Agenzia nazionale per le nuove tecnologie,
l'energia e lo sviluppo economico sostenibile

Ministero dello Sviluppo Economico


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Report RdS/PAR2014/058

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Settembre 2015

Report Ricerca di Sistema Elettrico
Accordo di Programma Ministero dello Sviluppo Economico - ENEA
Piano Annuale di Realizzazione 2014
Area: Produzione di Energia Elettrica e Protezione dell'Ambiente
Progetto: B.3.2 Attività di fisica della Fusione complementari a ITER
Obiettivo: B2
Responsabile del Progetto: Ing. Aldo Pizzuto, ENEA

# Indice

# 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 is a fundamental step towards the development of fusion energy. To this purpose, IFMIF (International Fusion Materials Irradiation Facility) represents the reference option to provide the fusion community with a source capable of irradiating samples at a damage rate of up to 20 dpa/fpy (in steel) in a volume of 0.5 l. This concept is based on a high-speed liquid lithium target which is stricken by a 10 MW double deuteron beam to produce 14 MeV-peaked neutrons. 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 under the EVEDA (Engineering Validation and Engineering Design Activities) phase of the IFMIF project 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 increase the limit on its lifetime imposed by the neutron-induced swelling effects. In the framework of the current Annual Realization Plan (*Piano Annuale di Realizzazione*, PAR 2014) of the ENEA-MSE Agreement, 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 in collaboration with the University of Palermo by means of a 3-D finite element (FE) model implemented through a qualified software package. A detailed neutronic analysis has been also performed using the MCNP code to obtain the prompt nuclear responses to be used as input for the thermo-mechanical calculations. Based on the results obtained from such analyses, an optimized BP configuration has been selected, which allows to safely withstand the termo-mechanical loadings acting at the end of the start-up phase and those imposed by the swelling phenomena during nominal irradiation period, thus demonstrating that the prescribed minimum requirement of one year of full power operation for the BP lifetime is met.

# 1 Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is a joint effort of the international scientific community within the framework of the Broader Approach Agreement established between Europe and Japan. IFMIF is an accelerator-based neutron source [1] which is devoted to test and qualify candidate materials to be used in future fusion reactors, allowing, in particular, the development of a material irradiation database for the design, construction, licensing and safe operation of the DEMO fusion power reactor. The IFMIF neutron source mainly consists of two 40 MeV continuous linear accelerators which deliver two 125 mA current beams of deuterons on a flowing liquid Lithium target, where D-Li stripping reactions take place, providing an intense neutron flux of about $10^{18}$ $nm^{-2}s^{-1}$ characterized by an energy spectrum peaked at 14 MeV, which enables materials testing up to a damage rate of more than 20 dpa/y [1]. With the aim of having a stable liquid Lithium flow, a target system, consisting of a Target Assembly (TA) properly integrated with a Lithium loop, has been designed. The TA is mainly devoted to create, within its removable component, called bayonet Back-Plate (BP), a stable Lithium jet flowing at a nominal speed of 15 m/s to remove the 10 MW heat power released by deuteron beams and produce the desired neutron flux. A detailed description of the Lithium loop layout and of the target assembly can be found in [1,2].

Over the last few years, an intense research activity has been performed by ENEA, in collaboration with the Department of Energy, Information Engineering and Mathematical Models (DEIM) of the University of Palermo, on the IFMIF TA, aimed at investigating its thermo-mechanical performances under both steady-state and transient loading scenarios [3-12]. In particular, the typical steady-state loading scenario relevant to the end of the IFMIF start-up phase, in which only thermo-mechanical loads are considered [6,7,9], and the transient nominal operational scenario simulating one year of neutronic irradiation, in which volumetric swelling strain is taken into account [6], have been mainly investigated as well as start-up and shut-down transient operational phases [8] and the steady-state scenarios under design loading conditions [10]. During these analyses campaigns, attention has been particularly paid to the BP, since it represents the TA most critical component as it houses the deuterons-lithium interactions which originate the neutrons.
For this reason, one of the most important goals of the IFMIF TA design activity is the prediction of the BP lifetime. Results obtained from the previous research campaigns [9], performed considering the thermo-mechanical loads at the end of the TA start-up phase (namely without taking into account the swelling effects) and adopting the ITER SDC-IC (Structural Design Criteria for In-vessel Components) as reference structural design code, show that the prescribed design criteria are not completely fulfilled within the BP. This suggests that a design review is needed in such a way that the BP is able to safely withstand the thermo-mechanical loads it undergoes at the end of start-up phase and, moreover, that its lifetime can be extended to at least one year of full power irradiation which represents the minimum requirement envisaged for it.

Based on these outcomes, within the framework of the present Annual Realization Plan (*Piano Annuale di Realizzazione*, PAR 2014) of the ENEA-MSE Agreement, a new research campaign has been launched by ENEA Brasimone in collaboration with the DEIM Department of the University of Palermo [12] with the aim of selecting a BP geometric configuration able to safely withstand the thermo-mechanical loads it undergoes at the end of the start-up loading scenario and, at a later stage, during one year of full power operation.

This research campaign has been articulated in two separate stages.
In the first stage, a parametric study has been carried out in order to select a potential BP geometric configuration able to safely withstand the thermo-mechanical loads foreseen at the end of the TA start-up transient. Once selected the potential BP optimized configuration, a neutronic analysis has been performed on the TA equipped with it in order to calculate the spatial distributions of the nuclear heat power density and of the irradiation damage (DPA). These distributions have then been adopted in the second stage of the research campaign, aimed at investigating the thermo-mechanical behaviour of the potential BP optimized configuration when subjected to nominal operating conditions in terms of neutron-induced volumetric swelling strain fields.
All the thermo-mechanical analyses have been performed following a theoretical-computational approach based on the Finite Element Method (FEM) implemented through a qualified commercial software package.

# 2 Thermomechnical analyses of the Back-Plate

Thermo-mechanical analyses performed over the last years on the IFMIF TA have put into evidence that a BP design review is needed, in order to identify a BP geometric configuration able to safely withstand the loading conditions imposed by both steady-state thermo-mechanical loads at the end of the TA start-up procedure and by the swelling-induced deformation rate occurring during the nominal irradiation period, so as to maximise the BP operating lifetime.
To this purpose, a research campaign aimed at the BP geometric optimization has been launched by ENEA in close cooperation with the DEIM Department of the University of Palermo within the framework of the present Annual Realization Plan (*Piano Annuale di Realizzazione*, PAR 2014) of the ENEA-MSE Agreement. This research campaign has been articulated in two main stages.
In the first stage, a parametric approach has been followed in order to assess the potential influence of some critical geometric parameters on the thermo-mechanical performances of the BP, focusing the attention on the stress field arising within the BP.
In the second stage, thermo-mechanical analysis of the IFMIF TA endowed with the potential BP optimized configuration, selected at the end of the previous stage, has been performed, adopting the volumetric density of nuclear heat power and the irradiation damage (DPA) spatial distributions purposely calculated by ENEA by means of a Monte Carlo neutronic analysis performed through the MCNP code taking into account a geometric domain representing the TA equipped with the selected optimized BP.
The thermo-mechanical behaviour of the different BP configurations has been investigated by performing a post-processing stress linearization procedure in a proper set of paths located within the most critical BP regions and checking the fulfilment of the SDC-IC design criteria [13].
In particular, since the design of TA has to be based on a consistent set of rules taking into account requirements specific to irradiated components, the stress linearization procedure established in the ITER SDC-IC code has been carried out. This procedure foresees to evaluate the general and local primary membrane stress tensor ($P_m$ and $P_L$), the primary bending stress tensor ($P_b$), the general and local secondary membrane stress tensor ($Q_m$ and $Q_L$) and the peak stress tensor (F) in some particularly significant paths of the TA.
The calculated stress values have thus been used to verify whether the TA thermo-mechanical stress state

complies with the requirements prescribed by SDC-IC rules [13], that are comprehensive of all possible damage modes against which the component is protected within the highest level of criteria foreseen (level A criteria) in the code. In particular, in SDC-IC, as in conventional codes, primary stresses are limited in order to guarantee the components against M (monotonic) type damages, while secondary stresses are limited to preserve them against C (cyclic) type damages, namely the progressive deformation and the time independent fatigue [14].

As to level A, in case that thermal-activated phenomena (e.g., thermal creep) can be neglected, the following low temperature rules are imposed by SDC-IC code in order to protect components against M type damages [13]:

$$\overline{P_m} \le S_m(T_m, \Phi t_m)$$

$$\overline{P_L + P_b} \le K_{eff} S_m(T_m, \Phi t_m)$$

$$\overline{P_L} \le \min\left[1.5 S_m(T_m, \Phi t_m), S_{y,min}(T_m, \Phi t_m)\right] \quad \text{(in local non-overlapping areas)}$$

$$\overline{P_L} \le 1.1 S_m(T_m, \Phi t_m) \quad \text{(in local overlapping areas)}$$

where $\overline{P_m}$ is the general primary membrane stress intensity, $\overline{P_L}$ is the local primary membrane stress intensity, $\overline{P_L + P_b}$ is the stress intensity of the sum of the aforementioned tensors $P_L$ and $P_b$, $K_{eff}$ is an effective bending shape factor depending on the resisting section, $S_m$ is the allowable stress limit depending on thickness averaged temperature $T_m$ and neutron fluence $\Phi t_m$ and $S_{y,min}$ is the minimum tensile yield strength depending on thickness averaged temperature $T_m$ and neutron fluence $\Phi t_m$ as well.

Conventional design codes do not take into account secondary stresses (e.g., thermal stresses) when M type damages are verified since usually material ductility allows to accommodate these stresses. Anyway, since materials typically lose their ductility and become brittle when subjected to neutronic irradiation, some further rules have been included in SDC-IC code to properly take into account this phenomenon [14]. In particular, SDC-IC defines two different modes of potential failure due to the limited ductility of the materials: immediate plastic flow localisation and immediate local fracture due to exhaustion of ductility. The relevant design rules envisaged for these failure modes are [13]:

$$\overline{P_L + Q_L} \le S_e(T_m, \Phi t_m) \quad \text{immediate plastic flow localisation}$$

$$\overline{P_L + P_b + Q + F} \le S_d(T, \Phi t, r_2) \quad \text{immediate local fracture due to exhaustion of ductility}$$

$$\overline{P_L + P_b + Q} \le S_d(T, \Phi t, r_3) \quad \text{immediate local fracture due to exhaustion of ductility}$$

where $S_e$ is the allowable stress intensity dependent on thickness averaged temperature $T_m$ and neutron fluence $\Phi t_m$ and $S_d$ is the allowable stress dependent on r-factors, temperature T and neutron fluence $\Phi t$ at the point under consideration where localized stress arises. Analytical definitions of r-factors, $S_e$ and $S_d$ functions are reported in [13-15]. It has to be underlined that, given that irradiated EUROFER retains considerable ductility after necking, the potential failure mode due to immediate local fracture is not an issue, while that induced by immediate plastic flow localisation may be a matter of serious concern [16].

The first phase of the present PAR 2014 research activity has been aimed at optimizing, from the geometric standpoint, the BP design in order to attain a BP geometric configuration able to fulfil all the level A SDC-IC design rules with a margin such to guarantee, after the irradiation period, a lifetime of one year of full

power operation for the BP.
To this purpose, a proper set of stress paths (Figure 1), located within the most critical regions of the domain investigated, has been selected on the basis of the previous IFMIF thermo-mechanical analyses [9], as the starting point for the BP geometric optimization procedure.

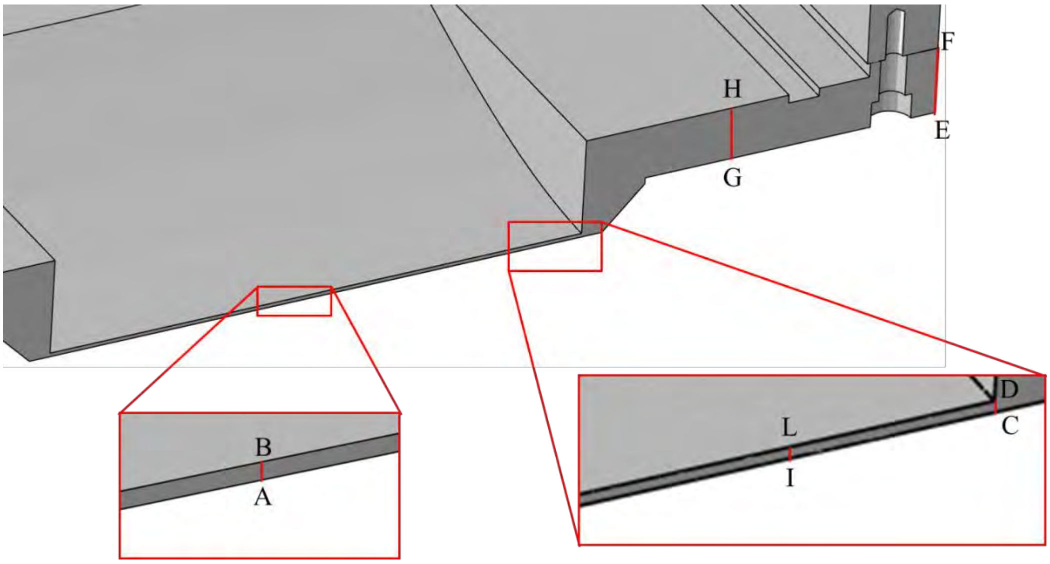


Figure 1. Stress paths taken into account for stress linearization procedure

The results, in terms of level A SDC-IC design rules fulfilment, obtained from the thermo-mechanical analysis carried out in the past considering steady state loads and boundary conditions relevant to the end of the start-up phase are reported in Table 1.
Firstly, it can be observed that, being the maximum temperature achieved in all the stress linearization paths considered less than 450 °C, the thermal-activated phenomena can be neglected [16] and, consequently, the fulfilment of the pertinent design rules have not been checked.
Secondly, the results have highlighted the necessity of a BP design review procedure aimed to set-up a geometric configuration able to safely withstand the thermo-mechanical loadings it undergoes at the end of the start-up phase with a margin such that its lifetime under neutronic irradiation can be possibly extended to one full power year of operation.
In fact, from Table 1, it can be observed that level A SDC-IC design criteria are not fulfilled, at the end of the start-up scenario, along paths CD and IL, approximately located within the lithium channel edges region. The $(P_m+Q_m)/S_e$ value of 1.5738 achieved in path IL is particularly significant, because this path is located within the BP most stressed region, and further reinforce the necessity of a BP design review strategy aimed at reducing the amount of stress within the BP at the end of the start-up phase (when the swelling effects are not yet present), so that it can be possible to extend the BP lifetime under neutronic irradiation, when the swelling effects significantly arise, up to the ideal goal of one year of full power operation envisaged for it.
The objective of the review analysis is therefore to identify an optimized BP configuration which ensures a minimization of the stress values arising within the BP due to thermo-mechanical loadings acting during the start-up phase and the fulfilment of the SDC-IC design criteria (level A) both at the end of the start-up transient and after the steady-state irradiation phase.

Table 1. Results of stress linearization procedure for the original (non-optimized) BP design

| | Path AB | Path CD | Path EF | Path GH | Path IL |
|---|---|---|---|---|---|
| $T_{Max\text{-}Path}$ | 282.70 | 251.50 | 346.10 | 397.10 | 250.60 |
| **Level A criteria** | | | | | |
| $P_m / S_m$ | 0.0035 | 0.0026 | 0.0004 | 0.0004 | 0.0020 |
| $(P_m + P_b) / K_{eff}{*}S_m$ | 0.0026 | 0.0018 | 0.0004 | 0.0004 | 0.0013 |
| $(P_m + Q_m) / S_e$ | 0.7835 | 1.3507 | 0.2603 | 0.5536 | 1.5738 |

## 2.1 Parametric steady-state analysis

As first stage of the BP design revision, a campaign of parametric analyses has been launched in order to optimize the BP thermo-mechanical performances under TA nominal conditions (but without swelling effects) which characterize the system at the end of the start-up phase.

The analysis has been performed adopting the latest 3D model of the IFMIF TA developed by ENEA, shown in Figure 2.

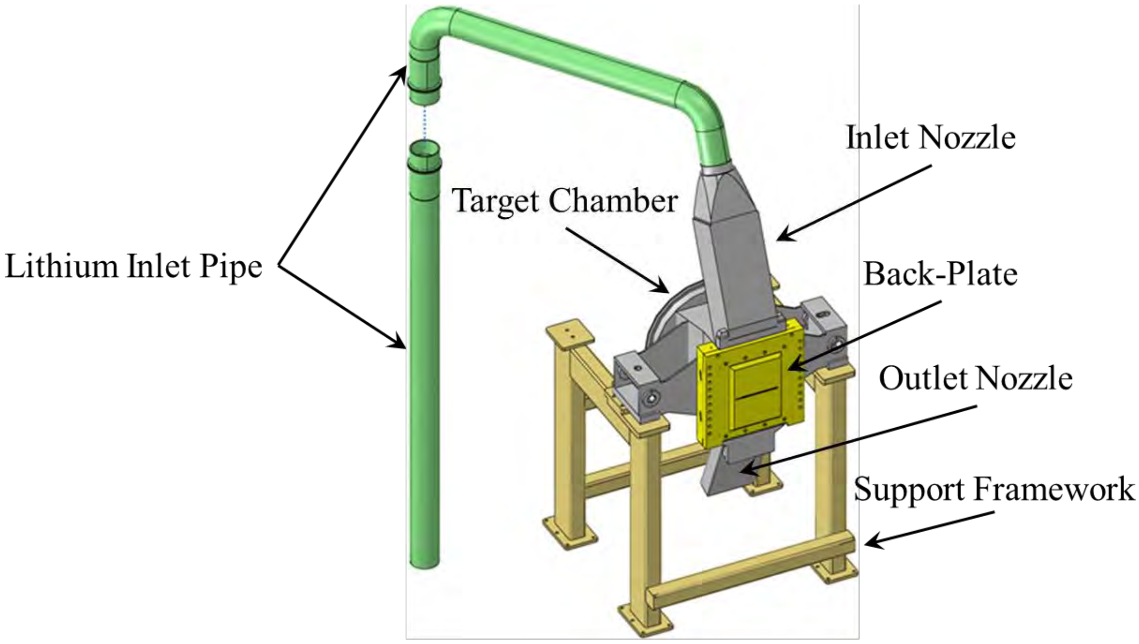


Figure 2. Latest 3D model of the IFMIF TA considered in the analysis

As a first step, the following two design review strategies have been considered in order to optimize the BP thermo-mechanical performances under its nominal conditions:

- increase of the BP lithium channel thickness
- reduction of the BP thickness

In order to assess the potential effects of each strategy, a specific parametric analysis has been carried out, following a theoretical-computational approach based on the Finite Element Method (FEM) by means of a qualified commercial code.
To this purpose, realistic 3D FEM models of the revised BP configurations considered have been set up and proper uncoupled steady state thermo-mechanical analyses have been performed, assuming the loading conditions of the nominal operational scenario. The TA system has been simulated using the FE model described in [9]. A stress linearization procedure has been carried out on the selected paths (Figure 1) at the BP midplane section and attention has been paid to verify whether SDC-IC safety criteria (Level A) were fulfilled.

The original thickness of the BP lithium channel (S = 1.8 mm) has been increased to assess the influence of the added thickness (W) on the overall BP thermo-mechanical performances. Values of the W parameter ranging between 1.0 and 1.7 mm have been considered (Figure 3).

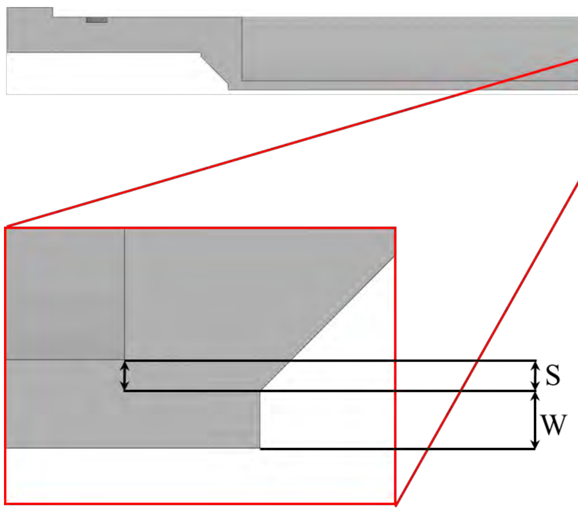


Figure 3. Increase of the BP lithium channel

On the other hand, the original thickness (D) of the BP  has been reduced to assess its effect on the overall BP thermo-mechanical performances. Values of the D parameter ranging between 12.8 mm and 17.8 mm have been considered, corresponding to a D reduction from 20 mm to 15 mm, respectively (Figure 4).

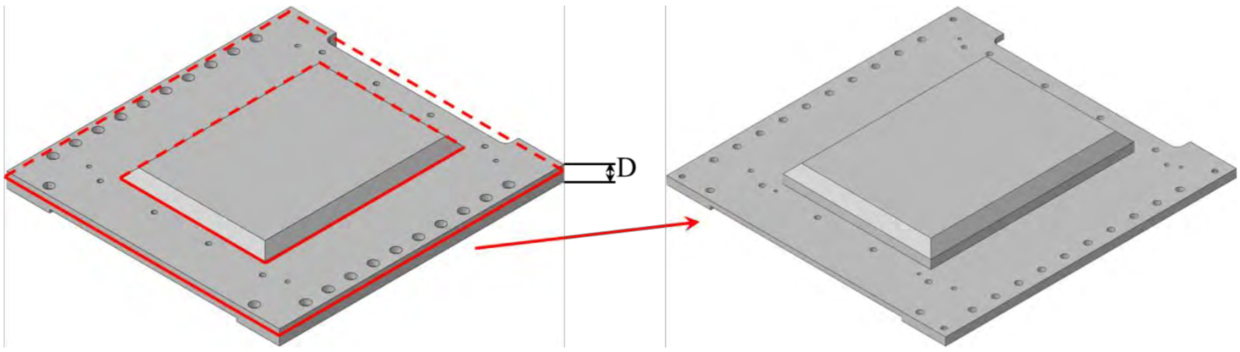


Figure 4. Reduction of the BP thickness

In order to set up the 3D FEM models, 8 different values of the W parameter have been taken into account while, regarding the D parameter, 6 different values have been considered.
The parameters values (in m) selected are reported below.

$$W = \begin{cases} 0.0010 \\ 0.0011 \\ 0.0012 \\ 0.0013 \\ 0.0014 \\ 0.0015 \\ 0.0016 \\ 0.0017 \end{cases} \qquad D = \begin{cases} 0.0128 \\ 0.0138 \\ 0.0148 \\ 0.0158 \\ 0.0168 \\ 0.0178 \end{cases}$$

Adopting these values, 48 BP different geometric configurations have been identified and a proper 3D FEM model has been developed for each of them. The thermo-mechanical parametric analyses have shown that, among all the 48 different configurations investigated, two BP configurations may be selected as the reference ones (Figure 5).
The first one, named Case 18, is characterized by a BP total thickness (D) of 12.8 mm and an additive thickness (W) of the lithium channel equal to 1.2 mm, which leads to a total lithium channel thickness of 3.0 mm. The second one, named Case 48, foresees a D value of 12.8 mm and a W value of 1.7 mm.

The Results obtained for these two geometric configurations are reported in terms of SDC-IC design rules verifications in Tables 2 and 3.

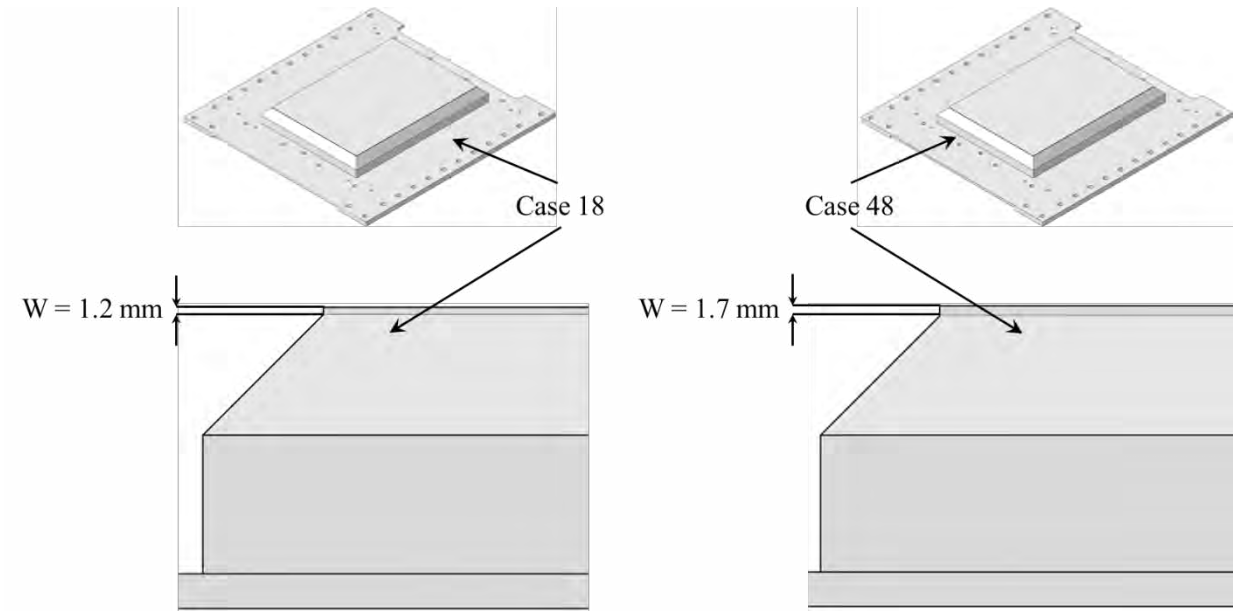


Figure 5. Potential optimized BP configurations selected from the parametric analysis

Table 2. Stress linearization results for Case 18

| | Path AB | Path CD | Path EF | Path GH | Path IL |
|---|---|---|---|---|---|
| $T_{Max\text{-}Path}$ | 283.4 | 251.8 | 264.2 | 362.1 | 252.6 |
| **Level A criteria** | | | | | |
| $P_m / S_m$ | 0.0017 | 0.0011 | 0.0008 | 0.0007 | 0.0014 |
| $(P_m + P_b) / K_{eff}*S_m$ | 0.0017 | 0.0008 | 0.0006 | 0.0006 | 0.0009 |
| $(P_m + Q_m) / S_e$ | 0.1530 | 0.9123 | 0.2276 | 0.6236 | 1.1245 |

Table 3. Stress linearization results for Case 48

| | Path AB | Path CD | Path EF | Path GH | Path IL |
|---|---|---|---|---|---|
| $T_{Max\text{-}Path}$ | 284.5 | 252.1 | 264.2 | 362.1 | 253.1 |
| **Level A criteria** | | | | | |
| $P_m / S_m$ | 0.0017 | 0.0013 | 0.0007 | 0.0022 | 0.0016 |
| $(P_m + P_b) / K_{eff}*S_m$ | 0.0016 | 0.0009 | 0.0005 | 0.0015 | 0.0011 |
| $(P_m + Q_m) / S_e$ | 0.1181 | 0.8794 | 0.2255 | 0.6238 | 1.0516 |

Tables 2 and 3 show that the rule $(P_m+Q_m)/S_e$ is not fulfilled along path IL.
Moreover, the results obtained for the Case 48 seem to be more encouraging than those relevant to Case 18, due to the thicker BP lithium channel. In conclusion, in order to optimize the BP thermo-mechanical performances, the results clearly indicate the need to focus the attention on the configuration named Case 48 and, at the same time, to adopt a different and more complex design review strategy involving all the TA components, especially those adjacent to the BP, in order to limit its stress values.
To this aim, the following further design review strategies have been taken into account:

- reduction of the BP lithium channel lateral thickness;
- BP external surface finning;
- reduction of the Target Chamber (TC) lithium guides thickness.

The first BP design review strategy taken into account has resulted in a halving of the BP lithium channel lateral thickness (LT), as shown in figure 6.

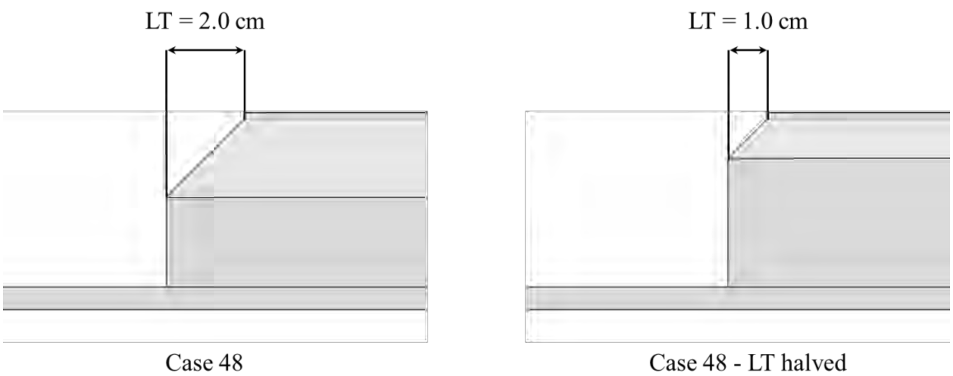


Figure 6. Halving of the BP lithium channel lateral thickness

Table 4. Stress linearization results for Case 48 with LT halved

| | Path AB | Path CD | Path EF | Path GH | Path IL |
|---|---|---|---|---|---|
| $T_{Max-Path}$ | 285.6 | 251.5 | 266.5 | 369.8 | 252.7 |
| **Level A criteria** | | | | | |
| $P_m / S_m$ | 0.0017 | 0.0011 | 0.0009 | 0.0008 | 0.0012 |
| $(P_m + P_b) / K_{eff}{*}S_m$ | 0.0012 | 0.0008 | 0.0006 | 0.0007 | 0.0009 |
| $(P_m + Q_m) / S_e$ | 0.0427 | 0.8096 | 0.2480 | 0.6636 | 1.0243 |

The results shown in table 4 have suggested that the strategy adopted is encouraging, therefore the effect of a further LT reduction has been investigated. Thus, a further reduction of the BP lithium channel lateral thickness down to 0 cm (LT = 0) has been studied (Figure 7).

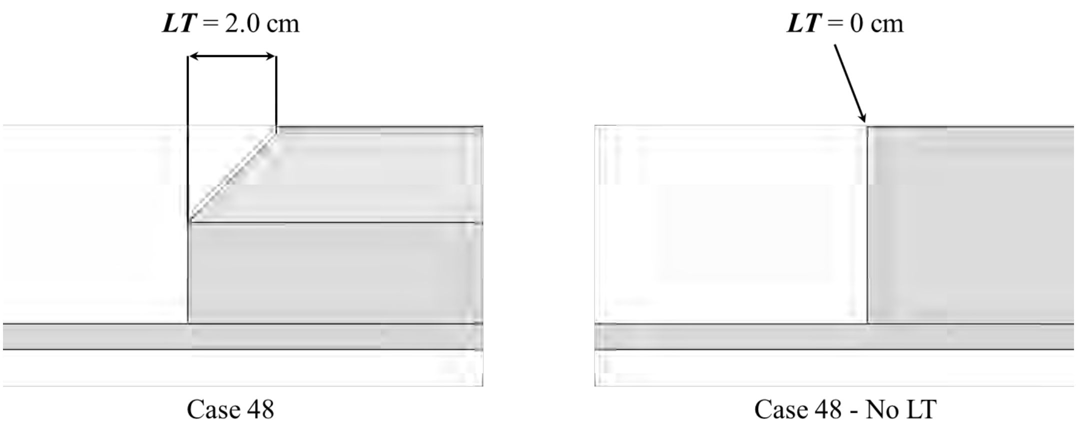


Figure 7. Reduction to 0 of the BP lithium channel lateral thickness

The Results show that the further reduction of the BP lithium channel lateral thickness down to 0 cm (LT = 0) leads to a significant reduction of the $(P_m + Q_m)/S_e$ value (Table 5). However, since $(P_m + Q_m)$/Se ratio still remains close to unity along path IL, thus leaving a small margin for the successive swelling-induced stresses, a further BP design review strategy has been considered.

Table 5. Stress linearization results for Case 48 with LT=0

| | Path AB | Path CD | Path EF | Path GH | Path IL |
|---|---|---|---|---|---|
| $T_{Max-Path}$ | 284.9 | 250.2 | 270.5 | 383.0 | 252.5 |
| **Level A criteria** | | | | | |
| $P_m / S_m$ | 0.0021 | 0.0015 | 0.0007 | 0.0011 | 0.0015 |
| $(P_m + P_b) / K_{eff}{*}S_m$ | 0.0018 | 0.0011 | 0.0006 | 0.0008 | 0.0012 |
| $(P_m + Q_m) / S_e$ | 0.0384 | 0.8007 | 0.2666 | 0.6298 | 0.9834 |

In particular, the abovementioned thermo-mechanical results have highlighted that the most critical SDC-IC criterion is the one concerned with the $(P_m + Q_m)/S_e$ ratio. In fact, it has been observed that high stress values are mainly due to the intense thermal gradient arising within the BP body. Therefore, in order to minimize this thermal gradient, the finning of the BP external surface has been taken into account as a further design review strategy.
As a consequence of a dedicated parametric study, not reported here for the sake of brevity, two batches of 115 fins have been assumed on the external surface of the "Case 48 with LT=0" BP geometric configuration (Figure 8), assessed in the previous thermo-mechanical analysis, and a proper 3D revised TA FEM model has been set up to investigate the steady state thermo-mechanical performances of the resulting finned BP configuration under nominal loading conditions.

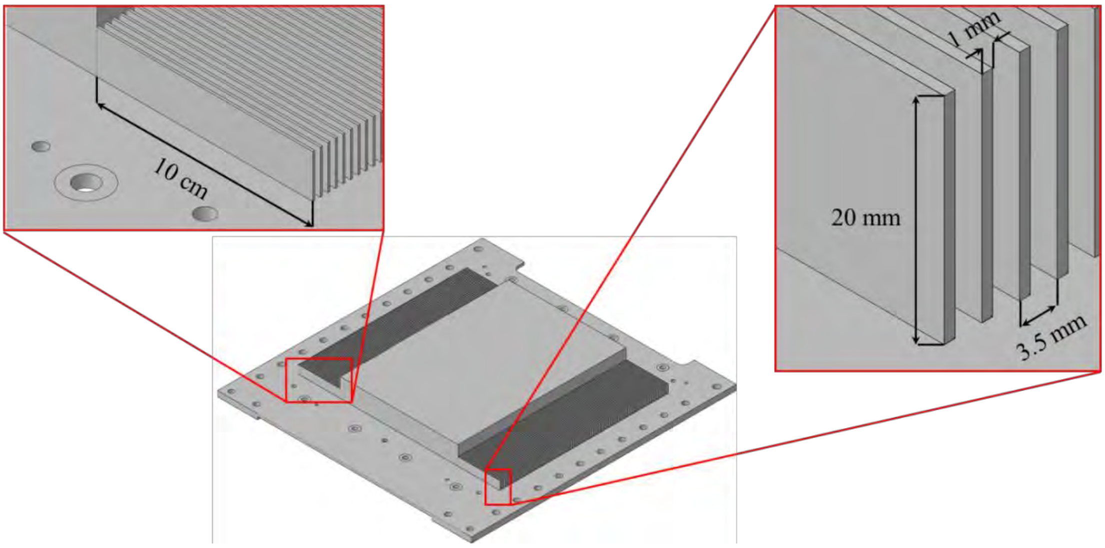


Figure 8. BP external surface finning

From the thermal point of view, the introduction of two batches of fins onto the BP external surface leads to a considerable reduction of the temperature values achieved within the component, so reducing the thermal gradients arising within the BP.
From the mechanical point of view, the results show that a significant reduction of $(P_m + Q_m)/S_e$ values occurs within the paths EF and GH, due to a remarkable temperature decrease within the regions where they are located. As to the paths CD and IL, only a slight reduction of $(P_m + Q_m)/S_e$ values can be observed (Table 6).

Table 6. Stress linearization results for Case 48 with LT=0 and external finned surface

| | Path AB | Path CD | Path EF | Path GH | Path IL |
|---|---|---|---|---|---|
| $T_{Max\text{-}Path}$ | 284.9 | 250.2 | 245.0 | 325.3 | 252.5 |
| **Level A criteria** | | | | | |
| $P_m / S_m$ | 0.0021 | 0.0014 | 0.0006 | 0.0010 | 0.0015 |
| $(P_m + P_b) / K_{eff}*S_m$ | 0.0017 | 0.0010 | 0.0004 | 0.0007 | 0.0011 |
| $(P_m + Q_m) / S_e$ | 0.0542 | 0.7014 | 0.1691 | 0.3446 | 0.9252 |

Therefore, the introduction of the finning can be considered to have a positive impact on the BP thermo-mechanical performances, even if a further design review strategy seems to be necessary. In particular, it has been observed that a large amount of heat power is deposited by neutrons and gammas within the volume of the Target Chamber (TC) lithium guides, giving a strong contribution to the BP heating.
Therefore, a reduction of the TC lithium guides volume (Figure 9) has been taken into account as an additional design review strategy, to be implemented together with all those considered so far.

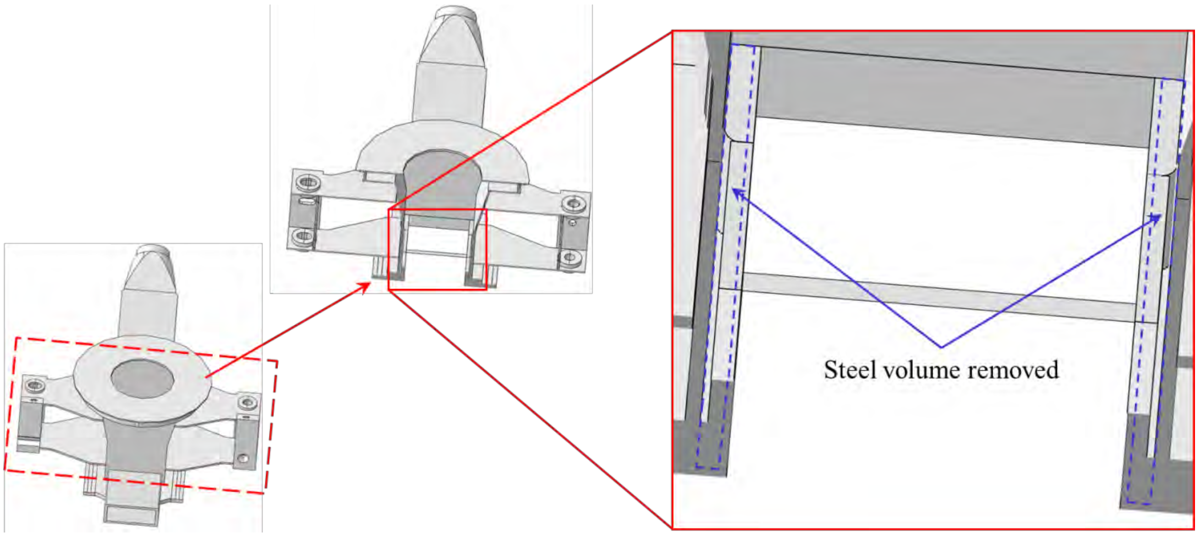


Figure 9. Reduction of the TC lithium guides thickness

From the thermal point of view, the reduction of the TC lithium guides thickness allows to predict a decrease of the maximum temperature achieved within the BP of about 20 °C (Figure 10).
From the mechanical point of view, stress linearization results show that a significant reduction of $(P_m+Q_m)/S_e$ values occurs within all the paths considered (Table 7), as a result of the minimization of the stresses in the BP (Figure 11).

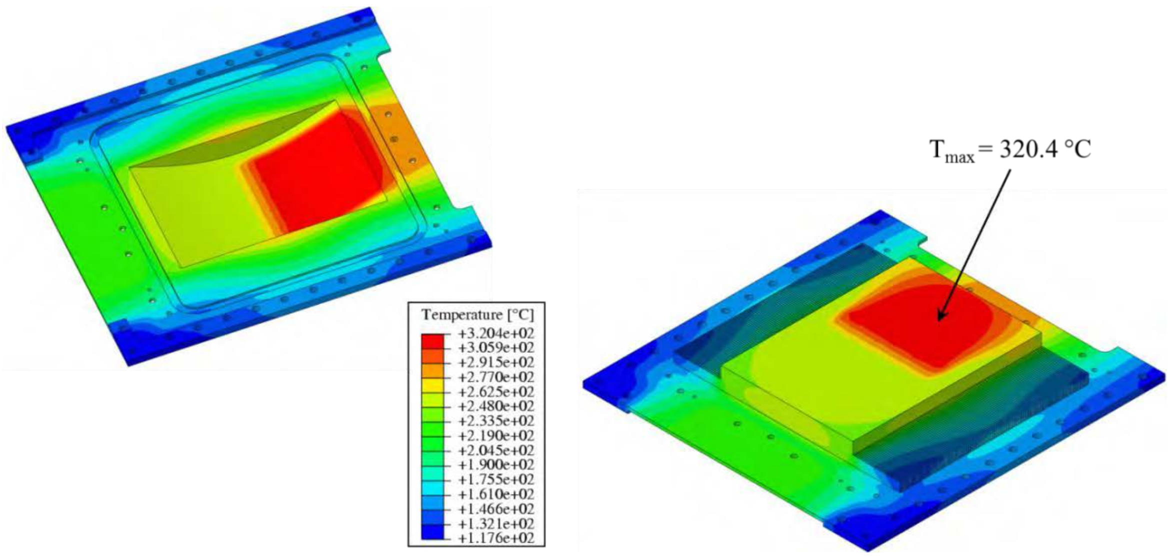


Figure 10. Thermal field in the optimized BP with LT=0, external finned surface and Li guides thickness reduction

Table 7. Stress linearization results for optimized BP with LT=0, external finned surface and Li guides thickness reduction

| | Path AB | Path CD | Path EF | Path GH | Path IL |
|---|---|---|---|---|---|
| $T_{Max\text{-}Path}$ | 282.4 | 250.3 | 153.8 | 214.7 | 267.9 |
| **Level A criteria** | | | | | |
| $P_m$ / $S_m$ | 0.0023 | 0.0012 | 0.0003 | 0.0007 | 0.0017 |
| $(P_m + P_b)$ / $K_{eff}*S_m$ | 0.0017 | 0.0009 | 0.0002 | 0.0005 | 0.0011 |
| $(P_m + Q_m)$ / $S_e$ | 0.3278 | 0.4170 | 0.1142 | 0.4266 | 0.7705 |

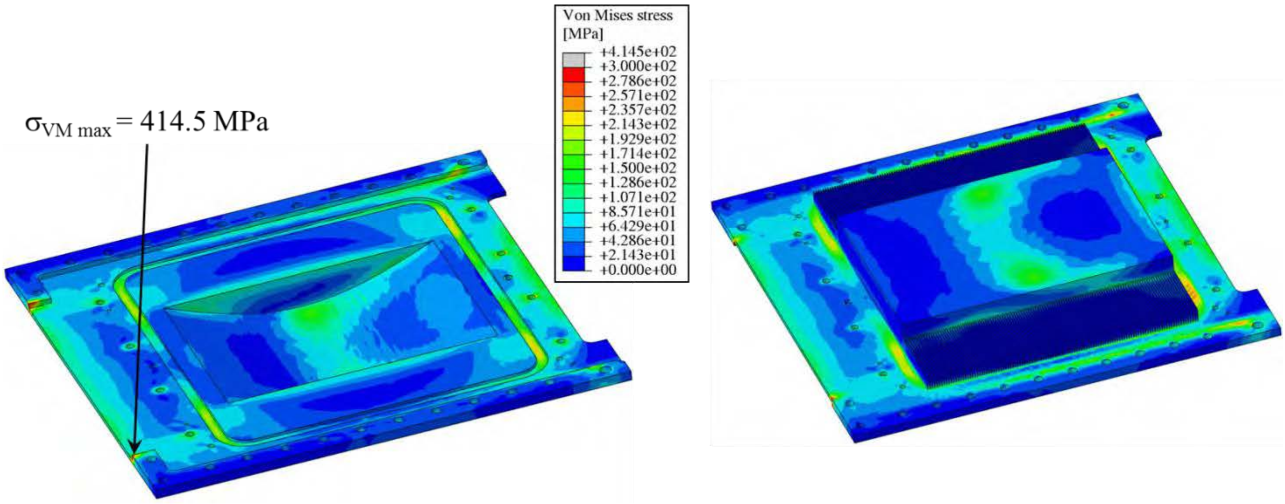


Figure 11. Von Mises stress field in the optimized BP with LT=0, external finned surface and Li guides thickness reduction

Thus, it can be concluded that the set of modifications adopted for the BP configuration leads to a strong reduction of the predicted BP average temperature. From the mechanical point of view, all the SDC-IC design criteria are largely fulfilled within all the paths considered.

## *2.2 Transient swelling analysis under nominal irradiation conditions*

Once assessed a BP geometric configuration that ensures, under nominal loading conditions, the total fulfilment of the relevant SDC-IC criteria, a transient thermo-mechanical analysis has been performed in order to investigate the effect of the volumetric swelling strain on the lifetime of such optimized BP configuration.

Mechanical and thermal loads as well as interactions and boundary conditions adopted to simulate the TA thermo-mechanical behaviour under the irradiation loading scenario are the same as those considered for the simulation of the TA at the end of the start-up phase, already described in the previous section [9].
In addition to these loads, the volumetric swelling strain field, arising within the BP as a result of a set of complex microscopic processes that typically take place when neutrons interacts with structural material

nuclei, has been imposed. In particular, the volumetric swelling strain field has been calculated imposing a linear dependence of the swelling strain on the dpa level only (at a fixed temperature of 400 °C)[17] and, moreover, assuming that after one year of neutronic irradiation the swelling strain value achieved at the beam footprint centre amounts to 0.75 %, which corresponds to the dpa value (~57 dpa) calculated at the same point by the neutronic analysis.
In order to set up the volumetric swelling strain field, the dpa spatial distribution calculated through the neutronic analysis for BP and TA geometric domains has been adopted while, fir the support framework and the lithium inlet pipe, a $1/r^2$ dependence has been supposed instead. The spatial distribution of the volumetric swelling strain reached after one full power year is reported in Figures 12-13.

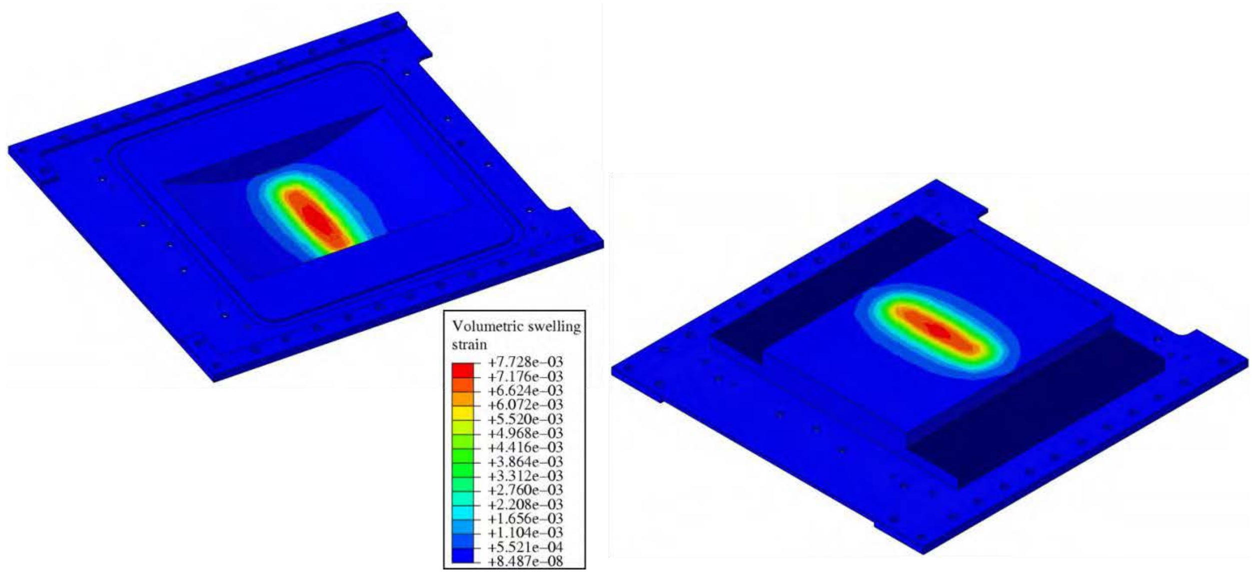


Figure 12. Volumetric swelling strain field in the optimized BP after one full power year operation

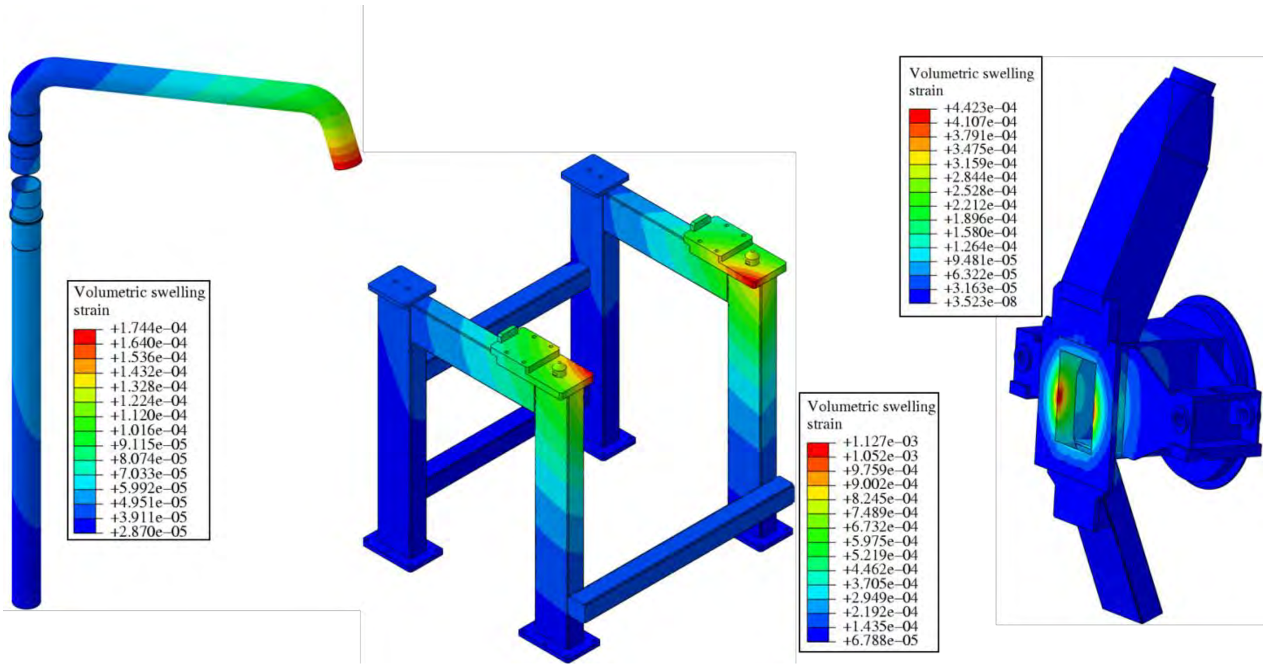


Figure 13. Volumetric swelling strain field in the TA components after one full power year operation

The time evolution of the stresses in the BP due to the swelling phenomena are illustrated in Figure 14 which shows the change of the $(P_m+Q_m)/S_e$ rule as a function of the accumulated swelling strain at the footprint center. Accumulated strain (or, equivalently, time) corresponding to $(P_m+Q_m)/S_e$ equal to unity represents the estimated lifetime of the BP. As this threshold is reached first in the path AB for a swelling strain of about 0.4%, this indicates that the BP lifetime is supposed to be around 6 months when temperature-dependence is not considered for the swelling law.

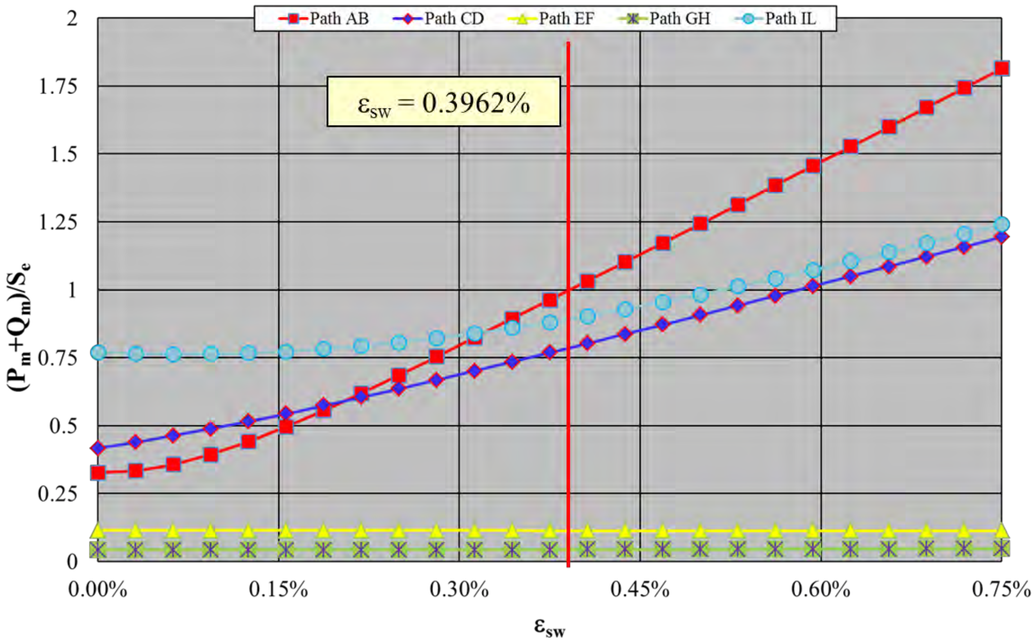


Figure 14. Evolutions of the stresses in the BP in terms of $(P_m+Q_m)/S_e$ rule as a function of the accumulated swelling strain at the footprint center

As a further step, the effect of temperature on the swelling strain has been taken into account. To do so, in accordance with experimental data reported in [18], the uniquely DPA-dependent swelling strain relationship ε(DPA) used before, have been properly scaled by means of a purposely set up temperature-dependent weight function ω(T). It has been thereby possible to introduce the volumetric swelling strain dependence on temperature T, defining the ε(DPA,T) swelling strain values as follows:

$$\varepsilon(DPA,T) = \omega(T) \cdot \varepsilon(DPA)$$

According to the aforementioned experimental data [18] and imposing a linear dependence of swelling on temperature, ω(T) has been assumed to be 0 for temperature values less than 360 °C, while ω(T) = 1 at T= 400 °C. For temperatures above 400 °C, experimental data show a decreasing of the volumetric swelling strain.

Since thermal analysis allows to predict a maximum BP temperature equal to 320 °C, it can be observed (Figure 15) that no swelling occurs within the BP when temperature effect on the dislocations and vacancies dynamics is taken into account.

The time evolution of the stresses in the BP due to the swelling effects, when the dependence on temperature is considered, is shown in Figure 16 where the $(P_m+Q_m)/S_e$ rule is plotted as a function or the accumulated swelling strain at the footprint centre. As it can be seen, the variation in each path is negligible and the curves remain always below unity which means that the failure threshold is never reached, i.e. the BP is expected to survive for the entire year of full power operation.

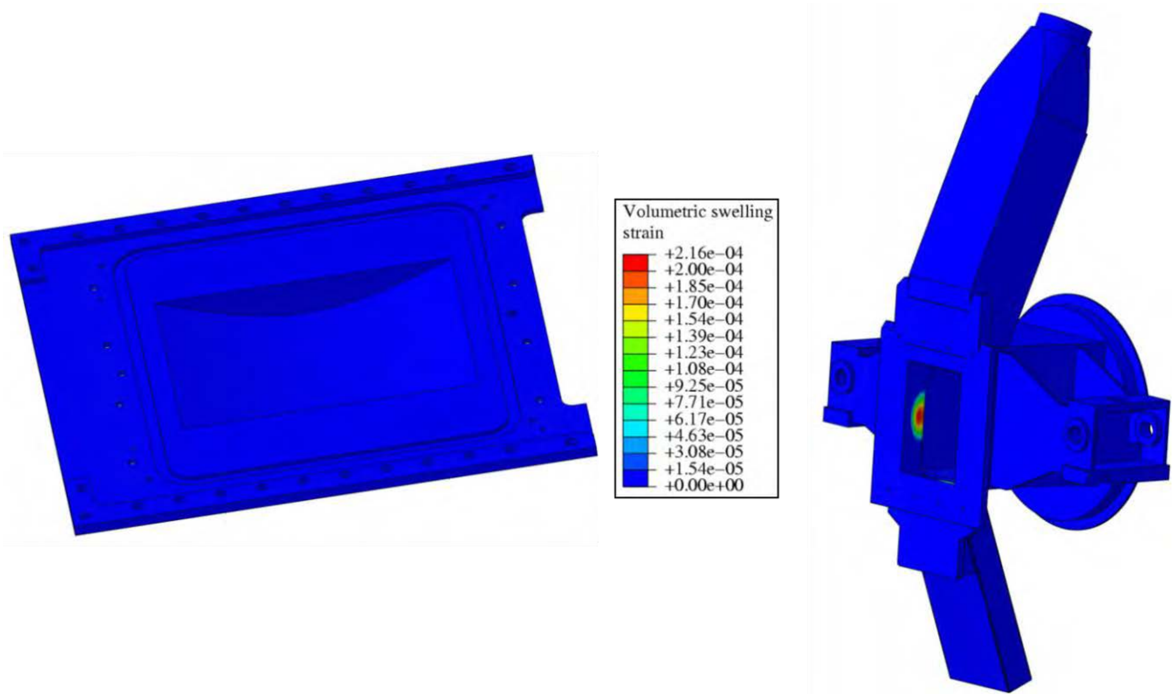


Figure 15. Temperature-dependent volumetric swelling strain field in the TA after one full power year operation

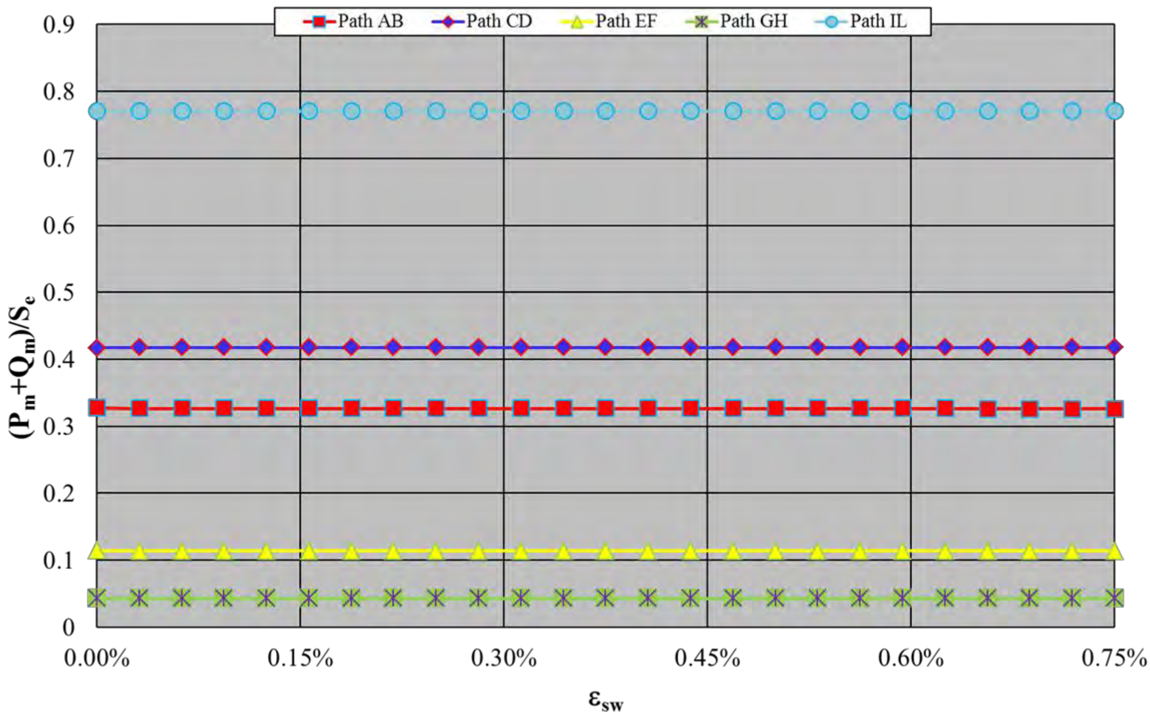


Figure 15. Evolutions of the stresses in the BP in terms of $(P_m+Q_m)/S_e$ rule as a function of the accumulated swelling strain at the footprint centre assuming temperature-dependent volumetric swelling strain

# 3 Conclusions

In the framework of the present Annual Realization Plan (*Piano Annuale di Realizzazione*, PAR 2014) of the ENEA-MSE Agreement, a research campaign has been launched by ENEA in collaboration with the DEIM Department of the University of Palermo with the aim of selecting a BP geometric configuration for the IFMIF TA able to safely withstand the thermo-mechanical loads it undergoes at the end of the start-up loading procedure and, at a later stage, during one year of full power irradiation under nominal operating conditions. This research campaign has been articulated in two separate stages.

In the first stage, a parametric study has been carried out in order to select a potential BP geometric configuration able to safely withstand the thermo-mechanical loads foreseen at the end of the TA start-up transient. Once selected a potential BP optimized configuration, a neutronic analysis has been performed on the TA equipped with it in order to calculate the spatial distributions of the nuclear heat power density and of the irradiation damage (DPA). These distributions have then been adopted in the second stage of the research campaign aimed at investigating the thermo-mechanical behaviour of the potential BP optimized configuration when subjected to nominal operating conditions in terms of neutron-induced volumetric swelling strain fields.

All the thermo-mechanical analyses have been performed following a theoretical-computational approach based on the Finite Element Method (FEM) implemented through a qualified commercial software package.

At the end of the parametric study, an optimized BP configuration has been determined following various optimization strategies (increase of the BP lithium channel thickness, reduction of the BP thickness, elimination of the lithium channel lateral thickness; finning of the BP external surface; reduction of the Target Chamber lithium guides thickness). This BP optimized configuration has then been analysed by simulating a full power year operation considering the swelling effects as a function of both irradiation damage and temperature.

The results have shown that, according to the reference design code ITER SDC-IC, no failure of the BP is predicted during its whole operating period and thus it can be concluded that the expected requirement of one year lifetime is met for the TA equipped with the optimized BP identified in the present work.

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