MAIN DESIGN FEATURES AND ENGINEERING CHALLENGES

Presented by G. Spigo on behalf of the joint Russian-Italian working group

TABLE OF CONTENTS

INTRODUCTION

The current project has been developed by ENEA under the leadership, guidance and supervision of Prof. B. Coppi of the MIT (Massachusetts Institute of Technology) in collaboration with Ansaldo (Italy) as industrial partner for the engineering the overall design.

In close cooperation with Prof. B Coppi and ENEA, Ansaldo performed the conceptual and detailed study in order to verify the structural and industrial feasibility of the object, forecast to ignite the toroidal plasma with a strong rate of ohmic heating.

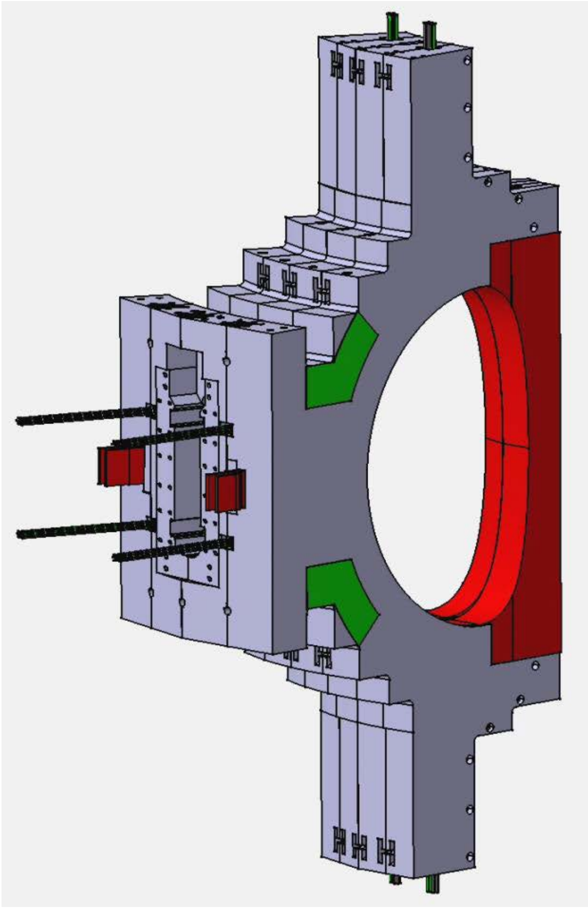
The most important items of the assembly, shown in the list below, were examined and studied exhaustively.

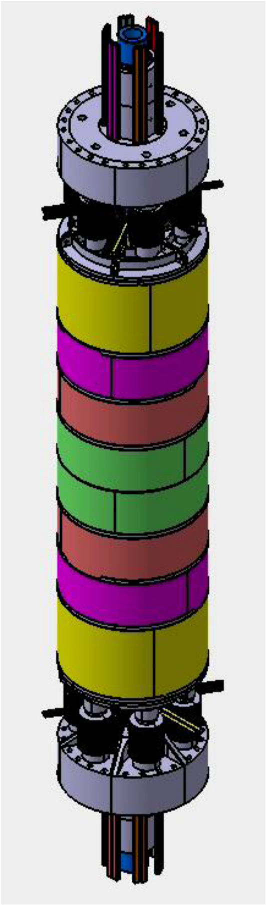
1) **Central Solenoid**
2) **Vacuum Chamber**
3) **First Wall**
4) **Radial Preloading System**
5) **C-Clamps Structure**
6) **Toroidal and Poloidal Coils**

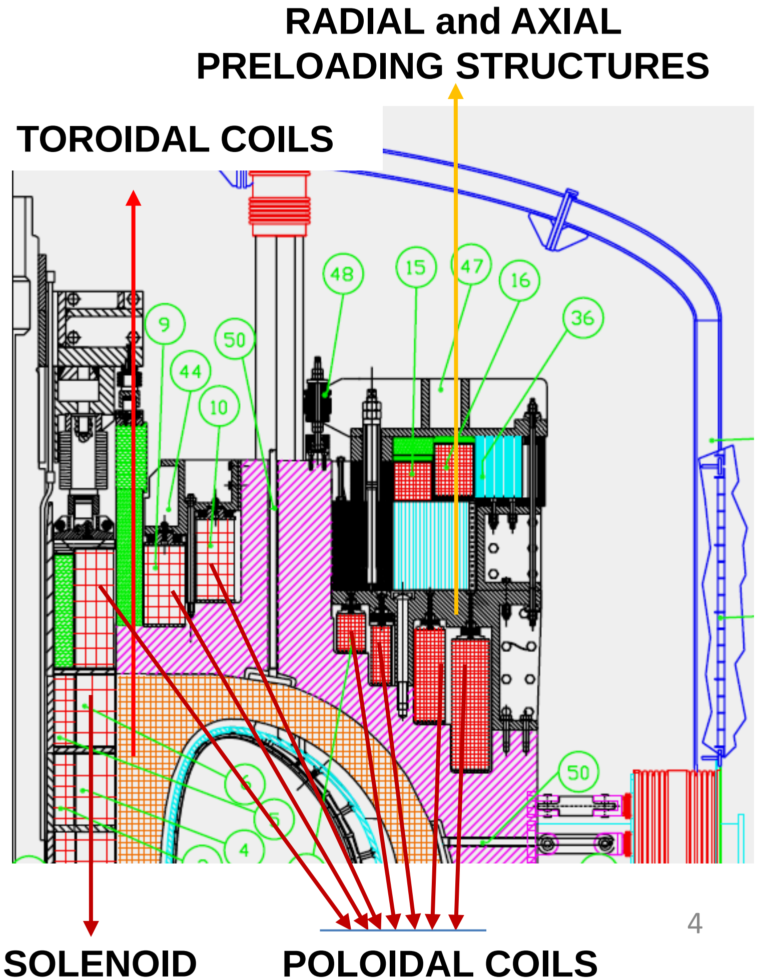
Subsequently, a complete design was carried out to understand the most critical points and the best possible ways to solve them conveniently. In addition, to obtain crucial information to validate the adopted decisions several mockups such as coils, vacuum chamber and stainless steel structures were manufactured and somehow tested in the meantime.

IGNITOR is a compact fusion machine studied for producing high plasma current in order to attain both the temperature and the energy confinement necessary for plasma ignition.

Its layout consists of twelve modules of 30° each housing two toroidal field coils. Poloidal coils are placed in the assembled aggregate and kept in position with both radial and axial preloading structures.







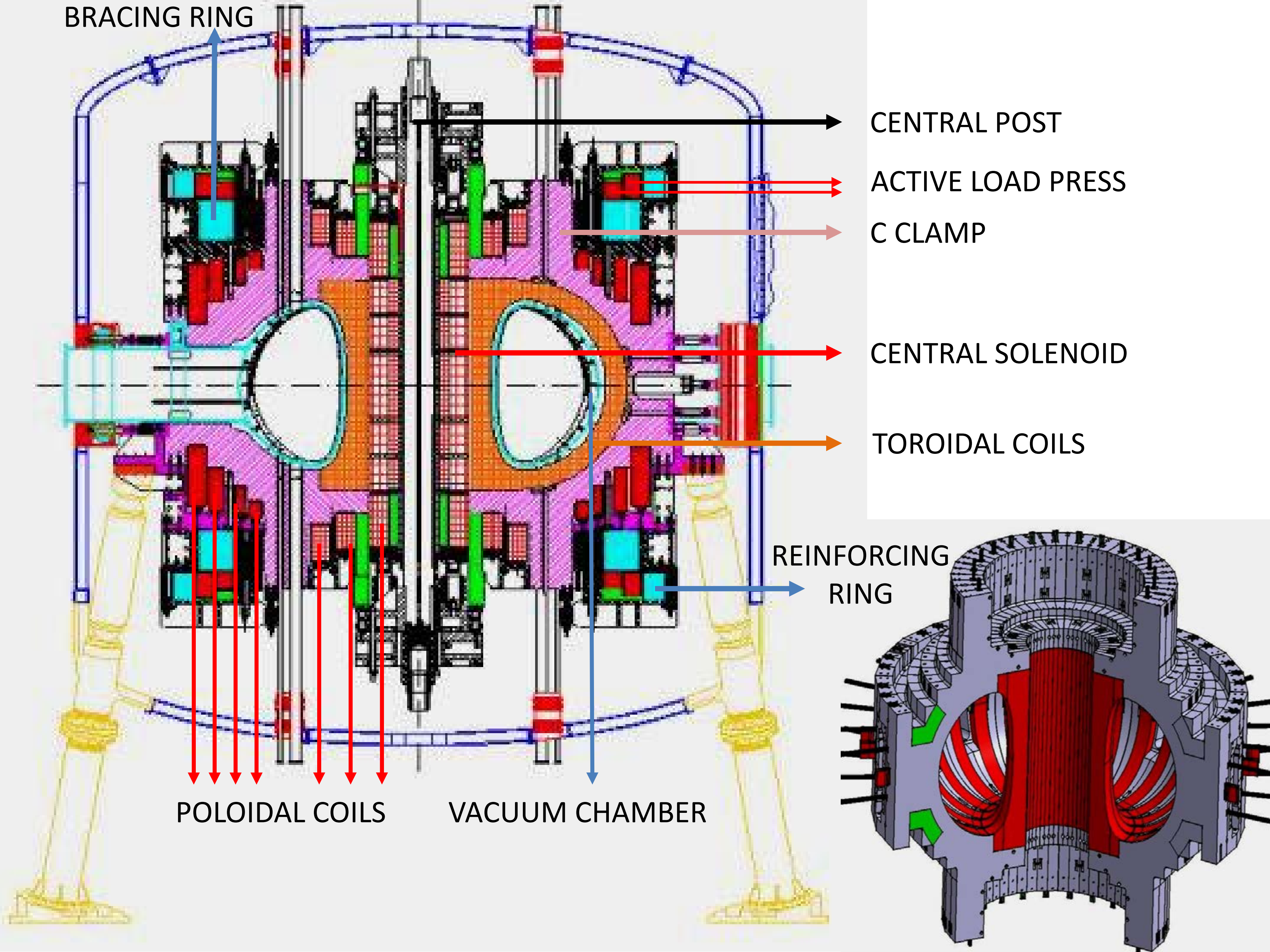
ELECTRICAL AND MECHANICAL COMPONENTS

The main electrical components of IGNITOR are the following:

1. Toroidal magnet assembly composed of 24 CuOFHC coils
2. Poloidal magnet arrangement constituted of 6x2 CuOFHC coils (up and down with respect to the equatorial section) plus 2x2 coils supplying the active preloading system (shrink fit).
3. Graded Ohmic Transformer (central solenoid) composed of 7x2 CuOFHC coils (different percentage of cold work among conductor layers).

The principal mechanical features of IGNITOR are the following:

1. Central post providing a compressing preload in vertical direction.
2. C-Clamp structure composed of 48 modules, 7.5° each, grouped in number of 4 to realize twelve 30° modules, each of them housing two toroidal coils and being the support of the vacuum vessel.
3. 2 bracing rings, surrounding the C-Clamps assembly producing a passive preload in radial direction and ancillary structures as support for the outer poloidal coils.
4. 2x2 circular coils, surrounding the C-Clamp, producing, when energized, an active compressive load in radial direction.
5. 2 reinforcing rings encircling the 2x2 coils generating the active compressive force when energized.
6. The vacuum chamber holding the first wall and enveloping the plasma.


BRACING RING
CENTRAL POST
ACTIVE LOAD PRESS
C CLAMP
CENTRAL SOLENOID
TOROIDAL COILS
REINFORCING
RING
POLOIDAL COILS
VACUUM CHAMBER

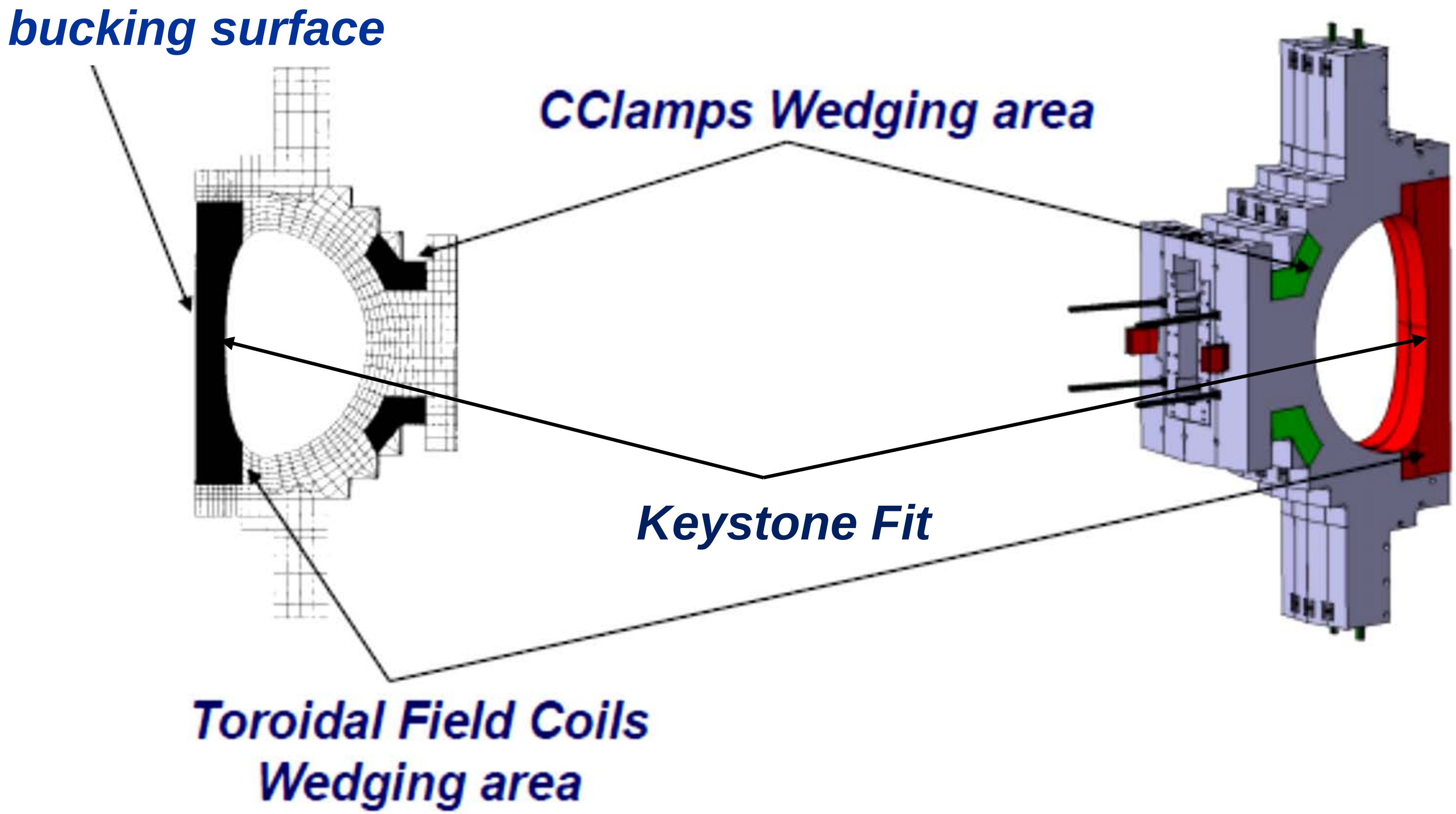
STRUCTURAL DESIGN CONCEPTS

The machine relies upon an accurate matching of the different components constituting the various subassemblies. The main design concepts are:

1. **Precise keystone fit of the inner portions of the Toroidal coils.**
2. **Faultless contact among the wedging areas of the C Clamps**
3. **High fitting precision between the central solenoid and the Toroidal coils**
4. **Strict fitting accuracy between the Toroidal assembly, the Poloidal coils and the Bracing rings**

The assembly techniques must be such that the aforementioned concepts could be fulfilled completely and relying on:

1. **Pre-tensioning of the bracing rings, insuring the suitable keystone positioning among all mating surfaces so that the inner portion of the Toroidal coils (legs) could act as "solid" column while the matching surfaces of the C Clamps could efficiently transfer the hoop stress produced by the energization withstanding the shear stresses in the Toroidal coils (TFCs), generated by the out-of-plane force and caused by the cross product of the poloidal field and the toroidal field coil current.**
2. **The close fitting between the inner portion of the Toroidal coils and the central solenoid allows a good transfer of the generated forces in opposite direction (centripetal for the Toroid and centrifugal for the Solenoid).**
3. **Calibrated central post dimensions in order to permit an appropriate axial pre-compression of the legs to bear the component of the magnetic forces acting in that direction.**

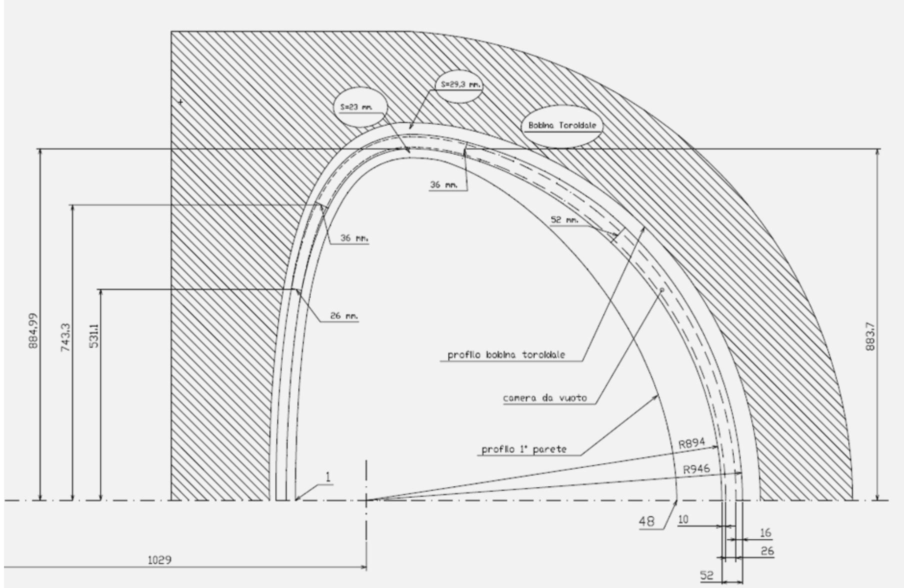


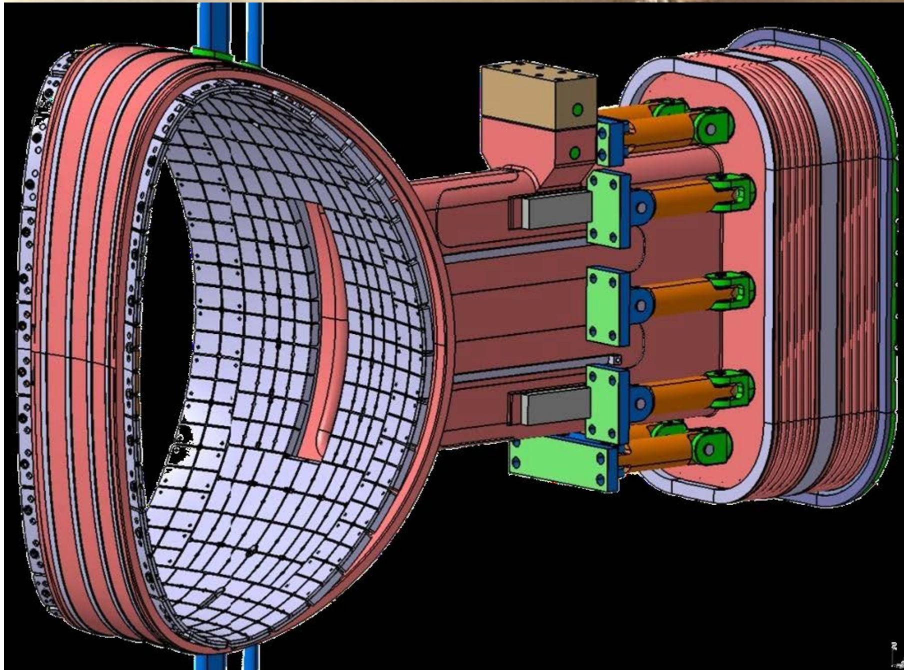
The size and the shape of the wedging and bucking surfaces are paramount to permit the most appropriate development of the force transfer chains for both radial and axial loads. Extensive runs of calculations show that the areas, indicated in the above pictures, are the most effective ones to fulfill the needs of mechanical robustness and electrical performance of the apparatus. To precisely fit all these components, it is also foreseen a proper machining of the radial gaps between the Solenoid and the TFCs during the initial machine assembly.

As already mentioned, the other essential component of IGNITOR is the toroidal shaped Vacuum Vessel (VV), which has variable thicknesses (26-36-52 mm) to withstand the Vertical Displacement Event (VDE) loads while having a more uniform stress distribution. It is worth noting that the VV is fully welded to achieve the required high strength and electric resistivity. The welding thickness among modules is always the same (26 mm) implying that the connecting surfaces are machined accordingly.

The VV also serves as support for the first wall protection composed of molybdenum alloy (TZM) tiles precisely positioned relatively to the magnetic field lines to minimized thermal loads concentrations. The size of the tile is defined considering the EM loads generated throughout plasma disruption.

The tiles are screwed to supporting plates (carriers), fixed to the VV by means of studs accurately arc welded to the VV wall.



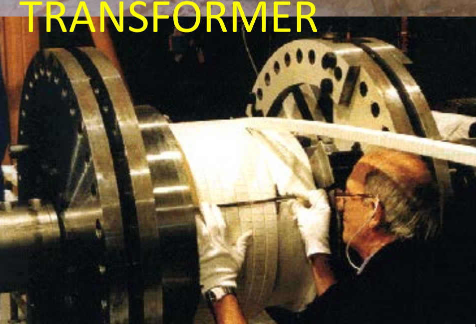


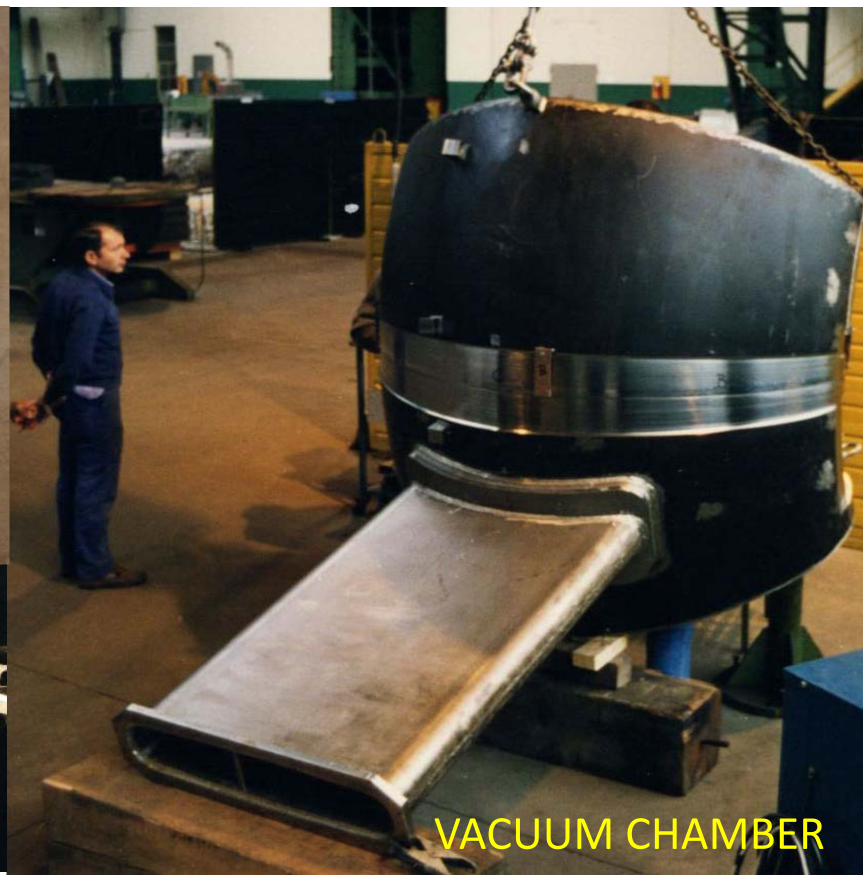
TECHNICAL AND DESIGN ISSUES TO BE SETTLED

The previous transparencies showed a well focused and complete design effort where the main choices, solutions and proposals were validated by models and prototypes documenting that a manufacturing process for the soundly blueprint objects can be launched.

In fact, in the years 2000 an intense R&D program was established to check the industrial feasibility of the design and, then, tune it up to be ready for the subsequent production step.

TRANSFORMER



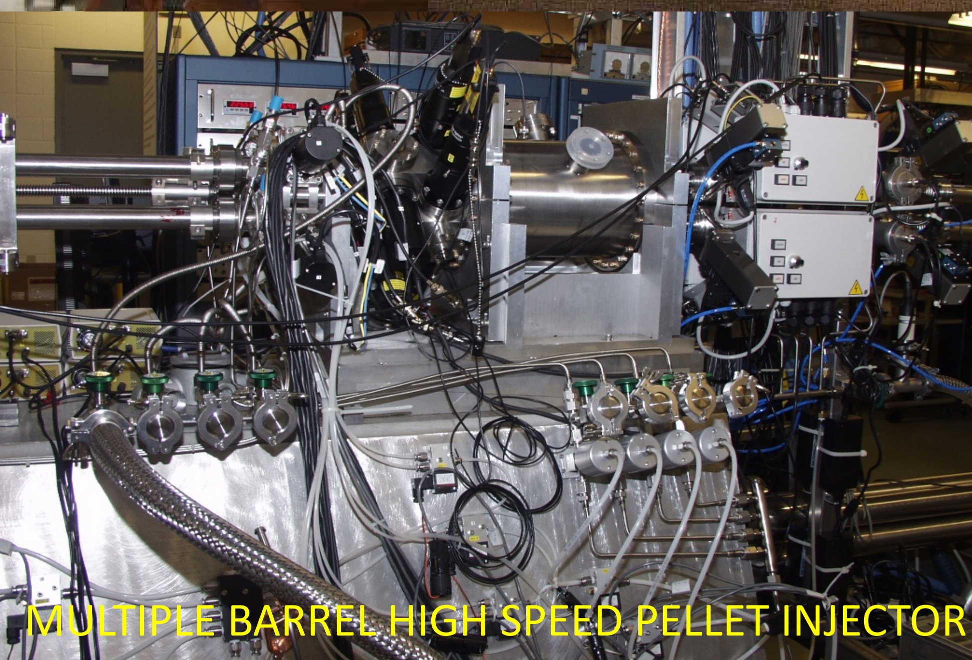


VACUUM CHAMBER

TOROIDAL COIL


TOROIDAL COIL
EB WELDING


C CLAMP


MULTIPLE BARREL HIGH SPEED PELLET INJECTOR


ICRH VACUUM TRANSMISSION AND ANTENNA

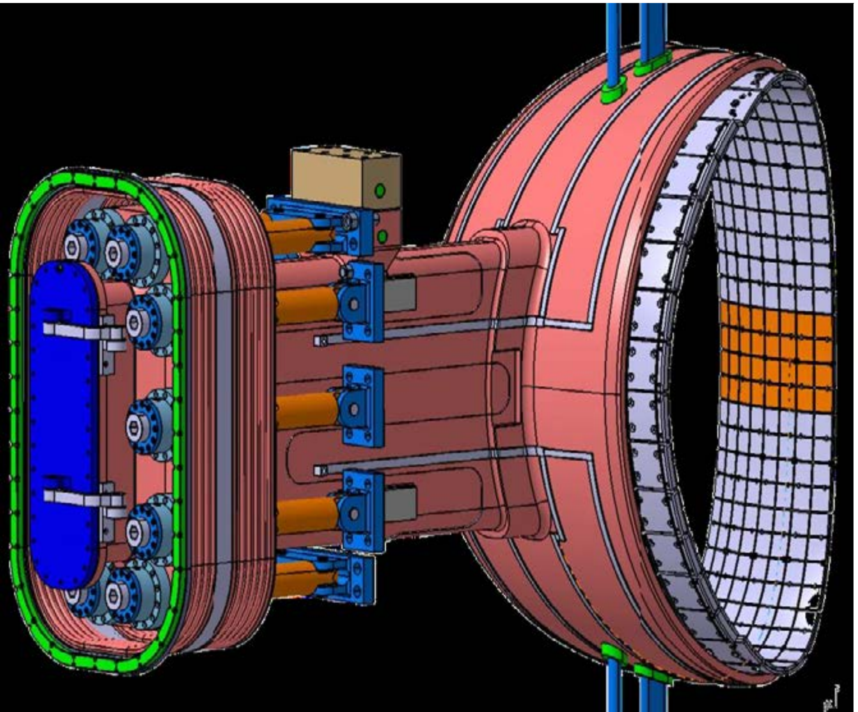
The joint Russian-Italian working group, in charge of the publishing of the Conceptual Design Review (CDR), in its analysis has highlighted specific technological points and topics needing further investigations and developments. Among all the analyzed subjects, the working group has identified and selected a list of matters to be resolved that are considered highly significant in order to be confident about the successful completion of the project.

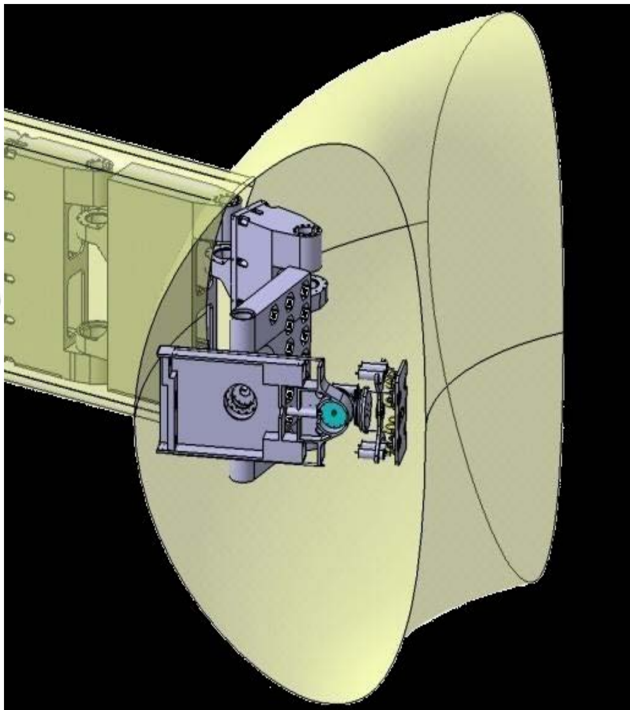
The identified issues, called mock-ups in the CDR, are the following:

1. **Welding for the closure of the Vacuum Vessel (tooling, procedures and tests).**
2. **Machining of the cooling groove in the Toroidal coil turn and Electron Beam Welding (EWB) of the cover plate and related inspections.**
3. **Welding of Nelson studs to the Vacuum Vessel. Definition of the welding parameters and procedures to obtain a parallel and straight position of the studs among themselves.**
4. **Measurement of the friction coefficient between mating interfaces.**
5. **Measurement of shear strength for the insulating material of solenoid coils.**
6. **Mechanical and electrical tests on central solenoid conductors.**
7. **Remote handling and manipulation of the TZM tiles.**
8. **Model of poloidal coil number 14 wound with an MgB_2 superconductor.**

CLOSURE OF THE VACUUM VESSEL – WELDING AND INSPECTIONS

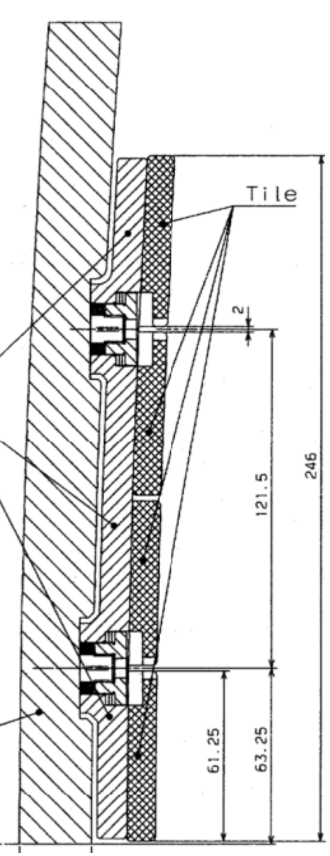
Due to the lack of space and access, the final assembly and the welding closure of the vacuum chamber needs to be executed remotely operating from the chamber equatorial port. This means that a specific tool is needed. This consists in an articulated boom inserted through the equatorial ports and equipped with either a welding torch (laser for root pass and TIG for filling the rest) or a welding inspection apparatus. Moreover, this tool will have to be able to carry out other devices in case of repair (grinding and cleaning tools). Thus, a dedicated mock-up, simulating a portion of the toroidal chamber with its access port, is necessary to perform tests with an expressly dedicated welding robot because industrial ones cannot fulfill the needs. This robot is an essential part of the R&D program, which might be adapted or used as it is for the subsequent final assembly on site.

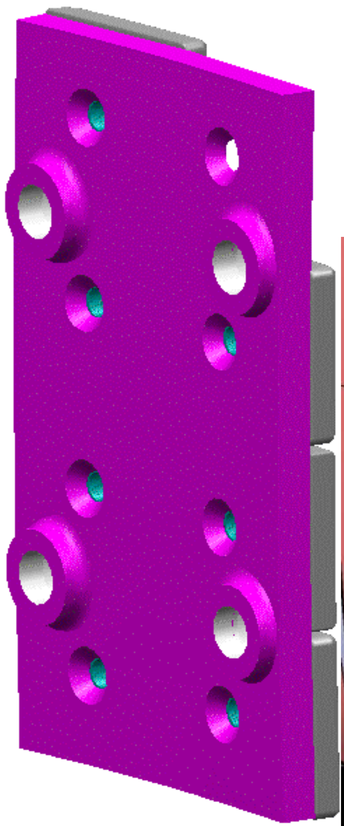


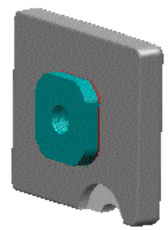


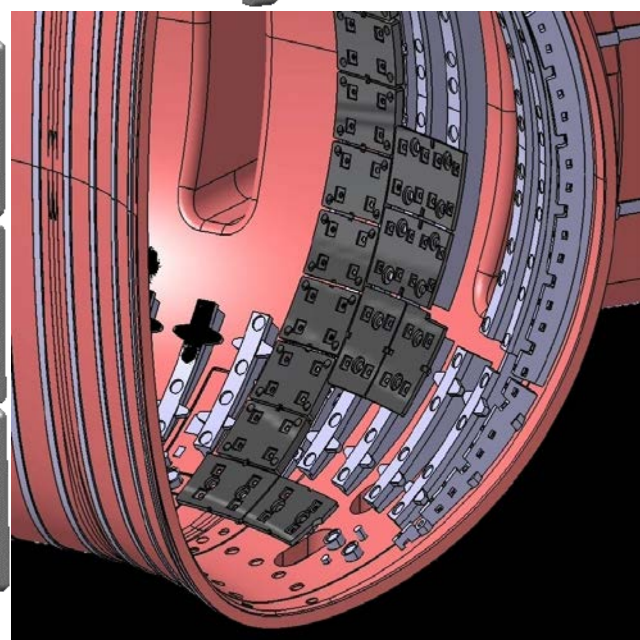
ARC WELDING OF THE STUDS TO THE VACUUM VESSEL

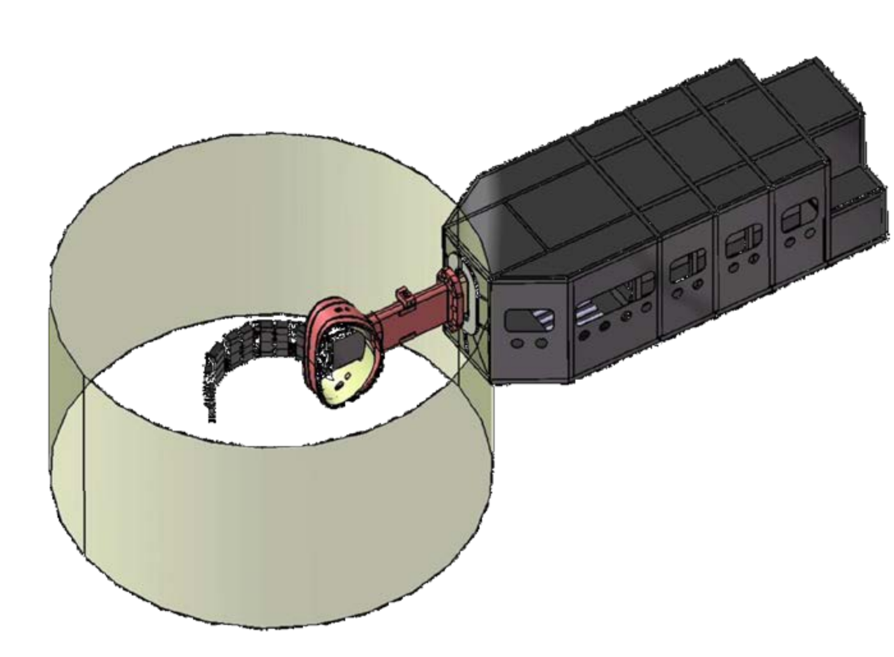
The first wall made of TZM tiles is a VV protective shielding for both particles and radiative heating that are produced by the plasma. These tiles cover the complete surface of the VV. The tile is brazed to a square back plate. The back plate is interlocked in the specifically shaped carrier groove and screwed to the carrier. The shape of the groove is such that any rotation of the tile is prevented. A given number of tiles are fixed to the carrier, which is bolted to the VV with special bolts engaging the protruding threaded Nelson studs arc welded to the VV. Therefore, the stud placement is paramount for both carrier fixation and upkeep.

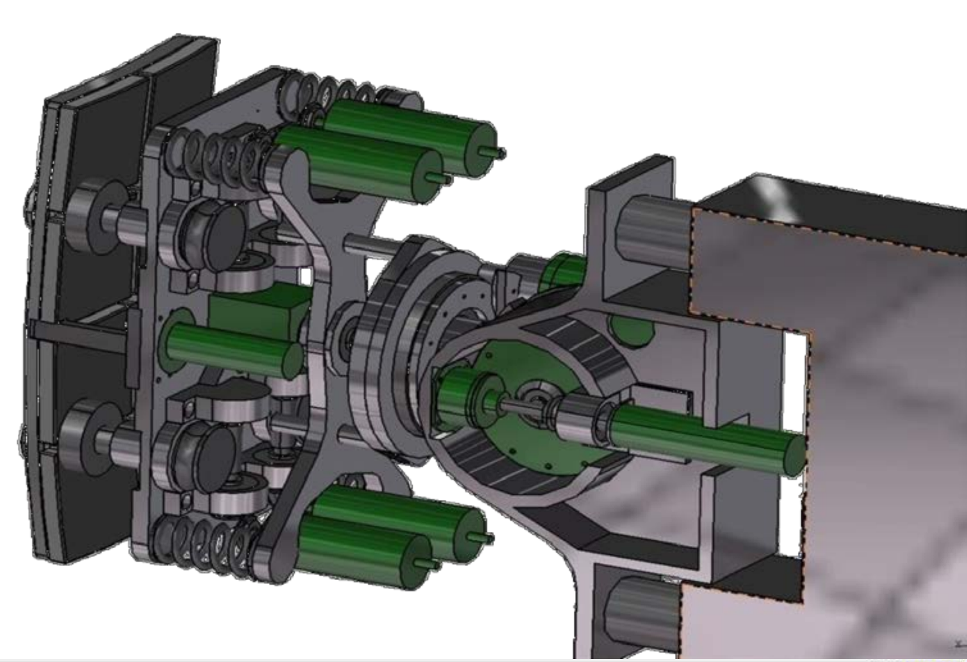


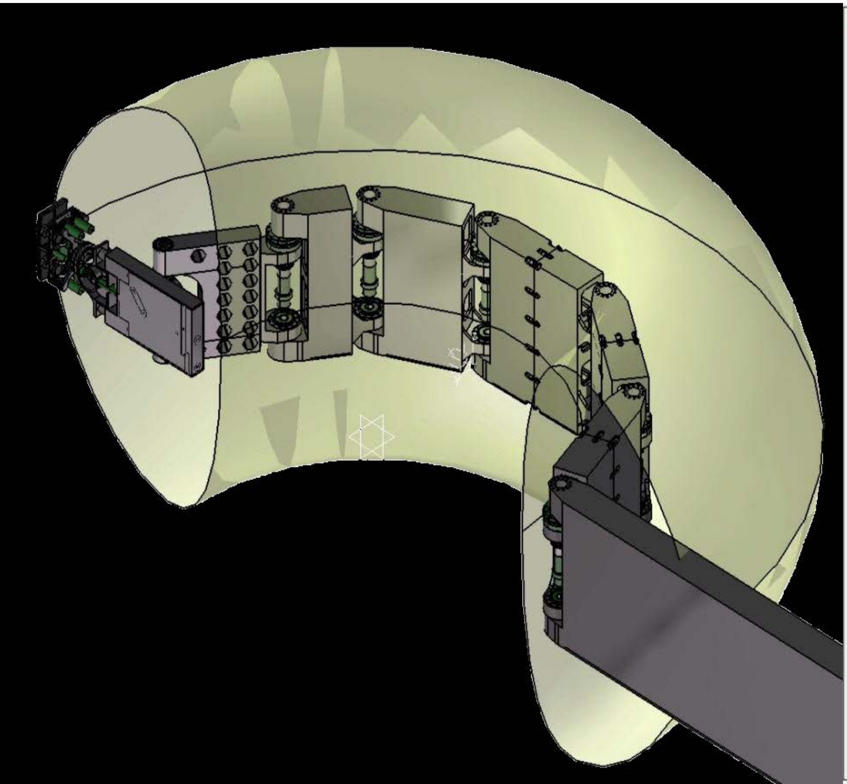


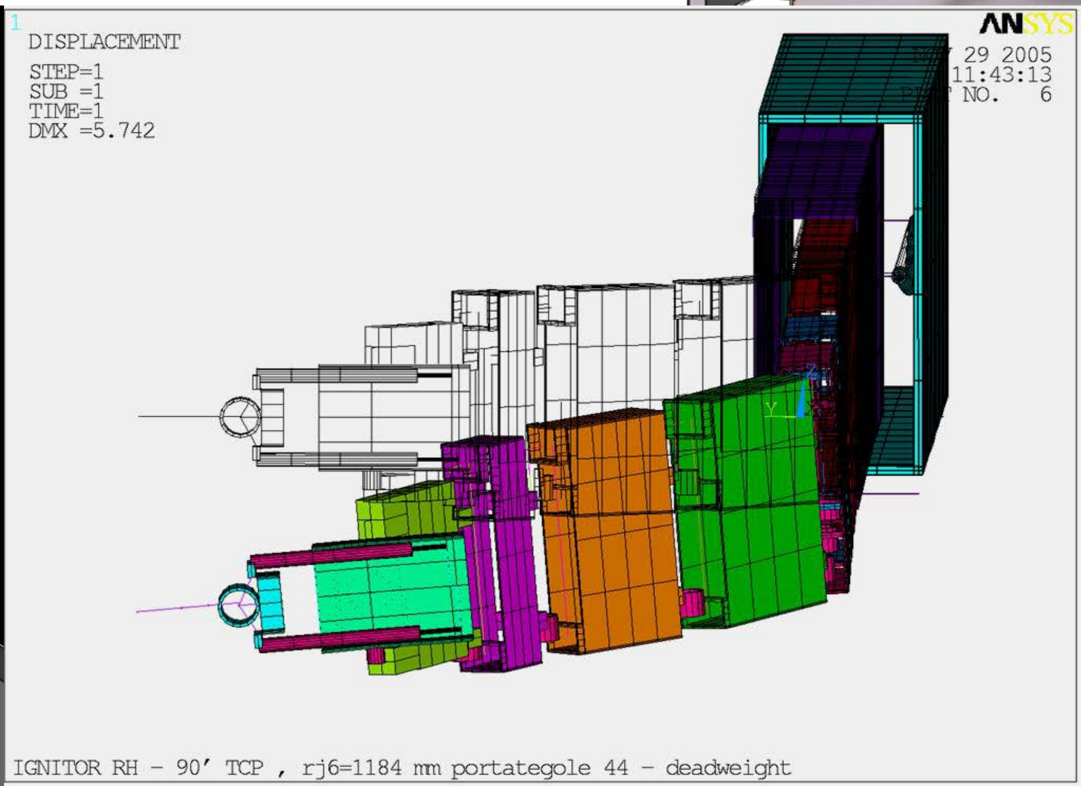








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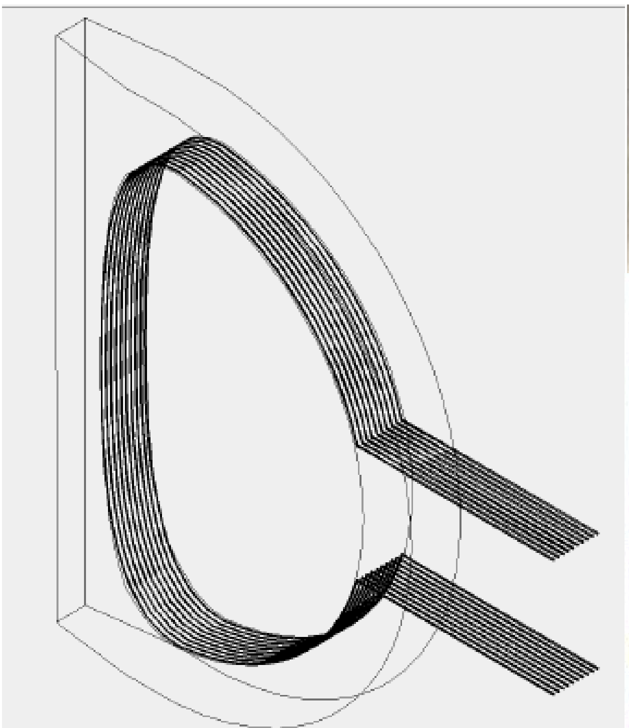
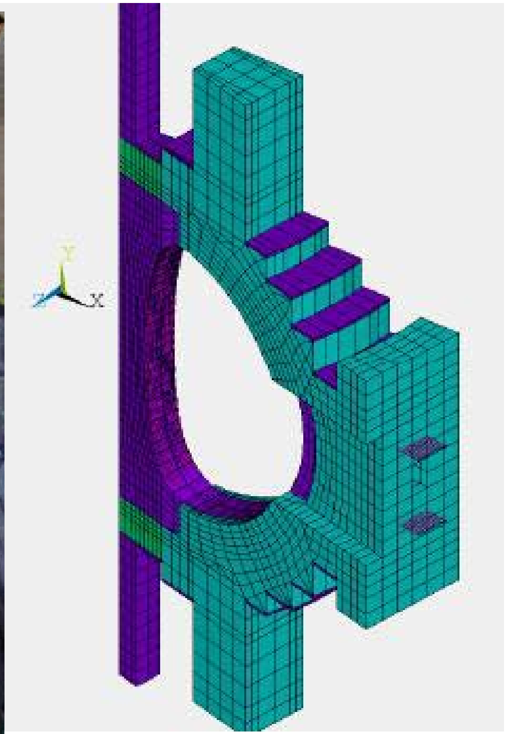
IGNITOR RH - 90' TCP , rj6=1184 mm portategole 44 - deadweight

TOROIDAL COIL TURN
COOLING GROOVE MACHINING AND COVER PLATE EWB WELDING

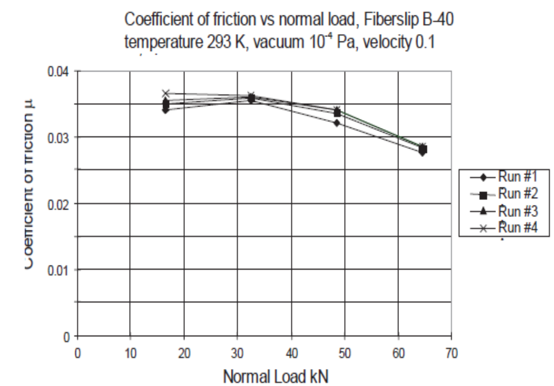
For a more efficient cooling of the toroidal coils and a subsequent shorter cooling time between two experimental attempts, the turns are cooled on their internal periphery by means of channels where the helium can flow. The channels are obtained by making a rectangular groove that will be covered with a strip that is going to be welded using the electron-beam technique. The mock-up must verify the feasibility of the machining, the accurate positioning of the closing strip and the following EWB welding requiring a vacuum chamber of adequate size. It ought to be furthermore tested the deep drilling connecting the inside channels to the inlet/outlet feeding cooling system.

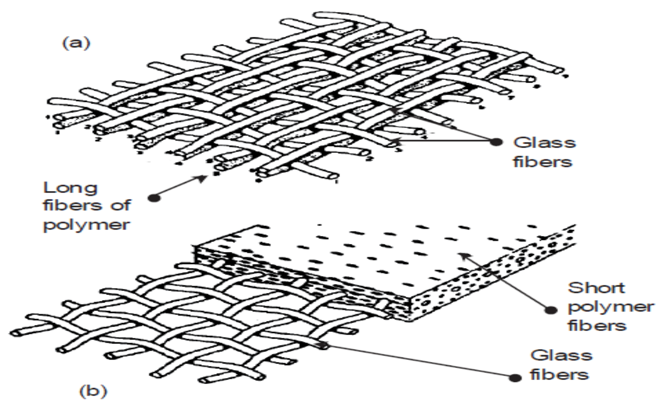


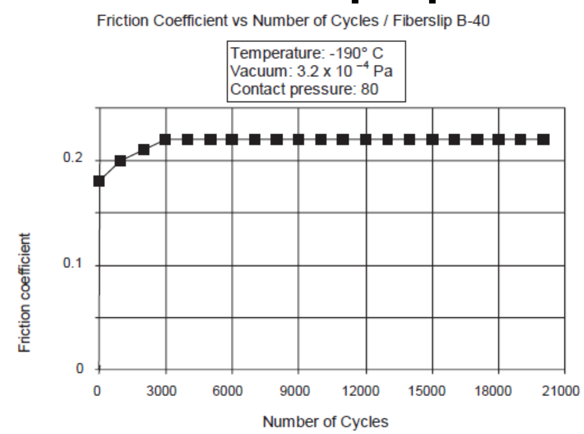


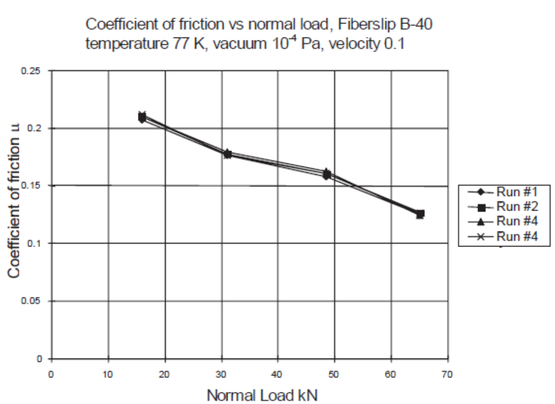
MATING INTERFACES FRICTION COEFFICIENT MEASUREMENT

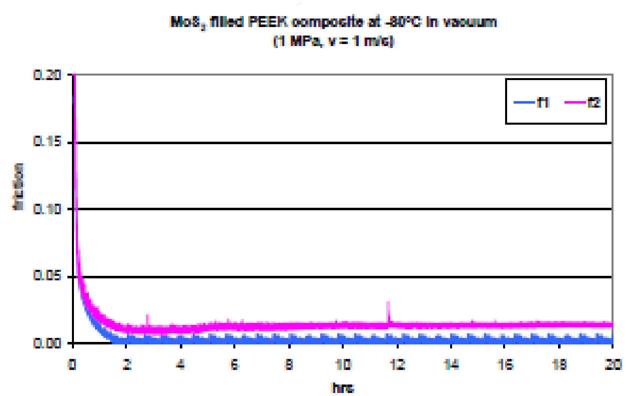
Materials having a low friction coefficient value, inserted between two mating surfaces are essential for the correct performance of IGNITOR. The interface between the C-Clamp and the Toroidal coil is one of the zones where this need is more evident. In addition to friction values ranging between 0.05 and 0.1 in vacuum and at cryogenic temperature, these materials must withstand pressures close to 150 MPa and, therefore, be extremely robust in terms of stress, cycling fatigue, abrasion and radiation resistance. For the interface between the solenoid and the TFCs, the pressure is even larger (around 300 MPa). Promising materials, already known and under study, must be checked and validated for our purposes.

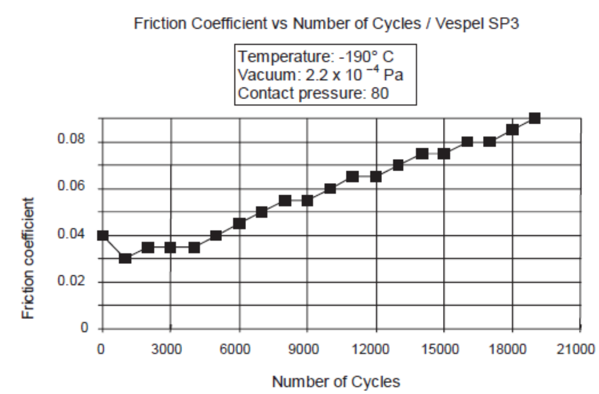










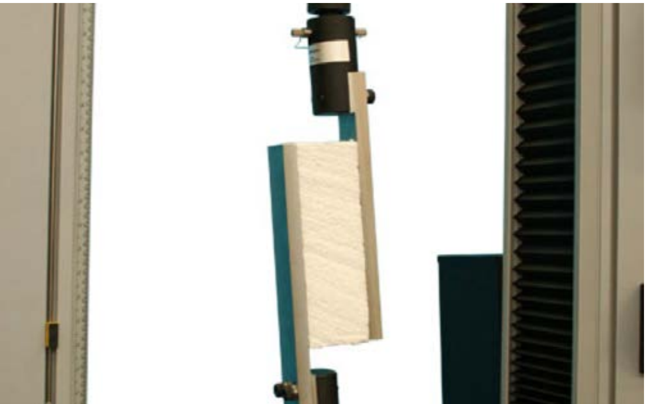


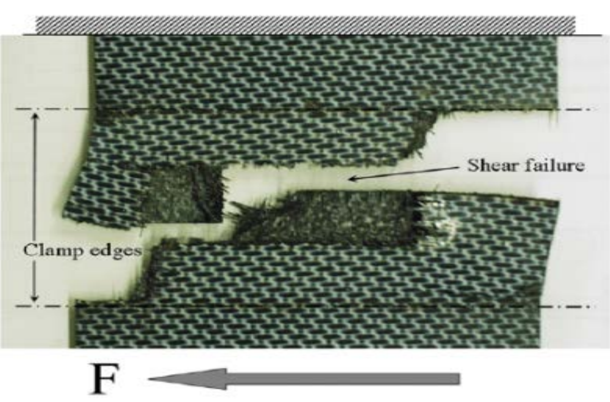
CHARACTERIZATION OF THE SHEAR STRENGTH PROPERTIES OF THE INSULATING MATERIAL FOR THE SOLENOIDAL COILS

It is of a great importance the evaluation of the shear strength τ as function of the compressive stress σ_n perpendicular to the insulation layer at both room and cryogenic temperature. The knowledge of these characteristics are fundamental for the manufacturing soundness of the most critical components of the machine. Previous performed tests results on TFCs turn insulation, at room and LN_2 temperatures, can be expressed and formulated with the two Coulombian laws shown below, where τ_0 is the shear stress at no compression.

$$\tau = \tau_0 + f_s \sigma_n = 55.4 + 0.289\,\sigma_n \qquad at\ 293\ K$$
$$\tau = \tau_0 + f_s \sigma_n = 87.1 + 0.325\,\sigma_n \qquad at\ \ 77\ K$$

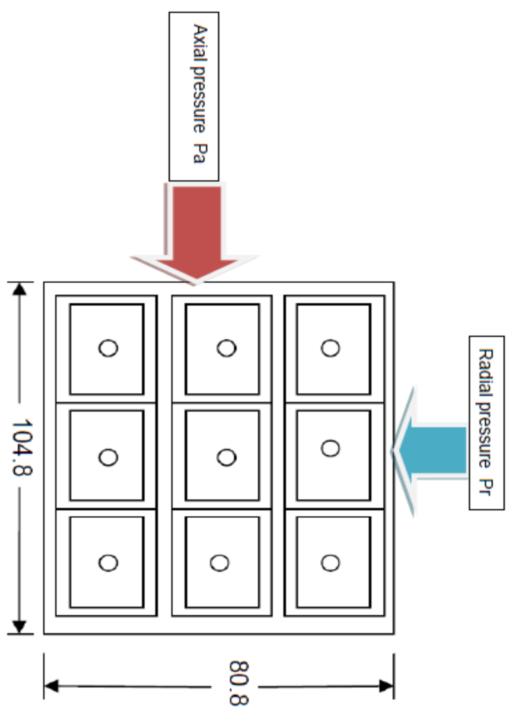
As no test was carried out for the insulation of the solenoid, the calculations were made considering a constant f_s value of 0.35 at any temperatures and τ_0 figures reflecting the insulation shear stresses under different scenarios. Therefore, the confirmation of the adequacy of τ_0 and f_s input in the FEA computation is essential to be confident for the subsequent production of the solenoidal coils.

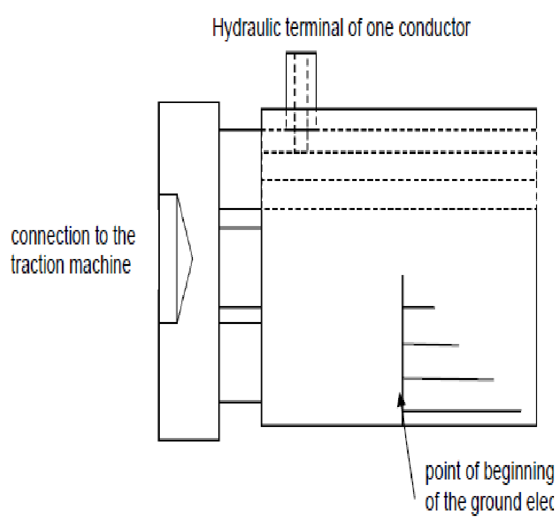


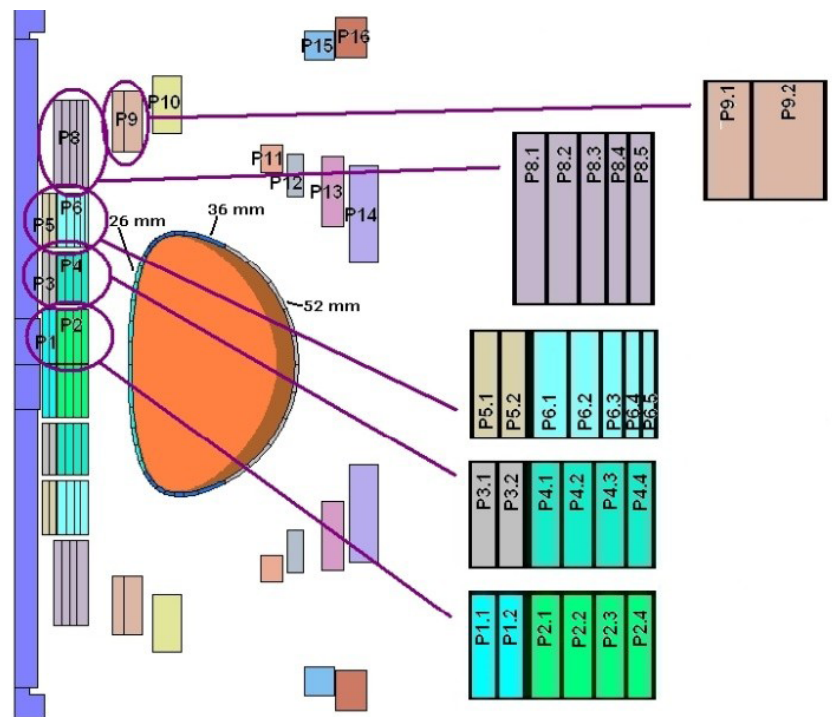


MECHANICAL AND ELECTRICAL TESTS ON SOLENOID CABLES

When the full current scenario is applied the coils P1 and P4 of the central solenoid will be heavily stressed due to their own EM forces and the radial interaction with the TFCs. The stress in the copper approaches the yield point while the electric insulation undergoes to high shear and compressive stresses. Calculations may make the designers aware of the stress level but cannot give any information about the stress conditions to which the weakest element of the winding, which is the coil insulation, is submitted. The information about the electric performance at working temperature can be obtained by loading a sample, composed of a block of conductors, with two compressive forces acting both axially and radially simulating the stress in the coil at full current.

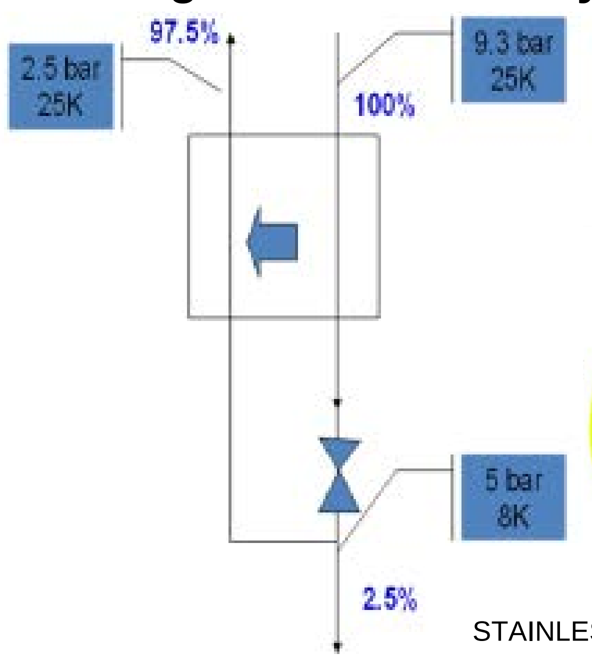


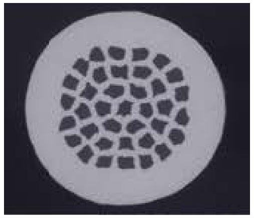


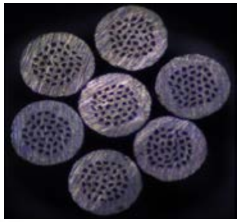


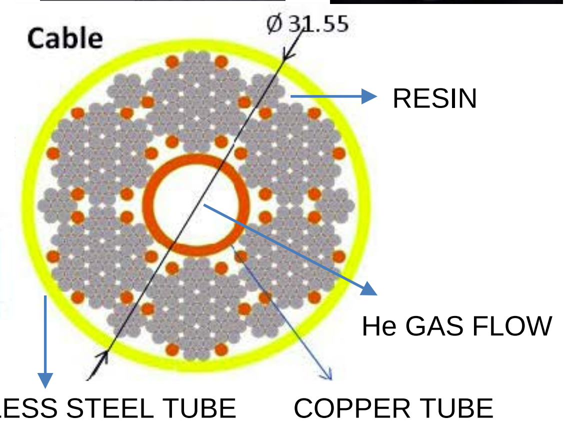
POLOIDAL COIL WOUND WITH MgB_2 SUPERCONDUCTING CABLE

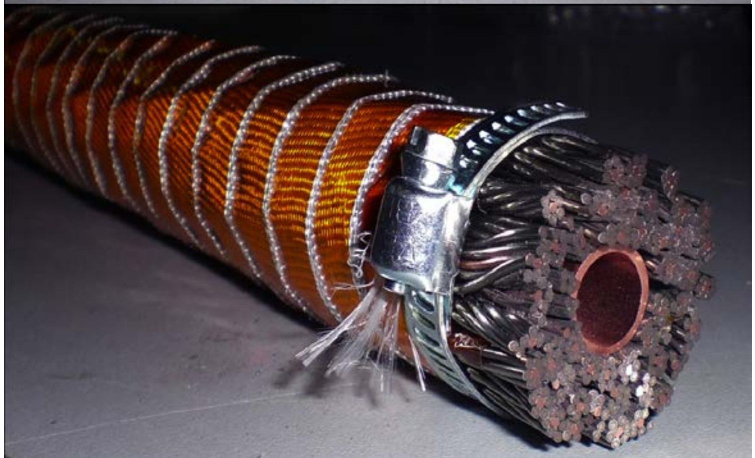
Due its size (Ø 5 m) and its operating current and field (34.7 kA and 5 T), the P14 is the best candidate to be wound with MgB_2 as the magnetic field for the other coils is higher. Since the original copper coil may present manufacturing issues due to its large size, a previous design revision proposed the possibility to make a coil with an HTc like the MgB_2 that in future projects, in combination of Cu coils, may improve the plasma duty cycle. Its application would permit a reduction of the dissipated power and an increase in mechanical strength. To attain the aforementioned performances, the MgB_2 coil is cooled at 8-10 K, which is compatible with He gas flow at 30 K of the cooling system of the machine by adding a heat exchanger and a Joule-Thomson valve to the actual cryogenic layout. The forecast model ($Ø_{inner}$ 1 m, $Ø_{outer}$ 1.9 m) will operate at the same current and magnetic field density leading to proportional loads and stresses in the coil.











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