EUROFUSION WPBB-CP(16) 15475

D Rapisarda et al.

Status of the engineering activities carried out on the European DCLL

Preprint of Paper to be submitted for publication in Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Status of the engineering activities carried out on the European DCLL

D. Rapisarda[1], I. Fernandez[1], I. Palermo[1], F.R. Urgorri[1], L. Maqueda[2], D. Alonso[2], T. Melichar[3], O. Frýbort[3], L. Vála[3], M. Gonzalez[1], P. Norajitra[4], H. Neuberger[4], A. Ibarra[1]

[1] CIEMAT, Avda. Complutense 40, 28040 Madrid, Spain
[2]ESTEYCO, C. Menéndez Pidal 17, 28036 Madrid, Spain
[3]Research Centre Rez, Hlavní 130, CZ - 250 68 Husinec-Řež, Czech Republic
[4]Karlsruhe Institute of Technology, Karlsruhe, Germany

The Dual Coolant Lithium Lead breeding blanket is being investigated as a candidate for the European DEMO. This blanket is based on the use of PbLi as breeder and coolant ("self-cooled breeding zone") and high-pressure helium for cooling the structures made of EUROFER. During the first part of the project, a conceptual design of the DCLL equatorial outboard module with the highest neutronic and thermal loads has been finalized, that meets the requirements of tritium self-sufficiency and shielding. It was designed to work under normal, undisturbed operational conditions. The present work shows the current DCLL design produced to comply with the in-box LOCA requirements, including the most relevant results on neutronics, thermal-hydraulic and mechanical calculations, as well as the advances on the Flow Channel Insert development.

Keywords: DCLL, FCI, DEMO, EUROfusion.

1. Introduction

In the framework of the EUROfusion programme, the Dual Coolant Lithium Lead (DCLL) breeding blanket is being investigated as a candidate for the European DEMO reactor [1]. The DCLL is based on the use of Pb-17Li as breeder and coolant ("self-cooled breeding zone") and high-pressure helium (8 MPa) for cooling the structures made of reduced-activation ferritic-martensitic steel EUROFER. During the first part of the Project a conceptual design of the DCLL equatorial module has been finalized, meeting the requirements of tritium self-sufficiency and shielding [2]. This first design was produced to work under normal, undisturbed operational conditions; therefore no special attention was paid on accidental scenarios (i.e. in-box Loss of Coolant Accident, LOCA).

A new design has been produced in a further step to go deeper into the conceptual design [2], consolidating DCLL specific design elements like the breeding zone lay-out, the thermo-hydraulic general scheme for the segment, the poloidal segmentation or the structural design. In order to comply with the in-box LOCA requirement higher robustness is needed. Thus, the number of radial stiffening plates has been increased and the walls of the main box structure have been reinforced. The helium circuit has been considerably simplified due to lower cooling needs than initially expected, reducing the total He pressure drop, contributing to improve the plant efficiency. Another objective has been to study the impact of the Heating and Current Drive (H&CD) Systems on the blanket segment, assessing possible modifications on the TBR.

This paper includes the most relevant results on neutronics, thermal-hydraulic (TH) and mechanical calculations for the present DCLL design. The rationale of the cooling scheme for the PbLi and He in the Back Supporting Structure (BSS) is addressed, as well as corrosion and magnetohydrodynamics (MHD) phenomena. Advances on the Flow Channel Insert (FCI) development are also presented, with special emphasis on two different proposals: a sandwich-like FCI which uses ceramic pebble beds between two steel plates or a simple highly dense alumina ceramic tube.

2. DCLL Engineering Design Activities

The present DCLL version has been developed for the DEMO2014 layout (16 sectors, 1572 MW fusion power) [1, 2]. The most important change and driver in the engineering design has been to adapt the structure to off-normal mechanical requirements, since the previous design was only devoted to work under normal operational conditions [2]. Thus, the new design safely accommodates the consequences of an accidental overpressure inside the module (in-box LOCA). The initiating event is a break of the helium channels (stiffening grid or external module structure) or in the helium manifold. It produces the spill of He into the PbLi of the breeder zone, pressurizing the compartments up to 8 MPa. The different box plates must withstand the occurring pressure difference. The in-box LOCA has been identified as a Category IV event according to RCC-MR [3], for which the membrane plus bending allowable stress is estimated in 400 MPa.

In order to reinforce the design different solutions were adopted. Firstly, the number of radial stiffening plates was increased from 3 to 5; therefore defining two new PbLi circuits compared to the previous design (see Fig. 1). The first wall (FW) width has been enlarged from 20 to 25 mm, as well as the left and right walls, from 20 to 30 mm. In addition, the number of helium channels in the different plates was reduced looking for higher strengthening. In the following subsections specific analysis on the present DCLL design are presented.

author's email: david.rapisarda@ciemat.es

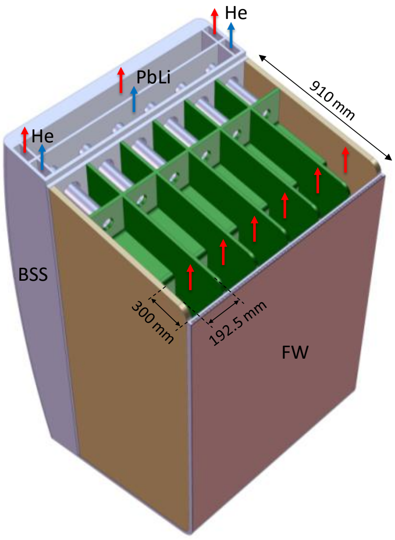

Fig. 1. Present design of the DCLL OBC equatorial module showing the breeder zone, the BSS, and main dimensions

2.1 Back Supporting Structure definition

As explained in [2] the DCLL segments are based on a Multi-Module configuration. It consists on a set of modules attached to a common manifold, the BSS. A detailed design of this component has been developed, consisting of a very long poloidal structure with small radial channels which distribute/collect both coolants (PbLi and He) to/from the different modules.

PbLi and He flow according to similar schemes, upwards through the segment at central and lateral channels, respectively (see Fig. 1). In order to limit the corrosion and the pressure drop in the PbLi channels, low velocity is desired. Since the mass flow changes along the poloidal direction because of the distribution or collection, such goal can be achieved by varying the hydraulic diameter of the channels. Moreover, it is advisable to maximize the cross section of the hot channel (550 ºC) by reducing the cross section of the cold channel (300 ºC), where a significantly lower corrosion rate is expected [4]. This can be schematically seen in Fig. 2, where a cross section at the level of modules 1 and 4 is also shown to highlight this difference.

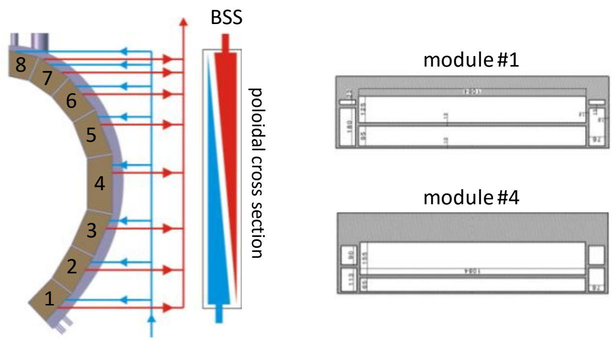

Fig. 2. (Left) Flow scheme of the coolants in the BSS (OB segment); (right) cut views at 2 different poloidal positions

2.2 Thermal-hydraulic calculations

The activity in TH has been focused on the detailed characterization of the performance of the outboard central (OBC) equatorial module, following the evolution of the design along the year. PLATOON (PLAtform for Thermal-hydraulic One-dimensional OutliNe) code [5] has been used to perform sensitivity studies on the module optimizing its TH performances. The most important parameters of this new DCLL release can be found in Table 1.

Table 1. Main DCLL thermalhydraulics parameters calculated with PLATOON

He parameters	previousOBC#4	new OBC#4
Mass flow rate	2.5 kg/s	2.74 kg/s
Inlet temperature	300 ºC	300 ºC
Outlet temperature	420 ºC	425 ºC
Pressure drop	0.37 MPa	0.25 MPa
extracted power	40 %	44 %
PbLi parameters	**previousOBC#4**	**new OBC#4**
Mass flow rate	50.0 kg/s	49.2 kg/s
Inlet temperature	300 ºC	300 ºC
Outlet temperature	550 ºC	550 ºC
Pressure drop (insulated)	0.18 MPa	0.09 MPa
extracted power	60 %	56 %

It is important to note an increase in the He outlet temperature, but also a higher pressure drop. The power extraction capability for both coolants is now 44/56%, the one coming from He mainly corresponding to heat extracted in the FW. The PbLi velocity in the front channels is maintained around 1.4 cm/s, although the pressure drop (considering the presence of FCI) has been diminished in almost 0.1 MPa. This value of velocity, together with the temperature in the channel, anticipates a corrosion rate of about 30 µm/y.

With all these numbers, the required PbLi mass flow rate for the whole DCLL-DEMO reactor is 21192 kg/s, 1177 kg/s in the case of He. The OBC segment presents a mean PbLi velocity at the cold and hot channels of 24 and 9 cm/s, respectively. These values lead to corrosion rates of, approx., 0.5 and 170 µm/year. Thus, in the case of the hottest channel the use of coatings in certain locations as corrosion barriers could be necessary.

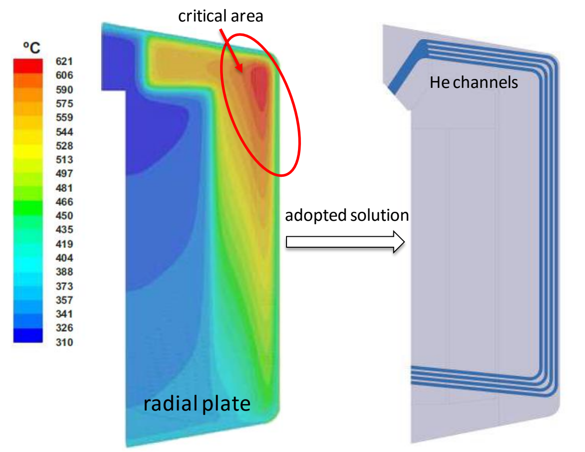

Fig. 3. (Left) Temperature map in the radial stiffening plate and (right) detailed design of the He cooling channels

A steady-state thermal analysis has been carried out in Fluent to optimize the amount of internal helium channels of the stiffening grid. A temperature map of a radial plate without helium channels has been obtained (Fig. 3, left), showing the effect of the flowing PbLi. The result has allowed identifying a critical zone which has to be cooled, simplifying considerably the cooling scheme of the radial stiffening plate (Fig. 3, right). The distribution and number of channels was driven by additional CFD analysis. One important implication has been the suppression of channels in the toroidal plates.

Detailed MHD calculations have been performed for the BSS, focused on the pressure drop along the PbLi channels. A simplified geometry, based on 2 parallel rectangular ducts with no curvature, perfectly insulated, has been evaluated. Thermal or gravity effects have not been considered. The most important results is that, once the system has reached the stationary state, the pressure presents a linear profile whose slope is directly proportional to the intensity of the external magnetic field. A pressure drop as low as 68.30 Pa/m has been obtained for the cold channel while a pressure drop of 78.51 Pa/m has been found in the hot channel.

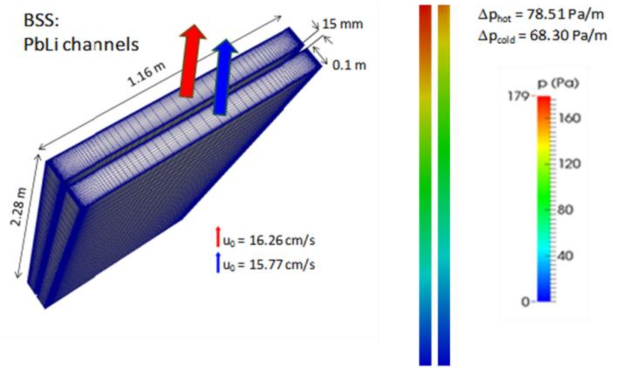

Fig. 4. (Left) Scheme of the mesh used to solve the MHD equations and (right) MHD pressure drop in the BSS channels

2.3 Sensitivity studies on First Wall cooling-ability

The FW is cooled in counter-flow manner for a more uniform temperature distribution. Different sensitivity studies were performed using CFD approach in order to evaluate dependence between geometric and operational (mass flow, temperature field, pressure loss) parameters [6]. In particular, it was investigated the channel cross section, the pitch between channels, the inlet He velocity… Present dimensions of the helium channels in the FW are 10 mm × 15 mm, with a pitch of 5 mm, Fig. 5. A final analysis was performed on this geometry, concluding it is possible to meet the <550ºC requirement in the EUROFER wall with different combinations for low channel pitch values and acceptable inlet velocities (Fig. 5). The effect of increasing the thickness between helium channels and the tungsten layer from 2.5 to 3 mm was also studied, trying to alleviate mechanical issues. However this introduced an increase of 10 ºC in the maximum EUROFER temperature.

2.4 Structural analysis

The OBC equatorial module was studied under two representative scenarios: normal pulsed operating conditions and in-box LOCA accidental event [7], considering thermal, nuclear and internal pressure loads. Transient analysis was performed for the pulsed scenario, considering 9 pulses per day with 2 hours of burn-time. Maximum stresses have been computed within the frontmost surface of the FW at the beginning of the plateau phase (Fig. 6, left), with peak compressive stresses in the order of 350 and 470 MPa in the toroidal and poloidal directions, respectively. These preliminary results are non-conservative, since the tungsten material has not been considered in the mechanical analysis.

During an in-box LOCA accidental event, high stress concentrations have been identified at the connection of the first with the radial walls (Fig. 6, right). Peak values computed for von Mises stresses are significantly higher than 400 MPa. These results seem to suggest that a reduction of the bending span in the FW (by increasing the number of radial stiffening plates) might be required, together with a diminution of the distance between the toroidal and the first wall.

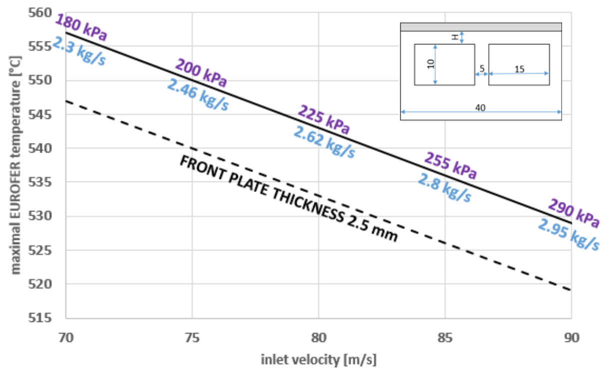

Fig. 5. Dependence of the max EUROFER temperature with inlet Helium velocity for two front plate thicknesses

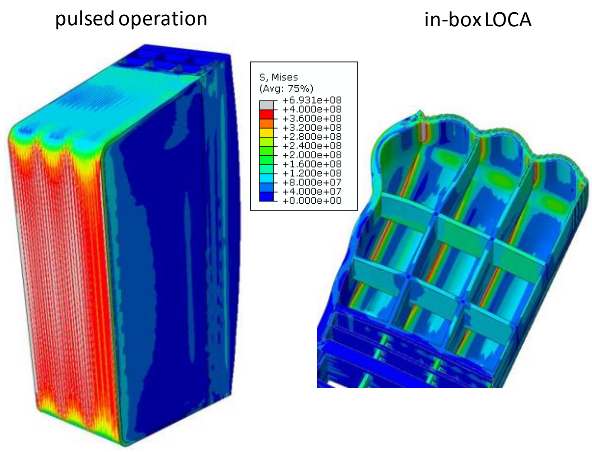

Fig. 6. Von Mises stress field during (left) pulsed operation and (right) in-box LOCA

2.5 Neutronics

Neutronic assessments have been specially focused on the evaluation of the Tritium Breeding Ratio (TBR) and shielding responses.

The overall TBR of the current design is 1.104, higher than the self-sufficiency criterion (1.1). There has been an important increase of the TBR in the IB modules, because of the larger radial build of the upper modules and the suppression of the intermediate stiffening toroidal wall in the lower modules [8]. However, the BSS contribution has been diminished because of assuming a more realistic design of the PbLi channels, instead of the previous homogenized block [2]. For this reason the TBR is slightly lower than the former (1.13). The obtained energy multiplication factor (1.198) is also higher than required.

Due to the central solenoid, which reduces the space available for shielding, and to the higher plasma density at the equatorial level, shielding is critical in the IB side at this level. Calculated responses show that the limits for the toroidal field coils (TFC) are satisfied: 50 W/m^3 of nuclear heating for the winding pack, 10^{18} n/cm^2 for the epoxy insulator and the superconductor, and 10^{-4} dpa for the copper stabilizer [9], the last two for the total TFC lifetime (6 FPY). Fig. 7 shows the nuclear heating calculated for two different compositions of the VV steel (with and without 2% of B).

The criteria for helium production (1appm He) and radiation damage (2.75 dpa) in the VV and FW steels (20 and 50 dpa for the starter and second phase blankets) are also fulfilled for their corresponding lifetimes.

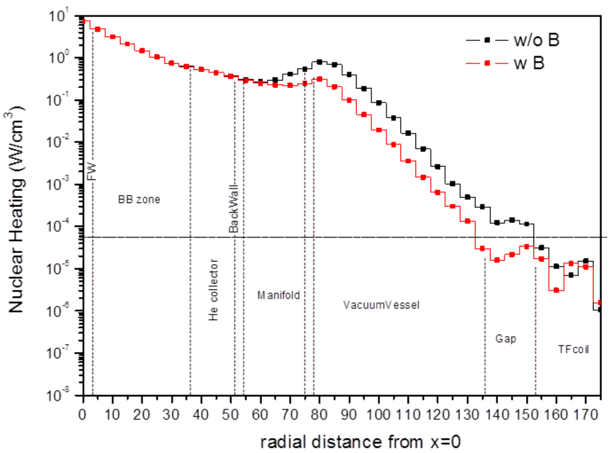

Fig. 7. Nuclear heating in the IB mid-plane from the FW to the TFC for 2 VV compositions, with and without 2% of boron

3. DCLL integration in DEMO reactor

During 2015 the possibility of using both the upper and lower ports of the vacuum vessel to allocate service connections of the OB segments has been considered. Besides the benefit of allocating the inlet and outlet pipes in the opposite ends of the BSS, the PbLi inlet pipe will be used to drain the segment in emergency case (Fig. 2). However, the IB segments have not access to the lower ports in DEMO2014 layout due to the large divertor. This forces to place all the pipes at the top of the segment and leaves no choice to allocate a PbLi draining pipe. Efforts will be performed to solve these important issues.

Other integration activity has been to study the impact the H&CD systems on the TBR [8]: electron and ion cyclotron resonance heating (ECRH, ICRH), and neutral beam injection (NBI). With the current DCLL design, the self-sufficiency objective is still fulfilled for most of the possibilities examined, as can be seen in Table 2. For instance, a TBR higher than 1.05 –which could be satisfactory- is still achieved considering up to 4 NBI, 8 ECRH (and vice versa) and ICRH occupying 10 cm in depth (Table 2).

Table 2. Combinations of heating systems and resultant TBR

	nº of Heating systems	TBR
NBI in pos. OBC#4 ECRH in pos. OBC#8 ICRH in pos. OBC#6	1NBI, 1ECRH, 5 cm 360º ICRH	1.088
	2NBI, 2ECRH, 5 cm 360º ICRH	1.083
	2NBI, 2ECRH, 10 cm 360º ICRH	1.073
	4NBI, 4ECRH, 10 cm 360º ICRH	1.064
	4NBI, 8ECRH, 10 cm 360º ICRH	1.060
	8NBI, 4ECRH, 10 cm 360º ICRH	1.050

4. Flow Channel Insert development

One of the most important issues related to the use of ceramic insulators is the effect of the radiation on the electrical properties. For this reason, Radiation Induced Conductivity (RIC) was also measured on a steel-coated alumina ceramic FCI, at 450ºC, by using a 1.8 MeV Van der Graaff e-accelerator, at CIEMAT. The samples were irradiated at 70, 700 and 7000 Gy/s, up to 4 MGy (Fig. 8). It was concluded that increasing the total dose seems to have a limited effect (saturation), and some hysteresis was observed in the material. The radiation resistance of the samples is comparable with that of other ceramic materials exhibit.

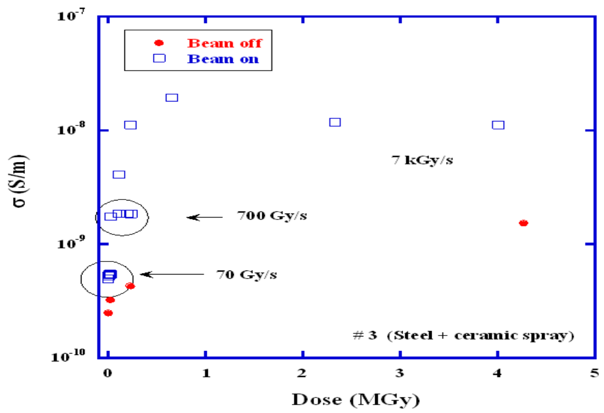

Fig. 8. (blue squares) electrical conductivity as a function of radiation dose (@450ºC) during irradiation at different dose rates. Red dots indicate values taken without irradiation

Another important achievement is related to FCI fabrication. New prototypes, based on a highly dense alumina ceramic tube, were developed by CIEMAT [10], Fig. 9 left. The dimensions are 80 x 80 mm square cross section; 100 mm large; 5 mm thick. The ceramic is protected with both inner and outer 1 mm steel sheets. These plates are not connected between them and were fixed with an alumina paste. Electrical and thermal conductivities of the insulator were measured (> 10^5 ohm @1000ºC and 12 W/mK @500ºC, respectively) being well below the required FCI values.

A new proposal was also made by KIT [11]. It consists of FCI which uses ceramic pebble beds instead ceramic plates as insulator interlayer (Fig. 9, right), and is based on the "tube-in-tube" conceptual design.

Zirconia has been proposed for the 1st study due to its good insulation properties.

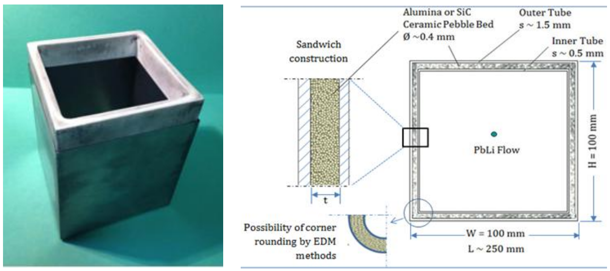

Fig. 9. (Left) Prototype of a highly dense alumina ceramic tube and (right) schematic representation of the FCI design with ceramic pebbles interlayer

5. Conclusions and next steps

Most relevant results on neutronics, thermal-hydraulic and mechanical calculations for the current DCLL have been presented. Main changes have been focused to safely accommodate the consequences of an in-box LOCA. New designs of the FCI have been presented, as well as the RIC effect on the insulator.

In a future development, main blanket performances will be adapted to the new specifications and CAD model of DEMO2015 (18 sectors, 2037 MW fusion power [12]). Special emphasis will be paid on segment draining, checking the minimum required pipe dimension and available space. Apart from obtaining the most relevant neutronics and TH figures, MHD calculations will be focused on the study of the PbLi flow in the transition zone between the BSS and the breeder zone. Structural assessment will be done in the entire blanket segment. Fabrication and testing of new FCI prototypes will be performed.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] L. Boccaccini et al., Objectives and status of EUROfusion DEMO blanket studies, Fusion Eng. Des. 109–111 (2016) 1199–1206
[2] D. Rapisarda, Conceptual design of the EU-DEMO Dual Coolant Lithium Lead equatorial module, IEEE Trans. Plasma Sci. (2016), http://dx.doi.org/10.1109/TPS.2016.2561204
[3] RCC-MR, Design and Construction Rules for Mechanical Components of Nuclear Installations, AFCEN, 2007
[4] J. Konys et al., Flow rate dependent corrosion behavior of Eurofer steel in Pb–15.7Li, J. Nucl. Mater., 1–3 (2011) 1191–1194.
[5] I. Fernandez, Thermal-hydraulic design of a DCLL breeding blanket for the EU DEMO, P2.163, this conference
[6] T. Melichar, Optimization of first wall helium cooling system of European DCLL using CFD approach, P3.119, this conference
[7] L. Maqueda, Transient thermal-mechanical analysis of fusion breeding blankets: Application to the European DCLL DEMO blanket, P2.161, this conference
[8] I. Palermo et al., Tritium production assessment for the DCLL EUROfusion DEMO, Nucl. Fusion 56 (2016) 104001
[9] U. Fischer et al., Neutronics requirements for a DEMO fusion power plant, Fusion Eng. Des. 98–99 (2015) 2134–2137
[10] M. González, Preliminary report on construction and characterization of FCI mock-up based on previous designs, EFDA_D_2MXVWZ v1.0
[11] P. Norajitra, Technological study on fabrication of FCI made of SiC material, EFDA_D_2MZNR7 v1.1
[12] G. Federici, et al. Overview of the design approach and prioritisation of R&D activities towards an EU DEMO, Fusion Eng. Des., 109–111 (2016), 1464–1474