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TOROIDAL FIELD COIL STRESS ANALYSIS

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I INTRODUCTION

The TCV Toroidal field coils are construced from 23mm thick copper plates. There are 16 coils of 6 turns each. The maximum current is 65.3kA giving a toroidal field of 1.43T at R=0.875m. Electrical insulation between turns is provided by sheets of fibreglass-epoxy. In the central section of the coil, the copper plates are wedged to form a vault structure. This section is vacuum impregnated. It constitutes a completely rigid assembly which can resist torsion about the vertical axis. The horizontal limbs as well as the outer vertical limbs are not impregnated. They are strengthened by a number of bolts, tying the 6 turns together. This basic design has been used in several other tokamaks (ISX, Doublet III, TCA and COMPASS) and is now considered to be proven technology.

The material used for the TCV toroidal field coils is a high-strength, high-conductivity copper alloy, containing 0.7% Cr and 0.1% Zr. The fatigue stress of this alloy is 225 MPa at 10^5 cycles. This gives the coil sufficient structural strength to carry all induced loads. The net centering force on each turn is taken up by the central vault structure and the tilting moments are carried by an external machine frame.

All elements of the coil are water cooled. For this purpose, copper tubes are inserted into grooves which are cut in the edges of the copper plates. The cooling system is designed to remove an averaged thermal power of 150kW. This allows tokamak operation at a rate of one pulse every 5 minutes. The coil temperature rise due to a pulse at full power is approximately 8°C.

II FINITE ELEMENT MODEL

The finite element model used in this analysis (Fig. 1) represents one complete coil with 6 turns, including the fibreglass-epoxy insulation. The model consists of 1319 three-dimensional elements with a total of 20018 degrees of freedom. Stainless-steel I-beams are fitted to the outer edges of the coil. The position of these beams is shown in Fig. 2. The thickness of the fiberglass-epoxy insulation is 2mm between turns and 8mm between coils. The epoxy is bonded to the copper plates only in the central column i.e. for R<400mm. In the outer sections of the coil, i.e. for R>400mm, the insulation layer transmits only perpendicular stresses, and no shear stresses, between adjacent copper plates.

III MATERIAL PROPERTIES

III.1 Copper

$E = 1.2 * 10^{11}$ Nm^{-2}
$\nu = 0.3$

III.2 Fibreglass-epoxy

$E_1 = 2.152 * 10^{10}$ Nm^{-2}
$E_3 = 8.0 * 10^{9}$ Nm^{-2}
$\nu_{21} = \nu_{31} = 0.28783$
$\nu_{13} = \nu_{23} = 0.107$

III.3 Stainless steel

$E = 2.03 * 10^{11}$ Nm^{-2}
$\nu = 0.3$

IV BOUNDARY CONDITIONS

The external support structure is simulated by 4 elastic supports. These supports can only transmit forces in the toroidal direction (y-component). Their position is shown in Fig. 2. The vertical and toroidal displacement of the support point No. 3 is assumed to be zero. The toroidal displacements, Δ_i, and the corresponding toroidal forces, F_i, are related by the equations

$$F_1 = \frac{\Delta_1}{\alpha R_1^2} - \frac{\Delta_2}{\alpha R_1 R_2} \qquad \Delta_3 = 0$$

$$F_2 = \frac{-\Delta_1}{\alpha R_1 R_2} + \frac{\Delta_2}{R_2^2}\left[\frac{1}{\alpha} + \frac{1}{\beta}\right]$$

$$F_4 = \frac{\Delta_4}{\alpha R_4^2}$$

$$\alpha = 1.16 * 10^{-8}\ N^{-1}m^{-1}$$
$$\beta = 0.98 * 10^{-8}\ N^{-1}m^{-1}$$

where $R_1 = R_4 = 615mm$
$R_2 = R_3 = 1459mm$

The boundary conditions in the central section of the coil, i.e. for R<400mm, are defined as follows : Each node (i) in the poloidal plane $\alpha = -11.25°$ (where α is the toroidal angle with respect to the vertical coil midplane) has a sister node (i') in the plane $\alpha = +11.25°$ with identical R and Z coordinates. We impose that the radial, toroidal and vertical displacements of the nodes i and i' are identical.

V LOAD CASES

The following loads are considered :

A) Stresses produced by thermal expansion as a result at a 10sec pulse at maximum current (65.2kA).

B) Forces produced by the interaction of the toroidal magnetic field with currents in the toroidal field coil (65.2kA).

C) Forces produced by the interaction of the poloidal magnetic field with currents in the toroidal and poloidal field coils. These forces depend on the current distribution in the poloidal field coils.

The loads A, B and C are always considered as superimposed. The following 5 cases are analyzed :

1)	A + B + C1	Disruption of a K = 3 racetrack plasma
2)	A + B + C2	Disruption of a K = 2.5 divertor plasma
3)	A + B + C3	Max. vertical field
4)	A + B + C4	Max. Radial field
5)	A + B + C5	Max. quadrupole field

In all cases the plasma current is assumed zero. Cases 1) and 2) appear in normal plasma operation whereas cases 3 - 5 are fault conditions.

Vertical forces acting on the toroidal field coils through the poloidal field coil supports are also taken into account.

VI STRESS CONCENTRATION IN THE JOINTS

Each turn of the toroidal field coil has four joints, two finger joints and two lap joints. In the finger joints, the copper cross section is locally reduced to 28% of the value which would be obtained if there was no joint. The corresponding figure for the lap joints is 32%. Since these joints are not included in the finite element model, we estimate their effect by assuming that tensile stresses in the vicinity of the joints are inversely proportional to the copper cross section.

VII RESULTS

Important results are summarized in the Table below :

Load Cases	**1**	**2**	**3**	**4**	**5**
Max. v. Mises Stress Copper [MPa]	161	153	203	220	145
Max. Shear Stress in 2mm Insulation [MPa]	15.6	12.6	9.6	12.8	9.4
Max. Shear Stress in 8mm Insulation [MPa]	9.8	8.4	8.8	9.6	6.4
LOADS ON SUPPORTS [KN]					
1) (R = 615)	- 39.1	- 57.7	7.2	29.2	0
2) (R = 1459)	- 58.5	- 31.0	85.2	- 41.2	0
3) (R = 1459)	58.5	36.2	- 85.2	- 23.4	0
4) (R = 615)	39.1	45.3	- 7.2	124.0	0
Max. v. Mises Stress in SS-I-Beams [MPa]	81.5	54.4	137.5	320	0
Toroidal displacement of node 3450 (outer edge, Z = 0) [mm]	0.86	0.25	1.01	12.99	0.40

VIII DISCUSSION

VIII.1 Copper

The copper alloy which is used for the toroidal field coil has a guaranteed yield strength of 360MPa and a fatigue strength at 10^5 cycles of 225MPa. If we assume that the load cases 1 or 2 (plasma) occur 10^5 times and that load cases 3, 4 and 5 (fault) occur only a few times, we obtain theoretical safety margins of 1.40 and 1.64 for plasma operation and fault conditions, respectively. These margins are very low, but they are thought to be sufficient when the following facts are taken into account :

1) Load case 1 simulates a disruption of a K = 3 racetrack-shaped plasma at maximum current (I_p = 1.2MA). This condition will certainly not occur 10^5 times throughout the life of the machine.

2) It may be possible to exclude the load case 4 by measuring the radial field at (R = 1.5m, Z = 0) and by switching off all power supplies whenever this radial field exceeds a certain value.

On the other hand, it must be remembered that the number of load cases analyzed is very small. It is entirely possible that other load cases exist which produce higher stresses than the cases which were analyzed. In addition, stress concentration due to local variations of the copper cross section were only evaluated in a very approximate way. There could easily be a 50% error in local stresses.

In conclusion we consider the safety margin of 1.4 as absolutely necessary and we do not recommend increasing the loads by increasing the coil currents beyond the design values.

VIII.2 Insulation

The maximum shear stress in the insulation is 15.6MPa. When this is compared with the rupture shear stress measured in a small sample, a safety factor of at least 3 must be applied. Therefore, we require an insulation system with at least 45MPa shear strength.

VIII.3 Stainless Steel I-Beams

The I-Beams are made of 316LN (1.4429) stainless steel, having a yield strength of ~300MPa. We note that under normal plasma operation the safety margin is sufficient but the fault condition (4) produces stresses in excess of the yield strength. This fact was noticed in December 1986 and consequently the cross section of the I-beam was modified such as to increase its moment of inertia by 50%. This modification will reduce the maximum stress under fault condition (4) to approximately 220 MPa.