Analysis of the thermomechanical behaviour of the IFMIF bayonet target assembly under design loading scenarios

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In the framework of the IFMIF Engineering Validation and Engineering Design Activities (IFMIF/EVEDA) phase, ENEA is responsible for the design of the European concept of the IFMIF lithium target system which foresees the possibility to periodically replace only the most irradiated and thus critical component (i.e., the backplate) while continuing to operate the rest of the target for a longer period (the so called bayonet backplate concept). In this work, the results of the steady state thermomechanical analysis of the IFMIF bayonet target assembly under two different design loading scenarios (a "hot" scenario and a "cold" scenario) are briefly reported highlighting the relevant indications obtained with respect to the fulfillment of the design requirements. In particular, the analyses have shown that in the hot scenario the temperatures reached in the target assembly are within the material acceptable limits while in the cold scenario transition below the DBTT cannot be excluded. Moreover, results indicate that the contact between backplate and high flux test module is avoided and that the overall structural integrity of the system is assured in both scenarios. However, stress linearization analysis reveals that ITER SDC-IC design rules are not always met along the selected paths at backplate middle plane section in the hot scenario, thus suggesting the need of a revision of the backplate design or a change of the operating conditions.

Keywords: IFMIF; target assembly; bayonet backplate; engineering design; thermomechanics

1. Introduction

IFMIF (International Fusion Materials Irradiation Facility) is a high-flux neutron irradiation source which is currently being designed with the aim to provide the fusion community with a machine for testing candidate materials to be used in future fusion power reactors [1]. The IFMIF source basically consists of two accelerated deuteron beams (40 MeV, 125 mA each) which impinge on a liquid lithium target producing an intense neutron flux with a spectrum similar to that of D-T fusion reactions. Specimen of testing materials are placed behind the target (inside the test modules) in order to be irradiated under controlled conditions at a level above 20 dpa/fpy.

In the latest years, significant progresses have been made in the development of the European concept of the IFMIF target assembly (TA) (the so called TA bayonet concept [2,3]) and its status is now in a well advanced stage [4]. With the aim of evaluating the performances of the system and supporting its engineering design, a close collaboration with the University of Palermo has been established to perform the thermomechanical analysis of the bayonet TA under both nominal and design steady state conditions. The calculations have been carried out by means of a qualified finite element (FE) code implementing a realistic 3D model [5-7] which takes into account all the mechanical and thermal loads including the nuclear heating due to neutron and gamma fields generated in the liquid target. The latter have been calculated as part of a separate, extensive neutronic analysis carried out through the MCNP transport code and then passed as input to the thermomechanical model.

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While the results of the analyses referring to nominal operating conditions have been presented in [7] and in [8] for steady state and transients cases respectively, the main outcomes for two selected design scenarios (a "hot" scenario and a "cold" scenario) are reported and discussed in this paper.

2. Finite element model

2.1 Geometry and mesh

A sketch of the latest design of the European TA with bayonet backplate (BP) is presented in Fig. 1. The FE discretization employed in the thermomechanical model is shown in Fig. 2. A mesh independency analysis has been performed to select an optimized mesh which allows accurate results to be obtained saving calculation time. A mesh composed of ~207000 nodes connected in ~880000 tetrahedral elements has been used, allowing numerical simulations to be carried out in about 9 hours.

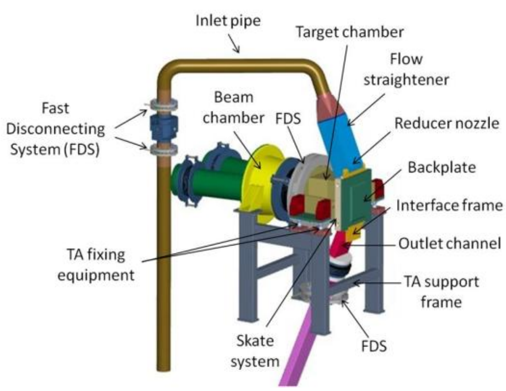

Fig. 1. European TA with bayonet backplate

2.2 Materials

European reduced activation ferritic/martensitic (RAFM) steel EUROFER has been considered as TA structural material. Lithium flow has also been modeled in order to properly simulate its thermal interaction with the TA. Materials have been considered homogeneous, uniform and isotropic. A linear elastic mechanical behavior has been assumed for EUROFER steel.

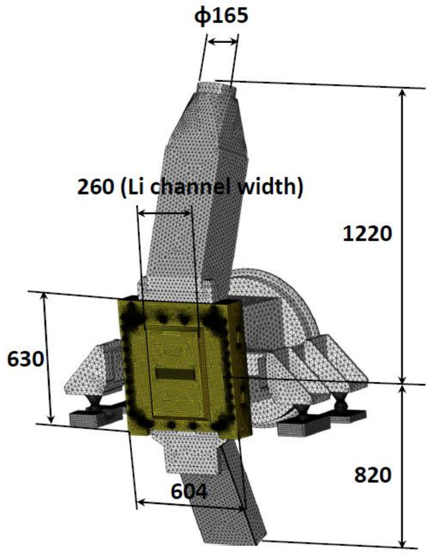

Fig. 2. Calculation domain and FE mesh. The BP is indicated in color. Dimensions are in mm.

2.3 Thermal loads and boundary conditions

The following thermal loads and boundary conditions have been adopted:

- Volumetric density of nuclear thermal power deposited in the footprint region of the lithium flow (only in the hot scenario, cfr. Sect. 3.1). An average value of 40 GW/m^3 has been assumed
- Volumetric density of nuclear thermal power deposited in the TA (only in the hot scenario, cfr. Sect. 3.1), as calculated by a parallel nuclear analysis performed through the MCNP transport code (Fig. 3)
- Forced convection between lithium and TA surfaces assuming a constant convection heat transfer coefficient of 34000 W/m^2 K [7]
- Radiation and conduction heat transfer through the He gap between BP and High Flux Test Module (HFTM) assuming h=0.1616/d W/m^{2}K (d being the gap between BP parts and HFTM). HFTM surface has been considered at 50 °C
- Conduction heat transfer between target chamber and beam duct. This has been modeled through a convective-type heat transfer coefficient assumed equal to 15.8 W/m^{2}K according to [9], and a non uniform bulk temperature analytically derived from a 1D simplified model of the conductive-radiative heat transfer in the beam duct
- Internal irradiation between lithium free surface and TA internal surfaces. EUROFER and Li emissivities have been assumed equal to 0.3 and 0.06, respectively [7]
- External irradiation between target chamber and test cell (TC) environment and between external surfaces of BP and frame and that of HFTM [7]

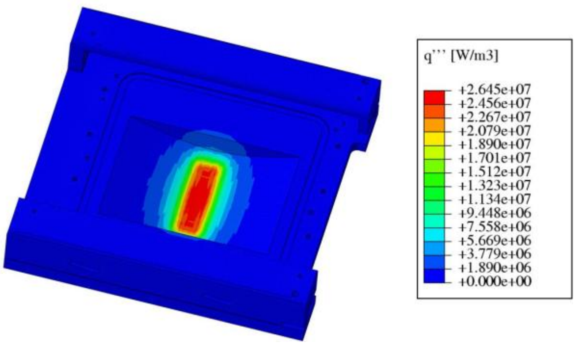

Fig. 3. Nuclear thermal power density deposition in the BP

2.4 Mechanical loads and boundary conditions

The following mechanical loads and boundary conditions have been imposed:

- Thermal deformations
- Internal and external pressures on the TA. Internal pressure has been applied to lithium wetted surfaces according to the results of the thermohydraulic analysis [4]
- BP tightening screw loads. These loads have been calculated by imposing that the tightening forces exerted by the screws induce a specific linear load onto the gasket horizontal segments equal to the optimum sealing value provided by the supplier (180 N/mm)
- Loads coming from the skate clamping system. These are calculated in the same way as for the BP tightening screw loads
- TA mechanical constraints

3. Operating conditions

3.1 Design scenarios

Two different design scenarios have been simulated:

- “Hot scenario”: lithium enters the BP channel at the maximum temperature allowed by the interlock system (310°C) [9] and at the minimum flow velocity of 7.7 m/s (inlet static pressure of 0.026 MPa), when the beam is on
- “Cold scenario”: lithium enters the BP channel at the minimum temperature allowed by the interlock system (240°C) [9] and at the maximum (design) flow velocity of 16 m/s (inlet static pressure of 0.068 MPa), when the beam is off

The hot scenario was studied with the aim to check if the temperatures reached under such design conditions are still within acceptable limits as well as if the corresponding displacements and stress levels are within design margins.

On the other hand, the cold scenario was studied with the aim to check if the thermal field reached under such design conditions is acceptable with regard to low-temperature issues such as lithium freezing or ductile to brittle transition temperature (DBTT) and if corresponding displacement and stress fields still meet the design constraints.

3.2 Common operating conditions

The following parameters common to both scenarios have been considered in the analyses:

- TA internal pressure: 10^{-3} Pa
- TA external conditions: He gas, p = 5 kPa ; T = 50 °C
- HFTM external surface temperature: 50 °C

4. Results

The results of the thermomechanical analysis for both design scenarios are reported hereafter in terms of temperature, stress and displacement fields in the whole TA and in the BP alone. Moreover, verification against ITER Structural Design Criteria for In-vessel Components (SDC-IC) [10] have been carried out and the results are summarized, as well.

4.1 Cold scenario

Fig. 4 shows the temperature distribution in the whole TA while the detail of the temperature field in the BP is reported in Fig. 5.

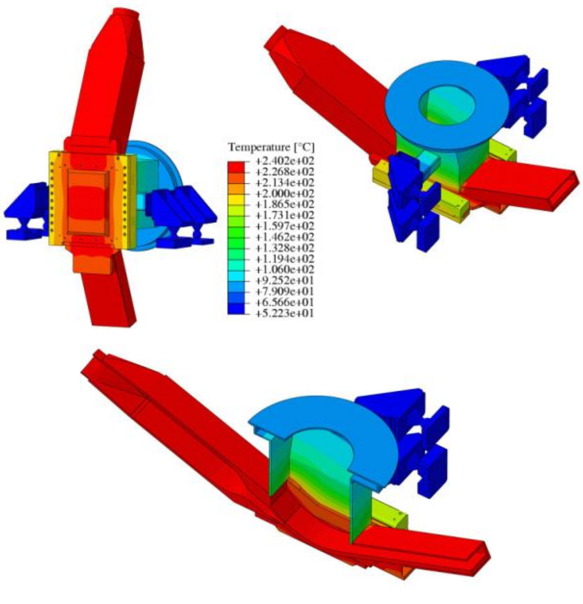

Fig. 4. Temperature distribution in the TA (cold scenario)

It is seen that quite low temperatures are achieved in the BP which might be even below the DBTT after irradiation and thus bring the BP in the brittle state.

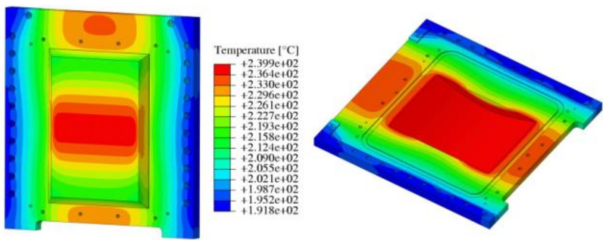

Fig. 5. Temperature distribution in the BP (cold scenario)

The Von Mises equivalent stress field in the whole TA and in the BP is reported in Fig. 6 (showing the most stressed region) and Fig. 7, respectively. Results indicate that the yield strength of the material is not reached anywhere except that in small, localized regions thus not posing any critical issue from the overall structural integrity point of view.

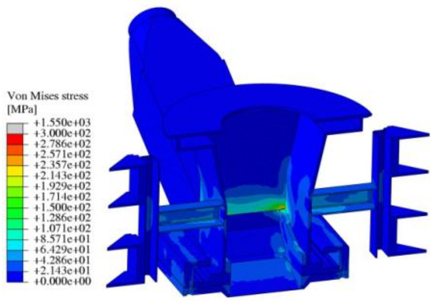

Fig. 6. Von Mises stress field in the TA (cold scenario)

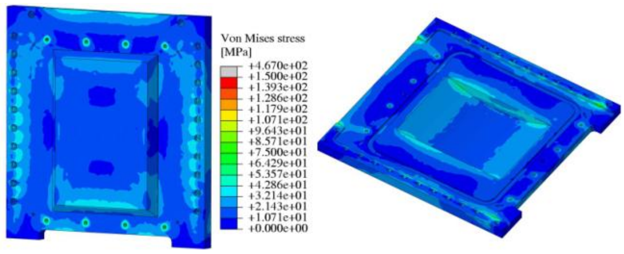

Fig. 7. Von Mises stress field in the BP (cold scenario)

Fig. 8 reports the BP displacement field along the beam direction (Uy). A maximum displacement of 6.32×10^{-4} m is found at the point nearest to the HFTM, which indicates that the contact between BP and HFTM is avoided (being 2 mm the nominal gap between the two components [4]).

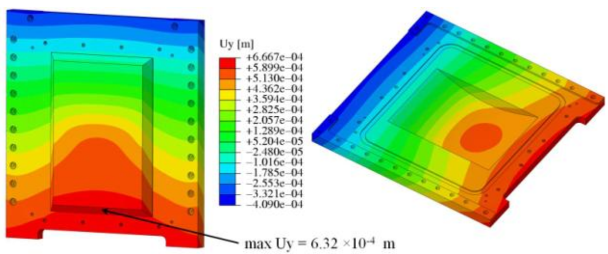

Fig. 8. Displacement field along beam direction in the BP (cold scenario)

Finally, a stress linearization procedure has been performed on significant paths lying on the BP middle plane section (Fig. 9) to check whether the SDC-IC design criteria are met. Five paths are considered as shown in Fig. 9. The detailed procedure and the meaning of the symbols adopted here are described in [8].

Tables I and II show the results of the design rules verification for the two heaviest stressed paths AB and EF (it must be noted that since the BP temperature is below the creep limit, the check of the high temperature rules is not requested). The rules for the other paths (not shown here) are all verified. Allowable stress limits are taken from [11] and [12].

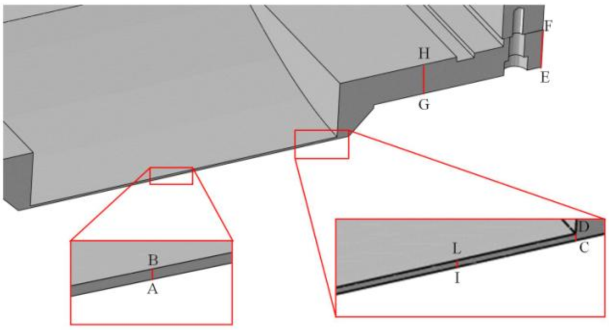

Fig. 9. Paths on BP middle plane section for stress linearization

TABLE I. STRESS LINEARIZATION – Path AB (cold scenario)

Calculated and allowable stress intensities			
T_m [°C]	S_m [MPa]	$K_{eff}S_m$ [MPa]	S_e [MPa]
283	171	256	262
	P_m	$P_m + P_b$	$P_m + Q_m$
	0.74	0.83	14.79
Rule verification			
P_m/S_m		4.3×10^{-3}	YES
$(P_m + P_b)/K_{eff}S_m$		3.2×10^{-3}	YES
$(P_m + Q_m)/S_e$		0.06	YES

TABLE II. STRESS LINEARIZATION – Path EF (cold scenario)

Calculated and allowable stress intensities			
T_m [°C]	S_m [MPa]	$K_{eff}S_m$ [MPa]	S_e [MPa]
194	180	271	412
	P_m	$P_m + P_b$	$P_m + Q_m$
	0.14	0.16	21.81
Rule verification			
P_m/S_m		7.8×10^{-4}	YES
$(P_m + P_b)/K_{eff}S_m$		5.9×10^{-4}	YES
$(P_m + Q_m)/S_e$		0.05	YES

4.2 Hot scenario

Figs. 10-14 show the corresponding results for the hot scenario, while Tables III and IV reports the outcomes of the design rules verification for the two most stressed paths (CD and IL). The rules for the other paths (not shown here) are all verified.

It can be observed that while the rules for pure primary (P) loads are verified on every path, this is not always true when also the membrane part of the secondary loads (Q_m) is taken into account as prescribed by the SDC-IC code in order to deal with the loss of ductility caused by irradiation.

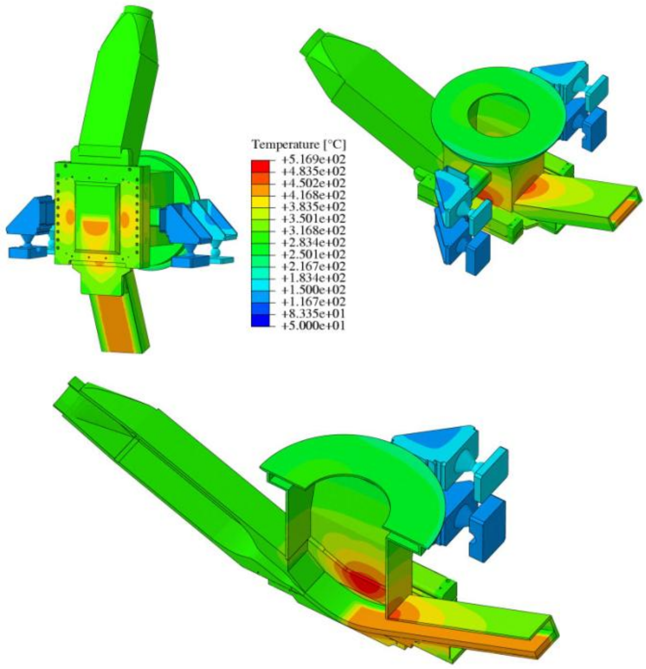

Fig. 10. Temperature distribution in the TA (hot scenario)

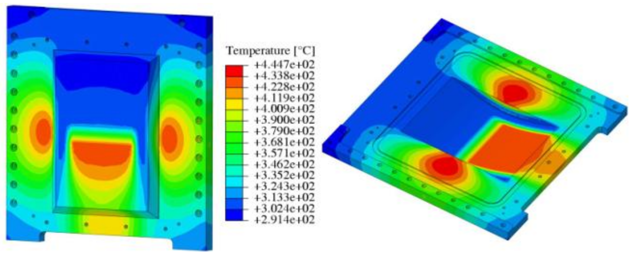

Fig. 11. Temperature distribution in the BP (hot scenario)

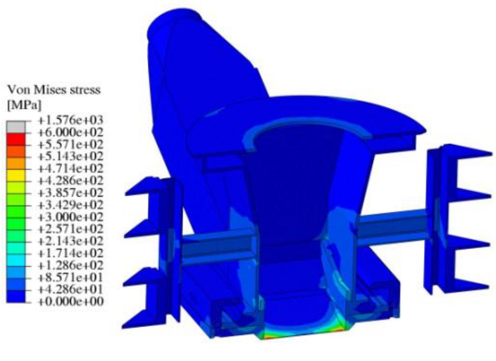

Fig. 12. Von Mises stress field in the TA (hot scenario)

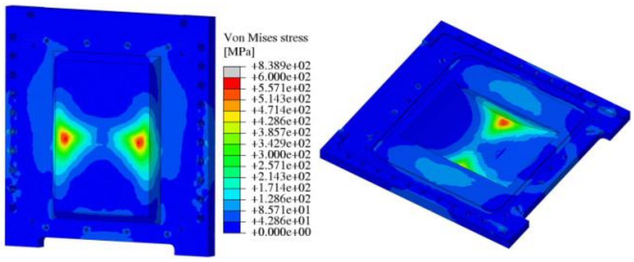

Fig. 13. Von Mises equivalent stress field in the BP (hot scenario)

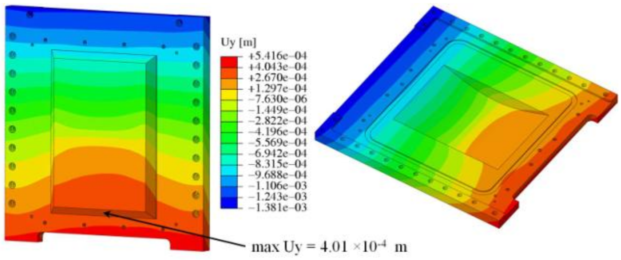

Fig. 14. Displacement field along beam direction in the BP (hot scenario)

TABLE III. STRESS LINEARIZATION – Path CD (hot scenario)

Calculated and allowable stress intensities			
T_m [°C]	S_m [MPa]	$K_{eff}S_m$ [MPa]	S_e [MPa]
252	174	261	303
	P_m	$P_m + P_b$	$P_m + Q_m$
	0.35	0.35	393.74
Rule verification			
P_m/S_m		2.0×10^{-3}	YES
$(P_m + P_b)/K_{eff}S_m$		1.3×10^{-3}	YES
$(P_m + Q_m)/S_e$		1.30	NO

TABLE IV. STRESS LINEARIZATION – Path IL (hot scenario)

Calculated and allowable stress intensities			
T_m [°C]	S_m [MPa]	$K_{eff}S_m$ [MPa]	S_e [MPa]
251	174	261	305
	P_m	$P_m + P_b$	$P_m + Q_m$
	0.39	0.43	554.59
Rule verification			
P_m/S_m		2.2×10^{-3}	YES
$(P_m + P_b)/K_{eff}S_m$		1.6×10^{-3}	YES
$(P_m + Q_m)/S_e$		1.82	NO

5. Conclusions

Within the framework of IFMIF/EVEDA engineering design activities, a collaboration has been launched between ENEA Brasimone and University of Palermo to investigate the thermomechanical behaviour of the bayonet TA, under two (hot and cold) design scenarios. The analysis has shown that:

- In the hot scenario, maximum temperatures of about 445 °C and 520 °C are reached in the BP and in the TA, respectively, which are within the acceptable limit for EUROFER steel. However, in the cold scenario, quite low temperatures are achieved which might bring the BP in the brittle state
- Maximum BP displacements in the beam direction allows to exclude the contact between BP and HFTM in both scenarios
- Thermomechanical stresses do not induce large scale yielding, thus proving the overall structural integrity of the system in both design cases
- Verification against SDC-IC design rules reveals that design criteria are not always met along critical paths at BP middle plane section in the hot scenario, thus suggesting the potential need of a design revision of the BP or a change of design operating conditions

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