SCIENTIFIC FEASIBILITY OF FUSION MATERIAL IRRADIATION EXPERIMENTS IN ESS-B

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Abstract

Material irradiation by protons is capable of simulating the effects of fusion neutrons (14 MeV, target damaging and He & H production) with a reasonably fast dose rate, according to theoretical calculations and previous experiments. Therefore, given that the ESS-Bilbao (ESS-B) accelerator, under construction in Bilbao, will provide an intense source of 50 MeV protons, with total currents of a few mA´s, a laboratory for fusion material testing is proposed.

This paper appraises the scientific feasibility of performing fusion relevant experiments in the proposed laboratory. Material characterization under proton irradiation (by in-beam techniques to assess mechanical properties) while monitoring mechanical, micro-structural and compositional changes of the irradiated materials are some of the laboratory goals. Special emphasis is placed on expected radiation damage parameters in structural and functional materials, the beam power deposition in the sample and the consequences of material activation for the laboratory design.

INTRODUCTION

First wall and blanket components for future fusion devices are expected to experience high neutron fluxes (~10^{14} n cm^{-2} s^{-1}). These 14 MeV neutrons, in addition to producing atomic displacement damage (dpa, displacement per atom), will also induce nuclear transmutation reactions [1]. In particular, helium, which will be generated at a high rate (10-100 ppm/week), will contribute to changes in the mechanical properties of the materials. Proton irradiation has been proposed for simulating radiation damaged including the He accumulation in many works, between them in TechnoFusión Facility [2].

In this paper, a proton irradiation laboratory dedicated to fusion material testing is considered for the ESS-B Facility (*P4M*, Proton for Materials) [3], the objective of which is to provide a high-current 50 MeV proton linear accelerator for a broad range of user applications. The feasibility of such a laboratory for a range of fusion-material relevant experiments is discussed here. For this the accumulated damage needed in such materials to study relevant effects as well as the working parameters of the ESS-B Facility are taken into account. Moreover, the energy deposition in target materials is estimated in order to foresee consequences for the laboratory design.

DAMAGE AND IRRADIATION TIME

One of the main parameters to be determined for such testing is the maximum power deposition that can be tolerated by a target in order to induce relevant damage in the material within a reasonable run time. As an example, 50 MeV protons incident on ^{56}Fe test targets (1 to 25 cm^2 square samples with 1 mm thickness), with average currents in the range of 1 to 2.5 mA, are considered with the intention of doing in-beam mechanical testing. For this, the collision processes in the target are simulated by the Monte Carlo code, SRIM/TRIM [4], which considers 2-dimensional ion penetration in solids. The energy lost by the 50 MeV protons in passing through the sample is small, i.e. the stopping power is 7.8 MeV/mm. However, at the high current density (as it is the case for *P4M*) the most restrictive requirement on sample thickness is removal from the sample of the heat generated by the passage of the proton beam. Likewise, the transiting protons, with ~42 MeV of energy must also be stopped in a beam dump with active cooling system (which will also require a detailed design).

The displacement damage induced in the whole sample by irradiation with 50 MeV protons is proportional to the product of density current and irradiation time. See figure 1 where damage has been calculated assuming as number of target vacancies the averaged in 1 mm thickness given by TRIM code.

Now, considering that 1 dpa/week is the typical relevant value for fusion materials [5] and that 1 week of ESS-B beam time is a reasonable experimental time, then the beam cross-section should be ~25 cm^2 with an average current of 2.5 mA (0.1 mA/cm^2) and ~200 hours of beam time will be required. Then for such conditions a sample power load of 0.7 kW/cm^2 is obtained. However, an active cooling system must be implemented at the rear of the sample for such a power load [6]. A prototype system is being designed in order to obtain a better understanding of temperature control of the test target for these conditions.

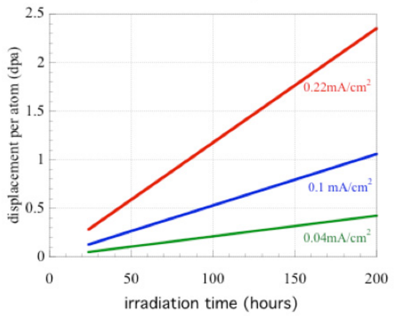

Figure 1: Displacement per atom (dpa) induced in a test target of ^{56}Fe due to proton beam (for 50 MeV and current densities 0.04, 0.1 and 0.22 mA/cm^2) versus irradiation time. Note that the power loads in the target is 1.6 kW/cm^2 (red line), 0.7kW/cm^2 (blue line) and 0.28 kW/cm^2 (green line).

He Production at Target

For the case of the 50 MeV protons, theoretical studies predict that the production rate of He by transmutation for a 1 mm ^{56}Fe target will be almost constant across the sample. It is estimated that this will be of the order of several appm/day (atoms produced per million) for a 0.1mA/cm^2 current density [1,7]. Moreover, the ratio of He production rate to damage production rate (appm/dpa) is critical for simulating radiation damage by fast neutrons. Indeed, a wide range of such ratios (1 to 100 appm/dpa) are predicted for several candidate materials in fusion device scenarios [7,8], these being for positions including the first-wall, the breeding-zone, etc. For the present context of interest, the predicted ratio ~50 appm/dpa in a 1 mm thick ^{56}Fe sample, for the conditions in ESS-B, will be of interests for fusion purposes [8].

POWER DEPOSITION IN THE SAMPLE

A total power deposited in the target of 0.7 kW/cm^2 has been estimated during irradiation over 200 hours at a current density of 0.1 mA/cm^2. Active water-cooling at the rear of the target is proposed in order to keep the sample temperature within reasonable values. A laboratory test is under design to demonstrate the effective evacuation of the heat.

As a consequence of the high thermal deposition, the testing of mechanical properties during irradiation is discarded for the first phase of the laboratory. The main difficulties arise in that the heat dissipation must be placed at the sample edges.

More detailed thermal effects of beam power deposition have been studied on a solid model using the COMSOL Multiphysics finite element analysis code and the main results are shown in another work presented at this conference [6]. One of the main results is that a cooling temperature of 343 K is necessary at the rear-face of the test target.

MATERIAL ACTIVATION

The main disadvantage of using a high current and high-energy proton irradiation is the amount of activation present in the irradiated samples. Thus radioprotection studies will be important for different aspects such as the design of bio-shielding for the vault as well as access to, and handling procedures for, the irradiated targets in order to assure that dose levels are acceptable for workers.

Similar studies have been undertaken for the TechnoFusión Facility [8] and currently additional computational studies are being performed for the specific parameters of ESS-B. The results of these studies, although outside the scope of this paper, will be of paramount importance for the final design of the laboratory.

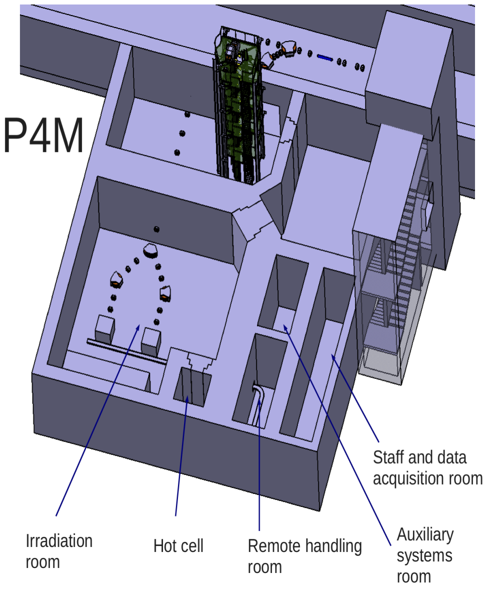

Figure 2: Preliminary layout of *P4M* laboratory.

Meanwhile, considering the high radiation levels expected during and after irradiation with ESS-B working parameters, a preliminary drawings of *P4M* laboratory have been produced (see figure 2). All these areas will be located at the accelerator level (-10 m). As can be observed a room is reserved for remote handling operations, if required. A more detailed explanation of the laboratory area distributions is in a paper presented at this conference [6].

SUMMARY

A laboratory for fusion material studies is being considered for the ESS-B Facility. The main results of this initial scientific feasibility study can be summarized as:

- The 50 MeV proton beam is a useful tool for reproducing radiation damage by fusion neutrons in reactor relevant materials.
- Proton irradiation with a current density of 0.1 mA/cm^2 yields a ratio of He production to displacement damage similar to that predicted for fusion neutrons.
- For a 0.1mA/cm^2 beam, active cooling of the rear of the sample is essential in order to dissipate the thermal load (about 0.7 kW/cm^2). A prototype is being designed.
- Due to the predicted thermal load the mechanical test experiments foreseen during irradiation have been discarded for the first phase of the project.
- The energy of the protons exiting the samples will be high (~42 MeV) so they must be stopped in a suitable dump with an active cooling system.
- Activation of the materials is a disadvantage of using high-energy proton in experiments. Simulations are being undertaken to estimate the materials dose rate as well as the time required after beam-off for accessibility to the laboratory. The results will be crucial for defining the experimental conditions and

the design of the laboratory, for example, to determine the necessity or not of remote handling operations.

- A room for remote handling operations has been reserved, if required, in the preliminary layout of *P4M* laboratory.

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