STRUCTURAL ANALYSIS OF COMPACT EXPERIMENTS FOR THERMONUCLEAR IGNITION

B. COPPI

Massachusetts Institute of Technology, Department of Physics,
77 Massachusetts Avenue, Cambridge, Massachusetts 02139, U.S.A.

A. TARONI

Centro Calcolo, Comitato Nazionale per l'Energia Nucleare,
Via dell'Arcoveggio 56/23, I-40129 Bologna, Italy

Abstract

Compact experiments for the study of α-particle heating in high density plasmas have led to verify the feasibility of toroidal magnet configurations, with aspect ratios as low as 2.1 and average magnetic fields of 12.5 T, and of coupled air core transformer systems capable to induce 5 MA of plasma current. The main results of the relevant structural analysis are presented.

1. Introduction

We consider compact toroidal devices for the purpose of reaching the ideal ignition temperature, in relatively high density deuterium-tritium plasmas [1]. The three main components are

-the toroidal magnet,

-the air core transformer system,

-the equilibrium field coils system.

Before each plasma discharge all of these magnets are brought to about 77° K by liquid nitrogen cooling. For this purpose the entire device is surrounded by a fiberglass cryostat as in the case of the Alcator and FT machines [2], and in addition each magnet system is provided with an appropriate set of cooling channels.

2. Toroidal Magnet

The main characteristics of the toroidal magnet have been chosen by the criterion that the toroidal cavity can be utilized to contain both: i) a plasma column with a fixed major radius ($R \simeq 80$ cm) and a sufficient minor radius to carry a current of about 5 MA; ii) the compressed and pre-compression stages of a plasma column that is subjected to a moderate adiabatic compression such as described in Ref. [1] by decreasing the major radius from 94 to 71 cm. In the compressed stage the considered plasma current is ≤ 4.2 MA. Thus we have adopted the following reference parameters of the toroidal cavity. $R_{oo} = 85$ cm, $a_c = 41$ cm, and $B_T(R = R_{oo}) = 125$ kG. Here R_{oo} and a_c are the relevant major and minor radius and B_T the toroidal field. A maximum total current of 52.8 MA- turn in the toroidal magnet can be carried by 176 copper turns with about 300 kA each. If we leave an internal hole, for the air core transformer, of radius $R_T = 23$ cm, the area of the equatorial cross section is $A_e \simeq 4420\ \mathrm{cm}^2$. If we let the corona with radii $R_{au} = 33$ cm and R_T to be filled with steel, this constitutes about 40% of the total equatorial cross section. The maximum average current density in the copper region is about 20 $\mathrm{kA/cm}^2$.

The toroidal magnet, together with the plasma chamber is subdivided in 8 modules which contain 22 copper turns each.

Every conducting turn is realized by a copper-steel element, a composite plate in which a steel reinforcing structure surrounds the conducting copper and is in mechanical contact with it. The conducting copper is taken "out" of each plate in the back of it, in such a way that the switching of current from a plate to the next is done on the outside of it [3]. Then the lateral surfaces of each plate lay exactly on a meridian plane. In the analysis that we have carried out we have assumed the thickness of each copper coil in the meridian plane to be constant, that is 11 cm. Each plate has a height of 140 cm and the distance of its outer edge from the axis of symmetry is 155 cm. The inner corner of each plate is "shaved" to make room for coils 2a) and 2d) of the air core transformer, as indicated in Fig. 1. The copper-steel plates system are supported by an external structure that exerts a vertical pressure in the range of 15 to 25 kg/ mm^2 over a two horizontal coronae whose radii measured from the torus axis of symmetry, are $R^{(1)} = 30$ cm and $R^{(2)} = 53$ cm. A thin insulating layer, laying on a meridian plane separates neighboring plates. We have taken this into account by assuming that the copper filling factor of the region that is not occupied by steel on the inner equatorial cross section is 95%. We have considered also the possible adoption of insulation between each copper coil and the surrounding steel "belt" in order to program differently the current that flows in the two materials. The purpose of this is to maintain the temperatures of the two materials at values that minimize the effects of thermal stresses in the copper. The typical current evolution consists of a rise time of 2 sec and a plateau, at maximum current of 1 sec.

We have also analyzed the option to adopt a copper-chrome alloy instead of copper with the results that we shall discuss in section 3. In this case the duration of the plateau has been reduced to 0.5 sec, the thickness of each conducting turn has been increased by 1 cm and the radius of the central hole has been increased to 24 cm. Another option that we have considered but not yet analyzed, is to adopt composite steel copper plates obtained by roll bonding as proposed by C. Weggel [4].

3. Structural Analysis of the Toroidal Magnet

In order to analyze the various types of structure that can be adopted for the toroidal magnet we have utilized the finite element code BERSAFE. This code can be used for two and tri-dimensional configurations to evaluate both mechanical and thermal stresses. We have coupled this code with one that incorporates the local temporal evolution of the temperature and current density inside the magnets [5]. Thus, we have evaluated a realistic distribution (Fig. 2) of volume forces and the effect that the temperature excursion produced by the current in the copper plates has on the evolution of the stresses. We have taken $E_s \simeq 2.4 \times 10^4$ kg/mm^2 as a reference value of Young's modulus for steel and $E_{Cu} \simeq 1.25 \times 10^4$ kg/mm^2 for copper. The Poisson's coefficient is 0.33 for both materials and the thermal expansion coefficients are $\alpha_s \simeq 1.5 \times 10^{-5}$ and $\alpha_{Cu} \simeq 1.7 \times 10^{-5}$. For the copper-chrome alloy that we have considered $E_A \simeq 1.4 \times 10^4$ kg/mm^2 and $\alpha_A \simeq 1.5 \times 10^{-5}$. We have taken dependences of the electrical resistivity, the thermal conductivity and of the specific heat on the material temperatures that represent published tabulated values.

The types of structures we have analyzed have in common the goal to decrease the stress level on the equatorial cross section of the toroidal magnet to values below the plastic limit. The maximum temperature excursion that has been considered starts at 77° and ends at 330° K. We have used the 3-D BERSAFE code with elements EZ60R and E245R. The relevant lattice, with the appropriate temperatures and forces, has been generated automatically, from the two-dimensional code [5] that evaluates the temperature and force distributions, by rigid rotation of the two-dimensional lattice over an angle $2\pi/80$ around the torus axis of symmetry. We recall that the copper-steel elements are subjected to a "wedge" effect by the tendency of each coil to implode toward the axis of symmetry and it is possible to eliminate this effect over a portion of each element by appropriate machining of the relevant vertical surfaces. In our 3-D analysis the "wedge" effect has been simulated by the condition that the toroidal component of the displacement is nul. Among the various configurations that we have studied we describe the results that we have obtained for two illustrative cases of the problems that are encountered.

Case a): There is no "wedge" effect between adjacent copper plates while this exists between adjacent steel belts that, in addition, are kept at liquid nitrogen temperature.

Case b): Both the steel belt and the copper plate are subjected to the wedge effect and are kept at the same temperature.

In Case b) the steel temperature is controlled, by programming the current induced in it, in order to maintain its thermal expansion close to that of copper. In addition each copper turn is subdivided into two concentric subcoils in order to improve the current density distribution during the current use time[1].Thus the radial temperature difference in the copper is reduced to less than 40°K. In addition the stress level and distribution is maintained about constant throughout the current plateau. When a vertical compression of 25kg/mm^2, as indicated earlier, is adopted the maximum Von Mises stress equivalent in the copper is 25 kg/mm^2. The relevant stress distribution on the inner equatorial cross section is in fact given in Fig. 3. In Fig. 4 we give the level contours of the stress equivalent and, thus, show that the region where this is maximum is very limited. We also observe that the maximum stress equivalent in the steel belt is about 72 kg/mm^2 and the corresponding toroidal component σ_ϕ, that is higher in the steel, lays in the range 47-54 kg/mm^2. We consider this estimate of σ_ϕ as significant in terms of the stress level that can be transmitted through the adopted insulating materials. We may take 33 kg/mm^2 as a representative value of the stress equivalent for the elasticity limit in copper materials[6]. An analysis that would allow the excursion of a limited region of the copper coil into the plastic regime is being undertaken in collaboration with the Engineering Division of J.R.C.-Ispra where a design study of external supporting structure is also being carried out. In this regard we observe that the vertical pressure to be exerted by the external structure can be decreased to values below 20 kg/mm^2 while the copper elasticity limit would not be exceeded. Notice that for case b) a 2D analysis is sufficient.

In case a) the thermal stresses induced by the differential heating of the copper coil plays the dominant role. Thus the worst stress conditions occur in the copper at the beginning of the current plateau while those for the steel belt occur at the end. To alleviate the stress levels in the two components we have adopted a higher vertical compression, of about 30 kg/mm^2. Thus we have the following maximum stress equivalent:

$$\text{beginning of plateau} \begin{cases} 33\ kg/mm^2 \rightarrow \text{copper} \\ 100\ kg/mm^2 \rightarrow \text{steel} \end{cases}$$

$$\text{end of plateau} \begin{cases} 31\ kg/mm^2 \rightarrow \text{copper} \\ 121\ kg/mm^2 \rightarrow \text{steel} \end{cases}$$

If we adopt a copper-chrome conductor with the changes in dimensions and plateau duration we have indicated earlier, the vertical compression can be reduced to 15 kg/mm^2 while the conductor remains within the elasticity limit. In particular, we have the following stress equivalent:

$$\text{beginning of plateau} \begin{cases} 41\ kg/mm^2 \rightarrow \text{Cu - Cr} \\ 120\ kg/mm^2 \rightarrow \text{steel} \end{cases}$$

$$\text{end of plateau} \begin{cases} 37.5\ kg/mm^2 \rightarrow \text{Cu - Cr} \\ 140\ kg/mm^2 \rightarrow \text{steel} \end{cases}$$

We refer to Figs. 5 and 6 for a further description of this case. Notice that in spite of the unfavorable conditions that have been chosen [in particular the conducting turn has not been split as in Case b) in order to decrease the radial temperature difference in it] the considered materials have been kept within their respective elasticity limits.

4. "Air-Core" and Equilibrium Coils Systems

In addition to performing experiments that combine ohmic heating of the plasma column with its adiabatic compression, we intend to investigate heating cycles that involve only ohmic heating and in which values of B_p around 30 kG are obtained at the outset and most of the toroidal cavity is filled up by plasma. In particular we choose for this a major radius R° = 80 cm and a horizontal minor radius a° = 34 cm, while the total plasma current is $I \simeq$ 5.25 MA. Notice that a distance of 12 cm is left between the outer edge of the plasma column and that of the toroidal cavity in order to reduce the influence of the magnetic ripple associated with the presence of access ports. This mode of operation sets more stringent requirements on the air core transformer system than that to produce the 4.2 MA plasma current on a major radius R_2 = 71 cm. This in fact corresponds to the compressed stage of the heating cycle described in Ref. [1]. Thus we require a total magnetic flux variation of about 9.4 volt-sec of which 6 are to be provided by the air core transformer system in a double swing and 3.4 by the equilibrium coils system.

The center element of the air core transformer has been subdivided in 3 parts. One of them is cylindrical with 70 cm height and 22.75 cm outer radius, while the inner radius is 12 cm. The two others are truncated cones with a cylindrical hole of 13 cm radius that, for the sake of simplicity, we have simulated by two cylindrical coils with 35 cm height and 30 cm outer radius in our calculations of the field produced by the entire transformer system.

In terms of mechanical construction, we adopt a set of concentric vertical solenoids. Each of these solenoids is carved out of solid copper cylinders. By this solution we obtain a structure that can combine the solidity of the "stacked pancakes" system adopted in the Alcator device of M.I.T., with the advantage of having electrical contacts only at the two ends of each solenoid as in the case of the Frascati Torus. Given the current density levels to be attained (18 kA/cm^2, average) and the relatively short time for which they are needed, this can be made of copper-chrome alloy.

The equilibrium field coil distribution has been designed to be compatible with the configuration of the copper-steel elements that compose the toroidal magnet. For reasons of brevity, we do not discuss the problem of the plasma chamber, and of the forces to which it is subjected, in this paper. We recall [1] that in our design the plasma chamber acts also as a limiter and we envision, among other possibilities, to realize it in 8 sectors that are integrated with each corresponding module of the toroidal magnet [3].

Acknowledgements

We wish to thank the Engineering Division of the J.R.C. of Ispra for their contribution and for suggesting the possibility to adopt a large circular cavity of the toroidal magnet. It is also a pleasure to thank G. Rostagni for his design solutions. This work was sponsored in part by the U.S. Department of Energy and the C.N.E.N. - Euratom Association.

References

[1] B. Coppi and A. Taroni, in Proceedings of the 1978 International Symposium on Plasma Heating (Publ. C.E.A., Grenoble, France, 1978), p. 113.

[2] B. Brunelli and B. Coppi, Nucl. Engineering International 23, 61 (1978).

[3] This solution was proposed first by G. Rostagni (private communications, 1978) in addition to that of adopting a modular structure of the toroidal magnet and vacuum chamber system.

[4] C. Weggel, Private Communication (1978)

[5] E. Bittoni, G. Cenacchi, L. Guerri, and A. Taroni, in "FORTE: Finite Element Code for Temperatures, Magnetic Fields and Forces in a Toroidal Magnet" Report to be published by C.N.E.N. Rome, 1979.

[6] C. Weggel, W. Hamburger, B. Montgomery and N. Pierce, in Proceedings of the 7th Symposium on Engineering Problems of Fusion Research, Knoxville, Tn., October 1977.

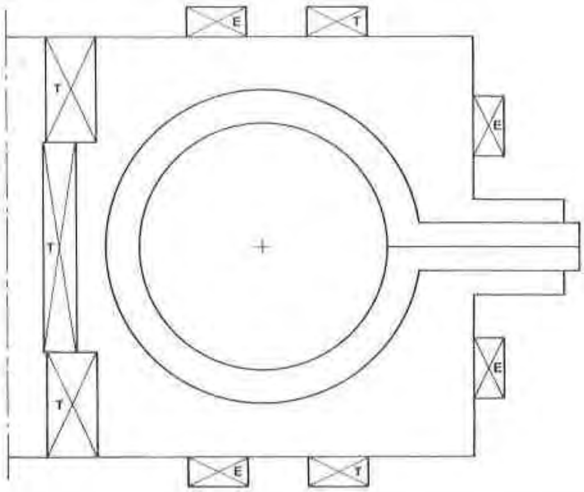

Fig. 1. Schematic of a copper steel plate, of the components of the air-core transformer, and of the equilibrium field system. The transformer and equilibrium field coils are labeled by T and E respectively.

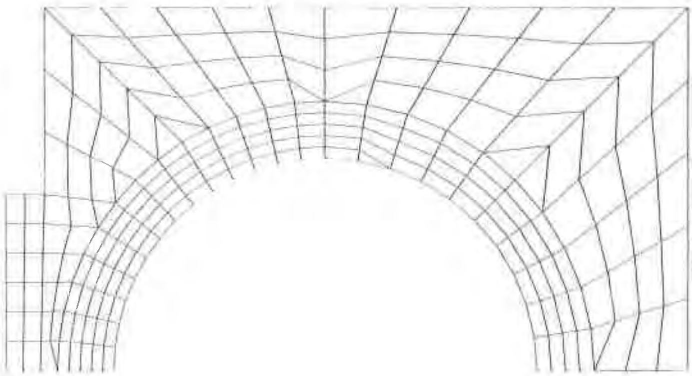

Fig. 2. Two-dimensional, finite element lattice used for the stress analysis described in Section 3 and where copper coils have been adopted.

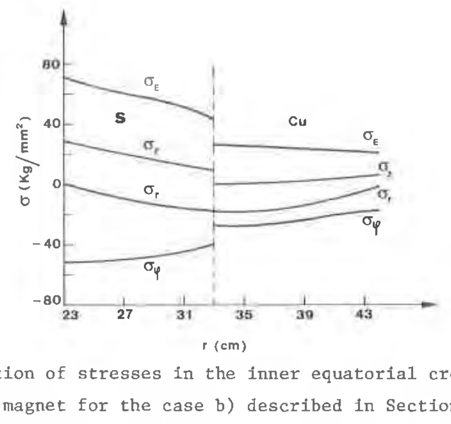

Fig. 3. Distribution of stresses in the inner equatorial cross section of the toroidal magnet for the case b) described in Section 3.

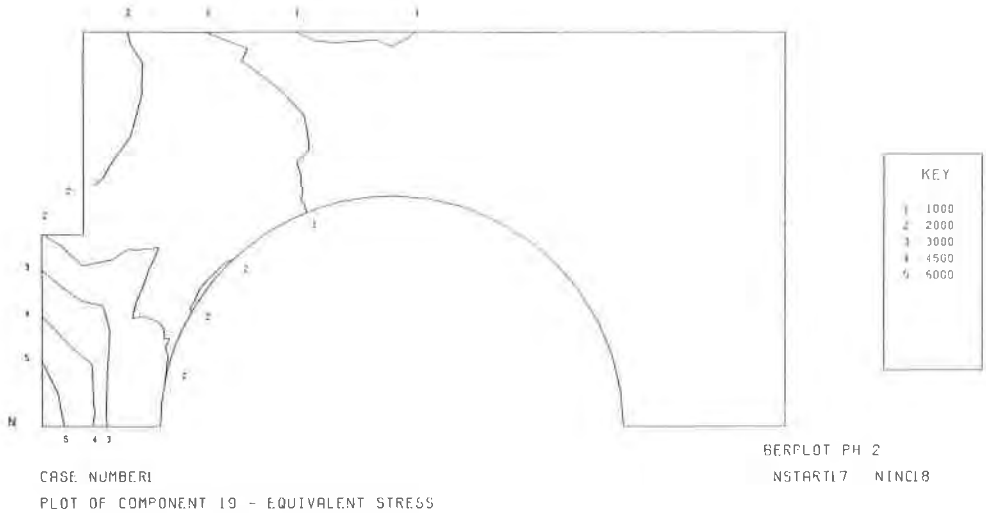

Fig. 4. Contour levels of the stress equivalent in a meridian section of the toroidal magnet for case b) described in Section 3. The values in the key table are in kg/cm^2.

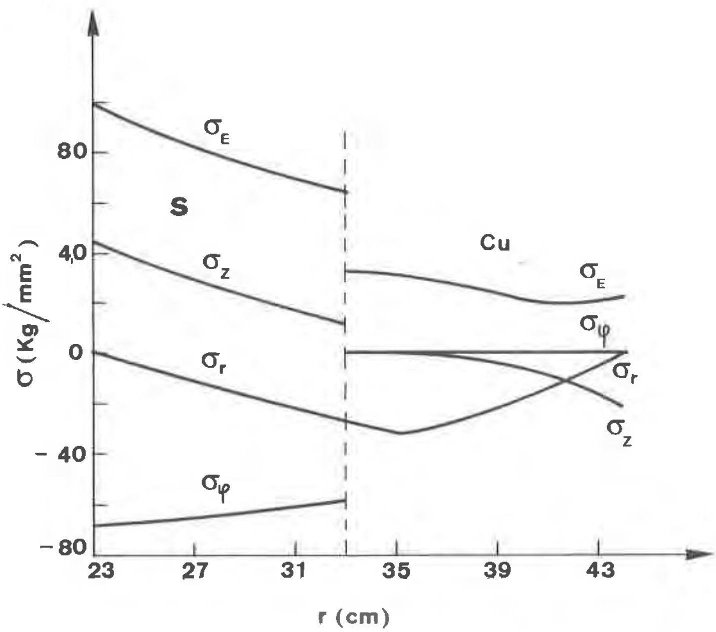

Fig. 5. Corresponds to Fig. 3 but refers to case a) when a copper conductor is adopted, as described in Section 3.

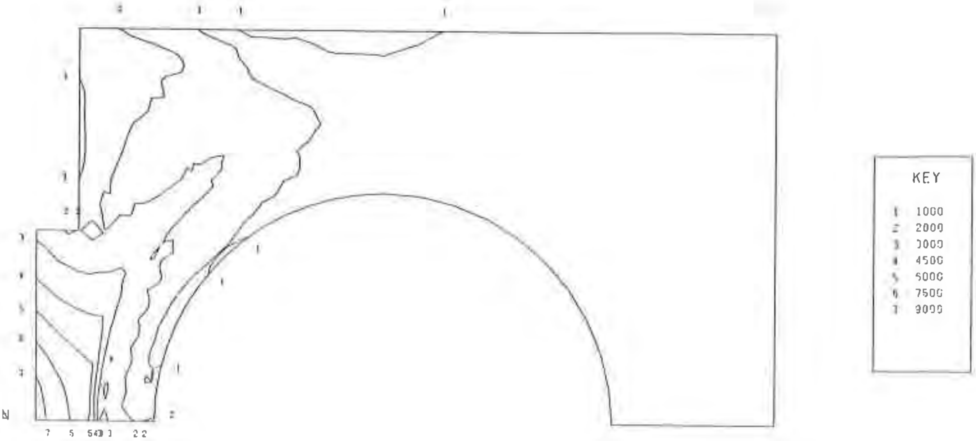

Fig. 6. Corresponds to Fig. 4 but refers to case a) when a copper conductor is adopted, as described in Section 3.

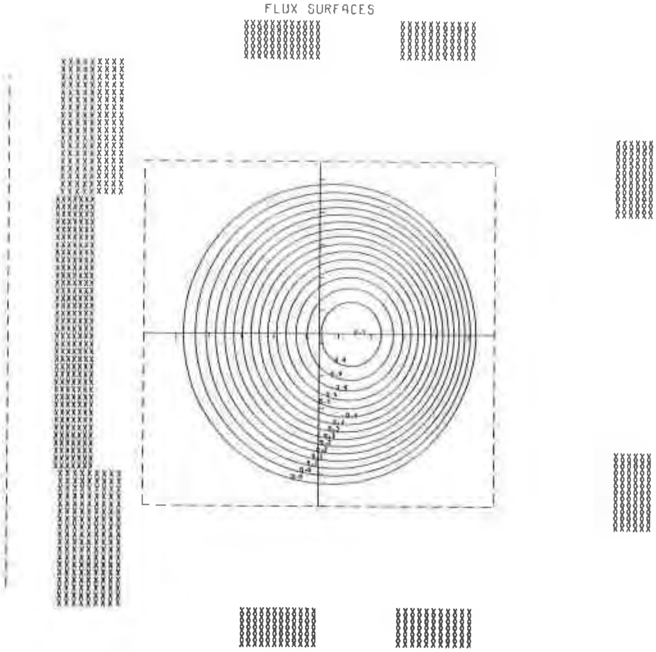

Fig. 7. Ideal MHD equilibrium configuration in the air-core transformer and equilibrium field systems for the pure ohmic heating mode of operation, as described in Section 4.