Determination of a pre-heating sequence for the DONES Target Assembly

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Within the activities promoted by the EUROfusion consortium in support of the design and construction of the DEMO Oriented NEutron Source (DONES), a mock-up of its Target Assembly (TA), based on the configuration with a "bayonet" Back-Plate (BP) and available at ENEA Brasimone labs, is being adopted for the execution of experimental activities aiming at the validation of specific aspects of the target design.

Despite the "integral"-TA concept is the current reference, experimental tests concerning the TA pre-heating phase are not significantly affected by the TA concept and are still representative even though conducted on the bayonet-TA concept. Indeed, the main objective of the pre-heating phase is to raise the TA temperature up to a value close to that of the lithium flow in nominal condition (250 °C). In particular, one of the main concerns is to keep the BP at a temperature higher than 200 °C to avoid possible local lithium freezing.

In order to support the afore-mentioned tests, a numerical research campaign has been launched by ENEA Brasimone in collaboration with the University of Palermo with the goal of determining an optimal design of the electrical heaters, both in terms of temperature set-points and geometrical layout. To this purpose, several configurations have been assessed following a theoretical-computational approach based on the Finite Element Method (FEM) and adopting the Abaqus FEM code. In a first phase, different electric heater layouts were assessed by means of steady state thermal analyses. Once the most promising scenario was selected, a detailed thermal transient analysis was carried out. An iterative procedure, based on the analysis of the maximum temperature achieved within the mock-up most critical components, was followed in order to determine the duty cycle of the electric heaters. The obtained numerical results are herewith reported and critically discussed.

Keywords: DONES, IFMIF, Target System, Pre-heating, FEM

1. Introduction

The construction of a facility devoted to study, test and qualify new performing structural materials to be adopted in future nuclear fusion power plants is one of the eight missions of the European fusion roadmap [1]. To achieve this objective, it is mandatory to build a device able to reproduce the environment typical of a nuclear fusion reactor, both in terms of nuclear damage and thermal field. To this purpose, the EUROfusion consortium is carrying on several design activities aimed at the fulfilment of this goal [2], represented by the construction of a neutron source, the so-called DEMO Oriented NEutron Source (DONES) [3]-[4].

DONES is a neutron source based on the IFMIF concept [5], where interactions between accelerated deuteron ions and a flow of liquid lithium generate an intense neutron flux. Differently from IFMIF, in DONES only one 125 mA deuteron beam at the energy of 40 MeV (instead of two beams) will interact with the liquid lithium flow in order to produce a neutron flux (~$5\cdot10^{18}$ $n\cdot m^{-2}\cdot s^{-1}$) to irradiate material samples. It is foreseen to reach a damage level of 20-30 dpa (calculated with the Norgett-Robinson-Torrens model - NRT) in less than 2.5 years in a volume of 0.3 l and a damage of 50 dpa (NRT) in <3 years applicable to 0.1 l volume [4]. Interactions between the D^+ beam and the liquid lithium will take place in the Target System (Fig. 1) and in particular in the component called Target Assembly (TA) [6]. Going more in detail, Li(d,xn) reactions happen in correspondence of the Back-Plate (BP), where lithium at the temperature of 250 °C flows with a velocity of about 15 m/s and a thickness of 25 mm in order to both produce neutrons and remove the heat power (5 MW) generated by the afore-mentioned reactions. In order to maximize the neutron yield, material specimens are placed in capsules allocated in the so-called High Flux Test Module (HFTM), placed in front of the BP at a distance of 2 mm.

In order to allow the lithium circulation within the Target System without freezing, the TA structure needs to be adequately pre-heated. Whether this is a quite standard procedure in case of thermally insulated or directly heated components, in the case of the BP the situation is different, since neither heaters nor thermal insulation can be applied onto its external surface because of the close presence of the HFTM. It becomes therefore mandatory to find a heater configuration on the TA able to guarantee the achievement of a temperature higher than the lithium freezing point (180.5 °C) on the lithium channel.

Thus, within the framework of the IFMIF-DONES

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design activities, ENEA has been commissioned to build a mock-up of the TA to perform experimental activities aimed at the validation and/or the qualification of different procedures, such as its pre-heating phase. Moreover, before performing the experimental campaign, a set of numerical analyses has been carried out to find out a configuration of the electrical heaters able to pre-heat the TA. Thus, the most promising one will be adopted for the conduction of an experimental campaign. The study has been conducted with a theoretical-numerical approach adopting the Finite Element Method (FEM) and using the Abaqus FEM code [8].

Assumptions made and results obtained are herewith reported and critically discussed.

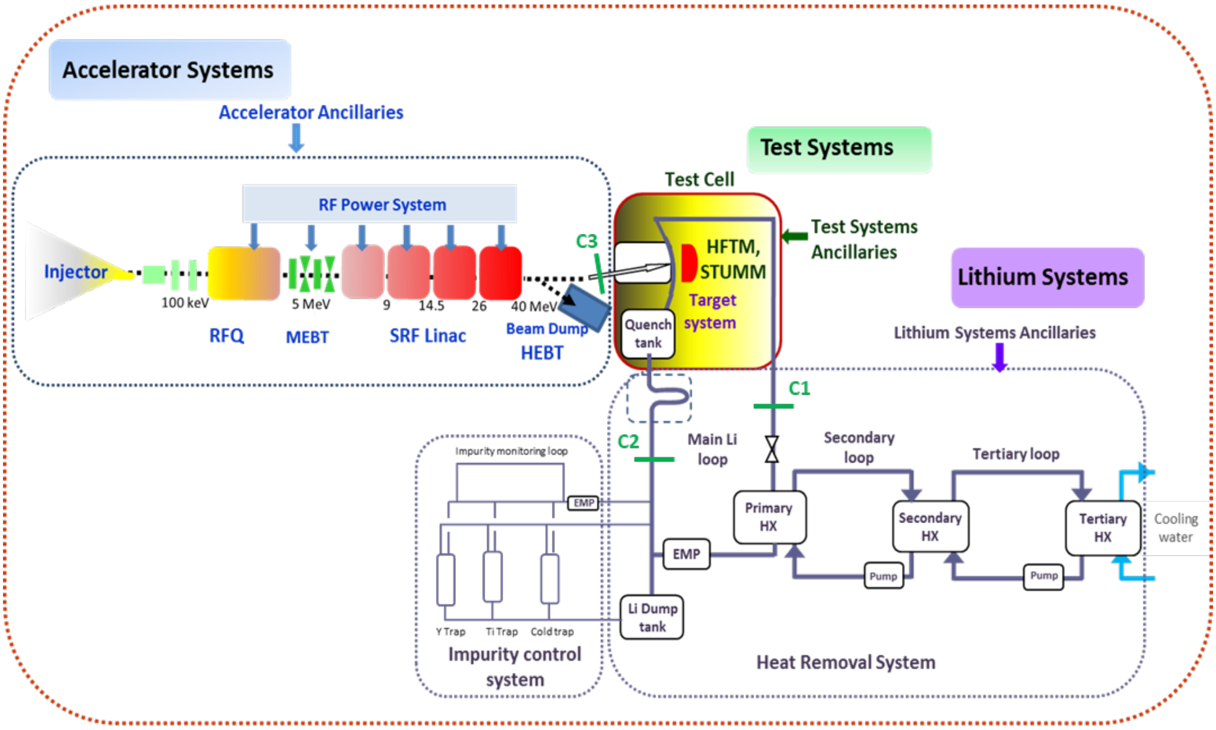

Fig. 1. Overview of DONES conceptual lay-out.

2. The Target Assembly mock-up

The prototypical mock-up of the DONES TA (Fig. 2a) present at the ENEA Brasimone Research Centre, in the experimental hall named Divertor Refurbishment Platform (DRP), is based on a previous version of the DONES TA. It consists of the inlet and outlet nozzles, the BP, the Vacuum Chamber (VC) endowed with the bellow and the beam ducts, the lithium inlet pipe with its Fast Disconnecting System (FDS) and the expansion gimbal joint, as well as the support framework. A view of the TA mock-up present in the DRP hall and its 3D model are reported in Fig. 2a and Fig. 2b, respectively.

The main difference between the mock-up and the current reference TA layout consists in the BP concept. Indeed, the mock-up is equipped with a replaceable BP while the current DONES design foresees an integral TA concept [6]. Other differences rely in the shape of the VC, that is longer and cylindrical in the current design, as well as in the shape of the lithium inlet pipe and the support framework. Despite these differences, the thermal transient and response are not significantly affected, since both BP concepts envisages a similar contact region, while the inlet pipe and VC lengths do not play a significant role in the BP pre-heating. Hence, the adopted mock-up is still representative of the TA thermal behaviour.

The TA heating system is based on a set of electrical heating jackets, purposely designed by THERMOCOAX GmbH company [7]. They consist of a resistive heating element encapsulated within a glass silk outer, with a maximum operating temperature equal to 450 °C. Moreover, additional heating tapes can be installed on the BP and/or the frame. Table 1 reports the values of the electrical power and the corresponding heat fluxes. The colour code reported in Table 1 is the same of that reported in Fig. 3, where the heated areas are identified with different colours depending on the heat flux value.

Table 1. Heating jacket electrical power and heat flux.

Jacket	Power [W]	Heat flux [W/m²]
Vertical pipe	4700	4360
FDS + gimbal joint	1800	4176
Horizontal pipe	3300	4080
Elbow	2000	4080
Inlet nozzle	4000	6000
Vacuum Chamber	3000	6400
Outlet nozzle	1500	4100
Back-Plate/Frame	TBD*	26000

*Heat power depending on the heating tape dimension

3. The Finite Element model

In order to find a heater working configuration able to raise the BP temperature up to the desired value maintaining the temperature on the adjacent component as lowest as possible, two sets of numerical thermal analyses have been performed. In a first phase, steady state thermal calculations have been run in order to down-select the most promising configuration. Then, a detailed transient thermal analysis has been performed, in order to determine a duty-cycle for the electrical heaters, necessary to gradually and uniformly raise the TA temperature.

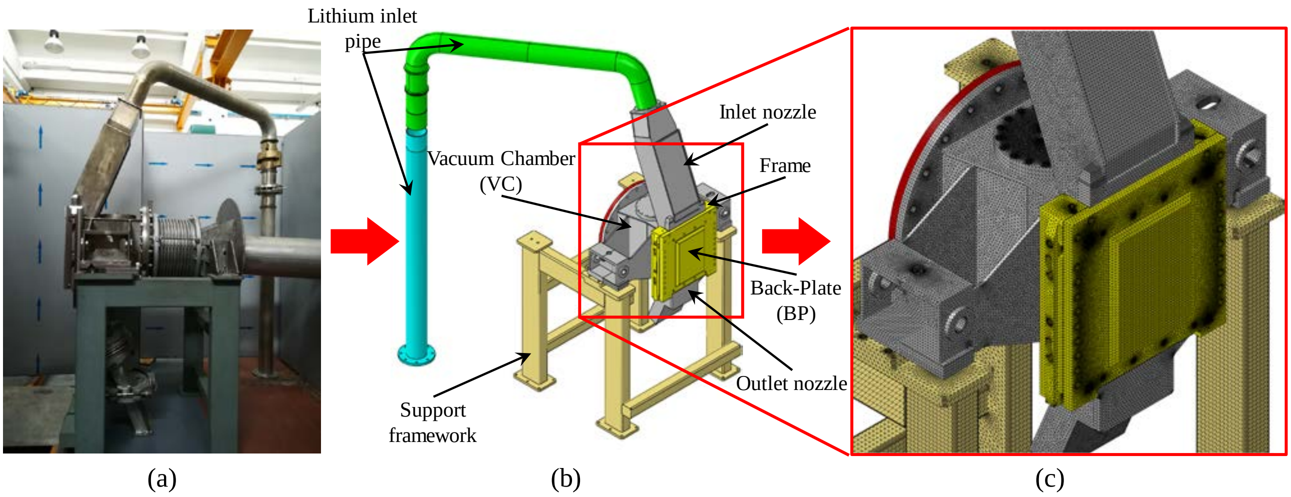

Fig. 2. TA mock-up (a), its 3D (b) and FE (c) models.

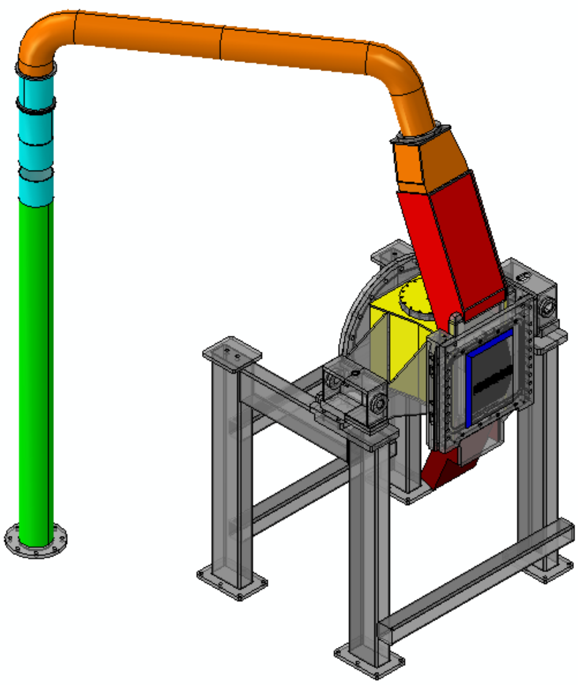

Fig. 3. TA mock-up heated regions.

A Finite Element (FE) model of the DONES TA has been therefore developed, consisting of a mesh composed of about 540k nodes connected in ~2.23M linear tetrahedral elements, reproducing the TA, the lithium inlet pipe and the support framework, as depicted in Fig. 2c. The temperature-dependent properties of the TA structural materials have been taken into account and properly implemented in the FE model.

A set of loads and boundary conditions has been adopted to reproduce the pre-heating phase of the start-up scenario. The unique difference between the steady state and transient calculations relies on the method that has been chosen to reproduce the heater effect. Indeed, in the steady state thermal calculation the electrical heater effect has been reproduced assuming that the heated surface is kept at a uniform temperature value equal to that of the set-point heater temperature (250 °C or 400 °C). On the other hand, in transient calculations the effective heat flux value has been adopted.

Thus, besides the effect of the electrical heaters, the rest of the loads and boundary conditions has been adopted for both kind of calculations. In particular, it has been considered:

- a room temperature of 10 °C;
- thermal interactions between components;
- internal irradiation with an emissivity of 0.3;
- external irradiation towards the environment (at 10 °C) with an emissivity equal to 0.3;
- TA mock-up natural convective cooling. It has been conservatively assumed air at 10 °C and a heat transfer coefficient equal to 10 W/(m²°C);
- heat transfer between BP and HFTM.

With particular regards to this last point, in steady state analyses two different scenarios have been investigated. The former envisages that the HFTM remains at room temperature, while the latter assumes that the HFTM is kept at the temperature of 100 °C by means of a dedicated electrical heater.

A total of 16 different steady state loading scenarios have been assessed, each one varying for the heater set-point temperatures and the HFTM temperature. It has to be underlined that heaters on BP and frame are not always active (N/A). The detail is reported in Table 2.

Table 2. The 16 steady state loading scenarios assessed.

Scenario	A	B	C	D
Component	**Set-point values [°C]**			
Inlet pipe	250	250	250	250
Inlet nozzle	250	250	250	250
Vacuum Chamber	250	250	250	250
Outlet nozzle	250	250	250	250
Frame	N/A	250	400	400
Back-Plate	N/A	N/A	N/A	N/A
HFTM	10	10	10	100

Scenario	E	F	G	H
Component	**Set-point values [°C]**			
Inlet pipe	250	250	250	250
Inlet nozzle	250	250	400	400
Vacuum Chamber	250	250	400	400
Outlet nozzle	250	250	400	400
Frame	400	400	400	400
Back-Plate	250	400	400	N/A
HFTM	100	100	100	100
Scenario	**I**	**L**	**M**	**N**
Component	**Set-point values [°C]**			
Inlet pipe	250	250	250	250
Inlet nozzle	250	400	250	400
Vacuum Chamber	250	400	250	400
Outlet nozzle	250	400	250	400
Frame	400	400	N/A	N/A
Back-Plate	400	400	400	400
HFTM	10	10	100	100
Scenario	**O**	**P**	**Q**	**R**
Component	**Set-point values [°C]**			
Inlet pipe	250	250	250	250
Inlet nozzle	250	400	400	400
Vacuum Chamber	250	400	400	400
Outlet nozzle	250	400	400	400
Frame	N/A	N/A	400	N/A
Back-Plate	400	400	N/A	N/A
HFTM	10	10	10	10

4. Results

Results obtained from steady state analyses have allowed excluding all those scenarios where the minimum temperature calculated on the BP lithium channel was lower than 200 °C, equal to the lithium melting temperature plus a 10% margin (Table 3). Moreover, results highlighted that heaters on VC, inlet and outlet nozzle play a pivotal role in the TA pre-heating. Indeed, all the eligible configurations foresee their set-point temperature at 400 °C. The only exception is represented by *Scenario F* and *M*, where their set-point value is 250 °C but HFTM is at 100 °C and the BP heater is active at 400 °C.

In order to compare results obtained from the different configurations, scenarios ensuring the achievement of the minimum BP temperature without implementing heaters on TA and/or BP, as well as the HFTM at room temperature have been considered for selection, since the installation of an electrical heater on the BP or frame surfaces of DONES TA could be difficult. Hence, the most promising and interesting scenario is that named *Scenario R*. In this scenario, it is possible to overtake the minimum temperature of 200 °C on the BP lithium channel even keeping the HFTM at the temperature of 10 °C and without the adoption of heaters onto BP and frame surfaces. It is clear that, in order to gain more margin against the lithium melting temperature, it is necessary to envisage the HFTM at higher temperatures and/or heaters on BP and frame active. Table 3 reports the minimum temperature values reached on the BP lithium channel in all the assessed loading scenarios.

Thus, at the end of the parametric campaign of steady state analyses *Scenario R* was chosen as the reference one to be assessed with a more detailed transient calculation, since it is the only one predicting a minimum temperature on the BP lithium channel higher than 200 °C without active heaters on frame, BP and HFTM. The thermal field achieved in the *Scenario R*, with a detail of the BP thermal field is depicted in Fig. 4.

Table 3. Minimum temperatures on the BP lithium channel.

Scenario	A	B	C	D
$T_{min, Li\ channel}$ [°C]	116.8	122.6	144.2	185.7
Scenario	**E**	**F**	**G**	**H**
$T_{min, Li\ channel}$ [°C]	180.9	226.2	269.5	251.7
Scenario	**I**	**L**	**M**	**N**
$T_{min, Li\ channel}$ [°C]	192.0	238.6	223.2	268.6
Scenario	**O**	**P**	**Q**	**R**
$T_{min, Li\ channel}$ [°C]	188.8	237.6	215.9	202.2

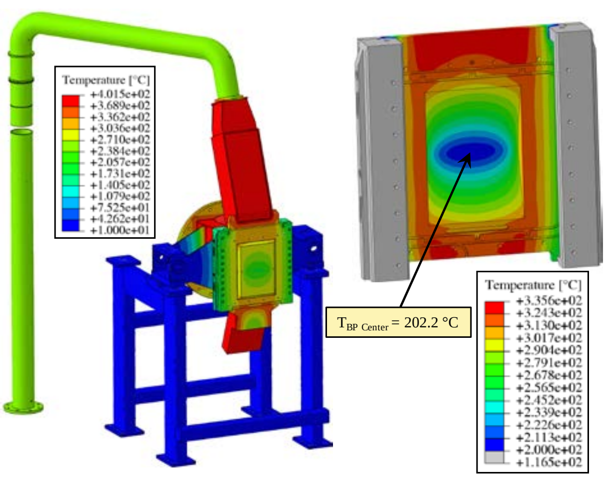

Fig. 4. TA mock-up thermal field - *Scenario R*.

Differently from steady state calculations, in the transient analysis the actual heat fluxes coming from the heating jackets have been considered, adopting the values reported in Table 1. The action of the heating jackets has been reproduced turning on and off the heat flux coming from them, in order to gradually and as more uniformly as possible raise the mock-up temperature. A *try and fail* approach similar to that reported in [9] has been adopted for the determination of the heater duty-cycle, in which the calculation was stopped and re-started once the maximum temperature of the *i-th* heated surface overcame the set-point one. Thanks to this method, it was identified a possible sequence for the heater operation.

The trend of the temperatures achieved in the different heated components (maximum values) and the BP lithium channel (minimum value) versus time in the first 24 hours of the pre-heating phase is reported in Fig. 5 and Fig. 6.

Results obtained highlight and confirm that the VC is the component driving the BP lithium channel pre-heating. Indeed, once this component reached and maintained the maximum temperature value of about 400 °C, the BP lithium channel minimum temperature reached a plateau (~12 hours from the beginning of the simulation). Then, the duty cycle of the VC heater was modified (from 2 minutes on and 3 minutes off to 1 minute on and 1 minute off). A maximum equilibrium temperature of about 450 °C was reached within the VC, whereas the minimum temperature on BP lithium channel was slightly lower than 150 °C, as it is reported in Fig. 6 and in Fig. 7. This value is considerably lower than the one obtained in the steady state analysis (150 °C vs. 202 °C). In Fig. 7, BP areas with temperatures higher than 200 °C are reported in grey.

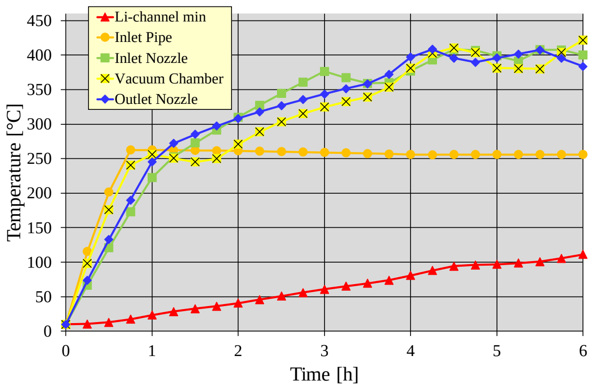

Fig. 5. TA temperature evolution from 0 to 6 hours.

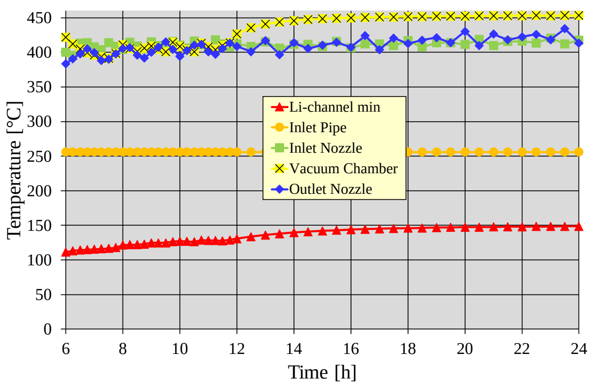

Fig. 6. TA temperature evolution from 6 to 24 hours.

The difference between the two calculations can be due to the fact that the heated surfaces of nozzles and VC does not reach a uniform temperature distribution, as supposed in steady state analyses, as it can be deduced from Fig. 7. Moreover, the heating jackets modelling approach (cycles of 1 minute) may have an impact on the final results. Indeed, the real Proportional-Integral-Derivative (PID) control system of the heating jackets is based on cycles of 2 seconds, with the effect that the heating power can be more smoothly and effectively delivered to the TA mock-up structure.

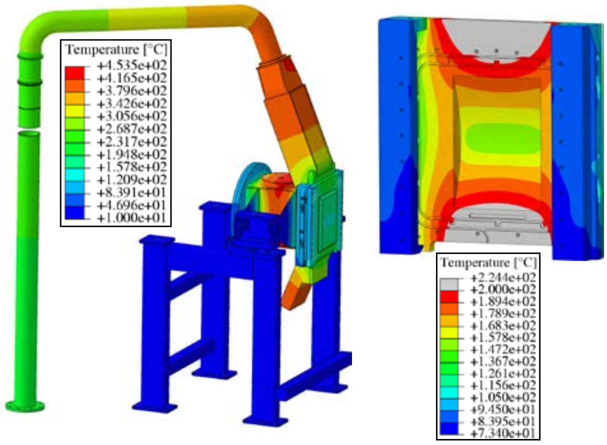

Fig. 7. TA mock-up thermal field at t = 24 hours.

5. Conclusions

Within the EUROfusion research activities on DONES, the pre-heating phase of the start-up scenario has been investigated. A theoretical-numerical approach has been pursued, adopting the ABAQUS FEM code, in order to identify an optimum configuration for the electrical heating system.

A parametric campaign of steady state thermal analyses led to the selection of a loading scenario characterised by the TA equipped with heating jackets on the lithium inlet pipe, vacuum chamber, as well as onto inlet and outlet nozzles external surfaces. The set-point temperatures for these electrical heaters have been determined as well.

Once the most promising scenario has been identified, detailed transient thermal analyses have been performed, applying a proper duty-cycle to the electrical heaters in order to increase the TA mock-up temperature as more uniformly as possible.

Differences in results obtained from the two sets of analyses are probably due to the modelling approach chosen for the reproduction of the heating jacket action, excessively “optimistic” in case of steady state analysis and probably too conservative in case of transient calculation. Nevertheless, since the lithium melting point is 180.5 °C and in order to validate the FE models, the scheduled experimental campaign will be initially started with the TA mock-up equipped with the electrical heaters in *Scenario R* configuration.

Acknowledgments

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References

[1] EUROfusion, European Research Roadmap to the Realisation of Fusion Energy, November 2018, ISBN 978-3-00-061152-0.

[2] G. Federici et al., Overview of the DEMO staged design approach in Europe, Nucl Fusion 59 (2019) 066013, doi: 10.1088/1741-4326/ab1178.

[3] A. Ibarra et al., The European approach to the fusion-like neutron source: the IFMIF-DONES project, Nucl Fusion 59 (2019) 065002, doi: 10.1088/1741-4326/ab0d57.

[4] D. Bernardi et al., Towards the EU fusion-oriented neutron source: The preliminary engineering design of IFMIF-DONES, Fus Eng Des 146, Part A (2019) 261-268.

[5] P. Garin and M. Sugimoto, Main baseline of IFMIF/EVEDA project, Fus Eng Des 84 (2009) 259-264.

[6] P. Arena et al., The design of the DONES lithium target system, Fus Eng Des 146 (2019) 1135-1139.

[7] THERMOCOAX GmbH, https://www.isopad-solutions.com/en/heating-jackets-gc11.html.

[8] Abaqus v. 6.14-2, © Dassault Systèmes Simulia Corp., 2014, Providence, RI, USA.

[9] P. Arena et al., On the thermomechanical behavior of the European target assembly design of IFMIF-EVEDA lithium test loop under start-up transient scenarios, Fus Eng Des 88 (2013) 774-777.