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The ignitor radial electromagnetic press system (new concept)

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Abstract

A new concept of radial passive and active press, to replace the previous axial design is presented in this paper. This solution reduces the stresses in the components concerned and at the same time it improves the assembly, operation and maintenance of the machine. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Axial design; Plasmas; Poloidal

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1. Introduction

Ignitor is a high field compact machine proposed and designed to achieve ignition in D–T plasmas. The machine has been conceived as completely integrated system of its major components (toroidal field system, poloidal field system and plasma chamber) (Fig. 1).

The toroidal field magnet is made of 12 modules (Fig. 2), each including two toroidal field coils (TFC), contained by 4 C-Clamp elements.

The structural performance of the machine relies on an optimised combination of ‘wedging’, in the TFC inboard legs and in the outboard of the C-Clamp, and ‘bucking’ between the TFC and the central solenoid (CS) [1–3].

The inboard legs of the TFC are preloaded to resist the vertical components of the Lorenz forces. The load is applied through the upper and lower parts of the C-Clamp (the C–clamp ‘noses’) by means of bracing rings (passive system) and an electromagnetic radial press (active system) (Fig. 3).

The vertical electromagnetic press adopted in an earlier machine design had the disadvantage of preventing the disassembling of the central solenoid without cutting the central post. Moreover, the final load of the inboard TFC legs by the bracing rings had to be applied with the machine at low temperature (~ 30 K) in order to exploit

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the mechanical properties of the C-clamp materials. The stress distribution in the new configuration has been optimised within the allowable stress limit of the C–Clamp (at 293 K). The stress level in the TF coils does not raise concerns for and complies with the good wedging conditions.

2. The new radial press system

The C-Clamp nose can move freely under the action of two press systems (Fig. 4): the mechanical permanent preloading and the active electromagnetic press.

The first system envisages a radial bracing ring and 48 wedges, located between the ring and the C-clamp nose; the ring reacts against the wedges applying a radial inward force of 180 MN at 30 K. The second loading system consists of an electromagnetic press producing a nominal force of 193 MN in the radial direction (redundant force of 25% is available). Supporting beams keep the press systems in position and withstand vertical electromagnetic loads. The design is such to allow the C-Clamp nose movement and thermal expansion of the coils. The radial electromagnetic press is made of two concentric coils (inner coil 210 × 210 mm^2; outer coil 210 × 275 mm^2) made of oxygen free copper (OFHC). The inner coil pushes the C-clamps 'nose' inward through a steel tapered spacer (0.72 mm); the outer coil is fitted with a reinforcing ring. The insulation system is made of glass fabric plus kapton tapes; the coil is vacuum impregnated with an epoxy resin. The maximum temperature increase, after a pulse, is ~ 30 K for the outer coil and 20 K for the inner coil. The press coils are cooled down (< 1 h) with a forced flow of helium gas at 30 K and a pressure of ~ 20 bar.

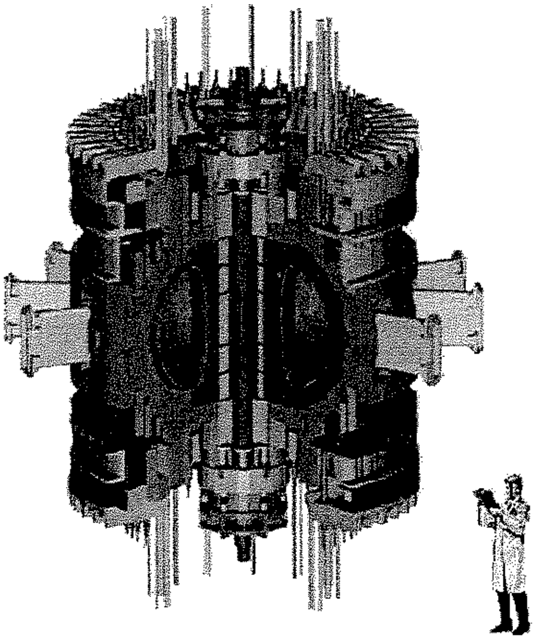

Fig. 1. IGNITOR view.

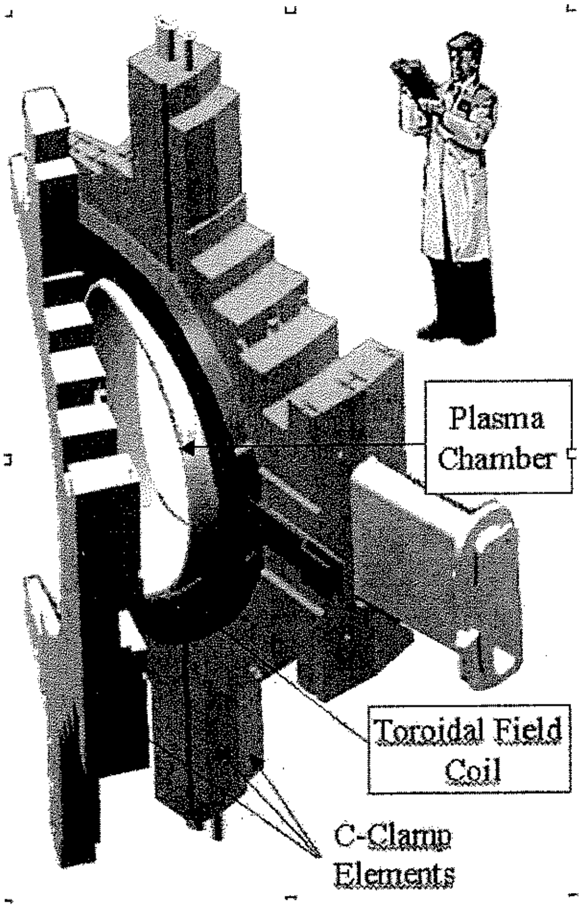

Fig. 2. IGNITOR magnet module.

The current flowing in the radial electromagnetic press is modulated during the plasma discharge to follow the mechanical and thermal loads evolution on the TFC. In the highest plasma current scenario (12 MA, 13T), the electromagnetic press is brought to its maximum load in coincidence with the beginning of the current flat-top in the TFC ($t = 4$ s) (Fig. 5). At that time the electromagnetic loads in the TFC inner legs are high and the temperature in the copper is low. Then, the coil temperature increases, causing the expansion of the TFC and loading the passive bracing ring up to 340 MN ($t = 8$ s). For this reason at $t = 5$ s the electromagnetic press is deactivated.

3. Electromagnetic analysis

The formation of the desired plasma equilibrium configurations have been verified for all operational scenario (Figs. 5 and 6) taking into

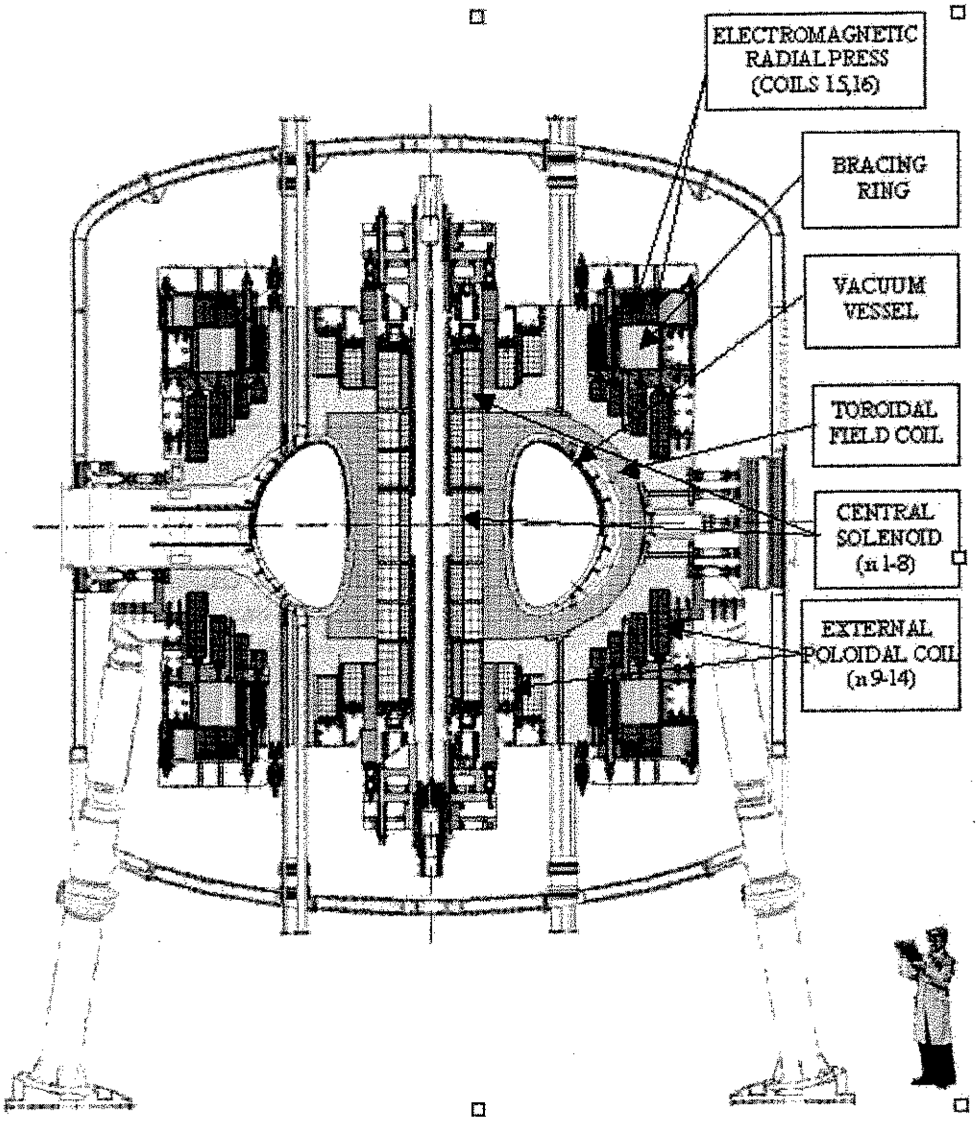

Fig. 3. IGNITOR machine cross section.

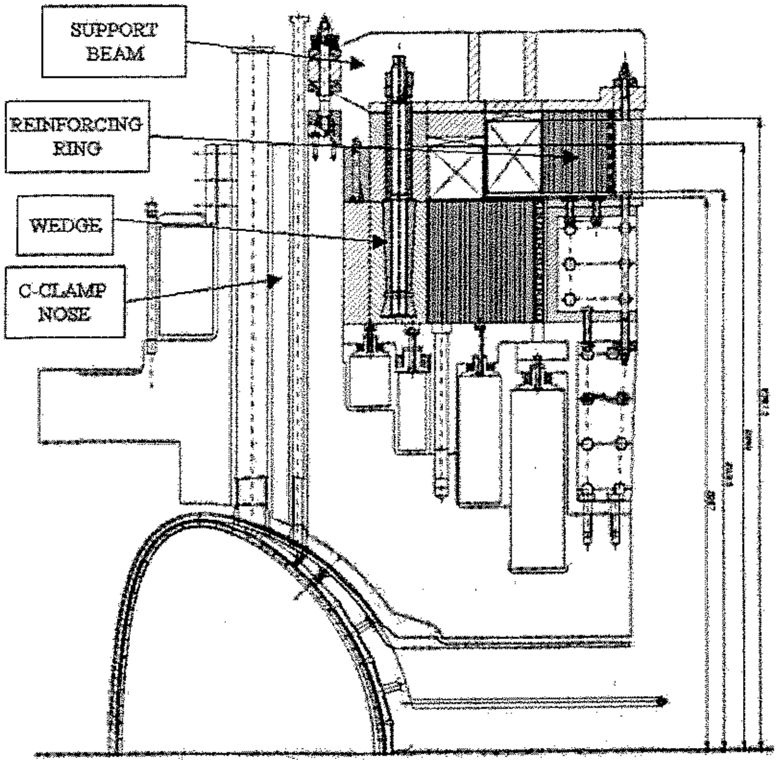

Fig. 4. Radial press system.

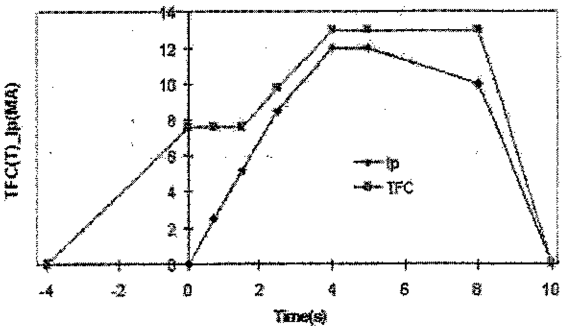

Fig. 5. Plasma current and toroidal magnetic field.

account the effect of the magnetic field induced by the radial press coils.

The 193 MN force is generated by 3.72 MAt. The magnetic field induced by the press coils does not perturb significantly the plasma border. The radial electromagnetic press is powered after plasma start-up avoiding any additional stray fields during this critical phase. Inner press coil current and plasma current of the same direction cause a radial electromagnetic force increase from 106 to 193 MN. Aiming to reduce the axial electromagnetic loads, an off-set of 60 mm of the press coils is envisaged. In the range from $t = 4$ to 5 s the electromagnetic axial loads are toward the equatorial plane of the machine (Table 1).

4. Thermal mechanical analysis

The Finite Element Method (FEM) has been employed to analyse the stresses of the load assembly structure using the ANSYS code (Fig. 7).

The substructure technique which allows the combination of two and three-dimensional elements has been adopted. The TFC, CS and Bracing Ring materials have been modelled using me-

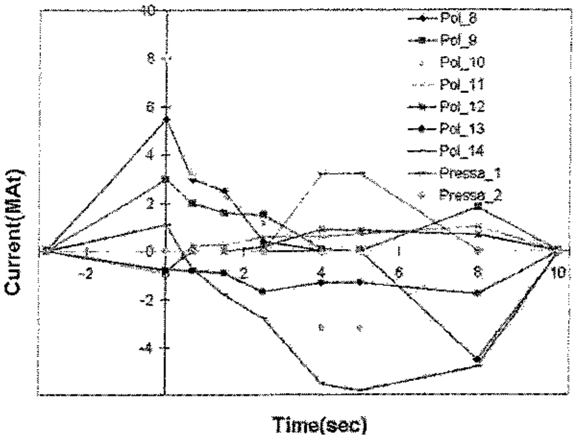

Fig. 6. Poloidal coil currents (12 MA scenarios).

chanical and thermal orthotropic smeared properties. The in-plane and the out-of-plane load analyses have been carried out separately. Structural analysis are performed at the most significant times of the operating scenario, including preload at room temperature and at 30 K (Table 2).

The highest stress values in the TFC throat (inside and outside) correspond to the end of the plasma current flat-top ($t = 5$ s, max. electromagnetic loads), and at the end of the pulse ($t = 10$ s, max. temperature). The calculated stresses in the TFC are summarized in Table 3 and Fig. 8.

Since the whole machine is cooled down at the lower temperature (30 K) it improves the TFC coils wedging performances. This is important mainly at the startup ($t = 0$ s) because of the lack of balance between CS centrifugal forces (445 MN) and TFC centripetal ones (-170 MN). The maximum Von Mises stress on the outer coil (at $t = 5$ s) of the magnetic press is 249 MPa ($\sigma_{Y0.2\%} = 320$ MPa at 77 K) and the maximum shear stress on the insulation is ~ 8 Mpa (within the allowable stress). The maximum Tresca stress on the outer coil bracing ring is 414 MPa (AISI 316 LN steel sheet 25% cold worked, $\sigma_{Y0.2\%} = 800$ MPa at 77 K) with the maximum shear stress on insulation $\sim$ MPa. The maximum load on the passive bracing ring is 337 MN which gives a maximum Von Mises stress on the stainless steel of 388 MPa ($\sigma_{Y0.2\%} = 800$ MPa at 77 K).

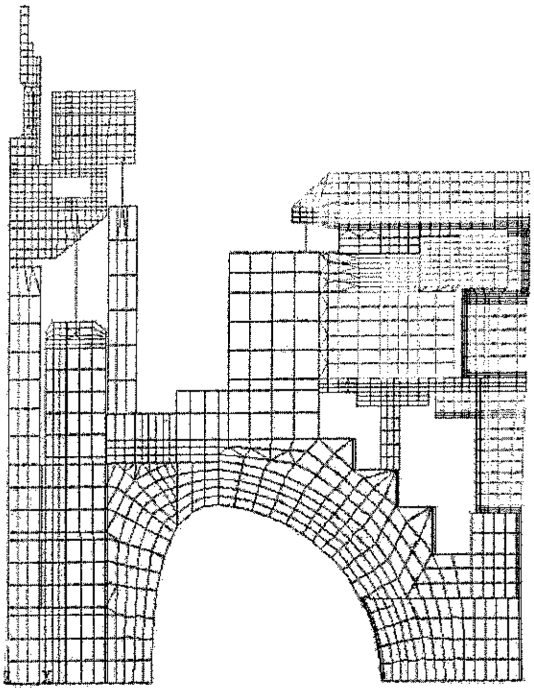

Fig. 7. FEM model of the IGNITOR load assembly.

Table 1

Time instant	Inner coil radial force [MN]/current [MAt]	Inner coil axial force [MN]	Outer coil radial force [MN]/current [MAt]	Outer coil axial force [MN]
Ramp-up (4 s)	−191.57 3.72	−2.64	196.30 −3.72	−3.38
Flat-top (5 s)	−193.81 3.72	0.17	198.11 −3.72	−6.39

Moreover the stresses in the structural components (i.e. C-clamps, Central Post and Bracing Rings) are within the ASME limits at the temperature of operation.

The bracing ring is made of laminated hard stainless steel and glass-fabric-epoxy. To avoid flux consuming toroidal loops, these rings are made by an winding of the steel strip with insulating inter-layers. The highest stresses in the CS coils that occur at the plasma start-up and at the end of the flat-top of the current pulse are within the allowable limits.

The analysis of the stresses produced by the out-of-plane loads has been performed during the toroidal field flat-top, at $t = 5$ and 8 s. It is worth noting that the out-of-plane loads do not increase the values of the maximum equivalent stresses found in the in-plane load analysis.

5. Radial press system assembly

The upper and lower bracing ring assemblies (passive system) are set in position resting on poloidal field coil supports, then the mechanical wedges are loaded simultaneously to reach the final tighten force (190 MN) (to make easy this operation the bracing ring can be slightly heated up). The C-Clamp nose radial displacement after the tightening of the passive system is 4.74 mm. Afterward, the inner coil (active system) is set in position with a precise fit to the C-Clamp noses through adaptor wedges. Outer coils and the relative bracing rings are shrunk fitted, while there is a clearance (~6 mm) with respect to the inner ones. 48 upper and lower supporting beams are than vertically preloaded to keep the radial press

Table 2

Time instant	Radial magnetic press			
	Total radial load [MN]	Passive ring load [MN]	Inner coil load [MN]	Outer coil load [MN]
Preload at 293 K withthe passive ring	190	190	0	10
Complete preload at 293K	192	185	7	10
Preload at 30 K	190	180	10	6
Start-up (0 s)	228	214	14	6
Ramp-up (4 s)	363	186	177	143
Ramp-up (5 s)	375	196	179	147
End flat-top (8 s)	364	337	27	8
End pulse (10 s)	246	232	14	8
Preload at 293 K with passive ring heating at 90 °C maintenance	115	92	23	10

Table 3

Time instant	$\sigma_{y0.2\%}$ [MPa]	Radial electromagnetic press		
		σ_{axial} TFC throat inside [MPa]	σ_{axial} TFC throat outside [MPa]	$\sigma_{Von\ Mises}$ maximum [MPa]
Ramp-up (4 s)	368	90	84	327
Ramp-up (5 s)	363	114	69	356
End flat-top (8 s)	356	16	193	348
End pulse (10 s)	352	−294	−130	295
Preload at 293 K passive ring at 90 °C maintenance	338	−92	−72	92

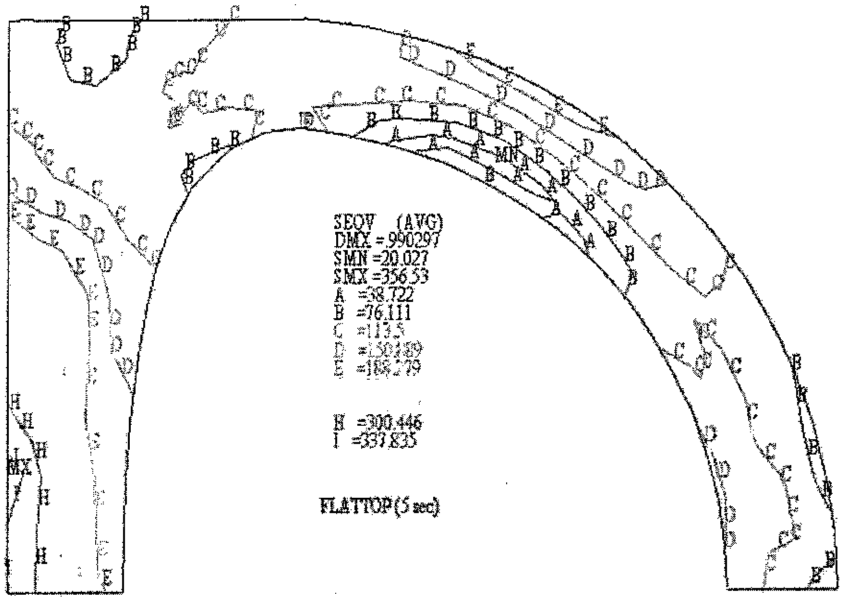

Fig. 8. Von Mises equivalent stress on copper material (MPa) at $t = 5$ s.

system in the radial position but allowing for thermal expansion.

6. Conclusions

The new adopted radial press system complies with all the requirements of the envisaged operational scenarios, keeping the stress level within allowable values and maintaining the TFC good wedging conditions. In addition, the permanent stress level in the C-Clamp and in the TFC leg (creep rate) have been reduced, thus improving the operability of the machine and its maintenance.

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