Agenzia Nazionale per le Nuove Tecnologie,
l'Energia e lo Sviluppo Economico Sostenibile

Ministero dello Sviluppo Economico

RICERCA DI SISTEMA ELETTRICO

Rapporto di avanzamento del progetto del target di IFMIF comprensivo di disegni e di analisi numeriche

D. Bernardi, G. Miccichè, M.Frisoni, F.S. Nitti, M.Serra

Report RdS/2011/387

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Novembre 2011

Report Ricerca di Sistema Elettrico
Accordo di Programma Ministero dello Sviluppo Economico – ENEA
Area: Governo, gestione e sviluppo del sistema elettrico nazionale
Progetto: Fusione nucleare: Attività di fisica e tecnologia della fusione complementari ad ITER, denominate "Broader Approach"
Responsabile Progetto: Aldo Pizzuto, ENEA

ENEA Ricerca Sistema Elettrico	**Sigla di identificazione** IM-G-R-017	**Distrib.** R	**Pag.** 3	**di** 30

Titolo

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Descrittori

Tipologia del documento: Deliverable

Collocazione contrattuale: Accordo di programma ENEA-MSE: tema di ricerca “IFMIF”

Argomenti trattati: IFMIF/EVEDA project, IFMIF Target Assembly, Bayonet Back-Plate, Engineering Design, Liquid Lithium free surface flow

Sommario

The present report describes the Engineering Design Activities concerning the development of the Target Assembly system based on the bayonet Back-Plate concept for the International Fusion Materials Irradiation Facility (IFMIF) currently under development within the Broader Approach agreement between Europe and Japan. The work has been carried out in the framework of the present EVEDA (Engineering Validation and Engineering Design Activities) phase of the IFMIF project (IFMIF/EVEDA project) as part of the Broader Approach activities during the reference period December 2010 – November 2011.

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			FIRMA			
REV.	**DESCRIZIONE**	**DATA**		**REDAZIONE**	**CONVALIDA**	**APPROVAZIONE**

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Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-based irradiation facility that is being developed within the Broader Approach agreement between Europe (EURATOM) and Japan, with the goal of providing a high intensity fusion-like neutron source for testing candidate materials for future fusion reactors under significant neutron damage rate (up to 30 dpa/fpy). The neutrons production in IFMIF is based on nuclear stripping reactions that occur within a free surface jet of liquid lithium flowing on a target exposed to two 40 MeV deuterons beams with a current of 125 mA each, delivering a total power of 10 MW on a 200x50 cm^2 footprint area. To remove such a high power density, the lithium in the target must flow at velocities as high as 20 m/s, while maintaining a stable thickness of the jet (25 ± 1 mm) in order to assure the requested neutron efficiency and to avoid the damage of the structural material. An hydraulic channel with a suitable concave profile is shaped on a steel plate (the so called *Back Plate*, BP) to guide the lithium flow and to create in it, by means of centrifugal forces, a pressure field that prevents its boiling (Fig. 1).

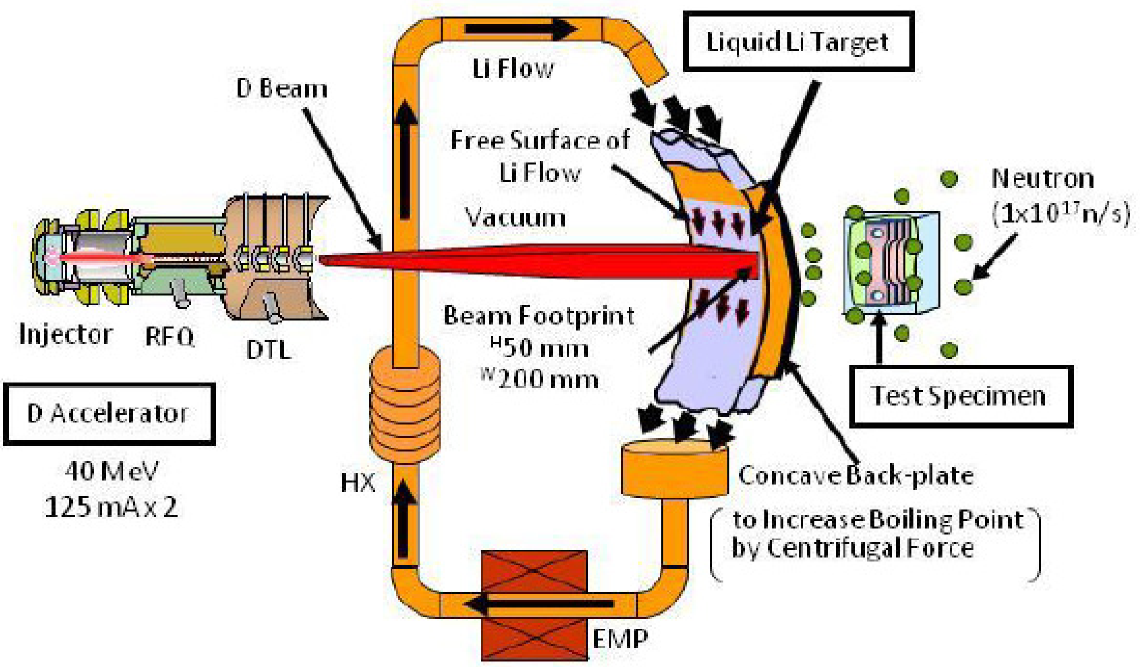


Fig. 1 – IFMIF concept

The BP represents one of the most critical components as it is exposed to a high-energy intense neutron flux and consequently to severe irradiation damage rates (up to 60 dpa/fpy). Within the IFMIF/EVEDA project, two different concepts are conceived for the IFMIF lithium target: the integral concept (to be developed in Japan by JAEA, see Fig. 2) and the so-called removable bayonet back-plate concept (to be developed in Europe by ENEA, see Fig. 3).

The integrated concept requires that, when the BP is dangerously degraded, due to the effects of neutron irradiation and exposure to high velocity liquid metal flow, the whole Target Assembly (TA), including the integrated back plate, is replaced. On the other hand, the replaceable concept foresees that only the back plate is replaced, while the rest of the target assembly, being less exposed to neutron irradiation, can survive for a longer time. Although technically more complex, this latter option has the advantage to limit the nuclear waste build-up and to make the replacement operations easier.

The solution proposed by ENEA to implement the removable BP concept is based on the so-called bayonet concept. This consists of a fixed plate (called the interface frame) attached to the main structure of the TA, on which the removable back plate can be slided and then rigidly connected by means of suitable skate mechanisms and tightening bolts.

The present report describes the main activities carried out in the reference period concerning the engineering design of the IFMIF Target Assembly system with bayonet BP.

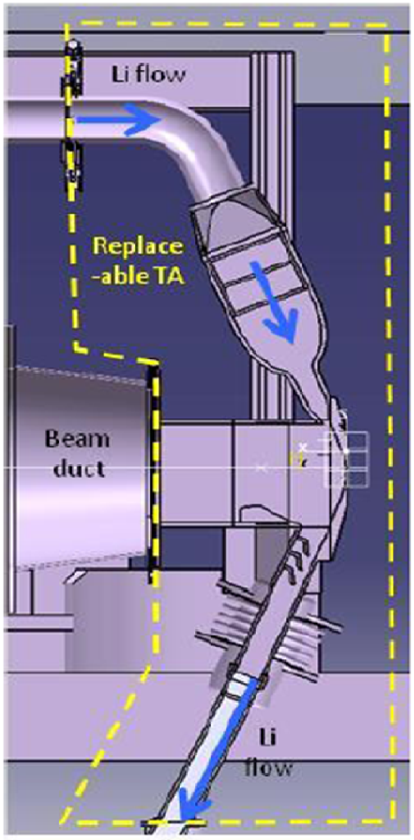


Fig. 2 - Integral TA (JAEA design)

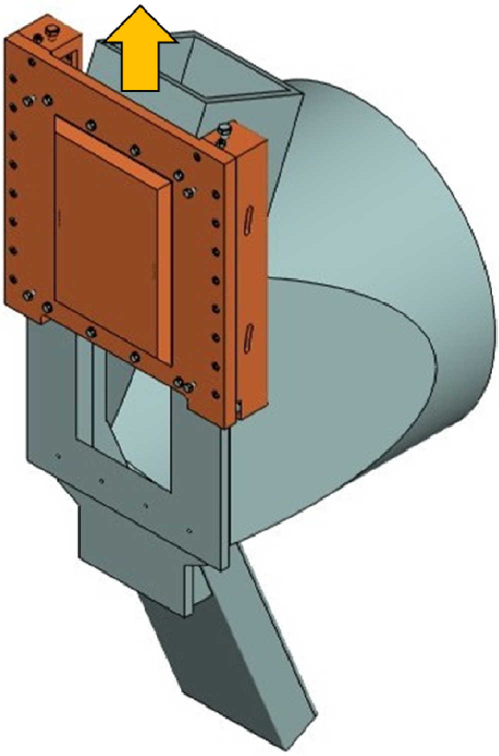


Fig. 3 - TA with removable bayonet BP (ENEA design)

1. IFMIF Lithium Target system

1.1 System requirements

The main requirements that the IFMIF target system must fulfill are summarized below:

• Beam total power	10 MW
• Footprint area	100 cm^2 (20 x 5 cm)
• Average heat flux	1 GW/m^2
• Li velocity	10-20 m/s
• Jet width	260 mm
• Li jet thickness	25 mm ± 1
• Li temperature at inlet	250 °C
• Pressure at Li surface	10^{-3} Pa
• Erosion/corrosion rate	1 µm/y
• TA replacement frequency	11 months
• Availability	95 %

1.2 Technical specifications and design assumptions

The target system must provide several functions which can be identified by means of a specific system functional analysis. To satisfy such functions, a set of technical specifications which meet the previous system requirements along with other complementary design assumptions are to be considered.

These specifications and design assumptions are given in Tab. 1 for each function identified:

Function	Specification / Design assumption
To produce neutron flux with sufficiently high intensity for irradiation of test modules	• BP min. thickness : 1.8 mm • Jet thickness: 25 mm (nom.) + 1 mm (max)
To remove the high thermal power deposited in the Li jet	v = 10 - 20 m/s
To protect the BP from direct exposure to the D beams	Jet thickness: 25 mm (nom.) – 1 mm (max)
To avoid Li boiling and vaporization	Curved BP
To maintain a stable high-velocity, free surface flow of liquid Li in front of the D beams	• Li profile with changing curvature (ENEA design) • Li channel entirely arranged on the BP

Function	Specification/ Design assumption
To guarantee high quality of the D beams	p = 10^{-3} Pa (at free surface)
To operate under irradiation condition in the TTC	replacement of the BP via RH operation
To guarantee low activation of materials	RAFM steel (EUROFER)
To assure easy, fast and reliable RH operation inside TTC	QDS (Quick Disconnecting System) concept for flange connections
To allow the replacement of the BP only	Removable bayonet BP concept

Tab. 1 – Technical specifications and design assumptions

1.3 The bayonet BP concept

The bayonet BP concept (Fig. 4), developed at ENEA Brasimone as an alternative to the integral target concept, is based on the possibility to remove and insert the BP while leaving in position the rest of the TA. This is achieved by means of special skate mechanisms installed on the BP which permit to slide the BP on the fixed part of the TA and to create the necessary closure force on the two lateral sides of the sealing gasket. The closure force on the other two sides (upper and bottom sides) of the gasket is produces by eight (4 in the upper part and 4 in the bottom part) tightening bolts (Fig. 4).

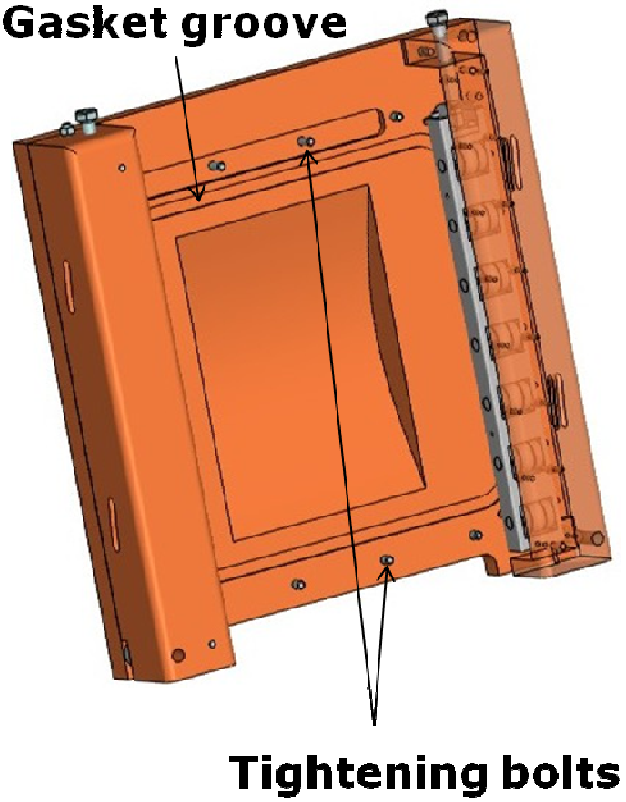


Fig. 4 – Bayonet BP

Each skate consists of a chassis in which triple bearings are mounted on 7 parallel axes (Fig. 5). Each bearing axis comprises three wheels: the two outside wheels push on the fixed frame while the central wheel runs on inclined planes (green part in Fig. 5) mounted on the skate support structure attached to the BP, and transmit the pushing force to the gasket. Each skate is handled indipendently by means of a driving screw (Fig. 6) that allows to engage or disengage the wheels from the inclined planes and therefore to connect or disconnect the BP from the fixed TA body.

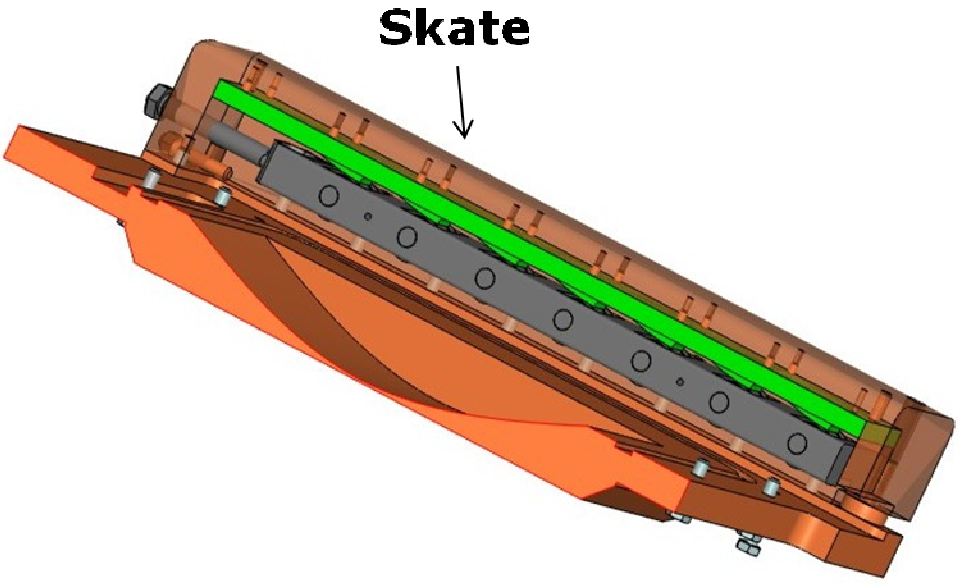


Fig. 5 - Skate mechanism (fixed frame not shown)

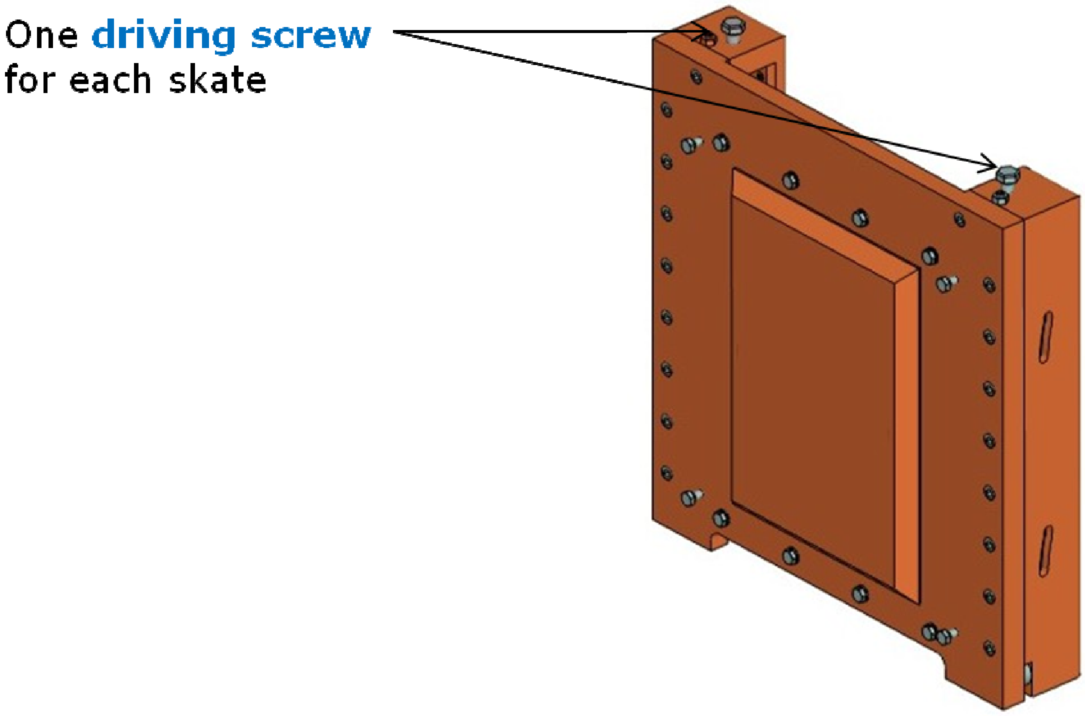


Fig. 6 - Skate driving screws

2. Engineering Design Activities

Within the IFMIF/EVEDA project, ENEA is in charge of the design of the IFMIF TA with bayonet BP. The engineering design activities (EDAs) that are foreseen for the development of the system are described in detail in the IFMIF Procurement Arrangement ED03-EU [1]. They include, in particular, the following tasks:

(1) Mechanical design of the TA system
(2) Nuclear analyses
(3) Thermohydraulic calculations
(4) Thermomechanical calculations

As a further ENEA commitment within the IFMIF Procurement Arrangement ED03-EU, the following specific activities are also foreseen:

(5) Design of the remote-handing tools specific to the TA with bayonet BP
(6) Safety assessment of the Li Target Facility

The present report does not include the activities (5)-(6), as they are still in a preparatory phase and need further data from the EDAs (1)-(4) to be really started.
Work carried out within tasks (1)-(4) along with the main products and outcomes obtained are described in the following Sections.

2.1 Mechanical design of the IFMIF Target Assembly

An updated 3D CATIA model of the Target Assembly system with bayonet BP has been produced during the reference period. This model consists of the following components (see Fig. 7):

- Inlet pipe with flange connection to the Li loop pipe
- Flow straightener
- Double reducer nozzle with Shima-type profile
- Target chamber with flange connection to the beam duct
- Interface frame
- Removable back-plate
- Outlet section with flange connection to the exit Li pipe

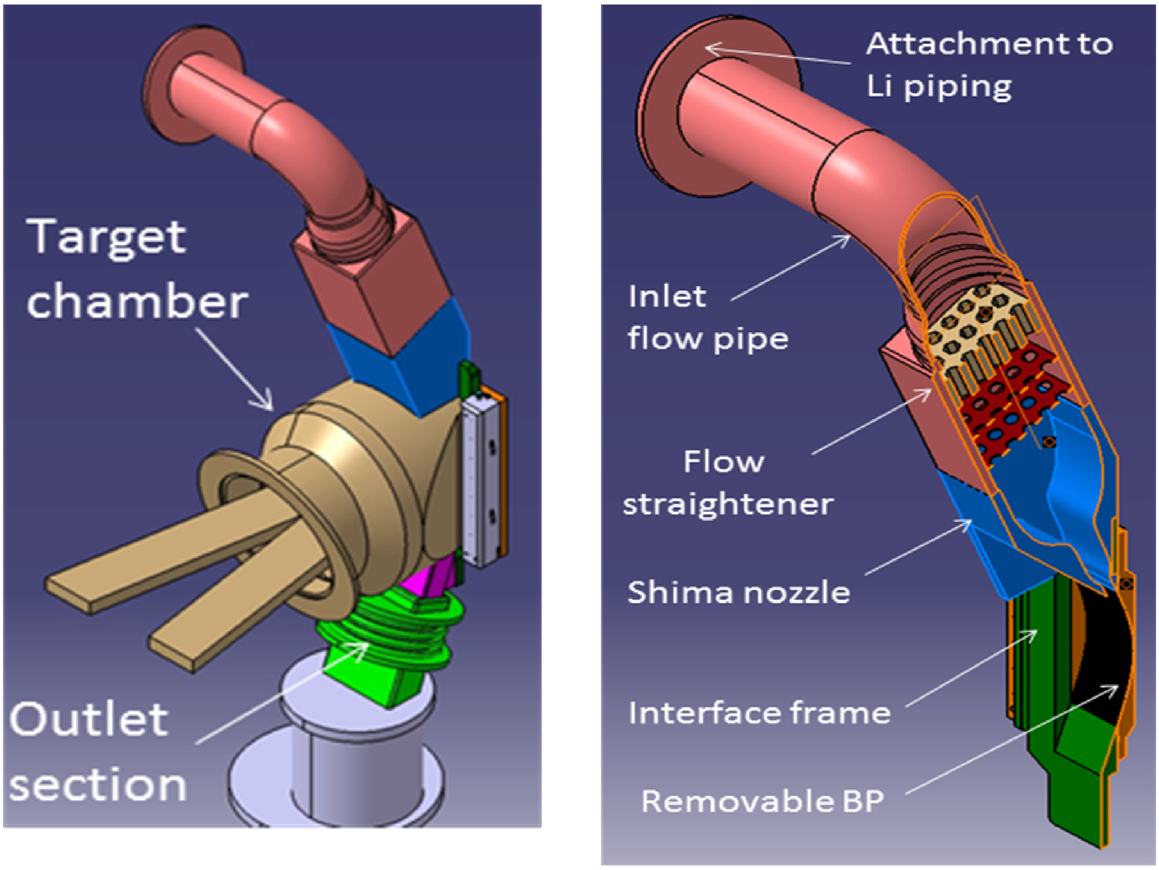


Fig. 7 – Components of the Target Assembly system

Starting from a first preliminary design (including only the BP and the interface frame), an updated version of the TA model has been developed in the reference period by introducing some modifications and optimizations and by adding all the components (e.g. flow straightener, target chamber, flanges,…) that had not been included before. In particular, the concept based on the flow channel entirely shaped on the back-plate (instead than having it distributed between the BP and the interface frame as in the TA prototype already developed by ENEA for the EVEDA Lithium Test Loop facility at Oarai in Japan) has been implemented.

The original “open” three-side structure of the interface frame has been turned into a closed structure in order to prevent possible manufacturing and sealing problems (see Fig. 8).

Attention has been paid to the right dimensioning and geometrical arrangement of all of the parts of the model in such a way that they can fit well together within the given overall dimensions of the TA system that are mainly imposed by the size of the Test Cell and the layout of the lithium loop. An accurate analysis has been done by means of the specific built-in CATIA tools in order to prove the full functionality of all of the TA components and in particular to assure that the BP could be extracted and inserted without any interference with the other parts of the TA.

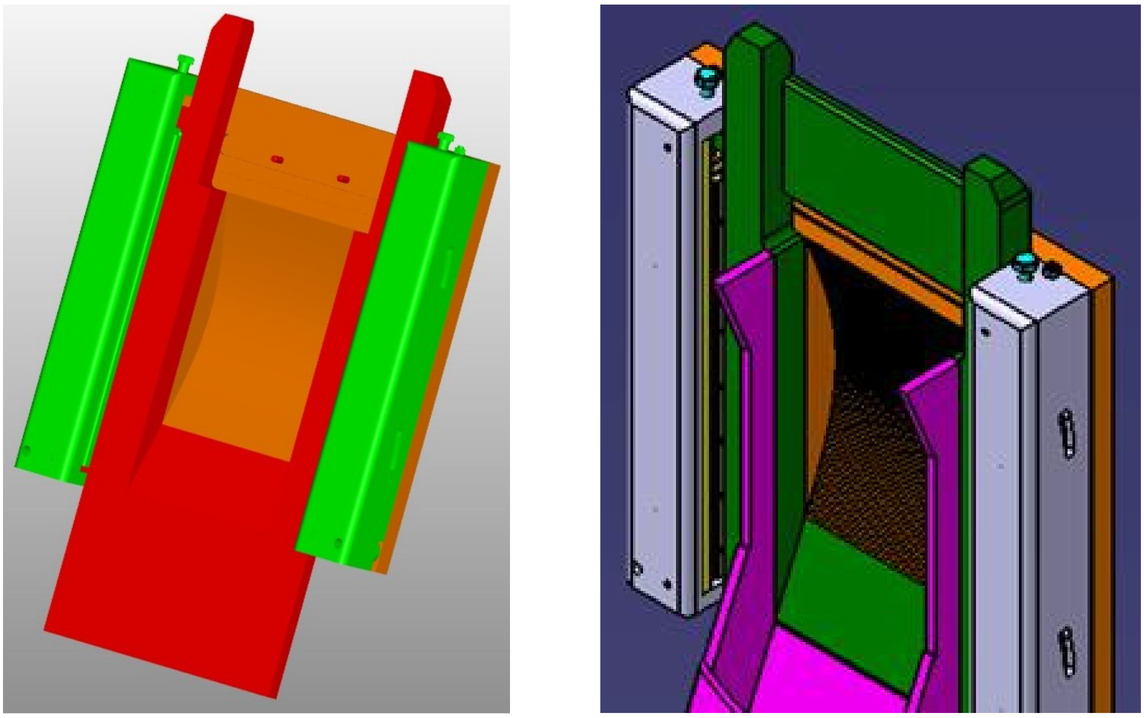


Fig. 8 – Open (previous) e closed (current) design of the target interface frame

The model has been completed with the design of the target chamber, of the flow straightener with its internal structures (1 honeycomb + 2 perforated plates) and of the inlet and outlet sections (Fig. 9). However, these components still need to be better assessed for what concerns the integration of the TA model with the Test Cell and the lithium loop that are still under development. For this reason, the present TA model might probably be subjected to some revisions in the future.

Some effort has been done in trying to reduce the weight of the assembly as much as possible: the total weight is now about 870 kg for the whole structure, but some improvements are still probably achievable (a further optimization is foreseen during the progress of the design work).

As for the interfaces, a possible solution for the mechanical connection of the Target Assembly with the Li loop and the beam duct has been preliminarily identified. This solution foresees the use of three customized Quick Disconnecting Systems (QDS, Fig. 10) to easily remove the Target Assembly via remote-handing tools for refurbishment operations. In particular, the solution proposed for the inlet and the beam connections is based on a QDS with inclined flanges in order to facilitate the extraction of the TA. While the use of an inclined flange at the inlet (Fig. 11) should not represent a matter of concern due to the limited dimensions of the pipe (6''), the same concept for the connection with the beam chamber (Fig. 12) which has much larger diameter (about 700 mm at present) requires a specific QDS design whose feasibility is still to be assessed. However, in case that this solution will demonstrate to be not feasible, a backup option based on the use a dismantling joint has been envisaged.

Future activity will be mainly devoted to the completion and optimization of the present model (also based on the indications coming from the detailed thermomechanical calculations) as well as to the design of the support structures and the integration of the system with the Test Cell and the lithium loop design currently under development in Germany (at KIT) and in Japan (at JAEA), respectively.

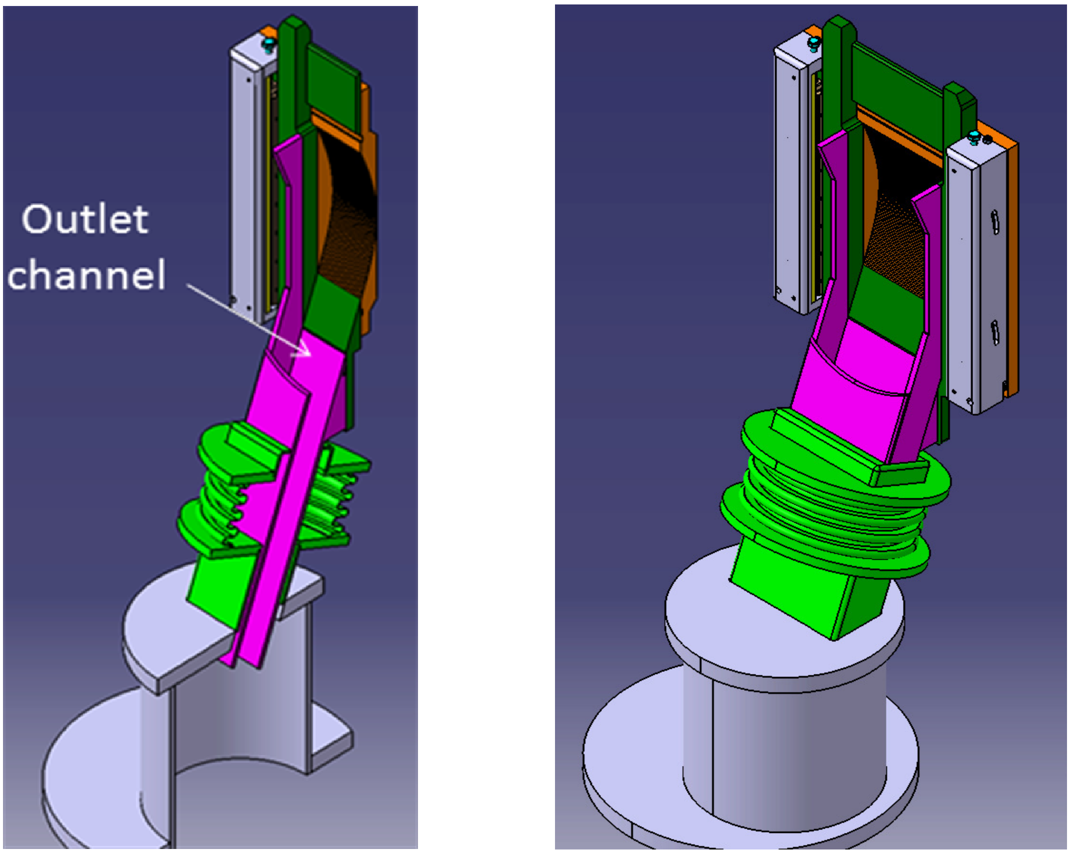


Fig. 9 – Outlet section of the Target Assembly

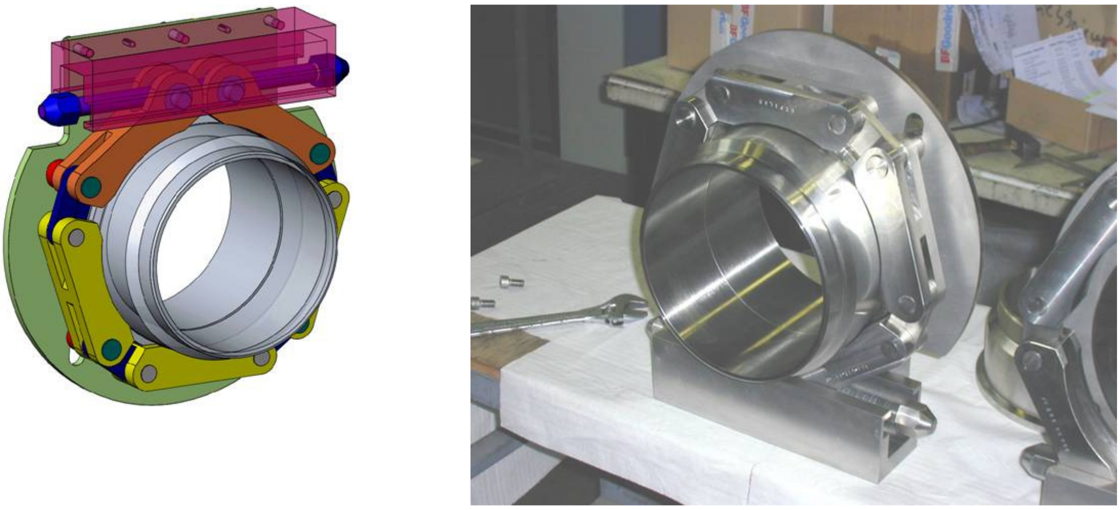


Fig. 10 – Quick Disconnecting System (QDS)

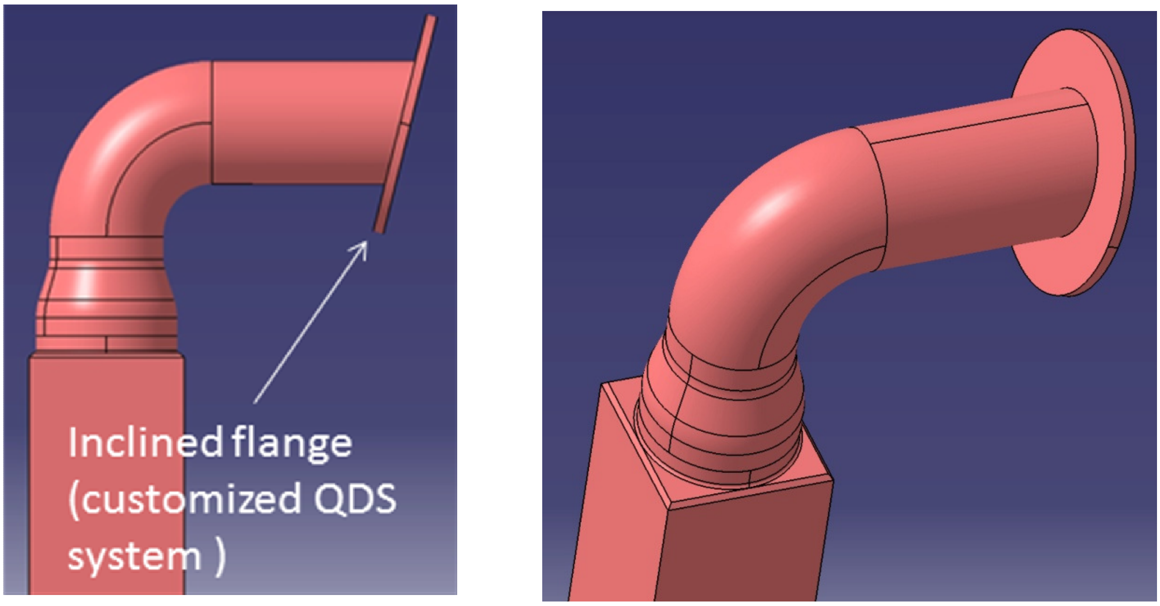


Fig. 11 – Inlet connection with QDS and inclined flanges

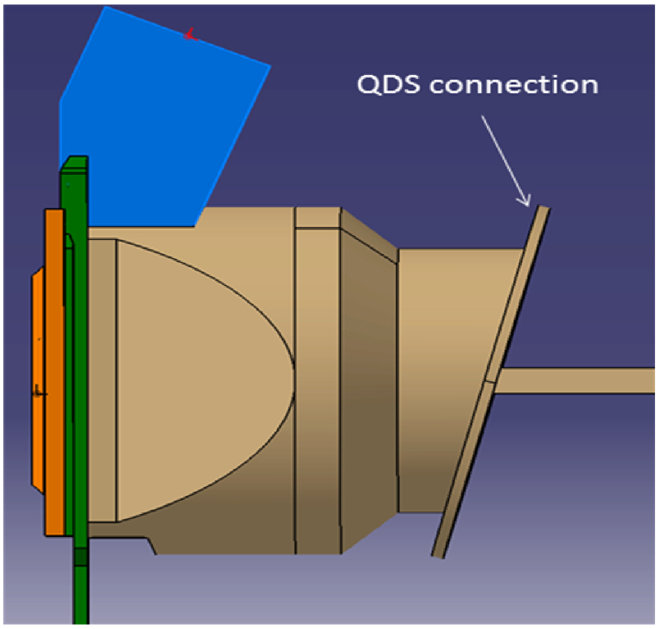


Fig. 12 – Beam connection (solution with QDS and inclined flanges)

2.2 Nuclear analysis

Preliminary neutron/gamma transport calculations have been performed for the BP through Monte Carlo MCNP5 code. The neutronic model included the lithium jet, the BP and the High Flux Test Module (HFTM) pertaining to the Test Facility, as shown in Fig. 13. The calculations have been performed for the BP using the “superimposed mesh tally” feature of MCNP5 code.

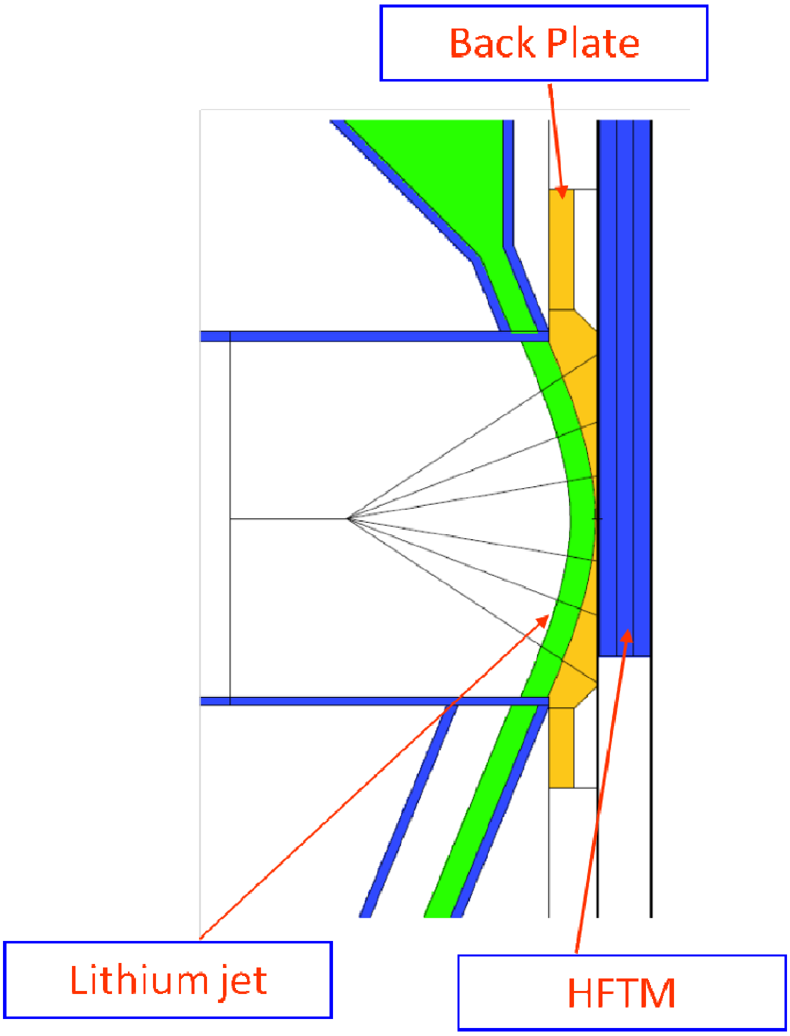


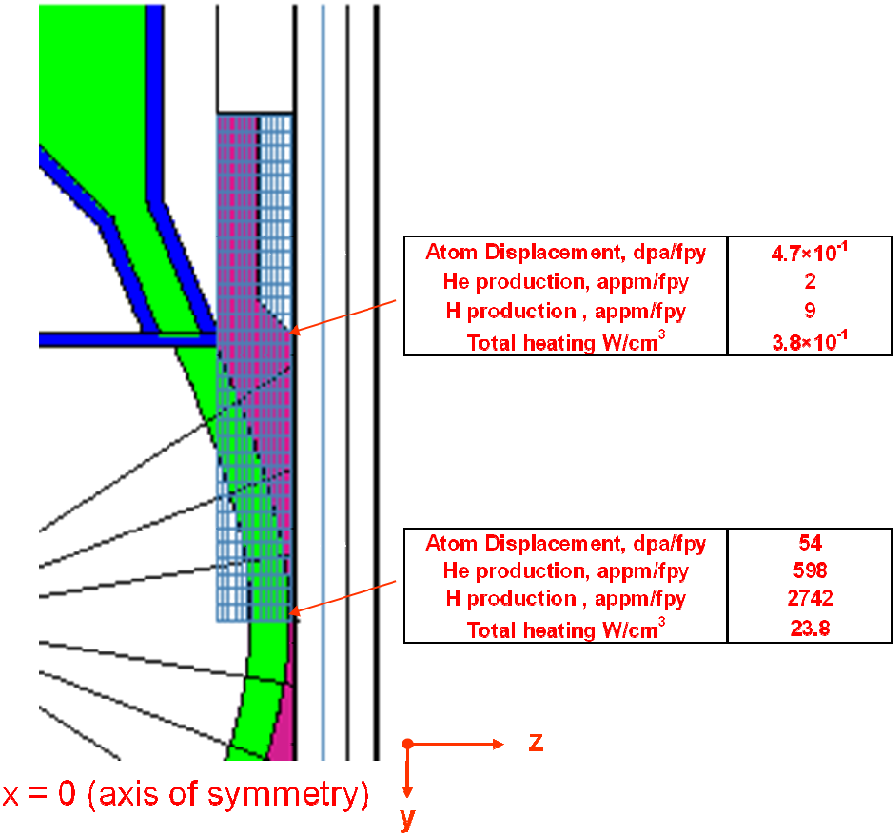
Fig. 13 - Neutronic model of the BP

The McDeLicious-05 neutron source code provided by KIT was used for the calculations.

This code uses the newly evaluated (d + ^{6,7}Li) cross section data files, produced under a collaboration of IPPE (Obninsk) and KIT (Karlsruhe), containing the cross sections and the energy-angle distributions of the reaction products for deuteron energies up to 50 MeV.

The neutron-induced cross section data files used in the calculations are mainly from IPPE-50 library, developed at IPPE-KIT, for neutron energies up to 50 MeV, and LANL-150N, developed at Los Alamos National Laboratory, for neutron energies up to 150 MeV.

Average results in terms of neutron damage, gas (He and H) production rates and nuclear heating are shown in Fig. 14 for two different positions, one of which located in the footprint region, i.e., in the highest exposed zone of the BP. Damage rates well above 50 dpa/fpy are achieved in this location with a He/dpa ratio of about 11 wppm/dpa and a nuclear heating of about 24 W/cm^3 .



Atom Displacement, dpa/fpy	4.7×10^{-1}
He production, appm/fpy	2
H production , appm/fpy	9
Total heating W/cm^3	3.8×10^{-1}

Atom Displacement, dpa/fpy	54
He production, appm/fpy	598
H production , appm/fpy	2742
Total heating W/cm^3	23.8

Fig. 14 – Neutronic calculation results

The deuteron power deposition profile in the lithium in the footprint area was also calculated.

In the IFMIF design two linear accelerators are foreseen each generating 125 mA of 40 MeV deuterons. These beams stop in the lithium jet delivering a total power of 10 MW on a volume of 5×20 ×2.5 cm^3. The deuterons loss their energy in lithium both for electronic and nuclear interactions.

A validated computational approach able to simulate the deuteron transport and to evaluate the deuteron nuclear interactions and consequent production of secondary particles is required. The current available Monte Carlo codes, those able to handle charged particle transport as MCNPX, when applied to deuteron transport calculations are not able to use deuteron cross sections evaluated data libraries and use built-in semi-empirical models to describe the deuteron nuclear interactions. These models were found unreliable in predicting the neutron and photon production induced by low energy deuterons, as those present in IFMIF.

The calculation of deuteron energy deposition in lithium was firstly performed with the “standard” MCNPX 2.7d code (β test version). This code version uses models to treat the deuteron nuclear interactions. The transport of deuterons, neutrons, protons and photons was considered. The calculation was performed by modeling a 250 mA deuteron beam of 40 MeV impinging on a footprint of 100 cm^2. The beam was considered on the z-axis. The 2.5 cm thickness of the lithium jet was subdivided in proper spatial intervals in order to calculate the power deposition (W/cm^3). Default values of MCNPX were used in the calculation, for example the straggling treatment of the energy loss following the Vavilov method. The total energy deposition profile (W/cm^3) vs. penetration depth (mm) is given in Fig.15. The curve shows the typical Bragg peak.

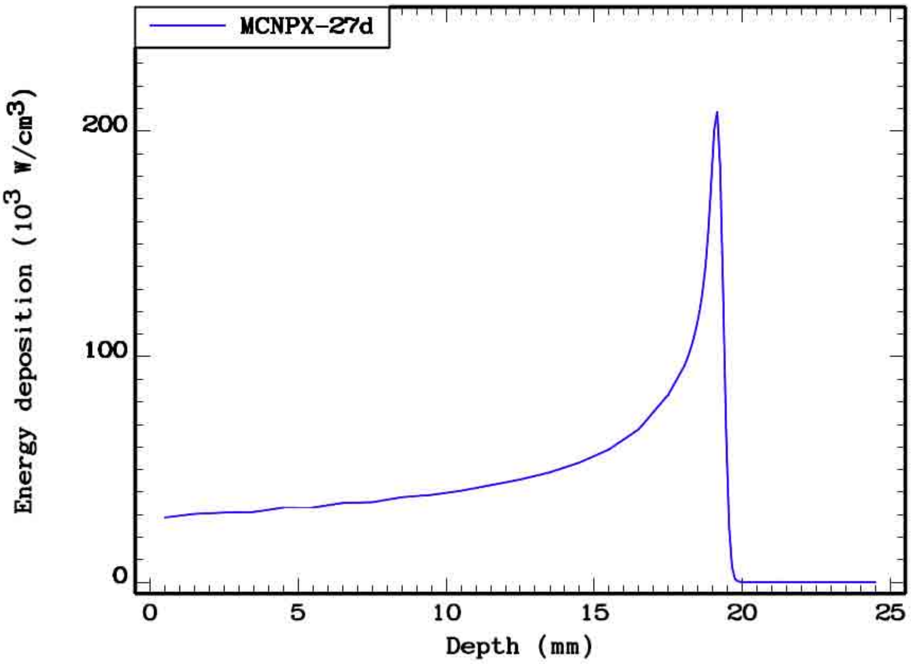


Fig. 15 – Total energy deposition profile (W/cm^3) vs. penetration depth (mm)

Recently, a new computational code, called MCUNED, has been made available [2].

MCUNED code is an extension of MCNPX 2.7d and it is able to handle the deuteron evaluated cross section data libraries allowing a better description of the deuteron nuclear interactions with matter.

A new calculation was performed with the MCUNED code by using the same geometrical model use in MCNPX-27d calculation.
The following evaluated nuclear data files in ACE format were used: d + ^{6,7}Li and n+ ^{6,7}Li provided by KIT, p + ^{6,7}Li from TENDL-2009 library.

The comparison between the energy deposition profile obtained with the "standard" MCNPX 2.7d and MCUNED is shown in Fig. 16. In MCUNED the different treatment of deuteron nuclear interactions produces a lowering of the peak value (from 209 KW/cm^3 to 161 kW/cm^3) and a slight shift of the peak position (from 19.1÷19.2 mm to 19.0÷19.1 mm)

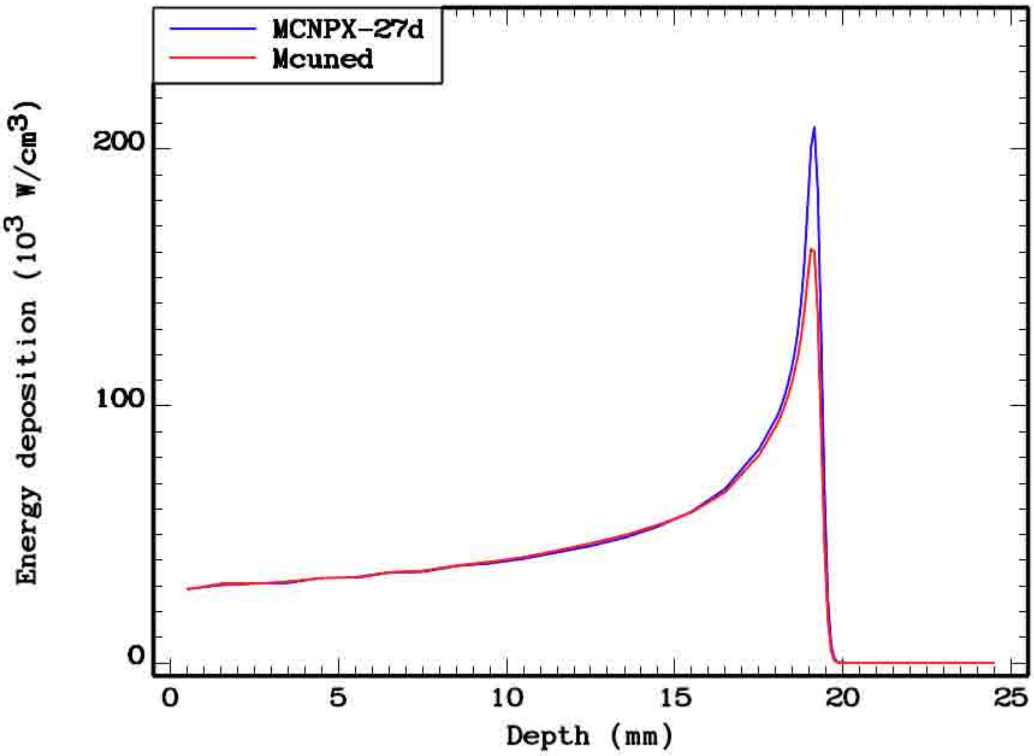


Fig. 16 – Comparison between the energy deposition profile obtained with the "standard" MCNPX 2.7d and MCUNED

The previous calculations were performed by considering a monochromatic beam of 40 MeV. The deuterons produced by the accelerator beam transport of IFMIF will have a gaussian energy distribution around the average value of 40 MeV.

In literature, the gaussian dispersion of the IFMIF deuteron beam is sometimes defined with a FWHM (Full Width at Half Maximum) equal to ± 0.5 MeV other times with a standard deviation $\sigma = 0.5$ MeV. Some calculations were performed with the MCUNED code considering different beam energy distributions.

Fig.17 shows the energy deposition profiles related to:

a) monochromatic beam of 40 MeV (blue curve)
b) beam with FWHM = ± 0.5 MeV (total FWHM = 1 MeV, see CDR [3]) (red curve)
c) beam with $\sigma = 0.5$ MeV (green curve)

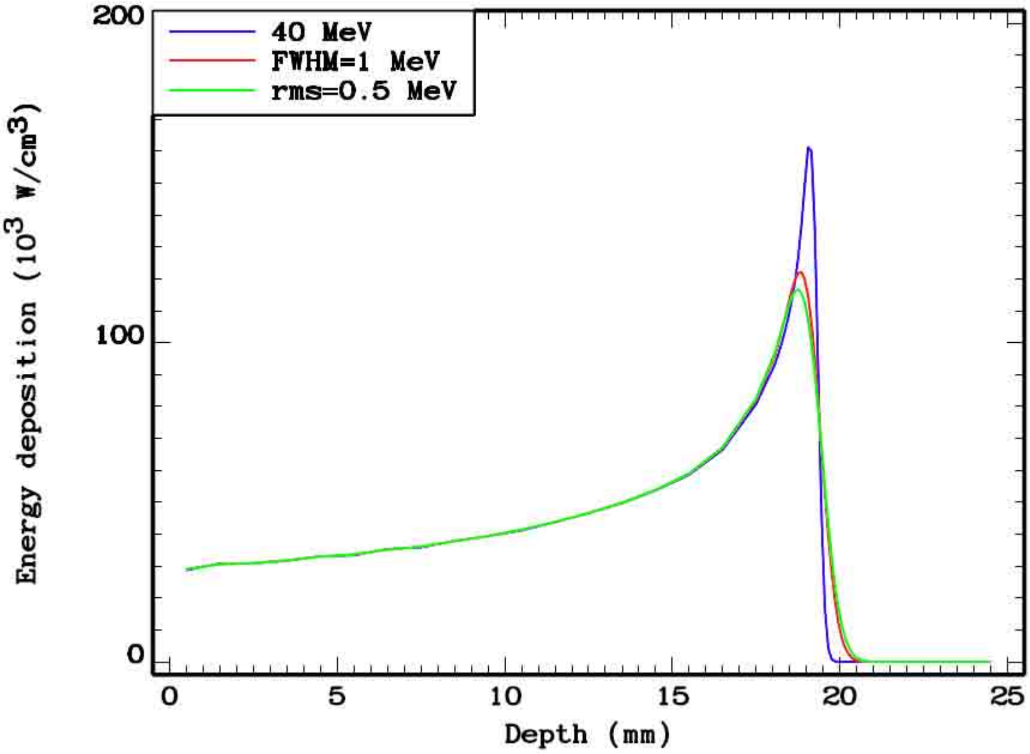


Fig. 17 – Energy deposition profiles for different beam energy distributions

The energy dispersion of the incident deuterons broadens the peak, reduces its height and shifts the peak at a lower position. The corresponding values for the three cases are:

a) peak value = 161 kW/cm3 between 19.0÷19.1 mm
b) peak value = 122 kW/cm3 between 18.8÷18.9 mm
c) peak value = 117 kW/cm3 between 18.7÷18.8 mm

These effects are more evident in case c) due to the relation between FWHM and σ: FWHM = 2.35482 σ. The energy dispersion slightly increases the beam penetration range in the target. Following CDR [3], case b) data can be considered as the reference one for which regards the deuteron beam energy distribution.

More detailed calculations for the deuteron power deposition in the footprint region taking into account the real beam intensity distribution, the lithium jet curvature and the 9° inclination angle of the two beams are in progress.

2.3 Thermohydraulic calculations

The main effort in designing an hydraulically suitable profile for the Li jet comes from the necessity to reduce, as far as possible the perturbations of the flow. It is generally accepted that, apart from the case of constant curvature, all the other profiles, having axial symmetry, imply accelerations/decelerations of the flow along its curvilinear coordinate. The theory of boundary layer [4] shows that the deceleration condition is very likely to promote a boundary layer detachment, even in turbulent flows. Since the boundary layer separation is associated with large energy losses and introduces new perturbations in the motion, it has to be avoided. For this reason, any sudden change of adverse pressure should be avoided and the pressure increase should be uniformly distributed along the flow path.

To achieve this result, the flow straight path is better replaced by a curved one, presenting gradual change of curvature together with gradual pressure increase. Experiments performed by Loginov at IPPE [5] demonstrated that the sudden transition from straight profile to the radius zone of reference curvature (R = 250 mm) of the CDR design [3], produces unwanted perturbations of the flow. To limit as much as possible such perturbations, an analytical correlation has been developed by ENEA [6], which permits to trace a channel profile able to apply gradual pressure changes to the free surface flow. Starting from simplified Navier–Stokes equations, this analytical correlation in cartesian coordinates can be written in implicit form as:

$$\sqrt{x^2+y^2}\left[Aarctg^3\frac{y}{x}+Barctg^2\frac{y}{x}+Carctg\frac{y}{x}+D\right]+x-\frac{v_\vartheta^2}{g}=0$$

where v_θ is the lithium velocity in tangential direction, g is the gravitational acceleration and A, B, C, D are numerical constants to be determined by imposing the geometrical constraints of the channel at its boundaries [7].

Fig. 18 shows the gradual pressure increase along the channel profile calculated by means of the FLUENT® code for the geometrical parameters given in Fig. 19 and assuming a lithium velocity v_θ = 20 m/s.

The shape of the calculated profile is shown in Fig. 19.

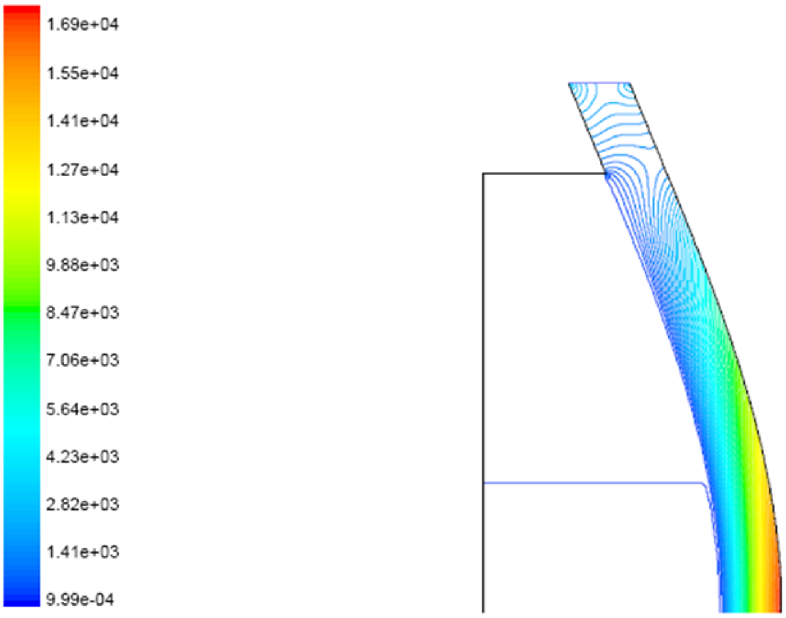


Fig. 18 - Pressure distribution along the Li channel

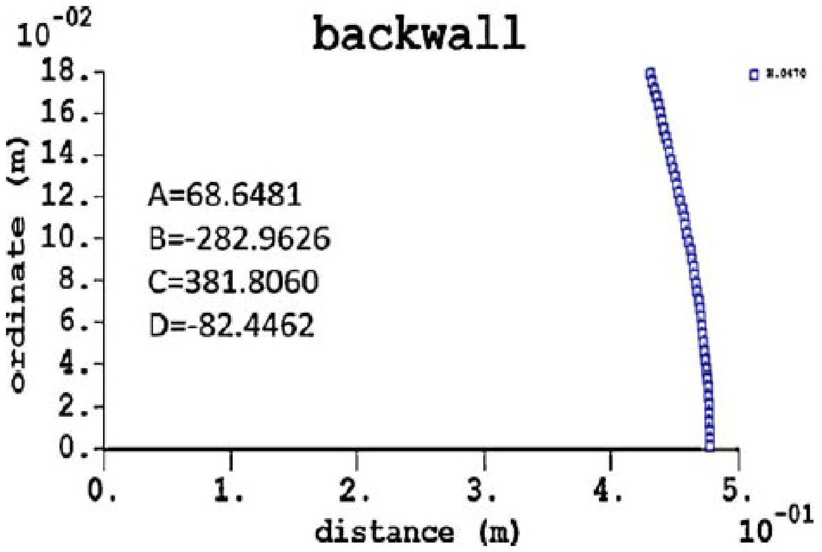


Fig. 19 – Analytically calculated shape of the Li channel profile

2.4 Thermomechanical calculations

Preliminary thermomechanical calculations have been performed to assess the capability of the skate support structures to withstand the high closure loads that are necessary to assure the tightening of the BP against the interface frame in order to guarantee the proper sealing of the gasket.

The analyses have been carried out considering typical design conditions characterized by thermal loads due to the lithium temperature (taken at a uniform value of 400 °C), irradiation condition of the BP towards the Test Cell atmosphere (assumed at 50 °C) with all the other TA parts thermally insulated and mechanical loads induced by the force produced through the skates and the tightening bolts on the BP.

Figs. 20 and 21 show the distribution of the calculated maximum principal stress in the structure. It can be noted that the component is globally working under safe (elastic) conditions. High stresses appear only in a very localized region near a sharp corner of the structure but these are most likely due to numerical singularities that arise because of the geometrical discontinuity and do not pose concerns from the thermomechanical point of view.

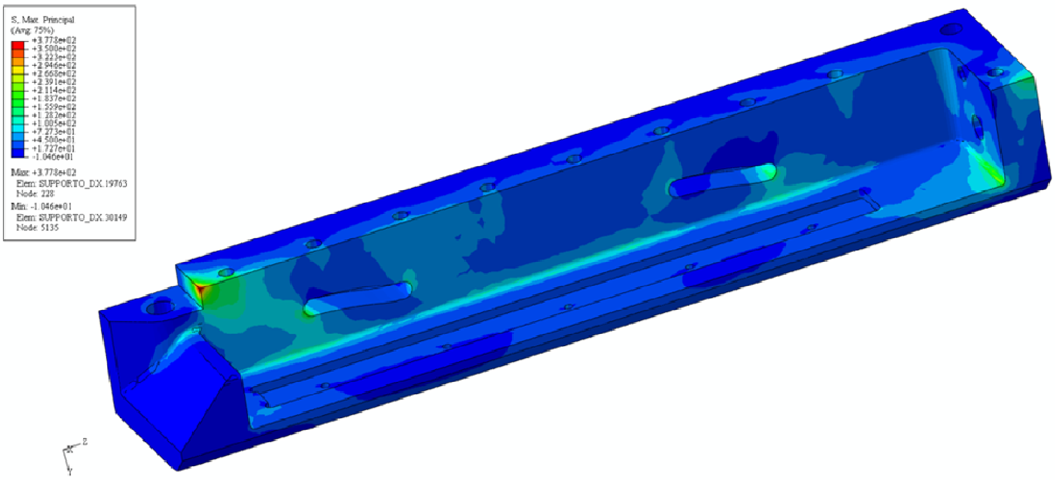


Fig. 20 - Maximum principal stress in the skate support structure (inside view)

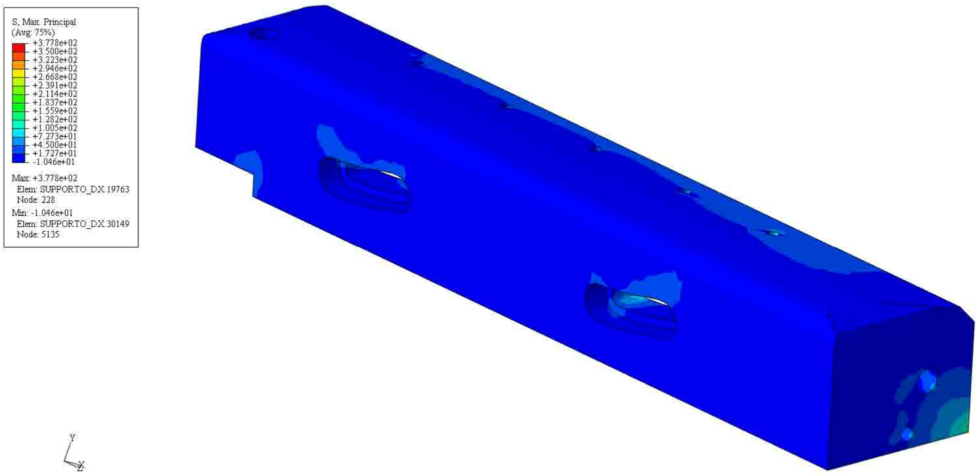


Fig. 21 - Maximum principal stress in the skate support structure (outside view)

The Fig. 22 and 23 also show the tensile and compressive fields in the part of the structure that bears the inclined planes, again demonstrating the capability of the component to safely resist against the applied loads.

Finally, in Figs. 24 and 25 the direction of the principal stresses are reported.

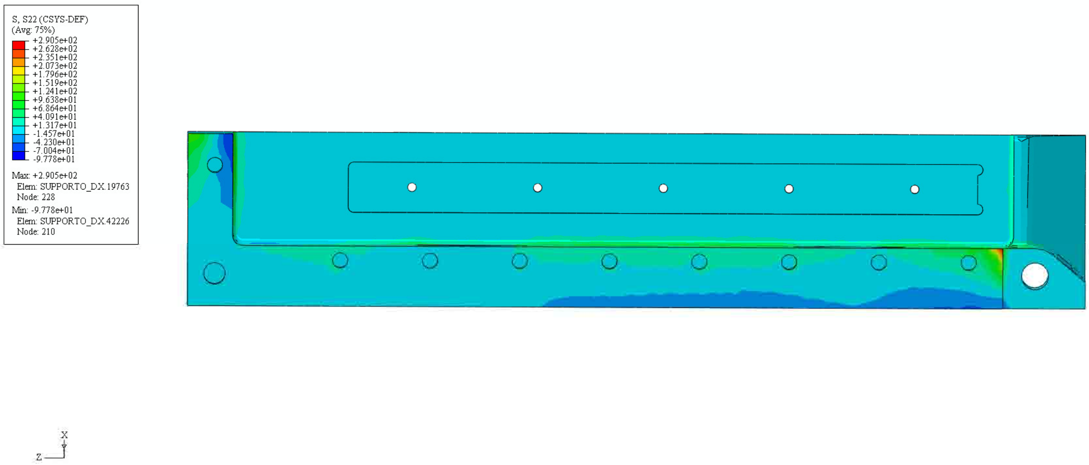


Fig. 22 - Tensile stress field in the part bearing the inclined planes

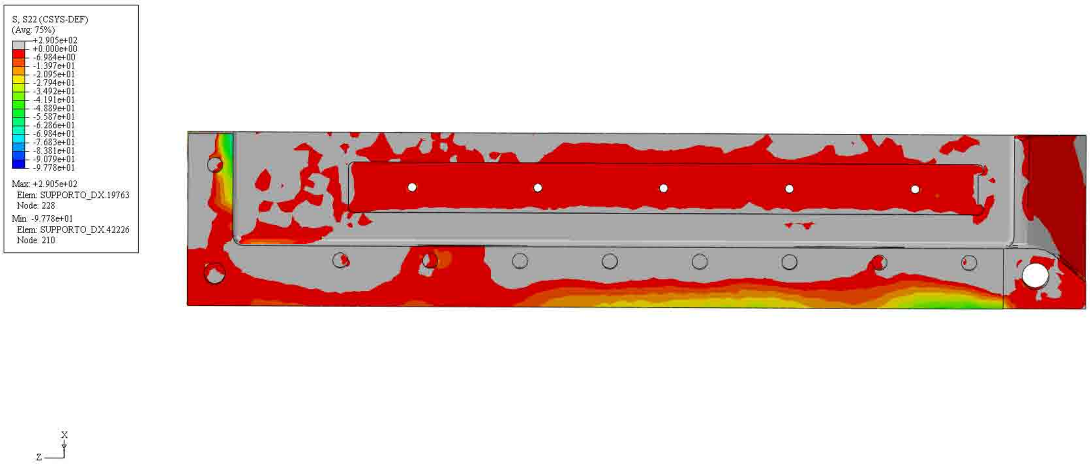


Fig. 23 – Compressive stress field in in the part bearing the inclined planes

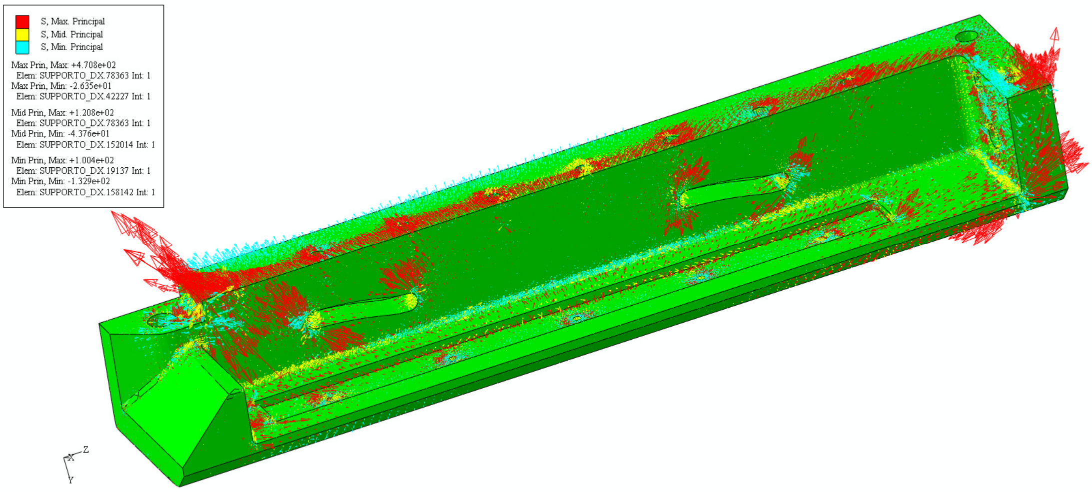


Fig. 24 - Direction of the principal stresses (inside view)

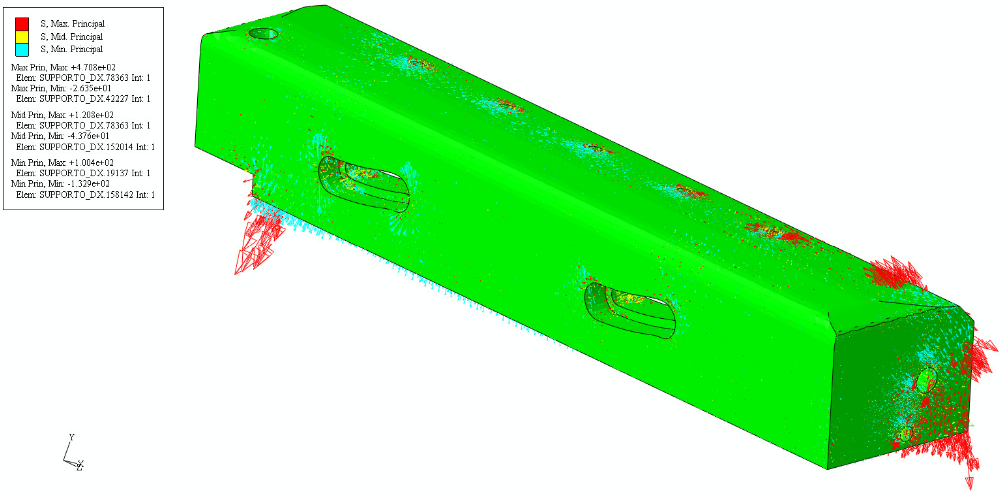


Fig. 25 - Direction of the principal stresses (outside view)

Conclusions

In the framework of the IFMIF/EVEDA engineering design activities, an updated model of the IFMIF Target Assembly system based on the European bayonet concept has been developed at ENEA Brasimone. A series of engineering tasks has been accomplished in order to support the design. These includes: neutronic analysis, thermohydraulic calculations and thermomechanical assessment. Some significant results obtained from such supporting analyses have been reported and briefly discussed, showing the feasibility of the bayonet TA concept and the possibility to fulfill the major system requirements. However, although in an advanced state, the design of the TA system still need further improvements and refinement work especially for what concerns the engineering integration with the other IFMIF facilities.

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