Load Assembly Design of the FAST Machine

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Abstract

The FAST [1][2] (Fusion Advanced Studies Torus) load assembly, which includes the Vacuum Vessel (VV) and its internal components, the magnet system and the poloidal field coils, is presented in this paper. FAST operates at a wide range [3][4] of parameters from high performance H-Mode (B_T up to 8.5 T; I_P up to 8 MA) as well as Advance Tokamak operation (I_P=3 MA), and full non inductive current scenario (I_P=2 MA). Helium gas at 30K is used for cooling the resistive copper magnets. That allows for a pulse duration up to 170 s (~ 40 times τres) at 3MA/ 3.5T. To limit the TF magnet ripple within acceptable values ferromagnetic insert have been introduced inside the outboard area of the VV. The VV, segmented by 20 degree modules, is capable to accommodate 40 MW RF power systems. The machine has been designed to house10 MW Negative Neutral Beam injection (NNBI) systems. Tungsten (W) and Liquid Lithium (L-Li) have been chosen as the divertor plates material, and Argon as the injected impurities to mitigate the thermal loads.

1. Introduction

FAST (Fig.1) is a proposal for a Satellite Facility which can contribute the rapid exploitation of ITER and prepare ITER and DEMO regimes of operation, as well as exploiting innovative Plasma Facing Component (PFC) systems for DEMO. FAST is a compact (Ro = 1.82 m, a = 0.64 m, triangularity δ = 0.4) and cost effective machine able to investigate, with integration capability, non linear dynamics effects of alpha particle behaviours in burning plasmas [2][5], the Plasma Wall interaction under ITER Load [6], ITER relevant Operational Problems (ELMs, Plasma Control,etc) [3] and, eventually Advanced Tokamak regimes, up to completely fully non inductive Plasma driven scenarios [2] [3].

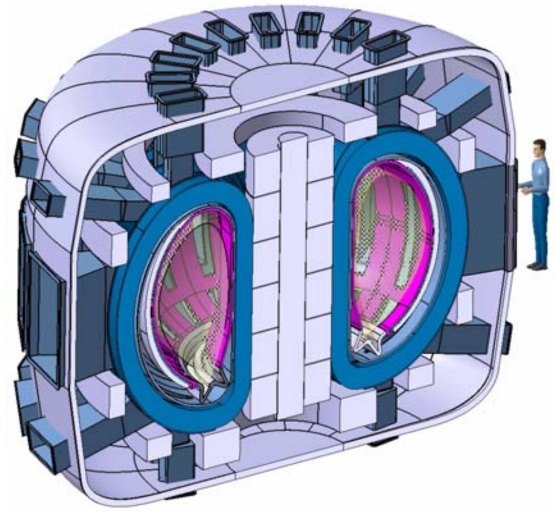

FIG. 1-FAST Load Assembly view

FAST Load Assembly (Fig 1), consists of 18 Toroidal Field Coils (TFC), 6 Central Solenoid (CS) coils, 6 External Poloidal coils (3+3), VV and its internal components and the mechanical structure. Resistive coils, adiabatically heated during the plasma pulse, are cooled down at cryogenic temperatures (30 K) by helium gas.
Cooling of the rest of the machine is assured by the good thermal contacts between the major components. VV is maintained by a dedicated system at around 100 °C temperature. The load

assembly is kept under vacuum inside a stainless steel a cryostat to provide the thermal insulation of the machine. The cryostat overall dimensions could be assimilated to a 8 m diameter 6-meter high circular cylinder.

FAST (Tab. 1) is a flexible device [3] in terms of both performance and physics, able to operate in H-mode reference scenario (6.5MA/7.5T) as well as in advanced tokamak regimes (AT2). The worst thermal condition is reached after a current long pulse (170 s in AT2), in which the toroidal coil temperature reaches about 150K in the leg region. The Poloidal Coil System reaches 85K as a maximum. Cooling of the magnet system is guaranteed by a global helium gas at 30K flowing of about 4 kg/s through suitable channels carved in the coil turns. The helium is supplied by a cryo-cooler.

Tab. 1- Operating scenarios

FAST	H-mode reference	H-mode extreme	Hybrid	AT	AT2	Full NICD
I_p (MA)	**6.5**	8	5	3	**3**	2
q_{95}	3	2.6	4	5	3	5
B_T (T)	**7.5**	8.5	7.5	6	**3.5**	3.5
H_{98}	1	1	1.3	1.5	1.5	1.5
$\langle n_{20} \rangle$ (m^{-3})	2	5	3	1.2	1.1	1
P_{th_H} (MW)	14 ÷18	22 ÷ 35	18 ÷ 23	8.5 ÷ 12	5 ÷ 7	5 ÷ 7
β_N	1.3	1.8	2.0	1.9	3.2	3.4
τ_E (s)	0.4	0.65	0.5	0.25	0.18	0.13
τ_{res} (s)	5.5	5	3	3	5 ÷ 6	2 ÷ 5
T_0 (keV)	13.0	9.0	8.5	13	13	7.5
Q	0.65	2.5	0.9	0.19	0.14	0.06
$t_{discharge}$ (s)	20	13	20	70	170	170
$t_{flat\text{-}top}$ (s)	13	2	15	60	160	160
I_{NI}/I_p (%)	15	15	30	60	80	>100
P_{ADD}(MW)	30	40	30	30	40	40

Each TF is contained in a stainless steel belt fitted to the outside zone of the coil. Two pre-compressed rings situated in the upper-lower zone keep the whole toroidal magnet structure in wedged configuration. TF magnet ripple has limited to 0.3% on the plasma separatrix with optimized ferromagnetic inserts.

VV is supported through equatorial ports by means of brackets attached to the TF coil case.

The First Wall (FW) consists of a bundle of tubes armoured with ~4 mm plasma spray tungsten. The divertor technology is the monoblock one, which has been tested in high value heat flux range. Moreover, successful tests in FTU of a liquid lithium capillary-pore limiter [7] indicate the development of an innovative lithium divertor concept.

FAST is equipped with three auxiliary heating systems: Ion Cyclotron Resonant Heating (ICRH), Electron Cyclotron Resonant Heating (ECRH) and Lower Hybrid (LH). The injection of 30MW ICRH accelerates the plasma ions to energies in the range of 0.7 ÷ 0.8 MeV in H-mode scenario (6.5MA/7.5T) [5]; 6 MW of LH have been adopted to actively control the current profile and 4 MW of ECRH are devoted to MHD control.

In the H-mode reference scenario (6.5MA/7.5T), the requested total peak power is ~450 MVA, considering a total heating power of ~100 MW and a stationary load of 25 MW. TERNA (Italian grid utility) analysed with positive results the effects of connection to a powerful node of the 400 kV Grid in Casaccia and Frascati ENEA sites.

The overall load assembly weight has been estimated equal to 1200 tonn.

2. Toroidal Field Coil System

The H-mode reference scenario foresees a TFS designed to produce a field of 7.5 T at the major radius R_0=1.82 m, corresponding to 67.5 MA-turn, with a pulse duration of 20 s. At lower magnetic fields (B_T=3.5 T), the pulse length can be extended up to 170 sec.

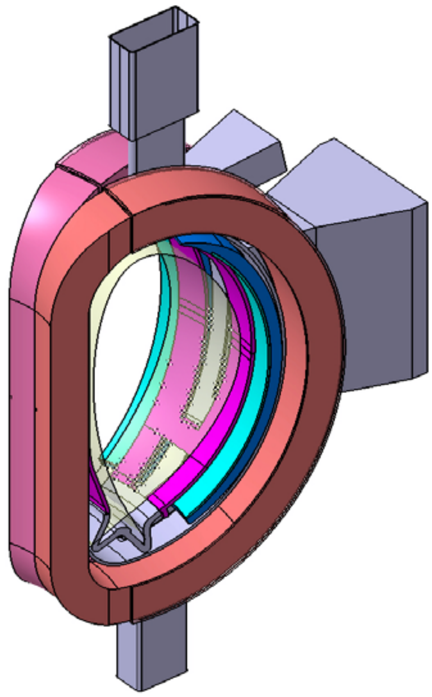

FIG. 2- Toroidal magnet module

The structure of the toroidal magnet system has a 20° modular configuration (Fig. 2). The magnet consists of 18 coils, each of them made of 14 copper plates suitably worked out in order to realise 3 turns in radial direction, with 89.2 kA per coil. The turns of each coil are welded on the most external region, in order to obtain a continuous helix. The maximum turn thickness is 30 mm. The plates are tapered at the innermost region in order to realise the needed wedged shape; the minimum turn thickness is about 15 mm.
The magnet dimensions have been determined to limit the coil temperature at the end of the longest pulses. The magnet insulation is made of glass-fabric epoxy both for ground and inter-turn insulation. With this solution, an average filling factor of about 0.9 can be achieved and, thus, the average current density in the reference scenario is about 45 MA/m^2 over the conductor inner cross-section, on the equatorial plane.

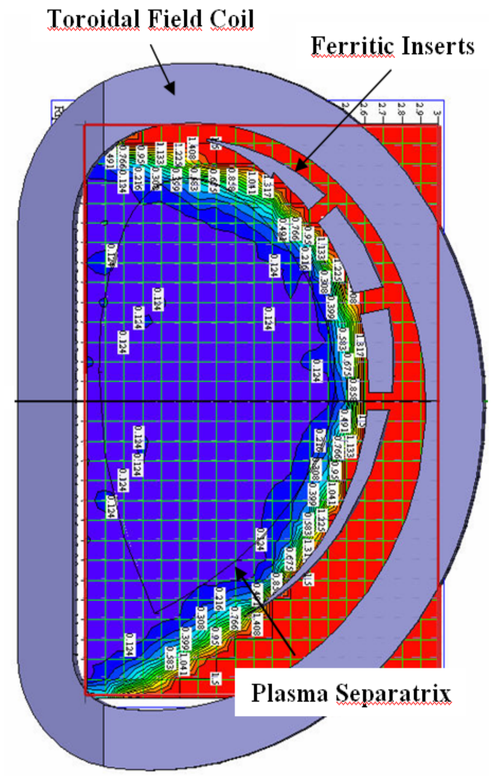

FIG. 3-TF ripple (%)

The coils are kept together by a steel structure which surrounds them. Two precompressed rings situated in the upper-lower zone keep the whole toroidal magnet structure in wedged configuration. The structure is also used to position the poloidal coils, which surround the toroidal magnet, and to fix the vacuum vessel supports.

The TF coil temperature at the end of the H-mode reference pulse (6.5MA/7.5T) rises up to a maximum of 110K in the inner leg. The electrical resistance of the whole TFS changes in the range 1.2÷9 mΩ during the pulse because of the temperature rises within the conductor and of the magneto-resistive effect. The inductance value is L=332 mH. The magnetic energy stored into the TFC system reached a maximum value of 1350 MJ.
During the flat-top of the H-Mode reference scenario, the radial inward force acting on each TF coil results F=-51.8 MN, while the vertical force on half the magnet system is 544 MN.
Ferromagnetic inserts have been introduced to limit within acceptable values the TF magnet ripple (Fig. 3) [3] [8], which could lead to significant losses of high-energy particles as well as to unwanted peaking in the heat loads on the FW. A detailed 3-D evaluation of the Toroidal Field Ripple (TFR) in the whole region inside the VV has been performed. A whole 20° toroidal sector of FAST has been modeled

with cyclic symmetry as boundary conditions. Without ferromagnetic inserts the TFR value exceeds 2% in the outboard plasma region near the equatorial plane.
The ferromagnetic inserts are located inside the outboard area of the vacuum vessel, corresponding to the TF coils area. The ripple on the plasma separatrix (near the equatorial port) has been reduced from 2% to 0.3% with optimized Fe inserts. An active Ripple Control has also been studied [3].

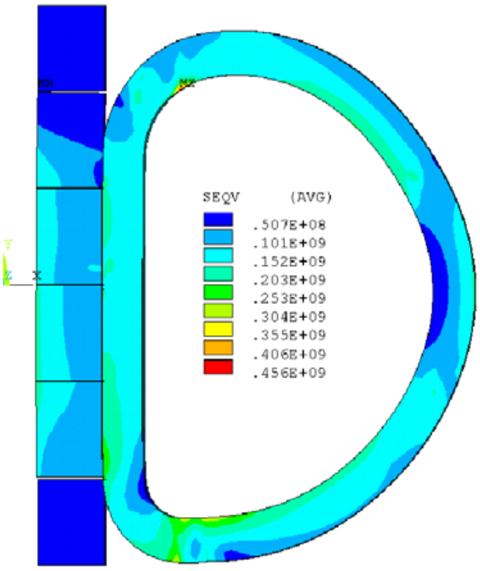

FIG. 4- VM stress (MPa) on copper

The TF system is considered to be supported by CS coils (Fig. 4). Due to the full structural cooperation, the Central Solenoid and the TF Coils have been modeled as a whole. The structural analysis has been performed by assuming the CS coils in two alternative state. Normal operating condition with CS coils energized with the scenario equilibrium currents and fault condition with CS coils de-energized. The in-plane EM loads, acting during the plasma current flat-top (i.e. t=8 s) of the reference scenario, are taken into account. The highest stresses, less than 250 MPa, have been found in case of coils de-energized. In normal operating conditions the stress is reduced to 200 MPa.
For Copper Alloy, the yield strength is 380 MPa at 77 K and 330 MPa at room temperature.
In conclusion, the structural analysis indicates stresses within the allowable values.
The fabrication process is based on well assessed technology utilized for FTU and other prototypical components. Therefore, no further R&D is required for the construction of the toroidal magnet.

3. Poloidal Field Coils System

The main components of the Poloidal Field System (PFC_S) can be identified as the Central Solenoid (CS) and the External Poloidal Coils (3+3 coils). The same mechanical structure supports both the vacuum vessel and the PFCs, thus ensuring their relative positioning. The CS is vertically segmented in 6 coils to allow for plasma shaping flexibility, and make the coil manufacturing easier while allowing for an effective cooling. The poloidal field coils and busbars are made of Copper hollow conductors. They have to withstand both the vertical and radial electromagnetic loads and the External Poloidal Coils are free to expand radially. All coils are layer-winding type, and have an even number of layers in order to locate all the electrical leads on the same side of the coil. Hollow copper conductors are used for cooling with a bore 8 mm or 10 mm, according to the cooling requirement. The conductors are wrapped in glass fabric and kapton tapes, and vacuum impregnated with epoxy resin. The insulation system has a thickness: 1.2 mm between turns, 1.8 mm between layers and 2.4 mm to ground. The obtained filling factors are about 0.85.
The CS coils are mounted around the central post of the machine. Radial grooved plates at the interfaces between coil segments maintain concentricity.
A spring washer system, assembled on the central post heads, ensures a pre-compression of the coils to prevent any relative vertical movement, though, it allows for thermal expansion.

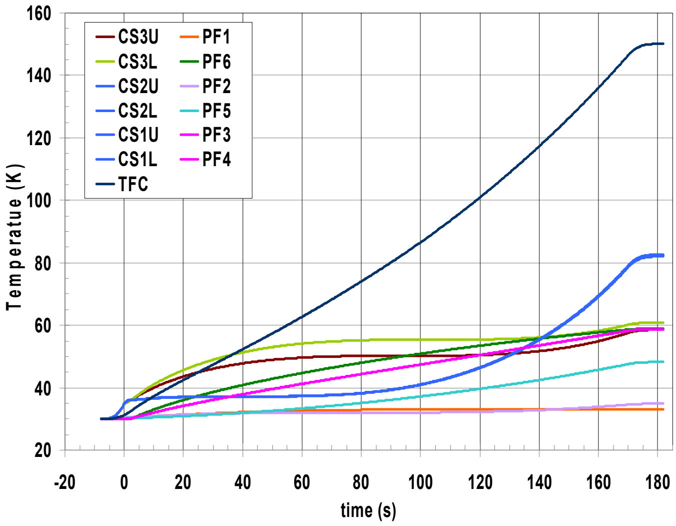

FIG. 5 - Max. Coils Temperatures for AT2

The coil-winding process includes operations such as brazing, hardening of the conductor after brazing, surface treatment, priming and insulating, winding of the conductor in the coil, and final impregnation already tested during FTU manufacturing.

The currents in the turns of the PFCs do not exceed 40 kA, in order to make it easy to design the relevant power supplies, busbars and penetrations through the cryostat of the machine.

The PFCs consist of concentric layers which, as far as their cooling is concerned, can be connected either in series or in parallel, depending on the amount of thermal energy to be removed. The coil temperatures have been calculated by taking into account the magneto-resistive effect with the presence of the plasma column.

In order to contain the temperature rise, the related current density does not exceed 32 MA/m^2 in any foreseen scenario. The final temperature at the end of the most demanding scenario is never expected to exceed 85K in any poloidal coil (Fig. 5).

During normal operation (H-Mode 6.5MA, 7.5T), the vertical and hoop forces on the PFC coils not exceed structural constraints regarding the central solenoid support (vertical outward force around 17 MN) and the external coils support (vertical outward force 30 MN).

Due to plasma VDE disruption, a ~ 9 MN vertical load is produced on the CS coils. This load is resisted effectively by the central post of the CS.

4. Vacuum Vessel

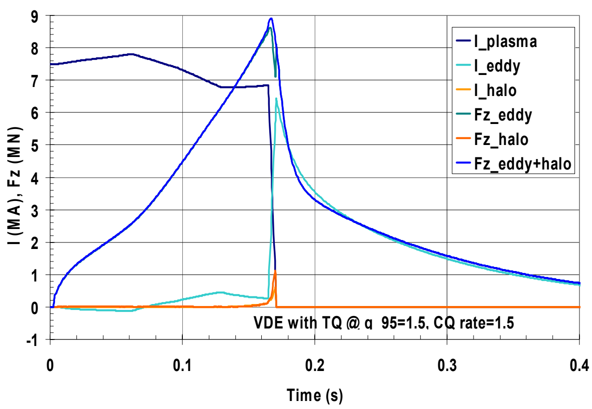

FIG. 6-VDE parameters and Fz EM force

The vacuum vessel (VV) is segmented by 20 degree modules. In order to minimise the flux consumption during the plasma start-up, the vacuum vessel shell is made of Inconel 625 and the ports of stainless steel. The shell maximum thickness is 30 mm, while the ports are 20 mm thick. Manufacturing of the shell is made by hot forming and welding.

The VV provides vertical, oblique and equatorial access ports for the plasma diagnostics systems, the vacuum system, the auxiliary heating system, the in-vessel remote maintenance system, etc.. Ports machine could accommodate 10 MW (45° inclined on plasma cord) NNBI system. Each vacuum vessel sector is equipped with 5 access ports.

During normal operation, the mechanical loads on VV are negligible. Instead, the main loads are due to plasma vertical displacement events (VDE) and disruptions.

The vacuum vessel is supported by the toroidal field magnet system by means of vertical brackets, that are attached to the TF coil case through the vessel equatorial port. According to this constrain scheme, thermal expansion/ contraction of the vessel is allowed, while non symmetric displacements that might appear during disruption or plasma VDE are restrained.
The loads (~9 MN) being taken into account for the stress analysis of the VV are those induced by the plasma disruption. The worst disruption expected is a VDE (Fig. 6) followed by a sudden loss of the plasma thermal energy (when the safety factor goes below 1.5) and then by a fast current quench (1.5 MA/ms) in the 8 MA H-mode extreme scenario. The global load has been obtained by using a proper axisymmetric finite element model with the MAXFEA MHD Code.

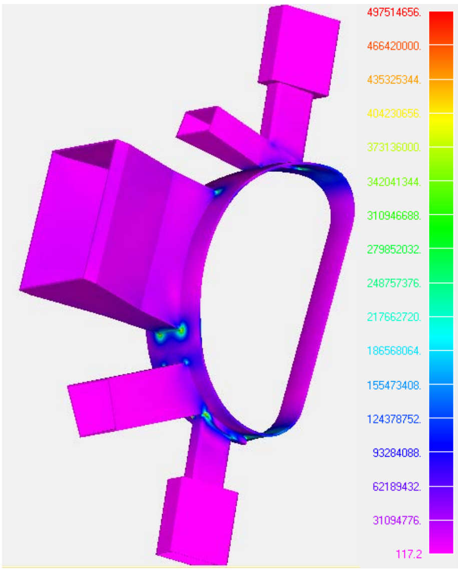

FIG. 7-VM stress (MPa) during the VDE

The stresses induced by the VDE loads have been obtained by modeling a 20° VV sector, and distributing in a proper way the load on the upper area of the VV. 3D finite element stress analyses of the VV performed applying ABAQUS Code showed average VM stresses of 250 MPa (Fig. 7) and maximum displacement of 12 mm. Stresses are within the acceptable limit (Inconel 625 Ys=420 MPa)
The operating temperature of the vessel ranges from room temperature up to ~100 °C. A suitable water loop is dedicated to regulate the vessel temperatures.
Preliminary analyses have been devoted to study the control of the plasma current, shape and position during the flat-top of 6.5MA/7.5T plasma scenario. A copper shell is inserted inside the vacuum vessel, to the purpose of aimed at slowing down the growth rate of the vertical instability around 13 s^{-1}. To avoid flux shielding during plasma breakdown, the shell is toroidally segmented.
The structure of the controller being used consists in a feedback loop, which controls the derivative of the vertical position (using CS2U-CS2L and PF3-PF4 coil pairs), and a slower multivariable feedback loop, which controls the plasma current, shape and position.
The maximum gap displacement after a minor disruption is less than 8 cm, with a settling time of about 2 s. The power required for this stabilization is about 14 MW.

5. Divertor and First Wall

The first wall consists of a bundle of tubes armoured with 4 mm plasma spray tungsten. The heat load impinging the first-wall is, on average, 1 MW/m^2 with a peak of about 3 MW/m^2. The adopted solution is well suited to resist these loads, having been tested up to 7MW/m^2. The first-wall is also adequate to work as a limiter during the plasma start up. Its temperature will be kept around 100°C in order to avoid impurities adsorption. The design has to be remote-handling compatible. The FW maintenance is made from upper ports.
The thermal loads on the divertor plates and of the core plasma purity for the proposed scenarios are governed by the complex relationships binding the core and the plasma edge [6]. In the high density regimes, $n_e \geq 3 \cdot 10^{20}$ m^{-3}, the SOL density is so high to reduce the sputtered impurity flux from W, and the radiation losses due to intrinsic impurities are small. As a

consequence, almost all the heating power is delivered to the divertor and the average power load on the plates could exceed 18 MW/m^2, so that mitigation with impurity seeding has to be considered [6].

The high power flux in the divertor makes suitable for target plates only monoblock W tiles (Fig. 8), constructed according to a recently developed technique. Extensive tests [9] on these tiles have shown that they can withstand without any damage a continuous heat load up to 18 MW/m^2, provided they are actively cooled. The armour consists of hollow tungsten tiles inserted in a heat sink copper tube. The heat flux component will be supported by a steel frame which acts also as cooling circuit.

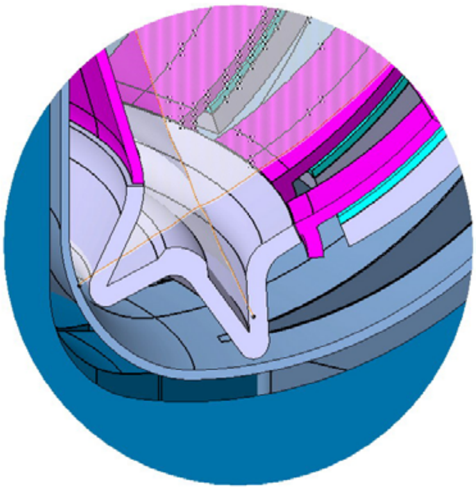

FIG. 8 - Divertor Concept

In the case of L-Li as divertor target, the very low radiative capability of Li implies to seed an impurity in all scenarios to keep the heat load at an acceptable level.

The ELMs impact on divertor has been analyzed by assuming the same spatial deposition profile as inter-ELM, and a factor 2 asymmetry in the in-out ELM energy deposition. The energy density on the inner divertor is expected to be about 0.4 MJm^{-2}, to be compared with 0.5 MJm^{-2}, which is limit value for tolerable W erosion in ITER. Since these condition are expected with the pedestal with low collisionality, high densities ($n_{edge}>10^{20}$ m^{-3}) and temperature comparable to the ITER values, FAST can reproduce quite closely the ITER edge conditions and is able to study and minimize the ELMs perturbation [3,6]

6. Assembly and Maintenance

Each sector of the load assembly completed with the most of FW panels and ICRH antennas will be moved and located to the adjacent sector. A remote operated welding tool will be used under close control by the operator to join the VV sectors. After the completion of each welded joint, vacuum leak tests will be carried out, followed by a full geometrical survey of the sector aiming at identifying any possible distortion to be recovered by machining of the adjacent sector. Two final closure welds will be performed, completely by remote. Once the VV is completed, the VV and TF coils will be moved from the assembly room to torus hall on a special trolley and posed in position. The machine load assembly will be then completed on site by adding support legs, central solenoid, PF coils and cryostat. The scheme of the divertor maintenance operation is as in ITER with the frame acting as a carousel all around the machine. The maintenance will be done from the lower port. The Divertor maintenance is based on the development of an ad hoc cassette mover tractor, capable to grasp and move the Divertor cassette. As far as the FW assembly and disassembly is concerned, an articulated boom plus a front end manipulator has been considered.

7. FAST power supply system

FAST power supply system includes three main subsystems: the 400 kV switchyards, the Poloidal Field Coils (PFC) power supplies (PS) and the Toroidal Field Coil (TFC) PS.

Fig. 9 shows the total power for the reference scenario I_P=6,5 MA; B_T = 7,5 T also including: 140 MVAr local Reactive Power Compensation system (using Static VAR Compensators) integrated with the Harmonic Filtering units, 150 MW (at grid level) for Additional Heating Systems and 25 MW for Auxiliaries. Due to the amount of requested power, connecting to a powerful node of the 400 kV Grid is needed. For this reason, an accurate check by TERNA S.p.A (owner of the National Transmission Grid, RTN), including both active and reactive power effects on the specific grid, has been performed and provided positive results for two potential ENEA's sites.

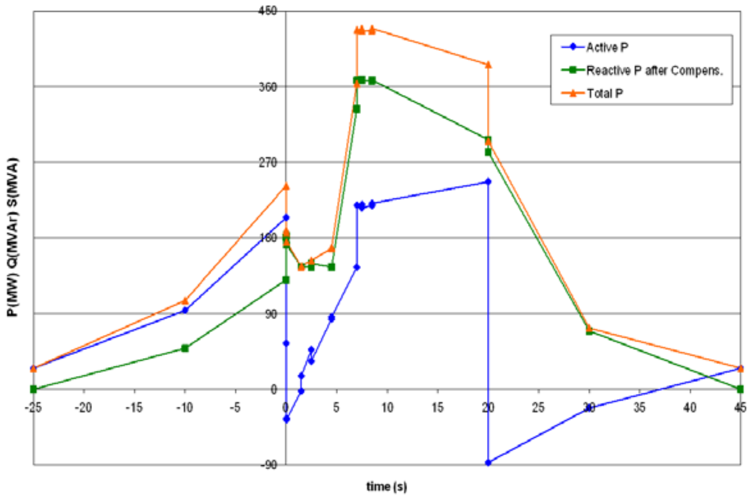

FIG. 9 -FAST Electric Power from the 400 kV grid

Within the assumed 400 kV reference solution, FAST needs a dedicated switchyard to supply PFC, TFC, Additional Heating Systems and Auxiliaries. All loads are fed by one Main Step Down Transformer (400/36 kV) with two secondary star connected windings (225 MVA each, grounded through a resistor) and a tertiary short-circuited, delta connected winding (150 MVA) to allow free circulation of third harmonic currents. On the basis of the analysis performed by TERNA, Active Power Shedding is not requested; in any case, if needed in the future, dedicated switched resistors might be connected to the tertiary winding, for this purpose.To share the total power between two secondary windings has the scope of making possible to use 36 kV level on the secondary sides (instead of the more expensive 75 kV level), thus limiting the rated current and short circuit current within the present breaker capability at this voltage.

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