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CONFERENCE PRE-PRINT

Design and qualification activity of the first divertor of the DIVERTOR TOKAMAK TEST FACILITY

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Abstract

The Divertor Tokamak Test facility (DTT) is a fusion device under construction in Italy, with the support of the EUROfusion consortium, dedicated to testing power exhaust solution alternative to the baseline adopted in ITER for the future nuclear fusion reactors. The divertor concepts they can be studied under integrated physics and technological conditions relevant for future fusion power plant. Several divertors which may differ in design or/and technologies or/and poloidal profile will be tested during the life of the machine. Hovewer, in the first phase of exploitation of the facility different magnetic configurations and scenarios will be study with the aim to identify the most promising. The first divertor will therefore have to be robust and flexible, able to withstand high thermal loads for long pulses and to accommodate strike points located at various positions according to the different equilibria. For this reason, almost the entire divertor plasma-facing surface is in Tungsten (W) monoblocks and the monoblocks are joined to CuCrZr pipes (plasma-facing units, PFUs) using the design and technology developed for the ITER divertor targets which, at the state of the art, is the most reliable.

However, the ITER PFU design was integrated with specific modifications required for the scope of the first DTT divrtor and testing campaigns were necessary to validate this design peculiarity. The paper reports the main challenges envisaged during the design as well as the main the results obtained in the experimental validation campaign carried out.

1. INTRODUCTION

The DTT tokamak is an experimental facility under construction at the ENEA Research Center in Frascati, Italy. Its scope is to provide reactor relevant conditions for the testing of the power exhaust and in particular of the divertor systems. To this aim, DTT has been designed with many features in common with ITER but it is also characterized by a large degree of flexibility in the magnetic configurations that makes it the ideal test bed for any future tokamak reactor [1]-[2]. The DTT Tokamak is a magnetic confinement device with a superconducting coil magnet system, capable of sustaining high-current (plasma current Ip=5.5 MA) discharges for up to 100 s duration. Furthermore will be equipped with high-power 45 MW of plasma additional heating (32MW of Electron cyclotron waves at 170 GHz, 8MW of Ion cyclotron waves at 60-90 MHz and 10MW of Negative Neutral Beam Injector at 510 keV.

Its divertor will necessarily have to be actively cooled to be able to sustain the thermal loads over the expected long times. A cooling system able to manage an overall water mass flow rate of 577 kg/s at a pressure 5MPa (at the inlet of the divertor system) and at an inlet temperature settable within 30-130°C is devote at this scope.

The design process began with a detailed definition of the key interfaces and overall constraints, which are expected to remain consistent for future divertors. These constraints include, for example, the precise positioning of the rails required for fixing the divertor structure to the vacuum vessel (VV), the maximum allowable external dimensions to ensure compatibility with the insertion procedures through the equatorial port of the machine, and the strict limitations on the total weight of the component to ensure it remains within the operational capacity of the remote handling system. These initial boundary conditions provided the framework within which all subsequent design choices were made.

These constraints influenced the toroidal segmentation of the divertor into 54 modules.
These features will probably be common to all future DTT divertors, what characterizes the first divertor is linked to the specific purposes of the first experimental phase of the DTT Facility.

The first operational phase of DTT will focus on studying multiple magnetic configurations to evaluate their performance in controlling plasma detachment, heat flux distribution, and material erosion. To support this experimental flexibility, the first divertor must be capable of accommodating varying strike point positions and sustain long-pulse, high-power discharges.

To meet these requirements, the Plasma Facing Units (PFUs) of the first DTT divertor adopt a tungsten monoblock design similar to that developed for ITER, leveraging the extensive R&D and industrial experience accumulated over the last decade. Nevertheless, the design modifications that were necessary to maximize the admissible heat flux under highly variable load distribution conditions required specific experimental verification campaigns. The paper provides a detailed description of the plasma facing units (PFU) design and reports the main results of the experimental activities conducted

2. PLASM FACING UNITS DESIGN DESCRIPTION

The development of the poloidal profile for the first divertor design was strongly influenced by the need to ensure compatibility with three reference magnetic equilibrium configurations that have been selected as representative for the operation of the device: the Single Null (SN), the X-Divertor (XD), and the Negative Triangularity (NT) configurations (see **Errore. L'origine riferimento non è stata trovata.**). Each of these equilibria presents distinct magnetic and geometrical features that the divertor must accommodate.

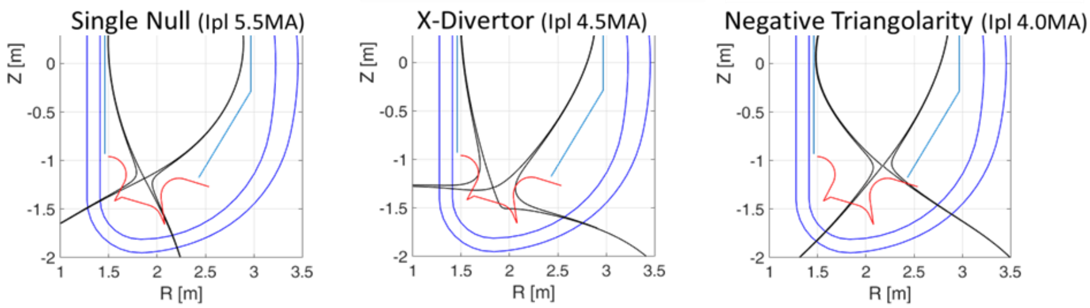

Figure 1 compatibility with the reference equilibria

Furthermore, the design had to comply with a set of geometric constraints (as illustrated in Figure 1) and technological limitations arising from the manufacturing processes. This dual requirement — compatibility with magnetic scenarios and adherence to production constraints — played a central role in defining the poloidal cross-sectional shape of the divertor where four targets can be identified for the strike points of the three reference magnetic configurations.

Moving to a three-dimensional view of the divertor (see Figure 2), three Plasma-Facing Components (PFC) can be defined in each divertor module: Inner Target (IT), Outer Target (OT) and Central Target (CT). In each PFC there are straight parts (targets) and curved parts (baffles). In the IT and CT components there are one baffle and one target, named, respectively, Inner Vertical Target (IVT) and Central Horizontal Target (CHT), whilst in the OT there are one baffle and two targets; the Outer Vertical Target (OVT) and Outer Horizontal Target (OHT).

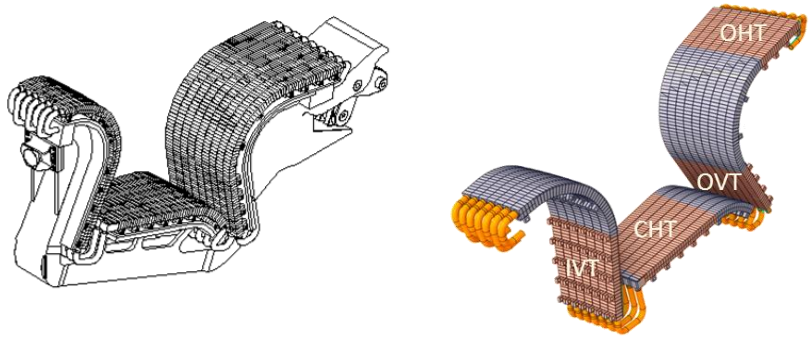

Figure 2 Diverotor module(left) and plasma facing component with targets highlighted (right)

For each divertor module IT and CT consist of 7 PFUs, while OT of 9. The 7 central PFU of the three components are connected in series by curved tubes hidden from direct plasma radiation, but not covered with monoblocks to leave free slots between the target allowing adequate pumping close to the strike point (Figure 2).

With the purpose to increase the flexibility in operational scenarios by maximizing the allowable thermal load, the monoblocks have a reduced plasma side thickness to respect of the ITER ones. The monoblock thickness of 3 mm was fixed compatible both with the erosion estimates in the DTT divertor area and with the manufacturing constraints.

The mechanical strength of a monoblock featuring a reduced plasma-facing thickness under cyclic thermal loading required experimental validation. To this end, a dedicated testing campaign was carried out at the GLADIS facility. In the initial phase of the campaign, two mock-ups equipped with monoblocks having plasma-facing armor thicknesses of 4 mm and 3 mm, respectively, were subjected to a comparative assessment. Both mock-ups underwent 1000 thermal cycles at a heat flux of 2 MW/m². The results obtained from these tests are detailed in [4].

Subsequently, the mock-up featuring 3 mm of armor was subjected to an additional 1000 thermal cycles under the same hydraulic conditions as in the previous phase of the campaign. However, in this second test, the duration of each heating cycle was increased from 1 second to 15 seconds, with the objective of extending the total residence time at high temperature. This parameter is particularly significant, as prolonged exposure to elevated temperatures promotes recrystallization processes in the material — a phenomenon known to contribute to surface degradation and the initiation of cracks.

The figure below presents a comparative image of the surface condition of the DTT mock-up with 3 mm-thick armour after undergoing 2000 thermal cycles at a heat flux of 20 MW/m² compared with an EU-DEMO target mock-up featuring an 8 mm-thick armour, which was tested under similar hydraulic conditions but for 500 cycles at the same heat flux.

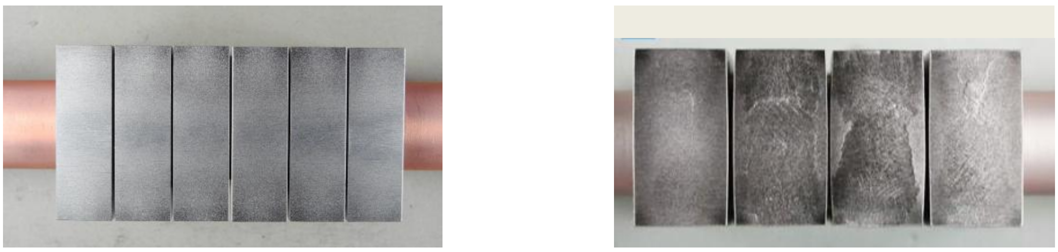

Figure 3 DTT mock-up loaded surface after 2000 cycles at 20 MW/m2 (left) and DEMO mock-up loaded surface after 500 cycles at 20 MW/m2 (right)

Surface recrystallization in the mock-up with a 3 mm-thick tungsten armour remains extremely limited and has not led to the formation of cracks. However, accidental events could still trigger significant recrystallization, even with the reduced armour thickness.

The onset of cracks is also influenced by the toroidal width of the monoblock, which, in the HOT (High Heat Flux Option Target), can reach up to 30 mm. To investigate this aspect, a dedicated test was carried out at the HADES electron beam facility. A mock-up with 3 mm of tungsten armour and a toroidal width of 30 mm was subjected to high heat loads over prolonged periods, intentionally inducing macrocracks on the surface.

Following this pre-cracking phase, the same mock-up was exposed to 1000 thermal cycles at the design heat flux of the target — 16 MW/m² — in order to assess whether, given the reduced armour thickness, the presence of cracks would compromise the structural integrity of the component.

The Figure 4 shows the surface condition of the mock-up after testing: no crack propagation or additional damage was observed, indicating that the component maintained its mechanical integrity under the prescribed conditions.

Figure 4 DTT HT mock-up intentionally cracked after 1000 cycles at 16 MW/m^2

The toroidal shaping of the DTT divertor plasma-facing components (PFCs) represented one of the most complex aspects of the design process.

In the monoblock concept, when the power loads are significant, it becomes essential to implement a toroidal bevel of the monoblocks to avoid the overheating of the leading edges. This design feature helps prevent localized damage to the protruding edges caused by the inherent gaps between PFC units and divertor modules and the tolerances due to the manufacturing and assembly.

However, this solution introduces a critical trade-off. When accommodating different magnetic configurations — each characterized by distinct magnetic field line (grazing) angles — the presence of a toroidal chamfer can, in certain configurations, lead to a substantial increase in local heat loads. These increases risk canceling the design gains achieved by reducing the tungsten thickness in an effort to increase the allowable heat flux.

The bevel angle of the monoblocks was carefully selected based on the predicted grazing angles for the three reference magnetic configurations (Single Null, X-Divertor, and Negative Triangularity) repoted in the Table 1. The design took into account both steady-state operating conditions and transient phases such as ramp-up and ramp-down, as well as realistic manufacturing and assembly tolerances.

Configuration	t (s)	I (MA)	IVT (°)	Top-IVT (°)	CHT (°)	OVT (°)	OHT (°)
SN	FT	5.5	2.09			1.92	
XD	FT	4.5	0.83		0.14		
NT	FT	4.0			3.6		1.2
SN ramp-up	5.00	2	0.8			0.9	
SN ramp-up	13.75	5.5	2.3			1.8	
Long Leg SN	FT	5.5	1.70	1.70		2.2	
Long Leg XD	FT	4.5	1.0		0.4		
Super XD	FT	4.5	1.7		0.5		

Table 1 Grazing angles on the four targets in the reference configurations (and not only)

By selecting an appropriate bevel angle and implementing a corresponding radial translation of the Plasma-Facing Units (PFUs), the design ensures that the side of the monoblocks remain protected in all operational scenarios — both across the gaps between adjacent PFUs and between divertor modules — regardless of the magnetic configuration.

The Table 2 summarizes the range of grazing angles encountered across the different targets.

GRAZING ANGLE	
	Range
IVT	0.8°-2.3°
CHT	0.1°-3.6°
OVT	0.9°-2.2°
OHT	1.2°-1.4°

Table 2 Range grazing angle experienced by each target

To maximize the allowable thermal load on the divertor, a unidirectional toroidal shaping was adopted for all four targets, including the central target (CT). This design choice ensures optimal thermal performance while maintaining geometric simplicity and consistency across the PFCs.

In the reference magnetic configurations, both the outer legs of the X-Divertor (XD) and the inner legs of the Negative Triangularity (NT) configuration are directed toward the central target. As a result, the NT configuration can be experimentally explored by reversing the direction of the toroidal magnetic field. This flexibility adds significant value to the overall experimental program.

However, a challenge arises from the fact that the grazing angles of the magnetic field lines on the CT differ considerably between the two configurations: approximately 0.1° for the XD and 3.6° for the NT. To accommodate this difference and ensure proper thermal handling, the central target was divided into two distinct sections, each dedicated to one of the configurations. This division allows each section to be optimized according to the specific heat flux conditions and geometric requirements imposed by the respective grazing angles.

The Figure 5 shows the cross-sectional view of the targets, and in particular one can see the segmentation of the CT to effectively fit both configurations..

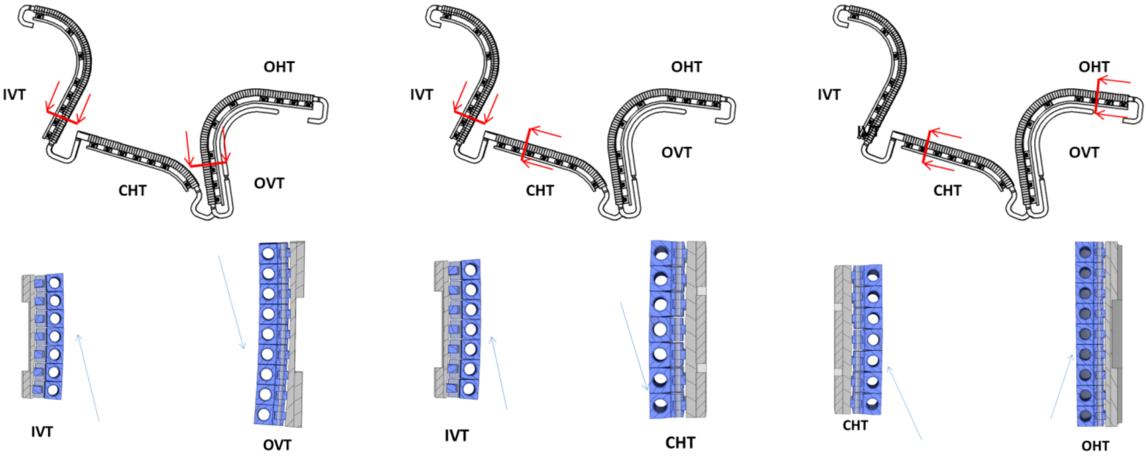

Figure 5 cross-sectional view of the targets

Considering the resulting moonoblock’s geometry, the allowable thermal load on each target was assessed and compared to simulation results obtained using the SOLEDGE2D-EIRENE code.

The SOLEDGE2D-EIRENE code was used to simulate a range of power levels crossing the separatrix for each reference configuration. The results — summarized in the Table 3 — show as input power increases, the electron temperature (Te) in the target zone rises accordingly.

SINGLE NULL					IVT	OVT	IVT	OVT
Case Study	n_sep *10^19	P_SOL (MW)	T_sp1 (eV)	T_sp2 (eV)	q_perp_sp1 (MW/m^2)	q_perp_sp2 (MW/m^2)	q_par_sp1 (MW/m^2)	q_par_sp2 (MW/m^2)
BD6_SN_1001	7	3,5	4	1,5	0,58	0,34	17,1	10,0
BD6_SN_1002	7	5	4	1,5	0,89	0,49	26,3	14,5
BD6_SN_1003	7	7	3,5	1,5	1,32	0,67	39,0	19,8
BD6_SN_1004	7	14	40,7	47,9	9,1	9,9	268,8	292,4
BD6_SN_1005	7	25	114,7	85,2	25,3	16,8	747,4	496,3

X-DIVERTOR					IVT	CHT	IVT	CHT
Case Study	n_sep *10^19	P_SOL (MW)	T_sp1 (eV)	T_sp2 (eV)	q_perp_sp1 (MW/m^2)	q_perp_sp2 (MW/m^2)	q_par_sp1 (MW/m^2)	q_par_sp2 (MW/m^2)
BD11_XD_1001	7	3.5	1.5	1.6	0.69	0.38	48.2	155.5
BD11_XD_1003	7	7	35	25.8	2.1	0.4	146.7	163.7
BD11_XD_1004	7	14	138	121	7.34	1.1	512.9	450.2
BD11_XD_1005	7	25	230	229	16.4	2.45	1146.0	1002.7
BD11_XD_1006	7	35	298	313	25.9	3.95	1809.8	1616.6
BD11_XD_1007	7	45	434	448	37.3	5.9	2606.3	2414.6

NEGATIVE TRIANGULARITY					CHT	OHT	CHT	OHT
Case Study	n_sep *10^19	P_SOL (MW)	T_sp1 (eV)	T_sp2 (eV)	q_perp_sp1 (MW/m^2)	P_perp_sp2 (MW/m^2)	q_par_sp1 (MW/m^2)	q_par_sp2 (MW/m^2)
BD15_NT_1003	6	7	29	68	3.51	1.97	56.2	90.3
BD15_NT_1004	6	14	112	133	9.34	4.48	149.6	205.4
BD15_NT_1005	6	25	193	207	8.73	14.81	139.8	678.9
BD15_NT_1006	6	35	205	236	13.68	27.3	219.1	1251.4

Table 3

Green rows in the table correspond to scenarios where both Te and the associated tungsten (W) sputtering remain within acceptable limits, allowing sustained operation.

Yellow rows indicate more critical conditions, where tungsten sputtering and plasma contamination could become problematic but might still be manageable for limited durations.

Red rows represent regimes that are likely unsustainable due to excessive plasma pollution from W erosion.

Once the toroidal shaping was finalized, a further analysis was conducted to evaluate whether the maximum allowable thermal load on the monoblocks would restrict the range of feasible physics experiments. A comprehensive review of all relevant scenarios revealed that, for all three magnetic configurations, the monoblock is capable of withstanding a separatrix power of up to 14 MW. This confirms that the divertor design does not impose any fundamental limitations on the planned experimental program.

The most demanding thermal scenario is observed on the Inner Vertical Target (IVT) when it is impacted by the internal leg of the X-Divertor (XD) configuration. In this case, although the theoretical perpendicular heat flux is approximately 7.3 MW/m² (see , the actual heat flux incident on the monoblock surface — due to the extremely shallow grazing angle — reaches as high as 21 MW/m². This represents the highest surface heat load encountered among all the configurations analyzed. Nevertheless, the monoblock design remains capable of withstanding this extreme condition, confirming its robustness and thermal handling capability under the most critical loading scenario.

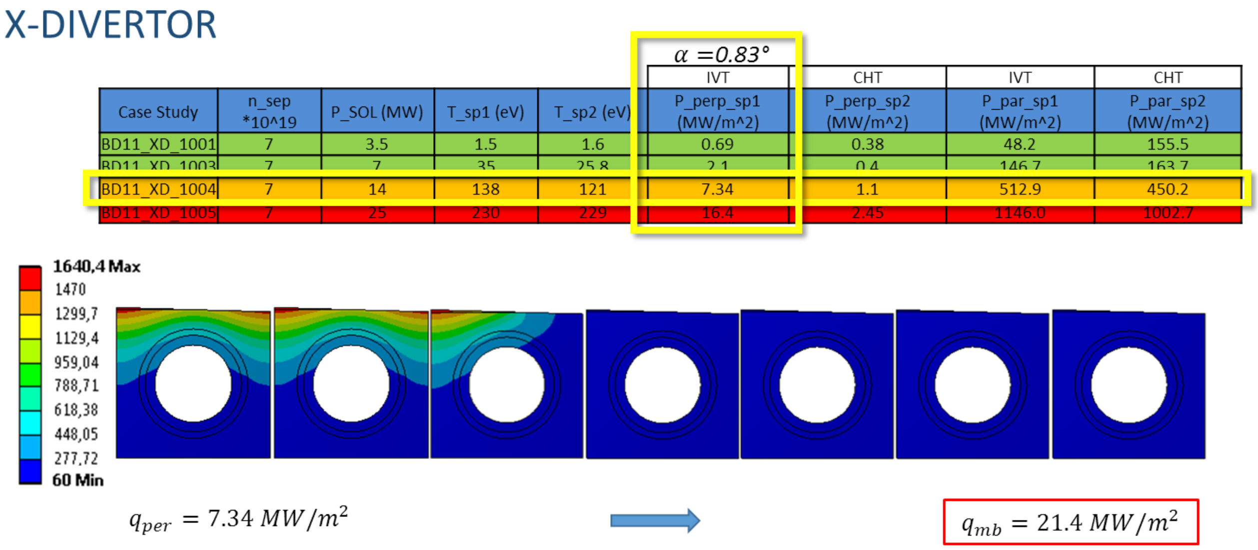

Figure 6 Expected temperature range on the IVT in the case of XD configuration and 14 MW of power at the separator

The toroidal shaping illustrated—particularly in the case of the Outer Target (OT)—introduces significant complexity in the 3D design of the component. Specifically, the OT includes two distinct regions: the Vertical Target (VT) and the Horizontal Target (HT), which feature opposite shaping directions and different bevel angles.

These two regions are joined through a transition zone known as the fitting reaction, which accommodates the geometric shift between the two target surfaces. The complexity is further compounded by several design factors: the differing bevel angles, the variation in toroidal widths required to match the evolving surface geometry away from the machine center, and the integration of mechanical fastening systems for securing the PFCs to the underlying cassette structure.

The final design of the OT comprises a total of 42 distinct monoblock construction drawings, each of which must be individually manufactured, tracked, and correctly positioned during the assembly process to ensure full functionality and alignment with the divertor's thermal and magnetic design requirements.

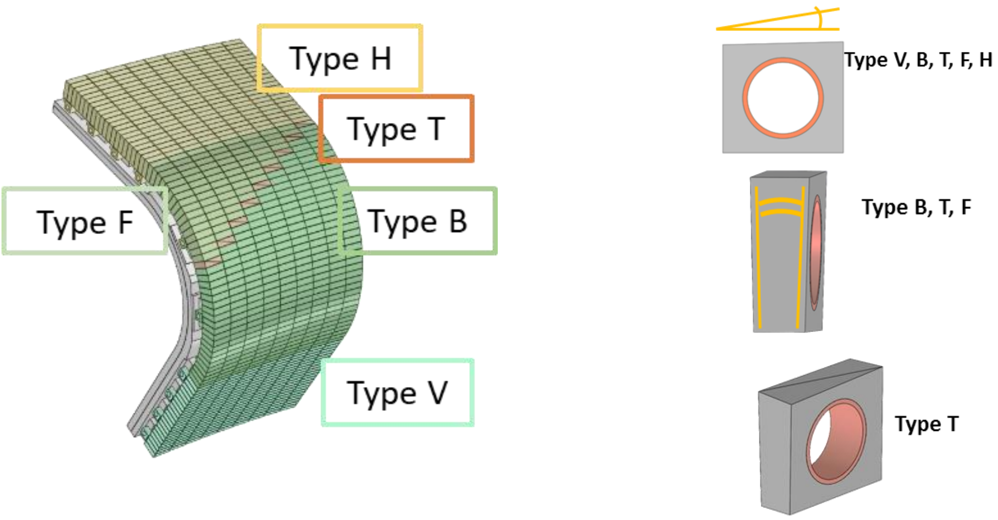

Figure 7 OT monoblock Types

3. CONCLUDING REMARKS

The construction of the Divertor Tokamak Test facility is progressing. The design of the first divertor has been completed with the requirement to be compatible with the three reference scenarios (SN, XD and NT) in order to allow for the definition of the requirement for the successive divertor shapes to be tested and optimized for one specific magnetic configuration. The design activity has been carried out with respect to the plasma facing unit as well the cassette structure and the integration process and taking into account interface constraints with the vacuum vessel and with those posed by the remote handling system. Also, the water-cooling system requirements have been verified with respect to the chosen design. Having completed the design, and also during the design phase, several experimental campaign have been performed to assess the robustness of the design choices. With these results, the procurement activity is about to start with the aim to complete the divertor production in time foe its insertion in the facility during the assembly.

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