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Engineering evolution of the ignitor machine

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Abstract

Ignitor is the first ignition experiment conceived and designed on the basis of existing technologies and knowledge of plasma physics. Recent design activities within the Ignitor program have led to improve several of the main machine components. The present design of the central post allows for assembling and disassembling of the central transformer coils. The central post can take up the repulsive forces between the coils, this allows for greater freedom in programming the currents in the central coils and flexibility in controlling the plasma shape, the Plasma Chamber (PC) is supported through the ports by the Toroidal Field (TF) magnet structure. The new supports are designed to withstand the electromagnetic forces due to plasma disruptions and to allow the appropriate thermal expansions. The entire machine is cooled by helium gas down to 30 K, a system preferred to the hybrid helium–nitrogen cooling concept. Cooling the structural components at this temperature improves the role of wedging in withstanding the electromagnetic forces on the toroidal magnet. A metallic cryostat under vacuum was adopted. The vacuum reduces temperature gradients in the space immediately surrounding the machine, provides good thermal insulation, and second containment system for tritium. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Ignitor; Plasma chamber; Support; Cryostat; Central post; Cooling system

1. Central post

The engineering evolution of the Ignitor machine, has led to an improved design of the central solenoid (CS) while the CS coils concept (7 + 7 coils) remains unaltered [1]. The mechanical design arrangement has the following features:

1. The fully assembled CS can be installed and removed from the machine load assembly (in the Torus Hall) with a relatively simple operation, which in principle can be carried out in Remote Handling (RH) condition.
2. The improved cooling system of the CS coils can better control the temperature of each coil and therefore to allow for a greater current range.
3. The central post heads (upper and lower) withstand the repulsive load produced by

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coils P5 and P6. A spring washer system, assembled on the heads, ensures a pre-compression of the coils to prevent any relative vertical movement (760 tons) but allowing for thermal expansion (Fig. 1).

4. Due to plasma Vertical Displacement Event (VDE), disruption at 5 s under the most pessimistic conditions, 1200 tons vertical load could be produced on the CS. This load is resisted by the friction between CS coil and TF coil (in bucking at that time).
5. The central post and coils sleeves design (Fig. 2) takes care of the interface problems between the coils and the central post. Each pair of coils 1–2/3–4/5–6/dummy-8/ is mounted on a sleeve made up by a steel cylinder and a disc.
6. Radial slots machined on the discs and axial grooves machined on the central post allow to run the coil electrical busbars and the hydraulic feed pipes through them and to resist the induced electromagnetic loads (Fig. 3).
7. Keys on the sleeve assemblies maintain the coil position and transfer torsional load to the central post.

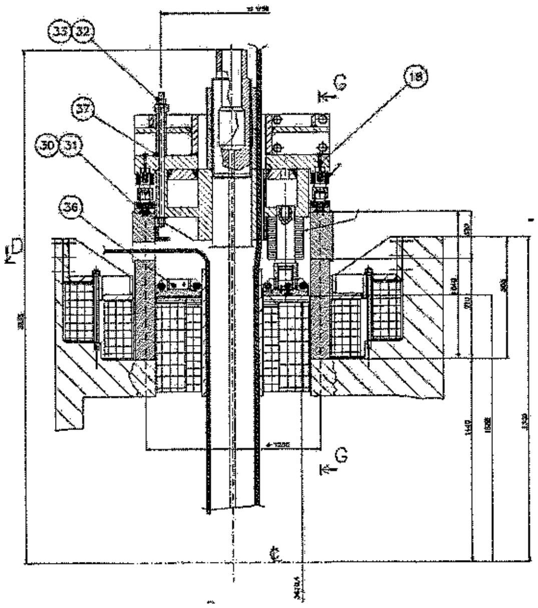

Fig. 1. Central post head.

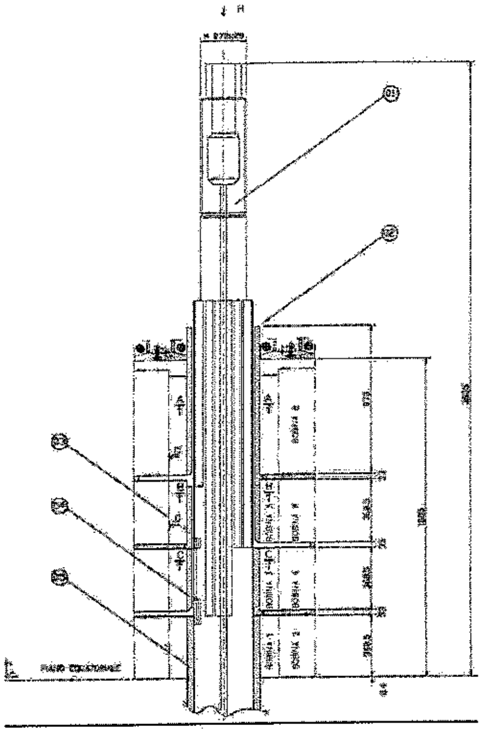

Fig. 2. Central post.

8. The sleeves, at the coil position 1–2–3–4, where the radial compression is higher, radially interact with the central post.
9. Low friction material, as Fiberslip, allows for both radial and axial differential thermal expansion between components at different temperature during the current scenarios.

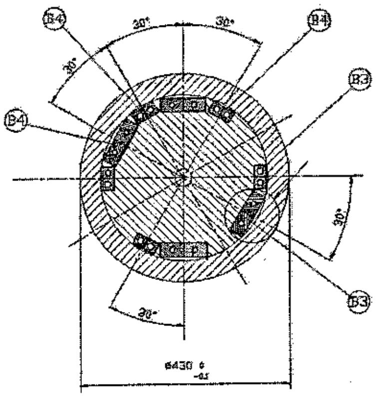

Fig. 3. Central post cross section.

10. The mechanical design is such that torsional loads, coming from the coils are not transmitted to the electrical and feed pipe tails.
11. The calculated stresses, of the central post and sleeves, are within the allowable values in accordance with ASME III Code. The centre post is a solid deep-drilled shaft, with double nuts engaged to the threaded ends. The end bore has been shaped in order to taylor the elasticity, to obtain an uniform load all along the screw threads.

2. Plasma Chamber (PC)—the new support system

The present design of the PC is described in [2]. Recent experimental results have brought to the development of a new plasma disruption model [3] which has resulted in higher loads. On the base of the new model the PC and First Wall (FW) protection needed a design upgrading which is still under way at the moment [4]. A new PC supporting system, capable to withstand the higher forces has been developed and is presented in this paper as reference design.

The (PC) is made up of 12 D-shaped, toroidal sectors of inconel 625 which are welded together to form a complete torus. Each sector carries a rectangular equatorial port (160 × 180 mm) plus $2+2$ vertical ports (tube type).

The PC is supported through the equatorial ports bearing on the C-clamp structure.

The support system consists of: vertical supports, radial supports, lateral supports, all acting on the PC equatorial ports [5]. One of the main functions of the PC supports is to react to the vertical and radial electromagnetic loads induced by a transient plasma disruption and to allow for free movement under thermal loads.

According to the new electromagnetic model, previously mentioned, the following forces are applied:

- vertical force of about 2.45 MN;
- radial force of about 4.1 MN (due to horizontal net force);
- centripetal force of about 3.87 MN (at the end of current quench).

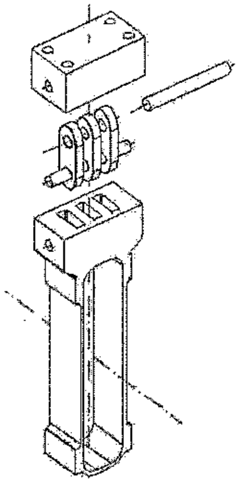

Fig. 4. Vertical support.

The *vertical supports* connect the radial port to the C-clamp structure by a multilink system. The system allows for thermal expansion of the PC, without altering its central setting position. The vertical supports are designed to withstand vertical force of about 2.45 MN (see Fig. 4). Due to the high stress level, the pins and links are made of inconel 718 material.

Radial supports work in both direction, (centripetal and centrifugal) with high stiffness. They connect the end of equatorial ports to the C-clamp structure. This connection will be normally free to allow for thermal movement; but only during the pulse the connection will be locked by the clamping sleeves hydraulically operated. The radial supports are designed to resist up to a maximum of 3.0 MN radial force. The stiffness of the plasma chamber wall, will contribute to share the radial loads among the other ports. A structural analysis is underway to assess the loads distribution of the ports and the stress level in the PC wall (see Fig. 5).

Lateral supports between equatorial ports and C-clamps have to resist the out of plane forces due to disruptions, as well as to accommodate thermal expansion. Each of these supports can react to a force normal to the post axis of about 0.75 MN. The lateral support design is basically unaltered with respect to the previous solution.

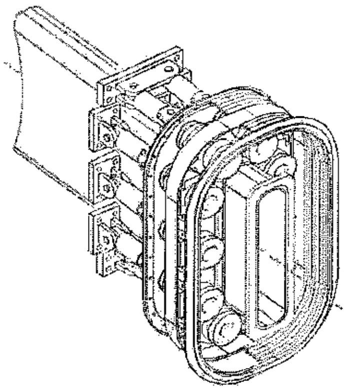

Fig. 5. Radial support.

2.1. Plasma chamber radial supports testing

Each equatorial port has a set of 10 clamping sleeves spaced along the outer perimeter of the port to prevent the radial movement (see Fig. 6).

Once the hydraulic pressure is applied, the clamps will prevent the sliding of the tie-rods by friction.

The test results show the following:

- maximum axial loads of 35 tons with a hydraulic pressure of 300 bar; tie rod diameter 80 mm;
- the clamping sleeve system shows an elastic behaviour up to the maximum load;
- the shaft is clear to slide after each releasing of the hydraulic loads;
- the stiffness of the clamping system is about 1 MN/mm.

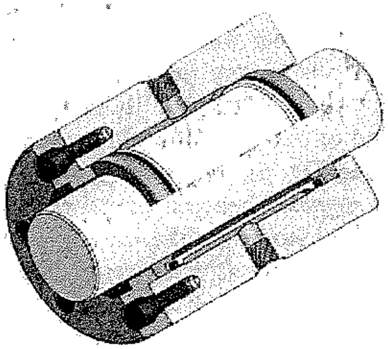

Fig. 6. Clamping sleeve section [9].

3. Cooling system

The entire machine is cooled down by helium gas at 30 K. The PF coils are cooled through hollow conductors ($\varnothing = 8$ mm) with gas pressure of about 20 bars. The TF cooling is realised circulating gas through a space between the coil surface and the ground insulation, with low hydraulic impedance and it requires low pressure supply (2 bars) [6].

Components, valves and fittings, requiring maintenance, are located in a secondary cryostat outside the biological shield. Many separate cooling circuits guarantee the correct control of the temperature between 25 and 300 K and consequently the control of the thermal stress of each component.

The electric and cooling feedtroughs are operating under high voltage. The separation of electrical and hydraulic function, is achieved by insulating breaks placed in dedicated cold-boxes external to the main machine cryostat.

The calculated cooling time, to bring down the temperature of the load assembly to 30 K, is about 120 h. The cooling time of the coils (after 10 s duration pulse) is about 5 h.

The complete integration among the different major components,with a good thermal contact among them, ensures the cooling of all the components at 30 K. In fact, the good and large contact area between C-clamps and PFC and TFC allows the cooling of the C-clamps with good temperature distribution (see Fig. 7). The central post is cooled by a cooling channel through the axis.

4. Cryostat

A vacuum metallic cryostat (10^{-4} mbar) is the Ignitor reference design and it provides the thermal insulation of the machine at the temperature of 30 K [7]. In addition during the D-T operation, the cryostat provides second barrier of tritium containment. The main design features are: the cylinder and the domed ends are segmented to allow for easy access during maintenance; the panels are removable, with fasteners and rubber

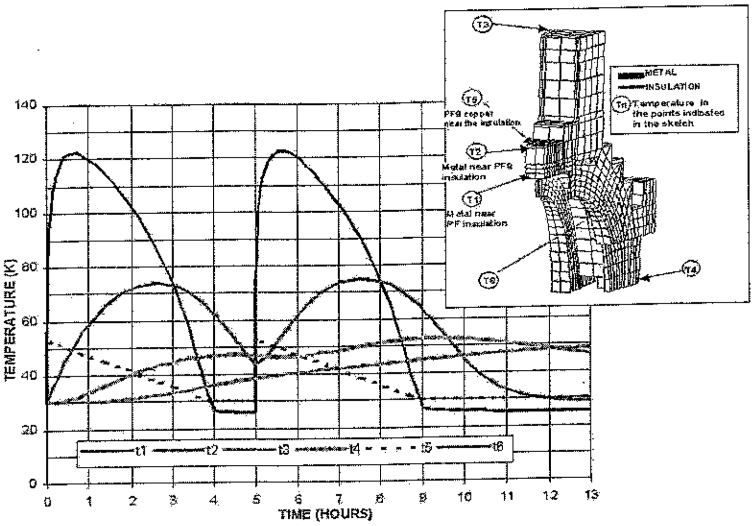

Fig. 7. Temperature evolution C-Clamp.

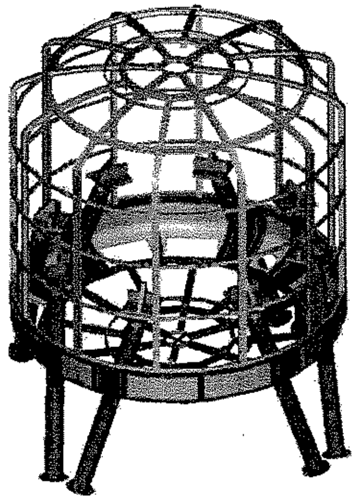

Fig. 8. Cryostat.

seals during the first plasma operations, and are welded, (lip joints), during the tritium phase. Cutting and welding of the lip joints can be operated by RH tools.

The L-shaped bottom is fixed and it contains the machine legs and all electrical cooling feed through. All panels are insulated to prevent electrical loops (see Fig. 8).

Structural analysis of cryostat carried out under operational and seismic condition shows acceptable values [8].

Buckling analysis satisfies ASME code Sect. III Div. 1. Subs. NE.Estimated heat losses rates:

- 2500 W through the cryostat; 810 W from the plasma chamber at RT; 1300 W through the supporting legs; 1200 W by electric-fluidic feedthrough; 4800 W by radial locking supports; 1000 W by vertical posts.

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