



Ricerca di Sistema elettrico

Progettazione dei sistemi ausiliari del Target Assembly di IFMIF

D. Bernardi, M. Frisoni, G. Micciché, M. Serra

con il contributo di:

P.A. Di Maio, P. Arena, G. Bongiovì

PROGETTAZIONE DEI SISTEMI AUSILIARI DEL TARGET ASSEMBLY DI IFMIF

D. Bernardi, M. Frisoni, G. Micciché, M. Serra (ENEA)

Con il contributo di:

P.A. Di Maio, P. Arena, G. Bongiovì (Università di Palermo)

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Index

SOMMARIO.....	4
ABSTRACT	5
1 INTRODUCTION	6
2 THE IFMIF TARGET SYSTEM.....	7
2.1 TARGET ASSEMBLY	8
2.2 LITHIUM LOOP	11
3 TARGET ASSEMBLY THERMO-MECHANICAL ANALYSIS.....	13
3.1 NOMINAL STEADY STATE SCENARIO	13
3.2 THE FEM MODEL.....	13
3.3 THERMAL INTERACTIONS, LOADS AND BOUNDARY CONDITIONS.....	18
3.4 MECHANICAL INTERACTIONS, LOADS AND BOUNDARY CONDITIONS.....	19
3.5 STEADY STATE ANALYSIS AND RESULTS	20
4 CONCLUSIONS	28
5 REFERENCES	29
6 ACRONYMS	30

Sommario

Nel quadro delle attività di progettazione di IFMIF, l'unità UTIS dell'ENEA Brasimone ha condotto nel corso degli ultimi anni, in stretta collaborazione con il Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici (DEIM) dell'Università degli Studi di Palermo, un'analisi numerica dettagliata per indagare il comportamento termomeccanico del Target Assembly di IFMIF sia in condizioni di funzionamento stazionario che transitorio. Come ulteriore sviluppo dello studio realizzato nell'ambito dell'ultimo Accordo di Programma MSE-ENEA (PAR 2012), è stata avviata nell'ambito del presente PAR 2013 una campagna di ricerca finalizzata a valutare le prestazioni termomeccaniche del Target Assembly di IFMIF opportunamente integrato con la sua struttura di supporto e con il tubo di ingresso litio, inclusi i sistemi ausiliari di ancoraggio del target al frame di supporto, del giunto cardanico di compensazione e dei sistemi di connessione/disconnessione rapida (FDS), che non erano stati inclusi nei modelli precedenti del sistema. In particolare, la presente analisi è stata effettuata considerando lo scenario di carico indotto dalle condizioni operative nominali, prestando in particolare attenzione al potenziale insorgere di deformazioni significative che potrebbero modificare la geometria del canale di litio provocando instabilità del jet, causare interferenze con il modulo di test ad alto flusso (HFTM) o eventualmente generare un disallineamento tra i fasci di deutoni e l'area bersaglio (footprint) sul getto di litio. E' stato inoltre indagato lo stato tensionale complessivo cui è soggetto il sistema con l'obiettivo di verificare che i carichi applicati non portino alla sua crisi strutturale. A tal fine, è stata effettuata, nell'ambito del modello elastico-lineare adottato, una procedura di linearizzazione degli stress (stress breakdown) nelle regioni più critiche del dominio con lo scopo di valutare il soddisfacimento dei criteri di sicurezza strutturale contemplati nel codice di progettazione SDC-IC di ITER per il design dei componenti interni del tokamak.

Lo studio è stato condotto mediante un approccio teorico-computazionale basato sul metodo degli elementi finiti (FEM) implementato tramite un qualificato pacchetto software commerciale già ampiamente adottato in seno alla comunità scientifica internazionale coinvolta nelle tecnologie della fusione. I risultati hanno dimostrato che, dal punto di vista termico, nessuna criticità sembra evidenziarsi per i componenti esaminati e che il trasferimento di calore per convezione naturale tra l'atmosfera della Test Cell che ospita il target e le superfici non isolate della struttura di supporto consente un significativo raffreddamento della stessa. Di conseguenza, un sistema di raffreddamento attivo per il frame di sostegno non appare necessario. Inoltre, i risultati meccanici hanno dimostrato che le regole di progettazione SDC-IC risultano essere generalmente soddisfatte con margini sufficienti ad eccezione di quelle connesse con la potenziale perdita di duttilità del materiale, che in alcune zone maggiormente sollecitate situate in corrispondenza della sezione mediana della piastra posteriore del target (backplate) non risultano verificate, suggerendo la potenziale necessità di una revisione di design della backplate.

Abstract

Within the framework of IFMIF design activities, a detailed analysis has been launched over the last years by ENEA Brasimone in close cooperation with the Department of Energy, Information Engineering and Mathematical Models (DEIM) of the University of Palermo to theoretically and numerically investigate the thermo-mechanical behaviour of the IFMIF Target Assembly under both steady state and transient conditions. As a further development of the study performed in the last MSE-ENEA Agreement (PAR 2012), a research campaign has been launched within the present MSE-ENEA Agreement (PAR 2013) aimed at promoting and supporting the study of the thermo-mechanical performances of the Target Assembly, properly integrated with its support framework and the lithium inlet pipe, which were not included in the previous models of the system.

In particular, the present analysis has been carried out under the nominal steady state loading scenario, paying a particular attention to the potential onset of significant deformations, which may deeply change lithium channel layout inducing flow instability, cause interferences with the High Flux Test Module (HFTM) or generate a misalignment between deuteron beams and lithium footprint, as well as to the yielding occurrence, which might even lead the Target Assembly to its structural crisis. Moreover a stress linearization procedure has been performed in order to assess the fulfillment of the ITER Structural Design Criteria for In-vessel Components (SDC-IC) within the most critical regions of the domain investigated.

A theoretical-computational approach based on the Finite Element Method (FEM) has been followed and a quoted commercial FEM code, qualified for the numerical simulation of thermo-mechanical behaviour of solids and already widely adopted within the international scientific community involved in fusion technology, has been adopted to perform the study.

Results have shown that, from the thermal point of view, no particular concerns seem to arise for the components investigated and the natural convective heat transfer between the Test Cell atmosphere and the support framework non-insulated surfaces allows a significant framework cooling. Consequently, an active cooling system for the support framework seems to be not necessary.

Furthermore, mechanical results have shown that SDC-IC safety rules for level A criteria have resulted to be generally fulfilled with sufficient margins except for those connected to the potential loss of ductility in particular heavily stressed regions located approximately on the back-plate middle section along the beam direction, suggesting the potential need of a back-plate design revision.

1 Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is an international joint project [1] established under the Broader Approach Agreement between Europe (EURATOM) and Japan and devoted to the development of an accelerator-based irradiation facility to test and qualify candidate materials to be used in fusion reactors, allowing, in particular, the development of an irradiated materials database for the design, construction, licensing and safe operation of DEMO and future fusion power reactors.

IFMIF 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 $10^{18} \text{ m}^{-2}\text{s}^{-1}$ characterized by an energy spectrum peaked at 14 MeV, which enables materials testing up to a damage rate of more than 20 dpa/fpy. With the aim of having a stable liquid lithium flow, a target system, consisting in a Target Assembly properly integrated with a lithium loop, has been designed. It is mainly devoted to house the beam footprint, to remove the 10 MW heat power released by deuteron beams and to produce a stable lithium jet with a wave amplitude less than 1 mm at a nominal speed of 15 m/s [1,2]. A detailed description of the lithium loop layout may be found in [2].

Within the framework of IFMIF design activities, a detailed analysis has been launched over the last years by ENEA Brasimone in close cooperation with the Department of Energy, Information Engineering and Mathematical Models (DEIM) of the University of Palermo to theoretically and numerically investigate the thermo-mechanical behaviour of the IFMIF Target Assembly under both steady state and transient conditions [3]. As a further development of the study reported in [3], a research campaign has been launched within the present MSE-ENEA Agreement aimed at promoting and supporting the study of the thermo-mechanical performances of the Target Assembly, properly integrated with its support framework and the lithium inlet pipe, which were not included in the previous models of the system.

In particular, the present analysis has been carried out under the nominal steady state loading scenario, paying a particular attention to the potential onset of significant deformations, which may change lithium channel layout inducing flow instability, cause interferences with the High Flux Test Module (HFTM) or generate a misalignment between deuteron beams and lithium footprint. Attention has been paid also to the stress state and yielding occurrence, which might even lead the Target Assembly to its structural crisis. To this end, a stress linearization procedure has been performed in order to assess the fulfillment of the ITER Structural Design Criteria for In-vessel Components (SDC-IC) within the most critical regions of the domain investigated. A theoretical-computational approach based on the Finite Element Method (FEM) has been followed and a quoted commercial FEM code, qualified for the numerical simulation of thermo-mechanical behaviour of solids and already widely adopted within the international scientific community involved in fusion technology, has been adopted to perform the study. In the present report, the results obtained are presented and critically discussed.

2 The IFMIF Target System

The IFMIF lithium target system has the functions to remove the 10 MW heat power deposited by the deuterium beams, to maintain a stable lithium jet at a nominal speed of 15 m/s, to control impurity levels, to guarantee a sufficient safety with respect to lithium hazard and tritium release and to achieve the required system availability during plant lifetime [2].

The concept of the IFMIF target system is reported in Fig. 1. It mainly consists of the Target Assembly (TA) and the lithium loop.

The former is devoted to provide a fast, reliable and stable flow of lithium, mainly characterized by a jet thickness of 25 ± 1 mm, a flow velocity range of 10–16 m/s and an inlet lithium temperature of 250 °C [2]. The latter is articulated in a main loop and a purification loop and it is intended to feed lithium to the Target Assembly by an electromagnetic pump, routing it through the heat exchanger and the purification loop which consists of one cold and two hot traps. The Target Assembly is connected to the lithium loop by means of three Fast Disconnecting Systems (FDS), two located on the lithium inlet pipe and one in the outlet channel attached to the Quench Tank (Fig. 1).

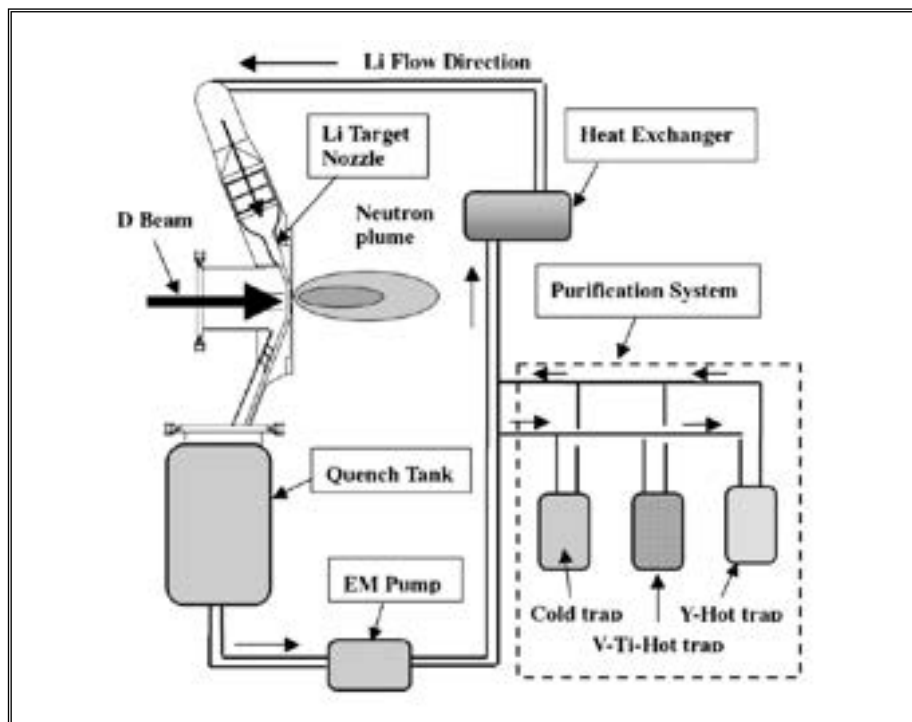


Figure 1. Concept of IFMIF target system.

2.1 Target Assembly

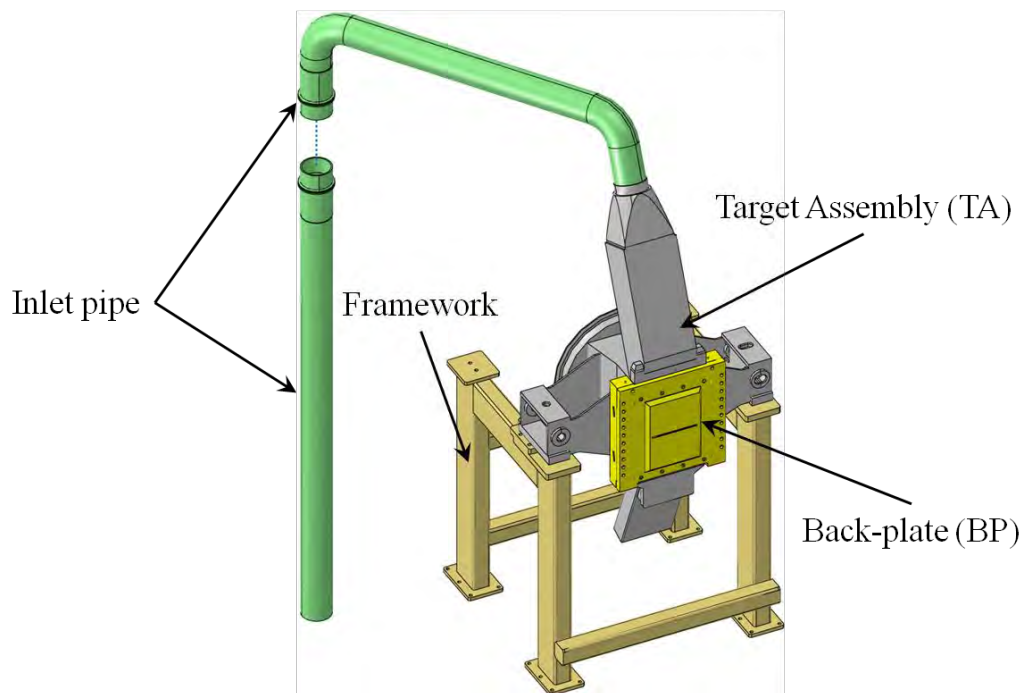
A sketch of the entire TA including its framework support and lithium inlet pipe is shown in Figs. 2 and 3.

The Target Assembly, made of reduced activation ferritic/martensitic steel (EUROFER), is approximately 3 m tall (considering the support structure) and 1000 kg heavy. It is located in the test cell at a nominal distance of 2 mm from the high flux test module placed behind it and it is supported by arms laying on a proper framework. The TA mainly consists of the flow straightener, the reducer nozzle, the back-plate, the target chamber and the frame (Fig. 3). A more detailed description of its layout can be found in [1,2].

The flow straightener is provided to smooth the flow before entering the target section. The reducer nozzle is placed at the exit of the straightener to contract and accelerate the flow. In particular, since the TA is required to contract the lithium flow with a total contraction ratio of 8 and a single stage cannot operate at the required high speed without introducing unacceptable perturbations in the flow, a two steps Shima type nozzle has been selected. It is characterized by contraction ratio values of 3.2 for the first nozzle and 2.5 for the second nozzle and it allows the transverse component of flow velocity to remain under the prescribed limit. The back-plate (BP) is the most heavily irradiated TA component (Fig. 4). It is devoted to house the beam footprint resulting to operate under severe conditions of neutron irradiation damage (~ 60 dpa/fpy) [4]. Its expected lifetime under irradiation is estimated to be about 1 year. Therefore, the reference TA design is conceived with a remotely replaceable back-plate.

A curved profile has been envisaged for the back-plate in the beam footprint region in order to allow centrifugal forces arising within lithium flow to increase its pressure and, consequently, its saturation temperature, avoiding the risk of vaporization under the 10 MW power deposition due to the interaction with deuterons. The TA design proposed by ENEA foresees a removable BP, so that the latter can be easily replaced using a remote handling device without removing the whole Target Assembly. This concept is based on the adoption of a so-called BP “bayonet” design, which consists in a replaceable back-plate that can be inserted to and removed from the TA fixed frame by means of a sliding-skate mechanism [4,5].

The TA arms are connected to the support framework (Fig. 5) which is also made of EUROFER steel and directly fixed to the test cell floor by means of a proper bolting system. The support framework allows the sliding of one of the TA arms during the nominal operational in order to allow the TA lateral deformation and avoid thermal stresses due to constrained displacement.



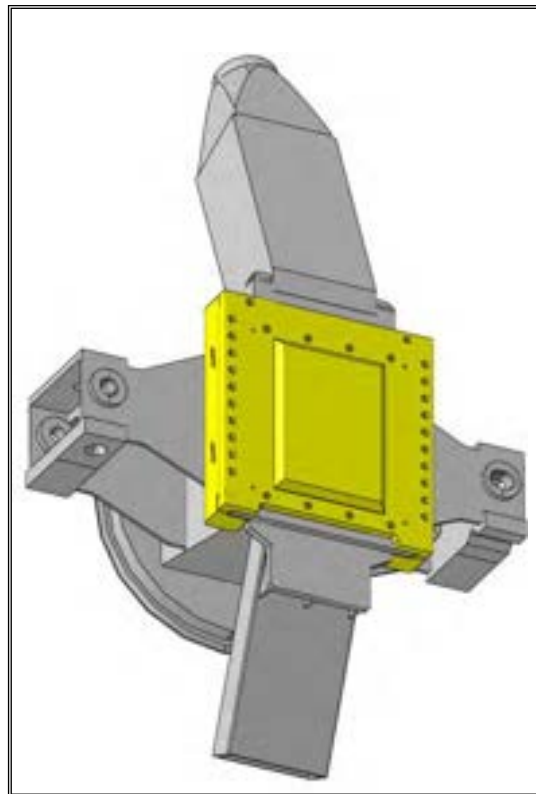


Figure 2. IFMIF Target Assembly including support framework and inlet pipe (top) and TA alone (bottom)

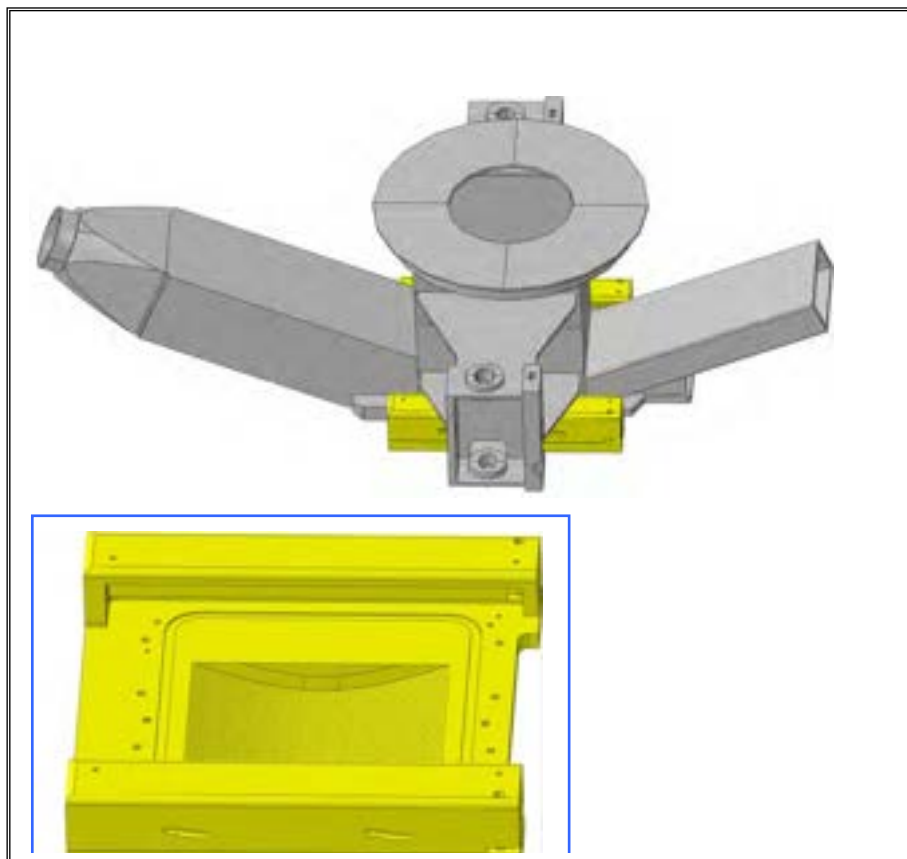


Figure 3. IFMIF Target Assembly exploded view.

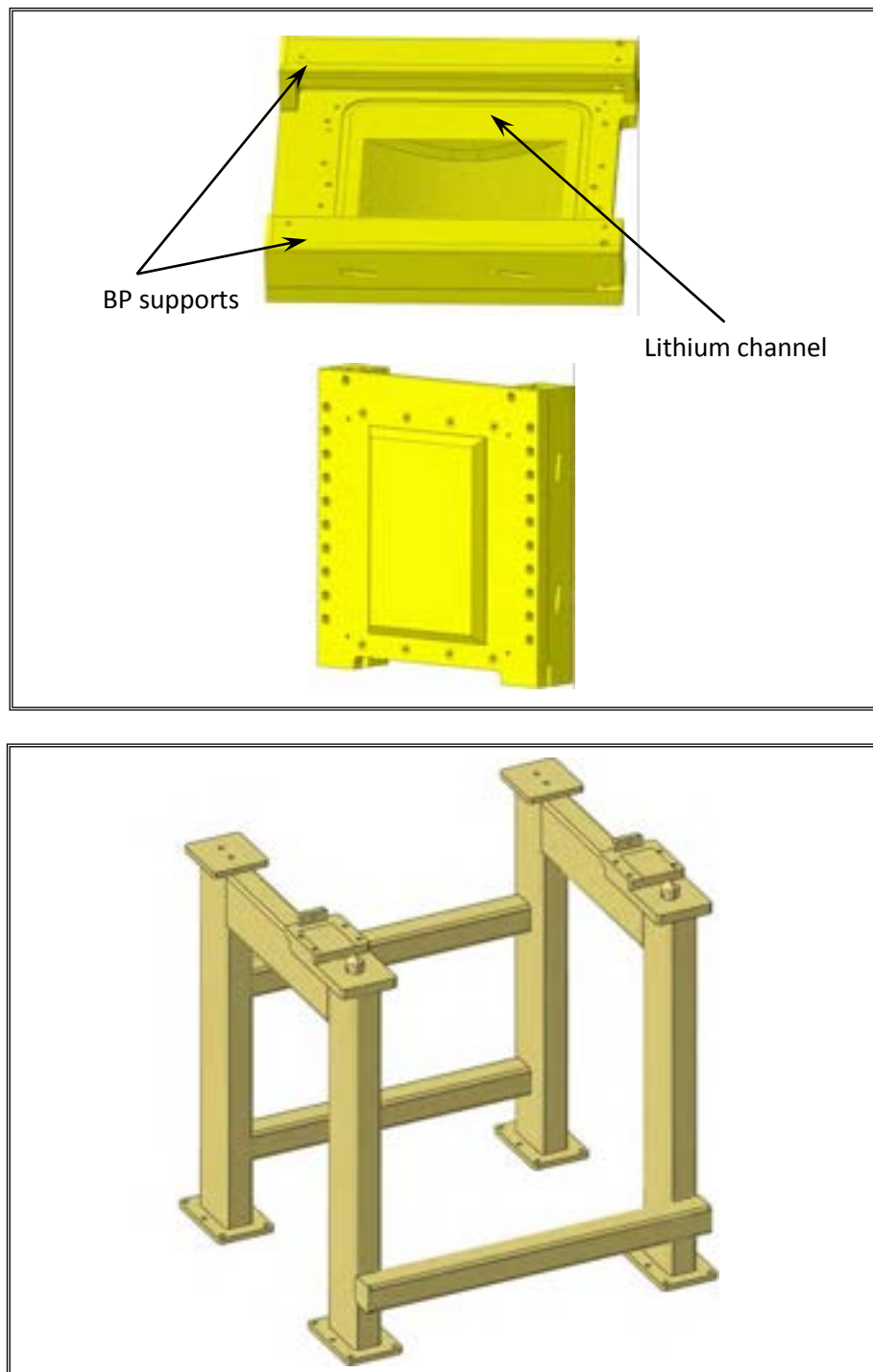


Figure 5. TA support framework.

2.2 Lithium loop

The lithium loop is articulated in a main loop and a purification loop. Its design specifications are reported in Tab. 1. Further details may be found in [1,2]. The main loop stably supplies liquid lithium of the adequate flow rate and temperature to the TA. The loop mainly consists of the quench tank, the dump tank, the main electromagnetic pump and two heat exchangers. There are, in addition, a trace heating system (to maintain the temperature throughout the loop above the melting point of lithium), thermal insulation, valves, electromagnetic flow meters, instrumentation and connections to vacuum and argon headers [2]. Among the main loop components, in order to investigate the thermo-mechanical performances of the IFMIF Target Assembly, attention has been paid to the lithium inlet pipe devoted to supply lithium to the TA section. The lithium inlet pipe is articulated in two sections, connected each other by means of two Fast Disconnecting Systems (FDS) and a gimbal expansion joint (Fig. 6).

Table 1. Main lithium loop specifications [2].

Lithium inventory	9 m ³
Lithium flow rate	97.5 l/s (nominal)
Lithium flow velocity	10 – 16 m/s (velocity range at the target section)
	15 m/s (nominal)
Lithium temperature	250 °C (nominal condition at the nozzle inlet)
Lithium pressure	10 ⁻³ Pa (at vacuum interface in the target chamber)
	12 kPa (maximum value at BP interface)
	10 ⁻³ Pa (target quench tank under operation)

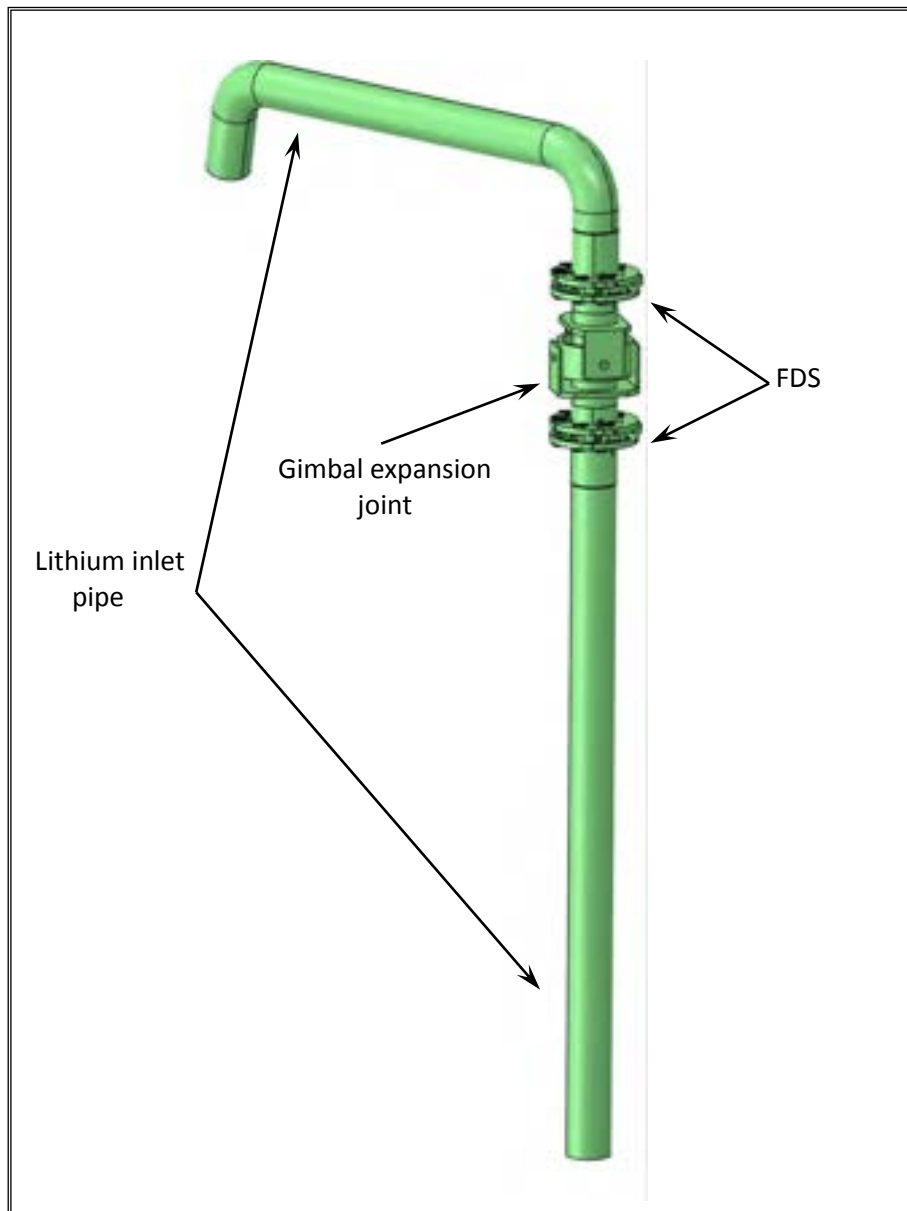


Figure 6. Lithium inlet pipe.

Each FDS permits to easily and quickly connect and disconnect the flanges by simply acting (by remote) on only one screw. The seal is the heart and most delicate item of the FDS, and it is ensured by a metallic gasket operating by axial pressure mode. Apart from the removable flange and the gasket which are removed together with the Target Assembly, the rest of the FDS is attached to the fixed part of the lithium loop. The FDS is equipped with a leak detection system, used to get an alarm in case the liquid lithium would flow out of the two connected flanges. A more detailed description of FDS, leak detection system components and of the detachment system functioning is reported in [4]. The gimbal expansion joint is able to compensate angular movements between the flanges of the two inlet pipe sections. It is aimed to compensate thermal expansions during IFMIF normal operation phase and misalignments during target system installation. Further details on the gimbal expansion joint foreseen for the lithium inlet pipe may be found in [4].

The purification loop consists of a cold trap and two hot traps, to remove various impurities, and of auxiliary supporting equipments. Major impurities are Protium (H), Deuterium (D), Tritium (T), ^7Be , activated corrosion products and other species (C, N, O) [2].

3 Target Assembly thermo-mechanical analysis

The present research has been aimed to assess the TA thermo-mechanical behaviour under the reference nominal steady state scenario, in order to verify whether TA components can safely withstand the thermo-mechanical loads it undergoes without incurring in significant deformations, which may warp lithium channel inducing flow instability, cause interferences with the Test Module or generate a misalignment between deuteron beams and lithium footprint, as well as without yielding, which may lead it to structural crisis. Attention has been focussed also on the fulfillment, in the most critical area of the domain investigated, of the SDC-IC structural safety criteria. The research campaign has been performed adopting a theoretical-numerical approach based on the Finite Element Method (FEM) and a qualified commercial FEM code has been used to perform the study.

3.1 Nominal steady state scenario

The reference nominal steady state scenario represents the loading scenario that the Target Assembly, integrated with its support framework and the lithium inlet pipe, is envisaged to experience due to the thermo-mechanical loads and boundary conditions. In particular the nominal operation phase is mainly characterized by lithium flowing within the lithium inlet pipe and through the TA, where it enters the lithium straightener at 250 °C and at a static pressure of ~60 kPa, up to the outlet nozzle, where it reaches ~300°C and a static pressure of 10^{-3} Pa, prior to be discharged in the quench tank [2,4]. During this phase, deuteron accelerators remains under full-power irradiation conditions (two 125 mA current beams), allowing heat power to be deposited by deuterons, neutrons and photons within lithium coolant, TA components, support framework and lithium inlet pipe. The neutron swelling induced within the structural material has not been taken into account in the present research campaign, because the latter has been aimed at investigating exclusively the thermo-mechanical response of the structure during the nominal steady state operational phase.

3.2 The FEM model

A realistic 3D FEM model, reproducing the Target Assembly integrated with its support framework and the lithium inlet pipe, has been developed and a mesh independency analysis has been performed to select an optimized spatial discretization which allows accurate results to be obtained saving calculation time. A mesh composed of $\sim 4.0 \times 10^5$ nodes connected in $\sim 1.55 \times 10^6$ tetrahedral elements has been selected, whose views are reported in Figs. 7-14. The so formed spatial discretization allows numerical simulations to be carried out in about 3 hours. The two FDS and the gimbal expansion joint of the lithium inlet pipe have not been directly modelled, since their mechanical effects have been simulated, as widely explained in the following, imposing, for the former, an appropriate contact model that permits to consider the flanges tightened by the FDS as perfectly tied while, for the latter, a proper kinematic model, that allows the coupling of the rotational and translational displacements of the two lithium inlet pipe sections connected by the gimbal expansion joint. EUROFER steel has been assumed as the TA, support framework and lithium inlet pipe structural material. Lithium flow has been modelled too in order to properly simulate its thermal interaction with TA. To this purpose a flow velocity at the inlet nozzle exit amounting to 15 m/s has been adopted. Materials have been considered homogeneous, uniform and isotropic. Their thermo-mechanical properties have been assumed to depend uniquely on temperature as indicated in [6-10] and, in particular, EUROFER mechanical behaviour has been simulated adopting a linear elastic model.

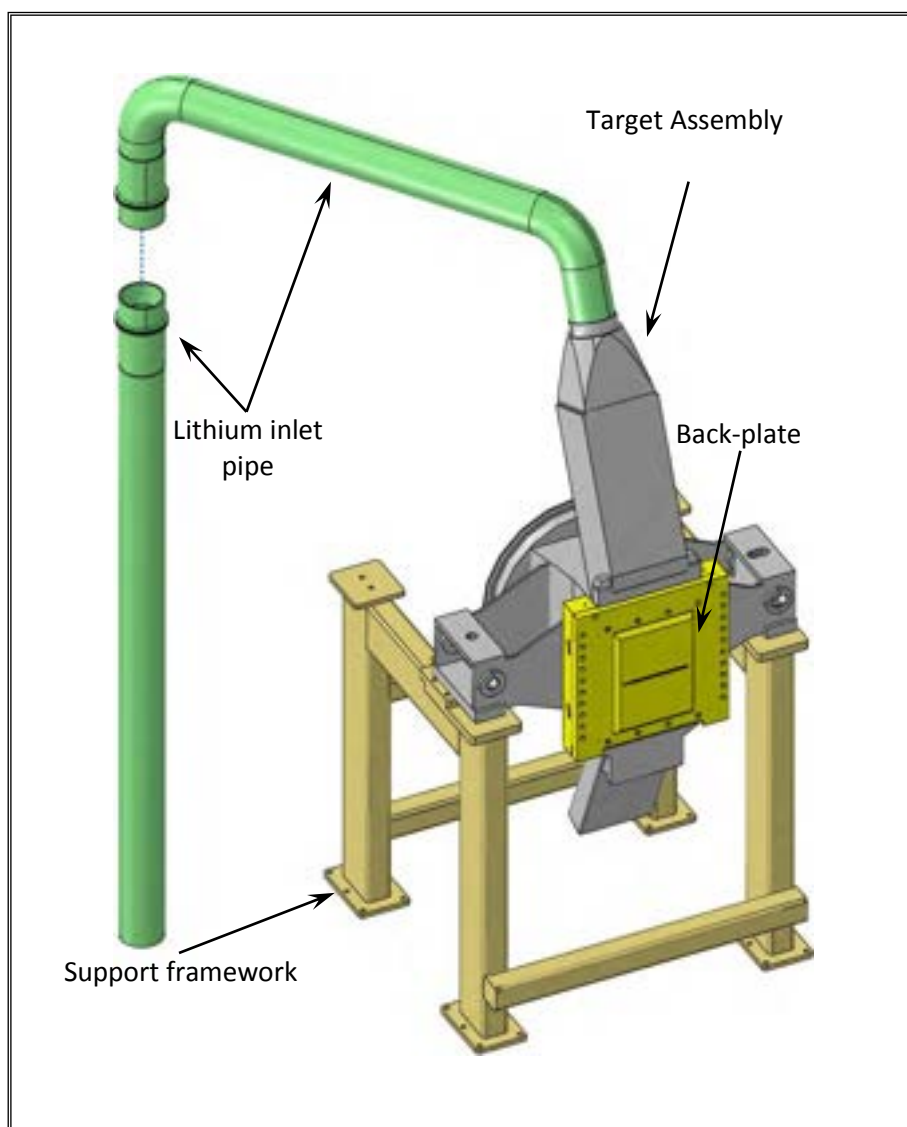


Figure 7. FEM model – Computational domain

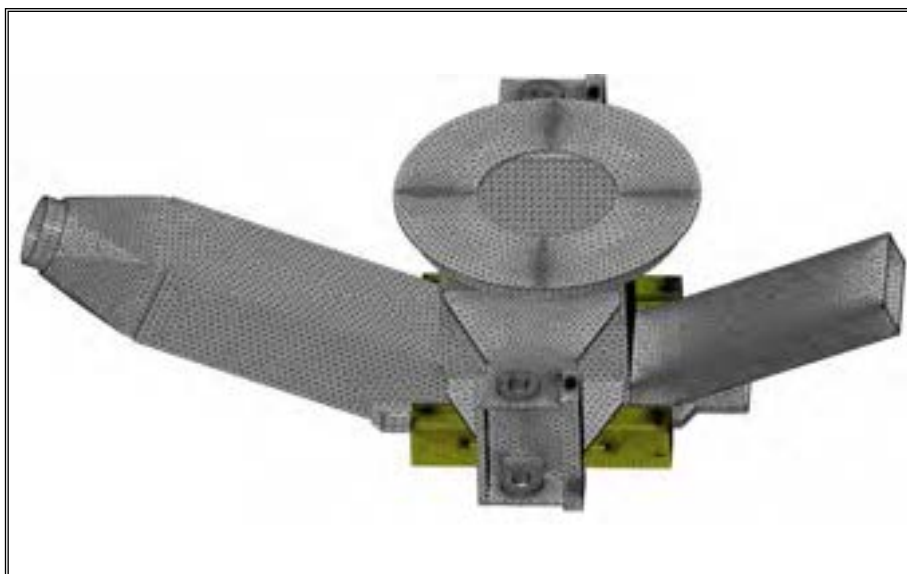


Figure 8. FEM model - Target Assembly lateral view.

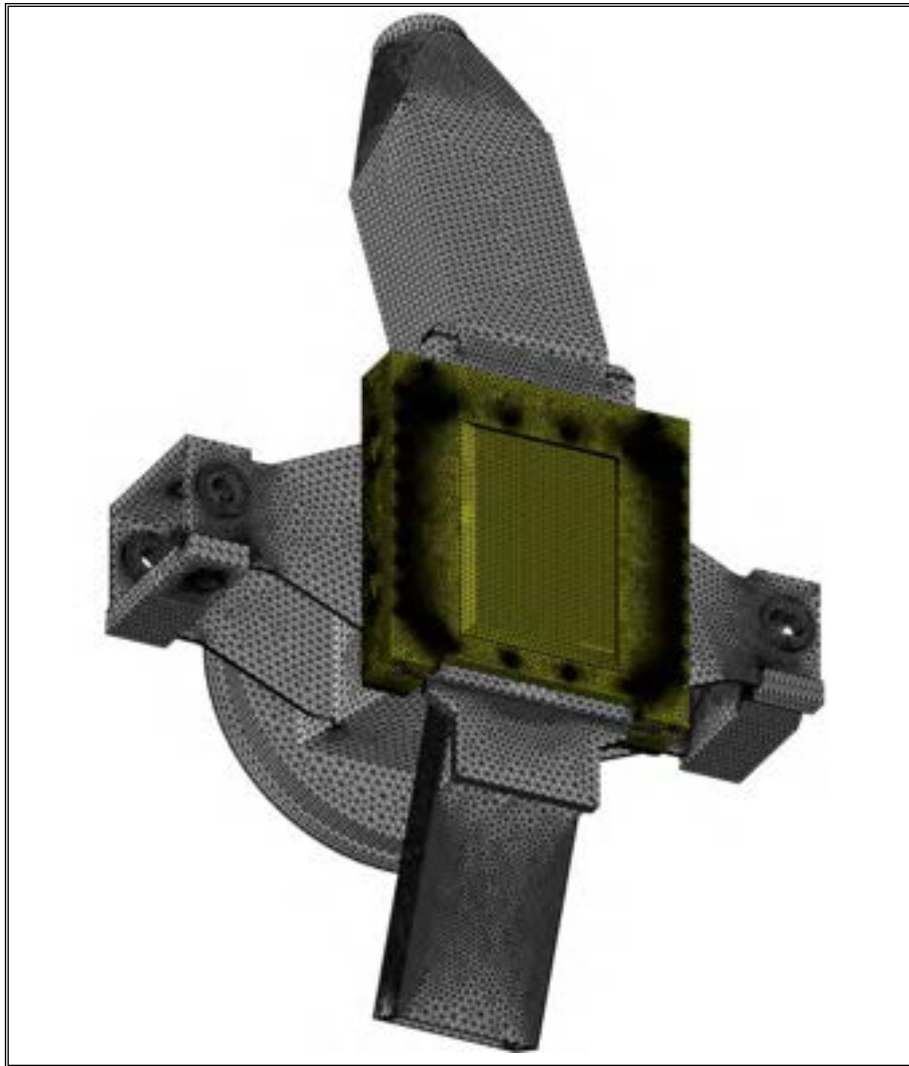


Figure 9. FEM model - Target Assembly front view.

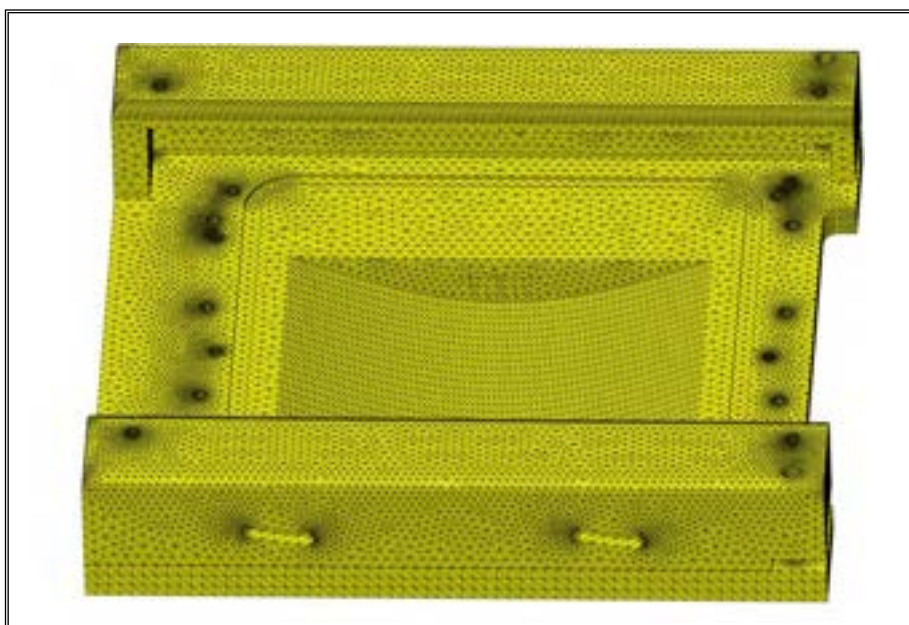


Figure 10. FEM model - Particular of the back-plate.

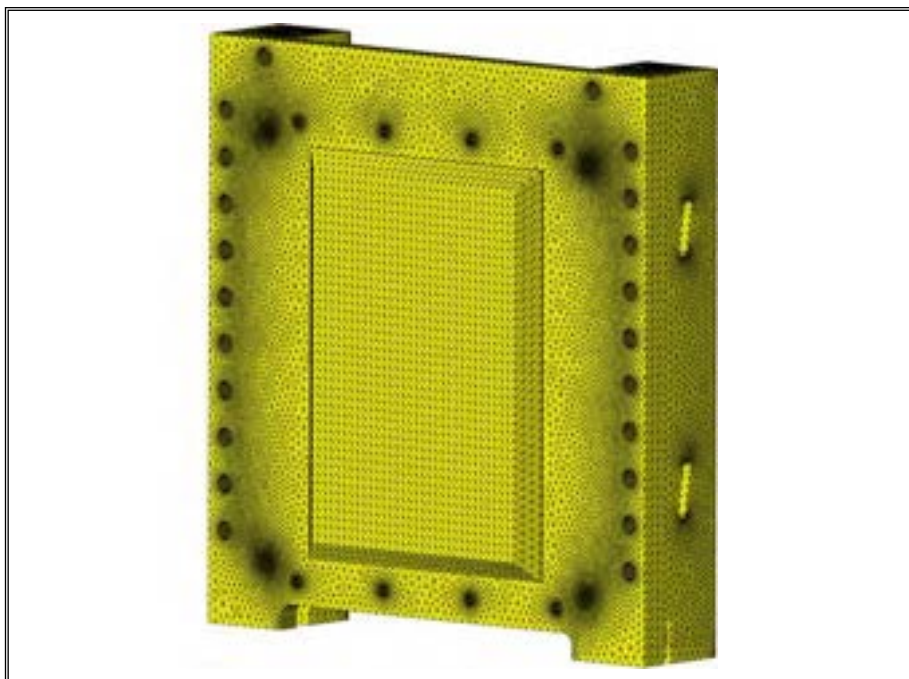


Figure 11. FEM model - Particular of the back-plate.

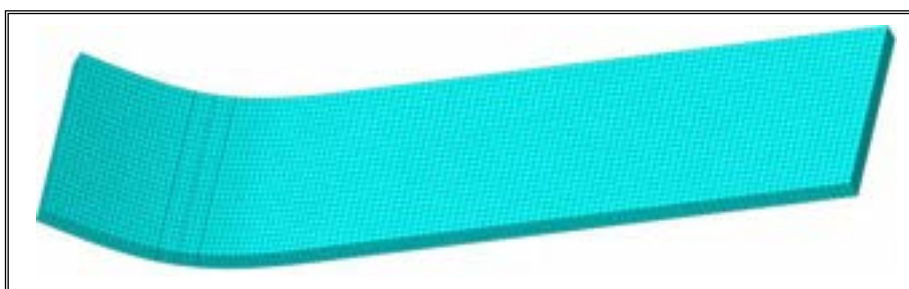


Figure 12. FEM model - Particular of the lithium flow domain.



Figure 13. FEM model - Particular of the support framework.



Figure 14. FEM model - Particular of the lithium inlet pipe.

3.3 Thermal interactions, loads and boundary conditions

The following thermal interactions, loads and boundary conditions have been assumed to simulate the TA integrated with its support framework and lithium inlet pipe:

- thermal interactions;
- volumetric density of heat power deposited in the lithium flow footprint region;
- volumetric density of heat power deposited within TA, framework and inlet pipe;
- forced convection with lithium;
- heat transfer between BP and HFTM through helium gas;
- heat transfer between target chamber and beam duct;
- internal irradiation;
- external irradiation;
- TA natural convection cooling;
- support framework cooling

In particular, regarding the support framework cooling, three different conditions, named respectively Condition 1, Condition 2 and Condition 3, have been investigated in order to assess the effects of different framework cooling strategies on the TA thermo-mechanical performances.

In Condition 1, the natural convection cooling between framework non-insulated surfaces (in red in Fig. 15) and helium filling the Test Cell atmosphere has been simulated, by imposing a Cauchy boundary condition in which convective heat transfer coefficient has been set equal to $10 \text{ W/m}^2\text{°C}$ and the helium bulk temperature has been imposed to be 50 °C . In Condition 2, the forced convection cooling of the support framework with helium at 50°C has been simulated supposing a value of $1000 \text{ W/m}^2\text{°C}$ for the convective heat transfer coefficient.



Figure 15. Support framework non-insulated surfaces.

Finally, a further cooling strategy for the support framework, named Condition 3, has been taken into account. In particular, the heat power removal by coolant water at an average bulk temperature of 50 °C and at atmospheric pressure, circulating in an embedded cooling coil and removing heat from the internal support framework surfaces (in red in Fig. 16), has been simulated. An effective convective heat transfer coefficient equal to $13336 \text{ W/m}^2\text{°C}$, so to extract the 300 W heat power arising from the framework by means a total water mass flow rate of 0.2 kg/s with a thermal rise of 0.36 °C , has been estimated using the

Dittus and Boelter correlation [11]. Furthermore a convective heat transfer coefficient value of $10 \text{ W/m}^2\text{°C}$ has been imposed on the support framework non-insulated surfaces in order to take into account the natural convective heat transfer between the component and the Test Cell atmosphere. A more detailed description of the thermal interactions, loads and boundary conditions listed in this section can be found in [12].

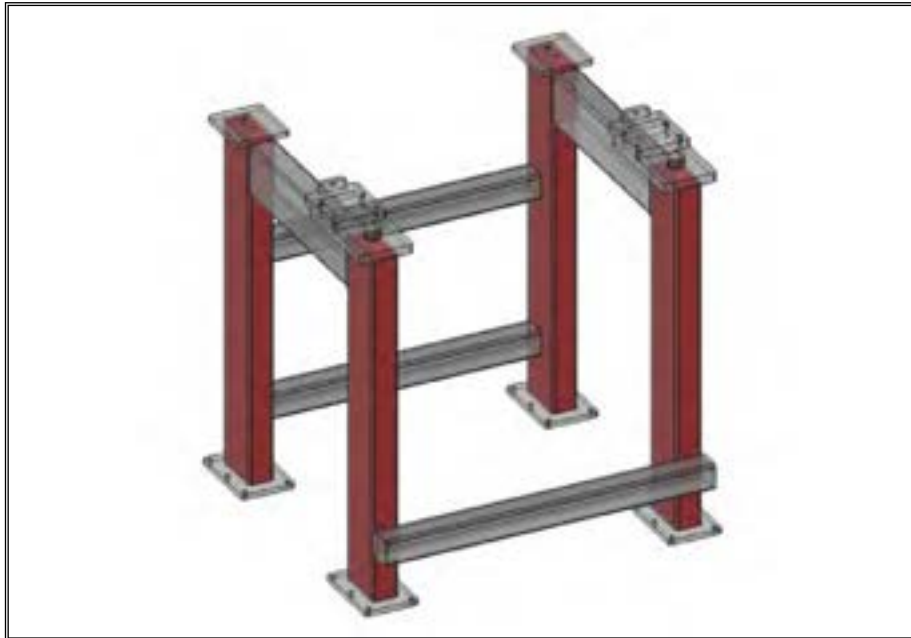


Figure 16. Support framework internal surfaces.

3.4 Mechanical interactions, loads and boundary conditions

As far as the mechanical analysis is concerned, the following mechanical interactions, loads and boundary conditions have been assumed to simulate the TA thermo-mechanical behaviour under nominal steady state scenario:

- mechanical interactions;
- thermal deformations;
- weight force;
- internal and external pressures;
- tightening screw loads;
- skate-based clamping system loads;
- support framework constraints;
- Lithium inlet pipe constraints;
- TA system constraints;
- Lithium inlet pipe gimbal expansion joint

A more detailed description of the mechanical interactions, loads and boundary conditions listed in this section can be found in [12].

3.5 Steady state analysis and results

An uncoupled thermo-mechanical steady state analysis has been carried out to investigate the thermo-mechanical behaviour of the TA integrated with its support framework and the lithium inlet pipe, under the reference nominal scenario in order to assess the potential aptitude of the system to safely withstand the loads it undergoes without incurring in significant deformations and yielding-induced structural crisis of the structure, with a particular attention on its replaceable back-plate.

Three steady state thermal analyses, one for each thermal condition taken into account, have been carried out to obtain the corresponding thermal field distribution. Every thermal analysis has been followed by two independent steady state mechanical analyses intended to assess separately the distributions of total and secondary stresses and to derive that of primary stresses, as the difference.

In order to study the structure thermal behaviour, attention has been mainly focussed on the assessment of the spatial distribution of its thermal field. On the other hand, in order to investigate its mechanical behaviour, attention has been paid to the assessment of the spatial distribution of the Von Mises equivalent stress field, σ_{VM} . Moreover, in order to verify that no significant deformations occur which might warp BP channel inducing lithium flow instability and cause an overlapping between BP external surface and HFTM, a particular attention has been paid also to the analysis of the BP deformation field and to the displacements of its surface directly faced to HFTM. Finally, the potential insurgence of a misalignment between deuteron beams and lithium footprint, due to excessive BP displacements on the plane normal to the beams direction, have been investigated too.

Since the design of TA has to be based on a consistent set of rules taking into account, at the same time, regulation requirements for nuclear components, the peculiarities of EUROFER mechanical behaviour and the specific operating conditions foreseen for IFMIF environment, a stress linearization procedure has been carried out, with the specific aim to evaluate general or local primary membrane stress tensor (P_m or P_L), primary bending stress tensor (P_b), general or local secondary membrane stress tensor (Q_m or Q_L), secondary bending stress tensor (Q_b) and peak stress (F) in some particularly significant paths of the Target Assembly BP (Fig. 17). Stress values calculated have been adopted to verify whether the TA thermo-mechanical stress state complies with requirements prescribed by SDC-IC rules [13] for level A criteria that are both the most conservative and comprehensive of all possible damage modes. 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]. A complete description of the SDC-IC rules adopted in the present study are available in [12].

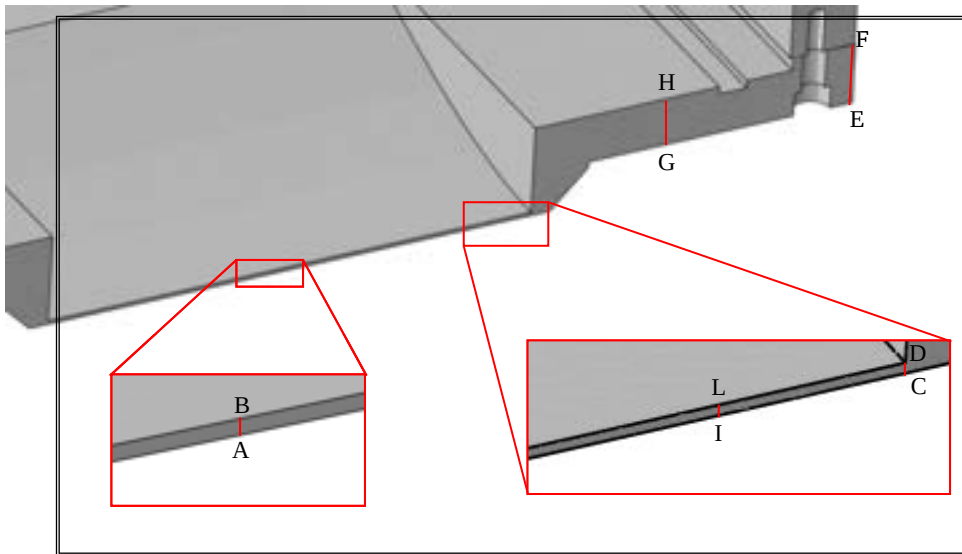


Figure 17. Stress linearization paths.

Results obtained in terms of thermal and displacement fields are summarized in Tabs. 2-4. As it can be observed, in Condition 1 the minimum value of the misalignment (u_x and u_z) between the deuteron beam and the lithium footprint and the lowest maximum displacement of the BP external surface toward the HFTM ($u_{y,Max}$) are predicted. Therefore, Condition 1 has been selected as the reference one and a stress linearization procedure has been performed only for it, in order to verify the fulfillment of the SDC-IC low temperature safety rules. Consequently, results obtained from Condition 1 thermo-mechanical analysis in term of thermal field, Von Mises equivalent stresses field, displacement field and SDC-IC safety rules verifications are reported in the following (Figs. 18-27 and Tab. 5). Results obtained from Condition 2 and Condition 3 thermo-mechanical analyses in term of thermal field, Von Mises equivalent stresses field, displacement field and SDC-IC safety rules verifications have not been herewith shown for sake of brevity. Anyway, they have been diffusely reported in [12] by means of appropriate groups of Figures and Tables as well as herewith shown for Condition 1 results.

In particular, from the thermal point of view, results obtained for Condition 1 show that neither the limit temperature for thermal activated phenomena of 450°C [13] nor the maximum EUROFER allowable temperature of 550 °C are overcome in Condition 1 analysis. Consequently, SDC-IC high temperature rules have not been considered and only low temperature SDC-IC safety criteria has been performed.

As far as the mechanical results are concerned, it can be observed that the highest values of the Von Mises equivalent stress are reached in a very small area, probably due to numerical singularities within the FEM model. In fact, the whole structure experiences Von Mises equivalent stress values lower than 550 MPa in a widely diffused region of the geometric domain investigated.

As for the displacement field, the deformed (in red) vs. un-deformed (in grey) configuration of the whole model and a detail of the BP are reported, adopting an isotropic amplification factor equal to 50 for the deformed configuration in order to amplify the structure displacements in respect to the initial configuration. Particular attention has been paid to the potential misalignment between the deuteron beams and the lithium footprint, the slipping that may occur between the target hamber arms and the support framework and finally to the BP external surface displacements, in order to check that no overlapping with the HFTM surface takes place.

Table 2. Maximum and minimum components temperatures.

Maximum temperatures [°C]				
Condition	BP	TA	Inlet pipe	Framework
1	369.4	428.7	250.0	80.4
2	369.4	428.7	250.0	57.3
3	369.4	428.7	250.0	68.4
Minimum temperatures [°C]				
Condition	BP	TA	Inlet pipe	Framework
1	205.8	69.0	250.0	51.6
2	205.8	51.6	250.0	50.0
3	205.8	63.0	250.0	50.0

Table 3. External central BP node displacements.

Condition	u_x [mm]	u_y [mm]	u_z [mm]
1	-0.224	0.900	0.015
2	-0.260	0.901	-0.180
3	-0.278	0.923	-0.151

Table 4. Maximum BP displacement along the beam direction ($u_{y,Max}$).

Condition	$u_{y,Max}$ [mm]
1	1.081
2	1.083
3	1.110

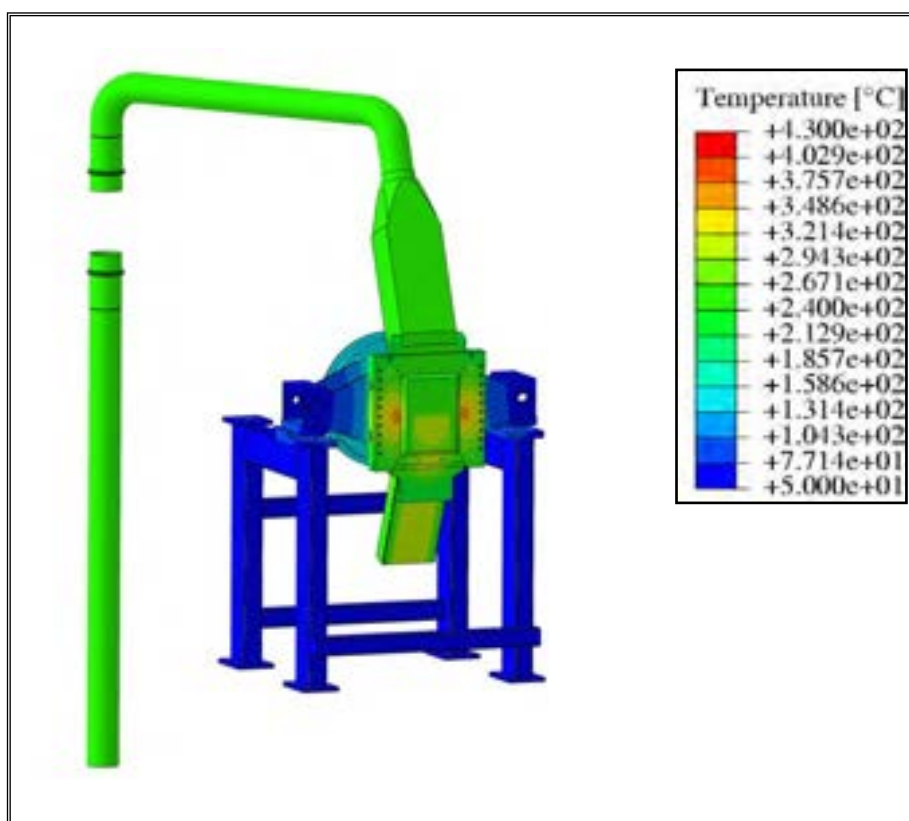


Figure 18. Condition 1 – Thermal field.

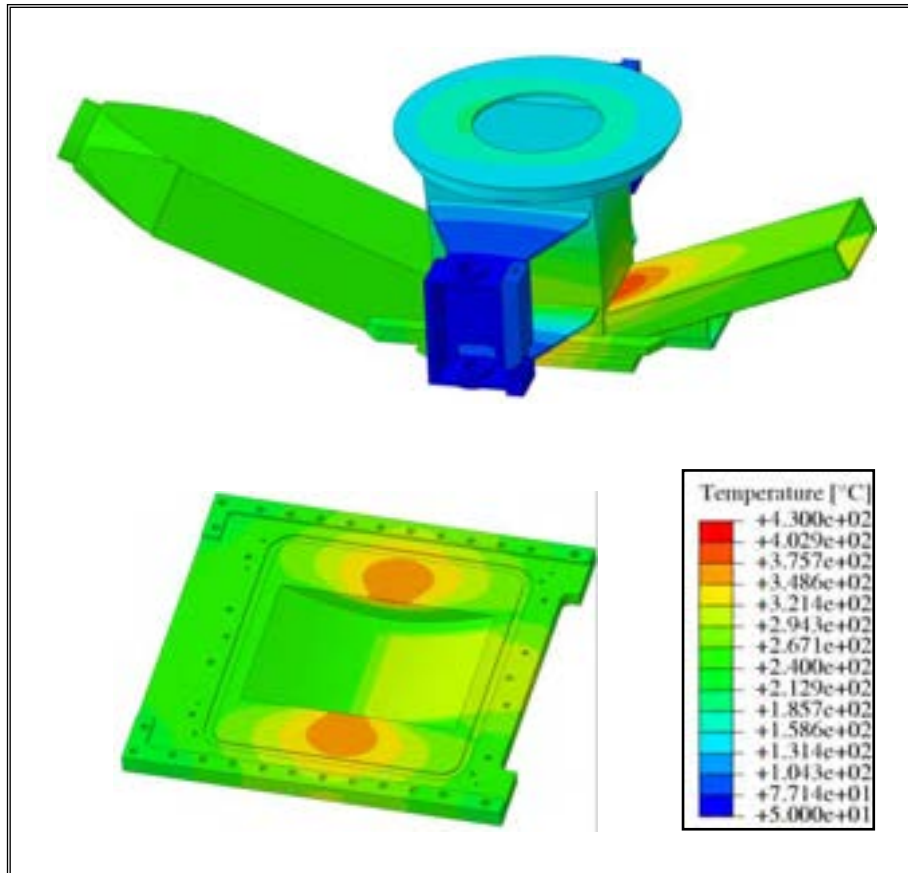


Figure 19. Condition 1 – TA and BP thermal field.

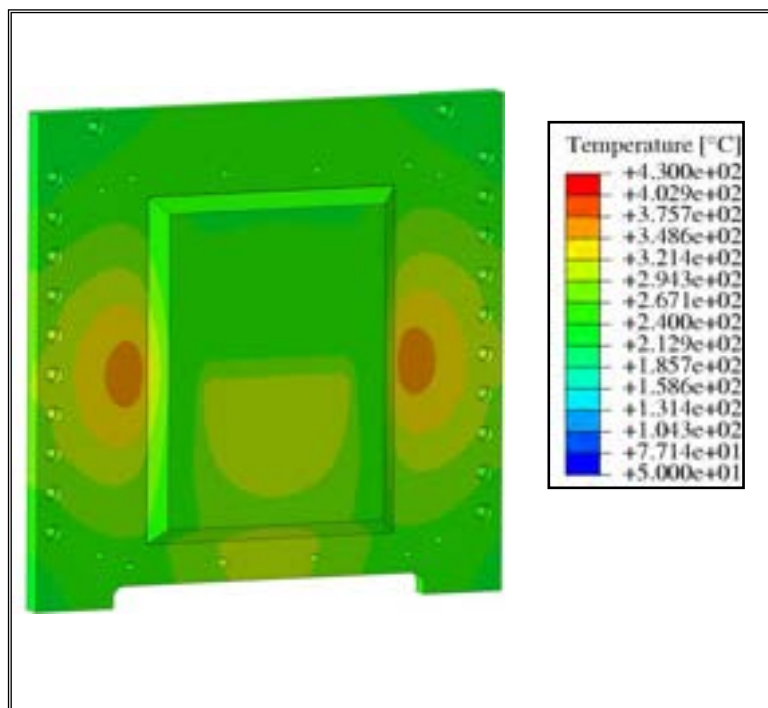


Figure 20. Condition 1 – BP thermal field.

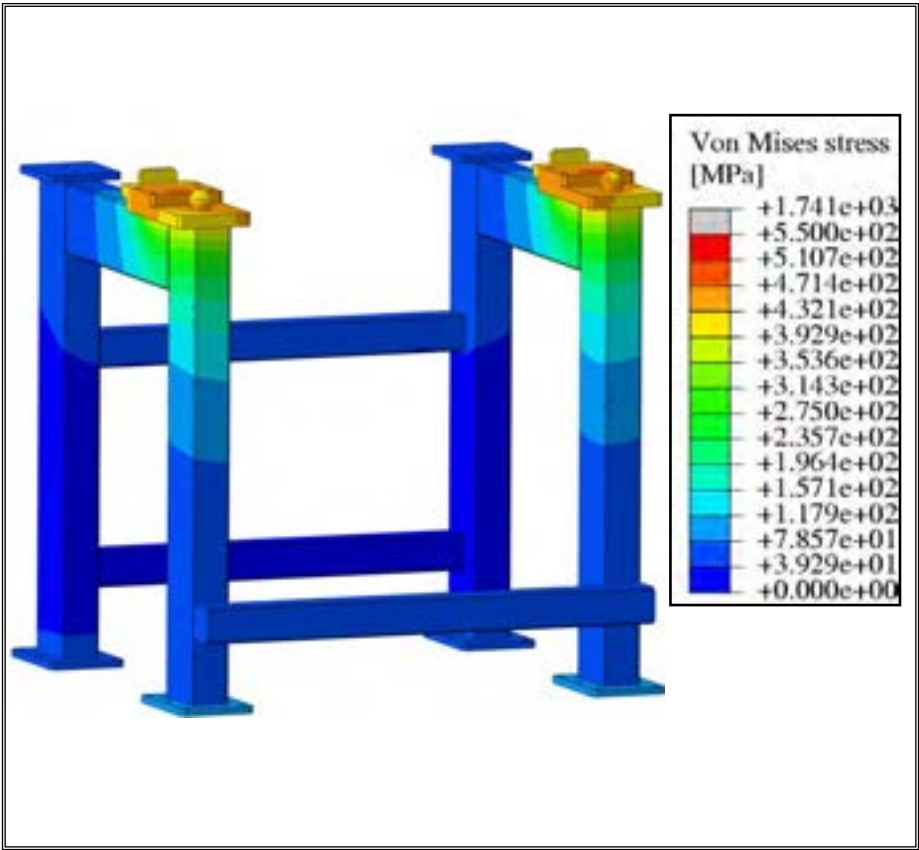


Figure 21. Condition 1 – Support framework thermal field.

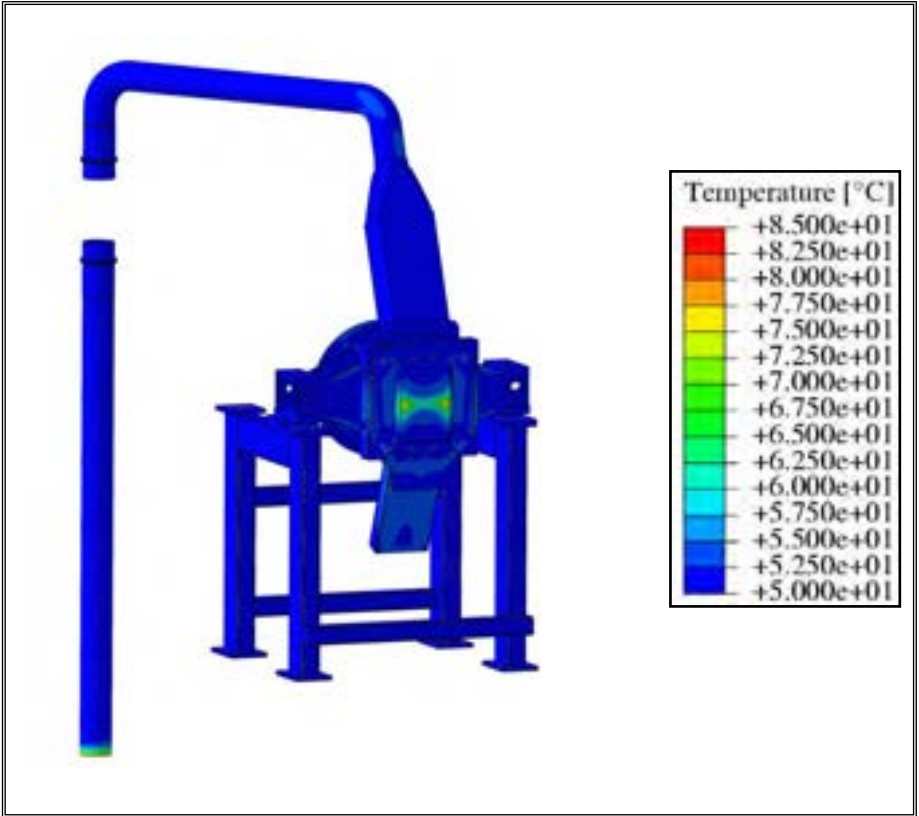


Figure 22. Condition 1 – Von Mises stress field.

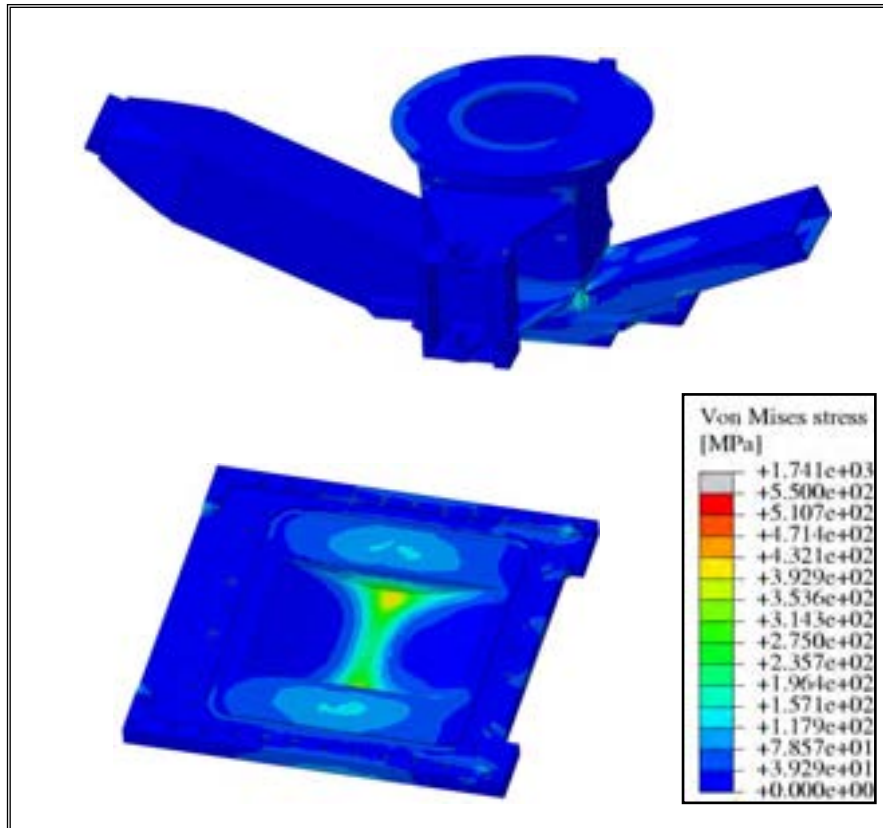


Figure 23. Condition 1 – TA and BP Von Mises stress field.

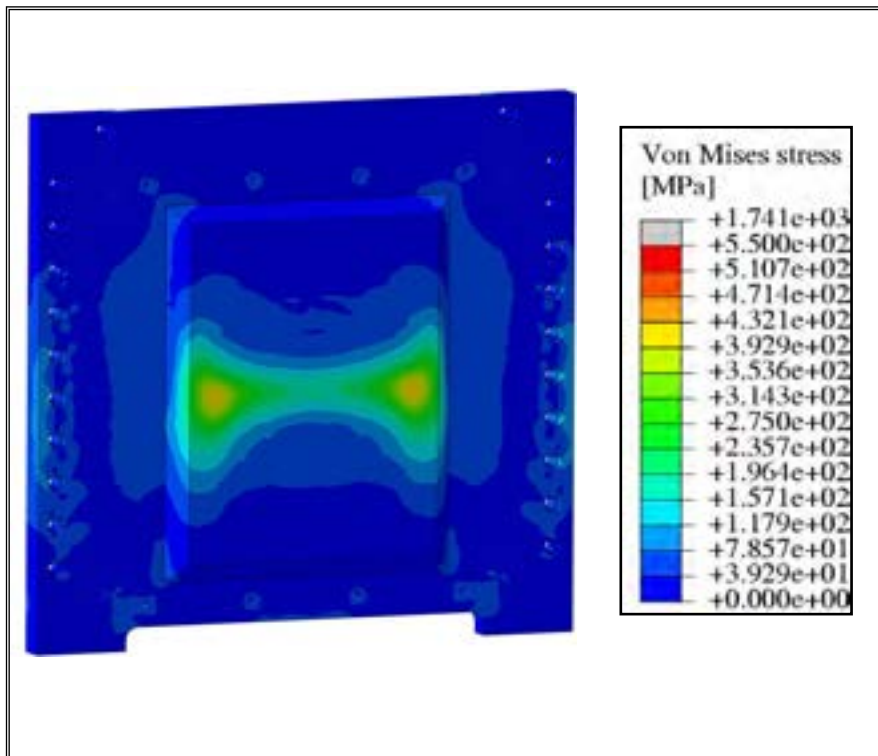


Figure 24. Condition 1 – BP Von Mises stress field.

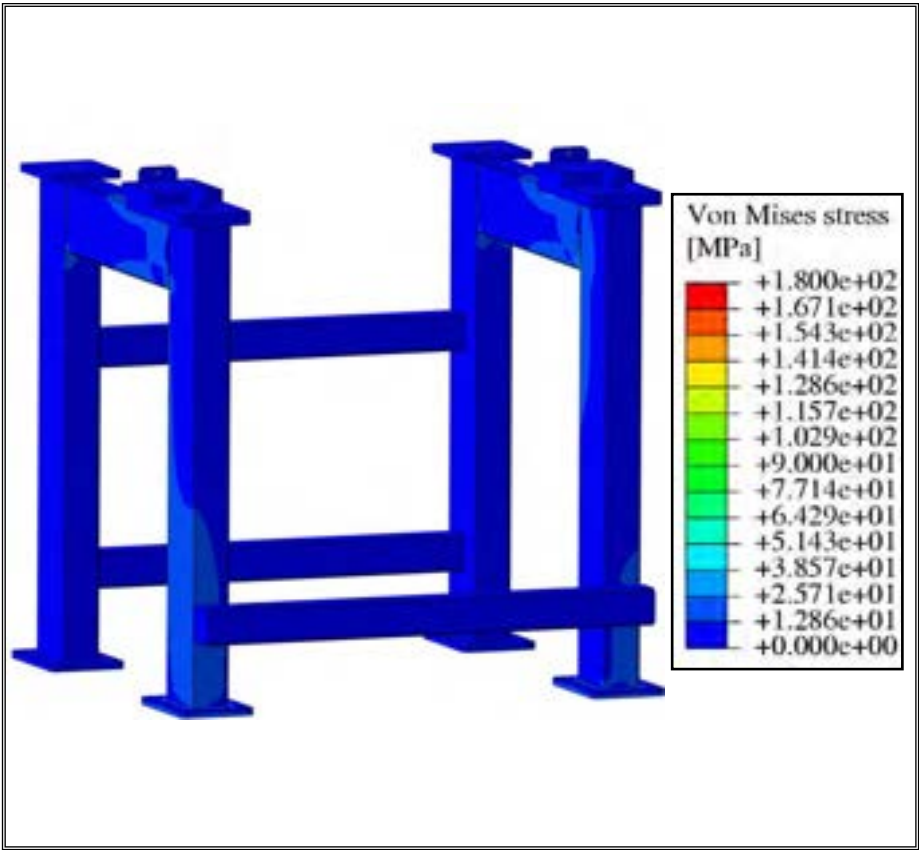


Figure 25. Condition 1 – Support framework Von Mises stress field.

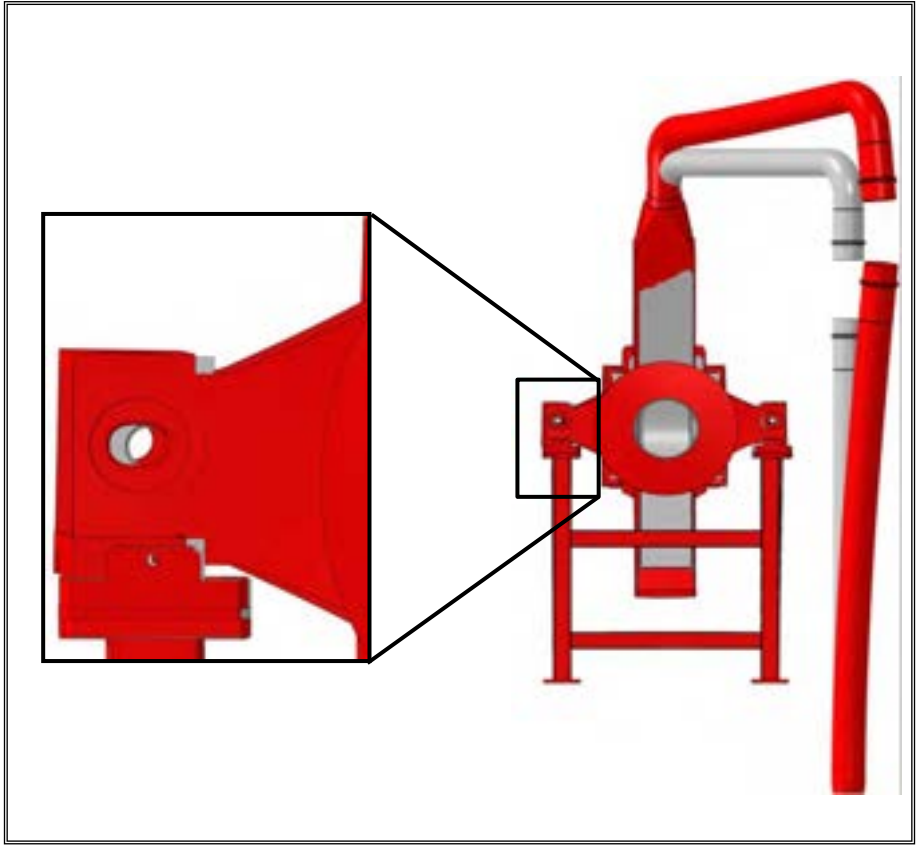


Figure 26. Condition 1 – Deformed vs. un-deformed configuration.

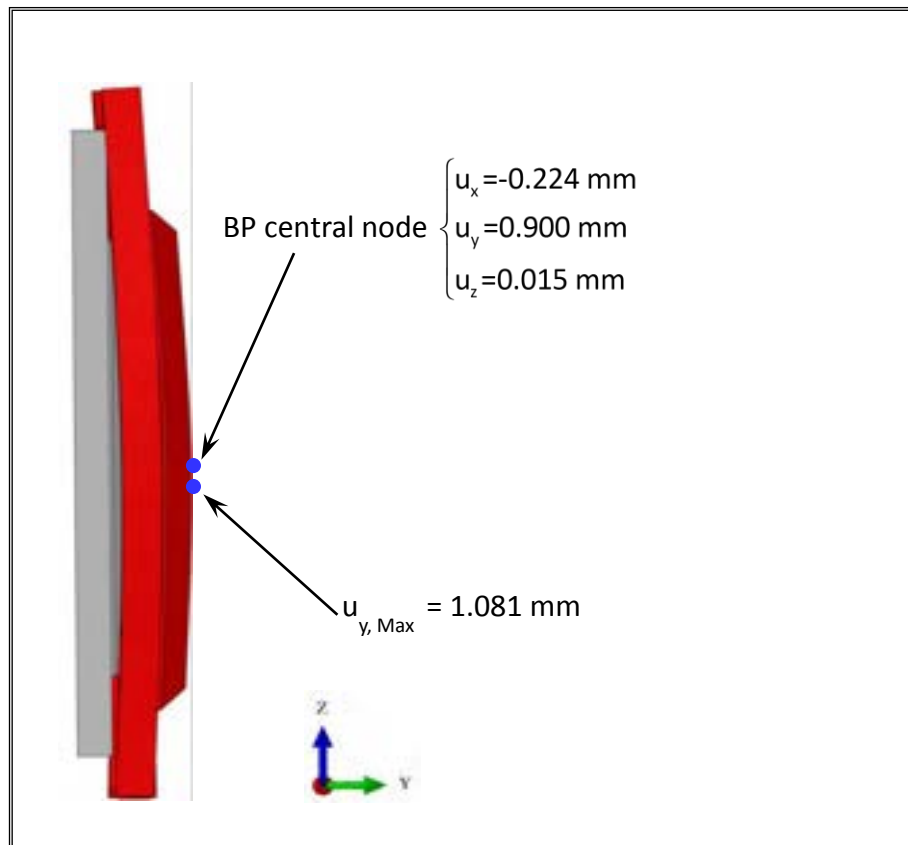


Figure 27. Condition 1 – BP deformed vs. un-deformed configuration.

Table 5. Condition 1. SDC-IC low temperature safety rules

	Path AB	Path CD	Path EF	Path GH	Path IL
$T_{\text{Max-Path}} [^{\circ}\text{C}]$	286	252	296	367	250
P_m/S_m	0.0040	0.0015	0.0002	0.0006	0.0018
$(P_m+P_b)/(K_{\text{eff}}*S_m)$	0.0027	0.0012	0.0003	0.0007	0.0013
$(P_m+Q_m)/S_e$	0.6993	1.0632	0.3038	0.4930	1.4017

4 Conclusions

As part of IFMIF design activities a research campaign has been launched during the current MSE-ENEA Agreement by ENEA-Brasimone in close cooperation with the Department of Energy, Information Engineering and Mathematical Models of the University of Palermo to theoretically investigate the thermo-mechanical behaviour of the IFMIF Target Assembly integrated with its support framework and lithium inlet pipe under the nominal operation loading scenario, to verify whether the component can safely withstand the thermo-mechanical loads it undergoes without incurring in significant deformations and yielding-induced structural crisis.

A theoretical approach based on the Finite Element Method (FEM) has been followed and a qualified commercial FEM code has been adopted to perform the study.

Three different thermo-mechanical loading conditions have been investigated and that named Condition 1, that foresees the support framework natural convective cooling, has been selected as the reference one.

Thermal results have indicated that the EUROFER critical temperature of 550 °C is never reached within the module, since a maximum temperature slightly lower than 430 °C is predicted at localized region of the target chamber at the edge with the frame and the back-plate, in all the three thermo-mechanical conditions assessed. In particular, Condition 1 results have shown also that the maximum temperature of 80.4 °C reached within the support framework suggests that no further cooling strategies are necessary for it, except for the natural convection cooling taken into account in this loading condition.

Mechanical results have shown that an intense Von Mises equivalent stress field is predicted at the edges of the back-plate flow channel, due to both high temperatures and geometrical discontinuity.

Mechanical results have also indicated that in Condition 1 the minimum value of the misalignment (u_x and u_z) between the deuteron beams and the lithium footprint and the lowest maximum displacement of the BP external surface toward the HFTM ($u_{y,Max}$) are predicted. In particular, the maximum BP displacement along the beam direction amounts to be 1.081 mm towards the HFTM. Therefore, BP and HFTM contact can be excluded, being 2 mm their nominal gap under room temperature.

Finally, SDC-IC safety rules have resulted to be generally fulfilled with sufficient margins except for those connected to the potential loss of ductility in particular heavily stressed paths lying on the BP middle section along the beam direction, suggesting the potential need of a BP design revision.

5 References

- [1] IFMIF Intermediate Engineering Design Report (IIEDR), IFMIF/EVEDA Integrated Project Team, June 2013
- [2] M. Ida, K. Watanabe, Lithium Target Facility (LF) - DDD-III_ED03JA, IFMIF DMS BA_D_22CXHK, 2013.
- [3] P.A. Di Maio, P. Arena, G. Bongiovì, Analysis of the thermo-mechanical behaviour of IFMIF Target Assembly, Report of the research activity of the consulting contract ENEA/2013/20303/UTIS.
- [4] D. Bernardi, Target assembly with bayonet backplate - DDD-III_ED03EU, IFMIF DMS BA_D_22W67Z, 2013.
- [5] G. Micciché, B. Riccardi, Design, manufacture and testing of the IFMIF lithium target bayonet concept, *Fusion Engineering and Design* 75–79 (2005) 807–811.
- [6] K. Mergia, N. Boukos, Structural, thermal, electrical and magnetic properties of Eurofer 97 steel, *Journal of Nuclear Materials* 373 (2008) 1–8.
- [7] T. Chehtov, J. Aktaa, O. Kraft, Mechanical characterization and modeling of brazed EUROFER-tungsten-joints, *Journal of Nuclear Materials* 367–370 (2007) 1228–1232.
- [8] E.I. Gol'tsova, *High Temperature* 4 (1966) 348.
- [9] E. E. Shpil'rain, I.F. Krainova, *High Temperature* 8 (1970) 1036.
- [10] J.W. Cooke, *J. Chem. Phys.*, 40 (1964) 1902.
- [11] F. P. Incropera, D. P. De Witt, *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, 4th Edition, 1996.
- [12] P.A. Di Maio, P. Arena, G. Bongiovì, Analysis of the thermo-mechanical behaviour of IFMIF Target Assembly integrated with its support framework, Report of the research activity of the consulting contract ENEA/2014/48465/UTIS.
- [13] ITER Structural Design Criteria for In-vessel Components (SDC-IC) code, ITER IDM G 74 MA 8 R0.1, 2004.
- [14] A. Li Puma et alii, Potential and limits of water cooled divertor concepts in view of their use for DEMO, CEA report SERMA/LPEC/RT/12-5272, pp. 17-20 (2012).

6 Acronyms

BP	Back-plate
DEIM	Department of Energy, Information Engineering and Mathematical Models
dpa	Displacement per atom
FDS	Fast disconnecting system
fpv	Full power year
HFTM	High Flux Test Module
IFMIF	International Fusion Materials Irradiation Facility
MSE	Minister of Economic Development
PAR	Annual Program of Realization
SDC-IC	Structural Design Criteria for In-vessel Components
TA	Target Assembly