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Plasma facing components: a conceptual design strategy for the first wall in FAST tokamak

C. Labate[1], **G. Di Gironimo**[2] **and F. Renno**[2]

[1] CREATE, Department of Engineering, University of Naples Parthenope, 80133 Napoli, Italy
[2] CREATE, Department of Industrial Engineering, University of Naples Federico II, 80138 Napoli, Italy

E-mail: carmelenzo.labate@uniparthenope.it, giuseppe.digironimo@unina.it and fabrenno@unina.it

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Abstract

Satellite tokamaks are conceived with the main purpose of developing new or alternative ITER- and DEMO-relevant technologies, able to contribute in resolving the pending issues about plasma operation. In particular, a high criticality needs to be associated to the design of plasma facing components, i.e. first wall (FW) and divertor, due to physical, topological and thermo-structural reasons. In such a context, the design of the FW in FAST fusion plant, whose operational range is close to ITER's one, takes place. According to the mission of experimental satellites, the FW design strategy, which is presented in this paper relies on a series of innovative design choices and proposals with a particular attention to the typical key points of plasma facing components design. Such an approach, taking into account a series of involved physical constraints and functional requirements to be fulfilled, marks a clear borderline with the FW solution adopted in ITER, in terms of basic ideas, manufacturing aspects, remote maintenance procedure, manifolds management, cooling cycle and support system configuration.

Keywords: fusion technologies, plasma-wall interaction, first wall, cooling cycle, locking system, remote handling, tokamak design

(Some figures may appear in colour only in the online journal)

1. Introduction

The successful achievement of ITER and DEMO programs lies on the active contribution of satellite experiments, required to investigate crucial points and provide alternative solutions against key ITER's operational issues [1].

Such a framework benefits the development of Fusion Advanced Studies Torus project, namely FAST [2] and [3] (figure 1): a flexible tokamak, able to operate both in H-mode scenarios and in advanced tokamak regimes, and designed to achieve the confinement of Deuterium plasmas (then in absence of Tritium), with a power amplification factor about 2.5 and in a dimensionless plasma parameters' range close to ITER machine. In the perspective of ITER and DEMO, FAST program moves along a multiple direction, including the investigation of α-particles' non linear dynamics, ELMs, and plasma - wall interaction with a heat loading significant both for ITER ($P/R \sim 22$ MW m^{-1}) and for DEMO ($P/R^2 \sim 12$ MW m^{-2}), and, in addition, the exploration of technical ITER and DEMO-relevant solutions for plasma facing components, such as the advanced liquid metal divertor target and the full-tungsten first wall (FW).

Focusing on plasma facing metallic components, which represent the most critical and stressed physical parts during plasma operations, the main objective of this paper consists in the introduction of a conceptual design strategy for the FW in FAST. In other terms, an efficient and innovative proposal, completely detached from the main existing solutions adopted for other tokamaks (overview shown in figure 2).

ITER FW, indeed, is based on 440 1×1.5 m Beryllium blanket modules, 18 per each poloidal cross section (figure 2(*a*)), subject to $2 \div 4.7$ MW m^{-2}heat load and cooled via

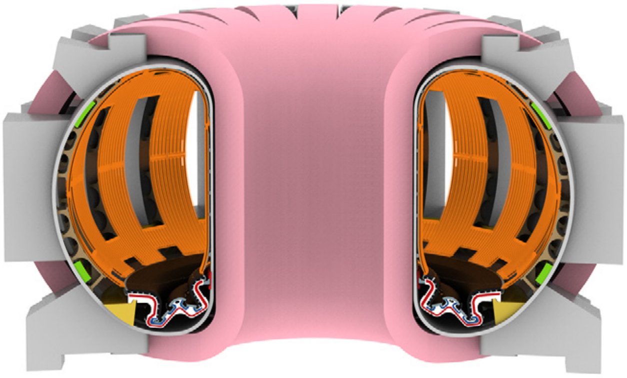

Figure 1. Overview of the FAST machine.

an external and physically segregated auxiliary system [4]. Concerning JET, instead, over the years the FW configuration has been modified and upgraded, passing from 4404 Carbon-Clad tiles to a ITER-like FW [5]. The latter consists in 1700 solid Beryllium tiles, inertially cooled, segmented with 2 ÷ 3 mm gap to minimize eddy forces, castellated to avoid thermal stress cracking, and shaped in order to maximize the power handling (figure 2(*b*)). A further solution for FW is provided by EAST [6], where the FW consists in 16 actively water-cooling panels mounted on 2 toroidal continuous rings, joined to the VV via base rings in order to reduce the resulting thermal stress (figure 2(*c*)).

Assuming such FW solutions as starting points and comparison terms, in the following sections a detailed design of FAST FW is presented, with a particular attention to the novelties concerning typical key points of plasma facing components design, i.e. basic conceptual idea, cooling cycle and support system.

2. An overview of FAST FW design strategy

General requirements and design choices, at the base of such a strategy, are hereinafter presented together with the physical background and the design process phasing.

2.1. Physical background

The FW design take places within the physical framework provided by a plasma confined in the tokamak chamber. This means facing a major concern in plasma operations: the contacts between plasma and the surrounding structures. Plasma disruptions need to be avoided as they yield a sudden loss of plasma energy content and the consequent thermal exchange between the ionized gas and the mechanical structures, with an intolerable heat load on the plasma facing components.

Indeed, ITER scenarios, simulated by coupling CREATE-NL free boundary equilibrium code with JETTO transport code [7] and [8], have highlighted that forcing a H-L transition during the plasma current ramp down implies leading the plasma towards the Central Solenoid (being this movement indicated by the decrease of the internal inductance) when the level of plasma thermal energy exceeds 300 MJ (figure 3). In this case the plasma shape controller, based on a standard proportional-integrative action, is able to counteract plasma drift phenomena by driving the poloidal field currents.

However the shape controller might be not sufficient to cope with fast plasma drifts, because of the limited time response of the controller itself. In addition, the possibility of saturations occurring on current or voltage actuators may spoil the control action and require the application of advanced constrained control techniques to enhance the achievable results in terms of plasma shape control [9], as shown in figure 4(*a*). In any case the risk of plasma disruptions occurring in ITER cannot be ruled out for certain.

Concerning FAST, although the H-mode plasma current should reach 6.5 MA (rather than 15 MA in ITER), both the power load ($P/R \sim 22$ MW m^{-1}) and the plasma dimensionless parameter range (i.e. elongation $k_{95} = 1.7$, triangularity $\delta_{95} = 0.4$, safety factor $q_{95} = 3$) are significant with respect to ITER performance [10] (figure 4(*b*)). This means that FAST tokamak is foreseen to be affected by the same plasma-wall issues encountered in ITER. Nevertheless, as the satellite machine is in an early design stage, with plasma scenarios and shape controller not properly defined yet, the improvement of plasma-wall interaction needs to rely on a ‘mechanical contribution’ which must be provided by suitable FW design choices.

2.2. Phase #1: design core

The main FW idea consists in a bundle of toroidally flanked stainless-steel envelopes (figure 5(*a*) composed by:

- a main body, obtained by sweeping a 32 × 32 mm square section along a poloidal curvature line consistent with the Vacuum Vessel (VV) poloidal cross-section,
- a coaxial pipe, whose internal and external pipe diameters are 16 mm and 26 mm respectively, dug in correspondence of the envelope’s centre and in charge of cooling operations (explained in detail in section 3),
- a couple of symmetrical lateral wings, with 2 mm thickness and variable span (1 ÷ 13 mm).

From the poloidal point of view, the definition of FW curvature is strictly linked to the physical issue presented in the previous subsection and meets the necessity to optimize the space available for the plasma within the chamber, principally in the inner part. Providing the plasma as much allowed area as possible means placing the FW as close as possible to the VV, except for a minimum tolerance to fill with the supporting structure. Furthermore, in the outer part of the chamber, the poloidal curvature needs to take into account the presence of the in-vessel coils (as shown in figure 5(*b*)), placed between the equatorial and the vertical ports and exploited for magnetic control purposes, i.e. the improvement of the vertical stabilization and radial position control and the mitigation of Edge Localized Modes [11].

About the geometry of the main body, although a dedicated thermo-structural analysis [12] returns that a circular

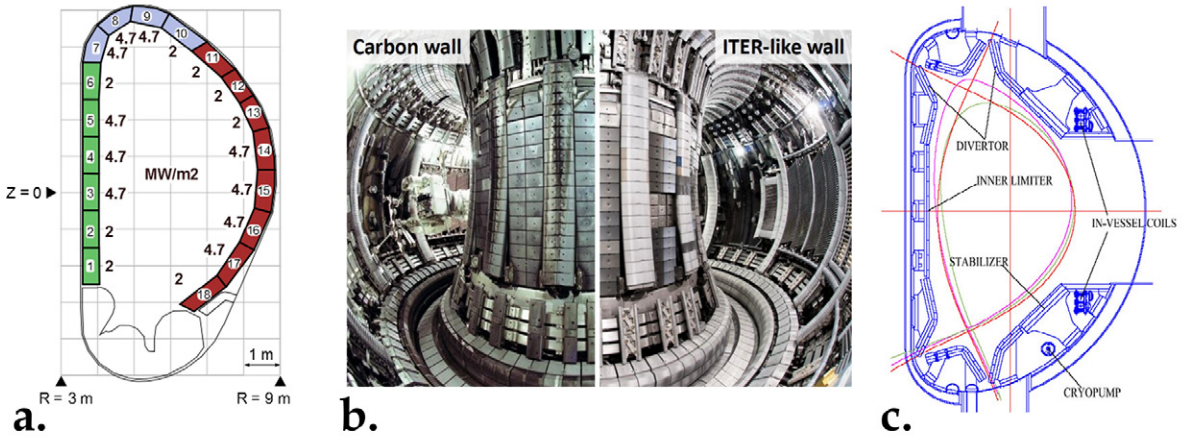

Figure 2. Overview of the main FW design solutions adopted in other tokamaks: ITER (*a*), JET (*b*), EAST (*c*).

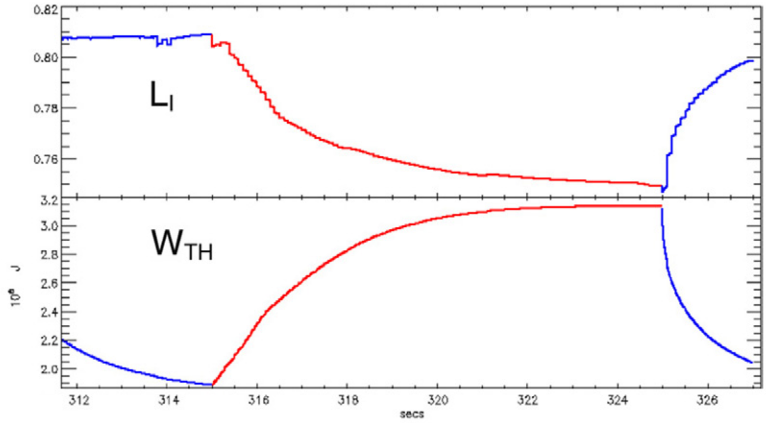

Figure 3. Time evolution of ITER internal inductance (l_i) and plasma thermal energy (W_{th}) in L-mode (blue) and H-mode (red).

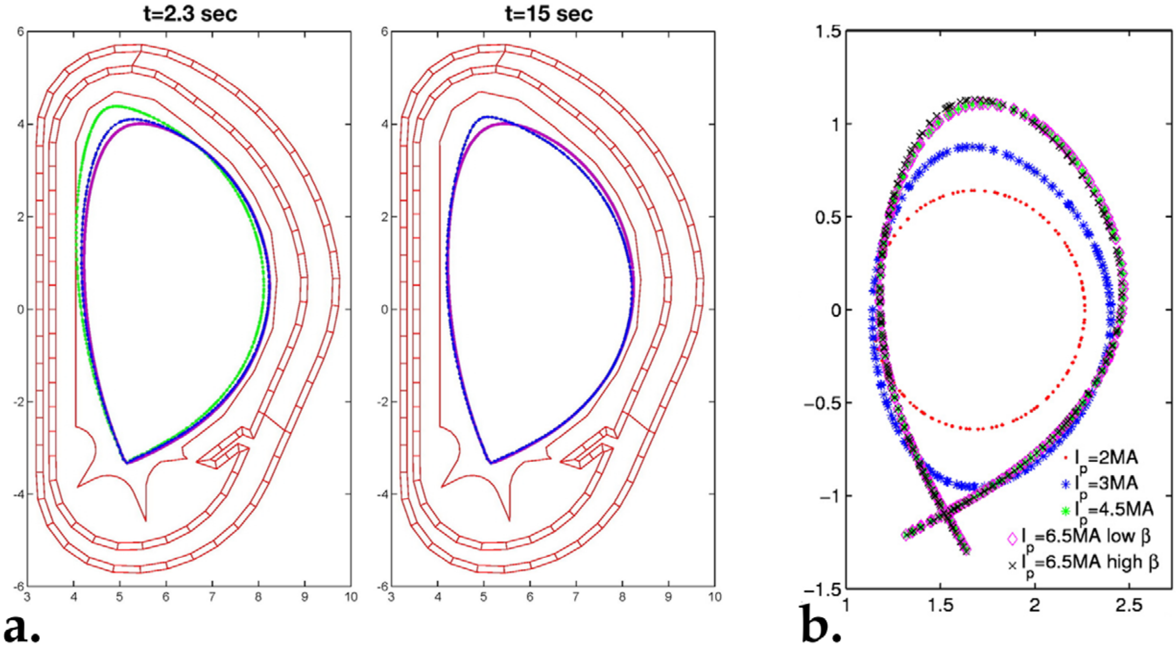

Figure 4. (*a*) Time evolution of ITER plasma shape in $r - z$ coordinates, evaluated via equilibrium snapshots at different time instants: starting initial equilibrium (magenta), shape evolution with an advanced control technique applied to the shape control (blue), shape evolution with a standard shape controller (green). In the latter case, run stops at about 2.5 s because of the loss of control. (*b*) Time evolution of FAST plasma shape in $r - z$ coordinates, according to increasing plasma current (I_p) values.

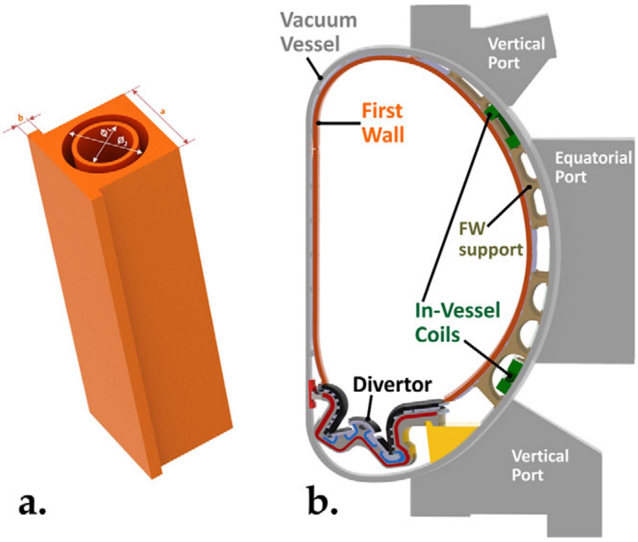

Figure 5. (*a*) Particular of a pipe envelope at the base of FW concept, being $a = 32$ mm the side of the squared-section body, $\phi_1 = 16$ mm and $\phi_2 = 26$ mm the internal and external pipe diameters respectively, and $b = 2$ mm the thickness of the lateral wings. (*b*) Poloidal cross-sections of the FW, whose curvature takes into account the presence of supports and inner coils.

section is more performing in terms of the thermal stress, the choice of a square section is adopted in order to benefit both the manufacturing and the W plasma-spray process.

The functional aspect of lateral wings is associated to the toroidal coverage of the 20° sectors, which the VV is divided into, being 18 VV sectors needed to span the entire torus. The reason behind variable wings' width is linked to the number of envelopes needed to cover a VV sector, which, in turn, is constrained by the minimum pipes size (see section 3). Hence, on the base of the above mentioned constraints, a first FW classification per VV sector foresees (figure 6):

- Inner Half, from the divertor area up to the vertical port, composed by 10 pipes,
- Outer Half, from the divertor port up to the vertical port, composed by 18 pipes.

Such a segmentation yields the wings span's trend reported in table 1, being z_{eq} the quote at the equatorial plane ($z = 0$), and $z_{\max}$ and $z_{\min}$ the ones in correspondence of the vertical and divertor ports respectively. It highlights how the span increases when moving to a larger sector part (as shown in figure 6).

From a macroscopic point of view, this wings' sizing guarantees a flat toroidal surface directly facing the plasma, uniformly distributed except for a 2 mm intra-wings space, to be armored with a plasma coating W-layer.

2.3. *Phase #2: remote handling issues*

The feasibility of a remote maintenance via the equatorial port represents a further main requirement in FW design, whose fulfillment is constrained, from one part, by the size of the charged port (1460 mm height and 315 mm minimum span), and, on the other hand, by the available plasma chamber volume, defining the operating range of an eventual RH system. Therefore, based on a campaign of movimentation tests (see figure 7(*a*)), a second FW segmentation is considered as follows (see figure 7(*b*)):

Table 1. Trend of FW wings' span.

Quote	Pipe type	Wing span
$z_{\min} \rightarrow z_{\mathrm{eq}} \rightarrow z_{\max}$	outer	$2 \rightarrow 7 \rightarrow 1$ mm
$z_{\min} \rightarrow z_{\mathrm{eq}} \rightarrow z_{\max}$	inner	$4 \rightarrow 3 \rightarrow 13$ mm

- Quarter I, coinciding with the upper Outer Half,
- Quarter II, coinciding with the upper Inner Half,
- Quarter III, coinciding with the lower Inner Half,
- Quarter IV, coinciding with the lower Outer Half,

being the physical separation between adjacent quarters obtained via the introduction of a 5 mm clearance.

In order to simplify maintenance operations, FW Quarters are further split into smaller subgroups (see table 2), to be fed via a suitable manifolds and ex-vessel pipes system, explained in detail in section 3.

A couple of remarks are worth to be underlined:

(i) The design of a FW remote handler, with the correspondent maintenance procedure, is out of the scope of this paper.

(ii) In spite of remark (i), the FW design, presented in this paper, is RH-oriented, which means that, in the operating scenario considered hereinafter, outer Quarters are deprived of pipes subset located in front of ports. Indeed, although a detailed presentation of the RH procedure is out of the scope of this paper, during the maintenance phase, these pipes are the first components removed in order to get the port's access way free and allow the handler to enter the chamber. On the other hand, from the cooling process point of view, these pipes are treated in the same way of the remaining module they belong to.

3. The integrated cooling system

A main novelty introduced in this design is represented by the integration of the cooling system within the FW itself, rather than a segregated auxiliary system.

3.1. *The coaxial pipes philosophy*

From the thermal point of view, the average heat load, impinging on the plasma facing surface provided by FW segments, is estimated to be about 0.5 MW m–2, with peaks of 3 MW m–2. The thermo-structural analysis [12] demonstrates the feasibility of FW active cooling with the preservation of the plasma coating-steel junction by using 4 MPa pressurized water flowing at a 8 m s^{-1} speed. Envelopes' lateral wings represent the most thermally stressed point, quantifiable in an

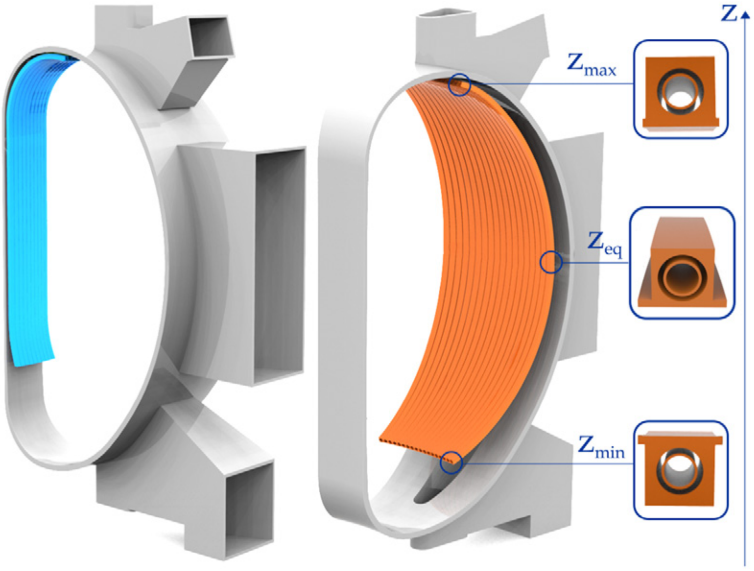

Figure 6. FW segmentation into Inner Half (on the left, in blue) and Outer Half (on the right, in orange), with the evaluation of lateral wing span on the outer envelopes.

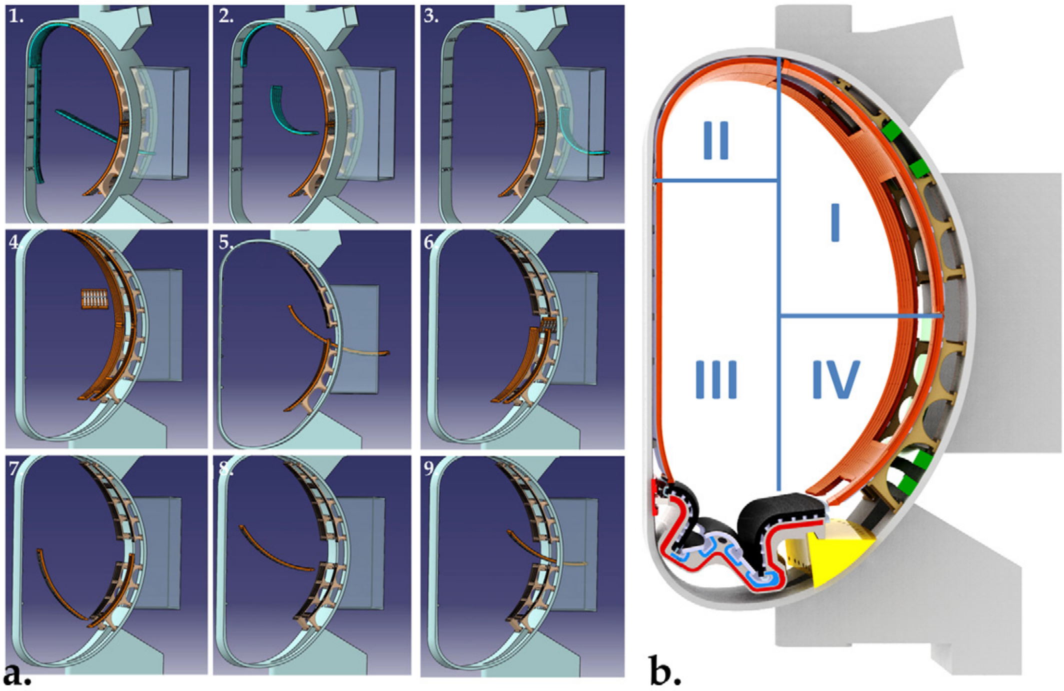

Figure 7. (*b*) Campaign of movimentation tests. (*b*) FW segmentation into Quarters.

expected 380 °C temperature in correspondence of the maximum wings' span.

As introduced in section 2, the cooling principle relies on coaxial pipes, centred in envelope's main body. The cooling water, pumped from en ex-vessel system, flows through the external pipe, then the coolant, whose temperature increases considerably on the first route, is inverted and transmitted to ex-vessel zones via the internal and concentric pipe (see figure 8). On the base of the minimum pipes' size, dictated by the above mentioned thermal analysis, and the topological aspects, presented in section 2, the size of internal and external pipe diameters is set to 16 mm and 26 mm respectively.

Table 2. FW modules segmentation.

	Modules		
Quarters	#	Pipes	Type
I	2	5-pipes	Lateral
	1	8-pipes	Central
II	2	5-pipes	Twins
III	2	5-pipes	Twins
IV	2	5-pipes	Lateral
	1	8-pipes	Central

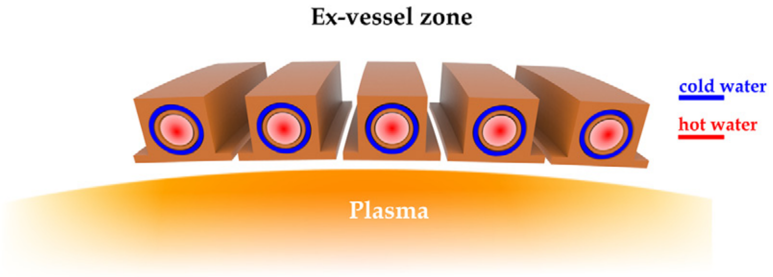

Figure 8. Cooling principle via hot and cold water flowing through the pipes, shown in correspondence of an envelopes cross section.

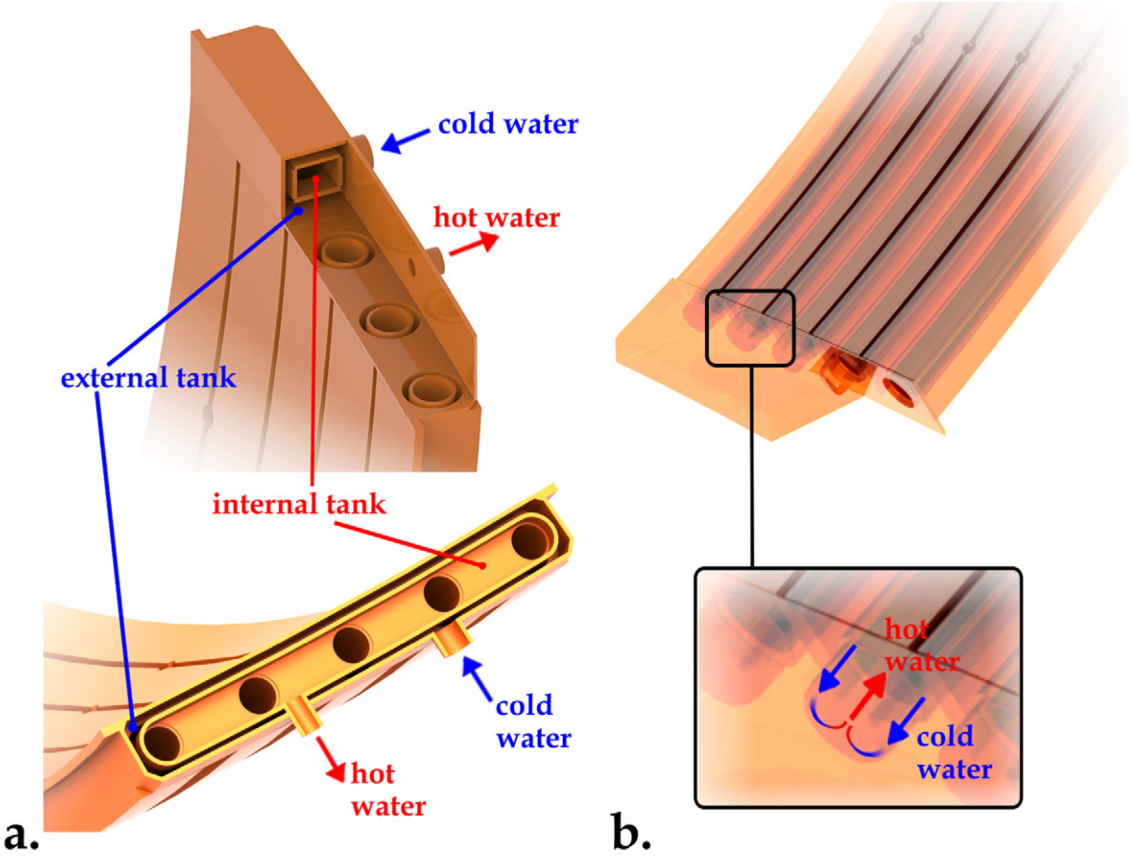

Figure 9. Particulars of Quarter IV end-of-lines. (*a*) Different views of Matryoshka tanks, suitably sectioned. (*b*) View and particular of a 'U turn' zone, suitably sectioned.

3.2. The end-of-the-line management

The critical point of such a cooling system design can be identified in pipes' extremities, where the collection and sorting of flows, directed towards both in- and to ex-vessel zones, needs to be supported. Furthermore, on the structural-wise side, the presence of water collectors must guarantee a physical link among different pipes belonging to the same FW segment, referring to table 2, with the consequent possibility to treat and handle a 5- or 8-pipes module as an only component.

The manifolds, designed to define boundaries of FW modules, can be classified in two complementary categories:

- *'Matryoshka' tank* (see figure 9(*a*)). This manifold manages the path of coolant between FW segments and the external transmission lines, and it is constituted by two differentiated tanks, nested but completely decoupling. The internal tank collects the hot water, coming form the internal pipes and to be transmitted out of the VV, whereas the external one receives the coolant, coming from the ex-vessel system and to be sorted to the external pipes. The decoupling about both tanks is kept also in the transmission line with the ex-vessel area, accomplished via two independent pipe unions with 8 mm and 12 mm diameter for the internal and external tank respectively.
- *'U turn' zone* (see figure 9(*b*)). This manifold manages the path of the cooling water within the same FW segment. It consists in a 5 mm-radius spherical concavity allowing the coolant, which comes from the external pipes, to invert its flow and access the internal pipes route.

Any FW segment is bounded by a couple of complementary manifolds, i.e. a matryoshka tank in one extremity implies the mutual presence of a U-turn zone in the other

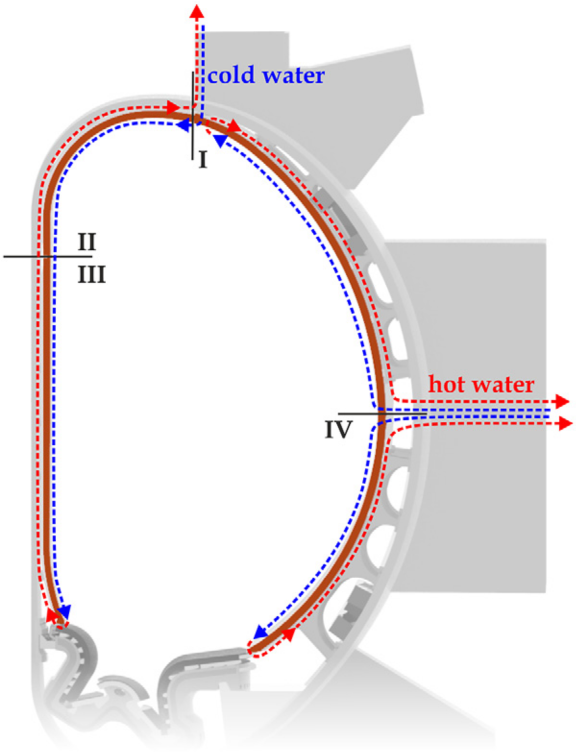

Figure 10. Overview of the cooling process, highlighting the quarters accessibility the overall flow of cold (in blue) and hot water (in red) to/from the ex-vessel zone.

edge, with the exception of Quarter II. Indeed, due to the lack of accessibility from outside concerning the lower inner part of plasma chamber, and the consequent inability to directly connect Quarter III with the ex-vessel area, this segment is interconnected with Quarter II via in-vessel pipes, shielded by suitable protection plates (30 mm height and 2 mm width). For this reason, in the lower part Quarter II module is bounded by nested tank communicating with the one of Quarter III module, whereas the upper part is limited by a second matryoshka tank communicating with the external transmission lines.

Both types of manifolds are accompanied by the eventual addition of material in order to guarantee a uniform surface, coherent with the FW poloidal profile.

The position of nested tanks, linked to FW modules' accessibility from outside (see figure 10), is framed as follows:

- Quarter I accessible from the equatorial port,
- Quarter II accessible from the vertical port,
- Quarter III accessible from the vertical port via Quarter II,
- Quarter IV accessible from the equatorial port,

It is worth to remark that the design of the transmission lines, acting as interface between the FW tanks and ex-vessel systems, is out of the scope of this paper.

4. The FW/vessel interface

The FW concept design takes into account also the interface issues with the Vessel, mainly related to locking and unlocking requirements. Such a fulfillment is implemented via a consistent FW support system, whose design is based on the following guidelines set:

- locking/unlocking operations are handled by a remote maintenance system—which is out of scope—accessing the plasma chamber through the equatorial port;
- the trade-off, between a solid support structure and an eventual overload on the VV, cannot be neglected;
- the clearance necessary for the in-vessel coils must be guaranteed;
- an auxiliary system, playing the role of FW/support interface, needs to be envisaged, due to the conformation of FW modules and the consequent impossibility to be directly screwed to supports;
- the addition of such an auxiliary system, furthermore, implies an increase of stiffness, coping with the troubling flexibility of FW modules, due to their shape, curvature and dimension
- the arise of inducted currents must be limited.

4.1. The auxiliary rib system

The design of the auxiliary system, crucial for the FW/support interface, comes from the idea of a rib cage to be welded onto the outermost surface of FW modules. Of consequence, from a poloidal perspective ($r - z$ plane), rib profiles are coherent with FW pipes which they are in contact with (see figure 11(a)).

The cage structure relies on the following classification:

- *Vertical Ribs* (VRs), also called intra-pipes ribs, are placed in correspondence of the space between two adjacent FW pipes. It means that, due to the definition of FW segments (5 or 8 pipes each, see table 2), rib modules can include 4 or 7 VRs, which, in terms of dimension, follow the correspondent FW module's one. Due to their strategical placement, VRs act both as locking/unlocking helpers and 2nd- *absorption layer* for particles penetrated through the FW intra-wings space.
- *Horizontal Ribs* (HRs) are placed in a smart and symmetrical manner, depending on the length of the FW segment of interest, and for this reason the number of ribs per module is not standard. About the dimension, HRs' angle spanned on the r-ϕ planes, representing almost entirely the welding area, is bounded by the first and last pipes of the correspondent FW module.

Locking operations foresee that, at first, the auxiliary rib system, with the connected FW modules, is placed on the physical supporting structure and, in a second stage, ribs are screwed onto the supports via a suitable pins' matrix, which implies a correspondent matrix of screw holes to be realized at the crossroads of VRs and HRs (see figure 11(b)).

In terms of segmentation, the entire rib cage follows the FW Quarters conformation, presented in section 2, in a consistent manner. An overview of the auxiliary system segmentation is reported in table 3.

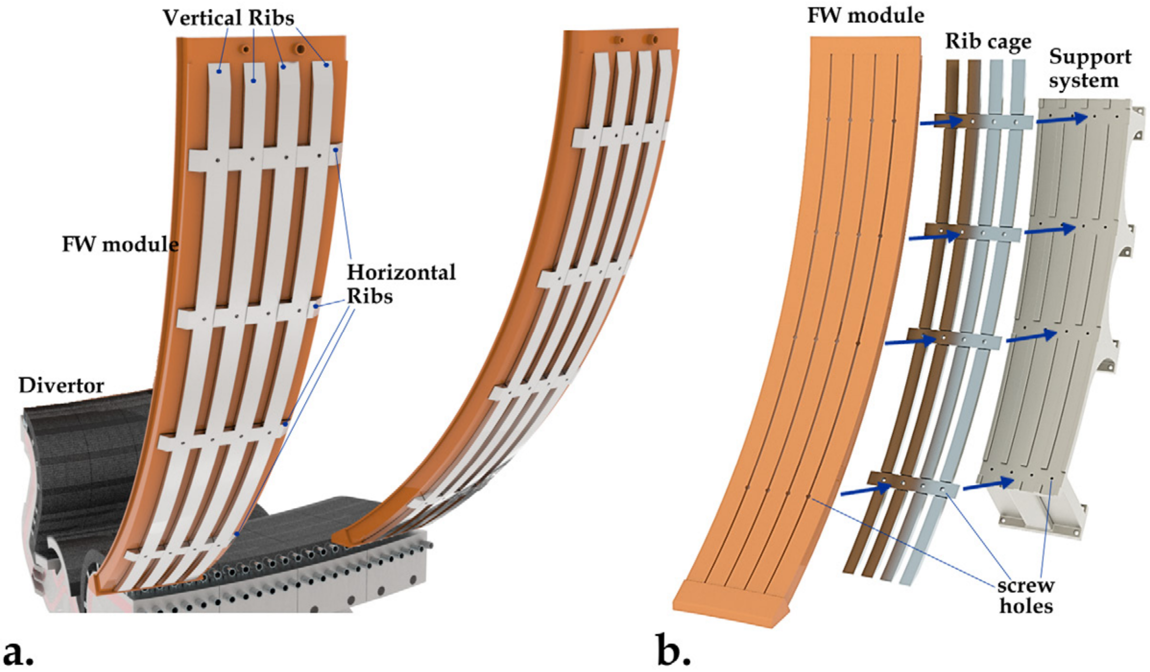

Figure 11. (*a*) Back view of Quarter IV, highlighting the rib cage. (*b*) Locking operation procedure.

Table 3. Rib system segmentation.

Quarters	Modules				
	#	VRs	HRs	Type	Screw holes
I	2	4-VRs	5-HRs	Lateral	20 (4 × 5)
	1	7 VRs	1 HRs	Central	7 (7 × 1)
II	2	4-VRs	7-HRs	Twins	28 (4 × 7)
III	2	3-VRs	7-HRs	Twins	21 (3 × 7)
IV	2	4-VRs	4-HRs	Lateral	16 (4 × 4)
	1	7-VRs	1-HRs	Central	7 (7 × 1)

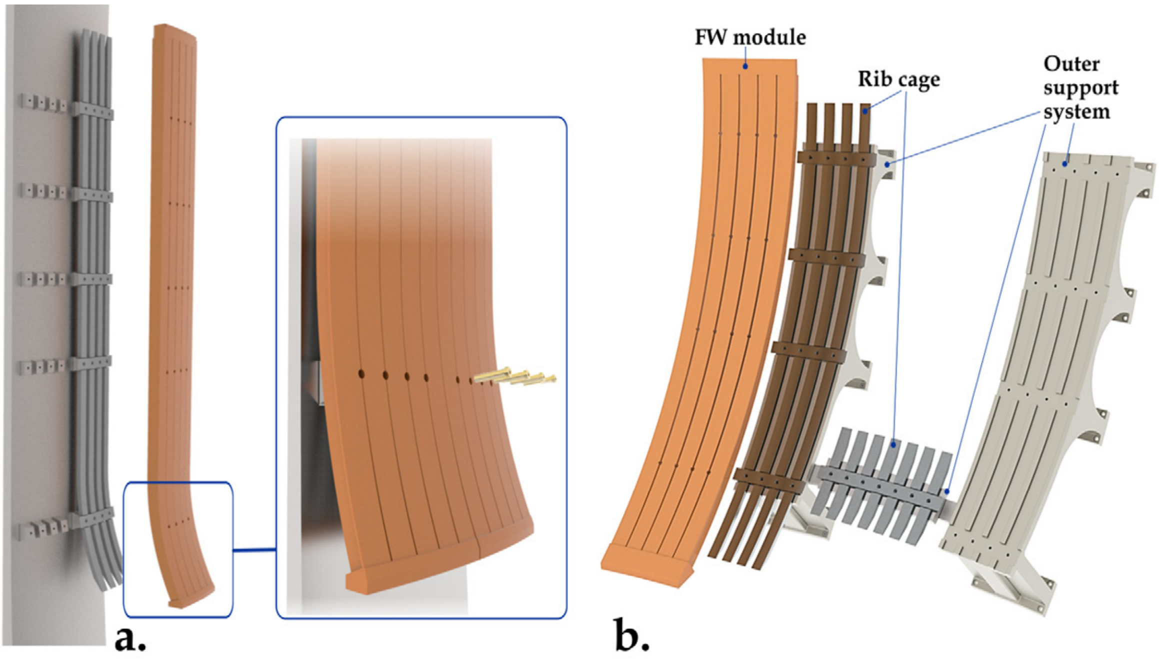

Figure 12. (*a*) View of the inner support system, embedded in the VV, for Quarter III and particular of the locking procedure. (*b*) View of the outer support system for Quarter IV, highlighting the several FW layers.

4.2. The support system

The physical supporting structure is strongly influenced by the choices taken during the preliminary FW design phase, especially the minimization of the space occupied by FW pipes in the inner part of the chamber, which is a critical area during plasma operations. This determines a huge discrepancy between the inner part, where the FW-VV clearance is very small (the worst case is 20 mm on the equatorial plane), against the outer part, where the space margins for adding a further component are pretty high, even taking into account the clearance needed for the in-vessel coils.

In both cases, regardless the different approaches adopted for inner and outer parts, 28 mm-long and 6 mm-diameter pins are foreseen for locking the FW segments, by screwing from the centre of the chamber towards the VV.

4.2.1. The inner support system. About FW Quarter II and III, i.e. in proximity of the Central Solenoid from the divertor zone up to the vertical port, the high complexity level of inserting and handling a material FW-VV interface is overcome through a support system embedded in VV modules (see figure 12(*a*)). Obtained via suitable extrusion operations, it allows the locking of FW modules directly to the VV via a matrix of blind screw holes, able to house the pins, matched with the correspondent rib cage's ones.

4.2.2. The outer support system. Differently from the inner FW segments, due to larger available space in the outer part of the chamber, Quarter I and IV exploit a proper support system (see figure 12(*b*)), which allows locking operations according to a *plug/socket principle* played with the correspondent ribs system. At this aim, the main characteristic is the coherency with the rib modules to be housed, in terms of vertical and horizontal grooves, poloidal profile, and blind screw holes' matrix. Outer supports' conformation implies both a slim and robust structure and a tolerable additional weight on the VV, whereas the supports' shape fulfills the required clearance for the in-vessel coils. Consistently with FW segmentation (see table 2), the outer support system is divided into lateral and central modules: the former are fixed to VV in positions homologous to HRs, the latter are screwed to the lateral modules they are in between.

5. Conclusions

The present work takes shape within the satellite tokamak frame and is focused on an innovative design strategy for the first wall in a fusion power plant. The key points, which such alternative design relies on, can be summarized as follows:

(i) the plasma facing wall is provided by a quasi-uniform toroidal surface, obtained via a bundle of flanked square-section envelopes, provided of lateral wings with variable span,
(ii) the FW is split into suitable modules in order to manage the required remote handling procedures,
(iii) the cooling cycle is implemented via suitable coaxial pipes, dug at the envelop centre, which means an auxiliary cooling system integrated in the FW itself, rather than physically segregated,
(iv) the manifolds, realized as nested tanks or flow inversion zones, support the cooling cycle and the structural stability of FW segments,
(v) an auxiliary rib cage is welded onto the outer surface of FW modules in order to benefit locking/unlocking operations,
(vi) locking operation of outer FW segments onto the correspondent support system are foreseen according to a plug/socket principle,
(vii) the inner support system is integrated in the VV.

As next step, a macroscopic analysis needs to be carried out in order to validate the overall FW design, support system included, from the thermo-structural point of view. In a second stage, a FW remote maintenance procedure, including the design of a proper RH system, has to be well defined.

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