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Thermo-mechanical analysis of irradiation swelling and design optimization of the IFMIF target assembly with bayonet backplate

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HIGHLIGHTS

- The optimization of IFMIF bayonet BP has been evaluated, in order to ensure a lifetime of one year of full power operation.
- Several BP design review strategies have been considered in order to select a potential optimized BP configuration.
- The selected optimized BP has been assessed from the neutronic standpoint in order to obtain updated thermal loads.
- Thermo-mechanical analyses have predicted the total fulfilment of SDC-IC criteria over one year of full operation.
- The ABAQUS v. 6.14 FEM code and the MCNP code have been used for thermo-mechanical and neutronic calculations respectively.

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ABSTRACT

The availability of a high flux neutron source for testing candidate materials under irradiation conditions, which will be typically encountered in future fusion power reactors (ITER, DEMO, FPR), is a fundamental step towards the development of fusion energy. To this purpose, the International Fusion Materials Irradiation Facility (IFMIF) represents the reference option to provide the fusion community with a DEMO-relevant neutron source capable of irradiating samples at a damage rate of up to 20 dpa/fpy (in steel) in a volume of 0.5 l. In the framework of the engineering design activities of IFMIF, ENEA is committed in the design of the lithium target assembly (TA) with removable (bayonet) backplate (BP) whose development has recently progressed up to a well advanced stage. However, an optimization of the system is still to be accomplished. In particular, the BP design needs to be revised in order to totally satisfy the ITER SDC-IC reference design criteria and fulfil the requirements on its lifetime which is limited by the neutron-induced swelling effects. In this work, a full thermo-mechanical analysis of the whole TA including a pseudo-transient simulation of the swelling effects in the BP over one year of full power operation has been performed by means of a 3D finite element (FE) model implemented through the quoted ABAQUS v. 6.14 code. A detailed neutronic analysis has been also performed by ENEA using the MCNP code to obtain the prompt nuclear responses, in terms of DPA and volumetric density of deposited nuclear heat power, to be used as input for the thermo-mechanical calculations. A new BP design capable to verify the SDC-IC design criteria and ensure its required swelling lifetime is proposed and described on the basis of the results of the performed analysis.

1. Introduction

The Department of Energy, Information engineering and Mathematical models of the University of Palermo (DEIM) is developing the IFMIF R&D activities, within the framework of a scientific collaboration with ENEA, being in charge of assessing TA thermo-mechanical performances under different sets of thermo-mechanical loading conditions [1–7]. Results obtained from DEIM analyses have put in evidence the necessity of a BP design review, in order to ensure its safely withstanding of thermo-mechanical loads it undergoes, allowing to extend its lifetime as much as possible.

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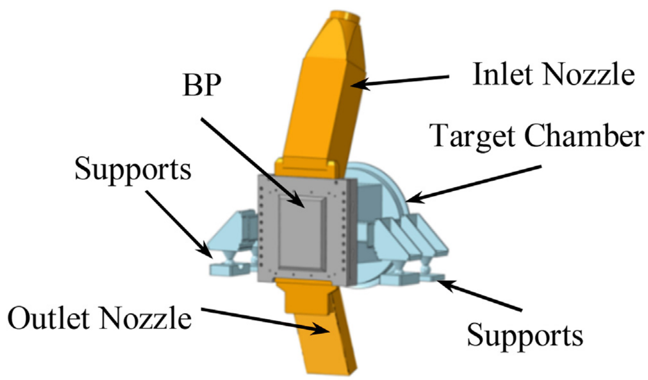

Fig. 1. IFMIF TA preliminary design.

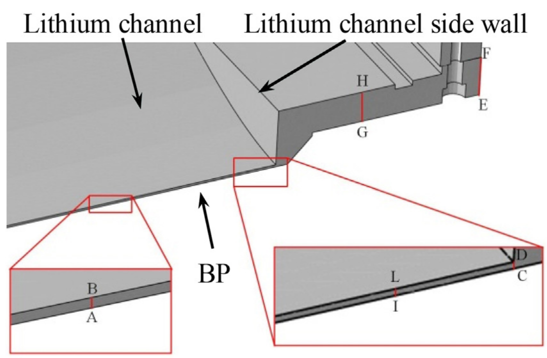

Fig. 2. Paths used for SDC-IC safety criteria check.

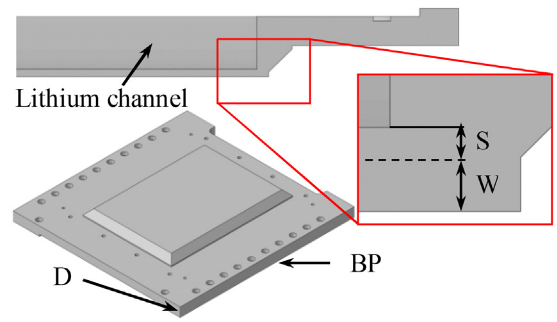

Fig. 3. Lithium channel and BP thicknesses.

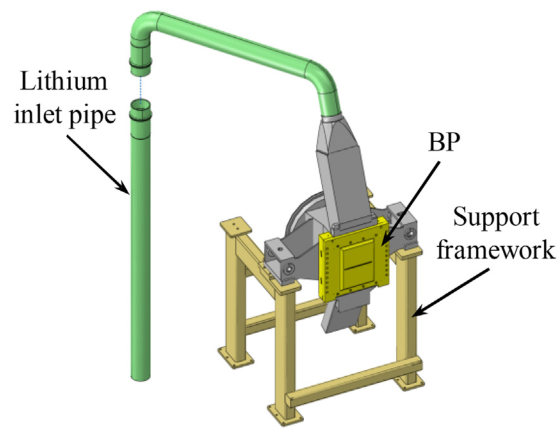

Fig. 4. IFMIF TA more realistic design.

To this purpose, an intense research campaign has been launched at DEIM, in close cooperation with ENEA, in order to select a BP design able to totally fulfil the SDC-IC structural design criteria [8] under nominal loading conditions, extending its lifetime under neutronic irradiation up to the reference value of one year. The study has been articulated in two separate sections.

In the first one, a parametric assessment has been carried out in order to select a potentially optimized BP configuration able to satisfy the SDC-IC safety rules under both IFMIF-relevant steady-state and transient loading scenarios.

In the second phase a neutronic analysis has been performed by ENEA, according to the analysis procedure described in [9], in order to calculate the volumetric density of deposited nuclear heat power (q''') and DPA spatial distributions, pertinent to the TA endowed with the previously selected BP geometric configuration, which have been adopted in a further batch of thermo-mechanical analyses performed at DEIM. In particular, the full performance operation phase consisting of two deuteron beams each of 40 MeV, 125 mA working continuously for 1 year have been considered in the neutronic calculations.

2. The BP design optimization procedure

Results of thermo-mechanical analyses [4,6] on the IFMIF TA preliminary design (Fig. 1) have shown that the SDC-IC criterion against immediate plastic flow localisation, $(P_m + Q_m) < S_e$, is not completely met under the envisaged steady-state nominal loading scenario.

In particular, highest values of the $(P_m + Q_m)/S_e$ ratio (~1.57) have been calculated in BP middle plane section, along path IL (Fig. 2) which is the most critical among those considered.

On the basis of these results, a BP optimization procedure has been launched. Its first section has been divided into five phases, while the second section has represented the thermo-mechanical assessment, considering purposely determined neutron-induced loads, of the BP configuration selected in the first one. For sake of brevity, FE models and loading scenarios adopted are not deeply described herewith. Details can be found in [4–7]. It has to be remarked that the steady-state nominal scenario refers to the end of TA start-up, while transient scenario takes into account swelling effect during one year of nominal full power irradiation.

2.1. Section 1 – phase 0 of the BP design optimization

In Phase 0, the following design review strategies have been separately applied to optimize the BP design:

- BP lithium channel thickness increase, from S = 1.8 mm, by the addition of the steel layer (W) (Fig. 3) 1.0, 3.0, 3.7 and 4.2 mm-thick;
- BP thickness (D) reduction, from 32.8 down to 17.0 mm (Fig. 3);
- Combined strategy obtained by the simultaneous application of the previous two.

FE models of the preliminary TA design, equipped with each potential BP optimized configurations, have been set-up. Most promising results have been obtained from combined strategy, for which steady-state analyses have shown that a BP having D = 17.0 mm and W = 2.0 mm ensures the narrow fulfilment of SDC-IC rules in all paths, being $(P_m + Q_m)/S_e$ ~0.99 along path IL.

2.2. Section 1 – phase 1 of the BP design optimization

Phase 1 concerns the implementation of the BP configuration selected at the end of Phase 0 within the more realistic geometric model of TA (Fig. 4).

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