regime (~ 60 s for 850 K and ~ 1000 s for 750 K). Analysis for ESS-Bilbao (10–20 cm) and HiPER in a silica lens of 5 cm thickness.

broad peak that extends beyond the 350 nm band. In addition, a second peak associated to E'-centres appears at 213 nm. In ESS-Bilbao the E' centre generation rate is lower than in HiPER. This is because the formation of E' centres does not depend linearly on the dose rates but it scales quadratically. Therefore, as in ESS-Bilbao the level of irradiation is lower than in HiPER, for the same temperature, the E' centre peak (213 nm) is less marked, as appreciated in Fig. 4.

The temperature determines the defect evolution in silica because defect annealing is a thermal activated process. As an example, Fig. 4 shows the role of temperature. Irradiations in ESS-Bilbao at 750 K will lead to defect concentrations and hence absorption coefficient similar to those of HiPER at 850 K. Therefore an adequate temperature control in an ICF plant will be necessary to maintain the silica final lens absorption below tolerable limits [9]. On the other hand, the temperature in an experimental facility as ESS-Bilbao will be a crucial parameter to understand the defect kinetics and in turn elaborate models to apply in realistic situations.

Experimental data from ESS-Bilbao will allow us to validate materials and improve available models. For example the Marshall-Latkovsky model used in this section does not include the influence of the neutron spectrum or the effect of light species and impurities.

Fig. 5. Neutron flux per unit lethargy in different nuclear facilities using: ESS-Bilbao, HiPER, Demo, HFR, IFMIF, and ESS. The neutron flux for Demo, HFR, IFMIF and ESS are obtained from Ref. [3].

Fig. 6. PKA spectra of different nuclear facilities using ^{56}Fe as the reference material. The analysed facilities are ESS-Bilbao, HiPER, Demo, HFR, IFMIF, and ESS. The lower curve of ESS-Bilbao corresponds to the regions nearer the target (10 cm) and the upper to the regions further from the target (20 cm). The regions near the target have a higher presence of high energy PKAs. The neutron flux for Demo, HFR, IFMIF and ESS are obtained from Ref. [3].

5. Other neutron irradiation facilities

In the previous sections, the damage analysis for ESS-Bilbao and its comparison with HiPER is shown. However it is also interesting to compare ESS-Bilbao with other experimental facilities. In the last decades, the adequacy of different neutron sources for fusion materials irradiation has been addressed, in Ref. [3] Vladimirov and Bouffard give an interesting comparison between different neutron facilities. Of special interest are Demo, HFR, ESS and IFMIF. These facilities represent different types of neutron sources: (a) Demo as a magnetic confinement nuclear fusion prototype power plant, (b) HFR (Petten) as a typical mixed spectrum fission reactor, (c) ESS as a spallation neutron source and (d) IFMIF as a facility developed specifically for the irradiation of nuclear fusion materials.

A comparison of these facilities with ESS-Bilbao and HiPER is shown in Figs. 5 and 6, and Table 2. The neutron flux in ESS-Bilbao is much lower than in other experimental facilities. Regarding the

Table 2

Damage comparison for the reference facilities, using iron (^{56}Fe) as the reference material. The damage characteristics for DEMO, IFMIF, ESS and HFR have been obtained from Ref. [3].

	Damage (dpa/fpy)	H (appm/y)	He (appm/y)	H/dpa	He/dpa
ESS-Bilbao	0.05–0.14	2.2–7.2	0.6–2.2	42–51	12–15
HiPER	7.3	306	97	42	13
Demo	30	1240	320	41	11
IFMIF	20–55	1000–2400	250–600	35–54	10–12
ESS	5–10	160–360	25–60	33–36	5–6
HFR	2.5	1.9	0.8	0.76	0.32

Fig. 7. Methodology used for the analysis presented in this work.

neutron spectrum (Fig. 5) we realise that none of the neutron sources is able to reproduce the neutron spectrum generated in fusion plants, characterised by a marked peak at 14 MeV. The best approach to the fusion spectrum is obtained in IFMIF and ESS-Bilbao. Although in the latter case the neutron flux is low, in both cases the spectrum presents a sharp drop at neutron energies slightly higher than 14 MeV. Regarding the PKA spectra (see Fig. 6), it is obvious that IFMIF provides the PKA spectrum that best resembles the fusion plants. Next, as discussed in Section 4, ESS-Bilbao produces an acceptable PKA spectrum. However, the other two neutron facilities, ESS and HFR, strongly differ from the fusion PKA spectra. In ESS a marked tail of high energy PKAs is present that would probably dominate the neutron effects on an irradiated material. On the other hand, in HFR the average PKA energy is too low to reproduce the effects induced by fusion neutrons.

Summarising, the comparison with other neutron facilities shows that it is not easy to obtain spectra as those expected in future fusion power plants. Fast reactors do not turn out a good option to mimic fusion damage. On the other hand, spallation sources have shown their potential, but some factors have to be considered such as differences in the PKA spectra, light species production and spallation product yield [4,7]. IFMIF, constructed ad hoc for fusion materials irradiation, shows a spectrum adequate for fusion dam-

age reproduction. The difficulty to find appropriate neutron sources and the short-term availability of ESS-Bilbao, puts in value its use for fusion materials studies.

6. Conclusions

We have analysed ESS-Bilbao as a facility for the study of materials irradiation under nuclear fusion conditions. Throughout the article we studied the neutron spectra, PKA spectra, dpa and light species production in different materials. This showed that the spectra in ESS-Bilbao matches quite well the fusion spectra and comparable irradiation patterns are expected. When comparing the PKA spectra of ESS-Bilbao and IFMIF, a similar shape is observed, much better fitted for fusion damage reproduction than fast reactors or spallation sources.

Damage rates in ESS-Bilbao will be low and qualification of structural materials (up to tens of dpa) will not be possible. For that purpose, facilities like IFMIF will be necessary. In the field of structural materials, ESS Bilbao could contribute to address the initial stages of damage. On the other hand, ESS-Bilbao can play an important role in the analysis of silica-based optical materials for fusion. The role that ESS-Bilbao can play is related to the improvement of damage models and validation of materials.

Apart from studies on silica, other materials relevant for the fusion community could be studied in ESS-Bilbao. This is the case of lithium ceramics, ceramic insulators or electronic components. In addition, ESS-Bilbao is originally planned to serve as a testing facility for components of ESS-AB. In this context, ESS-Bilbao could be useful for testing irradiation modules of ESS-AB or even of IFMIF.

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Appendix A. Radiation transport

In order to solve the radiation transport problem several models have been developed with the code MCNPX [23]. Fig. 1 shows the model used to reproduce ESS-Bilbao conditions. This model was developed by the Target Group of ESS-Bilbao and is described in

Table 3

Parameters for the silica defects model.

Parameter			Parameter			Parameter		
σ_{ODC} (m ²)	1.70×10^{-21}	[22]	σ_E (m ²)	3.20×10^{-21}	[22]	β_E (Gy ⁻¹)	7×10^{-5}	[22]
λ_{ODC} (nm)	248	[30]	λ_E (nm)	214	[30]	τ_0 (s)	4×10^{-10}	[22]
$\Delta\lambda_{ODC}$ (nm)	13	[30]	$\Delta\lambda_E$ (nm)	15	[30]	T_0 (K)	21,000	[22]
M_n ($\frac{\text{defects}}{\text{keV-P(KA)}}$)	0.37	[22]						

Ref. [10]. For HiPER we assumed a 6.5 m radius spherical chamber for the structural material (iron) with the final optics (5 cm-thick silica lenses) placed 16 m away from the chamber centre. This model uses the fusion neutron spectra calculated with the code LASNEX [24] in the framework of the Aries project for a 154 MJ direct target [25].

The calculation of the PKA (primary knock-on atom) spectrum generated by neutrons has been carried out using the methodology presented in Fig. 7. We used double-differential cross sections, $\sigma(E_i, E_s)$, to take into account the scattered particles (PKA) from incident particles (neutrons). The scattered particle will have different energies depending on the scattering angle and energy loss (non-elastic reactions). These processes are calculated as follows:

$$R_s(E_s) = \int_0^\infty \sigma(E_i, E_s) \cdot \phi_i \cdot N \cdot dE_i \quad (\text{A.1})$$

where R_s is the reaction rate, E the particle energy, ϕ the particle flux, N the density of the material, and the subscripts i and s refer to the incident and the scattered particle, respectively. In our case, the incident particle is a neutron and the scattered particle the generated PKA.

The double differential cross sections are available in nuclear libraries only for neutron energies up to 20 MeV. We extract them from the nuclear library with the NJOY code [26]. For higher energies (>20 MeV) no tabulated data is available and computational models must be used. In this article simulations were run with Bertini/Dresner model using the module HTAPE3X of MCNPX. From the results a postprocessing is done to obtain the simulated cross sections.

The displacements per atom (dpa) are determined from the PKA spectra using the standard NRT model [20]. The NRT model is used in this work, as a tool for the comparison of the different facilities, for a more realistic damage estimation more complex models (such as Molecular Dynamics) should be used [27]. For the application of the NRT model, a displacement energy (E_d) of 40 eV has been used with a recombination factor (k) of 0.8.

Appendix B. Damage on silica model

After neutron irradiation, colour centres are formed in silica. The most relevant colour centres regarding final lenses for laser fusion plants are the ODC (Oxygen Defect Centre) and the E'-centre [27–29]. In this section the model described by Marshall [21] and reviewed by Latkowsky [22] is presented. With this model the concentration of ODC and E' defects in silica and their associated absorption coefficient are studied.

The model calculates the defect concentration from the irradiation dose rates, the ODC to E' conversion and the annealing factor. Taking into account all these factors the evolution of the defect concentration is described as:

$$\frac{dN_{ODC}}{dt} = M_n \cdot D'_n - \beta_{E'} \cdot D'_\gamma \cdot N_{ODC} - \frac{N_{ODC}}{\tau} \quad (\text{B.1})$$

$$\frac{dN_{E'}}{dt} = \beta_{E'} \cdot D'_\gamma \cdot N_{ODC} - \frac{N_{E'}}{\tau} \quad (\text{B.2})$$

where N_{ODC} is the concentration of ODC, $N_{E'}$ the concentration of E'-centres, τ is a generic defect annealing time; M_n is the number of defects per PKA; β_E accounts for the ODC to E' conversion; D'_γ is the gamma dose rate, D'_n is the neutron dose rate and τ is the characteristic annealing time (τ).

The annealing term variation with temperature can be approximated to an exponential law:

$$\frac{\tau}{\tau_0} \approx e^{\frac{T_0}{T}} \quad (\text{B.3})$$

where τ_0 is the characteristic annealing time at a temperature T_0 .

Finally, from the defect concentration the absorption coefficient (α) can be calculated as:

$$\alpha(\lambda) = \sum_i \sigma_i N_i L_i(\lambda) = \sum_i \alpha_i L_i(\lambda) \quad (\text{B.4})$$

$$L_i(\lambda) = \frac{1}{1 + \frac{(\lambda_i - \lambda)^2}{(\Delta\lambda_i)^2}} \quad (\text{B.5})$$

where α_i is the absorption coefficient of a defect i ; σ_i the defect production cross section; N_i the defect concentration; λ the absorption wavelength, λ_i the peak wavelength for a defect i and $\Delta\lambda_i$ the half width, and the inclusion of $L_i(\lambda)$ comes from the lorentzian approximation of the microscopic absorption coefficient.

The values used for the parametric model are listed in Table 3.