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Studio della sostituzione da remoto del divertore e della prima parete in FAST e EAST

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STUDIO DELLA SOSTITUZIONE DA REMOTO DEL DIVERTORE E DELLA PRIMA PARETE IN FAST E EAST

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Index

SUMMARY ... 4

1 INTRODUCTION ... 5

2 DESCRIPTION OF ACTIVITIES AND RESULTS ... 6

2.1 FW DESIGN STRATEGY. ... 6
2.2 REMOTE HANDLING ISSUES. ... 8
2.3 FW REMOTE HANDLING DESIGN ... 11
2.4 CONCEPTUAL DESIGN OF FW REMOTE HANDLING SYSTEM FOR FAST ... 13
2.5 CONCEPTUAL DESIGN OF THE ROBOT ... 14
2.6 STRUCTURAL ANALYSIS ... 15
2.6.1 Geometry ... 15
2.6.2 Material properties ... 15
2.6.3 Contacts and joints ... 15
2.6.4 Mesh ... 16
2.6.5 Loads ... 16
2.6.6 Results ... 18
2.7 HANDLING ROBOT ... 19

3 CONCLUSIONS ... 20

4 REFERENCES ... 21

5 ABBREVIATIONS AND ACRONYMS ... 22

Summary

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, high criticality needs to be associated to the design of plasma facing components, i.e. First Wall (FW) and divertor, for both topological, remote handling 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 report 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 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. Finally, a first concept of remote maintenance procedure is presented.

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].
Focusing on plasma facing metallic components, which represent the most critical and stressed physical parts during plasma operations, the main objective of this research activity consists in the introduction of a conceptual design strategy for the First Wall (FW) in FAST conceived taking also into account the possibility to adapt a similar solution to EAST tokamak. In other terms, an innovative proposal, completely detached from the current solution adopted for ITER, where the FW design is based on a number of 440 beryllium modules of 1x1.5 m, cooled via an external and physically segregated auxiliary system.
In the following sections, a detailed design of FAST FW is presented, with attention to the typical key points of plasma facing components design, i.e. basic conceptual idea, remote handling issues, cooling cycle and support system.

2 Description of activities and results

2.1 FW DESIGN STRATEGY.

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

The general design guidelines can be summarized as follows:

- Main purpose: providing locking/unlocking operations of FW to the Vacuum Vessel.
- Auxiliary system: Usage of a Ribs system, to be welded onto the outermost FW surface, as interface between FW and Supports.
- Reference configurations: FTU's FW Support system.
- Philosophy: Ribs/Supports interface according to a plug/socket principle.
- Locking criterium: Ribs located and screwed onto Supports from the centre of the chamber towards the VV.
- Remark: Ribs presence adds stiffness to the FW modules (currently very flexible due to shape, curvature and dimension).

The main FW idea consists in a bundle of toroidally flanked stainless-steel envelopes composed by:

- a main body, obtained by sweeping a 32 x 32 mm square section along a poloidal curvature line consistent with the Vacuum Vessel (VV) poloidal cross-section,
- a coaxial pipe, in charge of cooling operations, dug in correspondence of the envelope's centre,
- a couple of symmetrical lateral wings, with 2 mm thickness and variable span (1-13 mm).

The definition of the poloidal curvature meets the necessity to optimize the space available for the plasma within the chamber, principally in the inner part of the chamber due to its criticality during plasma operations. Indeed, in several scenarios with diverted configuration, and mainly after a L-H transition, the shape controller needs to counteract plasma drift phenomena towards the Central Solenoid and avoid plasma disruptions, caused by contacts with surrounding physical structures and yielding a sudden loss of confinement and energy content. Apart from the controller response times, plasma-wall clearance can be improved by leaving plasma as much allowed area as possible, which means a placing of the FW as close as possible to the VV, except for a minimum tolerance to fill with the supporting structure. Furthermore, the poloidal curvature needs to take into account the presence of the in-vessel coils, placed between the equatorial and the vertical ports and exploited for magnetic control purposes (Edge Localized Modes, vertical stability, radial position).

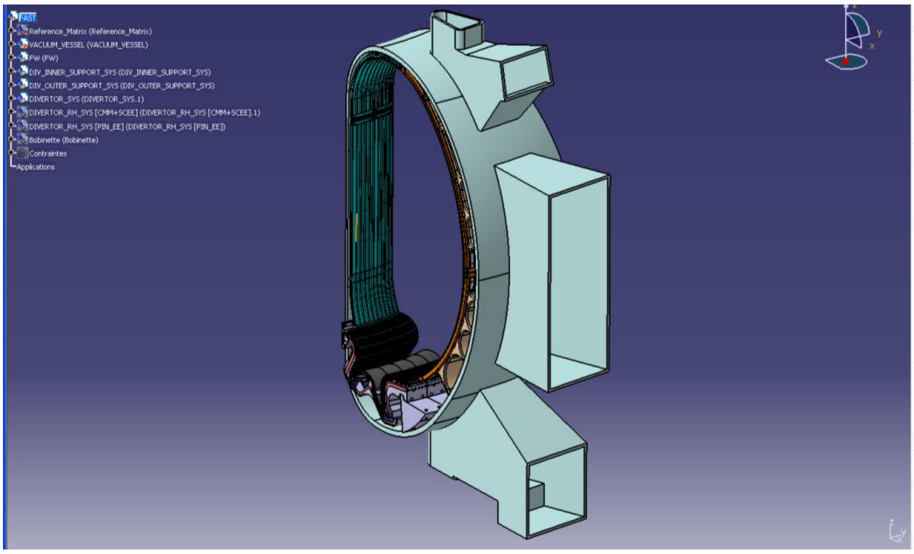

Fig. 1 – 20° Sector of FAST tokamak

About the geometry of the main body, although a dedicated thermo-structural analysis [7] returns that a circular 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 (Fig. 2). 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. Hence, on the base of the above mentioned constraints, a first FW classification per VV sector foresees:

- 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.

About the lateral wings, a detailed span trend is 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 the equatorial plane in the outer part) and vice versa (as the equatorial plane in the inner part). 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 armoured with a plasma coating W-layer of 3 mm thickness.

Table 1. Trend of FW wings' span.

Quote	Pipe Type	Wing Span
zmin -> zeq	outer	2.5 -> 7:5 mm
zmax -> zeq	outer	1 -> 7:5 mm
zmin -> zeq	inner	4 -> 3 mm
zmax -> zeq	inner	13 -> 3 mm

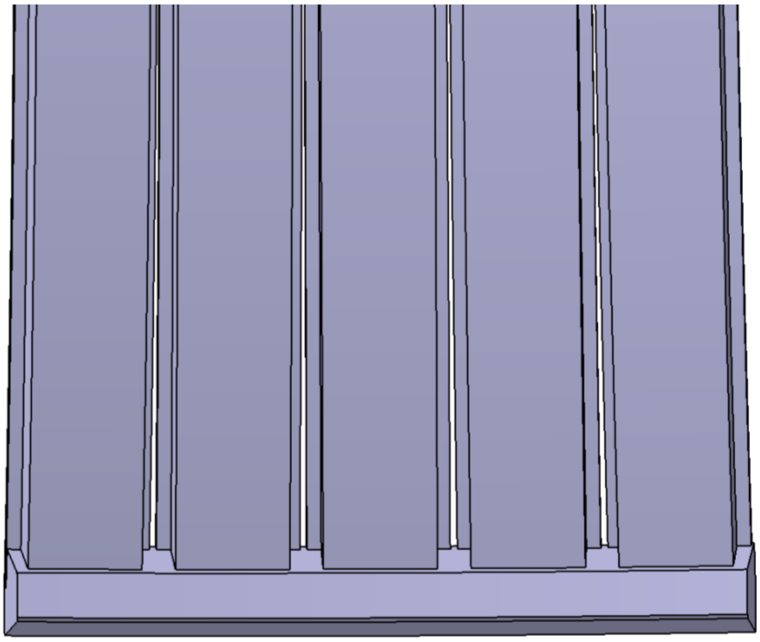

Fig. 2 – Example of FW wings' span

2.2 REMOTE HANDLING ISSUES.

The feasibility of a remote maintenance via the equatorial port represents a further main requirement in FW design, whose fulfilment 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, on the base of motion tests a second FW segmentation is considered as follows (figure 3):

- Quarter I, outer part from z_{eq} to z_{max},
- Quarter II, inner part from z_{max} to z_{cut},
- Quarter III, inner part from z_{cut} to z_{min},
- Quarter IV, outer part from z_{min} to z_{eq},

being z_{cut} the vertical cutting quote for inner pipes, chosen in the perspective of easily moving FW inner modules through the equatorial port. The physical separation between adjacent quarters is obtained via the introduction of a 5 mm clearance.

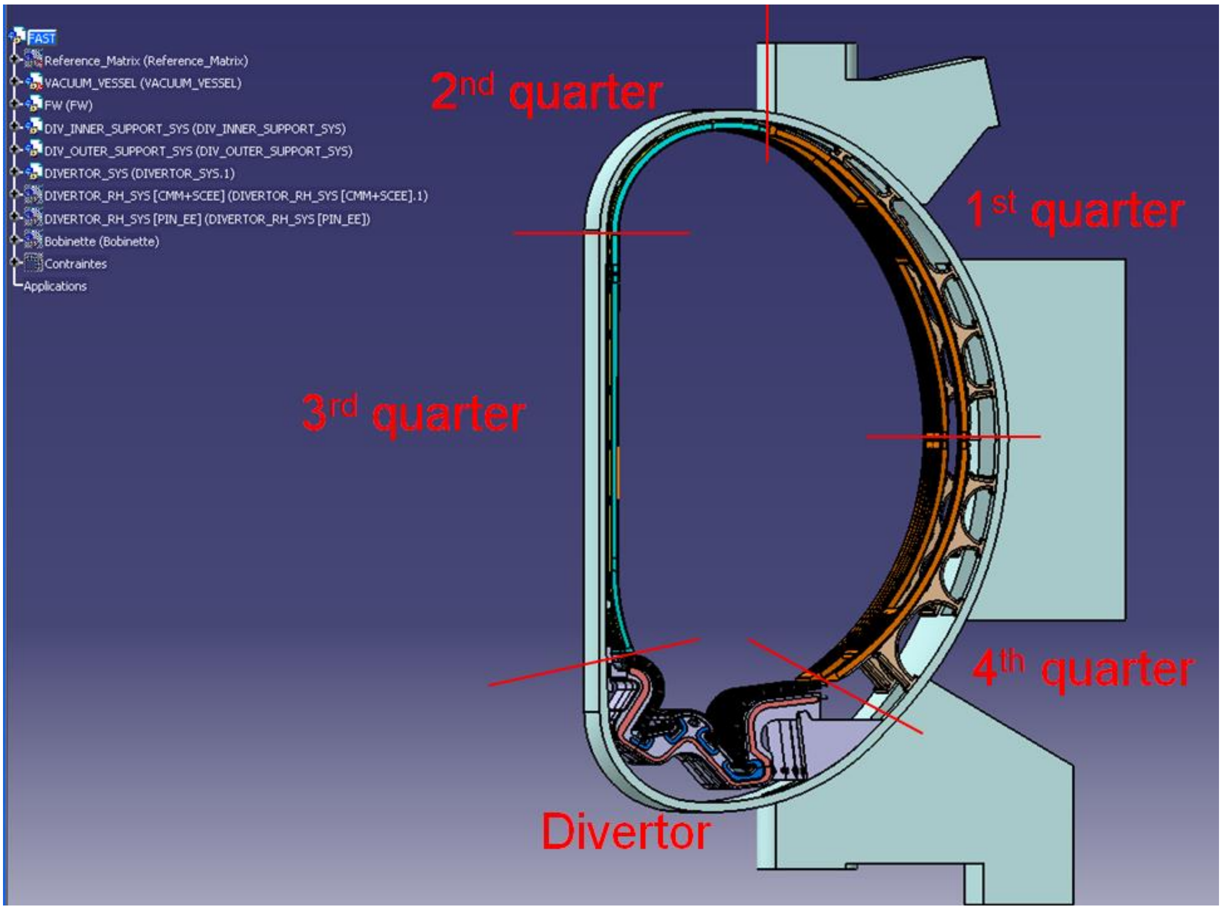

Fig. 3 - Four quarters of FAST tokamak

Every quarter is made of several sub modules. Every sub module is made of Plasma facing components and a rib interface for fixation to the support. The Plasma Facing components are made of several pipes, and the rib interface is made of several vertical ribs (VR) and horizontal ribs (HR).

The ribs design guidelines can be summarized as follows (figure 4):

- Profile coherent with FW's one.
- Vertical Ribs (VR) placed in correspondence of the space between 2 adjacent external pipes of a FW module.
- Due to the definition of FW modules (5 or 8 pipes each), Ribs modules have 4 or 7 VR.
- Horizontal Ribs (HR) placed depending on the height of FW modules in an equidistant manner.

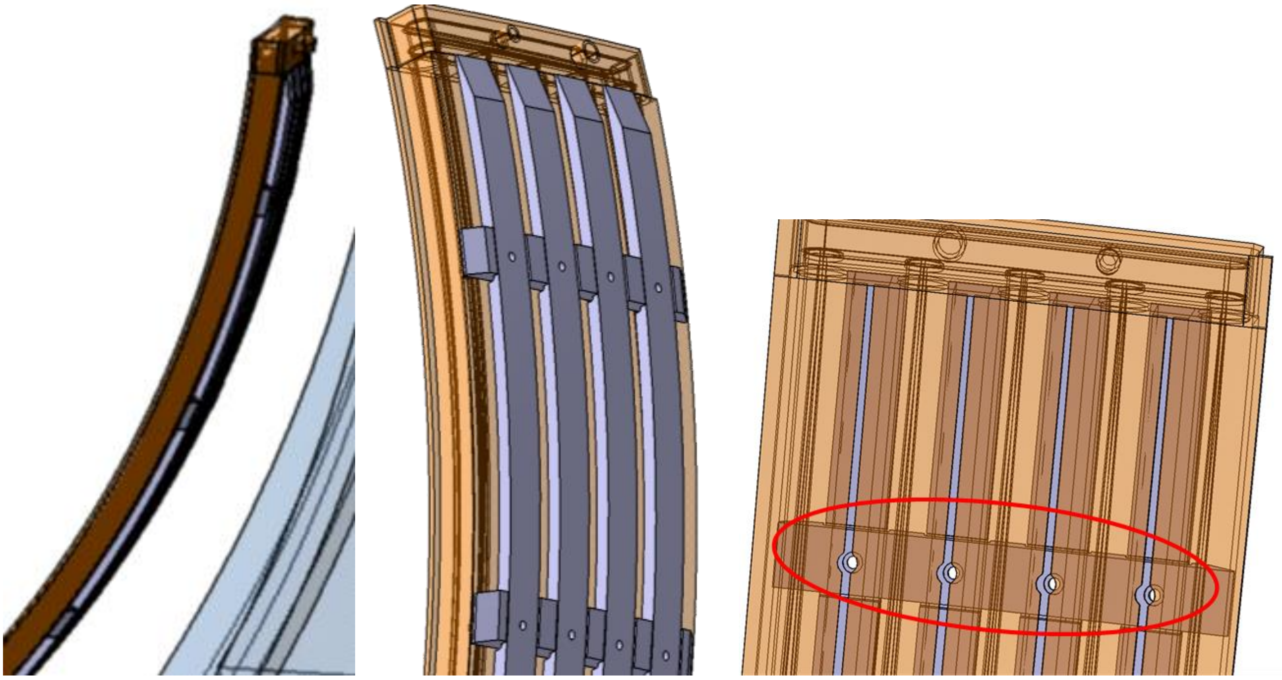

Fig. 4 - Ribs design

According to the locking criteria (screwing onto supports from the centre of the chamber towards the VV), profile of FW wings was modified in order to allow screwing operations.
For the design of the 1st quarter the following guidelines have been followed (figure 5):
With regards to FW/Rib interface,

- FW submodules: 2 lateral submodules of 5 pipes + the central one of 8 pipes.
- 2 lateral Ribs submodules: 4 VR + 5 HR + 20 screws (4x5 Rib/Support pins).
- Central Ribs submodule: 7 VR + 1 HR + 7 screws (7x1 Rib/Supports pins).

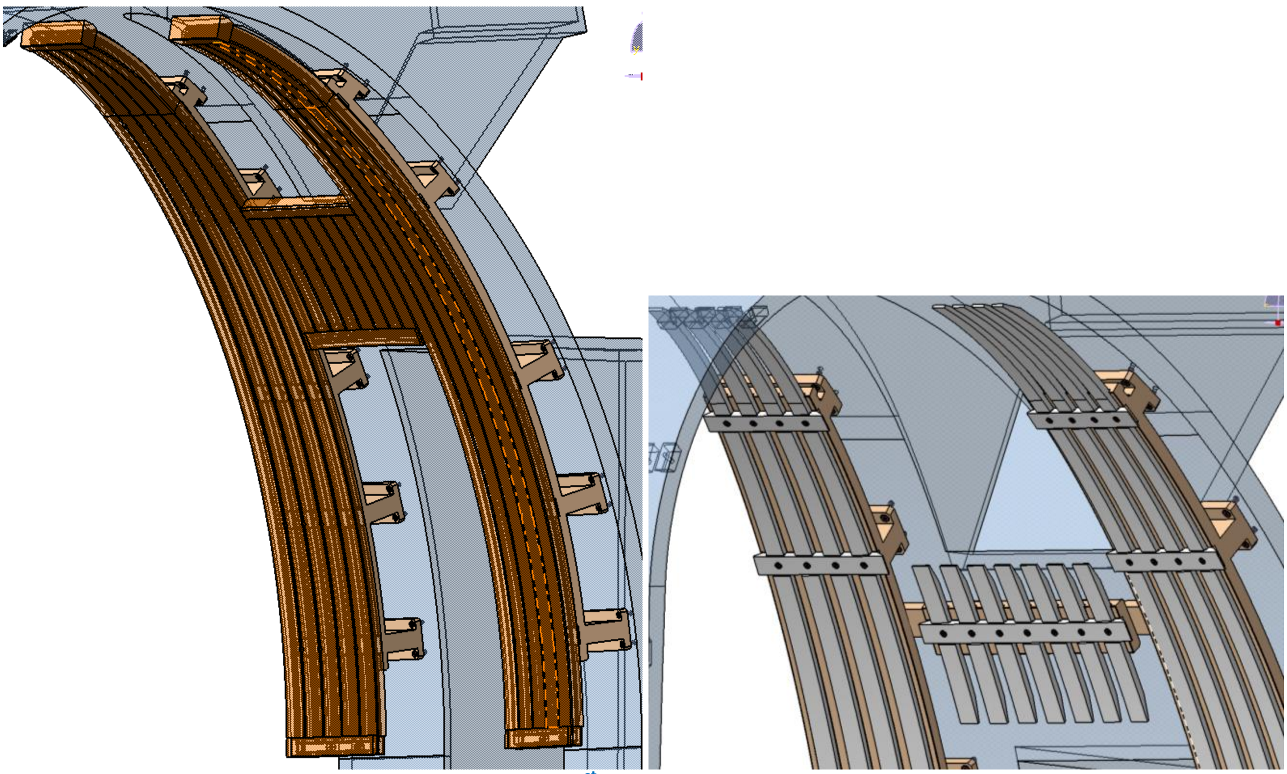

Fig. 5 – 1st quarter of the FW

With regards to Ribs/Supports interface:

- 2 lateral Supports submodules: 4 VR sockets + 5 HR sockets + 20 screws (5x4 Support/VV pins).
- Central Ribs submodule:7 VR sockets + 1 HR socket + 8 screws (4x2 Support/Support pins).
- No interference with the internal coil (between ports) to be guaranteed.

For the design of the 4th quarter the following guidelines have been followed (figure 6):
With regards to FW/Rib interface,

- 3 FW submodules: 2 lateral submodules of 5 pipes + the central one of 8 pipes.
- 2 lateral Ribs submodules: 4 VR + 4 HR + 16 screws (4x4 Rib/Support pins).
- Central Ribs submodule: 7 VR + 1 HR + 7 screws (7x1 Rib/Supports pins).

With regards to Ribs/Supports interface:

- 2 lateral Supports submodules: 4 VR sockets + 4 HR sockets + 16 screws (4x4 Support/VV pins).
- Central Ribs submodule: 7 VR sockets + 1 HR socket + 8 screws (4x2 Support/Support pins).
- No interference with the internal coil (between ports) to be guaranteed.

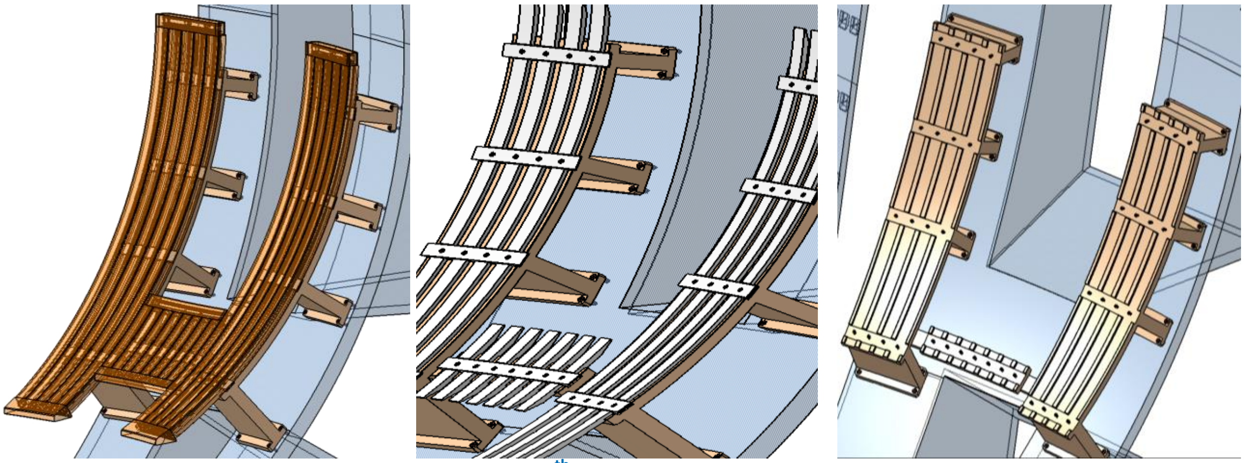

Fig. 6 – 4th quarter of the FW

In the 2nd and 3rd quarters the supports for the FW are very small and embedded in the VV.

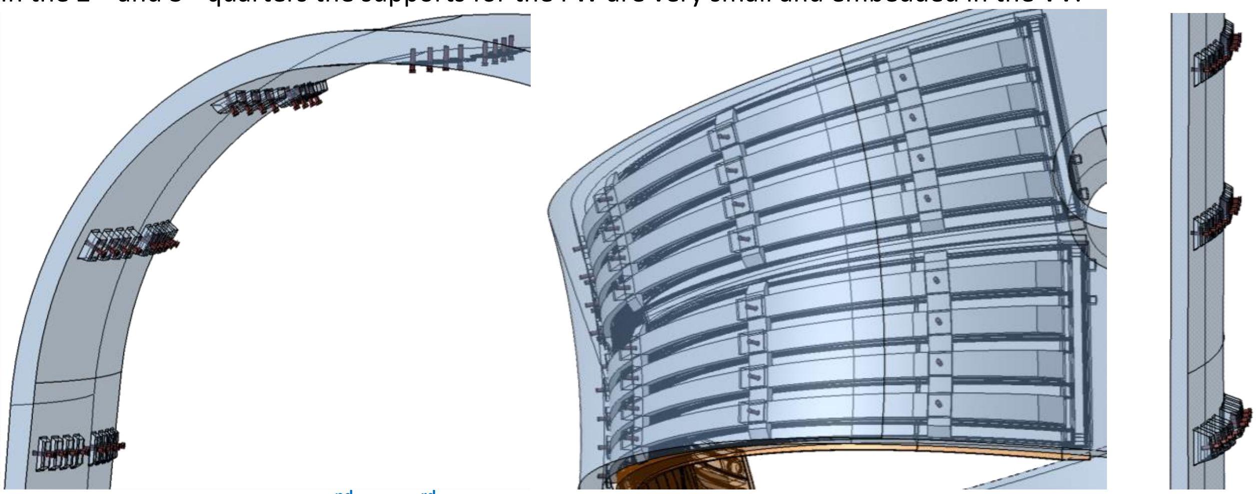

Fig. 7 – 2nd and 3rd quarters of the FW: the supports are embedded in VV.

The FW components are mainly made of 316L stainless steel. The heaviest FW component is about 55 kg, in the 1st quarter.

2.3 FW REMOTE HANDLING DESIGN

A lot of publications deal with design considerations about Remote Handling in experimental Tokamak. Most of them deal with the JET experience. The main idea about RH design and experience are summarized in this paragraph

- The first JET experience teaching is about the design of RH devices. RH devices have to be considered as a full integrated system of any tokamak, and not as an outside system. So it is necessary that RH system is considered from the very beginning of a tokamak design process.

- The component inside the tokamak have to be RH compatible, so RH engineers have to be involved in the design of components from an early stage in order to ensure their compatibility. A standard remote interface has to be created, and it has to be saved through the design evolution.

- The RH system has to be flexible. The configuration of an experimental Tokamak may have to change during its lifetime, so the RH device has to be completely independent from the tokamak configuration.

- Different handling operations have to be done to remove different components, so the RH system has to be adaptable to suit all of the necessary tasks. It is not possible to predict every event that will occur in a tokamak, such as failure. The RH system has to be able to work in operation, and has to be flexible enough to face any kind of event.

- Another point is about preparation of RH operation. Any unexpected situation during operations should be avoided. A carrefull control of “As-Built” component has to be carried out to ensure that they can fit in the tokamak and to their adjacent elements. On top of that handling operations have to be tested outside the Tokamak in order to get some experience.

- The RH operator needs feedback during operations. Forces and Torques sensors and cameras are necessary to get information from the robot. The use of virtual reality can also be very useful as cameras only show a small part of the tokamak inside chamber.

- Concerning the use of existing elements to manufacture the RH system, it seems that standards electrical and electronic equipments and software can be used for the creation of a robot. However, mechanical components are often customised solutions.

The JET RH system is made of two arms that are called octant 1 boom and octant 5 boom, named according to the number of the equatorial plug they depend on. These two arms can be seen on **Errore. L'origine riferimento non è stata trovata.**. These octant booms look like a kind of "snake", that can go all around the torus. These two arms can enter the torus through equatorial plug (Fig. 8).

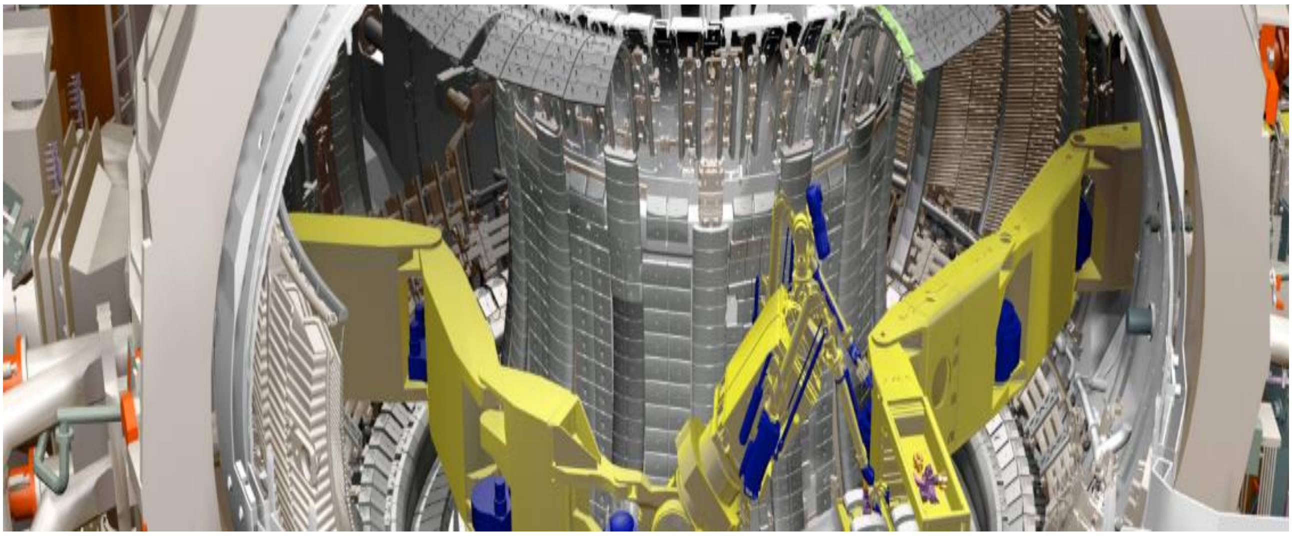

Fig. 8 - Octant 1 boom (right) and octant 5 boom (left).

The octant 5 boom (left) is made for handling and tooling operations and octant 1 boom (right) is used as tool storage where octant 5 boom can change its tool. The octant 5 boom can access +/- 190° in the torus of the TOKAMAK, which means every components in the tokamak can be removed. The octant 1 boom can access +/- 120° in the torus of the tokamak. It does not need to access the whole tokamak because the other arm actually can. For such system, it is necessary to have a long rail length (about 8m for JET) for the robot to access all positions in the torus. Some space is left between every segment for a motor (in blue on the previous picture)

The principle of two arms, one for RH and the other to bring the tools, seems to be a good concept for FAST. As an experimental Tokomak, several equatorial ports may have to be used for diagnostics. As the space around a tokamak can be limited, using only two equatorial plugs can be a good solution. On top of that a limited number of hot cells is definitely easier to handle for a nuclear installation. Even though FAST will not be a nuclear reactor, it aims to test RH solutions for future experimental fusion reactor, so the hot cell aspect is important.

The JET tokamak is not actively cooled, so the tiles that were used to cover the first wall were quite small compared to the components of FAST first wall. So the weights of JET tiles are less important than FAST components. this means that the JET manipulators may not suits FAST requirements. The JET manipulators are made of two small arms that can carry 20 kg. A similar system could be used for FAST tokamak but it should be able to carry heavier loads. One "large arm" could be used to carry and hold the component and a "small arm" could be used as manipulators and tools. In JET, a winch is used to carry the divertor.
As said earlier, one of the octant boom in JET is used as a kind of "storage" inside the tokamak for the different tools. It is made like a classical drawer, were the two arms can go and choose the right tool for the task they need to accomplish. This arm is shorter, because it doesn't need to access the whole tokamak. An access of +/-120°, as used to JET, seems reasonable. As this arm is shorter, its design won't be presented in this report, and the structural analysis won't be studied here, because the loads on the carrying robot are more conservative.

2.4 CONCEPTUAL DESIGN OF FW REMOTE HANDLING SYSTEM FOR FAST

According to previous considerations, the concept of FW remote handling will be the following:

- One "drawer arm" that will bring the different tool.
- One "operational Arm" that will perform tooling operation (welding, cutting...) and handling operation. Two different robots will be used on this arm.
  - One handling robot for carrying the submodules and put them in place with a sufficient number of fixations to handle the sunmodules weights.
  - One Tooling robot that will perform that will perform other operations: weld/cut pipes and put/remove all fixations not necessary for maintaining the module in place.

In this part a conceptual design for the "snake" part of the robot will be presented. The concept is very similar to JET RH system. The Manipulator will be presented in further paragraphs.
According to the size of the tokamak and the equatorial port plugs, the following parameters have to be considered as fixed:

- The robot is made of 6 parts: on long segment fixed on a rail system, 4 central segment of equal size, and the manipulator, which won't be presented here
- The length between two segments connections has to be 1.3m for the arm to access +/- 190°.
- The width of the five first segments is 250 mm. The width of the manipulator cannot exceed 350 mm in order to go through the equatorial port plugs.
- The height of the first five segments is 740 mm.

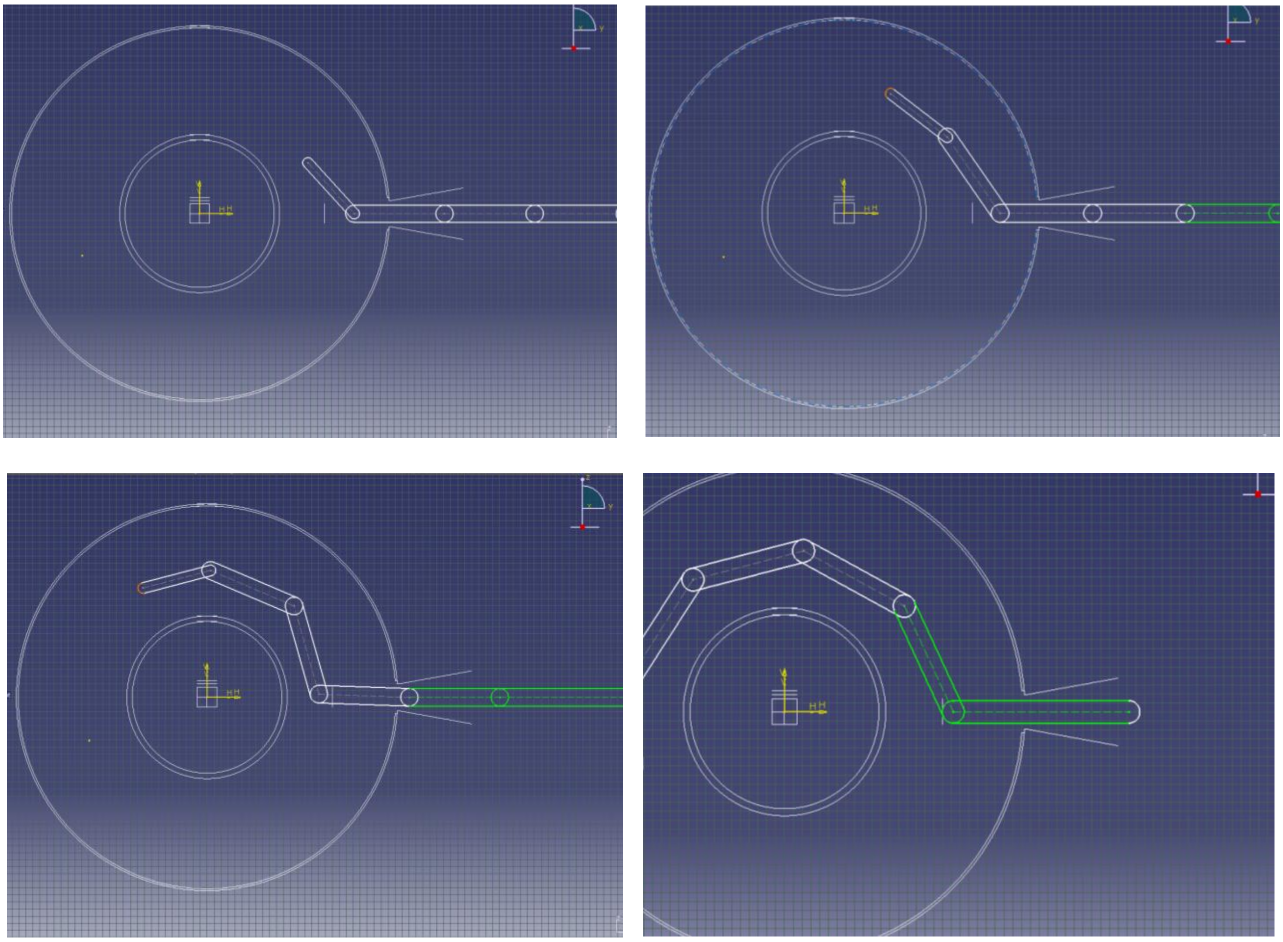

Fig. 9 - First schematic representation of FAST FW RH system

Some simple schematic drawings were made in CATIA in order to check that this dimension could fit FAST dimension (figure 9). The minimum and maximum radiuses are represented as well as the critical width of the equatorial port plug at the top (respectively the bottom) of the segment. A spline line was created to simulate the trajectory of the robot. In the JET tokamak, a program is used to constrain the robot in a safety area in an average centroid line inside the tokamak.
Figure 9 shows that the actual dimensions of fAST allows to insert a robot with the characteristics previously mentioned and to reach +/-190°.

2.5 CONCEPTUAL DESIGN OF THE ROBOT

The last segment - the manipulator- is not presented here. This design is a concept. The motors are not represented, but some space was left between every segment in order to insert a motor, as for the JET design. Every segment is made of aluminium and is empty in order to reduce its weight. Some slanting stiffeners were added inside in order to prevent torsion. Some shafts are used to link the segments together. Every short segment weights 156 kg and the long segment weights 225 kg (Figure 10).

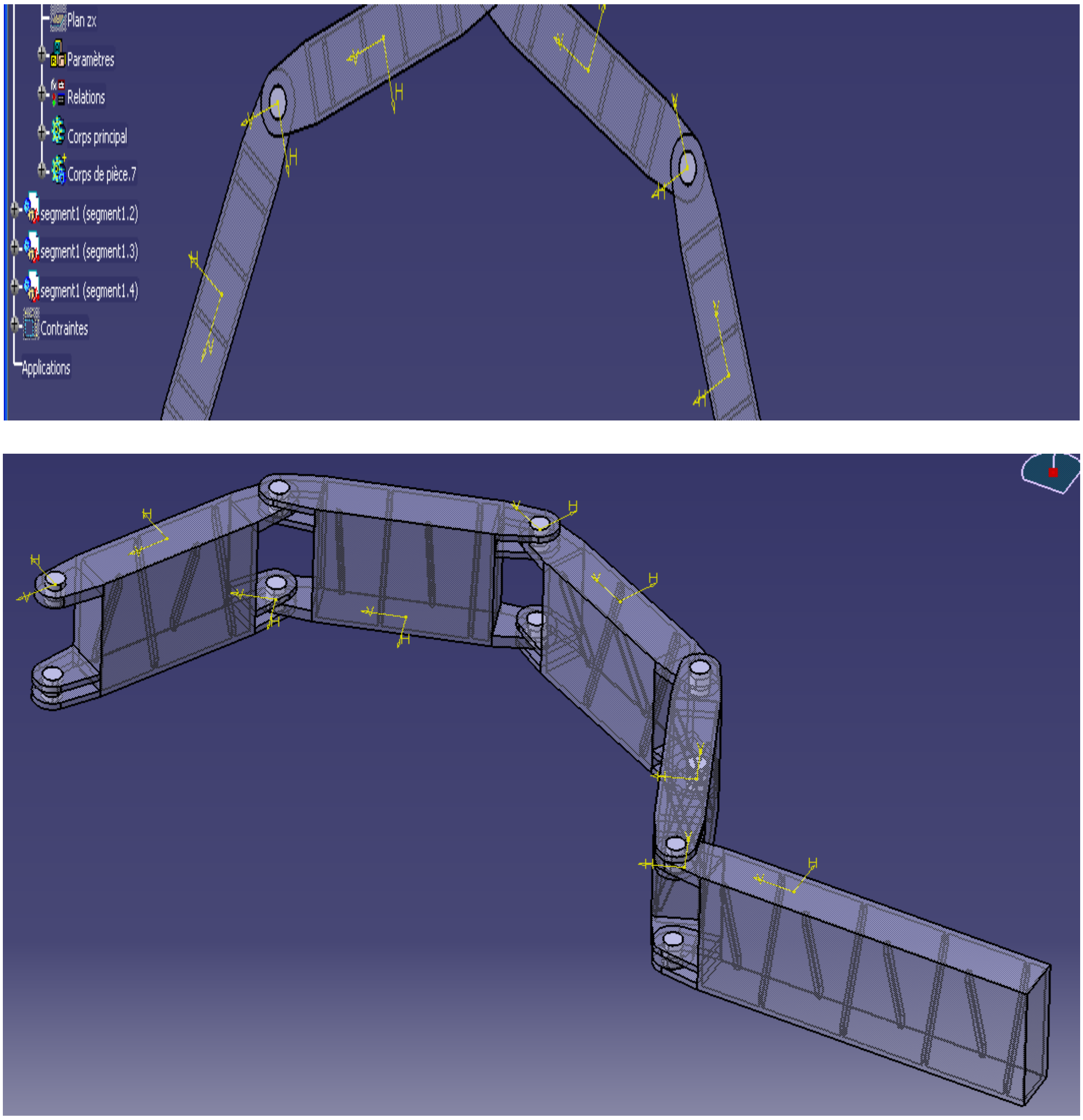

Figure 10 : First concept of the “snake” part of the robot

2.6 STRUCTURAL ANALYSIS

A simple ANSYS analysis was carried out to determine if this robot could handle the weight of the different component.

2.6.1 Geometry

The geometry is the same as the previous paragraph. The robot is completely deployed in the tokamak, which the most conservative case. The shafts are not represented in this model, because this analysis aims to study the mechanical behaviour in the different segments.

2.6.2 Material properties

As said before, the material studied here is aluminium alloy. Aluminium is light and its good mechanical properties should suit the robot requirement. The density of Aluminium alloy is 2770 kg/m3. Its Young modulus is 71 GPa and its Poisson ratio is 0.33. Its yield stress is about 280 MPa.

2.6.3 Contacts and joints

Every horizontal contact is set to frictionless (figure 11).

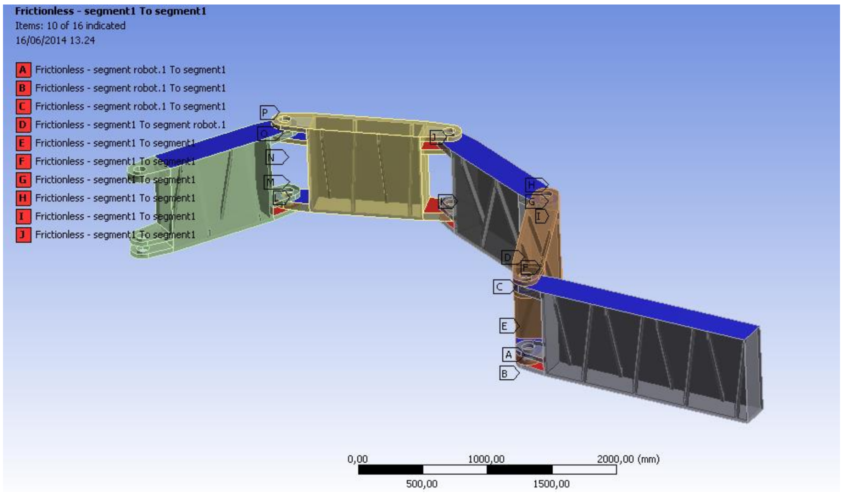

Fig. 11 - Horizontal frictionless support

As the shafts are not modelled here, some joints are created (Fig. 12). Only a vertical translation is allowed, because in reality the rotation around the z-axis will blocked by motors.

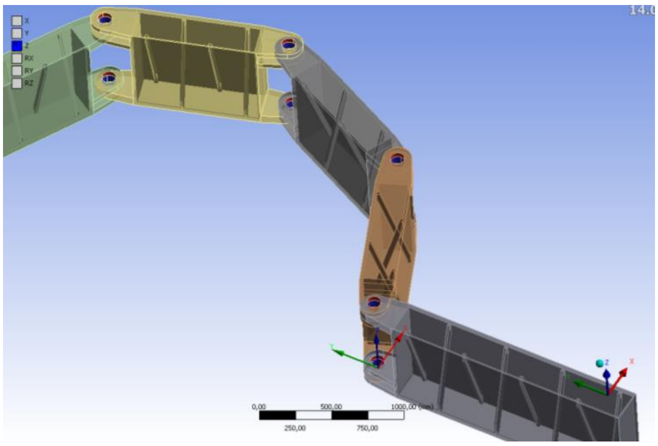

Fig. 12 - Joint connections.

2.6.4 Mesh

The model is made of 331241 nodes and 67977 elements.

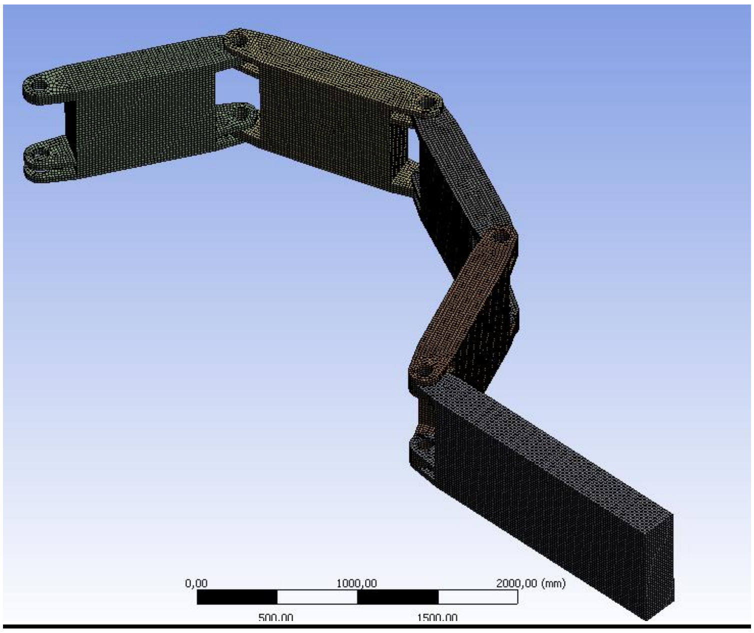

Figure 1 - Mesh of the model

2.6.5 Loads

The considered main load is the weight of the different segment, so standard earth gravity is applied. To simulate the weight of the motors and the shaft between each segment, a load of 300 N is applied on the face between each segment.

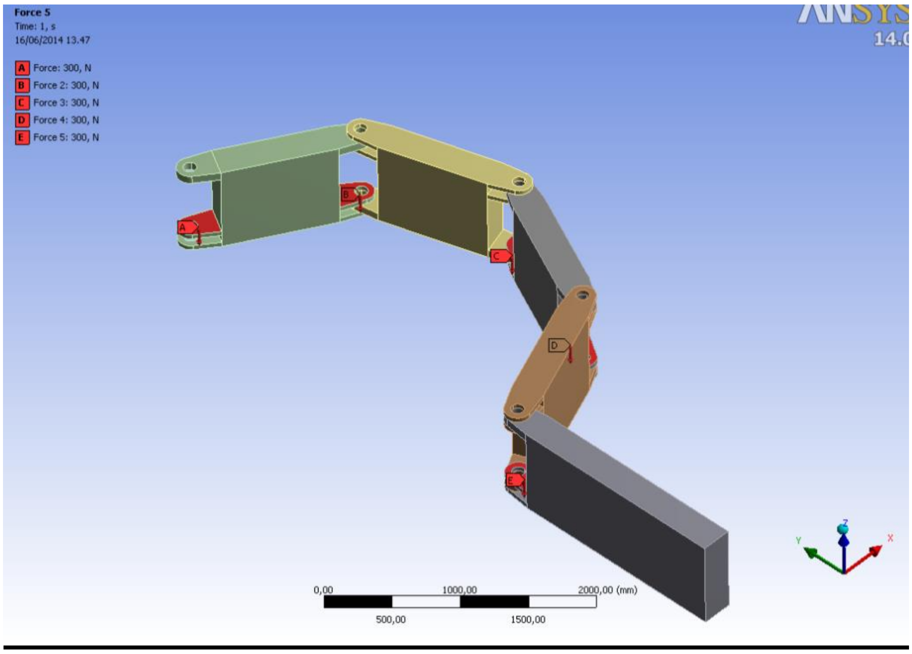

Figure 2 : Motors weight

A remote force is added at the end of the robot, at 650mm from the last connection joint, to simulate the weight of the last segment and one component of first wall. The weight of this equipment is estimated to be 300kg, to be conservative.

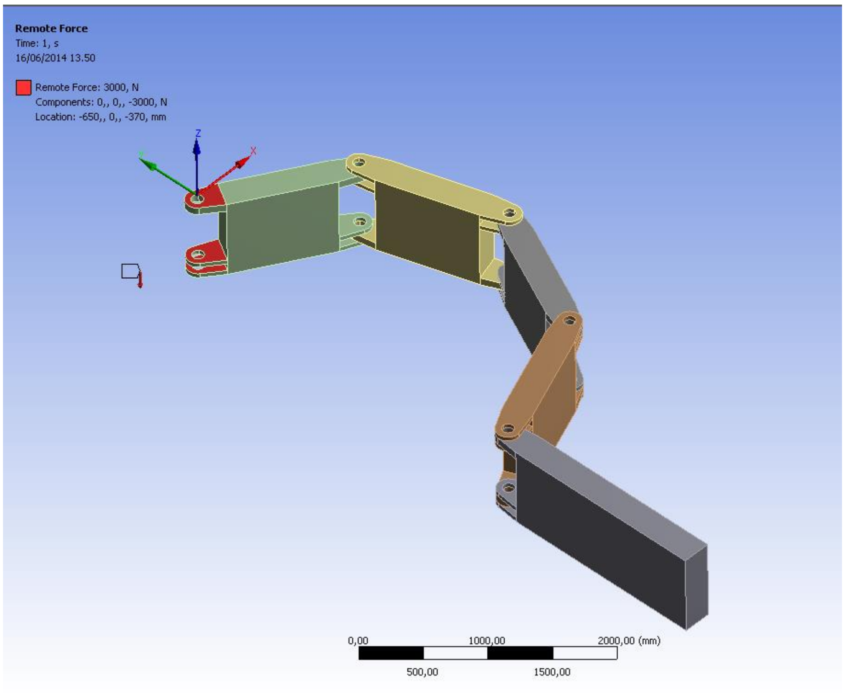

Figure 3 - Last segment weight

Finally, the back of the long segment is fixed.

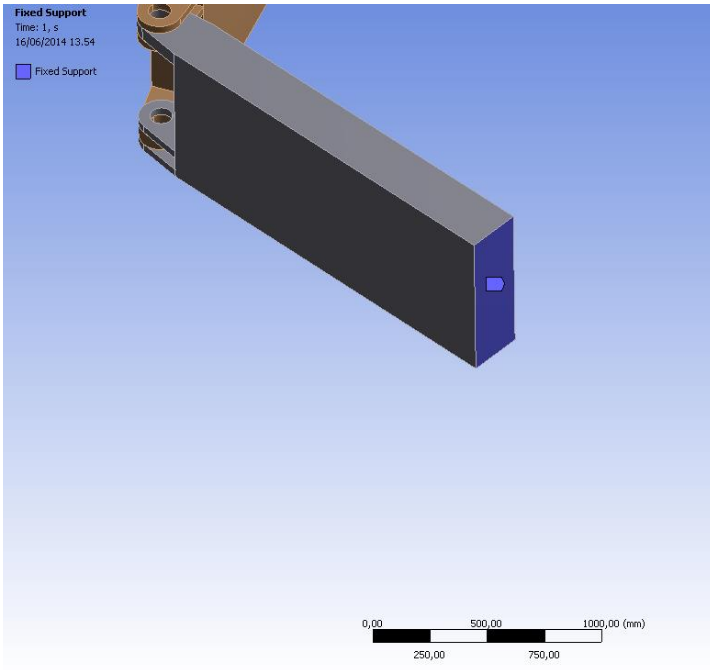

Figure 4 - Fixed support

2.6.6 Results

The maximum stress is 30 MPa. This means that the robot can perfectly handle the loads. As the security factor is around 10, this means that a lot of optimization could be done in the design. The main loads problem should be on the motors, and not on the robot's structure. This result validate the concept of the "snake robot"

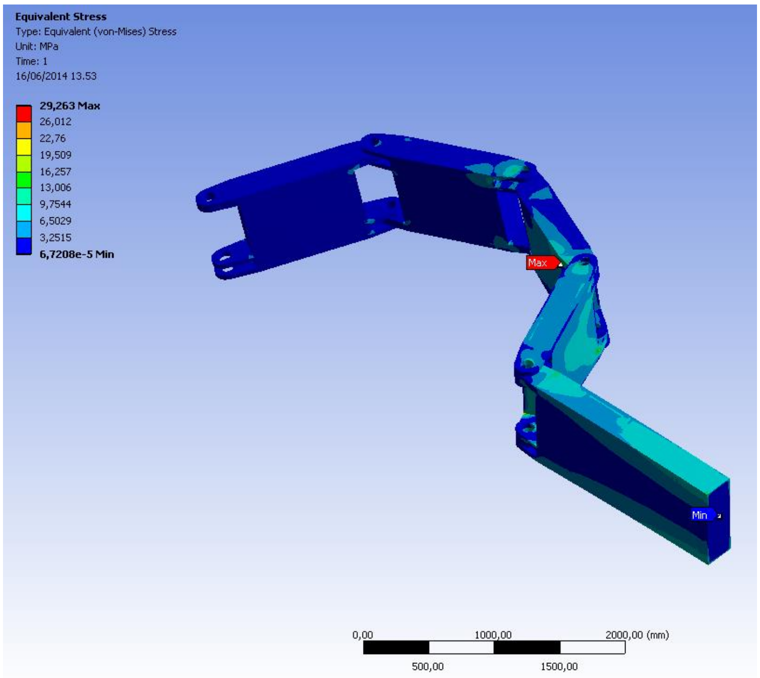

Figure 5 - Stress in the robot arm

The vertical deformation is about 9 mm

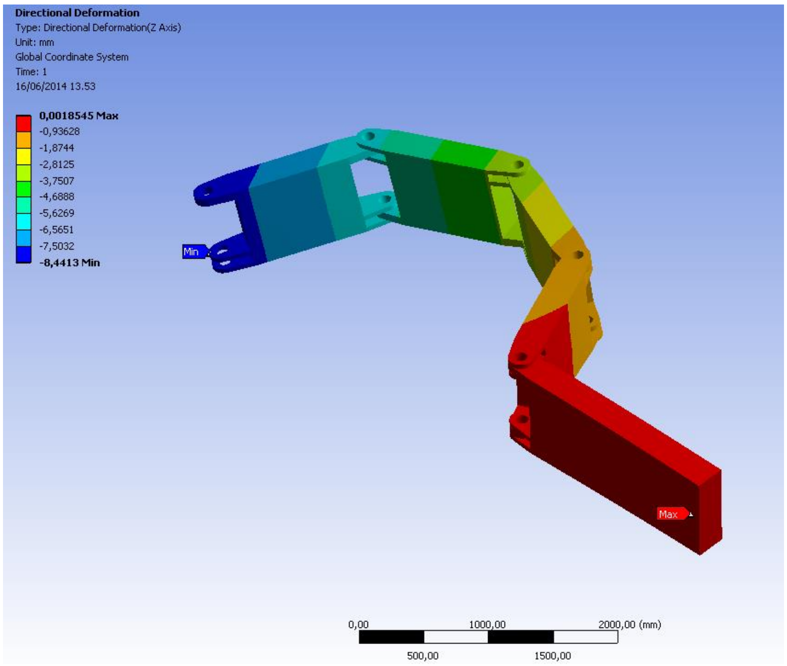

Figure 6 - Deformation in the robot arm

2.7 HANDLING ROBOT

The design of the handling robot is a 5 axis robot. This robot just needs to be able to go at the right position to handle a first wall component so it is not necessary to have 6 axis. Every segment is quite short to reduce the torque at every motor. The design presented here is conceptual, it just aim to verify if the kinematics is fine for RH operation. The kinematics chain is shown on the next pictures.

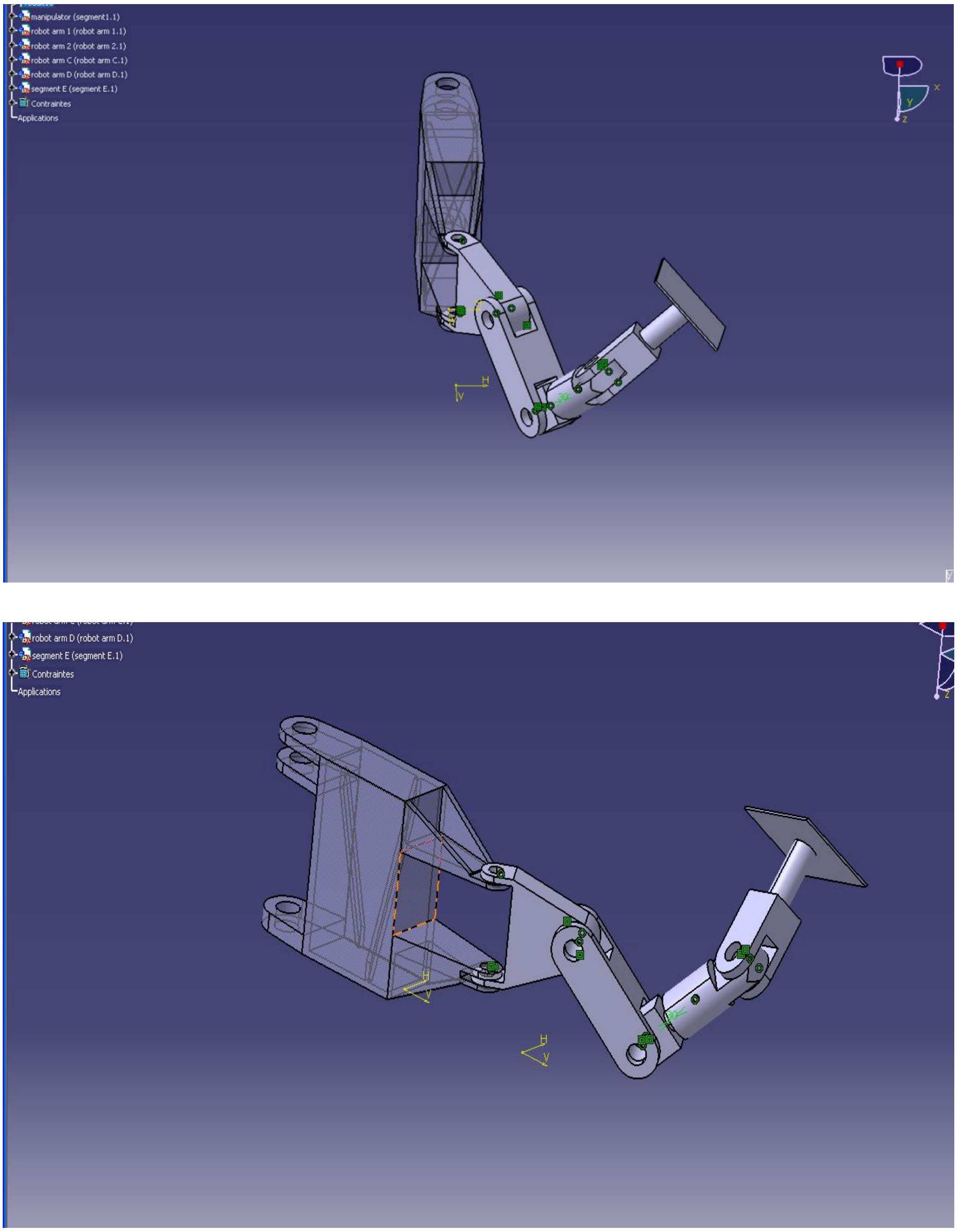

Figure 7 - Last segment handling robot

3 Conclusions

The present activity 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.

A first FW remote maintenance procedure, including the design of a preliminary concept of RH system, has been carried out.

The studies carried out in this research activity can be perfectly adapted to the EAST tokamak. Indeed EAST machine has almost similar dimension then FAST [8]. Different material constituting the First Wall (it is under study the application of SiC coated graphite tiles) will need similar structural and kinematic analyses in order to define the typology of robotic arm to be used for remote handling operations.

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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