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The neutron irradiation module at the European Spallation Source ESS

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Abstract. The neutron Irradiation Module at the European Spallation Source will make use of the high intensity fast neutron spectrum to study the behaviour of the materials used in the facility, set within the ESS research and development program for the target station. By studying how these materials are affected by radiation, estimates of the material degradation in irradiated bespoke samples will allow to optimise of the design and lifetime of regularly replaced target components. The general design and a set of results from the neutronics calculations, aimed at estimating proton and neutron flux distributions, displacement damage, heat deposition and activation for the radiological hazard analysis of the Irradiation Module, set within the Italian contributions to the ESS construction phase, are reported.

1. Introduction

In order to obtain experimental information available on the behaviour and lifetime of spallation target components, ESS has set a test and development programme for structural materials used in radiation environments of spallation facilities [1]. In particular, knowledge of the changes of mechanical properties and microstructure induced by the high neutron flux from the 5 MW ESS spallation source, will allow to define improvements in lifetime and reliability of structural components of the ESS target systems. The outcome of such programme is expected to contribute to the relevant databases for the research and development on high-power spallation target assemblies [2]. The design and construction of the neutron Irradiation Module (IM) at the European Spallation Source is set within the Target In-Kind TIK 4.3 contribution agreement between ESS and CNR. Its primary function is for the study of the materials used in the facility. By using the fast neutron spectra, samples and components contained in the IM can be irradiated and used to support ESS own research and development program for the target station. Samples to be irradiated shall be located as close as possible to the target material, in a position offering both a representative radiation spectrum and an acceptable disturbance of moderator performance. Based on criteria and boundary conditions set by the spallation source construction phase, the IM will be located in the ESS pre-moderator and will be passively cooled by the thermal moderator



water flow. This set-up is intended to provide a proof-of-concept module, paving the way towards next generation neutron irradiation modules at ESS with active temperature control and large irradiation volume. The positioning of the IM inside the moderator reflector plug is reported schematically in Figure 1 below. With reference to the ESS Target Coordinate system (defining the centre of the Target monolith) the module is located in $(x=-16; y=90\div 150; z=+96)$ mm.

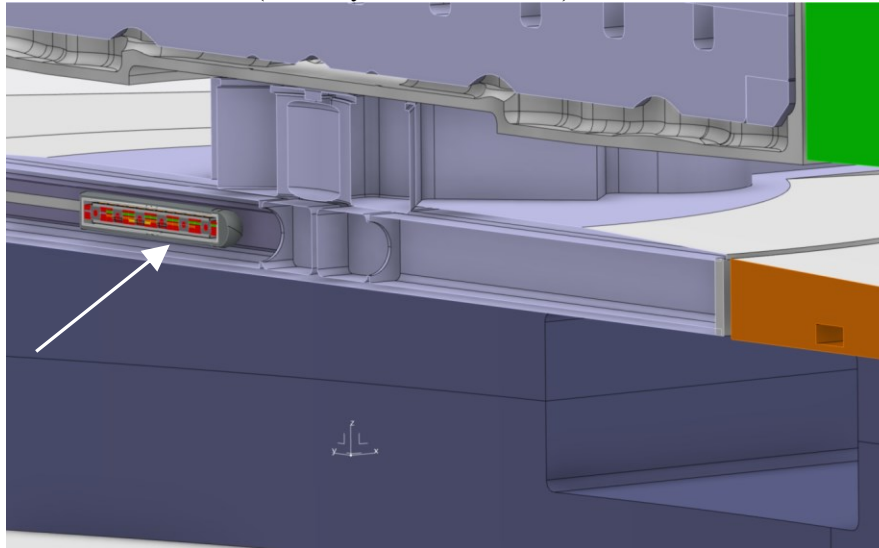


Figure 1. Positioning of the Irradiation Module (indicated by the arrow) into the ESS water pre-moderator

The module consists of a concentric cylinder-shaped container (vessel) enclosing ferrous and non-ferrous metal samples packed and assembled under helium atmosphere. Figures 2 and 3 report the sketch of the vessel and sample assembly, composed of 168 mini, mm sized samples. The external length of the module is 12.5 cm.

The post irradiation examination on the irradiated samples will make use of reference comparison with an identical set of samples that will not be irradiated. The characteristics of the ESS neutron spectrum, with energies up to 2 GeV and power on target up to 5 MW, from the initial to the design operation stages, respectively, will represent a unique opportunity to obtain data from a spallation neutron environment, that is beyond what is available from thermal or fast reactors. In particular, the flux of fast neutrons (integrated between 0.1 MeV and 2 GeV) on the module will be in the order of 10^{16} neutrons $\text{cm}^{-2} \text{s}^{-1}$ [3].

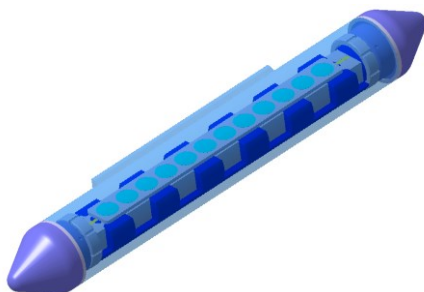


Figure 2. Schematics of the outer vessel containing the samples.

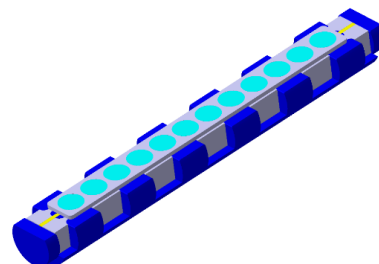


Figure 3. Schematics of the samples assembly

This manuscript reports in section 2, as an example of the expected damage on representative samples, the results of the neutronics calculations for the estimated displacement damage for Al alloy tensile samples. A complete report of the neutronics calculations in terms of neutron and proton fluxes, source

brightness losses, gas production, heat deposition, and samples activation will be presented in a dedicated publication [3]. In particular, the design is tailored to guarantee that: 1) the ferrous metal samples will get the same damage dose that is equivalent to the displacement per atom value of approximately 6 dpa in the stainless steel SS316 L, that is of the target vessel's steel -lifetime reference values; 2) the gas production will be in the range of approximately 15 He-appm/dpa, similarly to the damage occurring in fusion related materials [2]; 3) the neutron flux at the irradiation module position is at least 10^3 times more intense than the proton flux.

2. Neutronics calculations

The development of the neutronics model and the IM design was based on inspection and optimization, using neutronics calculations, of the following main parameters:

- Neutron flux in the range of interest
- Impact on moderator's performance
- Radiation damage (dpa)
- Gas (H, He) production
- Heat load
- Activation

The calculations were carried out by making use of the MCNPX code [4]. We report here only an example of the estimated radiation damage on a set of Al alloy samples which will be used for tensile tests. Figure 4 reports the simulation geometry with respect to the primary proton beam.

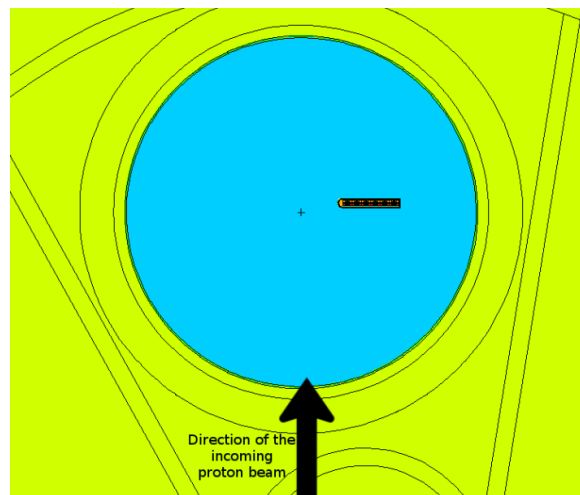


Figure 4. Input geometry for the MCNPX calculations. The Irradiation module is placed downstream with respect to the incoming proton beam. It is about 1.5 cm apart from the centre of the top moderator disk along the beam direction.

Figure 5 reports, as an example, the calculated radiation damage for Aluminium 6061-T6 alloy tensile samples, as a function of the distance from the moderator centre. These calculations shown for proton energies of 570 MeV (30.0 mA average current) and 2 GeV (46.0 mA average current), the former representing the parameters for the initial ESS operation phase, and the latter representing the parameters for the design operation. Both calculations were carried out per “effective year”, corresponding to 5400 hours of operation per year. Therefore, the total dpa achievable in a typical - two years irradiation time, will be slightly less than the corresponding dpa from similar irradiation times at PSI [2], but with a much

lower gas production per dpa, since the present module will receive an almost pure neutron irradiation [2,3].

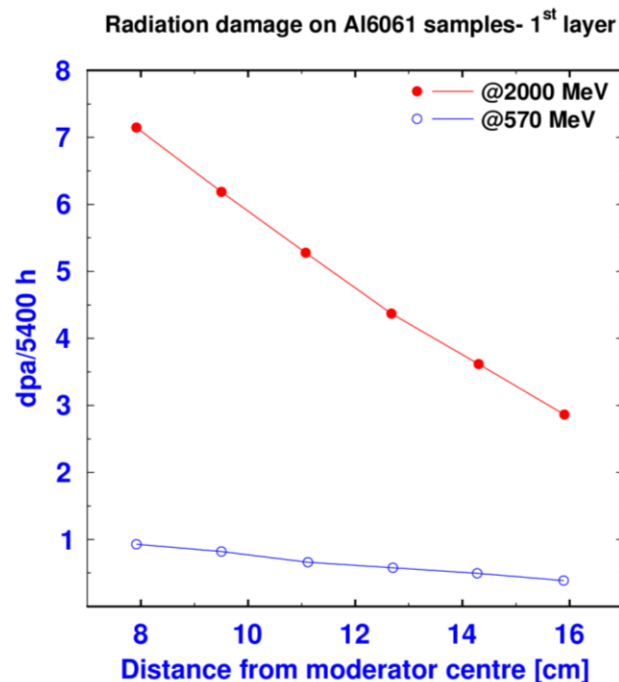


Figure 5. Radiation damage rates for the 6061-T6 alloy tensile samples in the first layer of the module, which is the closest to the target, as a function of their distance from the centre of the moderator. Calculations are reported for primary proton energy of 570 MeV (blue open circles), and 2000 MeV (red full circles), respectively.

3. Conclusions and outlook

The fast neutron irradiation module at ESS will provide relevant knowledge of target materials degradation from the intense neutron radiation field at ESS. The manufacturing of samples, holder, vessel and their assembly has been completed and the module will be integrated into the ESS thermal moderator at the beginning of 2018. Extensive details of the design, neutronic calculations and tomographic analysis of the assembled module will be presented in a forthcoming publication [3].

4. References

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