Eurofusion-DEMO Divertor - Cassette Design and Integration

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The Eurofusion-DEMO design will complete the Pre Conceptual Design phase (PCD) with a PCD Gate, named G1, scheduled to take place in Q4 2020 that will focus on assessing the feasibility of the plant and its main components prior to entering into the Conceptual Design phase. In the paper first an overview is given of the Eurofusion-DEMO Divertor Assembly including design and interface description, systems and functional requirements, load specification, system classification, manufacturing procedures and cost estimate. Then critical issues are discussed and potential design solutions are proposed, e.g.:
- Neutron material damage limits of the different (structural) materials present in the divertor assembly (as CuCrZr, Eurofer) and in the vacuum vessel (AISI 316L(N)-IG);
- Temperature hot spots in parts of the divertor assembly exposed to high nuclear heating and high heat radiation (from the plasma core or the separatrix) causing difficulties for active or passive cooling (e.g. cassette body structure, liner support structures, mechanical supports, divertor toroidal rails);
- Arrangement and design of plasma-facing components and liner with pumping slot in the divertor cassette to enable pumping of exhaust gases from the lower port.

1. Introduction

In the frame of the EU fusion roadmap activity Horizon 2020 [2][3] the Pre Conceptual Design phase (PCD) of DEMOnstration Fusion Power Plant (DEMO) has been launched by the EUROfusion Consortium. The PCD will complete with a PCD Gate Review, named G1, scheduled to take place in Q4 2020 [4]. **Table 1** reports the main DEMO parameters, compared with the ones of ITER reactor used as reference.

Table 1. DEMO main parameters. Comparison with ITER

		DEMO	ITER
Major radius	R (m)	8.94	6.20
Minor radius	a (m)	2.88	2.00
Toroidal field	B_t (T)	4.89	5.30
Plasma current	I_P (MA)	19.07	15.0
Elongation	k	~1.6	~1.8
Power in SOL	P_{sol}(MW)	~150	~90
Parallel Heat Flow	$q_{\|\|}$	~5	~1.8
Poloidal Heat Flow	q_{pol}	~2	~0.6

One of the main DEMO in-vessel components is the divertor with relative plasma facing components(PFCs) [5] and [6].

The DEMO divertor will extract the alpha particle power, helium and impurities, and the heat load that comes from the plasma Scrape-Off Layer (SOL) during the normal and transient operation, and also during off-normal events. It will restrict the backflow of neutrals to prevent its Helium content become excessive.

At the same time the divertor will provide neutron shielding for the Vacuum Vessel (VV) and superconducting magnet coils.

3. Divertor Design description

The 2019 CAD reference for the DEMO divertor design is show in Fig. 1. The divertor is made of 48 divertor assemblies. The main divertor components are:

- Inboard vertical target (IVT);
- Outer Vertical target (OVT);
- Shielding Liner (SL);
- Reflector Plates (RP);
- Divertor Cassette (DC);
- Inner locking on VV, so-called “nose”;
- Outer locking on VV, so-called “wishbone”;
- Cooling tubes and manifolds.

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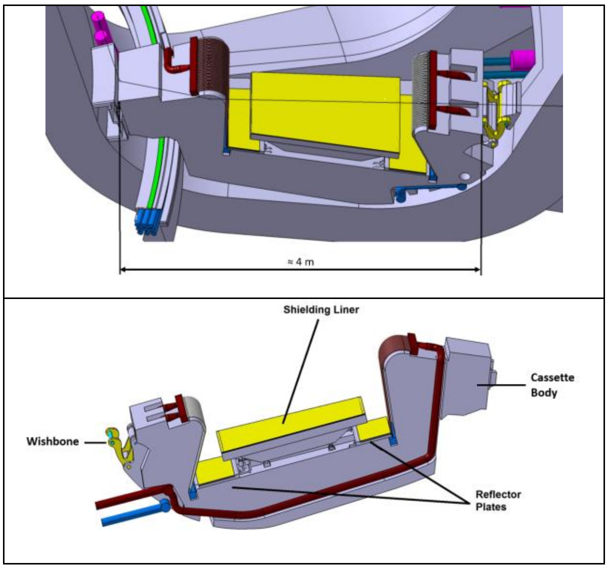

Fig. 1. CAD model of 2019 DEMO divertor assembly.

Description of the design activities for Divertor sub-assemblies and components are reported in [6] and [23].

3.1 IVT and OVT

Each cassette carries two Vertical Targets (VTs): inner (IVT) and outer (OVT). IVT is ~ 0.76 m high x 0.82 m wide. OVT is ~ 0.65 m high x 1.07 m wide. One OVT includes 45 Plasma Facing Units (PFUs) and one IVT includes 33 PFUs.

The PFUs (Fig. 2 left) are made of Tungsten (W) monoblock (28*23 mm - axial thickness/axial gap/toroidal gap 12 mm/0,5 mm/0,5 mm) cooled by water flowing in CuCrZr tubes (D_{est} = 15 mm, D_{int}=12 mm). A 1 mm Cu interlayer is foreseen between W and CuCrZr. Toroidal shadow issues have not yet been taken into account, therefore the design of the monoblocs has not yet been finalized from this point of view.

The W-monoblocks are brazed to support leg (Fig. 2 right). A pin connection link the support leg to a support plug welded in the divertor cassette. The support leg, support plug and the pin are made of Eurofer (or as in ITER made in austenitic stainless-steel XM-19 -UNS number S20910).

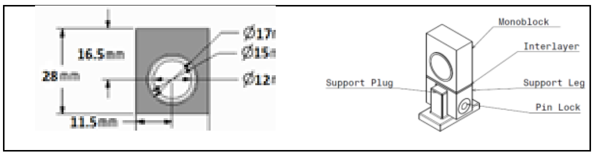

Fig. 2. ITER like PFC for DEMO divertor. left) W-monoblok-cooling tube detail; right) PFC support.

Each PFU array has been fixed to the cassette as shown in Fig. 3 with a pitch of about 5*12.5= 62.5 mm between two axial support plugs. The removal of PFCs from cassette body during maintenance activities is not currently foreseen, but the maintenance strategy is defined to replace the whole CB+PFCs assembly after 1.5 full power year (fpy).

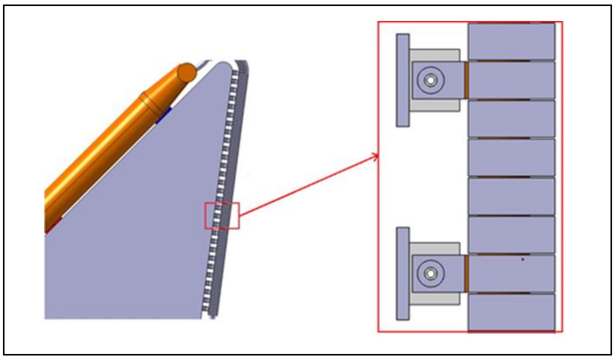

Fig. 3. PFC connection scheme on cassette divertor.

3.2 Shielding Liner

The main SL function is to provide neutron shielding for the VV and magnet coils. Due to the pumping opening on the cassette (Fig. 1) the neutron shielding performance is particularly important for the SL.

The SL is made of Eurofer with a first layer of 3 mm of tungsten and cooled by the cassette cooling circuit (Fig. 1 and Fig. 4**Error! Reference source not found.**).

With the collaboration of an industrial partner, a preliminary manufacturing sequence including machining, welding and NDT steps is proposed. The preliminary assessment takes into account know-how on Eurofer manufacturing and assembly technologies assessed of the ITER TBMs (Test Blanket Modules) [7],[8],[9] and [10] and the DEMO BB (Breeding Blanket) [11], [12] and [13]. Two main routes are envisaged:

- Parallel production of the cooled plates (blue and green colors in Fig. 4) and final assembly of both;
- Assembly in series by successive addition of layer.

The proposed manufacturing technology is based mainly on HIP process. For the 2-steps HIP, the cycle at low temperature in a low pressure atmosphere allow to seal the periphery of the interface before the cycle at high temperature in a high pressure atmosphere without collapsing the channels. Between the two HIP cycles, the channels are opened by drilling or milling in order to put them under pressure during the second HIP cycle. The latter allows to achieve full bonding and reach good joint mechanical properties [1].

To protect the SL steel from erosion due to impact of particles, a tungsten coating is foreseen as for the BB FW. Differences in the coefficients of thermal expansion between the W coating and the steel substrate of the FW can be compensated by a functionally graded interlayer. Successful production has been obtained by using vacuum plasma spraying technique to deposit a W layer on small Eurofer surface. Layers do not present any damage after testing its resistance to thermal fatigue (until 500 cycles at high temperature). Regarding the layer adhesion, testing at high temperature reveals a good metallurgical bonding to the substrate. Next steps will consist in checking the feasibility to produce similar quality on larger surface areas.

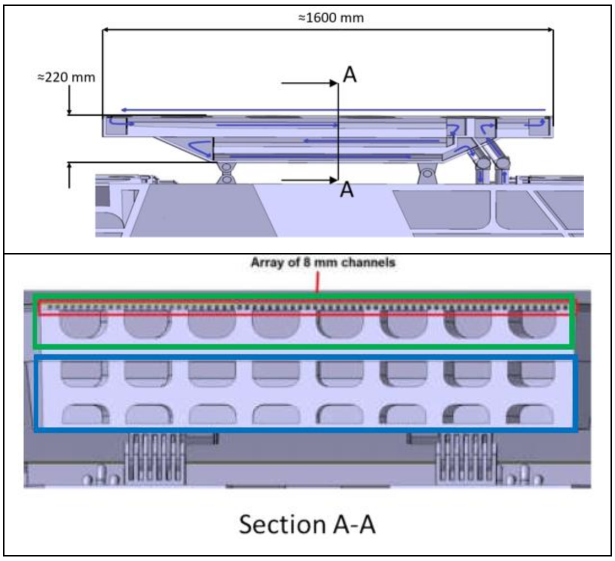

Fig. 4 - Shielding Liner

3.3 Reflector Plates

The main RPs functions are to provide thermal, alpha particle and impurities shielding for the PFC manifold/distributor cooling underneath components. As the SL the RPs are made of Eurofer with a first layer of 3 mm of Tungsten (Fig. 5).

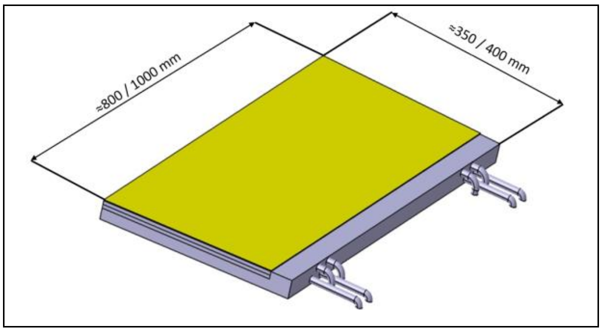

Fig. 5 -Reflector Plates

3.4 Divertor Cassette and locking systems on VV

The DC is an Eurofer welded structure made of two 30 mm external shells and internal ribs of 30 mm cooled with the same water circuit of liner and deflector plates (Fig. 6).

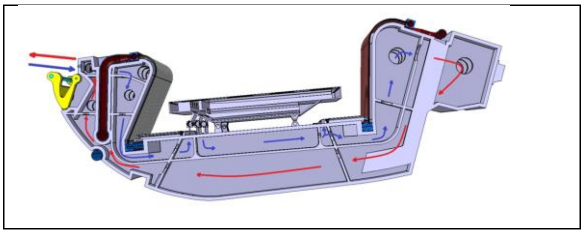

Fig. 6 – Divertor assembly section with detail of cassette section and cassette cooling path.

Several solutions for fixation of CB to VV have been studied in the pre-conceptual design stage [24].

In the current design, on the inboard side the DC is fixed to the VV with two shear key-like structures called "nose". On the outboard a flexible component called "wishbone" (made in Ti-6Al-4V) fixes the DC via pin connections to the VV. These mechanical attachments, see Fig. 7, support the DC against all loads acting on the cassette assembly, see Table 1, Table 3 and Table 5**Error! Reference source not found.**.

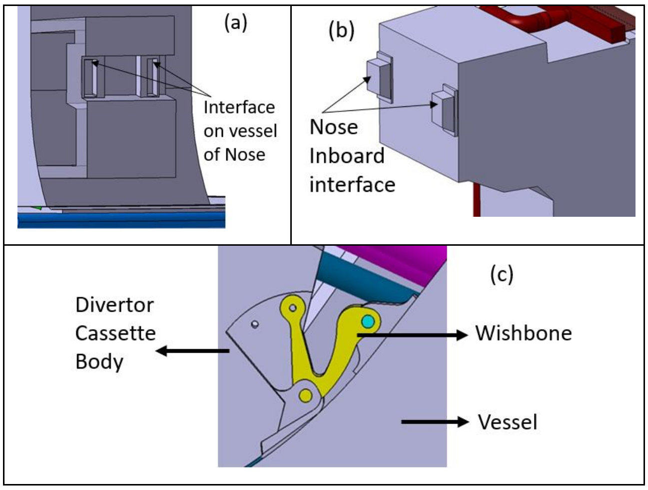

Fig. 7- Divertor Cassette and locking systems on VV a) and b) inner locking; c) outer locking system.

12.5 mm of maximum differential thermal expansion in Normal Operation Condition (NOC) has been obtained by means of a thermal calculation of the DC/VV under Backing and NOC.

Fig. 8- Divertor Cassette and locking systems on VV a) and b) inner locking; c) outer locking system.

The differential thermal expansion causes a maximum radial force on the DC attachments of about 25 tons given the elastic spring constant of the Wishbone of 2 tons/mm (see Fig. 9).

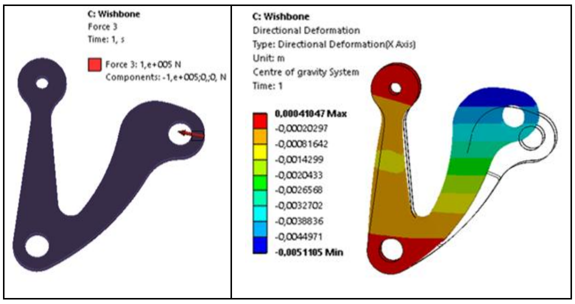

Fig. 9 -Wishbone elastic spring constant calculation: K=F/displacement= 100000 N/5.11mm= 19.6 kN/mm =2 tons/mm.

4. Loads Specification and main analyses for Divertor Assembly

The main loads considered for the DEMO divertor can be found in [15]. In the following the most important results are reported.

4.1 Baking and NO Condition

Baking conditions:

VV:	T= 180°C p~ 2 MPa
DC (including SL and RPs)	T= 240°C p~ 4MPa
Divertor PFC	T= 240°C p~ 4 MPa

Normal Operating Conditions:
Vacuum vessel temperature: T=40°C p~ 2 MPa
DC (including SL and RPs) T_{inlet}= 180°C p_{inlet}~ 3.5MPa
Divertor PFC T_{inlet}= 130°C p_{inle}~ 5 MPa

4.2 Heat loads

For thermal-hydraulic calculations, a constant value of 1.5 MW/m^2 has been assumed as heat flux incident onto both SL and RPs plasma facing surfaces. **Error! Reference source not found.**Table 1 reports a preliminary evaluation of Surface Heat Load and Nuclear Volumetric Heat Load for SL, RFs and CB.

Table 2- Summary of Heat Loads considered for SLs, RP and CB.

Component	Surface Heat Load			Nuclear Volumetric Heat Load	Total Heat Load
	Plasma-Facing Surface [m^2]	Heat Flux [MW/m^2]	Power per Component [MW]	Power per Component [MW]	Power per Component [MW]
SLs	1.51	1.50	2.27	1.49	3.75
RP	0.84	1.50	1.26	0.12	1.38
CB	0.00	0.00	0.00	1.58	1.58
TOTAL			3.53	3.19	6.72
Total Deposited Power per Cassette [MW]					6.72
Total Deposited Power per 48 Cassette [MW]					323

Table 3 reports the summary for Surface Heat Load and Volumetric Heat Load for the OVT, IVT and relative piping. In order to calculate the heat power due to surface heat loads a uniform heat flux due to radiation equal to ≈ 1 MW/m^2 and a peak heat flux at the strike point of 20 MW/m^2 have been assumed (Fig. 10) [15].

Table 3 - Summary of Heat Load considered for Divertor OVT, IVT and Piping.

Component	Surface Heat Load				Nuclear volumetric Heat Load	Total Heat Load
	Plasma-Facing Surface [m^2]	Peak Heat Flux [MW/m^2]	Background Heat Flux [MW/m^2]	Power per Component [MW]	Power per Component [MW]	Power per Component [MW]
OVT	0.62	20.0	0.98	1.38	0.34	2.76
IVT	0.49	20.0	0.98	1.04		
Piping	0.00	0.0	0.00	0.00	0.12	0.12
TOTAL				2.42	0.46	2.88
Total Deposited Power per Cassette [MW]						2.88
Total Deposited Power per 48 Cassette [MW]						138

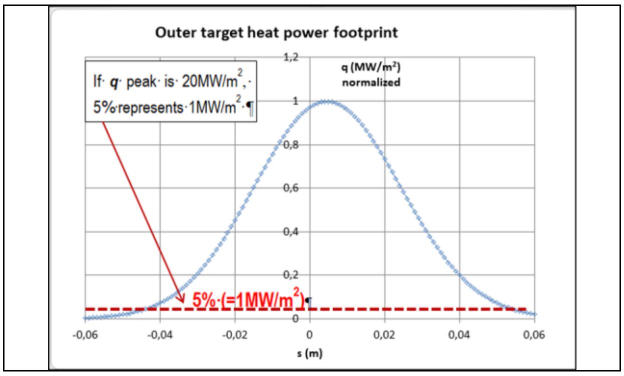

Fig. 10 - The latest predictions of the DEMO plasma outer target heat flux footprint indicate an exponential distribution that, scaling to the worst case scenario considered, can be represented by a transient partial loss of detachment with a peak heat flux of 20 MW/m^2, and considering as high heat flux (HHF) the region that remains above 1MW/m^2 [15].

4.3 Neutronics calculations

Neutronics calculations for the DEMO divertor 2019 configuration, reported in Fig. 1, are in progress. For the present assessment the volumetric nuclear heating value results calculated in 2018 [15] [16] have been used and extrapolated to the 2019 configuration.

Error! Reference source not found. and Table 3). Fig. 11 shows the 2018 neutronics models.

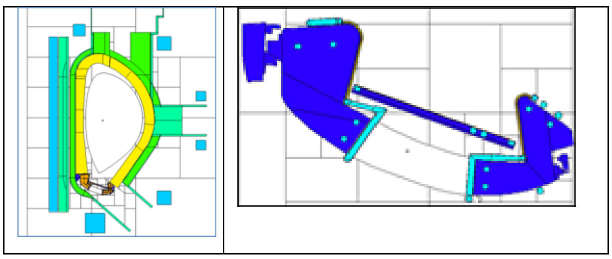

Fig. 11 left) DEMO neutronic model; right) Divertor Cassette model

The nuclear quantities calculated in the divertor neutronics analyses are as follows [16]:

-Spatial distribution of neutron flux ($n/cm^2/s$);

-Total nuclear power and breakdown in each component (kW);

-Spatial distribution of nuclear heating density (W/cm^3) in all divertor components (IVT, OVT, SLs, DP, CB and supports);

-Maps of Nuclear heating density (W/cm^3) used as input for thermal analyses;

-Spatial distribution and damage (Dpa/full power year (FPY), for Eurofer, Cu and W;

- Spatial distribution of He-production (appm/FPY,) in Eurofer, Cu and W;

-Evaluation of the shielding performances of SL, DPs and CB;

-Impact on CB and SL on SL and CB supports of nuclear heating and damage.

The maximum values of the neutron damage in divertor and VV are reported in Table 4.

Table 4 Maximum neutron damage (dpa) on Divertor (components/materials layers) and Vacuum Vessel.

Material/Layer	Dpa/FPY	Dpa /(2 FPY)
W/ PFC- Ist layer	1.98	3.96
W/ Liner- Ist layer	1.76	3.52
Cu /PFC- IIIrd layer	7.14	14.3
Eurofer /PFC-supports	4.38	8.77
Eurofer /Liner- II layer	4.91	9.82
	Dpa/FPY	**Dpa /(6 FPY)**
AISI 316 L(N) - VV layer	~0.55	~3.3

In particular the neutronics analyses showed some critical issues related to the lack of fulfillment of design criteria for the divertor and VV:

- *Cumulated damage (dpa) in Eurofer*: in order to limit the material properties degradation under low temperature irradiation (<180°C), the damage on Eurofer shall be below of 6 dpa over its lifetime here assumed to be 2 FPY [17].

- *Cumulated damage (dpa) on VV*: a maximum damage of 2.75 dpa over 6 FPY have been fixed for AISI 316L(N) IG in order to have negligible irradiation damages in temperature range of 20 to 375°C [14].

A possible solution for these issues can be to reduce the lifetime of Cassette from 2 to 1.22 FPY. The possibility of increasing the neutron shielding performance of the CB/SL system in the 2019 design (Fig. 1) is also under evaluation in order to increase the lifetime of the VV.

4.4 Thermo-Hydraulic analysis

The cooling scheme of the DEMO divertor consists of two separate cooling circuits. One is for all Divertor Eurofer components as CB, SP and RPs with p_{inlet}/T_{inlet}= 3.5 MPa/180 °C [18] and the other one is for PFCs with p_{inlet}/T_{inlet}= 5 MPa/130 °C [19].

For the thermal-hydraulic analysis the principal inputs are obtained from plasma surface heating and volumetric neutron heating (see §4.2). The main design limits that should be taken under control are:

1) Divertor Cassette cooling circuit (Fig. 12):

- Maximum Temperature on the Eurofer < 550 °C;
- Maximum water pressure drop < 1.4 MPa;
- Margin against water saturation temperature > 20°C

2) Plasma Facing cooling circuit (Fig. 13):

- Maximum water velocity in PFC tubes < 16m/s
- CHF margin > 1.4;
- Maximum pressure drop < 1.4 MPa;

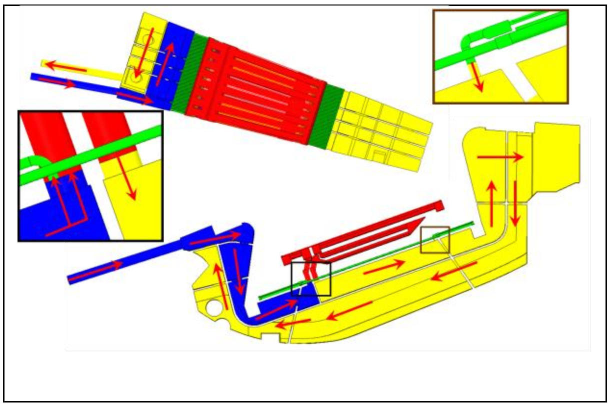

Fig. 12 – Cooling circuit of CB, RPs and SL.

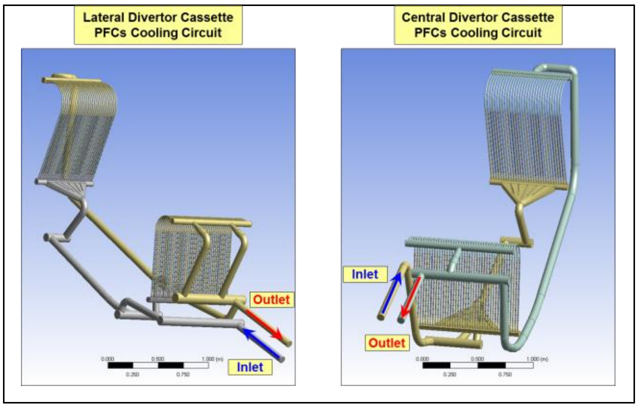

Fig. 13 – PFCs Cooling circuit layout.

A physical mock-up of the OVT for the verification of the thermo-hydraulic performances has been designed [25] and it is currently under testing.

4.5 Electromagnetic(EM) analysis

The EM loads are the most important mechanical loads on the divertor components and in particular for the supports design (e.g. cassette, PF, SP and DPs supports). In [15],[20] and [21] the following divertor relevant EM conditions have been studied:

- Vertical Displacement Event Upward with a linear Current Quench of 74ms duration (VDEUP_74msLCQ)
- Toroidal Field Magnet Fast Discharge (TFC- MFD): a total TFC exponential current decay of 27 ms time constant is assumed;

Future work will taking into account the other EM load as downward VDEs or disruptions and also halo current effect.

The EM resultants (forces and moments) on the divertor assembly are reported in Table 5**Error! Reference source not found.**. An important load is the "Maxwell force on Ferromagnetic material" due to the magnetic influence of magnetic toroidal field on the Eurofer parts of the divertor assembly.

Table 5 - EM Force and Moment on Divertor assembly

	Maxwell loads on Ferromagnetic material	VDEUP (74msLCQ)	TFC-MFD		Maxwell loads on Ferromagnetic material	VDEUP (74ms LCQ)	TFC-MFD
Frad (kN) (max outward)	0	450	0	Mrad (kNm) (max outward)	0	1000	0
Frad (kN) (max inward)	-800	-150	-650	Mrad (kNm) (max inward)	0	-900	-60
Ftor (kN) (max outcoming)	0	400	0	Mtor (kNm) (max outcoming)	0	100	380
Ftor (kN) (max incoming)	0	-400	0	Mtor (kNm) (max incoming)	0	-400	0
Fver (kN) (max upward)	0	1300	-500	Mver (kNm) (max upward)	0	2400	0
Fver (kN) (max downward)	0	-400	-1500	Mver (kNm) (max downward)	0	-2700	-2800

5. Conclusion

A complete overview of the main design activities of the DEMO divertor have been presented together with the most relevant loads. Critical issues under study have been also pointed out, as for example, the damage on the materials of the divertor cassette (Eurofer) and on VV (AISI 316-L(N)-IG).

Acknowledgments

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