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Sviluppo di nuove configurazioni di plasma e di un nuovo divertore per l'esperimento FAST

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Contents

Summary

Within the FAST Project, the support obtained by the “Accordo di Programma tra Ministero dello Sviluppo Economico ed ENEA (Obiettivo D: FAST il nuovo esperimento satellite europeo)” has allowed the study of the “Snow Flake” (SF) magnetic topology for the divertor region. This SF configuration has shown the capacity of strongly reducing the Power Flow on the divertor plates. A reduction up to a factor of the order that five has been found, larger of what foreseen from simple topological arguments, indicating a possible role played by the behaviour of the neutrals in front of the plates itself. The achievement of this important possible result, has pushed to a complete design of an actual divertor compatible with the standard Single Null X point (SN) and the SF, in a such a way that, on the same plasma experiment the performances of the two configurations could be compared by using the same plasma scenario. An accurate evaluation of the magnetic loads, during the most critical phases of the extreme plasma scenarios, has been performed in the real 3-D geometry and including all the surrounding passive structures. Some iterations between the divertor design and the stress analysis has been necessary in order to bring down the all the stresses below the material main features. Eventually a complete magneto and thermal analysis is in progress to do the final check and to deeply study the compatibility of the chosen solution with all the Remote Handling constrains.

This work, Objective B.3.2.D.1 of the PAR 2012, has been carried out by CREATE and L.T. Calcoli (subcontractor of CREATE for the design, the EM analyses and the structural assessment) with the collaboration and coordination of ENEA. The deliverables expected for the results in this Objective were grouped in this single document, to ease the comprehension of the whole study integrating technology and physics perspectives.

1 Introduction

The conceptual development and design of FAST, a new machine for magnetic fusion experiments proposed as European satellite, is part of the international activities included in the Framework Program accompanying the ITER agreement, besides JT60SA activities. The final objective of this effort is the construction of FAST, a tokamak for fusion experiments with performance intermediate between those of JET (the European tokamak in Culham, England, in operation since 1983) and ITER (the tokamak to be built in Cadarache, France, resulting from an international agreement among the European Union, China, Japan, Russia, India, South Korea and USA). FAST could be operational from the last few years of the construction of ITER, with the aim of preparing the ITER plasma scenarios by simulating the effect of alpha particles by accelerated ions with auxiliary heating systems. This will make it possible to study a burning plasma without the use of tritium. The use of innovative technology for high heat flux components, developed by ENEA, and the capability of running long-lasting plasma pulses will allow the testing of crucial machine components in conditions relevant for the operation of ITER and DEMO (the future demonstration plant for the production of electricity from nuclear fusion). The FAST experiment was designed to be integrated to the JT60SA operations with complementary targets. Consequently, the integration of the experiments on these two machines can ensure an inclusive study of the physics issues still open on the way for DEMO. Moreover, FAST, as a compact and high-performance machine, can provide significant information regarding the possible development of nuclear fusion-fission hybrid reactors able to burn nuclear waste.

The FAST project envisages the construction, possibly in a ENEA site, of a tokamak machine with the related plants for power supply, cooling by cryogenic helium (30 K) and water, plasma heating by mean of radiofrequency (40 MW) and neutral beam injection. It is also included the construction of the diagnostics to measure plasma features, the development of the control system and the construction of proper technologic buildings. FAST was designed to study the plasma under conditions that simulate those of nuclear burning in a reactor, using an innovative and integrated approach to the variation of the parameters characterizing these regimes. FAST can therefore allow significant progress towards the full understanding of the behavior of the plasma and contribute to a more successful exploitation of ITER. These extreme plasma conditions can also provide a proper test bed to validate the advanced technologies for very high heat flux disposal, which will be crucial in the future fusion reactor. ENEA with the Italian industry are currently in the foreground of the development of new technologies able to dispose of the power coming out of the plasma, including solid tungsten mono-blocks and liquid metals (lithium) solutions, actively cooled and able to support high continuous heat loads (up to ~ 20 MW/m^2).

The current FAST design consists in a high magnetic field, high plasma current, compact size (major radius about 1.8 m) tokamak. The machine load assembly comprise 18 coils for the toroidal magnetic field, 6 inner coils for the transformer, 6 outer coils for the poloidal magnetic field, a supporting structure and a toroidal vacuum chamber which includes plasma facing components, among which the divertor. These components must be remotely replaceable due to the nuclear activation of the materials subsequent to the operation of the machine. The coils are made of copper and cooled with gaseous helium at a temperature of 30 K, in order to reduce the electrical resistivity. The coils supporting structure is composed by 18 C-shaped elements, connected between adjacent elements by toroidal structures giving the mechanical coupling. The upper and lower ends of the inner legs of the toroidal field coils are held together by pre-compression rings. The whole load assembly is enclosed in a metallic high-vacuum cryostat to ensure the thermal insulation of the machine. FAST was designed to operate over a wide range of plasma configurations, from those with a high magnetic field and plasma current (toroidal field up to 8.5 T, plasma current up to 10 MA, pulse duration of about 8 s) to those with long lasting plasma (reduced toroidal field up to 3 T, reduced plasma current up to 2 MA, increased pulse duration up to 170 s). The reference configuration provides for a 7.5 T toroidal magnetic field, a 6.5 MA plasma current and a 20 s pulse duration. This large range of operating parameters involves the need to adopt engineering solutions apt to satisfy different needs in different configurations and in different times of the operation scenario.

In the frame of the Annual Plan of Implementation ("Piano Annuale di Realizzazione") for the year 2012 of the Programme Agreement between the Ministry of Economic Development and ENEA, the activities relating to the Objective D (FAST, the new European satellite experiment) of the Project B.3.2 (Activities of fusion physics complementary to ITER) were focused on the development of new plasma configurations with reduced thermal loads on the plasma-exposed elements and on the design of a new concept divertor suitable for these new configurations in FAST.

This deliverable cover the activities accomplished on the sub-objective D.1 (Activities on the new concept divertor suitable for both standard Single Null and new Snow Flake magnetic topologies), addressed to the design and the relevant structural assessment of an innovative concept of divertor suitable to be used simultaneously with both a standard "X point" Single Null (SN) and an innovative "Snow Flake" (SF) magnetic configuration. The studies on the SF configuration were carefully analyzed to evaluate its potential in solving the power exhaust issues in a fusion reactor. This new concept divertor could therefore allow an experimental validation of the SF configuration properties through a direct assessment on the same machine and under the same experimental conditions.

The activities carried out by CREATE, L.T.Calcoli (subcontractor of CREATE for d.1.1 and d.1.3) and ENEA on this objective with the results achieved are grouped together (to integrate technology and physics perspectives) and reported in the chapters of the next Section 2 as follows:

- d.1.1 New concept divertor development and design, including also the revision of the machine load assembly to fit it and the evaluation of the remote handling constraints (Chapter 2.1);
- d.1.2 New concept divertor power exhaust and plasma bulk interaction studies, including also the analysis of the distribution of the thermal power load coming out the plasma and the evaluation of the neutral particles accumulation (Chapter 2.2);
- d.1.3 New concept divertor structural analyses with thermal and EM loads, for the worst expected plasma termination events (Chapter 2.3).

2 New concept divertor suitable for both standard Single Null and new Snow Flake magnetic topologies

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, it is one of the most critical parts of the design, to be considered as an essential part of the experiment itself with regard to the development of the materials and the design of different geometric and magnetic configurations, able to support as reliably as possible the huge thermal loads envisaged in a future reactor. The divertor shall be then changeable, accordingly to new experimental needs, during the lifecycle of the machine. Therefore, significant divertor study and design activities have been devoted to the mechanical supports, which should allow a relatively fast and easy replacement of the divertor modules with remotely controlled handling systems. It was also essential a 3D CAD validation of the real capability of removing the divertor from the machine without interfering with other in-vessel components.

The works carried out for the objective D1, described together in the next three chapters to ease the comprehension integrating technology and physics perspectives, allowed the completion of the planning, design and structural analysis for the new concept divertor suitable for both standard Single Null and Snow Flake plasma configurations. The structural analysis was performed evaluating the EM and thermal structural loads resulting from the most demanding conditions, namely a sudden disruption following a large vertical displacement of the plasma column. This analysis allowed to carry out the optimization of the divertor load-bearing structure and the dimensioning of the supports suitable for the remote handling. It was also performed the study of the interaction between the edge and bulk of plasma and the evaluation of the achievable reduction of the specific power load on the divertor surface exposed to the plasma.

This work, Objective B.3.2.D.1 of the PAR 2012, has been carried out by CREATE and L.T. Calcoli (subcontractor of CREATE for the design, the EM analyses and the structural assessment) with the collaboration and coordination of ENEA.

2.1 New concept divertor development and design (deliverable D1.1)

In order to comply both with a Singl-Null (SN) and a Snow-Flake (SF) configuration, and to allow remote handling operations, a new concept of divertor and of relative locking system were conceived and designed. In particular, the Divertor geometry was studied to move from the standard SN configuration to the SF configuration avoiding the replacement of the same Divertor.
Relevant upgrades in the design of the Vacuum Vessel (VV) and of the First Wall (FW) were also necessary and have been realized.
The upgrade for the VV, consisted on a new shape designed to improve the assembly: the lower area was modified to reduce the gap between the FW and the VV and to insert active reduction coils (ARC), between VV and the toroidal field (TF) coils (to keep toroidal field magnet ripple lower than 0.3%); the lower port was modified to improve the Remote Handling for FW and the Divertor (figure 1).

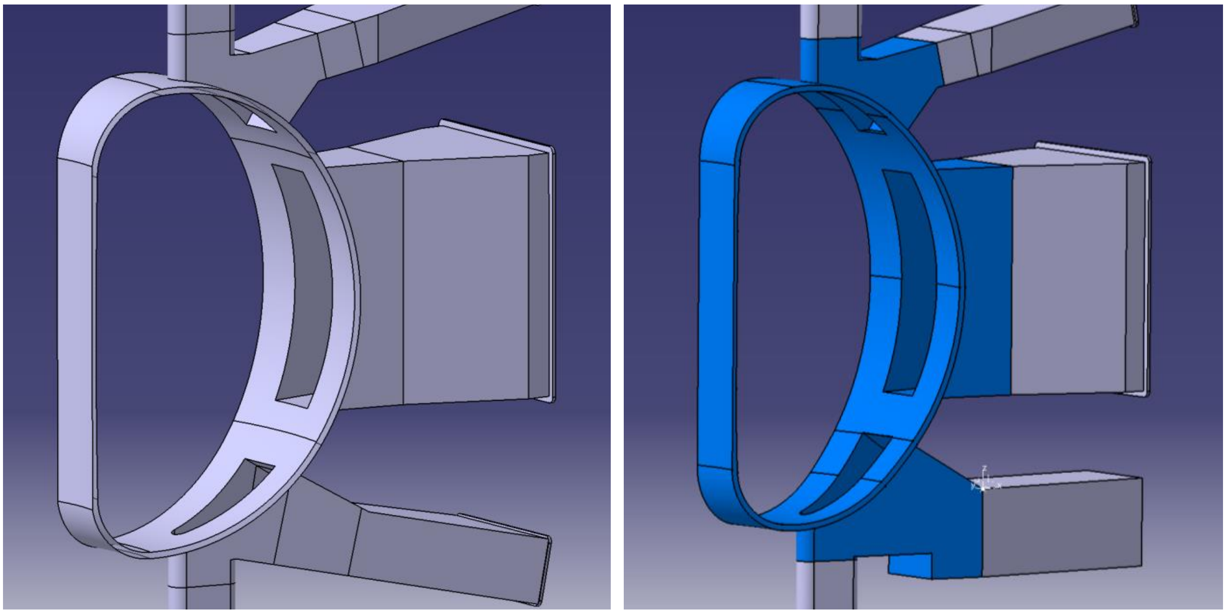


Figure 1. VV: older version (left); new version (right).

Concerning the divertor, each 5◦toroidal Divertor unit consists of Plasma Facing Units (PFUs) and a Cassette Body. The manufacturing concept for the PFUs provides Tungsten (W) mono-blocks, which were brazed on the CuCrZr tube of 12 mm diameter (1.5 mm thickness) by means of a 'soft' Cu Oxygen-free high thermal conductivity (Cu-OFHC) inter-layer 1 mm thick. The Cassette Body is made of AISI 316L and has the function to support the PFUs and to route the coolant (see Fig. 2).

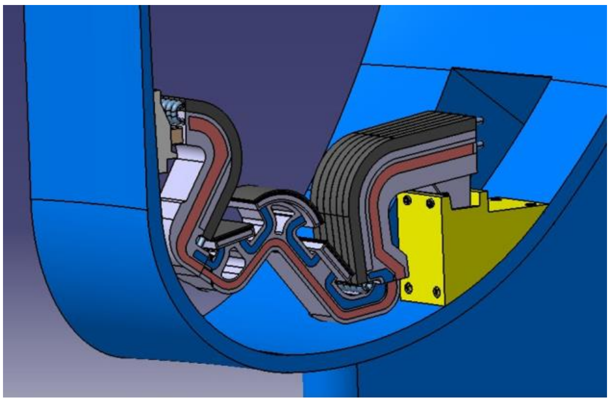


Figure 2. Divertor assembly (red and blue areas indicate the coolant path inside the Cassette).

Neglecting the power losses in the Scrape Off Layer (SOL), for the SN magnetic topology, the total power impinging on the Divertor in the standard H-mode scenario is 20 MW. The power on the Divertor is split between Outer Vertical Targets (OVT) (65%) and Inner Vertical Targets (IVT) (35%) as usually found in the experiments showed in [1] where 13 MW of the whole power goes to the OVT. Considering the radiation losses, the power is around 7.1 MW [2]).The heat flux on the OVT Plasma Facing surface was computed assuming exponential decrease in the SOL. In the standard H-mode scenario the energy decay length is 5 mm at the outer midplane and its magnetic flux expansion factor (F) to the strike point is equal to 5 [2]. The maximum heat flux at the strike point was 18.14 MW/m2.The Divertor will be actively cooled by pressurized water(4 MPa) flowing in the PFUS pipe at 20 m/s with an inlet temperature of 140◦C; the swirl tape in the straight part of the PFUs where the heat load is higher was inserted to increase the heat transfer coefficient (HTC).
The PFUs (see Fig. 3) were designed with W mono-blocks of 4 mm thickness along the coolant flow direction. The 4 mm thick-ness was introduced to mitigate the stresses arising at the interface due to the different thermal expansion coefficients (TEC) between the W and Copper [3]. Furthermore four mono-blocks 12 mm thick with T profile were used to have a quite robust fixing to the Cassette Body.

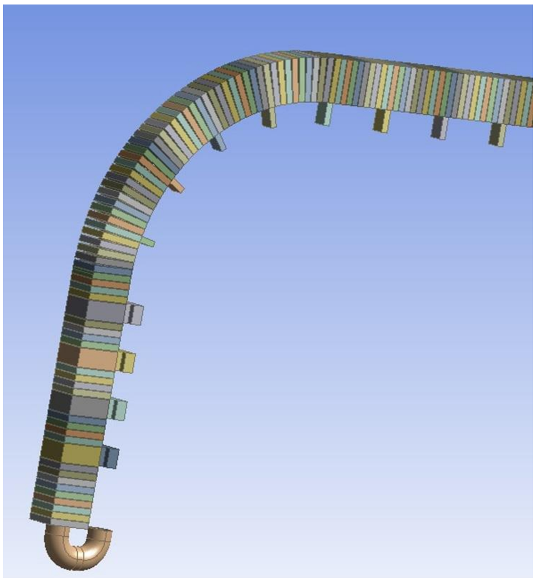


Figure 3. Plasma Facing Unit of the OVT geometry.

A finite element analysis (FEA) was made to reproduce the fluid dynamic behavior and the thermal stresses of the PFU for the OVT, which receive the highest power flux. The ANSYS code provides an integrated environment so that the mechanical behavior can be calculated using the results of the thermal simulation. The Temperature distribution, was calculated using ANSYS CFX. The shear stress transport turbulence model was used and the sub-boiling regime was not considered because the max temperature of the cooling water does not exceed 180◦C at the reference pressure. The maximum W temperature was 1641◦C on the W (see Fig. 4).

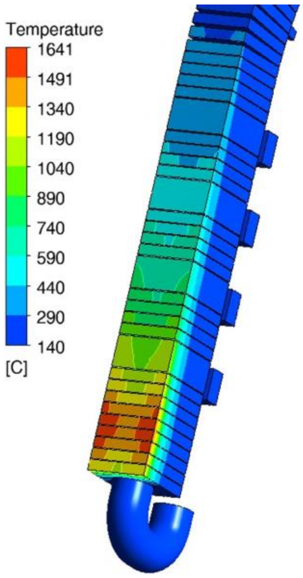


Figure 4. Temperature (◦C) distribution on the OVT for the SN configuration.

The mechanical analysis was carried out using the thermal fields calculated by CFX as loads. The design evaluation of the Divertor was made using the ultimate tensile strength for W [4] and the low cycle fatigue curves (LCFC) for CuCrZr and Cu-OFHC [4]. The difference between the TEC of Copper and Tungsten, generated a tensile stress in the W mono-blocks (considered as elastic material) and the maximum circumferential stress is 740 MPa (see Fig. 5). This stress generated the crack opening in the mono-block parallel to the pipe axis, as it is usually showed by many experimental results [5].

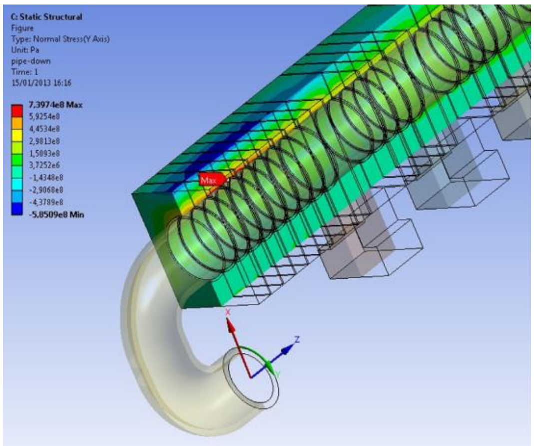


Figure 5. Circumferential stress (Pa) on the monoblock W.

In the Table 1 there is the comparison between the maximum circumferential stress and the ultimate tensile strength (Rm) at the corresponding temperature in the Tungsten mono-block. It was assumed that if the circumferential stress is higher than Rm, there is a probability of crack generation. The total strains of pure Copper and CuCrZr (considered as elasto-plastic materials) were calculated to estimate the fatigue life. The Cu-OFHC interlayer was used to soften the stresses at the joint surface caused by the difference of the TEC without compromising the heat flow. Due to its softening behavior and as evidenced from experimental results usually cracks could start from this zone.

Max Temp (◦C)	σ_{yy} max (MPa)	T at σ_{yy} max (◦C)	Rm (MPa)
1641	740	406 ◦C	~1052

Table 1. Tungsten rupture estimation.

Max Temp (°C)	Total strain (ε_t) %	Fatigue number of cycles
428	1.7	~500

Table 2. Pure Copper Fatigue Life Estimation.

Max Temp (°C)	Total strain (ε_t) %	Fatigue number of cycles
395	0.7	~5000

Table 3. CuCrZr Fatigue Life Estimation.

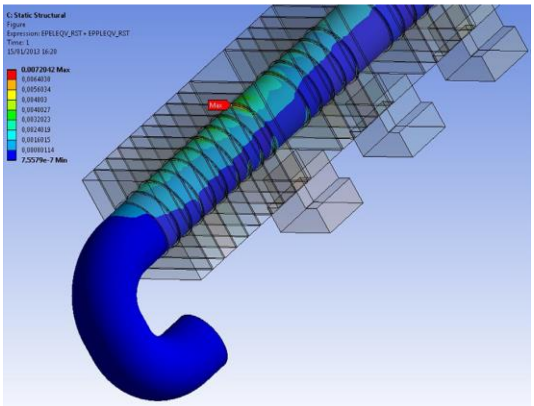


Figure 6. Total strain (%) on the CuCrZr.

The maximum total strain computed at the interlayer was 1.7%. Using the extrapolated LCFC [4] the estimated fatigue life was about 500 cycles (see Table 2). The low value found for the fatigue life did not contradict the experimental results because this interlayer did not have a structural function, so defects at Cu-OFHC do not prejudice the component life. The maximum total strain on the CuCrZr pipe was 0.7% and using the best fitting LCFC [4] we had an estimated fatigue life of around 6000 cycles (see Table 3; Fig. 6).
Finally the pressure drop of 2.8 MPa was calculated, using ANSYSCFX, along the whole cooling circuit (see Fig. 7).

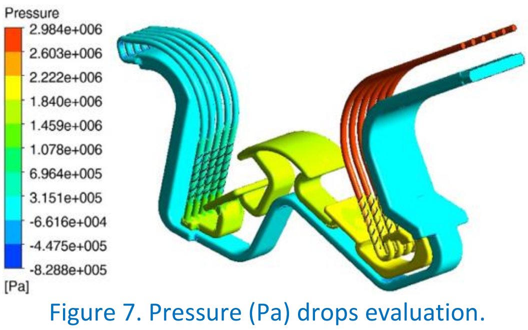


Figure 7. Pressure (Pa) drops evaluation.

Additionally a preliminary 3D thermo-hydraulic analysis was made to evaluate the possibility to operate with the SF configuration without replacing the Divertor. The thermal load along the target surface was estimated at the extreme case (advanced scenario [6]): 30 MW of power in the SOL. As for the SN analysis, the SOL losses were neglected while the power asymmetry of the Divertor legs was considered and the power was split between inner and outer vertical target in ratio of 1:2. Moreover the possibility to move vertically the X-point inside a range of ±40 mm was considered and the analysis was made at the most critical condition of 40 mm upward. In the SF configuration the larger expansion factor (F) results in a loaded area of the Divertor wider than in the SN configuration. To estimate the incident heat flux, the expansion coefficient, F, and the incident angle for the field lines, β, were evaluated as a function of the abscissa along the pipe axis. Applying the following law, $q(s) = q_0^{e-(s \sin \beta(s)/\lambda F(s))}$ where F(s) and β(s) were 5th order appropriate polynomials, q_0= 14 MW/m2 was found.

The temperature distribution, applying the same hydraulic parameters (140 C◦, 4 MPa e 2.1 kg/s), was reported in Fig. 8 with a maximum value of 1126◦C on the W.

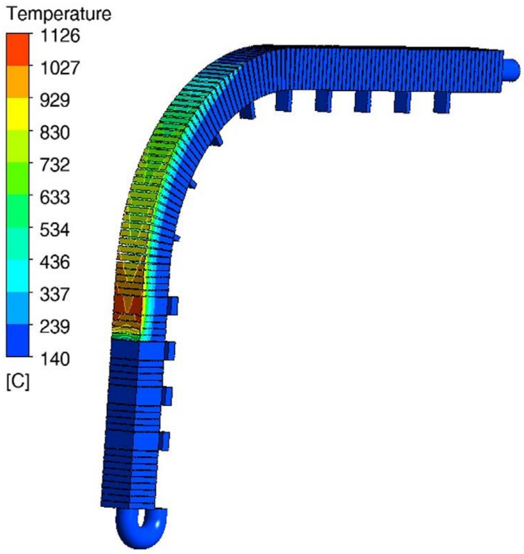


Figure 8. Temperature (◦C) distribution on the PFU for the SF configuration.

In order to fulfill divertor Remote Handling (RH) issues and to overcome design and technical weak points in the current maintenance procedure, we proposed the application of the Theory of Inventive Problem Solving (TRIZ) and we conceived and designed two different concepts with the help of a parametric CAD software, CATIA V5, using a top-down modeling approach.

FAST RH system, illustrated in Fig. 9, is mainly composed of two subassemblies, the Cassette Multifunctional-Mover (CMM) and the Second Cassette End-Effector (SCEE), the latter equipped with a further arm whose function consists in performing the critical operations of locking and unlocking the Cassette in its relative support system.

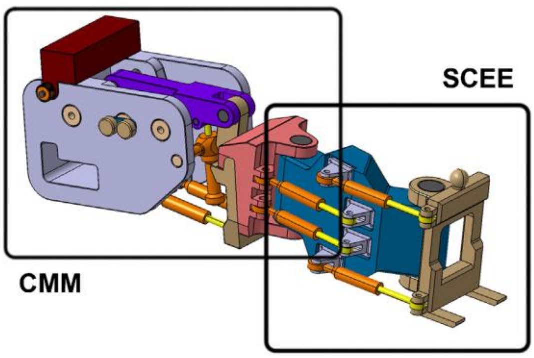


Figure 9. RH system for FAST tokamak.

Analysing the ITER-like solution, critical aspects were observed and put under discussion, concerning the use of the system known as “knuckle”. This system is a mechanism that locks and unlocks the divertor in the outer side of the tokamak, and thus requires very accurate geometrical and dimensional tolerances. Moreover, it was observed [7] that the knuckle might cause unwanted vibrations during the working period of the tokamak and that its maintenance might be difficult. In order to avoid these drawbacks a new solution was proposed in a previous study, aimed to propose a first concept design of the RH system, and a compatible divertor support system of FAST [7]. Nevertheless, the analysis of an alternative solution introduced new conflicts with the remote handling system. In particular, the cantilever arm of the 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. In Fig. 10 the original design of the outer hook is showed together with the RH system [7].

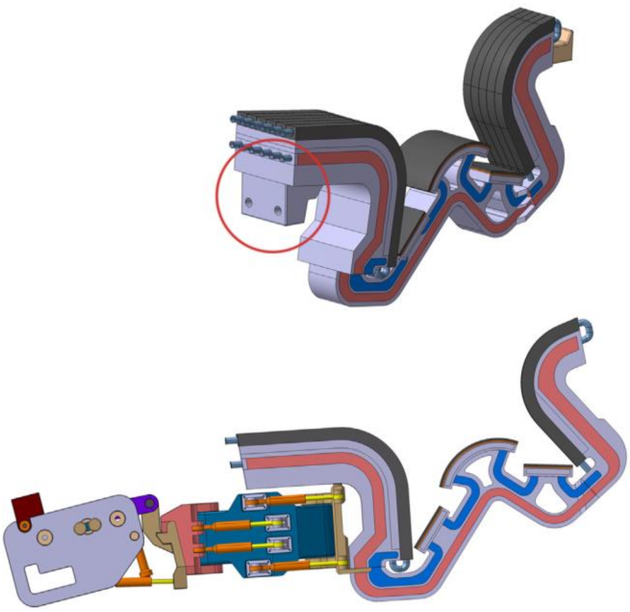


Figure 10. The conflict between the RH system and the outer hook.

In this study the components were re-designed in a smart way, solving technical conflicts observed during the simulation phases using the Theory of Inventive Problem Solving (TRIZ). 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). The comparison was based on the opinion of a panel of experts of the IDEAinVR Lab [8] and of the Divertor Test Platform 2 (DTP2) team [9], which finally selected the “best” concept.
The methodology adopted is illustrated in Fig. 11. The whole process starts with the identification of several design issues. Technical conflicts present in the considered system are translated in TRIZ language following the “contradiction matrix” approach, generating different concepts from specific solutions derived from TRIZ principles. The concepts are then designed in CAD software, performing kinematic simulations and analyses, where these can help comparing the alternatives. A set of criteria is thus selected, on which the comparison of concepts will be performed, following the AHP methodology. The final evaluation session is carried out in virtual environment, involving several experts in the judgment.

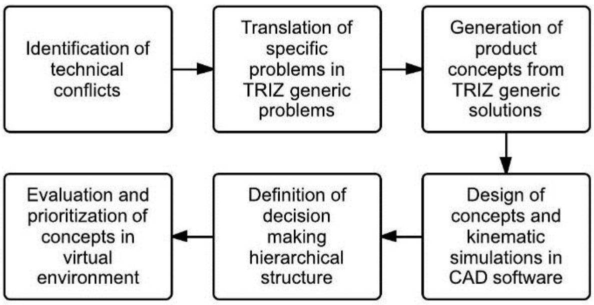


Figure 11. Flowchart of the methodology adopted.

TRIZ is the abbreviation of “Theory of Inventive Problem Solving”, in Russian “Teoriya Resheniya Izobretatelskikh Zadatch”. TRIZ is an engineering problem solving toolkit which provides a methodology useful to systematically solve problems, in which the principles of good inventive practice are encapsulated in a general problem solving structure [10]. TRIZ focuses problem understanding to the particular, relevant problem model and then offers conceptual solutions to that model. With TRIZ it is possible to save time, as the instrument lets the engineer focus on valid solutions to the problem and then develop those solutions [11]. The purpose of TRIZ is to overcome the psychological barrier in problem solving through the generalization of the specific problem to an analogous generic problem, for which a generic solution can be found. At this point, a specific solution can be identified, usually with the help of brain-storming sessions and experience. The use of brainstorming and technical knowledge is very useful because TRIZ works in a high level of abstraction [12]. TRIZ is a toolkit in which each tool covers an aspect of problem understanding and solving. TRIZ theory provides several techniques and methods, one of the most important being the contradiction matrix. The strength of this tool is to remove contradictions rather than finding compromises or trade-offs. During the problem solving activity, instead of a simple brainstorming activity, TRIZ theory brings 40 principles, widely available in literature, that suggest a direction for the innovation [11]. The steps to the solution are well summarized in [13, 14]:

1. define the problem and the elements that need to be improved;
2. in the contradiction matrix, map the elements of design in terms of the 39 parameters;
3. identify the solution direction to solve the problem and the elements that are in contradiction with them;
4. find inventive principles joining two characteristics in the contradiction matrix;
5. develop special solutions based on the suggestions of the inventive principles.

In order to generate and evaluate product concepts, parametric CAD software, CATIA V5 from Dassault Systèmes, was used. Inventive solutions provided by TRIZ were designed directly into the Assembly Design workbench of the software, adopting a top-down technique. The top-down logic is a typical approach to design complex products, due to the advantage of modeling parts automatically assembled in the right position without further operations [15–17]. In the Assembly Design workbench of CATIA, DigitalMock-Up (DMU) inspection capabilities were also used to review and check assemblies. Starting from a set of geometrical references of the product, several components were designed with respect of the whole assembly, with particular attention to the relation-ship between the parts, in order to achieve the maximum degree of freedom making changes in further steps of the designing process. All the changes applied to the reference geometry produce an automatic change in the assembly geometry; therefore, after the extensive work necessary to complete the CAD modeling, using the top-down approach was possible to change in any time product dimensions without any manual adjustment on the geometry, thus saving time [18]. The adoption of a top-down approach, allowed the designer having a complete view of the whole assembly, and making adjustments of the entire assembly in real time [19]. Kinematic mechanisms were created in CATIA V5's DMU Kinematics Simulator environment, an independent workbench dedicated to simulating assembly motions.

The comparison of concepts, their evaluation and eventually the choice of the best solution, were performed using the Analytic Hierarchy Process (AHP). The Analytic Hierarchy Process (AHP) is a technique developed by Thomas L. Saaty in the 1970s [20]. The technique is a multi-criteria decision making approach in which the factors that are important in making a decision are arranged in a hierarchic structure. Arranging goals, criteria and alternatives in a hierarchic structure is important to provide an overall view of the relationship between elements related to a decision process, and to help decision makers understand whether the elements in each level are of the same order of magnitude, so that they can be compared homogeneously. The main advantage of using AHP lies in the analytical nature of the methodology [21]. After the main goal of the process is defined, the entire decision hierarchy should be designed. The main goal is connected to a set of criteria, which can be also subdivided in several sub-criteria. The alternatives to be evaluated are in the lowest level. Once the hierarchical decomposition of the problem is completed, the elements for each level of the hierarchy are compared in pairs, defining a matrix of weights [21]. The comparison between elements is made using a scale of numbers that indicates how many times more important (or dominant) one element is over another with respect to the criterion to which they are compared [22]. All the n elements involved in the comparison are placed on the rows and columns of the matrix, obtaining a square matrix. The generic element of the matrix of weights is the result of the pairwise comparison between two attributes using the scale reported in Table 4, and hence it's equal to the ratio of the weights of the corresponding elements [20, 21].

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

Table 4. The scale used to make comparisons with AHP.

When judgments come from a group, to aggregate individual judgments into a single judgment, it was proved that the geometric mean, and not the arithmetic mean, should be used [22]. The generic element of the matrix of weights is hence obtained as the n^{th} root of the product of the several judgments is taken. When alternatives are measured on an objective scale, like meters or kilo-grams, a priority comparison on all the data available, without ascribing linearity to them, has to be made. The numbers should be interpreted using judgment and not mechanically; the judgment approach is the more effective procedure using AHP because the theory is descriptive, and needs interpretation [20,23]. In a general decision making process, it is not possible to evaluate the precise values of the elements, but only estimate them, considering estimates of these values given by experts who make small errors in judgment. The matrix of weights obtained is then an approximation of the real one [20]. Inconsistency of the matrix can be evaluated with a consistency ratio test (CR): CR = CI/RI.
The consistency index (CI) can be obtained from the following eq., where λmax is the principal eigenvalue of the matrix of weights and n its dimension.
$CI = (\lambda max - n)/(n-1)$
RI is a random index, and its values can be estimated from matrices with random entries. The estimate of the weights is accepted if CR does not exceed 0.10 [20,24]. The optimal concept can be selected basing on the answers given by experts users involved and interviewed in the evaluation session after a global score for each concept is calculated. The identification of the optimal concept ends the design process; however, the procedure can be iterated if the solution does not satisfy the designers: the proposed strategy can be applied again, looking for new design solutions [25].

The methodological approach of the TRIZ contradiction matrix was used in order to provide new and enhanced solutions. New innovative solutions that can overcome the existing difficulties were generated and innovative ideas were introduced, which can be effectively exploited on the final tokamak design. The use of TRIZ theory to solve the contradictions among quality elements passed though the detection of the relative improving/worsening TRIZ parameters based on the engineering characteristics of the product in conflict. The intersection between improving and worsening parameters in the contradiction matrix gave the TRIZ inventive principles to follow in order to find new possible engineering solutions. The main conflict arises from the presence of the outer hook, which prevents the correct positioning of the SCEE for RH operations. TRIZ analysis was performed in order to smartly make room for the hook plate and the cantilever arm of the SCEE while the RH system grapples the divertor. The elements in the contradiction matrix were chosen considering the functions in conflict in the system. The selection of the improving TRIZ parameter, "ease of operation" moved from the necessity to perform RH tasks minimizing the number of movements assigned to the whole system. At the same time, it was required that adjustments operated to the system in order to solve the conflict did not involve a significant change in the weight of the elements affected by the modifications. Thus, the worsen TRIZ parameter selected was "weight of moving object". Table 5 shows the result of the first TRIZ-related step, with the couple of TRIZ improving/worsening parameters for each conflict, and the inventive principles suggested finding special solutions.

TRIZ performance improved	TRIZ performance worsen	Inventive principles suggested
33. Ease of operation	1. Weight of moving object	3. Local quality 8. Anti-weight 10. Preliminary action 13. The other way around

Table 5. Conflicts translated into TRIZ.

All the principles found in the matrix of contradictions were taken into account in the brainstorming analysis, but not all of them were used to find new engineering solutions [11]. Special solutions for the real system were generated via the principle "The Other Way Around", composed of three steps:
I. Invert the action(s) used to solve the problem;
II. Make movable parts (or the external environment) fixed, andfixed parts movable;
III. Turn the object (or process) "upside down".
The first solution resulted from the third suggestion of turning the object "upside down". The idea was to assign the role of "hook" to the outer support on the vessel. The idea underneath the second concept coming from the first suggestion of inverting the action used to solve the problem consisted in using, for the outer support, the same principle on which the inner support is based: contact between spherical surfaces. The first position of the RH arm is lowered of a certain angle, and the rotation of the CMM's lift arm is adjusted. This solution allowed the divertor keeping the outer hook idea, creating space between the cantilever and the divertor.

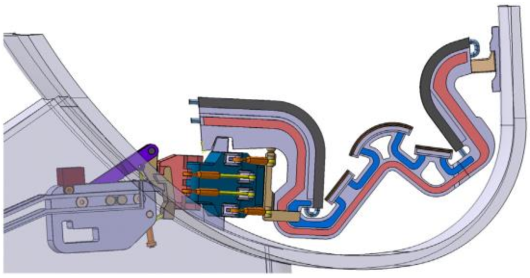


Figure 12. Concept I.

The concepts were modeled into the Assembly Design work-bench of CATIA. Following a top-down approach, a main references system was created to specify all the datum elements necessary to model the assembly. More in detail, a series of planes were created to characterize the overall dimensions of the product.
About the first concept (Fig. 12), the outer support was completely re-designed for its new scope. At the same time, the divertor was modified with material addiction, and excavated to create the groove that hosts the support. The locking system of the divertor is composed by two cap screws (18 mm diameter), which keep the divertor in 8 mm compression in its position, pushing it on the inner part of the vessel, where the inner support is present. Thanks to the spherical cap of the inner hook, the entire structure is kept in position during the working phase of the tokamak. A suitable adaptation of the RH system to this new solution was necessary. The cantilever, compared to the original design (Fig. 13), was shaped and carved according to the new support and the two lower ends of the hook plate were modified to hook the divertor in the lower part properly. The sphere on the higher part of the hook plate was kept unchanged.
To design the second concept (Fig. 14), starting from the divertor, material was added in two areas, in order to hook the divertor in the new position of the RH system. In order to avoid an excessive increase of weight of the divertor, the addiction of material was compensated on the two lower endings of the hook plate.

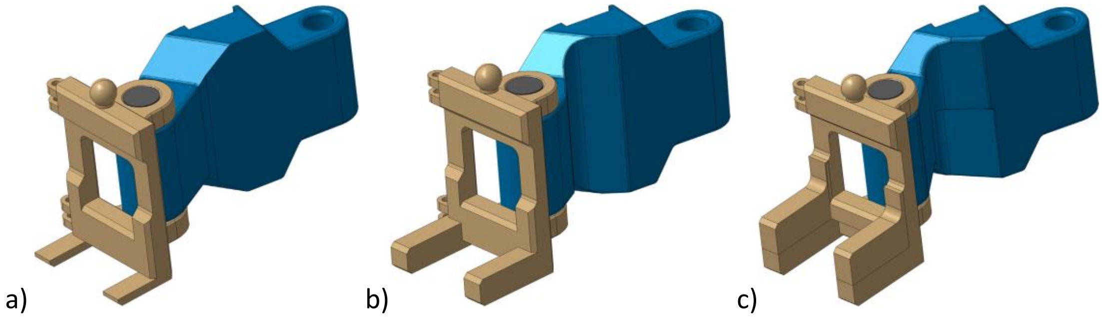


Figure 13. SCEE: a) original design; b) re-design for the concept I; c) re-design for the concept II.

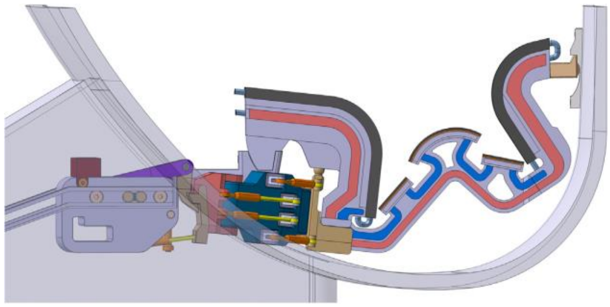


Figure 14. Concept II.

As for the first solution, the cantilever was shaped, and it was necessary to cave it also in the lower side, avoiding the interference with the vessel, caused by the lower position of the entire RH system in the new configuration (Fig. 13). With respect to the locking system of the divertor in this second concept, two pins (18 mm diameter) accomplish the function, together with extreme positioning precision of the components. This, indeed, would require an extreme grade of precision in terms of tolerances. In both the concepts, the inner hook and the inner support were not subjected of any re-design. After the design phase of parts, kinematic mechanisms were created to simulate the movement of the assemblies in order to evaluate the operation of the RH system.

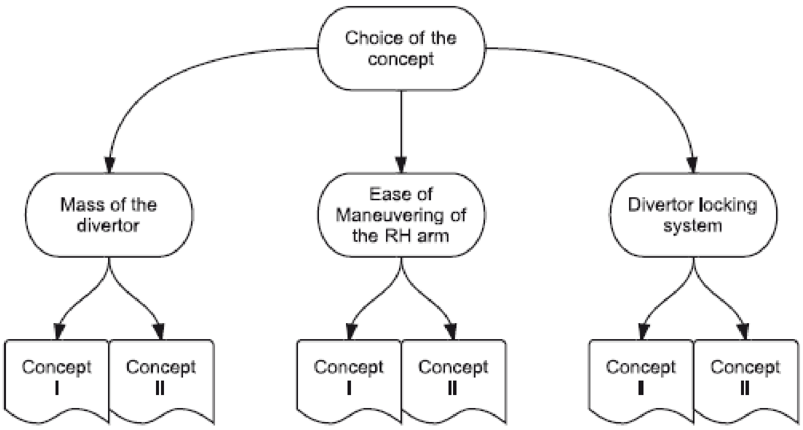


Figure 15. Hierarchical structure used for the comparison of concepts.

In order to compare product concepts, a qualitative evaluation was performed by a group of experts to collect their opinion about the importance of several aspects of the concepts evaluated, to achieve a quality classification for the product variants. The problem of the choice between the two concepts designed was decomposed into several levels, identifying a set of criteria and sub-criteria in order to classify the alternatives. The top level identifies the overall goal: the concept's choice. In the second level, three criteria, which contribute to the goal, were determined: mass of the divertor, ease of maneuvering of

the arm and divertor locking system. The last level is composed by the two concepts (Fig. 15). The first criterion, mass of the divertor, was selected because, considering an estimated weight of the entire divertor of about 400 kg, adding material to the part might influence the design and sizing of other components like the supports of the divertor and the RH arm. Moreover, this parameter was considered valid for a comparison because during the operation phase of the device, the mass of the divertor might be directly related to unwanted vibrations of the whole system. To estimate the mass added to the concepts, the software CATIA was used, assigning the same material (steel) to the modified body of both new divertors. A mass increment of 43.8 kg and 44.7 kg was evaluated for the first and the second concept respectively. Hence, a difference in terms of mass equal to 3.6 kg between both concepts, was detected, the first being slightly heavier than the second, which corresponds to an increase of about 1% on the total mass of the divertor.
The ease of maneuvering of the arm criterion was selected because the two concepts are the result of two different ways to conceive the operations of RH. In the concept I, once the arm has hooked the component, the extraction of the divertor is performed moving back the entire system in the first step. This is possible due to existing clearances between the divertor and the outer and inner supports. After the first translation, the RH arm is able to take out the divertor from the tokamak thanks to the rotations of the CMM and of the SCEE. On the other hand, in the concept II, there are no clearances between the divertor and the supports and the spherical surfaces are in contact. For this reason, the movements assigned to the RH system are different. In order to remove the cassette, the first steps are the simultaneous rotations of CMM as long as the release of the spherical cap of the inner hook (which is pushed against the inner support) is obtained. This motion is accomplished thanks to the spherical surfaces present in both the hook and supports of the divertor. For both the concepts, when the divertor is aligned with the vessel port, the RH arm scrolls back on the railways to complete the extraction of the cassette. The same movements are assigned for the insertion of the divertor, but in a reversed way.
Two simulations of the divertor extraction were performed using the DMU Kinematics tool with the purpose of a comparison between the concepts. The number of commands needed to perform a complete RH operation was assumed as comparison criterion: 32 movements required by concept I, whereas 42 by concept II.
The last criterion chosen for the comparison of the two concepts was the different divertor locking system. During plasma operations, the divertor is required to be in compression in its position to avoid both unwanted vibrations and the contact with adjacent divertors. In the first concept, the idea consists in using two cap screws keeping the divertor and the inner support linked in compression. Nevertheless, such a system would require a more complex unscrewing procedure. On the other hand, in the concept II, the divertor is kept in a fixed position by means of the contact between both surfaces. This would imply, for both the supports and the divertor hook, a zero-tolerance manufacturing with a very high grade of precision, which consequently increases the manufacturing cost.

Figure 16. Comparison of concepts in the IDEAinVR lab.

In order to proceed with the application of the Saaty methodology, the two different concepts were presented to a group of experts according to a participative design approach. The evaluation phase was carried out in the IDEAinVR lab at the Department of Industrial Engineering of the University of Naples "Federico II", where the two concepts were showed on two different screens together with the two simulations of the RH process (Fig. 15). The purpose of this phase was to collect information via a survey, in which the experts were asked to assign an adherence judgment to different sentences, with respect to the evaluation scale of importance reported in Table 1, performing a pairwise comparison between several criteria and product alternatives. The geometric mean of the scores obtained in the surveys was used to build the 3 × 3 pairwise comparison matrix A reported in in the following equation. This matrix passed the consistency test with a consistency ratio of 0.018, obtained from a CI of 0.006, while RI, for a 3 × 3 matrix, is equal to 0.580.

$$A = \begin{pmatrix} 1.00 & 0.14 & 0.20 \\ 7.30 & 1.00 & 0.77 \\ 5.54 & 1.00 & 1.00 \end{pmatrix}$$

From the comparison matrix, the weights of the criteria were derived. The AHP methodology allows the estimation not only of the criteria weight relative to the single product concepts, but also of their global importance. In particular, the mass of the divertor resulted the less weighted criterion according to the fact that the two concepts differ only by 1% in terms of mass. The knowledge of the weights of the three criteria allowed the evaluation of the final ranking for both the concepts (Table 3).The solution with the highest score was hence found to be the concept I with a weight of 68%. This result is mainly related with the greatest importance, for the concept I, of both the ease of maneuvering and divertor locking system criteria.

Criterion	Global weight	Concept I	Concept II
Mass of the divertor	0.07	0.40	0.60
Ease of maneuvering	0.44	0.79	0.21
Divertor locking system	0.48	0.63	0.37
Total weight	1.00	0.68	0.32

Table 6. Results of the AHP evaluation.

The figure 17 shows the final concept of the divertor and of its relative locking system, chosen for the next steps of the product development.

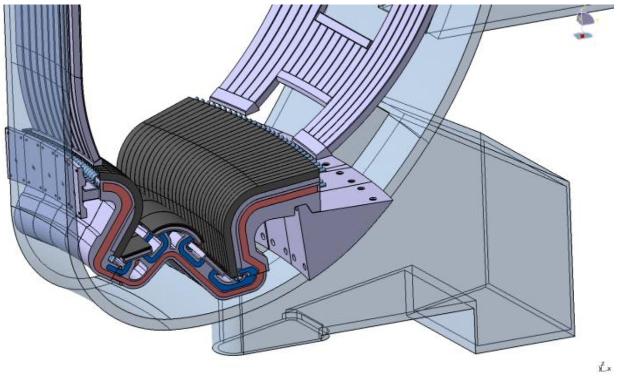


Figure 17. Final concept of divertor.

2.2 New concept divertor power exhaust and plasma bulk interaction studies (deliverable D1.2)

One of the most challenging gaps in view of DEMO is the power exhaust problem [1, 2]. By using the present available knowledge, and assuming a power plant of around 5 GW thermal, a fractional power around 1 GW must be safely exhausted, without affecting the good bulk plasma quality. Even assuming 80% of radiation, it is clearly impossible to guarantee a power flux to the divertor plates within the present technological possibilities (< 20 MWm^{-2}). As it is clear from this short summary, the problem is quite serious, also because what it is actually missing is not only a single aspect, but the full integration of very different physics and technical problems in a robust and reliable plasma scenario. FAST [3], from the very beginning, has been conceived with the main aim to tackle this problem integrating all the plasma wall interaction aspects. The power density stored within the machine (~ 1.5 MWm^{-3}) and the choice of working in a full W environment (First Wall and divertor) makes, clearly and immediately, the complete FAST relevance to the power exhaust problem in DEMO. FAST will have the unique capability of working at always relatively high density ($n_e \geq 10^{20} m^{-3}$), although ranging the extremes of the Greenwald limit. This fact will allow fully exploiting the possibility of varying the radiation fraction (between 30% and 80%, by using some slight impurity seeding) in the different plasma regions (bulk, SOL, divertor) trying, at the same time, to maintain very good plasma properties [4]. However, as just previously mentioned, even these specific capabilities could not be sufficient to limit the power deposited on the divertor plates.
A new divertor magnetic configuration, called snow flake (SF), has been recently suggested to mitigate the power load on the divertor targets of a fusion tokamak device [5]. As compared with the conventional single null (SN), as shown in Fig. 1, a degenerate double pole of the poloidal magnetic field B_{pol} replaces the first order null. B_{pol} then maintains close to 0 over a wider region around this point. The flux surfaces external to separatrix become more distant to each other and the magnetic field lines run more parallel to the toroidal direction. Therefore the larger flux expansion smears the power flux over a wider area and the longer path to be travelled allows particles and energy to diffuse deeper outwards, further spreading the power flow. The slower particle speed, due to the lower temperature usually found close to targets, further enhances this last effect. This longer dwell time in a colder region could also increase the volume power losses by radiation and by collisions with neutrals, if their density is non-negligible there.

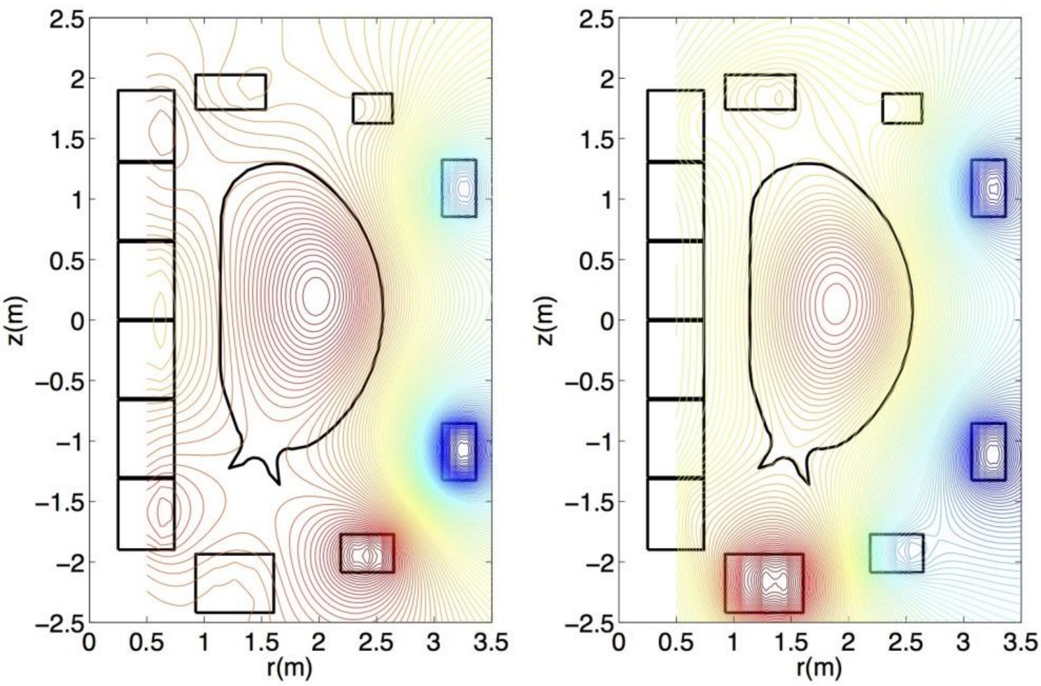


Figure 1. SN and SF comparison

From a mathematical point of view a SF consists in having, on the X point, both the conditions of $B_p = \partial B_p / \partial r = 0$. From a topological point of view this means that, instead of having an X point with 90° intersection of the flux lines, there is a magnetic structure with six lobes with 60° angles; in other words a second X point is made to converge exactly on the main one. Even if topologically very attractive, from the very beginning [6] it was pointed out that this configuration is not at all an optimal one, from the experimental point of view. This because the configuration is magnetically unstable and because to get the exact mathematical solution, it could require a large magnetic multipolar expansion, i.e., very large currents in the poloidal coils system. For this reason, in the same original Ryutov's paper, it was already proposed to study configurations where the two nulls are not exactly superimposed, but are "magnetically close". Of course a definition like this, being not mathematically well defined, could leave large space for a large family of configurations that are somewhat in the middle between an exact SF and an exact SN. What helps, in designing a SF configuration, it is what we really need from the power exhaust reduction point of view: a wide region (from the X point up to the divertor plates) where $B_p \approx 0$. Having in mind that in the proximity of a SF $B_p \sim B_{pe}(r/a)^2$ [7], (where B_{pe} is the poloidal field at the equatorial plane, a is the plasma minor radius and r is the distance from the null), it comes out that the SF flux expansion radius goes like $G_1 a(\lambda_E/a)^{1/3}$ [6], where the proportionality constant G_1 depends from the system geometry [6, 8]. Consequently a reasonable distance between the two single nulls must be, at the maximum, of the order of $G_1 a(\lambda_E/a)^{1/3}$. By doing an "intelligent" use of this relaxed condition, it turns out that a SF-like configuration can easily be produced by a standard tokamak poloidal coil system (remaining within their current density limit), once all the coils (including a segmentation of the central column) are fed separately. In Fig. 1 the equilibrium flux maps for the Reference FAST scenario [3] (I_p=6.5 MA, B_T=7.5 T, β_N=1.3, flat top time τ_D=20 s) are shown for the SN and SF divertor magnetic configurations. As it can be noticed, in the divertor region, the SF-like configuration is far from having the 60° angles typical of an exact SF; however, when comparing the flux expansion on the divertor plates geometry (optimized for the SN [7]) we have an increase by a factor around four.

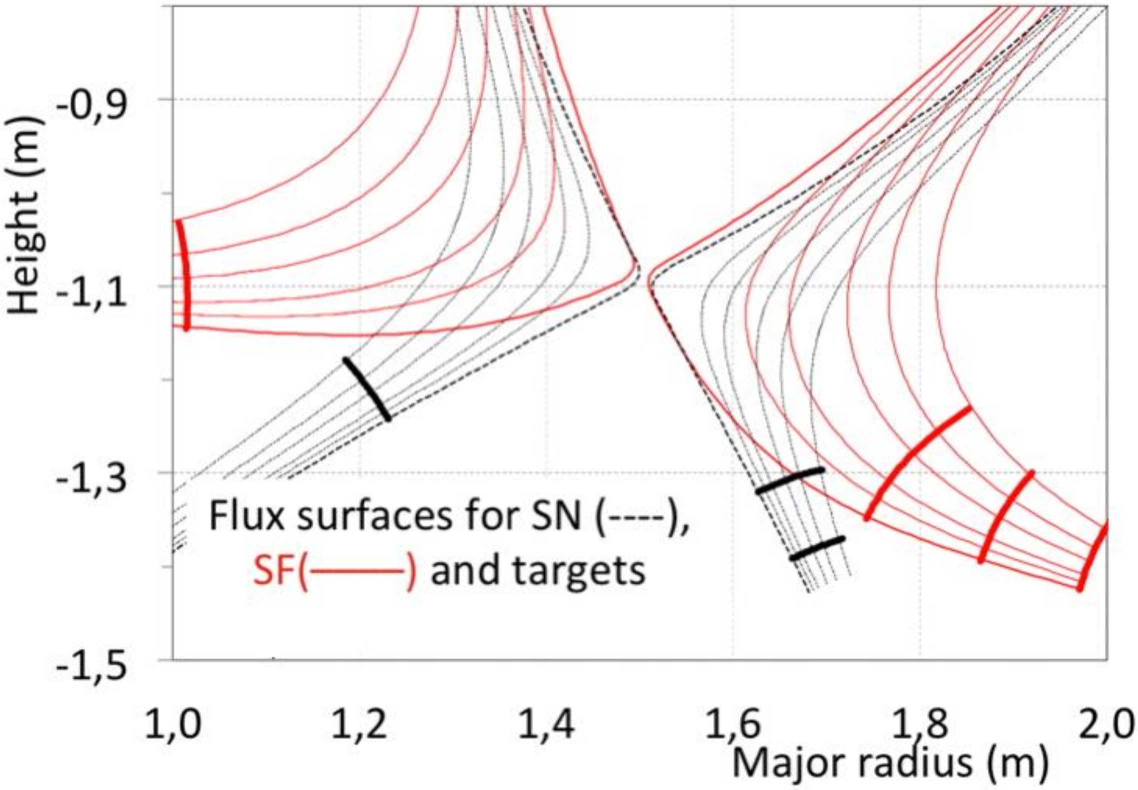


Figure 2. Comparison of the strike points for the SN and the SF configurations

Looking at Fig. 2 it is obvious that 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. It has been suggested [9] that an optimized SF divertor should be completely open and without any internal physical barrier (for instance without the so called dome). A solution like this is quite obvious when thinking that an ideal SF configuration could introduce some further strike points. However, when observing a SF-like configuration (as in FAST) this could not be the ideal solution. Moreover, considering an experimental test machine, we would need to have the possibility to experimentally compare the different topologies; even better if it could be possible to do this test on the same discharge, just modifying the plasma equilibrium. On FAST, in designing a SF compatible divertor, the criterion to have a divertor that, during the same shot, would allow to compare the two different geometries has been used. In Fig. 3 the CAD picture of such a solution is shown, with also indicated the SF flux lines. The lower part of the divertor is pretty similar to a traditional one, and, actually, it traces the original FAST SN divertor design [10]. The upper part and the connection with the FW have 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) has been realized to accomplish this target. Of course, this modification has led to a complete redesign of the bottom part of the vacuum vessel and of the FW, including all the support structures [11]. Although the divertor just discussed will be very flexible, as mentioned, it could not be the optimal choice for a SF divertor; moreover, since the main FAST target is the study of the power exhaust, the divertor choice cannot be limited on a SN and/or a SF, but the machine must have the possibility to test also other possible options, like, for instance, a liquid Li divertor.

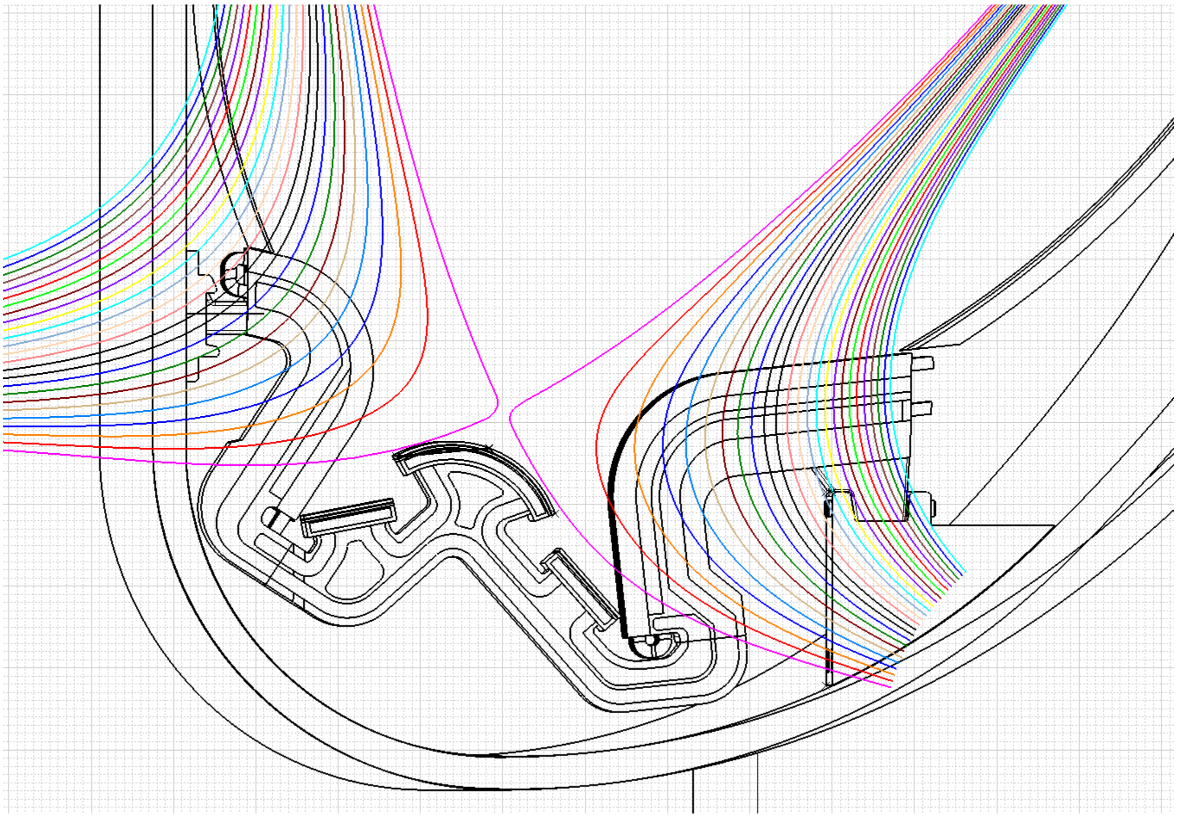


Figure 3. Design of a divertor compatible with the SX and the SF. The SF flux lines are shown

The code TECXY [12] has been used to study the main features of the SF divertor in FAST [13]. This 2D code takes into account all the main edge plasma physics occurring effects. A simple analytical model is used for the neutral dynamics and the divertor target plates are considered perpendicular to the flux lines. It turns out that with the SF the connection length is increased and, at the same time, a dense and cold plasma (with a large fraction of neutrals) is formed in front of the plates. The combination of these two effects strongly increases the radiation and the momentum losses. In Fig. 4 the power load perpendicular to flux surface is shown for a “pessimistic” case of very low edge plasma density ($n_{e\text{-}edge}$=5·$10^{19}$$m^{-3}$). Even in this pessimistic low density case a decrease of around a factor seven is evident in the power flux. At the highest FAST densities ($n_{e\text{-}edge}$=1.8·$10^{20}$$m^{-3}$), up to a factor 50 is found by the TECXY simulations [13], confirming the role played by the high density neutral cloud in front of the divertor plates.

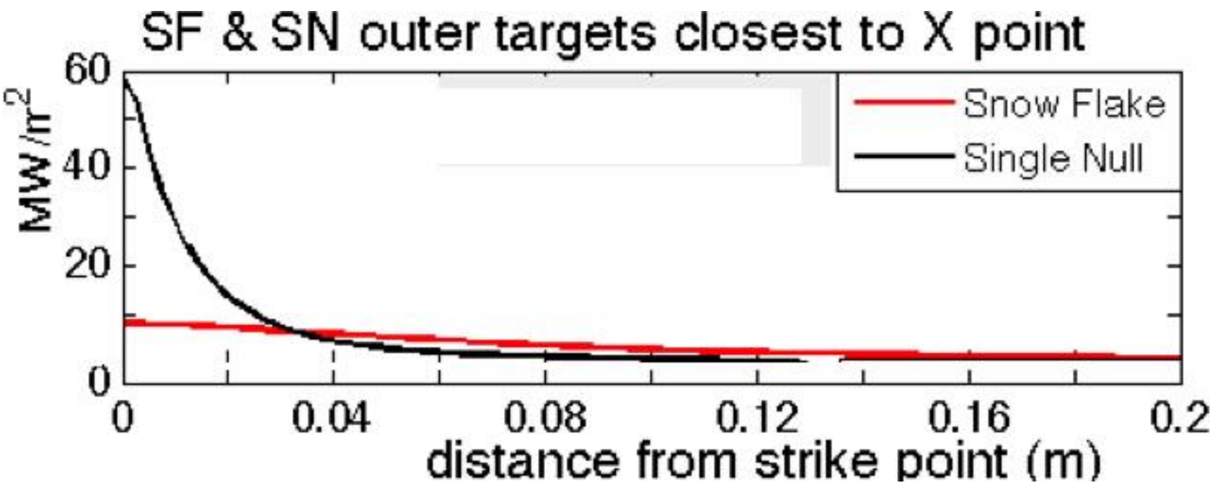


Figure 4. SX and SF Power Flux comparison for a pessimistic FAST low density case

2.3 New concept divertor structural analyses with thermal and EM loads (deliverable D1.3)

The conceptual design obtained for the FAST [1] divertor includes a compact divertor structure without cassette body with the body structure made of an array of tubular structures covered by PFUs (plasma facing units). A EM preliminary analysis of the whole divertor has been performed on the divertor solution conceived in [1]. Future analyses will be performed on the solution shown in chapter 2.1.

Electromagnetic Analysis for Divertor of FAST

The electromagnetic event considered is the 8MA Plasma Fast Down disruption event [2]. The EM loads during plasma disruption are mainly produced by toroidal field variation (TFV) during the thermal quench (TQ) and the current quench (CQ), Halo current (HC) during the CQ and poloidal field variation (PFV) during the TQ and the CQ.

The three EM analyses (TFV, PFV and HC) need different boundary conditions and different kind of excitations: orthogonal field at the boundary and poloidal excitation currents for TFV and the HC; tangential field at the boundary and toroidal excitation currents for PFV; furthermore the PFV and the TFV problems are at "imposed induced voltage", while the HC problem is at "imposed current".

Due to this, to take the maximum advantage of the component symmetries, the three cases have been solved using different EM models. In this way the various contributions have been easily added in the post-processing phase and the resultant forces and torques have been provided as input for related mechanical stress analyses.

Fig. 1 shows the structural FE model of the divertor developed using the finite element code Ansys [3]. To reproduce the FAST toroidal periodicity the model consists in a divertor detailed mesh (5◦ in toroidal direction).

The divertor model includes: the inner tubular PFUs vertical targets (IVT), the outer tubular PFUs vertical targets (OVT), the dome PFUs and the supporting structure that connects the divertor to the vacuum vessel (VV).

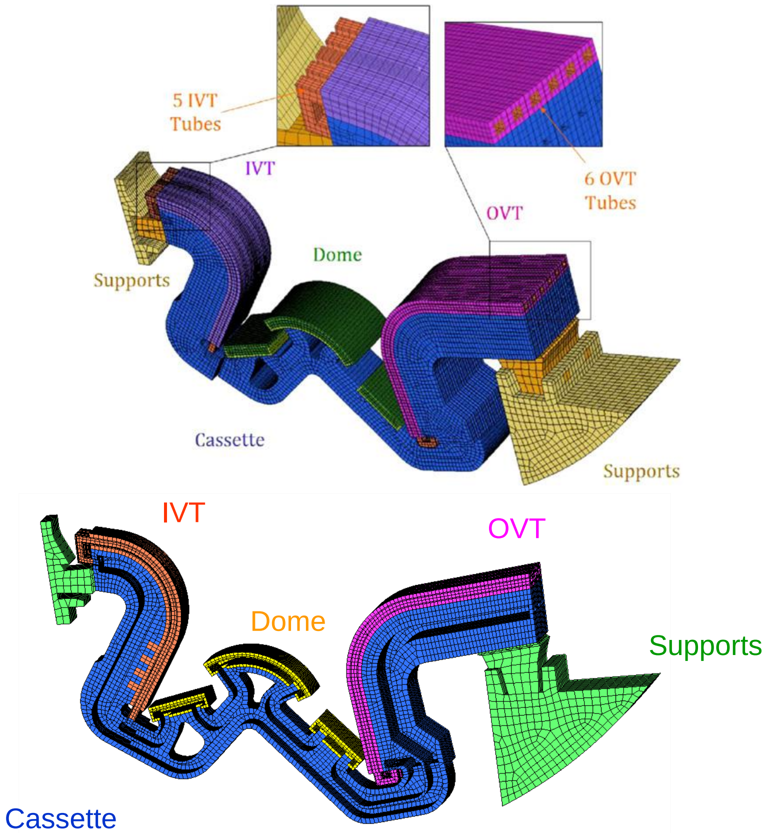


Figure 1. Complete model of the divertor and a section view.

The manufacturing solution for the PFUs of both IVT and OVT consists in tungsten monoblocks brazed on the copper tube of 12 mm diameter (Fig. 2).
All the copper tubes (6 tubes for OVT and 5 tubes for IVT in the divertor) are represented in detail in Fig. 1.
The PFUs were designed with tungsten monoblock thickness of 4 mm along the tube axis direction. This design, aimed to soften stresses at the tungsten/copper interface, makes them not conducting in the direction of the tubes. To simulate these effects suitable orthotropic conductivity properties have been defined for the material constituting the tungsten facing components, in such a way to avoid current conduction in the tubes direction.

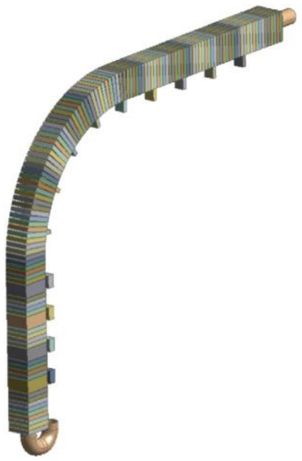


Figure 2. Plasma facing unit of the OVT geometry.

The DOME top surfaces are also made of rectangular tungsten tiles (Fig. 3), not conducting in both radial and toroidal directions. In this case the equivalent electrical resistivity of these top structures have been calculated performing separate EM analyses on a single element modulus reproducing in full detail the complex features.

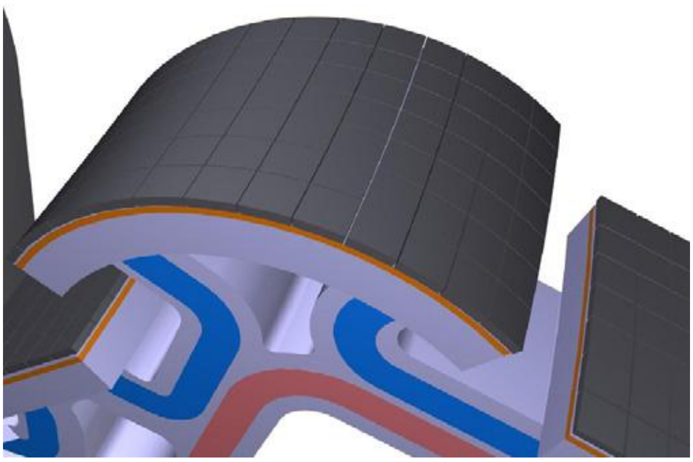


Figure 3. Dome plasma facing unit.

The EM loads from a Plasma Fast Down disruption event have been evaluated for the assessment of the divertor conceptual design.
As far as excitations are concerned, two different types of excitation currents have to be introduced in the model: the excitations related to DC currents flowing in poloidal field (PF) and central solenoid (CS) coils and the excitations related to plasma currents.
PF and CS coils are physically represented in the FE model (Fig. 4) and the definition of the related static currents can be easily carried out using standard Ansys procedures.

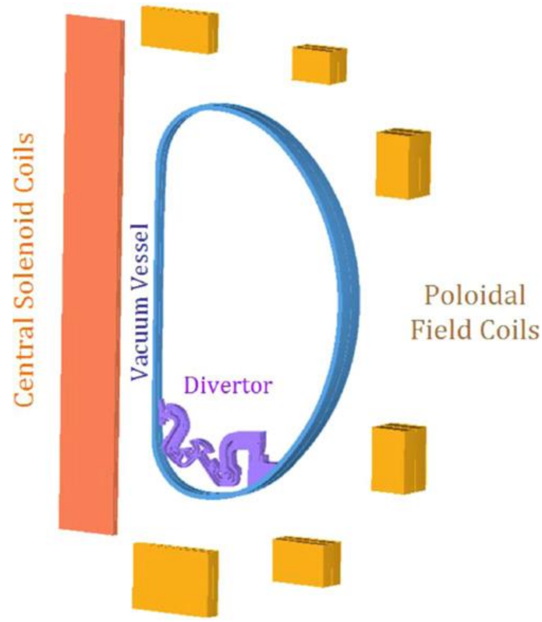


Figure 4. Plasma facing unit of the OVT geometry.

Normally, for almost all the in-vessel components, the toroidal field can be quite well approximated by the 1/R law: $B(r) = B_0 \times R_0/R$
where B_0 = 8.5 T and R_0 = 1.8 m (center of the coil). Being the toroidal field constant in time during the plasma disruptions, it can be easily added in the post processing procedures for EM loads evaluation.
The MAXFEA code has been used for the plasma behavior evaluation during a disruption event.
Fig. 5 shows the plots of the total plasma current, the toroidal magnetic flux and the halo current vs. time as output by the MAXFEA software for a Plasma Fast Down disruption event.

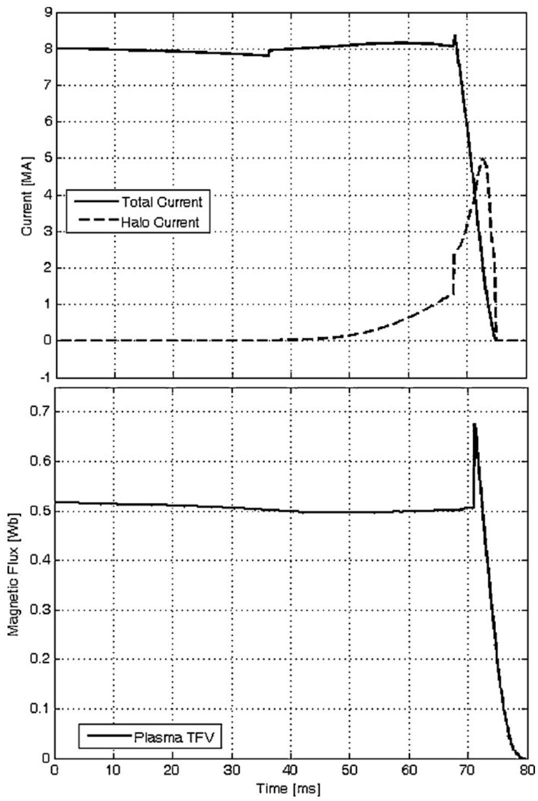


Figure 5. Total plasma current (MA), plasma HC (MA) and plasma TFV (Wb) vs. time (ms).

In Fig. 6 the position of the plasma center as a function of time is reported (r and z components represent the radial and vertical directions respectively).

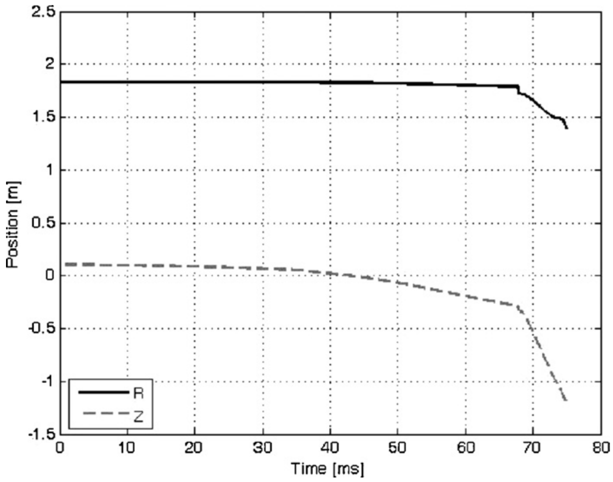


Figure 6. Plasma position (m) vs. time (ms).

The plasma disruption simulation by MAXFEA software provides as output current filaments in the plasma region, whose number and position vary with time. This fact would require a mesh change at each time step. This effect can be reproduced by axis symmetric excitations; the currents induced by the plasma on the excitation components will exactly compensate the EM transient generated by the variation of the plasma currents.
This technique allows modeling the PFV and TFV cases in more simple way as shown in Fig. 7. The elements surrounding the divertor structure and the VV represent toroidal excitations reproducing the plasma PFV, whereas the elements in the center of the plasma region represent poloidal excitation reproducing the plasma TFV.

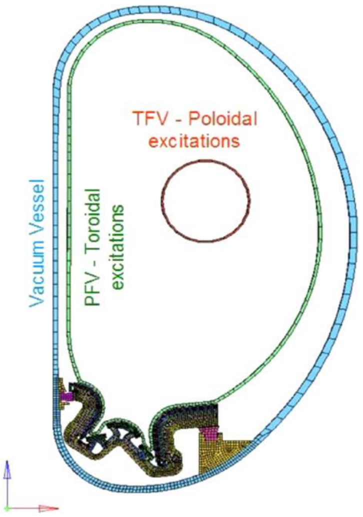


Figure 7. Model used for PFV and TFV analyses.

As regards HC analysis, the input and output positions of the current have been assumed as represented in Fig. 8 (input in IVT and output in OVT). According to ITER procedure, it has been assumed that 56% of total halo current (represented in Fig. 5) from a Plasma Fast Down disruption event enters into divertor.
As already stated, the three different excitation cases have been performed separately.

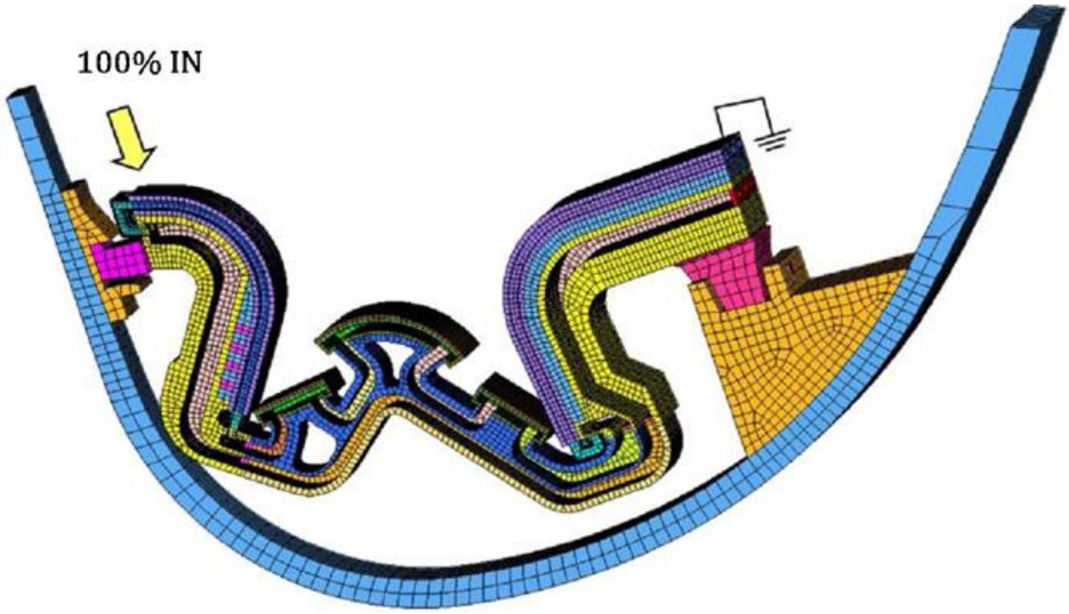


Figure 8. Model used for HC analysis.

Magnetic field distribution as well as induced currents and the related Lorentz forces have been evaluated for each PFV, TFV and HC. The EM loads have been combined element-by-element for the evaluation of the resultant forces and moments.
Toroidal field map for the maximum of HC (Fig. 9) shows magnetic field values lower than 0.4 T. In the divertor region the values of the magnetic field generated by TF coils are from 7.7 to 13 T.
As the self-magnetic field of HC is significantly below the external field, the described modelling technique gives a realistic estimation of integral EM loads on divertor cassette.

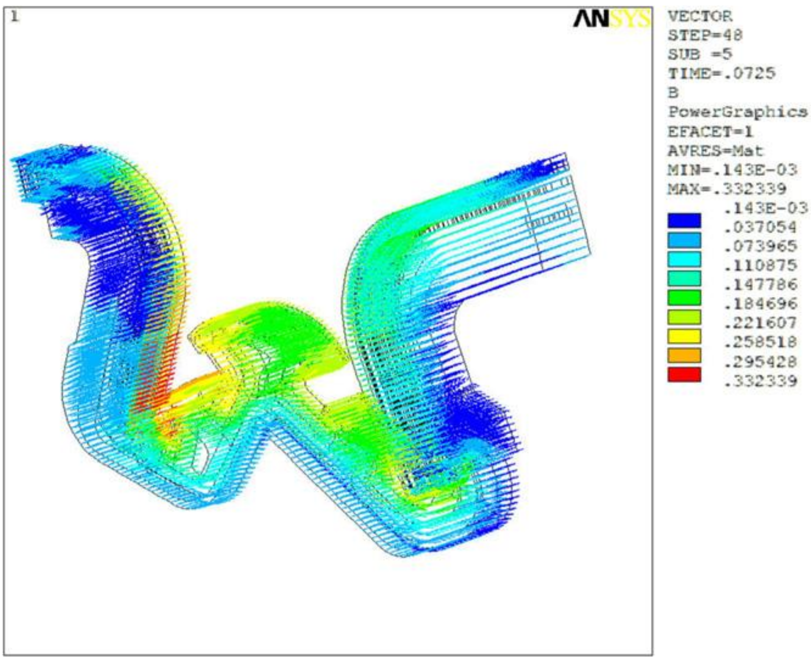
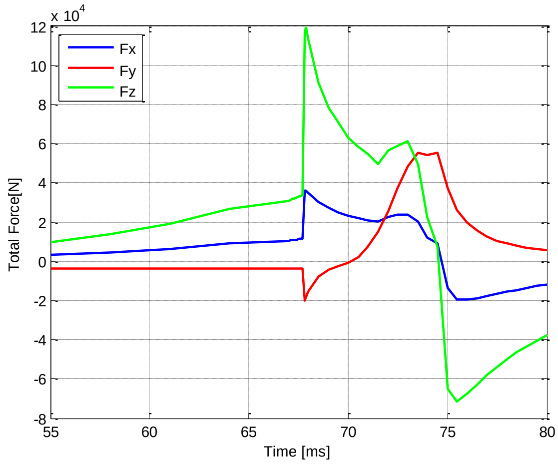


Figure 9. Toroidal field induced by HC.

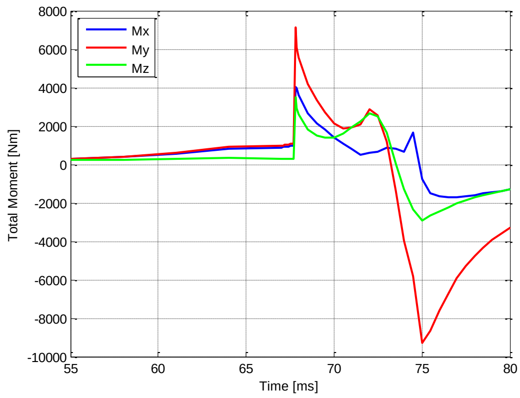
Figs. 10 and 11 show the resultant loads (forces and moments) vs. time acting on the whole divertor due to a Plasma Fast Down disruption event. The x-, y- and z-axes are in radial, toroidal and vertical direction respectively.
These loads include the cumulative effects of PFV, TFV and HC and the moments are calculated respect to the divertor center of mass: x = 1.596 m, y = 0.0 m, z = −1.16 m.

In fig.s 10 and 11 peak values of total force and moment components on the whole divertor are reported respectively.



	Peak Value [kN]	Time [ms]
Fx	36.28	67.9
Fy	55.39	74.5
Fz	119.91	67.9

Figure 10. Total force acting on all divertor structure.

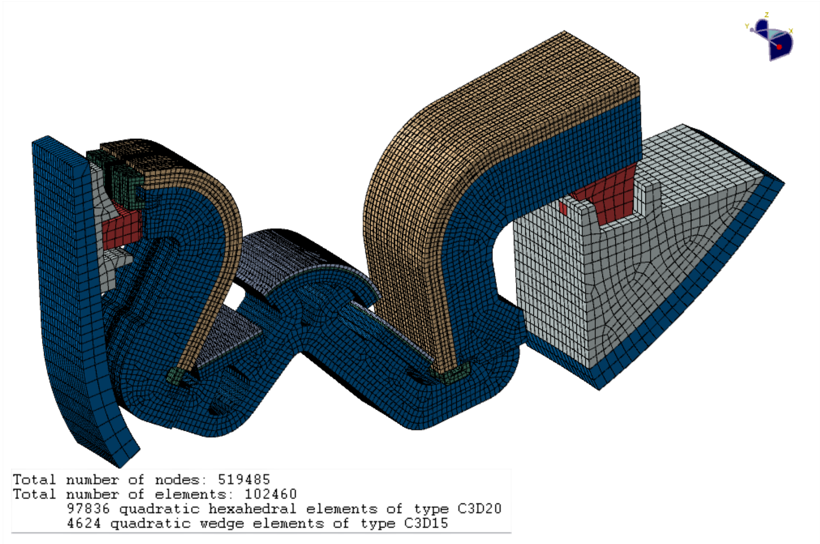


	Peak Value [kNm]	Time [ms]
Mx	4.01	67.8
My	-9.29	75
Mz	3.52	67.8

Figure 11. Total moment acting on all divertor structure calculated respect to the divertor center of mass: x = 1.596m, y = 0.0m, z = -1.16m.

Structural analysis

The structural FE Model has been based on the EM mesh (fig. 12).



Materials	Edge	Color
CUCRZR		
CUCRZR_CU		
NIALBR		
SS		
STEEL660		
W		
W_CU		

Figure 12. Structural FE Model.

Figure 13 highlights the boundary conditions imposed.

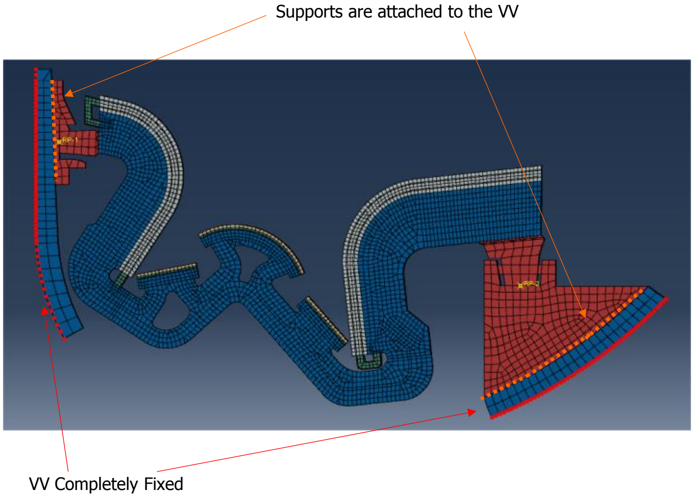


Figure 13. Boundary conditions.

The analyses have been carried out considering the most critical time instant evaluated in EM analysis. In the following figures we show the ***results at time instant "67.9 ms"***.

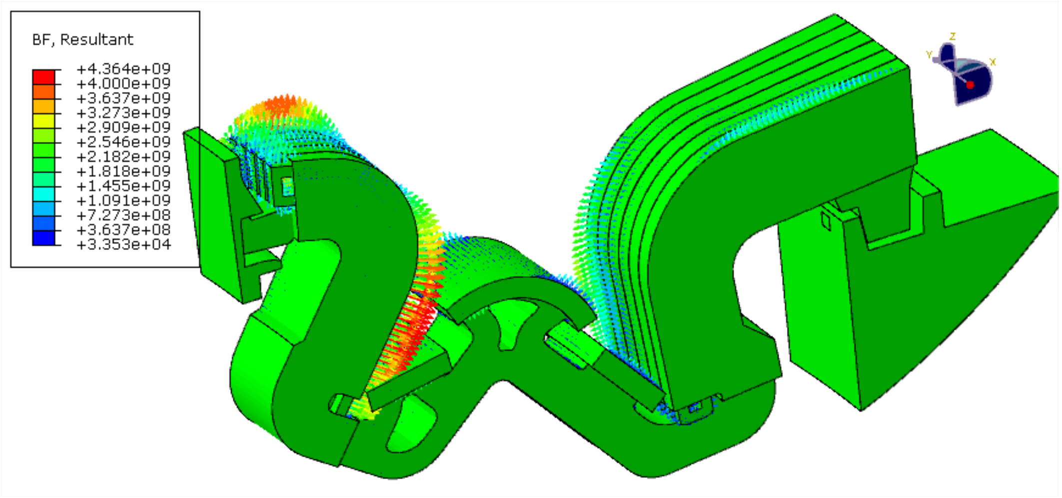


Figure 14. Body forces [N/m**3]: 67.9ms.

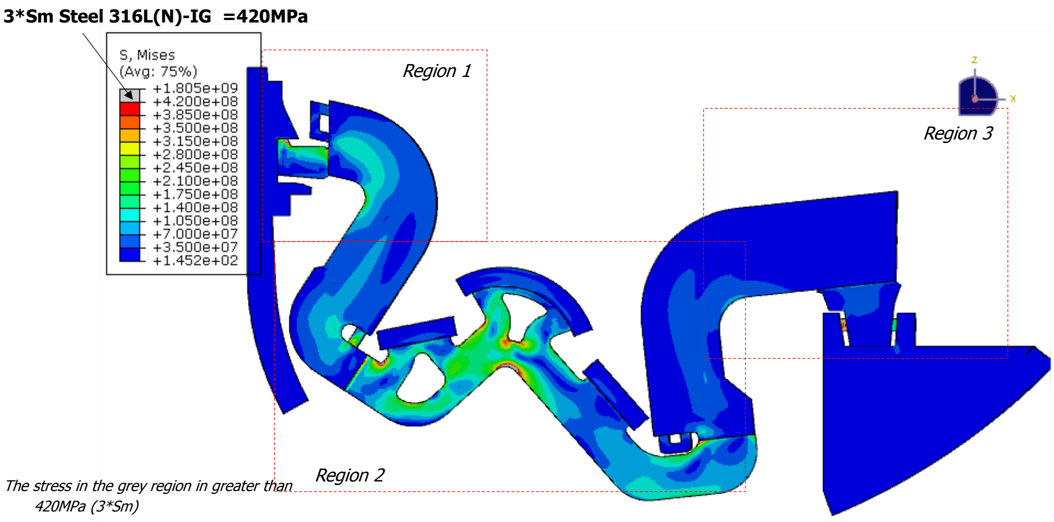


Figure 15. Von Mises Stresses overview: time instant 67.9ms.

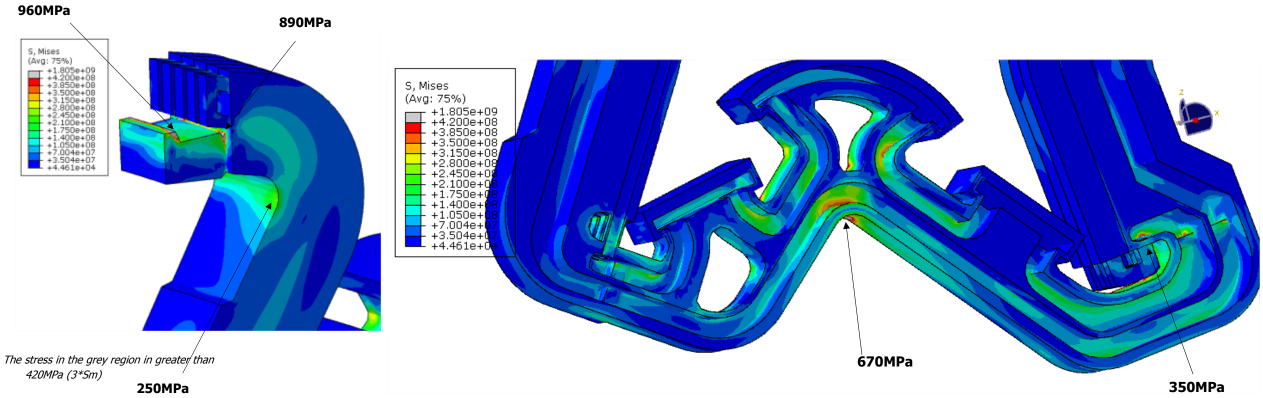


Figure 16. Von Mises Stresses region 1 (left) and region 2 (right): time instant 67.9ms.

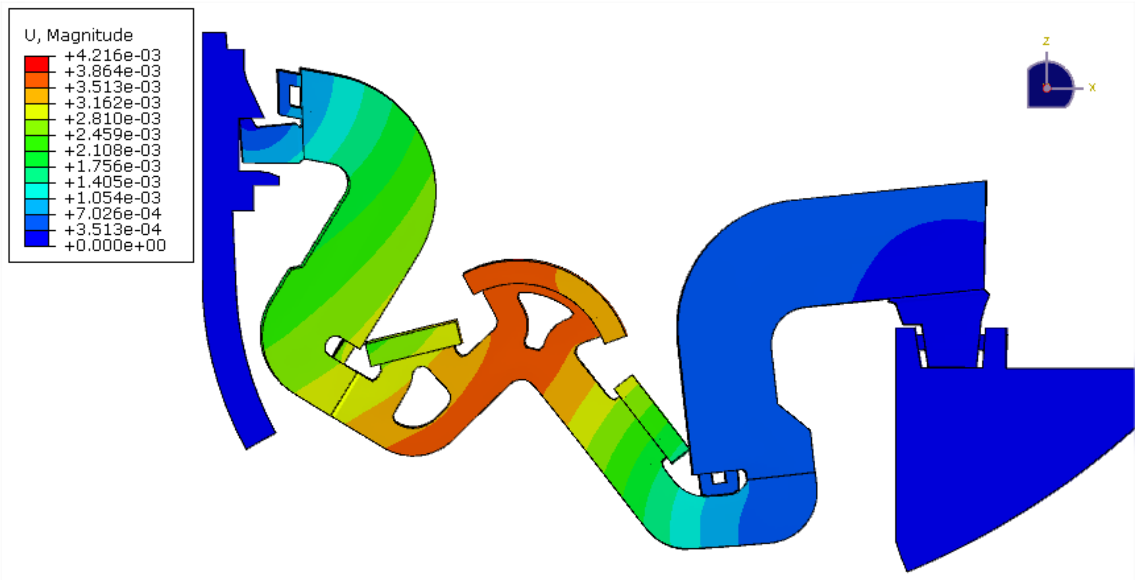


Figure 17. Displacements (m): time instant 67.9ms.

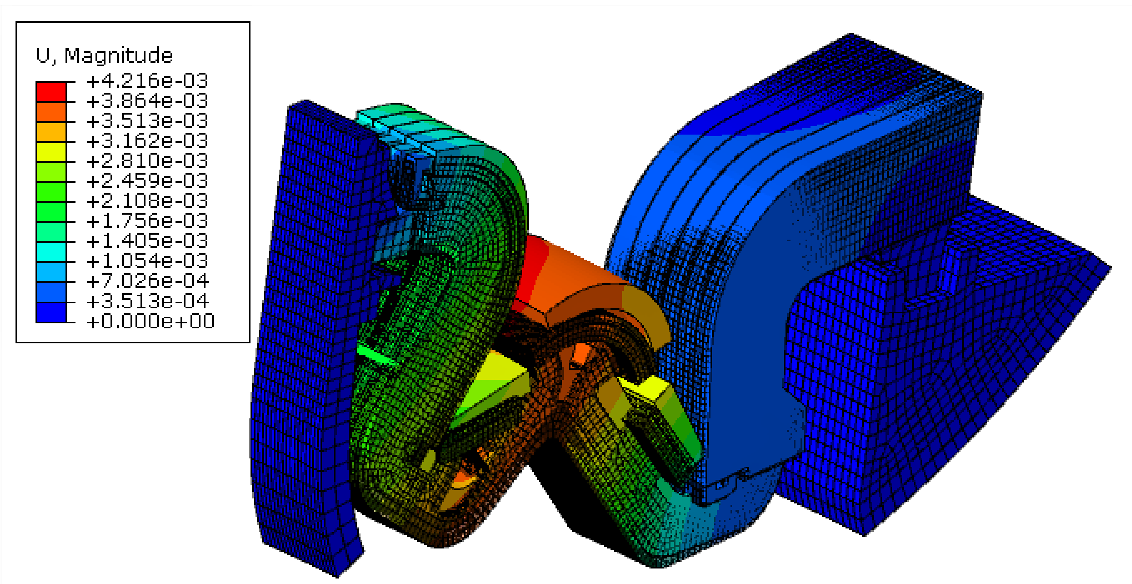
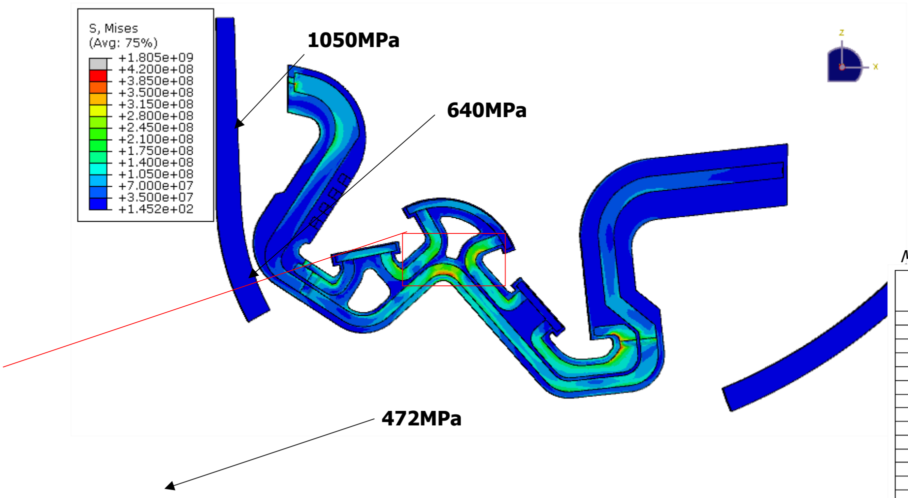


Figure 18. Displacements (m) – loaded vs. unloaded structure: time instant 67.9ms.

Plot limits: 420MPa, View cut

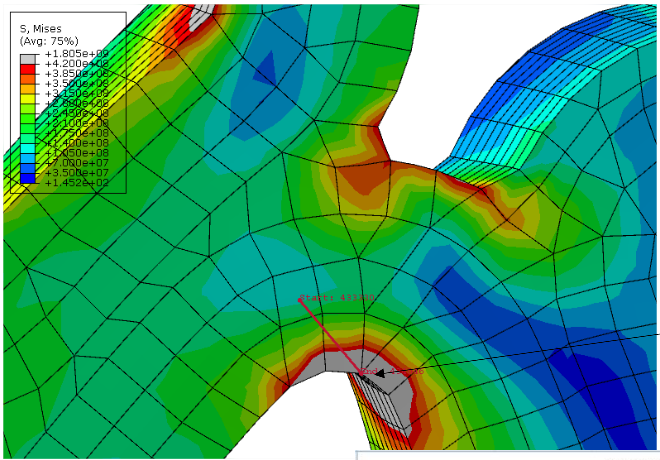


Material data:

Temperature	Minimum Tensile strength, Su	Minimum Yield strength, Sy	Design stress intensity, Sm
°C	MPa		
20	525	220	147
50	496	195	147
75	472	182	147
100	458	172	147
125	446	164	147
150	437	156	141
175	429	150	135
200	423	144	130
225	418	139	125
250	415	135	121
275	412	131	118
300	410	128	115
325	409	124	112
350	407	121	109
375	406	119	107
400	404	116	105
450	398	112	101
500	389	109	98
550	374	107	96
600	352	105	95

X-Z plane, view cut

Figure 19. Von Mises Stresses - SS316L(N)-IG Parts: 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

IC3121.1.1 Immediate plastic collapse and plastic instability							
ASSESSMENT			APPLIED	≷	ALLOWABLE	RESULTS	SAFETY MARGIN
Primary membrane	IC3121.1.1.2a Equation 42	$\overline{P_m} \leq S_m(T_m, \Phi t_m)$	$\overline{P_m}$ 369 [MPa]	>	$S_m(T,\Phi t)$ 147 [MPa]	FAILED	SM = 0.40
Primary membrane plus bending	IC3121.1.1.2a Equation 43	$\overline{P_L + P_b} \leq K_{eff} S_m(T_m \Phi t_m)$	$\overline{P_L + P_b}$ 634 [MPa]	>	$K_{eff} S_m(T,\Phi t)$ 221 [MPa]	FAILED	SM = 0.35

Figure 20. Von Mises Stresses - SS316L(N)-IG Parts – stress linearization along path: time instant 67.9ms.

The results highlight that the SS316 FAST Divertor parts 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.

Figure 21 shows the geometrical variation 1. The structural analyses showed in the following figures are related to this divertor geometry.

Geometrical Variation 1:

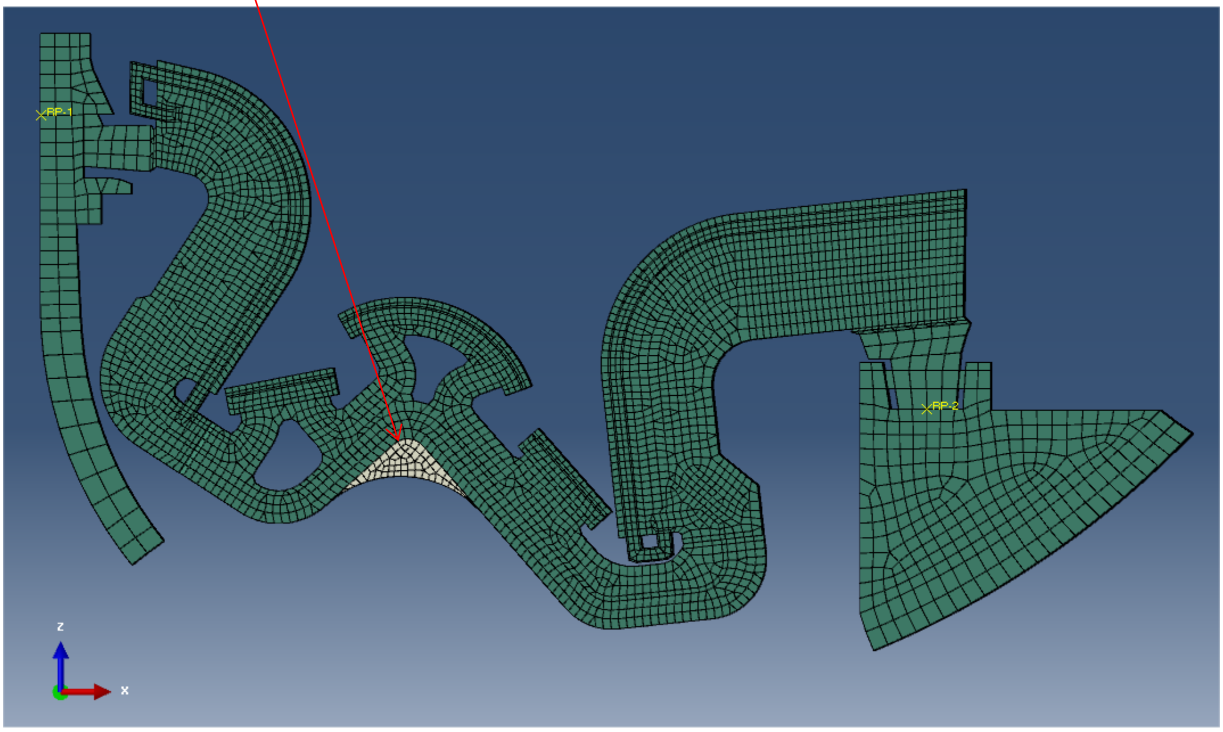


Figure 21. Geometrical variation 1.

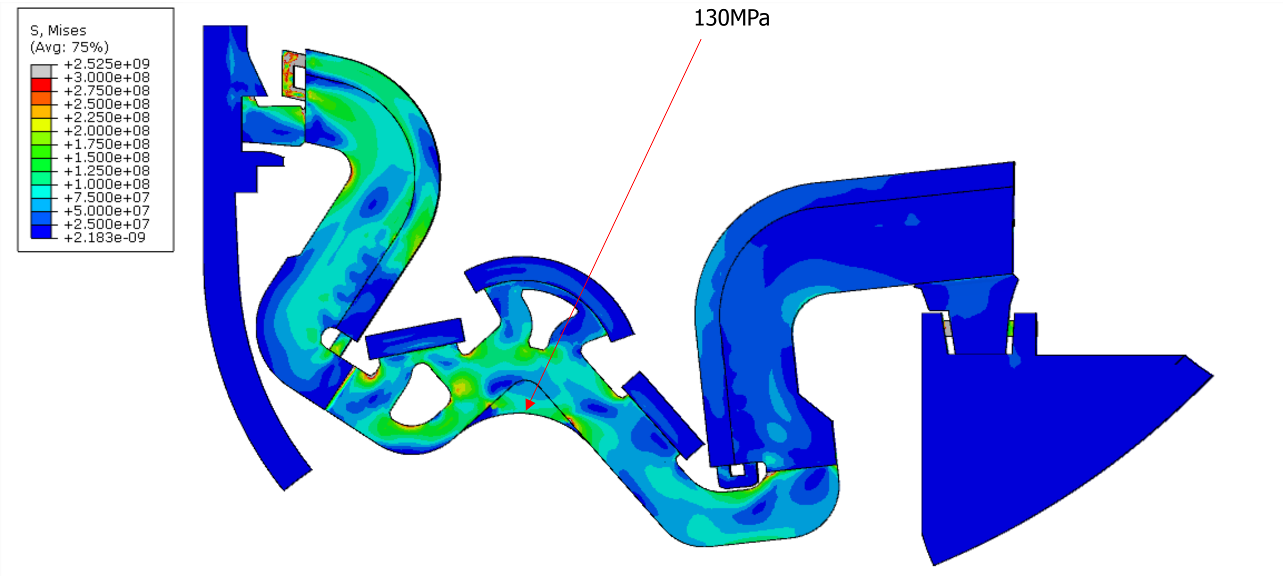


Figure 22. Geometrical Variation 1: Von Mises Stresses (Pa): time instant 67.9ms.

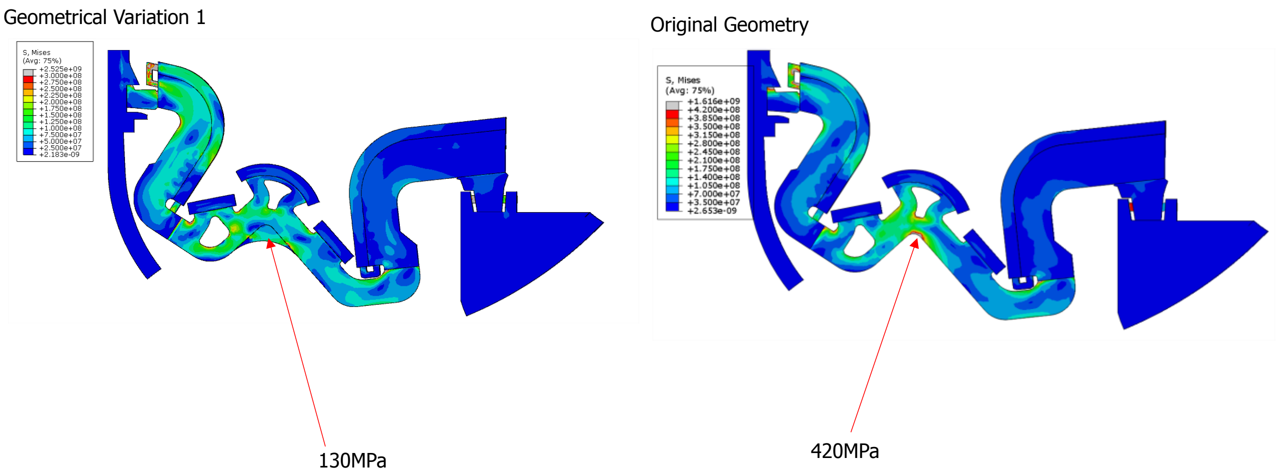


Figure 23. Geometrical Variation 1: Comparison with previous results.

The comparison with previous results highlights that there is a meaningful reduction of the stress state in Geometrical Variation 1 region.

Starting from the results of the structural analysis we decided to improve the geometry of the divertor as shown in figure 24.

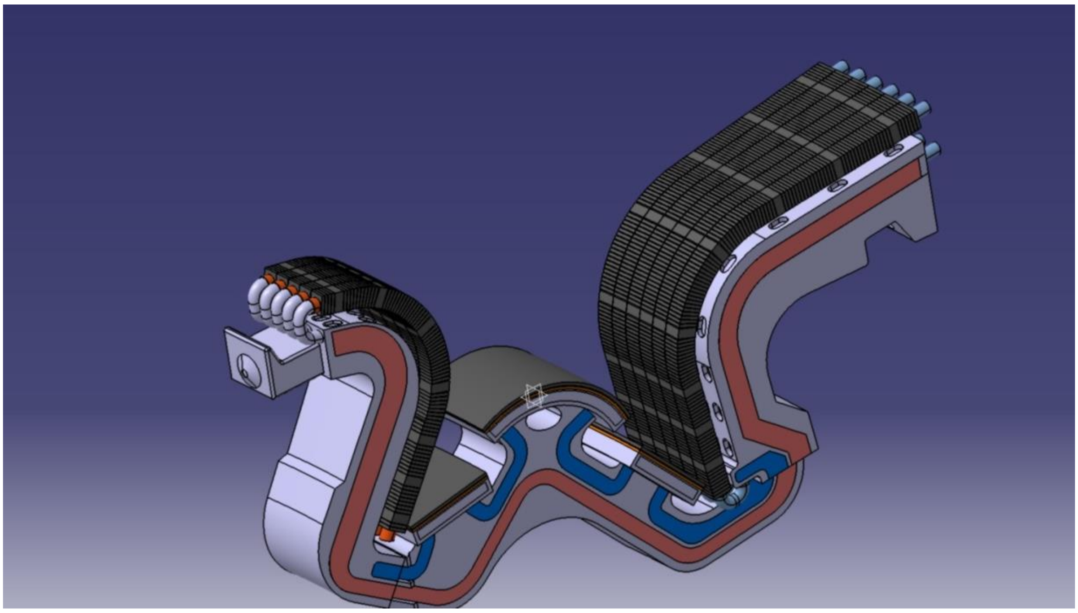


Figure 24. Final divertor concept design as result of RH and structural analyses.

3 Conclusions

The cooperation between different people and experience has allowed to deeply analyzing the “Snow Flake” innovative divertor magnetic configuration, underlining both the physics and technological advantages and drawbacks. The very promising features of the SF configuration have pushed to perform an actual design of an innovative divertor for the FAST machine, analyzing all the electromagnetic loads with an hint of the mechanical and thermal stress.

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5 Acronyms

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

6 Addendum A – CREATE Scientific Expertise

CREATE Consortium (www.create.unina.it) is a no profit research organisation possessing a legal personality; it belongs, according to the Italian law, to the class of Consorzi, where a number of subjects give life to an independent body intended to reach commonly agreed objectives (in the CREATE case, develop, support and stimulate applied research in Electromagnetics).
CREATE was founded in 1992 with the aim of establishing a stable link between industry and university. The partnership is made by the University of Cassino, the University of Napoli Federico II, the Second University of Napoli, the University of Reggio Calabria and the Ansaldo-Ricerche.

CREATE has a very well established experience in the analysis, the design and the operation of tokamak systems, based on the strong interaction between Academy and European Research Centers. In particular CREATE is part of the EURATOM/ENEA Association.
The technical and professional knowledge required for carrying out these activities should cover the three main overlapping areas of the Computational Electromagnetism, Nuclear Fusion Engineering and Mechanical Design. In the following we will summarize the features of the main computational tools available, as implemented and improved on the basis of a very deep experience gained by the CREATE team of scientists in the last twenty years in the electromagnetic analysis of nuclear fusion devices and in the virtual simulation of mechanical systems.
The CREATE team has a very long experience in eddy current calculation, plasma modelling and control design on several experimental devices and specifically on ITER (see [1-34]). The team members were also National Coordinators of various research projects funded by the Italian Ministry of Research about plasma modelling for control. The CREATE team has also a very long experience in CAD modelling and Virtual Reality simulations on complex mechanical assemblies (see [35-74]).
The team has also cooperated with UKAEA on the JET Extreme Shape Controller (XSC) and the upgrade of the JET Control System with particular reference to the vertical stabilization. The team also gave a contribution to the design of ITER from the initial phases of the project, e.g., in "ITER Concept Definition". ITER-1, Oct. 1988, and in ITER DDR e ITER FDR, Final Design Report, 1998. Various team members have been principal investigators of several EFDA contracts on 3D modelling of ITER conducting structures, as well as on the control and the stabilization of ITER plasmas.

CREATE has at its disposal the Virtual Reality Laboratory "VRoom" of the University of Naples Federico II. The lab is mainly devoted to: Computer Aided Design; Virtual Design; Virtual Maintenance, Virtual Manufacturing, Assembly/Disassembly simulations, Virtual Ergonomics, Human Robot Interaction, Virtual Robotics. Active courses provided at undergraduate level are: Virtual Prototyping, Computer Aided Design, Mechanical Drawing, Virtual Ergonomics, Automotive Ergonomics.
The VRoom co-operates with Italian big industries (Alenia Aeronautica, Piaggio Aero Industries, FIAT, Firema Trasporti, Ansdaldo Breda, Ansaldo STS), international Research Centres (VTT in Tampere – Finland, Fraunhofer Institutes - Germany, Supmeca in Paris – France, University of Vigo and Escuela Politecnica de Madrid – Spain, Italian Center for Aerospace Researches - CIRA, ENEA) and many Italian SMEs. The Lab is involved in the Editorial Board of the International Journal on Interactive Design and Manufacturing (IJIDeM) edited by Springer, and in the Scientific Committee of the International IDMME - Virtual Concept Conferences.
In the last years "VRoom" has coordinated the following research projects:

- 2002-04: MIUR Italy National Project PRIN 2001: "Classification and restoration of archeological finds by means of CAD-RP technologies"
- 2003-06: European Social Found – POR Campania 2000/2006 – Axis 3 – Measure 3.13, D.D. n. 590/ 06/10/2005: "Centre of Competence for Transport Systems of Campania Region"

- 2004-06: MIUR Italy National Project PRIN 2003: “Study and development of an immersive multimodal Virtual Reality system (visual-haptic) for functional, ergonomics and usability validation of equipment controls”
- 2007-09: MIUR Italy National Project PRIN 2006: “PUODARSI: Product User-Oriented Development based on Augmented Reality and interactive Simulation”
- 2007-11: MIUR Italy National Project for the realization of public/private Research Laboratories, D.D. 14 marzo 2005 prot. n. 602/Ric/2005; title: “Public/Private Laboratory for the development of technologies for the realization of new materials and the development of engineering design methodologies for the railway and aeronautical fields: TEST X TRANSPORT”
- 2007-2008: Campania Regional Project, Regional Law 5/02, “Design and development of a virtual environment for ergonomics studies of assembly and maintainability operations on transportation systems”. 2007-2008: Campania Regional Project, Regional Law 5/02, “Innovative engineering design of aid devices for people with disability. Analysis and optimisation, through modelling and simulation digital systems, of mechanical configurable devices, for disable people”.

On July 2008 “VRoom” has organized the first International Conference “VRTest 2008: Tools and perspectives in Virtual Manufacturing”.

Main characteristics of the VRoom: Graphics and Calculus System: SGI Onyx 4; Cluster of 6 PC Windows/Linux with a total of 48 cores; Visualization System characterized by: Powerwall BARCO ACTCAD 7.5m x 2.4m; 3 DLP Projectors Barco Galaxy 6000; Tracking System real time wireless optic with 3 ART TRACK cameras; 3D Input Systems for the manipulation of virtual objects and the navigation in virtual environments: gloves, Spaceball, flystick and joystick; Software: Virtual Design 2 by VRCOM; Virtual Decision Platform by IC:IDO; Catia V5 R19 P3, Solid Works 2010, DELMIA V5 R19, Quest and 3DVIA Composer from Dassault Systemes; Alias Studio 12 by Autodesk; ProEngineer e Division MockUp by PTC; Unigraphics NX5, Solid Edge, Jack, TeamCenterVisualization by Siemens – UGS, Ensight by CEI, Cinema 4D.

7 Addendum B – LT Calcoli Scientific Expertise

LTCalcoli (www.LTCalcoli.it) started in 1996 finalizing a long experience in Electromagnetic analyses carried out at ENEA (the Italian National Research Centre for Alternative Energies). Since LTCalcoli works in cooperation with national and international partners involved in scientific research, like universities and scientific agencies, its know-how is constantly maintained at high standards. This allows LTCalcoli not only to reliably analyze very complex systems and propose alternative designs, but also to develop innovative methods and customized solutions.

LTCalcoli operates since 1996 in several engineering fields, offering numerical analysis services aimed at designing, evaluating, improving and optimizing systems of varying complexity. Most numerical technologies used at LTCalcoli are based on the Finite Elements Method.

The following engineering fields are covered:

- electromagnetics
- electro-mechanical analysis
- structural mechanics
- thermal analysis
- thermo-structural analysis
- fluid dynamics
- vibroacoustics

In the field of Thermo-Nuclear Fusion Reactor devices, LTCalcoli is entitled of:

- Direct Contracts from ITER Organization for Electromagnetic analysis (eddy current, Lorentz forces and Maxwell Forces with Ferromagnetic Material), Electro-Mechanical, Thermal and Structural analysis of In-Vessel and Out-Vessel components
- F4E Framework Contract OPE-06-06:
  LOT 1: Electro-Mechanical analysis of ITER components
  LOT 3: Error field electromagnetic analysis

LTCalcoli has a very well established experience in the design analysis of Thermo-Nuclear Fusion Reactor machines. This experience has been built up from a strong and long-term collaboration with:

- ITER Organization
- ENEA (Italian National Research Centre for Alternative Energies)
- FUSION FOR ENERGY
- IPP (Max Planck Institute for Plasma Physics)
- CNR (Italian National Research Council)

The technical and professional knowledge required for carrying out this kind of activities covers the different and overlapping areas of computational electromagnetism, computational mechanics and nuclear fusion engineering.

The LTCalcoli team was involved in the design analysis of several nuclear fusion reactors and of the related components. Among these:

- ITER
- IGNITOR
- W7-X Stellarator
- JET
- FTU (ENEA Frascati Tokamak Upgrade)
- DEMO

Related to this, LTCalcoli has also developed and well validated (for instance on the ITER Divertor, Blanket Modules and on the IGNITOR First Wall) an electromagnetic “zooming” numerical procedure that allows to extract, from a complex electromagnetic system, the excitation induced on a subsystem, thus allowing a more detailed and separate analysis of the same subsystem in isolated conditions.

In particular, in the field of thermo-structural analysis and design optimization, LTCalcoli performed detailed analyses on the main nuclear fusion reactor components following various procedures:

- transient heat transfer analysis under the effect of the neutronic heat deposition or plasma heat flux
- static, dynamic elastic, elastic-plastic and limit analysis under different load conditions in accordance with the specified design criteria: dead weight, pre-load, thermal strain due to neutronic heat deposition or plasma heat flux, electromagnetic loads
- seismic analysis
- fatigue analysis
- structural assessment according to different standards like (among others) SDC-IC, ASME, RCC-MR

LTCalcoli is also supporting for Industry needs. LTCalcoli expertise in numerical analysis can support small, medium and large industries in the design, assessment and optimization of simple and complex systems, with the final objective of improving product performance and/or reducing development times.
The expertise in structural and thermal analyses available at LTCalcoli covers a very wide range of simulations. The possible fields of application of this kind of analyses covers practically every branch of engineering such as:

- structural and thermo-structural assessment, to verify that a system can support a predefined structural or thermo-structural load
- vibro-acoustics (including fluid-structure coupling)
- analysis and design of composite materials
- structural design of Formula 1 chassis parts
- metal forming and welding
- biomedical devices (stent, orthodontic archwires, spinal vertebrae spacers)
- buckling and post-buckling
- highly non linear material behavior
- modal/harmonic/transient dynamics
- high speed dynamics

Computational tools available:

- hardware
  - #1 DELL PowerEdge T710- #2 Intel Xeon X5660 - 32 Cores - 128 GB Ram
  - #1 DELL Dual Quad - T7400-Dual Intel Xeon X5482– 24 Cores - 32 GB Ram
  - #1 DELL Dual Quad - PE2900 III - Quad-Core Xeon X5460– 8 Cores - 32 GB Ram
  - #1 HP Dual Opteron - 4 Cores - 8 GB Ram
  - #4 DELL i7-2600 quad-core -12Gb Ram - AMD Radeon HD 6950 for each analyst
  - #2 Storage Servers for data managing and back-up
- software
  - Abaqus
  - Nastran
  - Patran
  - Ansys
  - Hypermesh
  - Fortran
  - Matlab
  - MSOffice
  - Linux
  - CATIA v. 5