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Ricerca di Sistema elettrico

Progettazione preliminare di un divertore per FAST ed EAST compatibile con configurazioni di plasma di tipo "Snow-Flake"

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PRELIMINARE DI UN DIVERTORE PER FAST ED EAST COMPATIBILE CON CONFIGURAZIONI DI PLASMA DI TIPO “SNOW-FLAKE”

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Index

Summary

Divertor is a crucial component in Tokamaks, aiming to exhaust the heat power and particles fluxes coming from the plasma during discharges. This report focuses on the optimization process of FAST divertor, aimed at achieving required thermo-mechanical capabilities and the Remote Handling (RH) compatibility. Divertor RH system final layout has been chosen between different concept solutions proposed and analysed within the principles of Theory of Inventive Problem Solving (TRIZ). The design was aided by kinematic simulations performed using Digital Mock-Up capabilities of Catia software. Considerable electromagnetic (EM) and mechanical analysis efforts and top-down CAD approach enabled the design of a final and consistent concept, starting from a very first dimensioning for EM loads.

In the final version here presented, the divertor cassette supports a set of tungsten (W) actively cooled tiles which compose the inner and outer vertical targets, facing the plasma and exhausting the main part of heat flux. W-tiles are assembled together considering a minimum gap tolerance (0.1÷0.5mm) to be mandatorily respected. Cooling channels have been re-dimensioned to optimize the geometry and the layout of coolant volume inside the cassette has been modified as well to enhance the general efficiency.

1 Introduction

The Fusion Advanced Studies Torus (FAST) [1-3] belongs to the category of the “ Satellite Experiment” which aims to support ITER and DEMO programs and actively contribute to their successful achievement.
One of the most challenging gaps in view of DEMO is the power exhaust problem [4, 5]. FAST, from the very beginning, has been conceived with the main aim to tackle this problem allowing the studies of the plasma wall interaction aspect in different plasma regions (bulk, SOL, divertor), also varying the radiation factor [6].
The divertor, in a tokamak machine, is the plasma facing component for disposal of the most of heat load produced by the plasma and by the auxiliary heating in a fusion experiment. Accordingly, the divertor design, and especially the optimization of its geometry, is a crucial point in the whole project, because of problems deriving from the interaction between plasma and surrounding. Such an aim can be achieved, at first, via the study of the plasma boundaries, including all the real geometry conditions, from the physics point of view and without a deep attention to engineering constraints, which provides an optimized “conceptual” geometry. Then, in a second step, such a solution needs to be tackled with all the mechanical design problems, including the remote maintenance facility.
According with the iterations cycle shown in the left side of the V model [7] (Fig.1), the design activities of FAST divertor have been characterized by a continuous refinement of requirements and several geometrical and engineering optimizations, which led to the final solution presented in this report.

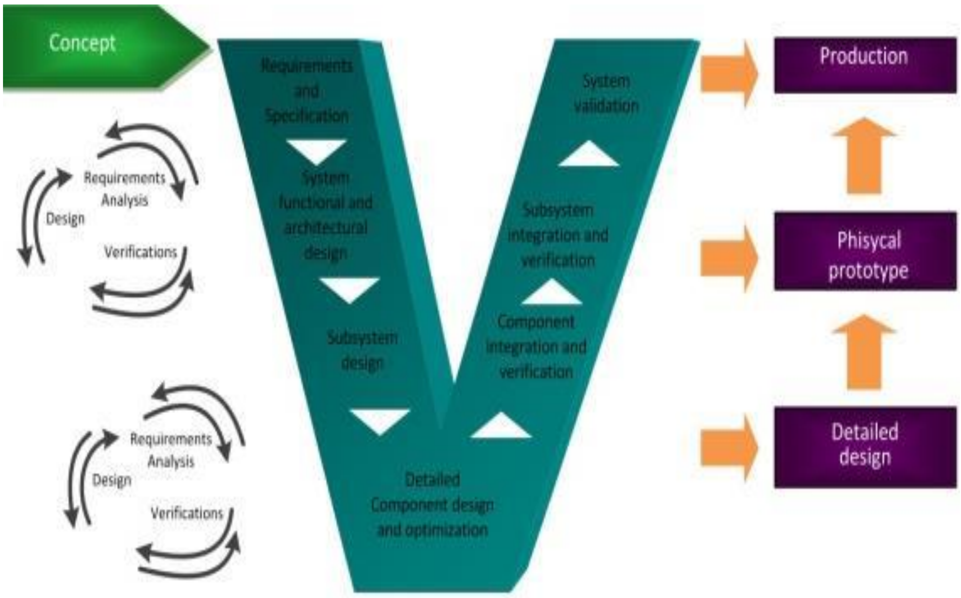

Fig. 1 – V model.

2 Description of activities and results

2.1 FAST divertor development

Several elements have been analyzed in the first FAST tokamak configuration: the shape and the dimensions of the divertor, the locking system and the space between the vacuum vessel and the cassette. Starting from an ITER-like solution, the first configuration of FAST divertor presented a 20° outer strike point angle, defined between the plasma leg and the outer vertical target. This configuration implies a very high power flux density in the divertor, in the order of 20 MWm^{-2}, which makes suitable as target plates only monobloc W tiles, constructed according a recently developed technique [3] .
In order to have the possibility to move the plasma from a diverter shape (or Single Null, SN) to the so called “snowflake” one (SF) [8], at first it was considered the possibility of a complete substitution of the divertor modules, characterized by a completely different geometry. The same divertor plates cannot be used for the SN and SF. A fundamental difference is that an SN divertor is essentially a closed divertor, while the SF is a very open one. Consequently, the support and locking system of FAST were object of

specific studies and several design review in order to overcome the drawbacks relates to the knuckle system (vibrations, maintenance difficulties). This resulted in a first improved configuration of the support system (Fig. 2) [9].


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Fig. 2 Alternative support system, [9].

Starting from this configuration, the power exhaust problem and the two alternative plasma configurations (SN or SF) was the object of further analyses and the focus of the divertor optimization. Since FAST is an experimental test machine, it is even better to have the possibility to experimentally compare the different topologies on the same discharge, just modifying the plasma equilibrium. The idea was to have a divertor that, during the same shot, would allow to compare the two different geometries has been used. The Divertor geometry was studied to move from the standard SN configuration to the SF configuration avoiding the replacement of the same Divertor: the lower part of the divertor was similar to a traditional one , the upper part and the connection with the First Wall (FW) was been completely changed, in order to best fit the power deposition on the divertor plates and to make it as flat as possible; consequently the divertor curvature (that modifies the striking angles) was been realized to accomplish this target [10].

A finite element analysis (FEA) was made to reproduce the fluid dynamic behavior and the thermal stresses of the Plasma Facing Unit (PFU) and 3D thermo-hydraulic analysis was made to evaluate the possibility to operate with the SF configuration without replacing the Divertor and validate the design [11].

Of course, this modifications have led to a complete redesign of the bottom part of the vacuum vessel and of the FW, including all the support structures [11]. Moreover, the analysis of an alternative solution introduced new conflicts with the RH system. In particular, the cantilever arm of the Second Cassette End Effector (SCEE) resulted partially obstructed in its movements by the presence of the divertor’s outer hook, this requiring a re-design of the entire system. The components were re-designed (fig. 3) in a smart way, solving technical conflicts observed during the simulation phases using the Theory of Inventive Problem Solving (TRIZ) [12]. The use of this engineering methodology suggested two different concept solutions, which have been compared with an analytic method known as Analytic Hierarchy Process (AHP).

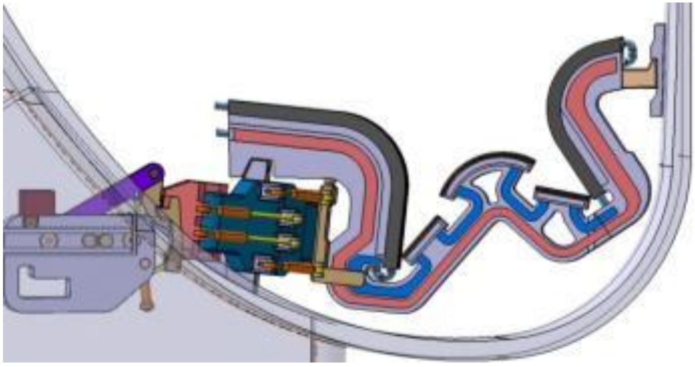


Fig. 3 Improved support system, [12].

The activities carried out for the improvement of the support systems, indeed, aimed to step forward in the geometry refinement process, performing structural analysis and further engineering phases for the optimization of the general features regarding the divertor. The considerations on this concept, the structural analysis with thermal and electromagnetical (EM) loads, came in as new, refined requirements, allowing the completion of the planning and the achievement of a final optimized divertor solution.

2.2 New Requirements: FEM analysis

2.2.1 Preliminary EM analysis

Alongside the studies on the support system, EM preliminary analysis of the whole divertor has been performed on the divertor solution conceived in [13]. The EM loads from a Plasma Fast Down disruption event have been evaluated for the assessment of the divertor conceptual design. The structural FE model of the divertor was developed using the finite element code Ansys. To reproduce the FAST toroidal periodicity the model consists in a divertor detailed mesh (5◦ in toroidal direction).

Magnetic field distribution as well as induced currents and the related Lorentz forces have been evaluated for each Poloidal Field Variation (PFV), Toroidal field variation (TFV) and Halo Current (HC). The EM loads have been combined element-by-element for the evaluation of the resultant forces and moments [14].

2.2.2 Preliminary Structural Analysis

The structural FE Model has been based on the EM mesh and the analysis have been carried out considering the most critical time instant evaluated in EM analysis. In the following figures (Fig.4, Fig.5) we show the results at time instant "67.9 ms".

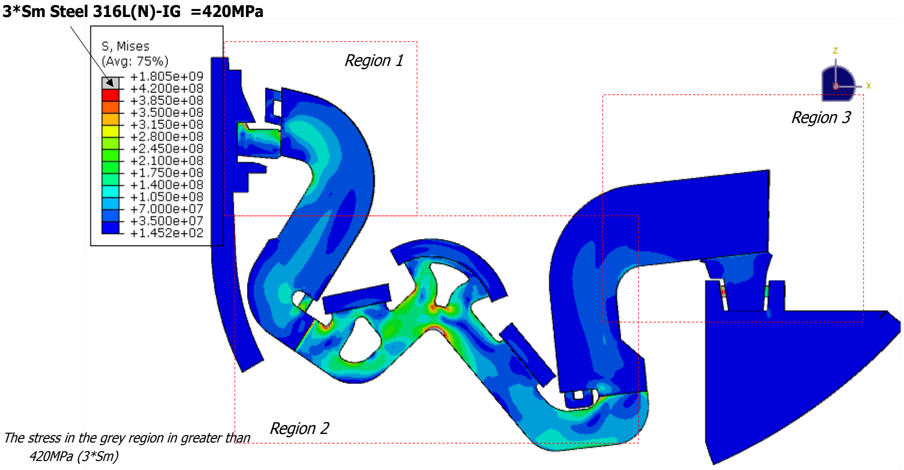
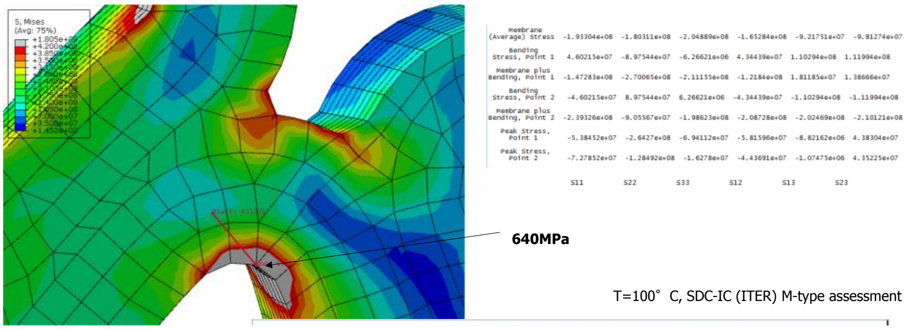


Fig. 4 Von Mises Stresses overview: time instant 67.9ms



	S11	S22	S33	S12	S13	S23
Membrane (Average) Stress	-1.93304e+08	-1.80311e+08	-2.04889e+08	-1.65284e+08	-9.21751e+07	-9.81274e+07
Bending Stress, Point 1	4.60215e+07	-8.97544e+07	-6.26621e+06	4.34439e+07	1.10294e+08	1.11994e+08
Membrane plus Bending, Point 1	-1.47283e+08	-2.70065e+08	-2.11155e+08	-1.2184e+08	1.81185e+07	1.38666e+07
Bending Stress, Point 2	-4.60215e+07	8.97544e+07	6.26621e+06	-4.34439e+07	-1.10294e+08	-1.11994e+08
Membrane plus Bending, Point 2	-2.39326e+08	-9.05567e+07	-1.98623e+08	-2.08728e+08	-2.02469e+08	-2.10121e+08
Peak Stress, Point 1	-5.38452e+07	-2.6427e+08	-6.94112e+07	-5.81596e+07	-8.82162e+06	4.38304e+07
Peak Stress, Point 2	-7.27852e+07	-1.28492e+08	-1.6278e+07	-4.43691e+07	-1.07475e+06	4.35225e+07

T=100° C, SDC-IC (ITER) M-type assessment

Fig. 5 Von Mises Stresses - SS316L(N)-IG Parts – stress linearization along path: time instant 67.9ms.

It results a maximum stress of 640 MPa at SS316 FAST Divertor parts, that doesn't satisfy the M-type assessment following the SDC-IC (ITER). For this reason, after several design review, geometrical variations to divertors shape have been proposed.

2.3 Innovative FAST divertor

The structural analyses have shown several possible intervention areas where the stress peaks resulted to be higher than the allowed values. Furthermore an ITER- like suitable and feasible locking system for the actively cooled W-Plasma Facing Components (PFCs) on the cassette body has been studied and designed.

2.3.1 Cassette Body

Following the analyses results and brainstorming sessions, several measures and changes of the divertor have been planned (Fig 6).

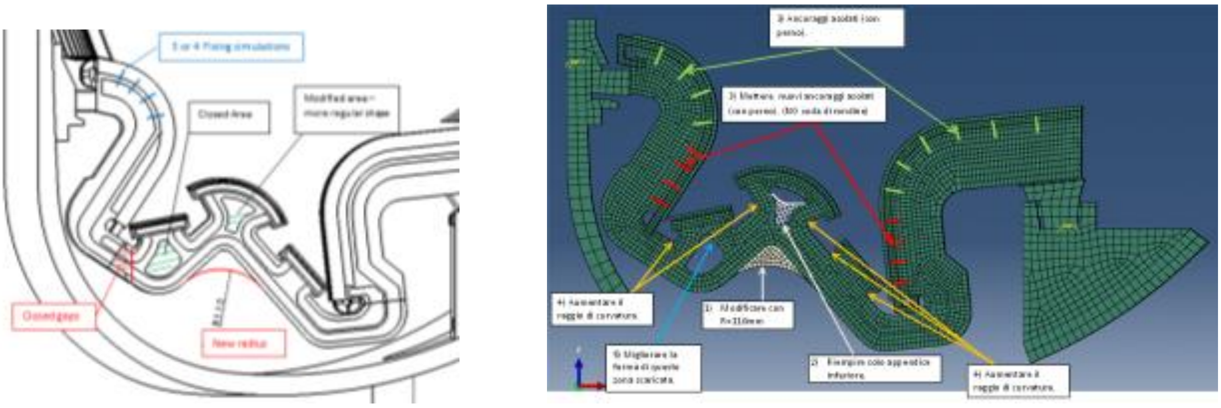


Fig. 6 Scheduled divertor modifications

At first a general cassette shape refining operation has been performed enhancing weak points, increasing joint angles where possible and providing a generally better layout of the cassette.

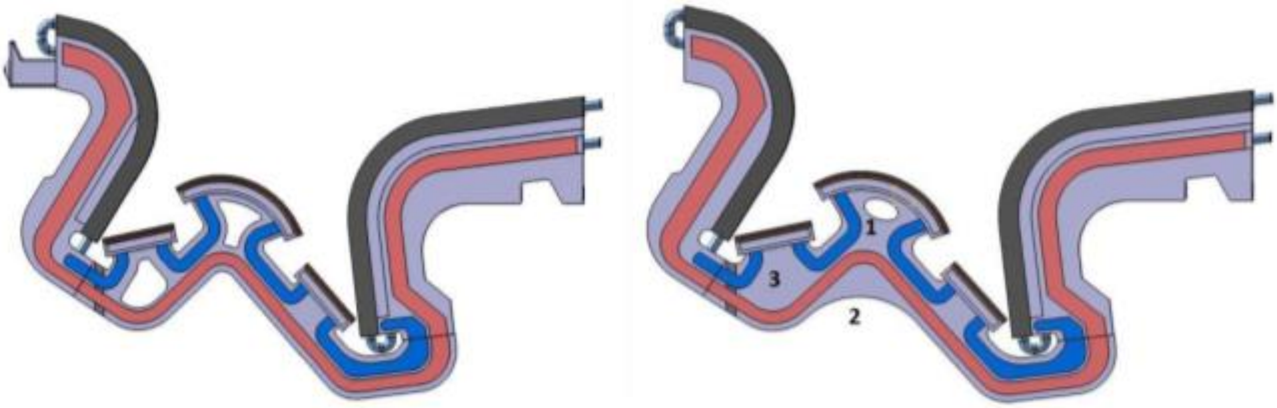


Fig. 7 Cassette Body review.

Some crucial improvements can be spotted (Fig.7):

1. The geometry of the lightening drill has been tuned to obtain better response at working loads. The shape is now much more regular.
2. The lower edge of the cassette has been redesigned to a new, higher curvature radius. As a result of this, the equivalent Von Mises stress decreases from 640 MPa to 130 MPa
3. Cassette body in this zone is now full, enabling lower stress values under working loads.

2.3.2 ITER-like Hooking System for W-Targets

Fast divertor, such as ITER's one, foresees a set of PFCs made of actively cooled W-tiles. These elements will be assembled on the cooling channels by means of brazing process and then fixed to the cassette. The idea is to reproduce the same hooking system employed for ITER's divertor targets. The hooking system is essentially based on a set of three elements (one socket, one connection slot and one locking pin) coupled together to fasten W-tiles to the cassette (Fig.8). The top surface of the slot element is going to be brazed together with special 12mm tile by means of a 1mm copper layer, as brazing material.

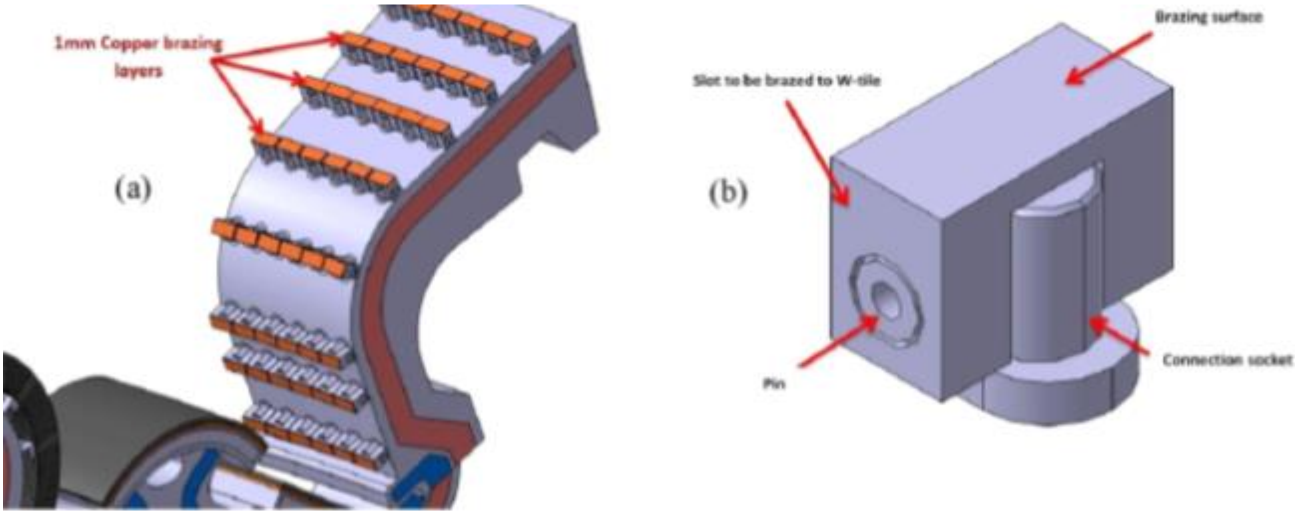


Fig. 8 - ITER-like Hooking System for FAST W-PFC

In order to allow the placement of the new hooking elements additional changes were required to the cassette body. Former swallow-tailed sockets have been substituted by an ITER-like hooking system. The old above mentioned socket has been removed in order to obtain a sufficient volume between W-tiles and the cassette. This operation affected both the inner vertical target and the outer vertical target, permitting the installation of new fastening elements. A 18mm gap between the cassette and the vertical targets (inner and outer) have been obtained by making the cassette body thinner, with a new layout of the side wall as well (fig. 9 and 10). Indeed, due to physic constraints, it is not possible to move the targets from their current position.

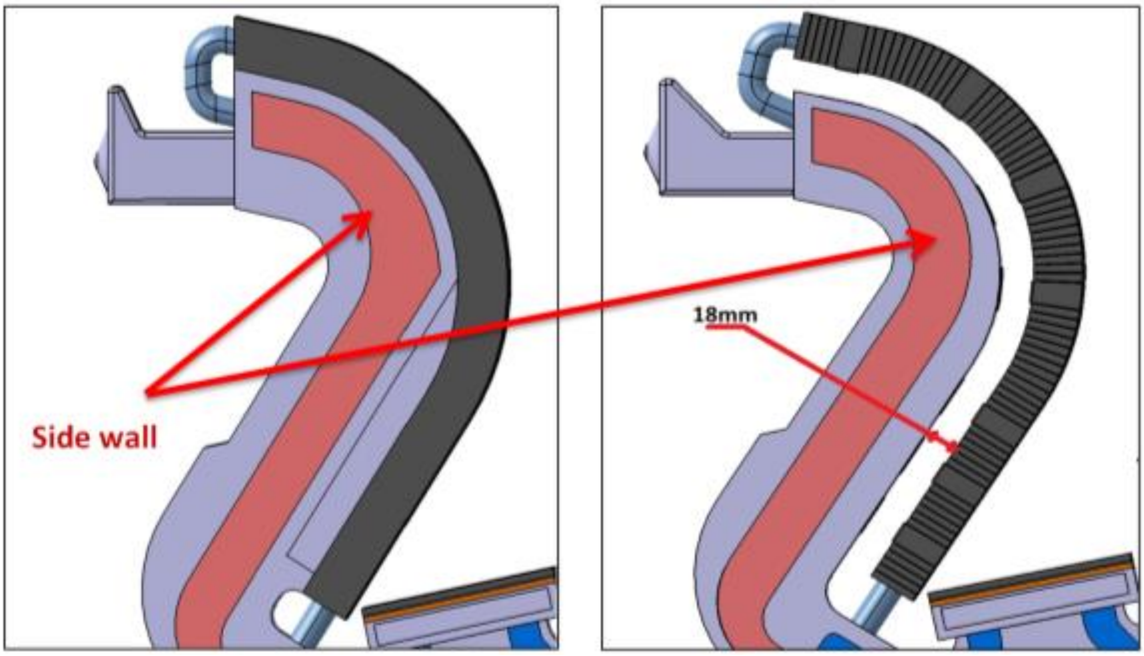


Fig. 9. Inner vertical target side

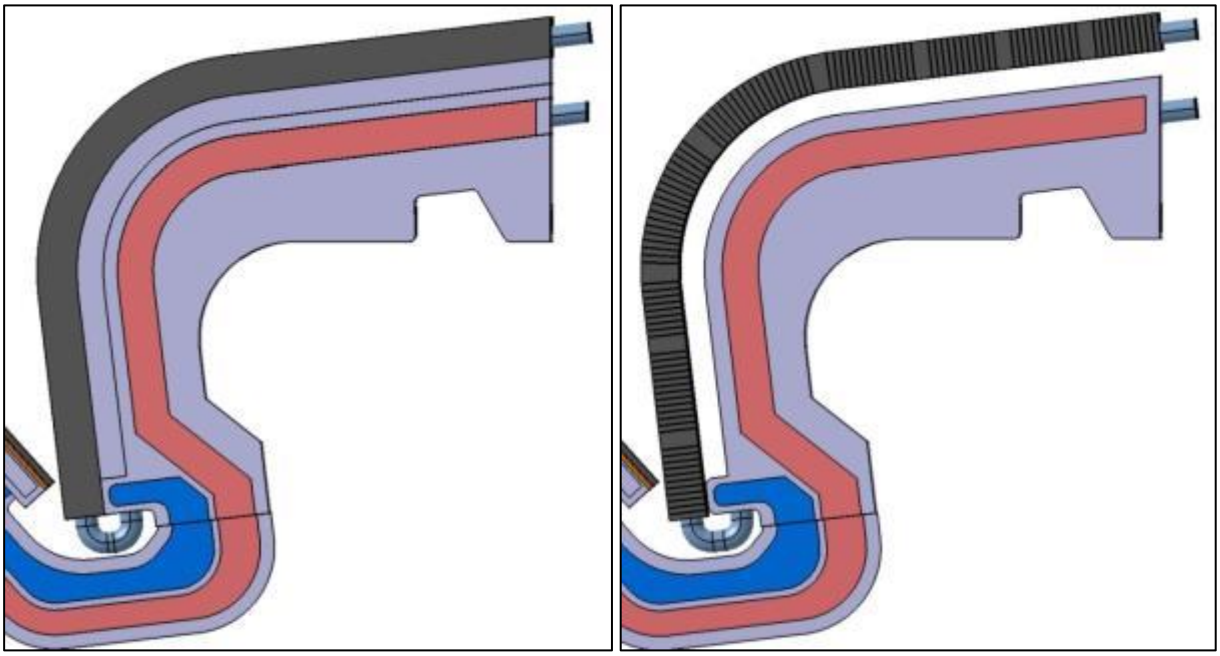


Fig. 10 Outer vertical target side

2.3.3 FAST W-PFCs for the inner and the outer vertical targets

The main aim of FAST device, as its acronym suggests, is to provide a reliable research environment in the tokamak field, in particular as a satellite tokamak of ITER.

Therefore the design of inner and outer vertical target elements has followed ITER's leading principles, foreseeing arrays of tungsten rectangular monobloc W-tiles to be installed on the machine, respecting appropriate displacement constraints and requirements.

Due to the scale difference between the two devices (FAST is much smaller than ITER) the design of such PFCs has represented a true challenge.

2.3.4 Project requirements

Tungsten tiles are routed along the cooling channels and fixed to the cassette by means of the hooking system previously showed. Current status of the divertor foresees a mixture of 4mm and 12mm tiles: 12mm tiles are those intended to be brazed on connecting slots, whereas 4mm tiles are the conventional sized tiles adopted in FAST tokamak (fig. 11).

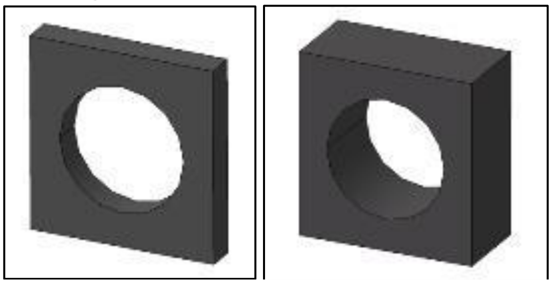


Fig. 11. 4mm and 12mm tungsten tiles

As technical requirement, a maximum gap of 0,5mm between tiles has been set. Tolerance on this gap sets the minimum value at 0,1mm (fig. 12).

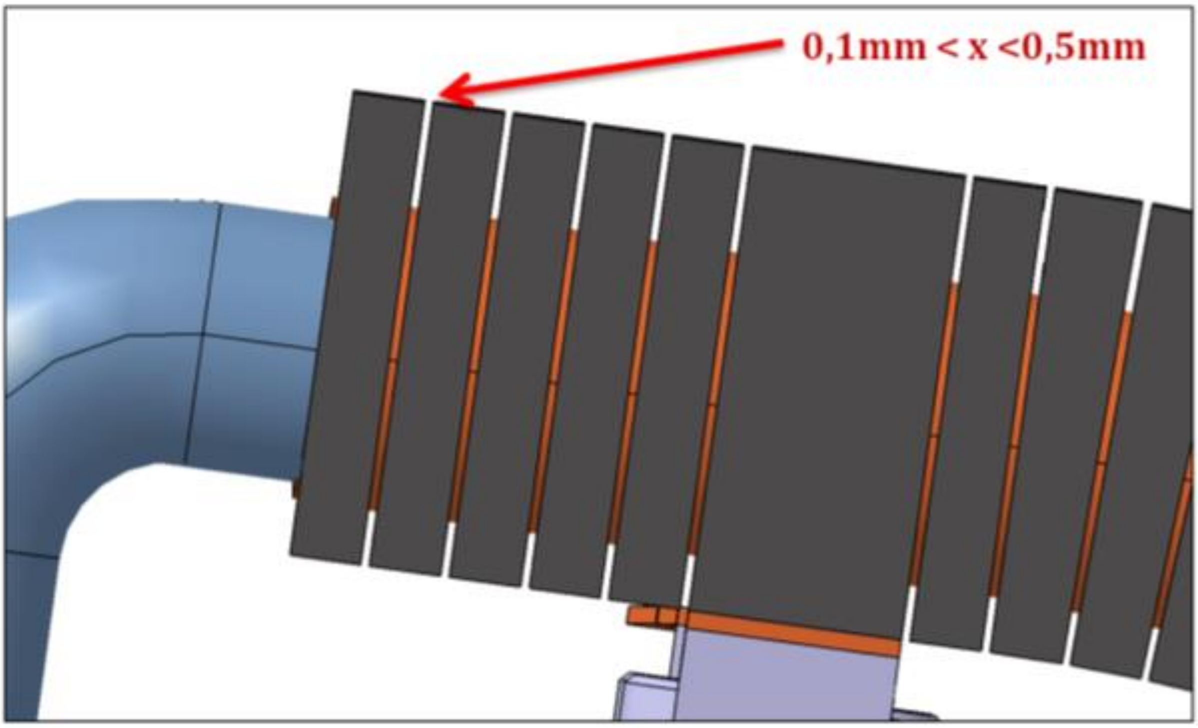


Fig. 12. Distance tolerance between W-tiles

2.3.5 Modeling issues

The positioning of all W-tiles within the respect of the above mentioned tolerance requirement has presented some complications: due to the small size of the FAST tokamak, seemed to be impossible to respect the given gap (max 0,5mm) between two consecutive w-monoblocs at the curved zone of the inner and vertical targets profiles.

Indeed, such a small radius of the machine, compared to ITER's one, impedes to put tiles all together in their place without going over that tolerance constraint. This problem becomes even more apparent at the interface between the 4mm and 12mm tiles.

2.3.6 Proposed solution

CAD model and simulations pointed out that is pretty much impossible to overcome this problem without thinking at the manufacturing of particular types of W-monoblocs to be inserted in the curved profile zone. Indeed, a first attempt solutions have been rejected after resulting ineffective: by setting the minimum possible gap at the bottom of the tiles (0,1mm) the result is not so good as trusted.

The Figure 13 clearly shows how the upper gap reaches values well over the 0,5mm given requirement.

This solution would have been the ideal one by the costs point of view. Indeed requires only two types of different tiles to be manufactured and then represents the less expensive option available.

Anyway it is not feasible at all, due to restricted tolerances.

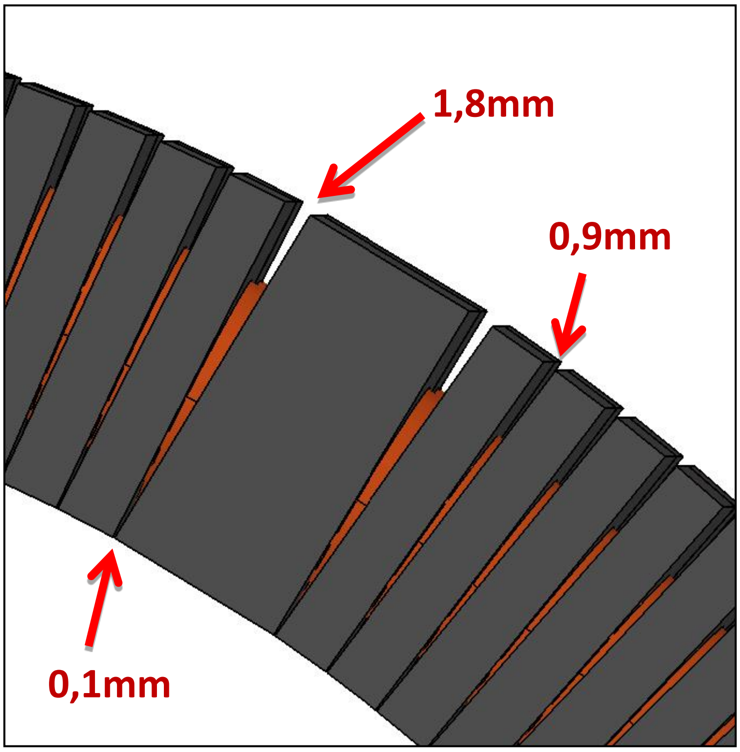


Fig. 13. This solution foresees only 2 different type of W-tiles

Then a feasible and reliable solution has been adopted: a particular V-shaped tile set is here employed to come over the problems shown above. In this case 6 different types of w-tiles have to be manufactured (2 different 4mm v-shaped tiles and 2 different 12mm v-shaped tiles, plus regular 4mm an 12mm tiles), with consequent costs rising (fig. 14).

Anyway this is the only feasible geometry permitting a constant gap between two consecutive tiles and then respecting the tolerance requirement of 0,5mm.

Since cooling channels are more than one per each side of the strikes, the project tolerance required gap has to be respected even in the toroidal way. Two consecutive tile profiles have to be separated, at the top edges, by a maximum gap of 0,5mm too.

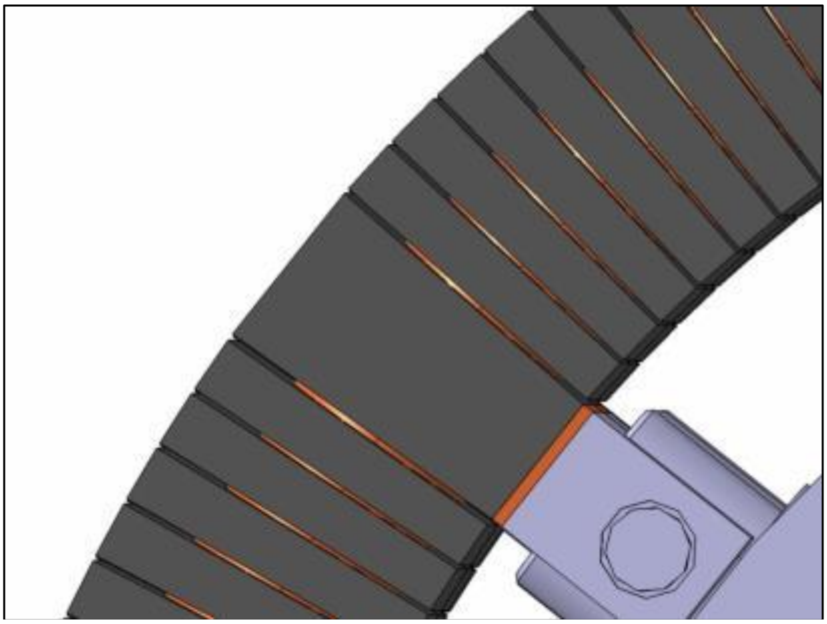


Fig. 14. Outer vertical target V-shaped tiles.

For this reason the set of tiles has been designed by means of an increasing width as the radial position of the item increases.

Figure 15 shows a single cassette sector. Each one sector extends for 5 degrees and needs to be shielded by tungsten target elements.

Between each cooling channel profile a maximum gap of 0,5mm must exist. To respect this constraint, tiles at higher radius have to be necessarily wider than those at minor radius.

Regrettably this aspect will negatively reflect on manufacturing costs, since several different elements will be installed instead of the above mentioned 6 elements needed of a single channel target.

The resulting list of elements per each single pipe line is proposed in the table 1.

INNER VERTICAL TARGET	
Number of 4mm tiles	21
Number of 4mm v-shaped tiles	41
Number of 12mm tiles	4
Number of 12mm v-shaped tiles	3
4mm v-shaped tiles draft angle	2,011°
12mm v-shaped tiles draft angle	6,192°
OUTER VERTICAL TARGET	
Number of 4mm tiles	68
Number of 4mm v-shaped tiles	39
Number of 12mm tiles	6
Number of 12mm v-shaped tiles	2
4mm v-shaped tiles draft angle	1,827°
12mm v-shaped tiles draft angle	5,939°

Table 1. W-tile Element list.

Fig. 15. Cassette 5° sector top view

2.3.7 Cooling channels

Cooling channels system has been totally reviewed since the first model of FAST divertor was released. Inner vertical target now houses 4 channels instead of 5 and the general modelling has been improved on The choice to shift from 5 to 4 channels is due to the need for available space to host the new hooking system. This decision has been taken in the frame of one of the several meeting, according to the iterative improvement process of the model and does not compromise the cooling efficiency.

While on the outer target side, due to the higher radial distance there is enough space to put (in toroidal sense) 6 set of locking elements (one per each pipe profile), on the inner target this is not possible. Indeed the available space, especially at minor radius zones, is not enough to house 5 slots, such as the foreseen number of cooling pipes (fig. 16).

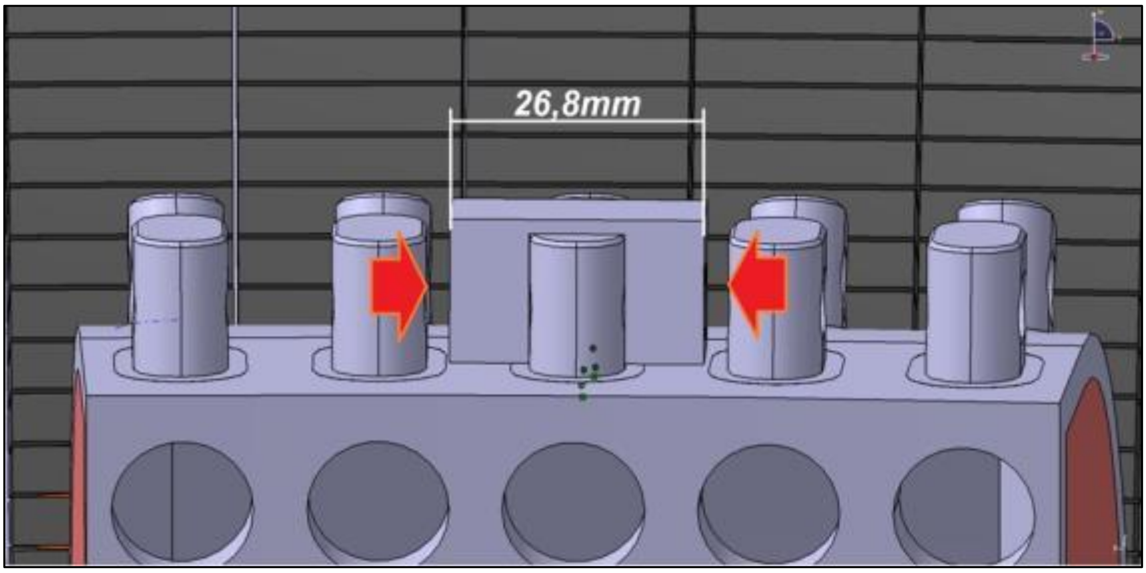


Fig. 16. ITER size slot installed on FAST cassette.

The figure 16 shows that is not possible to install slots on the cassette without making some modifications. Toroidal constraint is too strong and then it has been chosen to reduce the number of cooling pipes at the inner vertical target from 5 to 4, without compromising the cooling efficiency. Also width of the slots has been reduced to 25mm (fig. 17).

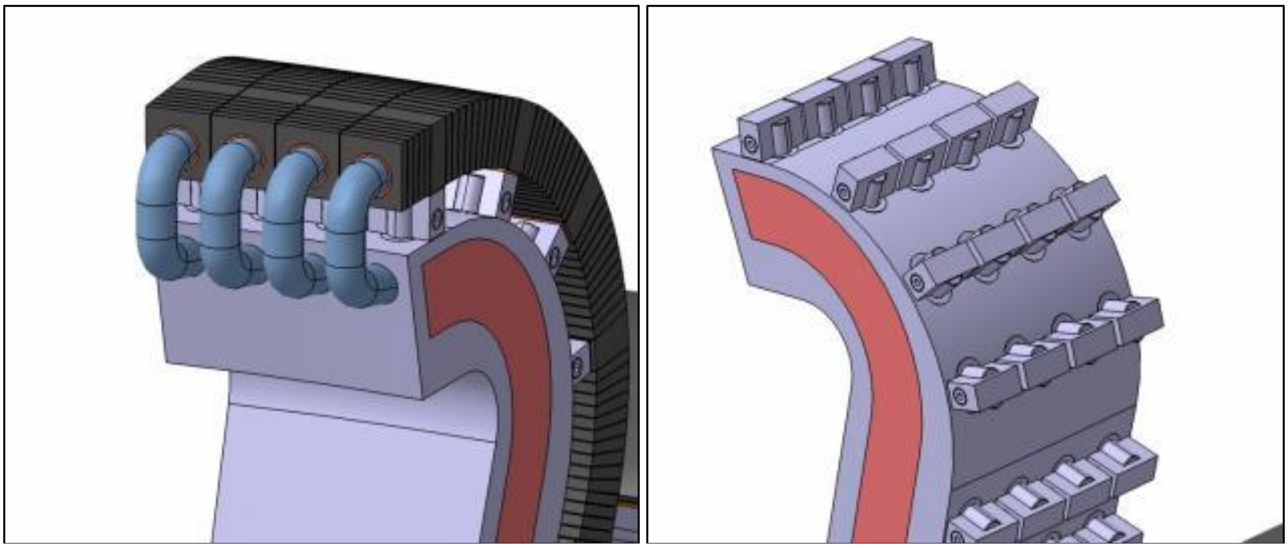


Fig. 17. Left: Four cooling pipes at the inner vertical target; Right: 25mm locking slots

2.3.8 Inner vertical target channel profile change

In the frame of the changes provided to the cassette geometry, the profile of the inner vertical target cooling channels has been modified.

One of the consequences of operations described is a certain loss of thickness occurring to the cassette body. Indeed, not being allowed to modify the spatial positions of tungsten PFCs and having to gain an 18mm opening to house the hooking system, the refinement of the cassette body has been pointed as the only feasible solution. As a consequence of this, cooling channels profiles, divertor's inner hook and side wall relative position have been modified (figg. 18, 19, 20).

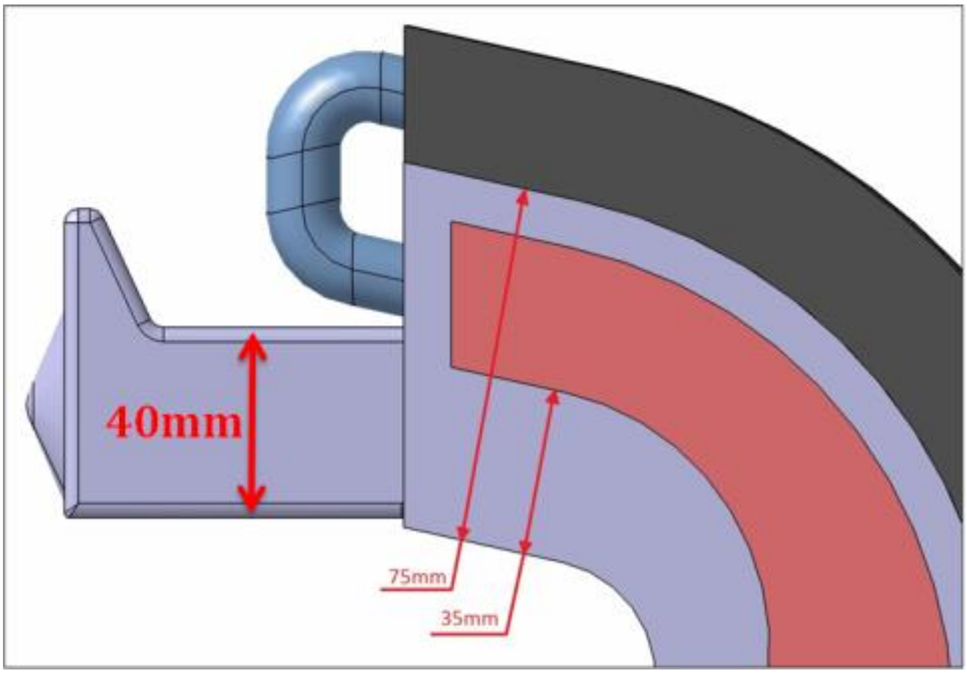


Fig. 18. Former geometry

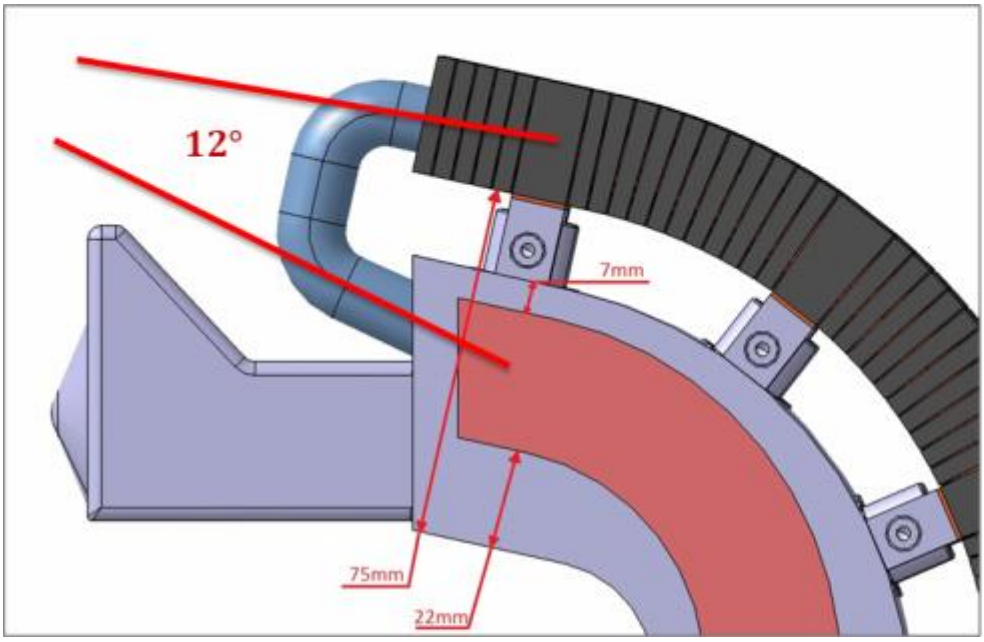


Fig. 19. Ultimate geometry.

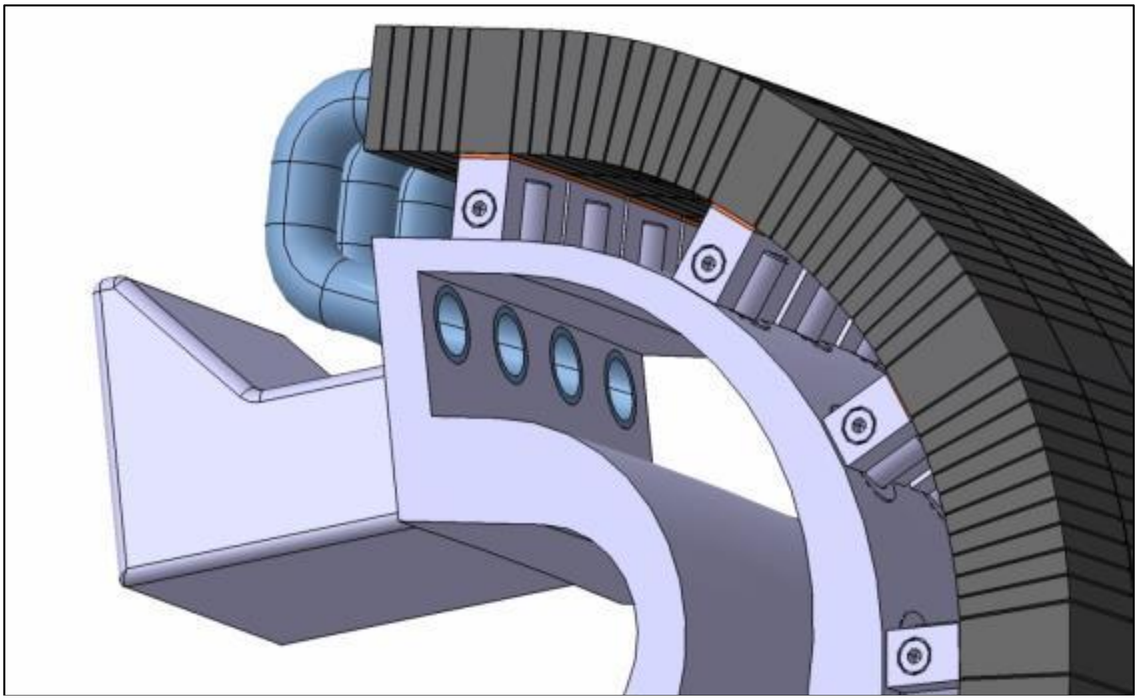


Fig. 20. Cassette vacuum chamber and pipes inlet.

2.3.9 Outer vertical target cooling channels and slot dimensioning

Cooling channels number at the outer vertical target, on the other hand, remains the same of the initial layout: 6. The only one alteration has regarded the dimensioning of the locking slots to be positioned on the cassette and brazed to the W-monoblocs. In this case 2 differently sized slots have been chosen (fig. 21):

- 25mm slot for the joint lines located at higher radius
- 23mm slot for the other joint lines

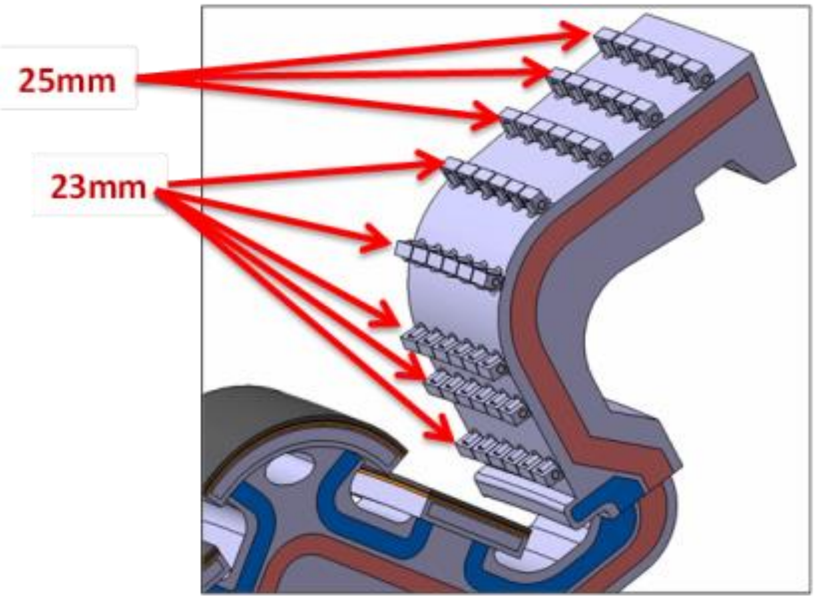


Fig. 21. Outer vertical target cooling channels

Other changes have been necessary to complete the develop process of the hooking system and finally a validated version of FAST divertor has been released (fig. 22).

Fig. 22 Divertor New Coolant Layout

2.4 *Structural Analysis: second iteration*

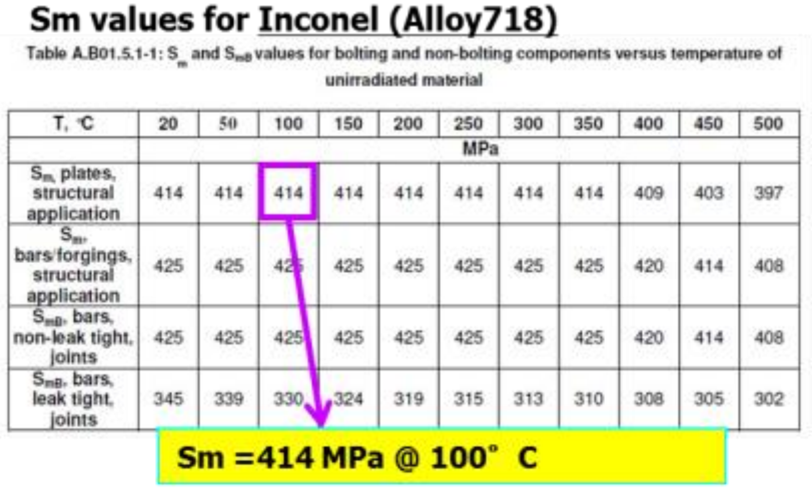
Once obtained a new divertor geometry, according to the V-model approach (fig. 1) a second structural analysis has been carried out.

The purpose of these analyses is the evaluation of critical issues in FAST's Divertor subject to EM loads.

These analyses represent still a preliminary evaluation of the behavior of the structure.

More details about the local behavior of the structure can be investigated through the analysis of submodels.

In order to improve the performance of the cassette under EM loads, the material choosen for the cassette is the Inconel 718, whose Sm values for different temperature are shown in figure 23.



Sm values for Inconel (Alloy718)

Table A.B01.5.1-1: S_m and S_{mB} values for bolting and non-bolting components versus temperature of unirradiated material

T, °C	20	50	100	150	200	250	300	350	400	450	500
	MPa										
S_m, plates, structural application	414	414	414	414	414	414	414	414	409	403	397
S_m, bars/forgings, structural application	425	425	425	425	425	425	425	425	420	414	408
S_{mB}, bars, non-leak tight, joints	425	425	425	425	425	425	425	425	420	414	408
S_{mB}, bars, leak tight, joints	345	339	330	324	319	315	313	310	308	305	302

Sm =414 MPa @ 100° C

Fig. 23. Sm values for Inconel (Alloy718)

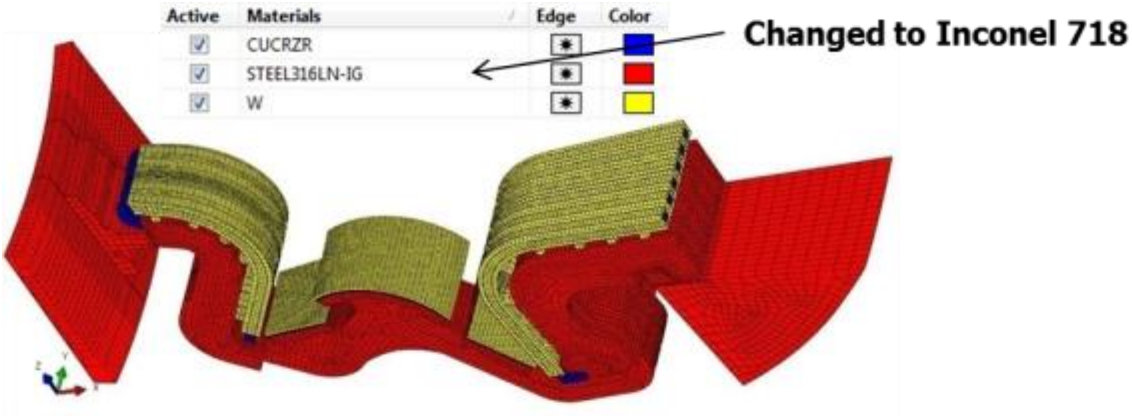


Fig. 24. Materials

The structural FE Model has been based on the EM mesh and the analysis have been carried out considering the most critical time instant evaluated in EM analysis. In the following figures (Fig.25) we show the results at time instant “67.9 ms” (Thermal Quench).

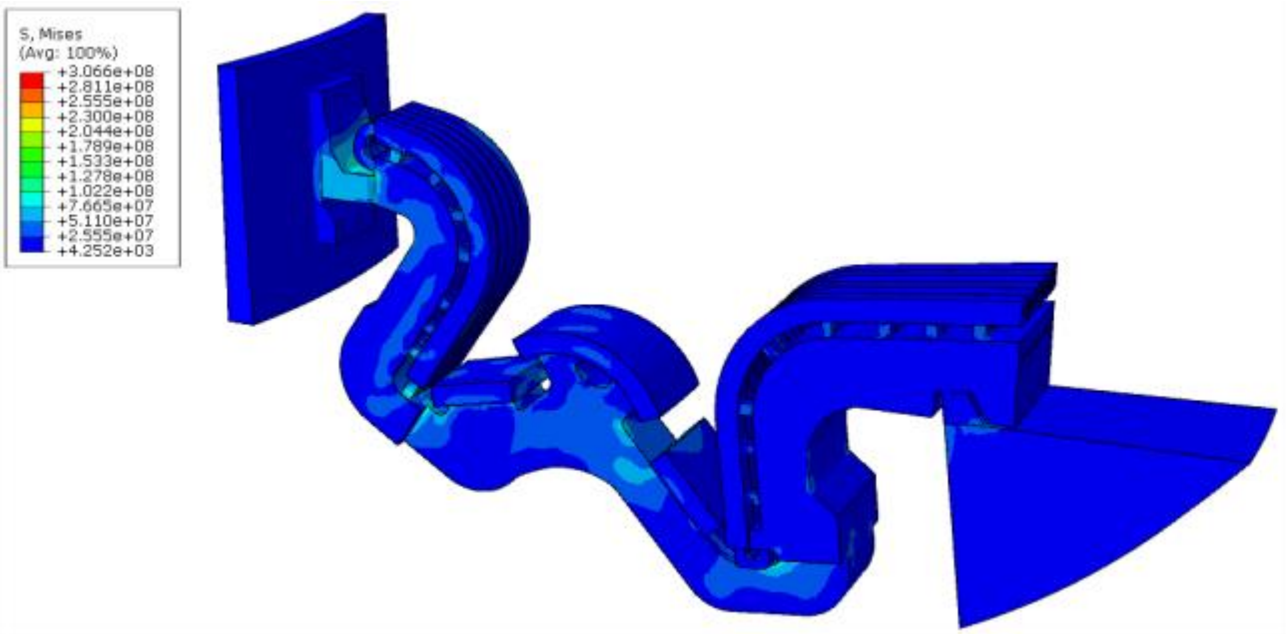


Fig. 25. Von Mises Stresses overview: time instant 67.9ms.

The results have been improved if compared with the previous one (figg. 4 and 5).
Anyway there are still some problems concerning the CuCrZr components that can be avoided by means of design changes and a new iteration according to the V-model approach.

2.5 FAST vs EAST Divertor

EAST (Experimental advanced superconducting tokamak) machine is a D-shaped full superconducting tokamak with actively water cooled plasma facing components. To achieve long pulse and high βH-mode plasma, new plasma position and shape have been calculated and optimized during the campaign of last year. In particular new divertors are designed and developed to fit the plasma and endure the heat flux up to 10 MW/m2. As for FAST, also the EAST divertor is ITER-like. It bases on monoblock and cassette technology and is composed of plasma facing component (PFC) units, cassettes, and support systems.
Monoblock structures are just employed on the PFC units of target plates of the divertors, thus W flat tiles are used on the baffles and dome. At the end of monoblocks, end boxes are applied.

Exactly like for FAST, cassettes act not only as the supports of the PFC units, but also as manifolds for the cooling channels of the units. The support systems consist of inner support rails, outer support rails, and auxiliary braces. The support systems are installed on the vacuum vessel before cassettes are put on. To dock the cassette with the support system, it is just lifted and pushed forward [15].
Figure 26 shows the 3D model of EAST divertor, while figure 27 shows the relative cooling channel system. They highlight a great number of similarity with the FAST divertor form the engineering design point of view.

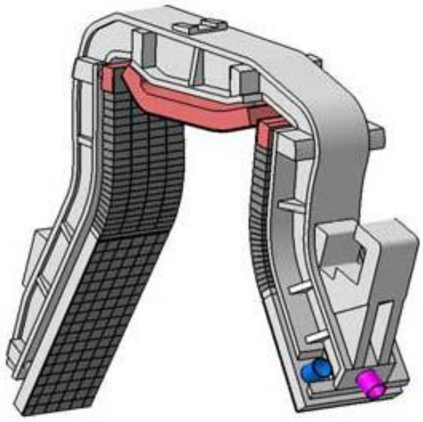


Fig. 26. EAST tungsten divertor.

Fig. 27 Cooling channel system of EAST divertor

3 Conclusions

The conceptual design of FAST divertor has been carried out through a continuous process of requirements refinement and design optimization, in order to achieve a design suited to the needs, RH compatible and ITER-like. FAST divertor is now characterized by more realistic, reliable and functional features. ITER’s shape has been approached even more and FAST will continue to give a very good base of study in the frame of Tokamak comprehension, with particular reference to EAST and ITER, and in view of DEMO. Consistency of design has to be confirmed by next detailed FEM analyses.

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5 Abbreviations and acronyms

3D	three Dimensional
CAD	Computer Aided Design
EM	Electro-Magnetic
FEM	Finite Elements Model
FW	First Wall
MHD	Magneto Hydro Dynamics
PC	Plasma Chamber
PF	Poloidal Field
RH	Remote Handling
SF	Snow Flake
SN	Single Null
SX	Super-X
TF	Toroidal Field
VV	Vacuum Vessel