INT 202/01 May 2001

Hard-wired coil protection in TCV

F. Hofmann, P.-F. Isoz, Ph. Marmillod, J.-M. Moret

Centre de Recherches en Physique des Plasmas,
Association EURATOM - Confédération Suisse,
Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

1. Introduction

Stress analysis of the TCV toroidal and poloidal field coils has shown that there are a number of critical areas where the maximum stresses can exceed the allowable limits if all coil currents assume their maximum values simultaneously or if the B_ϕ current exceeds its design value of 65kA. A hard-wired coil protection system has been built, tested and implemented which triggers an abort sequence whenever the coil currents violate certain conditions. These conditions will be discussed below.

2. F-coil supports

The maximum vertical force that can be applied to an F-coil is 1803kN. If we assume that this force is distributed equally over the 16 supports, we obtain a vertical force of 113kN per support. This force appears when coils F1-F4 carry maximum positive current and colis F5-F8 maximum negative current, a condition which never arises in normal plasma operation. The F-coil supports are designed such that they can accommodate very large attractive forces between two adjacent coils, but their tolerance for repulsive forces between adjacent coils is limited. In order to ensure that no excessive repulsive forces can be generated, the following seven conditions must be satisfied:

$$|F_1-F_2-0.5F_3-0.25F_4| < X$$

$$|0.5F_1+F_2-F_3-0.5F_4-0.25F_5| < X$$

$$|0.25F_1+0.5F_2+F_3-F_4-0.5F_5-0.25F_6| < X$$

$$|0.25F_2+0.5F_3+F_4-F_5-0.5F_6-0.25F_7| < X$$

$$|0.25F_3+0.5F_4+F_5-F_6-0.5F_7-0.25F_8| < X$$

$$|0.25F_4+0.5F_5+F_6-F_7-0.5F_8| < X$$

$$|0.25F_5+0.5F_6+F_7-F_8| < X$$

where F_i is the current in the i-th F-coil (in kA) and X=1.5 times the maximum current in an F-coil, i.e. X=10.5kA. If these conditions are satisfied, the maximum repusive force between adjacent coils is approximately one half of the maximum attractive force. The conditions do not interfere in any way with normal plasma operation, since they only prevent very large dipole currents in the F-coils.

3. Central column

Since the OH transformer in TCV is split in two sets of coils with independent power supplies (OH_1 and OH_2), the possibility exists that the currents in the two coil sets are not equal. This condition is not necessary for plasma operation, but can arise as a fault condition. The difference between the OH_1 and OH_2 currents creates a repusive force between the A and B coils, which produces tensile stress in the epoxy layer separating these two coils. The currents in the

E-coils can also contribute to this force, depending on their magnitude and sign. The epoxy is very weak under tensile stress so that the repusive force between A+E and B must be limited. The conditions, below, are designed to limit this force to tolerable values:

$$[OH_1+1.14E_1+0.48E_2+0.23E_3+0.13E_4] * OH_2 > -150\ (kA)^2$$

$$[OH_1+0.13E_5+0.23E_6+0.48E_7+1.14E_8] * OH_2 > -150\ (kA)^2$$

where E_i is the current in the i-th E-coil and OH_1, OH_2 are the OH currents (in kA). We note that when $OH_1= OH_2$, as is the case for normal plasma operation, the minimum value of the left hand side of the above inequalities is equal to -48 $(kA)^2$, which implies that the conditions are always satisfied.

4. B_ϕ coil finger joint

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 joint is 32%. Consequently, mechanical stresses in the vicinity of the joints have to be checked carefully. The load in the finger joint area consists of a superposition of a tensile force, two bending moments around the vertical and horizontal axes, and vertical and horizontal shear forces. The tensile force, the bending moment around the horizontal axis and the vertical shear force arise from the interaction of the toroidal magnetic field with the toroidal field coil current. The bending moment around the vertical axis and the horizontal shear force are produced by the interaction of the poloidal magnetic field with the toroidal field coil current.

The bending moment around the vertical axis, in the finger joint area, is particularly important because it is mainly responsible for the creation of shear stesses in the epoxy insulation of the central column. This bending moment is approximately proportional to the vertical magnetic field along the horizontal beam of the toroidal field coil and to the toroidal field coil current. Assuming that the toroidal field coil current is equal to its maximum design value (65kA), we obtain the following two conditions for the upper and lower finger joints:

$$|0.9F_1+1.0F_2+1.4F_3+1.6F_4+2.2F_5+2.7F_6+4.0F_7+5.0F_8+0.87\ OH_1+2.11\ OH_2| < X_1$$

$$|5.0F_1+4.0F_2+2.7F_3+2.2F_4+1.6F_5+1.4F_6+1.0F_7+0.9F_8+0.87\ OH_1+2.11\ OH_2| < X_1$$

where X_1=115kA. These conditions are never violated in normal plasma operation. For example, the 1MA shot (11368) produced less than 80kA on the left hand side of the above inequalities.

5. Vertical force on the ABE-coil lassembly

The vertical force acting on the ABE-coil assembly can be written as

$$F = OH_1\sum_i a_iF_i + OH_2\sum_i [b_iE_i + c_iF_i] + \sum_i\sum_j d_{ij}E_iF_j$$

The maximum force of 1.41MN is generated when OH_1=+27kA, OH_2=+27kA, $E_{1\text{-}6}$=+7kA, $E_{7\text{-}8}$=-7kA, $F_{1\text{-}3}$=+7kA and $F_{4\text{-}8}$=-7kA. This force will produce a compressive stress of 14MPa in the elastic support structure of the ABE assembly, which is far beyond the allowable limit. The maximum force is reduced by about a factor 3 if the condition

$$|2.69(F_1-F_8)+2.56(F_2-F_7)+1.47(F_3-F_6)+0.67(E_4-E_5)+2.12(E_1-E_8)+1.1(E_2-E_7)+$$

$$0.67(E_3-E_6)+0.21(E_4-E_5)| < 40\text{kA}$$

is satisfied.

6. Stainless steel I-beams on the outer vertical limb of the B_ϕ coil

The finite element analysis done by ZACE in 1988 (INT 153/88) has shown that the vertical limbs of the toroidal field coil are displaced toroidally by 13mm, in the equatorial plane, if the E and F-coil currents are such as to generate the maximum radial field and if the toroidal field coil current assumes its maximum design value (65kA). Such a large displacement would be catastrophic in TCV, since the clearance between diagnostic equipment and the elements of the toroidal field coil is nominally 10mm. The maximum displacement can be reduced by a factor 3 by imposing the constraint

$$|7.7(F_1-F_8)+6.8(F_2-F_7)+4.4(F_3-F_6)+2.5(F_4-F_5)| < X_2$$

where X_2=107kA. It should be noted that this condition is almost identical with the condition of section 5, if the E-coil currents are assumed to be zero.

7. Increasing the toroidal field above its maximum design value (1.43T)

Recently, the question has been raised whether the toroidal field in TCV could be increased above its nominal value, in order to shift the X2 resonance to larger major radii. Increasing the toroidal field has several consequences. In-plane forces acting on the toroidal field coils increase quadratically and out-of-plane forces increase linearly with B_ϕ. Shear stresses in the epoxy insulation of the central column also increase linearly with B_ϕ. Finite element analysis of the toroidal field coil (INT 153/88) has shown that the theoretical safety margins for plasma operation and fault conditions are 1.40 and 1.64, respectively. These margins were considered to be absolutely necessary in order to accommodate local stress concentrations, which were not included in the finite element model, and it was recommended not to increase the coil currents beyond their design values (INT 153/88).

Increasing the toroidal field above its nominal value will reduce the lifetime of TCV. Whether this reduction is significant cannot be juged on the basis of existing information. This would require extensive finite element calculations, similar to those performed in the 4T assessment for JET. In the absence of such an assessment, we can only make rough assumptions and try to minimize the effect of an increased toroidal field. If we assume that the critical elements are the finger joints and the stainless steel I-beams, we can modify the conditions given in sections 4 and 6 by making the values of X_1 and X_2 functions of the toroidal field coil current,

$$X_1 = [(77-I_\phi)/(77-65)] * 115\text{kA for } I_\phi>65\text{kA}$$

X_1 = 115kA for $I_\phi<65$kA

$X_2 = [(77-I_\phi)/(77-65)]$ * 107kA for $I_\phi>65$kA

X_2 = 107kA for $I_\phi<65$kA

This will allow useful operation up to toroidal fields of 1.55T. It will prevent operation when $I_\phi>77$kA or, equivalently, $B_\phi>1.68$T. It should be noted that the maximum current that the toroidal field power supplies can produce is 78kA. Application of the above constraints would allow a maximum current of 77kA in the toroidal field coil if the currents in the OH-coils and F-coils are zero. This would produce stresses in the toroidal field coil, due to in-plane forces, which are a factor of 1.4 above the design values.

8. Conclusion

The constraints discussed in sections 2, 3 and 5 have been implemented in 1996. The other constraints (sections 4, 6 and 7) are not yet implemented. They are being proposed to improve the safety of TCV operation and to allow limited operation at toroidal fields up to 1.55T.