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ENGINEERING DESIGN OF THE CENTRAL CORE OF THE TBR-E SMALL ASPECT RATIO TOKAMAK

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ABSTRACT

TBR-E is a small-aspect-ratio tokamak jointly proposed by the Institute of Physics of the University of São Paulo (USP), the Institute of Physics of the State University of Campinas (UNICAMP), and the National Institute for Space Research (INPE). The experiment is intended to investigate the spherical torus concept in conditions relevant to thermonuclear research, to develop new diagnostic techniques, and to explore new confinement regimes and current drive concepts.

The scientific program and basic design of the machine are described in another paper also presented to this workshop. The design of TBR-E brought up many novel engineering solutions, required to accommodate the inner legs of the TF coils (TFC), the main solenoid of the ohmic heating transformer (OHS) and the inner wall of the vacuum vessel in the very tight configuration of TBR-E, and yet to allow all of these components to be demountable.

Initially, this paper outlines the TBR-E TFC system, consisting of sixteen D-shaped coils. To increase coupling with the plasma loop, the inner legs of the toroidal field coils are placed inside the ohmic heating solenoid. Demountable joints between the outer TFC segments and the central straight segments are therefore required. The paper describes the technical solution for the problem of electrical connection between the inner and outer segments of the TFC as well as the use of these joints to provide the TFC system with a very compact and magnetically optimized scheme of symmetrical feeding buses.

The TBR-E OH solenoid (OHS) is discussed in the sequel. The OHS will be a two-layered, 220 turns, water cooled coil made of copper. A maximum current of 30 kA circulating in the coil will produce a maximum field of 7T. The paper outlines the geometry and electrical characteristics of the OHS. Of major concern for the design of central solenoids for tight aspect ratio tokamaks are mechanical and thermal stresses. The paper describes the accurate thermal analysis of the solenoid, considering the coupling of the temperature on both conductor and refrigeration fluid with the electrical potential and hydraulic pressure fields, and the mechanical stress estimates performed to assess the coil's safety.

THE TBR-E SMALL ASPECT RATIO TOKAMAK

TBR-E is designed to allow a continuous variation of the aspect ratio from 1.5 to 2.0, with fixed elongation and constant toroidal field, in order to characterize equilibrium, stability, and energy confinement as a function of the plasma aspect ratio. Because of its low aspect ratio, TBR-E will operate in the low collisionality regime even at rather low temperatures. Results obtained in TBR-E will thus extend the tokamak basis, in particular the confinement scaling, to low aspect ratio, in conditions physically equivalent to those achieved in large tokamaks.

A computer drawing of TBR-E is shown in Fig. 1. The overall dimensions, including the support structure, are 3.3 m high and 2.5 m wide. The major radius of the plasma column can be varied from 0.39 m to 0.50 m; the width of the plasma cross-section is approximately 0.25 m and the maximum elongation is 1.7; the maximum toroidal field at R = 0.50 m is B_T = 0.63 T. Finally, the maximum plasma current is I_P = 240 kA with approximately 80ms pulse duration. The basic constraint on the choice of parameters was the power available at the São Paulo Campus of USP, about 21 MW of peak power for short pulses. A rationale is given in [NASCIMENTO, 1991]. The device should cost around US$ 6 millions, including power supplies but excluding diagnostic equipment. Detailed engineering design, construction, and assembly is expected to take four years.

The most crucial problems encountered in the engineering design of TBR-E relates to its tight configuration. It's low aspect ratio strongly affects the design of the innermost components, *i.e.*, the inner legs of toroidal field coils (TFC), the main ohmic heating solenoid (OHS), and the inner wall of the vacuum vessel (VV). The narrow space available to layout these components requires their integration to a high level. Altogether, they constitute what is usually called *the central core*. A frequent solution is to wind up the central solenoid directly over a cylinder made by the inner legs of the TFC (the central column, CC). With this choice, the connections between the CC and the outer segments of the TFC can be placed in a larger radius, and the need of a gap between the CC and the OH solenoid is avoided. However, fabrication is in this case more complicated than if the components were fabricated separately. Moreover, a hazard in one system, say the OHS, jeopardizes also the other (the TFC). For this reason, in TBR-E these systems have been designed such that they can be independently fabricated and assembled on site.

MAGNET SYSTEMS

A cross-section of TBR-E showing the major coil systems is shown in Fig. 2. The current will be driven by an air-core transformer (OHT). This includes the the ohmic heating solenoid (indicated in Fig. 2 by M1) and three pairs of compensating coils (M2, M3, M4) to decrease the flux leakage in the plasma region. Plasma equilibrium and shaping will be provided by a pair of vertical field coils (VFC) and two pairs of shaping and control coils (SFC1 and SFC2). All the above coils constitute the *poloidal field coil system*. The number and the position of all coils in this system have been chosen such as to avoid interference with diagnostic ports. The ohmic heating solenoid envelops the central column (CC), made by the inner legs of the toroidal field coils. To allow assembling and easy fabrication, the TFCs will have demountable joints between their outer segments and the central column.

TBR-E will normally operate with natural or slightly more elongated configurations. In this case, the vertical stability of the plasma column is not a severe problem and stabilization can be provided by a simple feedback system using

coils SFC1. For highly elongated configurations, an extra pair of radial field coils may be required. It has been recently verified that some plasma equilibrium configurations can be strongly perturbed by the stray field of coils M2 at the end of the current pulse.

TOROIDAL FIELD COILS SYSTEM

The toroidal magnetic field will be produced by 16 D-shaped copper coils connected in series. The maximum toroidal field on the equatorial plane at R = 0.5 m is B_T = 0.63 T for a current I = 98.4 kA flowing on the TFCs. The main parameters of the toroidal field coils are given in Table 1. The shape of the outer TFC segments minimizes bending stresses produced by the coils self-field, thus allowing a small cross-section to be employed. A study was made to select the most appropriate shape, considering the low aspect ratio requirements, as well as enough clearance to diagnostics in the outer side of the machine, and a total coil height not greater than 2.40 m. The parameters of the free-bending shape curve adopted are R_1 = 0,07 m and R_2 = 1.12 m. The material of the TFC will be OFHC copper in full hard conditions. The outer segments will be made up from straight bars, with square cross-section 45 mm x 45 mm, bent to the appropriate D shape in a calender machine. The straight, wedged shaped inner sectors will be made by extrusion, with cooling holes obtained during extrusion or lately, by drilling. The 16 inner sectors, bonded together but electrically insulated by glass-reinforced epoxy layers, 1 mm thick, constitute the central column (CC).

THE TFC ELECTRICAL CONNECTIONS

Joints between the central column and the outer segments of the TFC are critical in low aspect ratio tokamaks. From one hand, a small radius for the CC means a small amount of material to resist to eletromagnetic loads that are proportionally higher than in conventional tokamaks, as they grow with the inverse of the distance to the machine axis. In TBR-E conditions are even worse, because the machine is designed to allow variable aspect ratio plasmas with constant toroidal field. Thus, the larger the aspect ratio of a discharge, the higher will be the required electrical current and so the electromagnetic loads.

- The TFC Crowns

For these reasons, a conventional bolted conection between the central column and the TFC outer segments was discarded. Instead, a *socket joint* was designed to ensure *mechanical continuity*, while *electrical connection* will be provided by *butt joints*, as shown in Fig. 3. Strips of *felt-metal* between the joining parts are used to decrease contact resistance. The required contact pressure has been experimentally determined for a sample of felt metal at room temperature. Fig. 4 shows the contact resistivity of a butt joint with a thin strip of felt metal as a function of the contact pressure. To achieve the pressure of 2 MPa required to keep the contact resistivity bellow 15 $\mu\Omega cm^2$, a chain with 8 small hydraulic jacks surrounding the butt joints was devised. The chain compresses all the 16 joints against the central column, with a load of about 5 tons in each jack.

To facilitate assembling, *lap joints* were introduced at top and bottom positions of the TFCs. The short pieces between these joints and the but joints with the central column (named the TFC *"crowns"*) will be machined from copper plates. The electrical connection between coils will also be at the position of the lap joints.

- The symmetrical feeding buses

The current will be transferred from one TFC to another through two feeding buses, as shown in Fig. 5. This novel solution offers minimum increase to the total resistance of the circuit as well as reduction of fabrication and assembling costs.

Each bus will be composed by a series of machined copper pieces, imbricated one to another, in order to complete a ring. Each bus will also have a compensation ring, provided to balance the net toroidal current flowing in the bus. Half of the coils will be fed by one bus and half by another. This guarantees the symmetry and correct curvature of the error field produced by the residual toroidal current, in the plasma region, as shown in Fig. 6. Furthermore, a large region is obtained with error field smaller than 0.15 G.

A sketch of the current flow between the coils is shown in Fig. 7(a,b). A "pipeline" representation of the electrical flow is given in Fig 7(c). The current will enter the circuit by the lower bus and feed the eight even numbered coils. Then, using one of the coils' sectors, the current will be transferred to the upper bus, feed the eight odd coils, circulate through the compensation ring in the opposite direction, return to the lower bus, and after compensating the net current in the lower bus, finally leave the circuit.

THE TFC STRUCTURAL BEHAVIOR

The TBR-E geometry is conditioned mainly by the geometry of the toroidal field coils (TFC). Free-bending, D-shaped coils allow considerable material and manufacturing savings, as well as simplification of the geometry of the joints between the inner and outer sectors of each coil. On the other hand, as the machine aspect ratio is reduced, free-bending curves become "taller" and the central column gets thinner than in conventional tokamaks, complicating the design of the support structures for the toroidal and poloidal field coils.

- The inner central column mandrels

The outer sector of each TFC imposes to the ends of the central column a vertical load of about 2.4 tons, transferred through the socket connection between the outer segments of the TFCs and the CC. There arises a moment in the wedged sectors of the central column, due to the eccentricity between load and reaction. Although the copper wedges confine each other, they are separated by a softer epoxy layer. Thus the end of each wedge tends to bend inwards, producing high bending stresses in the reduced cross section of the socket region. Moreover, compressive hoop stresses could damage the insulating material. To avoid excessive bending stresses in the copper, or compression in the insulation, a mandrel-type prop will be inserted at each end of the CC. After the machine is assembled, a low intensity electrical current circulating in the TF circuit will heat the CC until it reaches the design temperature ($81°C$), when the mandrel is expanded. When the CC cools down, the mandrel will be compressing its inner face. To avoid damage to the insulation layer, an external clamp will compress the CC ends. On doing so, the ends of the CC will remain permanently in a state of compressive hoop stresses.

- The support structure

Because the TFCs are rather tall, it was necessary to support them against the out-of-plane forces (due to the interaction of the current in the TFC with the poloidal fields), in four distinct regions, both to prevent excessive lateral bending of the outer segments of the coils as to avoid excessive torsion of the central column (CC).

The TFC support structure will be made of two rings and two cylindrical caps (made from a fiber glass reinforced resin), interlocked by stainless steel bars, as shown in Fig. 8. In rings and cylindrical caps will be symmetrically placed with respect to the machine equatorial plane. Each ring will be divided into four quadrant segments, connected by bolts. The support structure will conveniently balance all electromagnetic loads due to normal and abnormal operational conditions, as well as transfer the weight of the components to the ground. On the other hand, the structure will not resist the thermal expansion of the coils and vacuum vessel, thus avoiding undesirable thermal stresses to take place.

The lateral loads on the TFC will be transferred to the rings by supports that avoid the lateral displacement of the coils, without restricting their thermal expansion. These supports, shown in Fig. 9, also transfer to the rings the loads acting on the vertical field coils and on the arms that support the VV and the shaping coils.

The out-of-plane loads due to the interaction between the TF currents and symmetrical poloidal fields are anti-symmetric with respect to the machine equator. Their resultant is null, but vertical torques appear in each ring or cap. These torques will be counterbalanced by the torques on the opposite ring or cap, through the *anti-torque frame*, with its rods alternately in axial tension and compression.

Besides balancing the torque in the vertical direction, this frame has two other functions: *(1)* it transfers the weight of the components to the lower ring, and from this to the ground and *(2)* it reacts to half the vertical load imposed by the outer segments of the TFC to the central column (40 ton), by means of a hydraulic jack placed inside the upper cap. Rigid stoppers compressing the CC were discarded because they would introduce undesirable thermal stresses both in the central column and in the support structure. The load of the hydraulic jack will be applied to the upper TFC crown by a stiff disk. By its turn, the lower crown will lay in another disk, that transfer the hydraulic load and the weight of the central column to the lower cap, through a rigid stopper (instead of another hydraulic jacket). An implication of this asymmetry is that the thermal expansion of the CC will be totally upwards.

The disks will be employed also to react to the lateral electromagnetic loads on the TFCs. For this propose, the disks will be connected to the caps by thin plates that oppose their rotations, still offering very little resistance to their vertical displacement, thus allowing the central column to breathe. Additionally to the connections through the disks, the caps will be connected to the feeding busses of the TF coils by means of bolts (Fig. 5). An elastomer layer is provided between the feeding bus and the cap. Together, these connections avoid excessive lateral displacements of the TFC coils and twisting of the central column without restricting the vertical thermal expansion of the coils.

Due to the torque produced by the out-of-plane loads on the TF coils, there is a maximum load of 2.3 ton on the rods of the locking frame, and a maximum load of 3.9 ton on the rods of the principal frame. The vertical hydraulic system adds a tension of 4.2 ton on the rods of the locking frame and 3.7 ton on those of the principal frame.

Because of the low bending stiffness of the TF coils, the PF coils and the vacuum vessel (VV) could not be supported directly from them. Convenient support arms have been required, to withstand the gravity and electromagnetic loads on the PFC and VV.

PRELIMINARY STRESS ANALYSIS OF THE TFC

Stress analyses of the TFC were developed with the aid of an in-house finite element code (ANLEF). Fig. 10(a) shows the mesh employed. The in-plane loads (due to the self-field of the coil) are symmetrical with respect to the machine equator, while the out-of plane loads are either anti-symmetrical (in the case of normal and most of the abnormal poloidal field configurations), or symmetrical (in the case of fault conditions, characterized by a short-circuit in one TFC). Therefore, only one half of the coil was modeled, with convenient boundary conditions to represent symmetry or anti-symmetry. In the central column region, the TFC confine each other, thus an equivalent radial stiffness was simulated using spring elements.

- In-plane loads

Fig. 10(b) shows the resulting displacement in the TFC under the in-plane loads. Both displacements and the constant tension of 22 kN resulting along the outer sector of the coil agree well with the values predicted analytically. In the central column, the tension increases to 24 kN, due to the additional vertical load in the region of the joint. The end of the CC undergoes a vertical displacement of 0.27 mm which introduces some bending along the development of the coil. The bending moment is maximum at the end of the central column, due to the axial eccentricity between of crown and central column. The model did not consider the vertical compression system and the inner mandrel prop described above, which have been designed lately, specifically to limit stresses in the weak region of the socket connection.

- Out-of-plane loads

Magnetic fields and forces for the different scenarios of the current flow in the PFC (corresponding to normal and abnormal operational conditions) were computed with the aid of an in-house program (BFORCE). Displacements, bending moments, internal shear and torsion moments have been obtained from ANLEF for all the different scenarios, showing the safety of the TFC under normal condition out-of-plane loads. On the other hand, loads due to fault conditions are usually one order of magnitude larger than operational loads. Stresses is this case may well exceed the safety limits, even though larger allowable stresses are assumed, taking into account the low number of fault events. To avoid the mechanical failure of the coils during a short circuit, it may be necessary to provide them with removable intermediate spacers, which reduce the lateral deformation of the coils. Loads under fault conditions will be considered during the detailed engineering design.

OHMIC HEATING SOLENOID

The OHS, shown in Fig. 10, is the main coil (M1) of the plasma current drive and heating system (the *magnetizing system*), which comprises also three pairs of compensating coils, M2, M3, M4, connected in series with the OHS to decrease the flux leakage in the plasma region (the resulting field configuration

and "$|B| = constant$" curves for I_{OHS} = 30 kA, are shown in Fig. 11). A high-order null is produced at the equatorial plane. The error field is smaller than 10 G inside an approximately circular contour of 10 cm radius centered at the position of the field null).

The major parameters of the magnetizing system are shown in Table 2. The system lumped circuit parameters are: resistance R= 18 mΩ and inductance L =1.36 μH. The estimated mutual inductance with the plasma column, considered as a simple current loop located at the equatorial plane, at R = 0.45 m, is M ≅6.5 μH. Coils M1 (the OH solenoid) and M2 are two layer solenoids and will be helically wound. Coil M3 has only two radial layers and will be bound together with the shaping coil SFC2. Coil M4 has only one turn and will be located underneath the edge of some flanges of the vacuum vessel. To fit it in place, this coil will be made in two separate arcs which will be bolted together, during assembly, in the final position. All compensation coils will be made from copper bars of 2x2 cm² cross-section, including isolation. The maximum current density in these coils will be j = 8.3 kA/cm² and preliminary thermal analyses indicate that they can be cooled between shots solely by natural air convection.

By its turn, the OHS will be made by the winding in two layers (a total of 220 turns) of copper conductor. The conductor will have rectangular cross-section (As=9x15 mm^2), with a central cooling hole (ϕ=4 mm). The coolant will be demineralized water. In order to minimize the thermal gradient in the radial direction, each layer of will be cooled by an independent hydraulic circuit. The inner and outer radius will be 7.3 and 10.5 cm, respectively. The conductor will be wrapped with a Kapton strip. After winding, the turns will be glued with an epoxy resin, giving a total insulation thickness (Kapton + epoxi) of 1 mm. The electrical feeds of the central solenoid will be embedded in an epoxi jacket placed around the central column, as indicated in Fig. 3. This will require that the vacuum vessel be assembled in place before the central solenoid, which is then slid in between the central column and the vessel. Because of the narrow gaps (2 mm) between the solenoid and the other components of the central core, the tolerances in the coil final dimensions are very restrictive.

THERMAL ANALYSIS OF THE OHMIC HEATING SOLENOID

The OHS will be charged to a maximum current of 30kA and then rapidly discharged on a load resistor to produce plasma breakdown and current ramp-up. Because of the small space available between the inner wall of the vacuum vessel and the central column, the current density in the OHS is very high at the peak of magnetizing current, arising concern about the coil safety.

Due to the short pulse duration, shown in Fig. 13, heating of the OHS is practically adiabatic. Then solenoid will be cooled during the idle time between pulses. Although simple zero dimensional evaluations can be carried out the thermal excursion of the OHS, information about the thermal gradients on the coil due to the cooling process and the time required to cool down the system was obtained with the more sophisticated model sketched in Fig. 14, considering the convective heat exchange between conductor and coolant, as well as the material non-linearities. Since the each layer has an independent circuit, only the external one (total length 67.1 m) is discretized. Results can be roughly extended to the inner layer, taking the first 58.1 meters of the model.

The model was studied with the aid of the ANSYS program. The conductor and the hydraulic circuit were discretized with, respectively, thermoelectric and thermohydraulic unidimensional elements, connected with convective links. The applied loads were: electrical current on the initial end of the conductor and electrical potential on the final end; flow velocity and temperature (20 °C, equal to the initial coil temperature) on the initial end of the hydraulic circuit and zero *pressures* on the final end. Fig. 15(a) shows the temperature evolution in the initial and final ends and at some equispaced points along the conductor, for a flow velocity of 4 m/s. The total time to cool down the solenoid is about 4 minutes. Fig. 15(b), which shows the same curves plotted against the logarithm of time, helps visualizing the temperature excursion during the current shot as well as the maximum temperature reached by the solenoid, 47 °C.

Shear stresses at the insulation, due to the differential expansion between turns, are critical for the safety of the central solenoid. Fig. 15(c) shows the evolution of the temperature difference between nodes 1 and 2 (worst case). The maximum difference is 9.1 °C, at t = 3 s. Assuming a linear variation between nodes, a maximum temperature difference of 4.1 °C between turns is obtained. An axissymetric stress analysis showed that the shear stresses are bellow 5 MPa, an acceptable value. However, an excessive the pressure (3.6 MPa) was required to sustain a flow velocity of 4 m/s. A new analysis was then developed, reducing the velocity to 2 m/s. The total cooling time then increased to 8 minutes while the inlet pressure dropped to 1.1 MPa. The maximum temperature difference between nodes 1 and 2, although delayed to 5.5 seconds, raised to 10.1 °C, still an acceptable value.

Safety of the OHS against the eletrocmagnetic loads was also investigated. For the peak current flowing on the solenoid (30kA), there results an *average hoop stress* of 59.1 MPa. The *peak hoop stress* was evaluated with a thick pipe idealization, using Lame's formula, to give 93.4 MPa. However, the OHS will be under a further compressive load in the vertical direction due to the mutual attraction force between the solenoid and the M2 coils. Assuming this load to be fully transferred by the jackets of the CC to the solenoid, the average compressive stress in the vertical direction amounts 6.9 MPa. For OFHC copper and for an expected life-time of $2 \cdot 10^5$ cycles and if one admits $\sigma \leq 150$ Mpa, ., a 50% safety margin is obtained for the calculated values — since $\max(\sigma_\theta - \sigma_v) = 100.3$ MPa — that accommodates possible dynamic magnifications of the stresses.

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Parameters	Values
Number of coils	16
Current (kA)	98.4
Turns per coil	1
Shape	D
Height (m)	2.4
Inner radius, R1 (m)	0.05
Outer radius, R2 (m)	1.12
Outer leg cross-section (cm^2)	4.5×4.5
Inner leg cross-section	22.5 arc;$2.5 \leq r \leq 6.8$ cm
Material	OFHC copper (full hard)
Resistance ($m\Omega$)	1.5
Inductance (mH)	0.309
Toroidal field on axis, R=0.5 m (T)	0.63
Adiabatic temperature rise; inner leg (^0C)	51
Pulse repetition rate	1 pulse each 5 minutes

Table 1 Main parameters of the Toroidal Field Coils System.

Parameters	Values
Inside radius, r_1 (cm)	7.3
Outside radius,r_2 (cm)	10.5
Length, l (cm)	110.0
Number of turns, N	220
Number of radial layers	2
Conductor cross-section area (cm^2)	1.5 × 0.9
Insulation thickness (cm)	0.1
Cooling hole diameter (cm)	0.5
Packing factor	0.72
Maximum current density (kA/cm^2)	26.0
Resistance at 20 ^0C ($m\Omega$)	15.8
Inductance (mH)	1.15
Central field (T)	7.5
Total flux swing (Wb)	0.38
Material	OFHC
Peak hoop stress (MPa)	100.3
Adiabatic temperature rise (^0C)	83.5

Table 2 Main parameters of the ohmic heating solenoid.

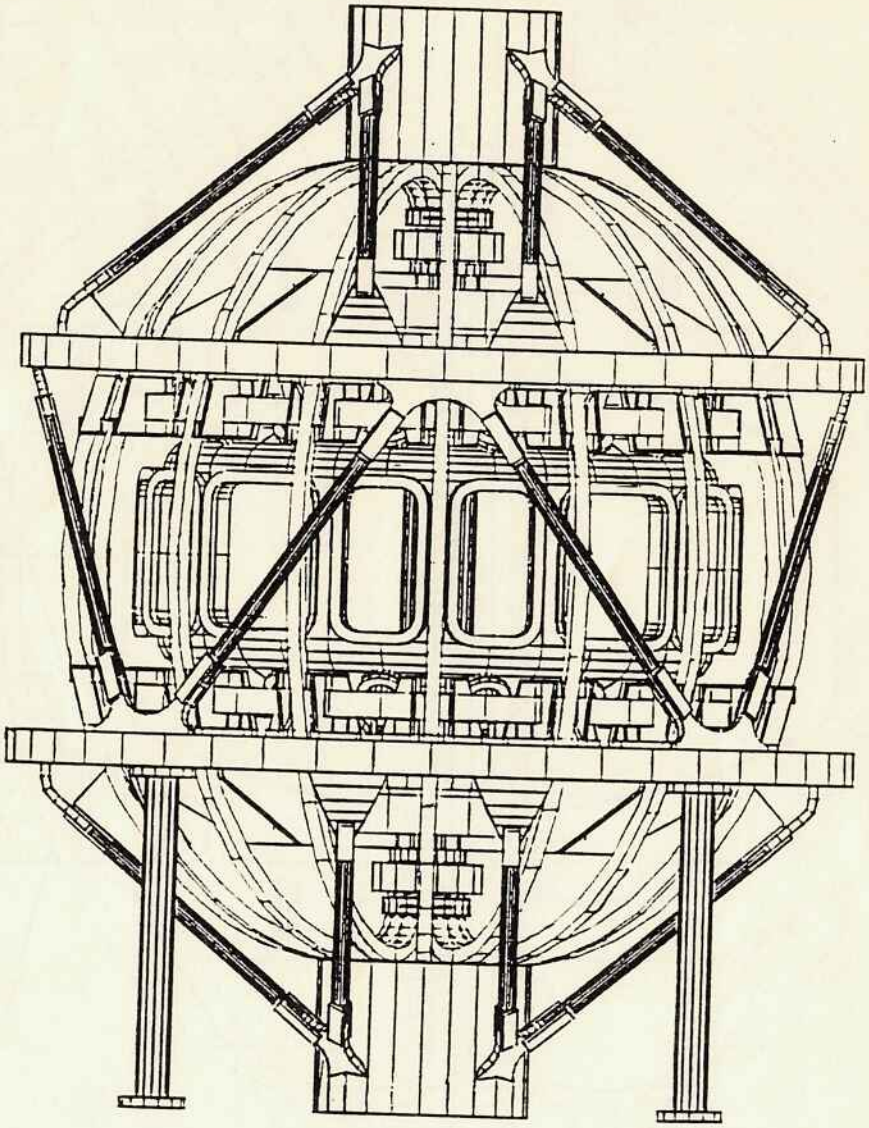

Figure 1 The TBR-E tokamak

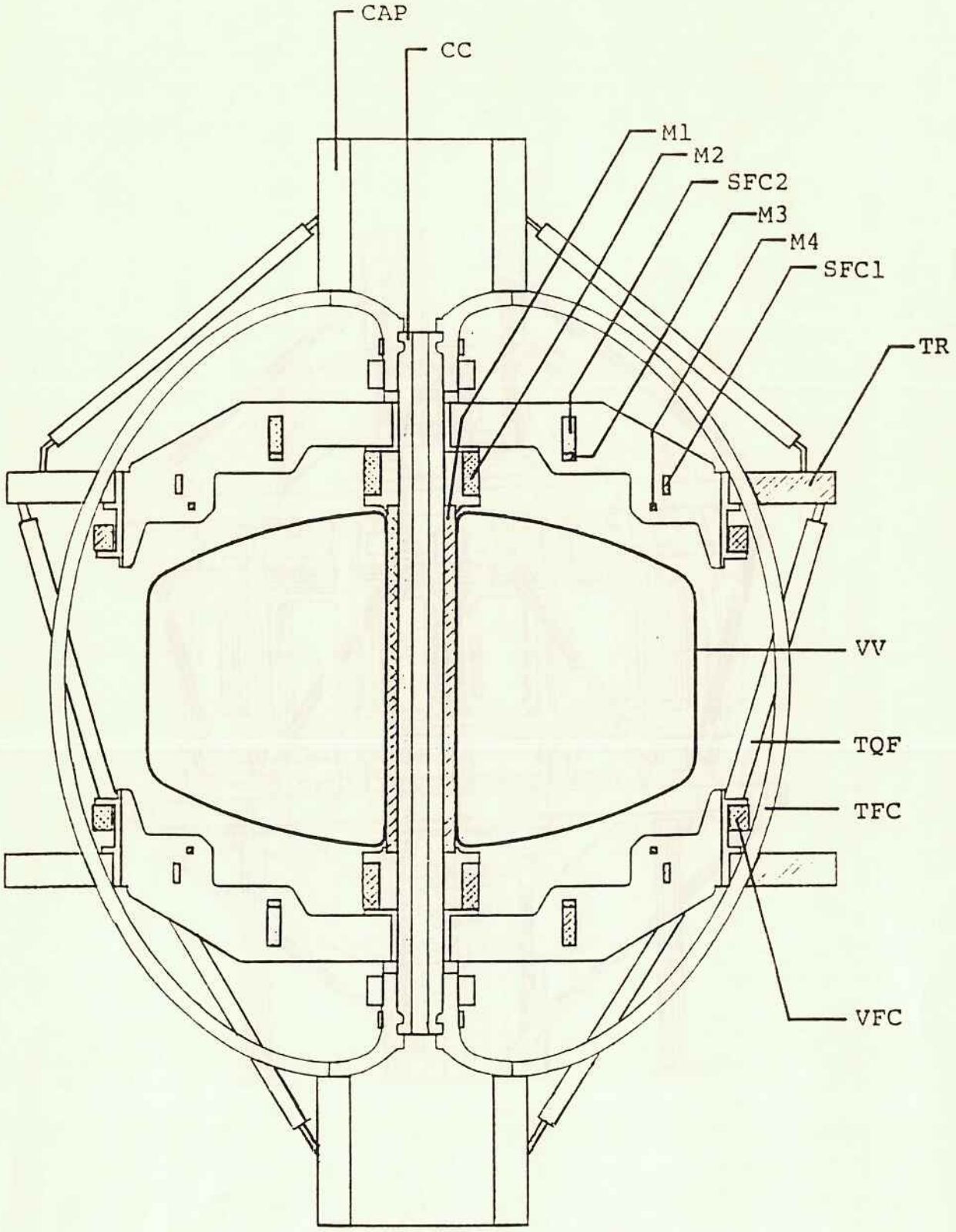

Figure 2 Cross-section of TBR-E showing the toroidal field coils (TFC), central column (CC), vacuum vessel (VV), magnetizing coils (M1-M4), vertical field coils (VFC), shaping coils (SFC1 and SFC2). Also shown is the support structure: toroidal rings (TR), caps, and torque frame (TQF).

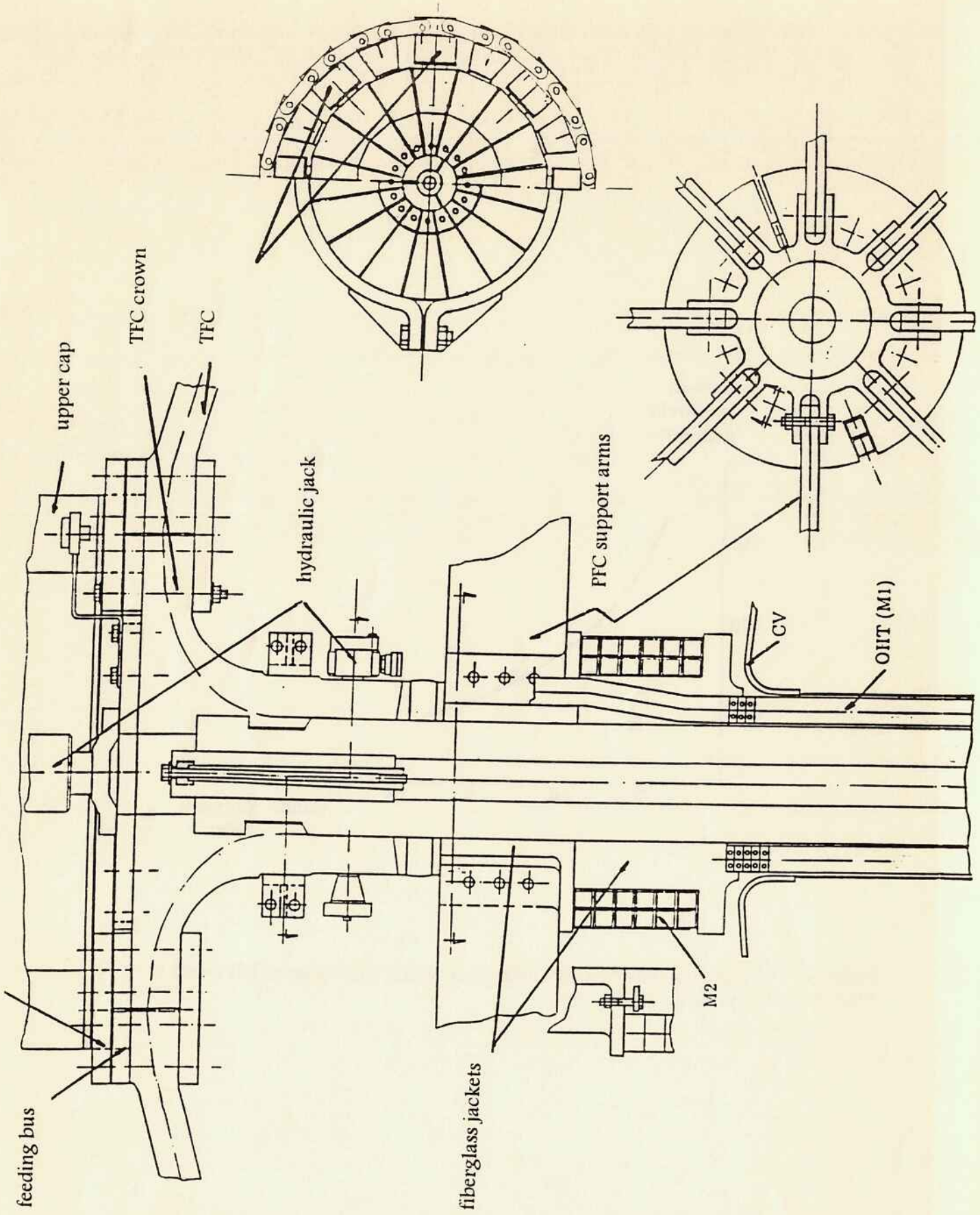

Figure 3 Arrangement of the central core of TBR-E, showing the ohmic heating solenoid M1, the compensating coil M2, the supporting arms of the poloidal field coils, the socket joint between the TFC crowns and the central column, and the hydraulic system employed to compress the ends of the central column.

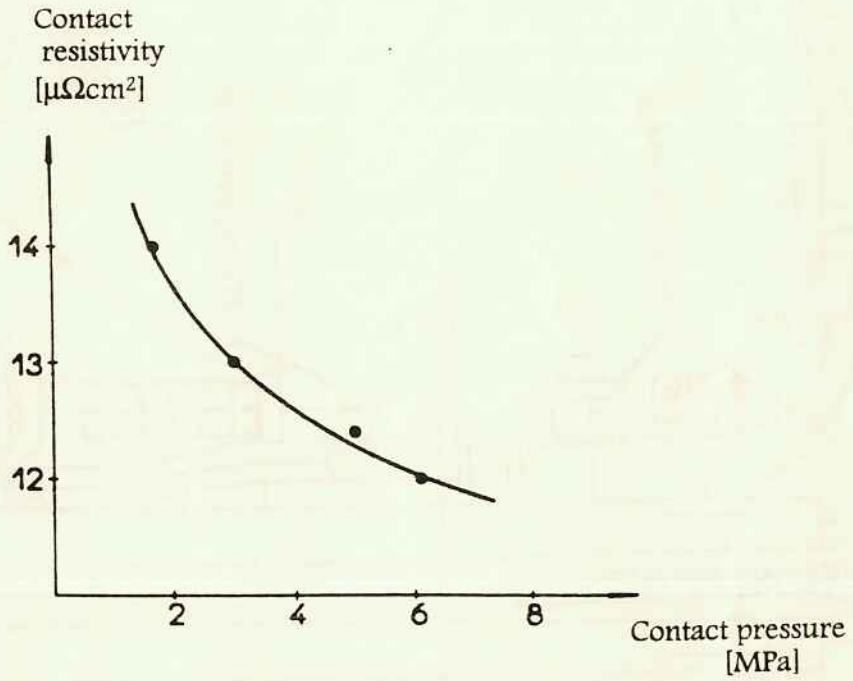

Figure 4 Contact resistivity of a butt joint with a thin layer of felt metal as a function of the pressure on the joint.

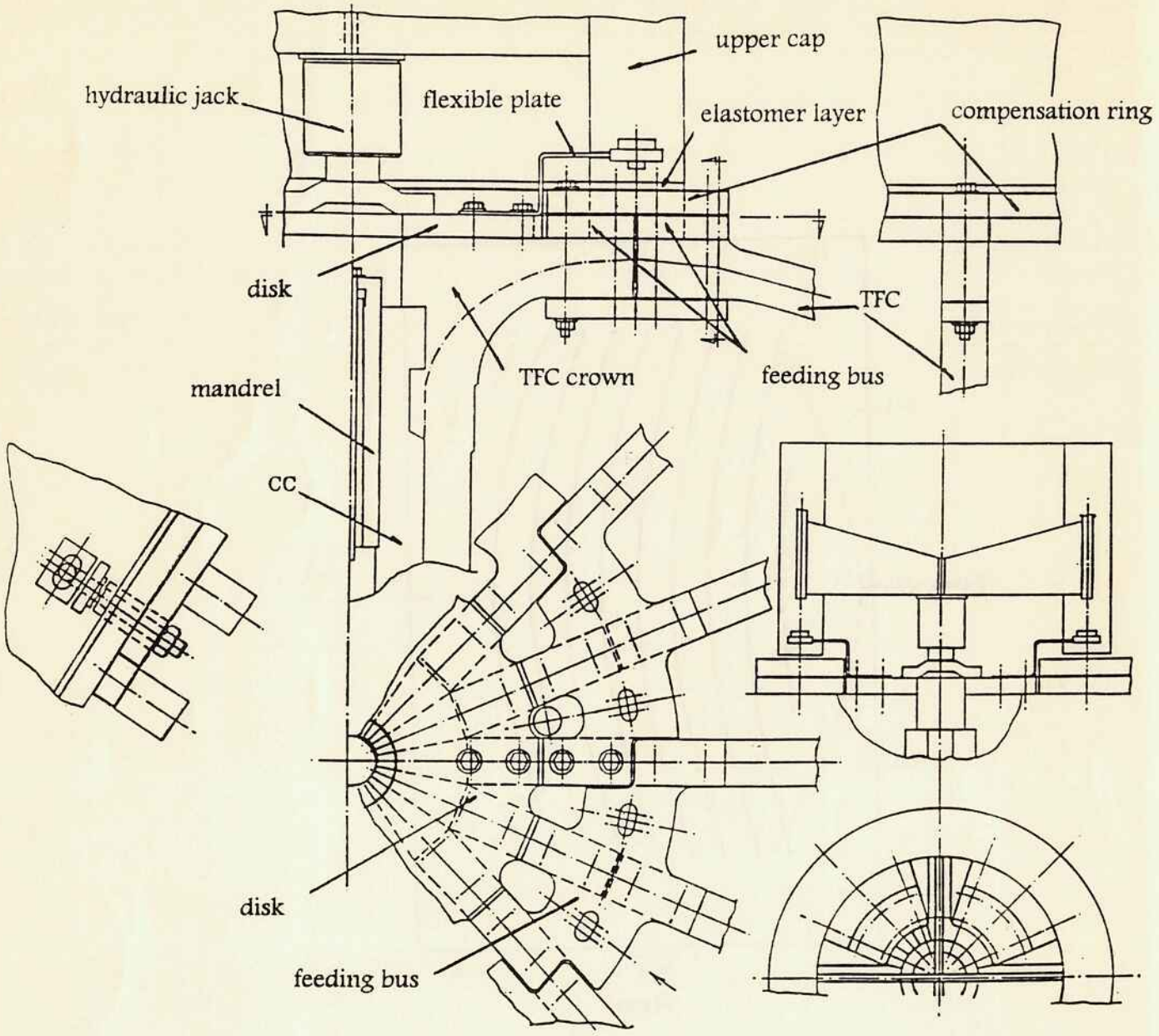

Figure 5 Detail of the TFC crowns and feeding bus.

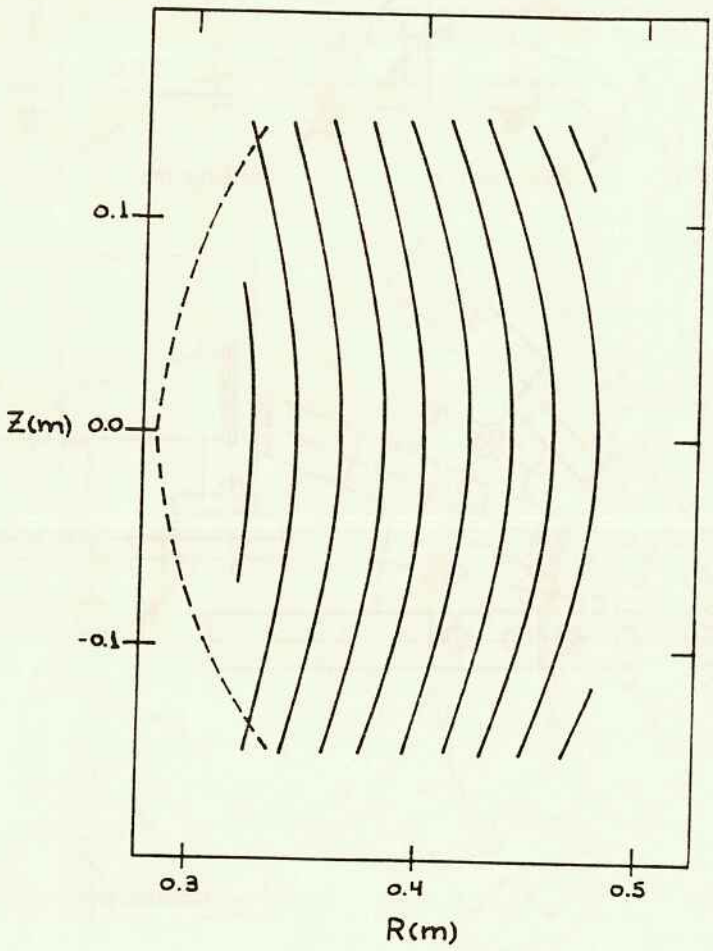

Figure 6 Field lines of the error field produced by the feeding buses of the toroidal field coils. The region to the right of the dashed line has an error field smaller than $1.5 \cdot 10^{-5}$ T for a current of 100 kA in the feeding buses.

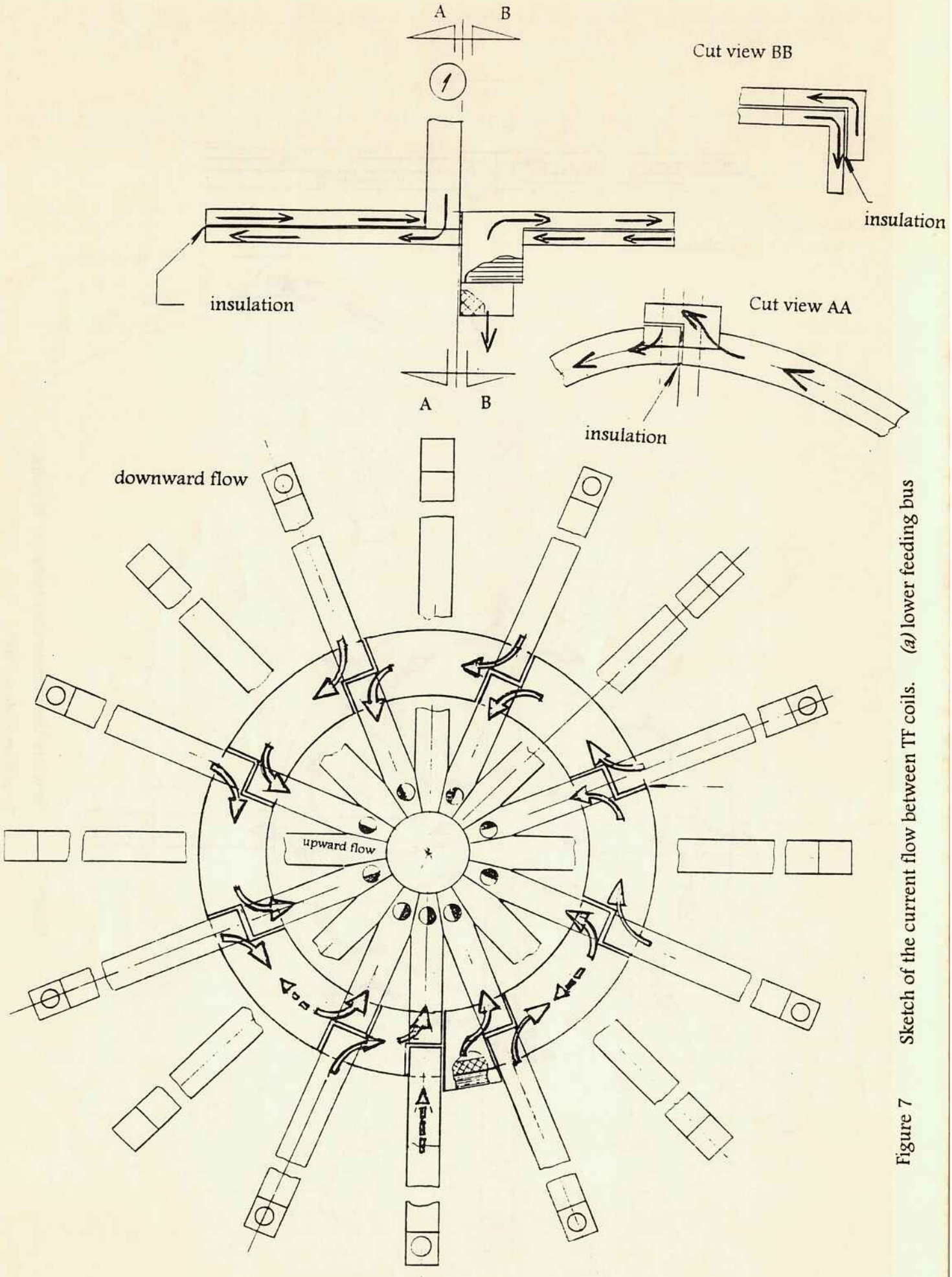

Figure 7 Sketch of the current flow between TF coils. *(a)* lower feeding bus

Figure 7 Sketch of the current flow between TF coils.
(b) upper feeding bus

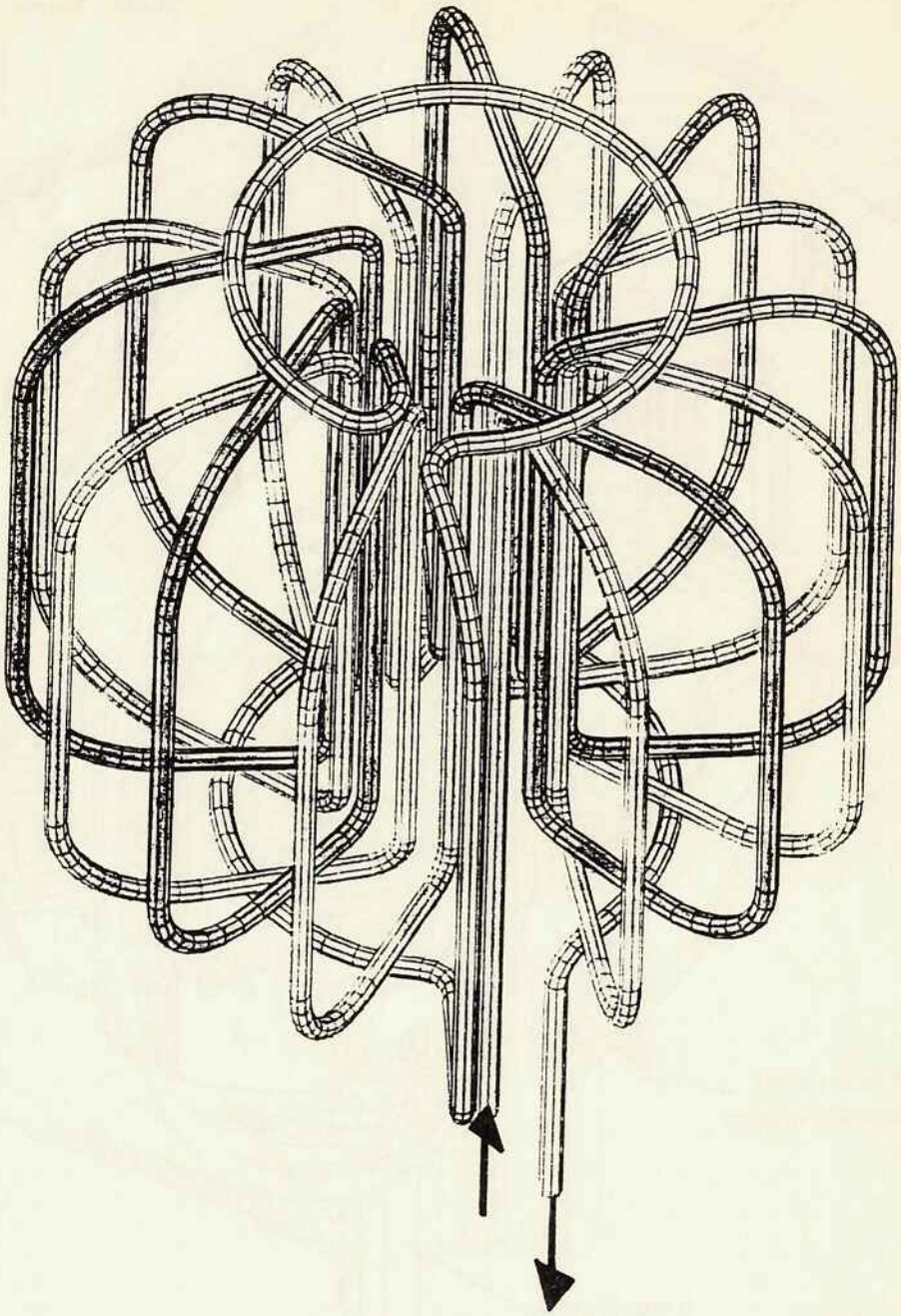

Figure 7 Sketch of the current flow between TF coils.

(c) pipeline representation of the electric flow in the TF coils

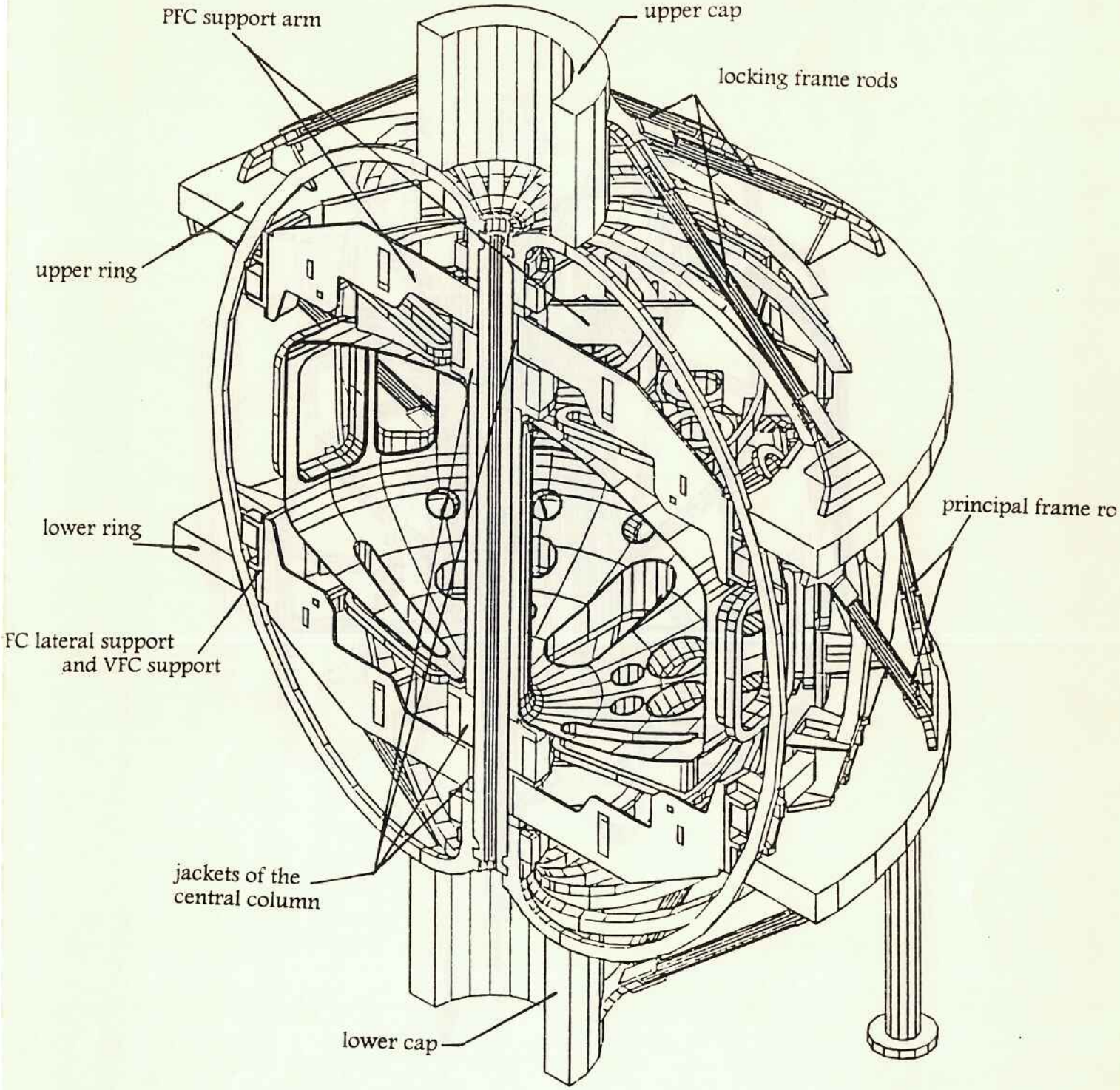

Figure 8 Main components of the support structure.

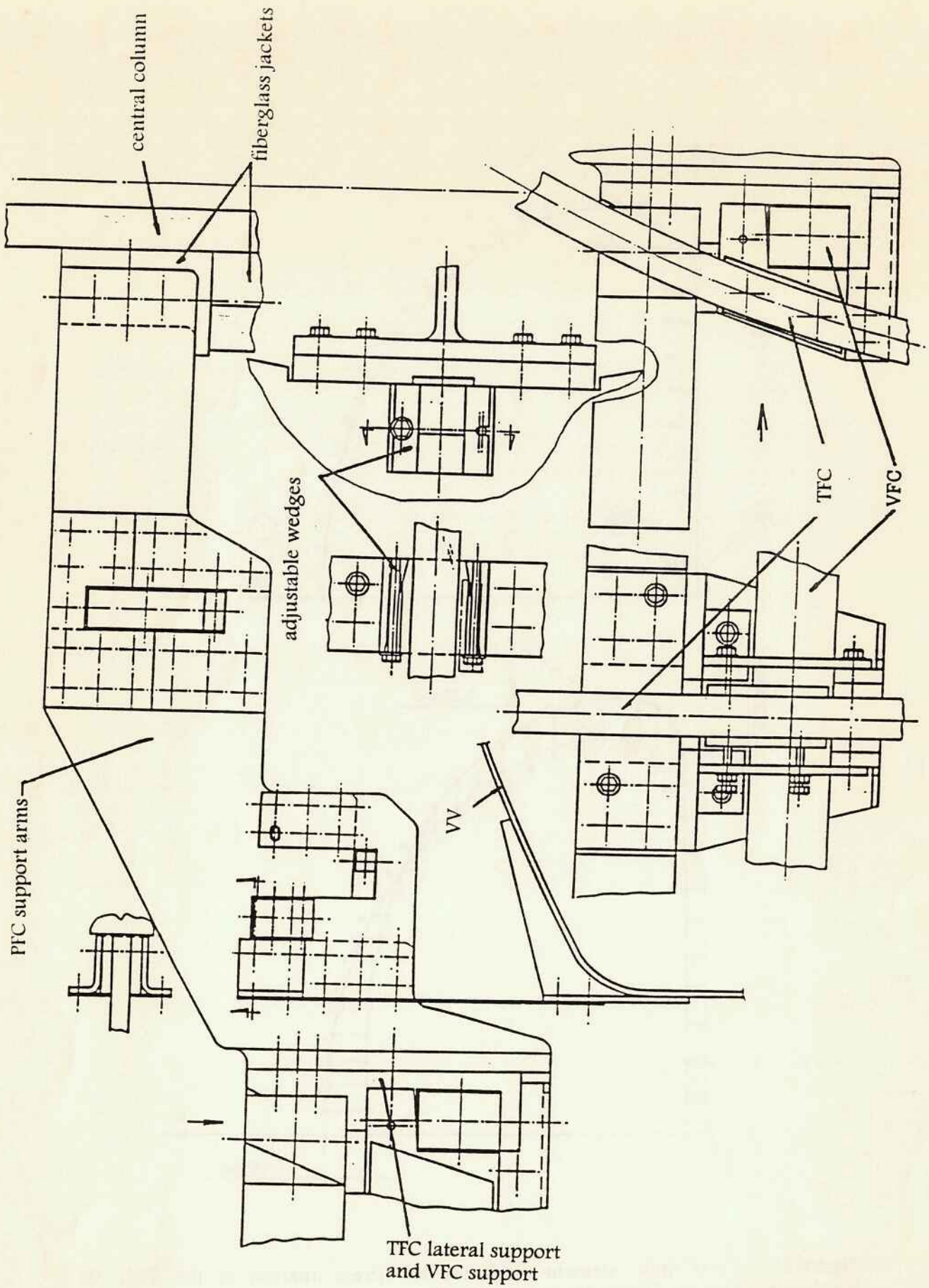

Figure 9 Supports of the poloidal field coils.

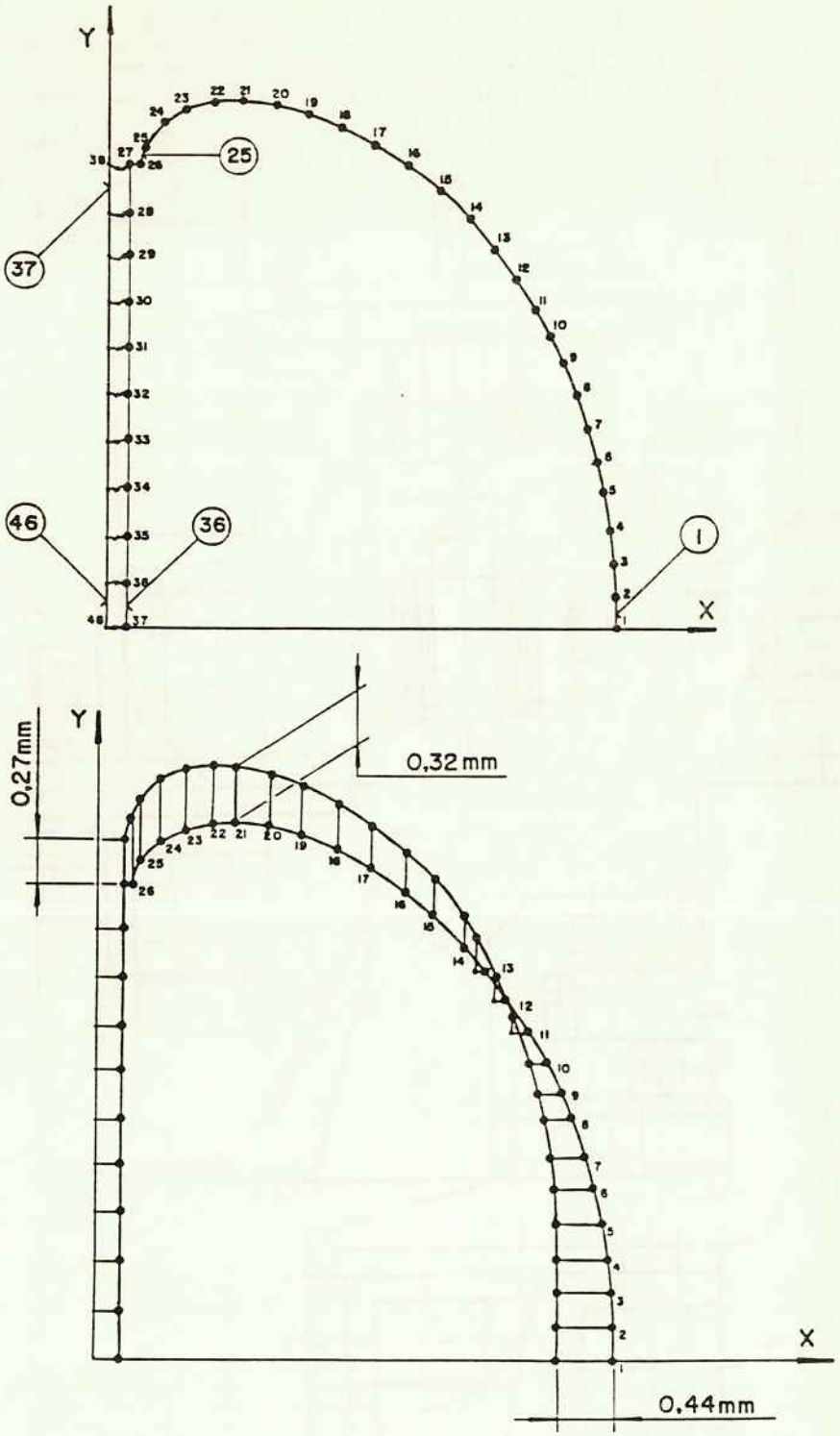

Figure 10 *(a)* finite element mesh for the stress analysis of the TFC; *(b)* displacements of the TFC under in-plane loads.

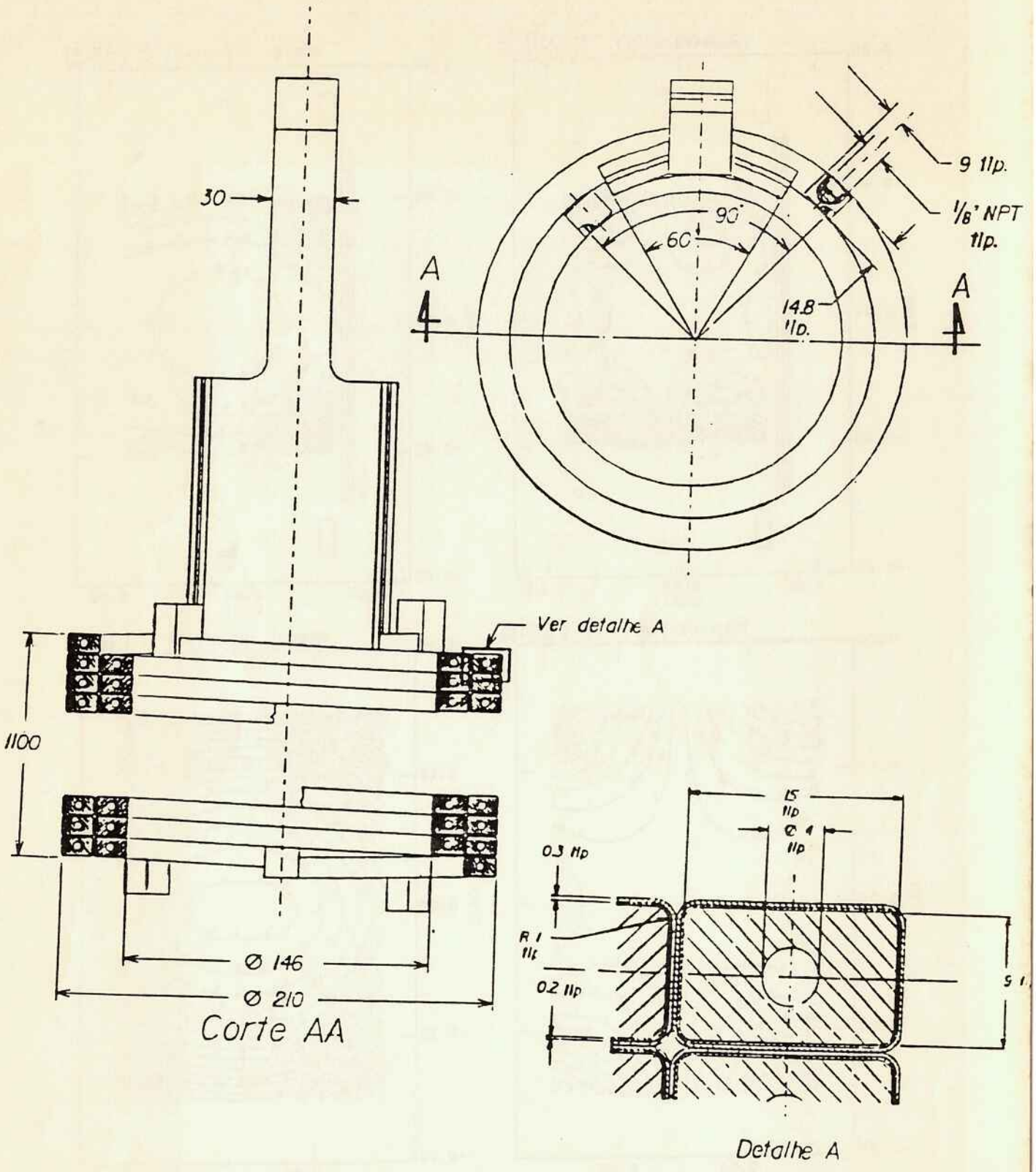

Figure 11 Ohmic heating solenoid (OHS).

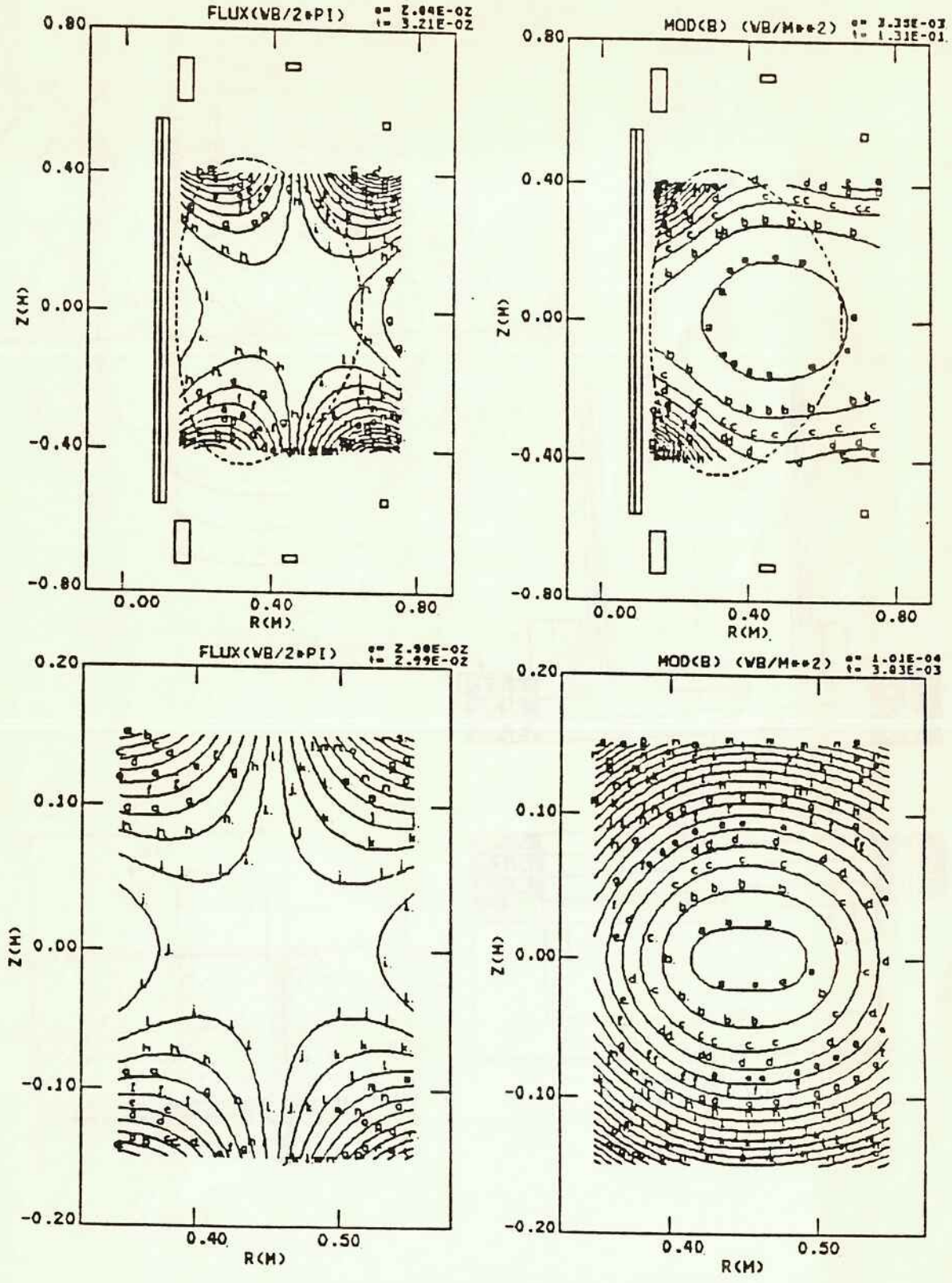

Figure 12 Field lines *(a), (b)* and $|B|$ = constant curves *(c), (d)*, for a current I=30 kA in the magnetizing coils.

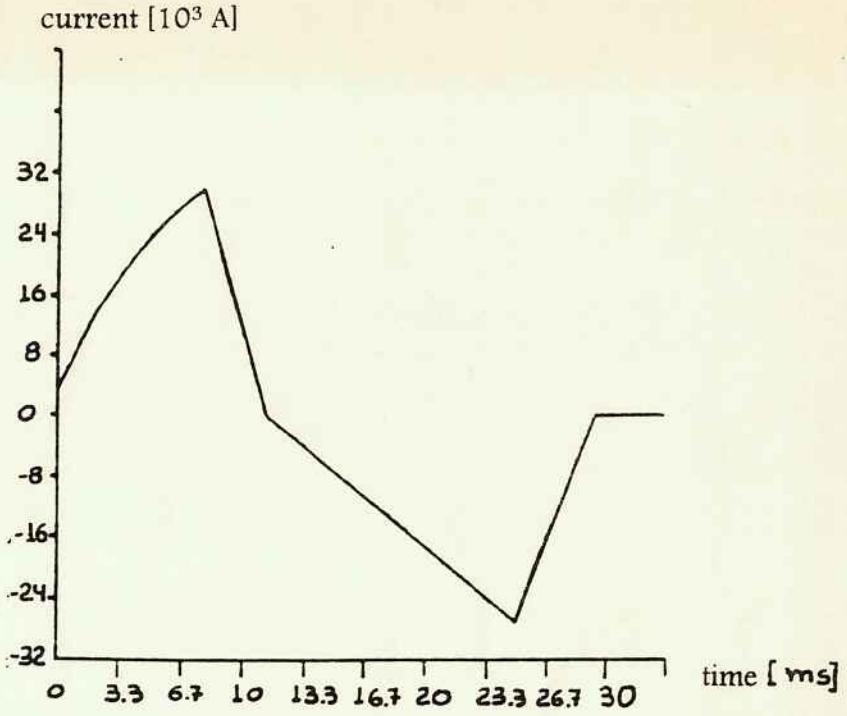

Figure 13 Current pulse applied to the ohmic heating solenoid.

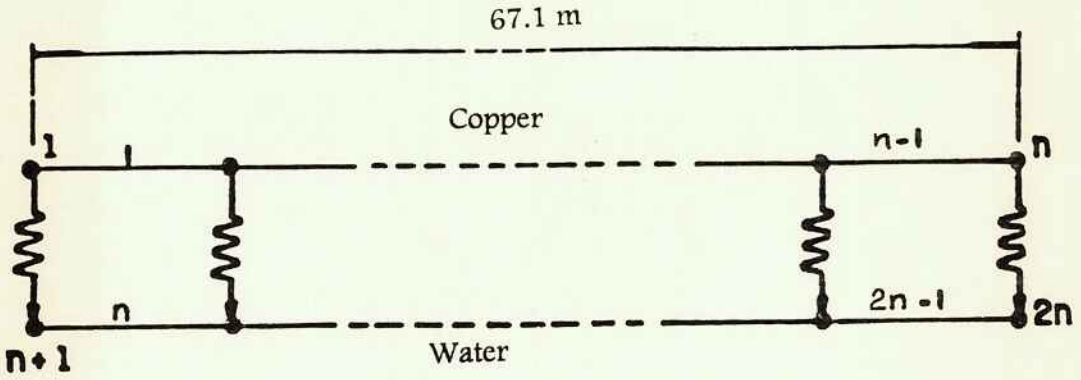

Figure 14 Finite element model for the thermal analysis of the ohmic heating solenoid.

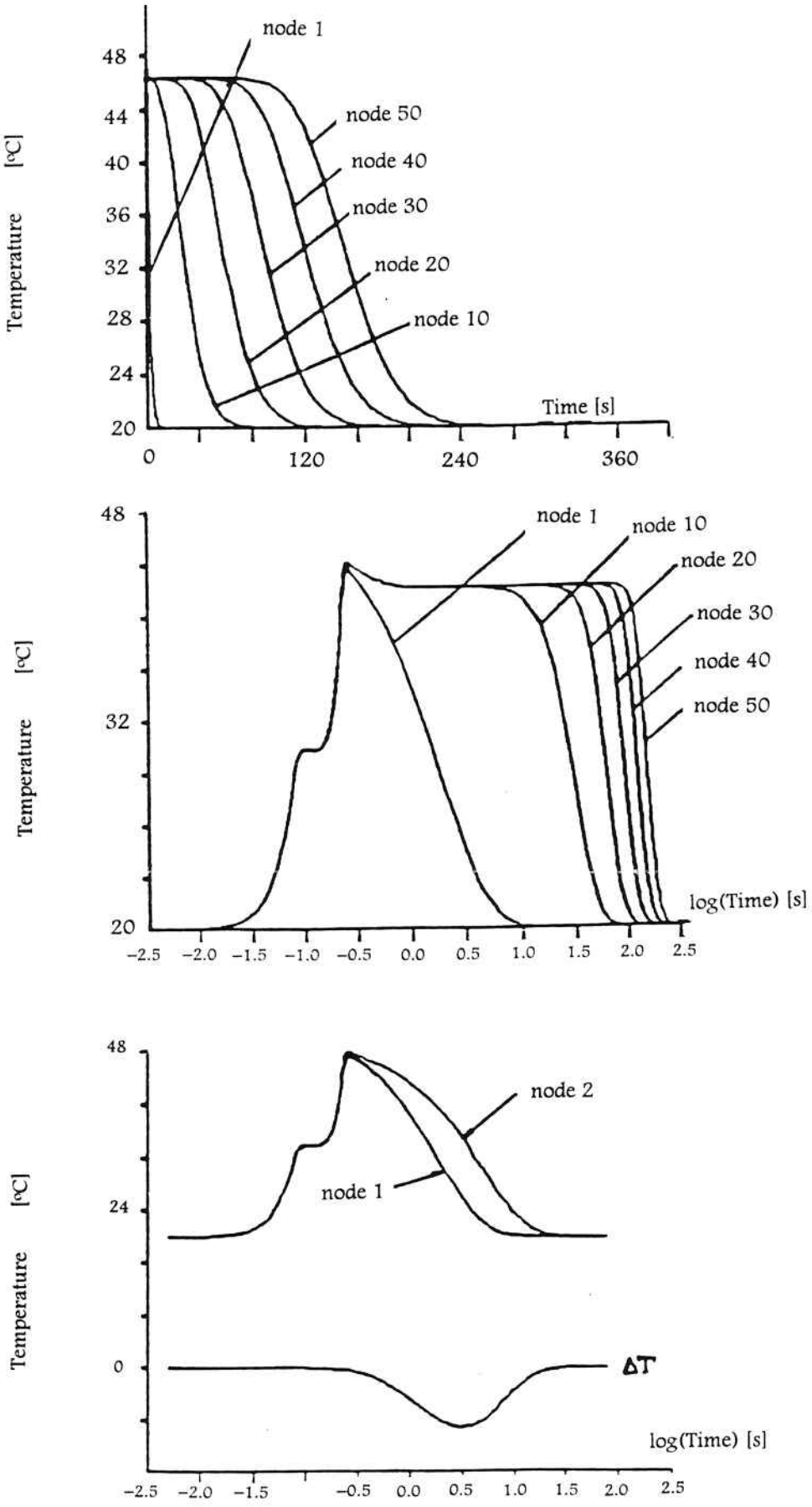

Figure 15 *(a)* temperature evolution in the initial and final ends and at some equispaced points along the OHS conductor development; *(b)* the same curves, plotted against the logarithm of time; *(c)* evolution of the temperature difference between nodes 1 and 2 (worst case).

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