MECHANICAL STRESS ANALYSIS FOR THE TWISTED COILS OF THE ADVANCED STELLARATOR WENDELSTEIN VII-AS

U. Brossmann, S.B. Mukherjee, J. Sapper

Max-Planck-Institut für Plasmaphysik, EURATOM-Association
D-8046 Garching, Federal Republic of Germany

ABSTRACT

The standard confinement field of the advanced stellarator WENDELSTEIN VII-AS is exclusively generated by a modularly designed coil set. Fourty-five twisted coils produce a toroidal field of 3 T during a pulse time of 5 sec. Water cooled copper wires carry a winding current of 40 kA at 3.3 kV. Force components in the radial, poloidal and toroidal directions are calculated for the individual coils using EFFI-code /1/. On the basis of an optimized support concept a stress analysis for the coils was carried out using SAP V (2) /2/.

1. INTRODUCTION

The design and manufacturing of the coil system in WENDELSTEIN VII-AS-device requires an accurate evaluation of the stresses, both mechanical and thermal, acting on the coils and on their supporting structure. The coil system is derived by discretization of the current, sheeth on a toroidal surface /3/. This configuration has five field periods and each of them contains nine different twisted coils, one of them with increased dimensions and current in order to provide sufficient access (fig. 1). The standard vacuum field configuration (B_o = 3T, $\iota\!\!\!-$ = 0.39) can be varied by an additional toroidal field (B_o = ± 0.5 T). The complex shape of the coils requires a new winding technique in order to avoid the spring back effect. Studies done by BBC-Mannheim, have shown that the manufacturing of the twisted coils can be realized by using stranded copper wires (flex). The present paper reviews the status of the mechanical stress analysis for the most unfavourably loaded twisted coil No. 2. This coil has the widest lateral deformation and a high magnetic field at the inner edge.

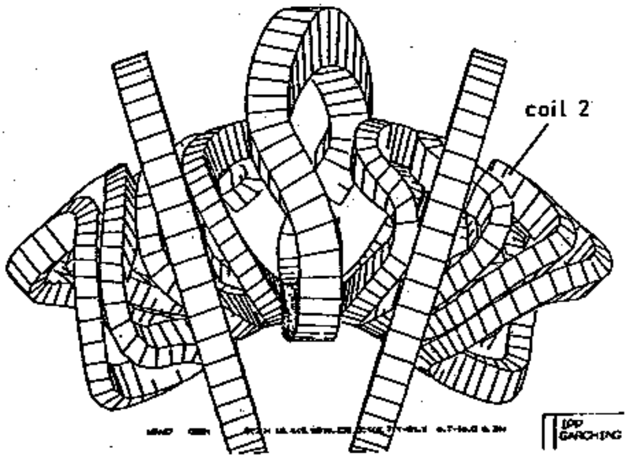

Fig. 1 Top view of coil system of W VII-AS.
One field period containing 9 twisted coils
and 2 planar toroidal field coils

2. DESCRIPTION OF THE PROGRAM SYSTEM

The program system STELLA /4/ is being employed for the computation of forces, stresses and deflections of a twisted coil. A detailed flow chart is being shown in fig. 2. The program SPULPRO determines the geometry of the stellarator coil system and subdivides a coil into macroelements. These subdivisions are too rough for the calculation of volume forces and mechanical stresses by the FE method. MESHGEN therefore makes further discretization of macroelements into small GCEs (general current element). The GCE-data are then fed into EFFI and FENGEN. The program EFFI produces element's 3D volume forces. FENGEN generates nodal co-ordinates and element descriptions as input for SAP V (2) and SHAPE. The program SHAPE converts an element's volume forces into its nodal forces and the data are fed into SAP V. The boundary elements, if required, are generated by BELGEN. With nodal co-ordinates and forces, element descriptions and boundary elements, SAP V then computes global displacements and stresses of a coil structure. Global stresses are converted into local stresses by the program STRFUN (COPLOLOS). Element's boundary reactions are optional for SAP V output.

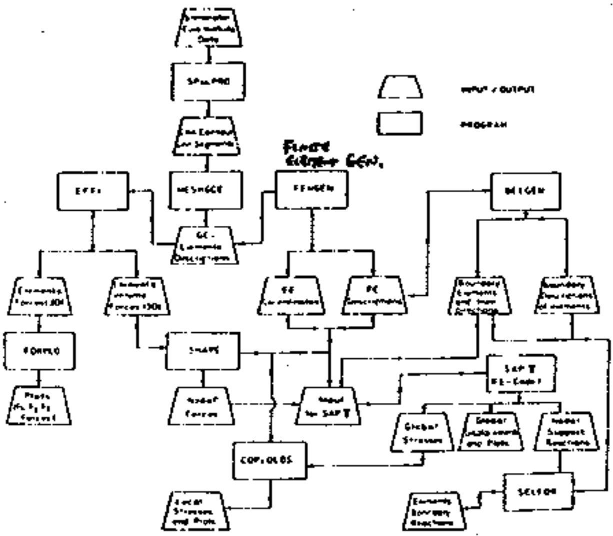

Fig. 2 Detailed flow chart (STELLA)

3. MECHANICAL STRESS ANALYSIS

The mechanical stress analysis was carried out for the end of the flat top time and includes the temperature rise (55 K) and the calculation of the magnetic volume forces of the twisted coils with the additional TF-coils.

3.1 FE-model and support concept

The FE-model applied is shown in fig. 3. A coil is sub-divided into 288 elements and each three-dimensional, isoparametric element has 20 nodes. The stress values at the center of an element (location number 21) are being obtained for analysis. The support regions (fig. 3) are optimized /5/ by the simulated boundary spring elements acting normally on the coil surface in a step by step method.

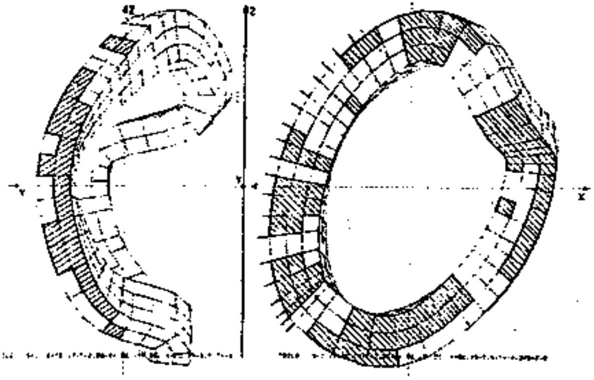

Fig. 3 FE subdivision and support

3.2 Forces

All forces are calculated for a superimposed magnetic field produced by the modular coil system (B_0 = 3 T) and the planar TF coils (B_0 = ± 0.5 T). The calculations include the two basic contributions: the self force of the individual coils and the interactive force between different (planar and non-planar) coils. Caused by the deflection of the coil currents in toroidal direction, varying loads act on the coils in circumferential and radial direction. The component forces are shown in fig. 4 as function of the coil's circumferential coordinate. All components act at the center of the respective finite macro-element of the coil. Typical maximum values of the force are 100 kN, 50 kN and 90 kN in the x, y and z direction.

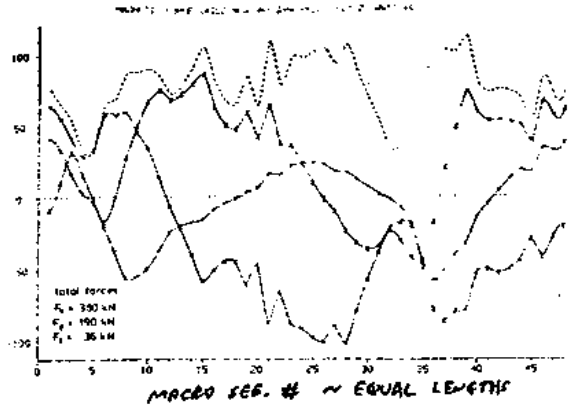

Fig. 4 Magnetic force (coil 2)

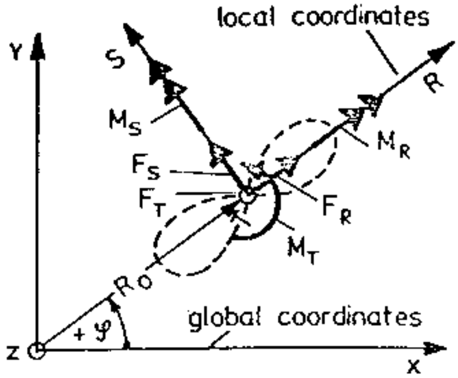

Fig. 5 Forces and moments acting at a twisted coil (schematic)

Summing up these component forces for one coil yields the total forces F in x, y and z directions (fig. 4). The net force F_x on coil 2 is -380 kN and acts towards the machine center.

Reducing these total forces into the coil center (plasma axis), it results in forces and bending moments on each coil in three dimensions as shown in fig. 5 and tab. I. Within one field period the toroidal and vertical forces and bending moments on the coils balance each other.

Table I. Forces and moments acting at the twisted coils.

coil	1	2	3	4	5
R_o [mm]	1982	2002	2038	2079	2220
φ [°]	3.31	10.17	17.6	26.08	36
Z [mm]	0	0	0	0	0
F_R [kN]	-234	-380	-409	-395	-1689
F_S [kN]	12,5	-144	-38	-85	0
F_T [kN]	12,5	30	-74	-17	0
M_R [kN cm]	12500	17146	2470	-2775	-17368
M_S [kN cm]	5367	-4065	-1580	143	0
M_T [kN cm]	27067	19350	12383	2833	0

3.3 Stresses and deflection at the twisted coil

Starting from the above mentioned basic geometry, FE model and support concept, the results for mechanical stresses and strains were obtained, which are represented in fig. 6 up to fig. 10. The stress spectrum is obtained as function of the coil's circumferential coordinate.

Depending on the complex coil shape (wide lateral deviation) the circumferential tensile stress spectrum σ_T (fig. 6) shows the influence of superimposed bending stresses. Its maximum value of σ_T = 73 MPa (without filling factor) occur at element row 36. The lateral compressive stress (fig. 7) of about σ_c = -68 MPa could be decreased and limited to σ_c = -30 MPa if an elastical coil bedding, taking up the thermal expansion, is being employed. The shear stress (fig. 8) reaches its peak value of 30 MPa at the element rows 8 and 35, which are identically with the smallest radius of curvature of the twisted coil.

An increase of this radius and better support conditions could decrease the shear stress to maximum values of σ_{ST} = 20 MPa. The equivalent stress (von Mises) (fig. 9) reaches its maximum value of σ_{VMH} = 94 MPa at element row 1 (without filling factor).

The deflection (fig. 10) of the twisted coil in x-direction does not exceed 2.1 mm.

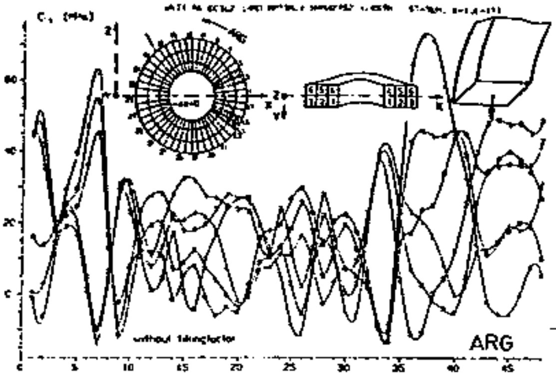

Fig. 6 Circumferential tensile stress

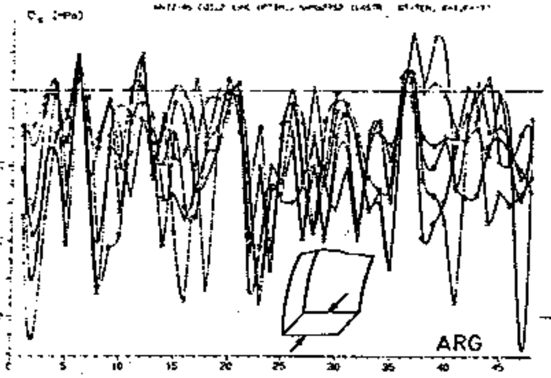

Fig. 7 Lateral compressive stress

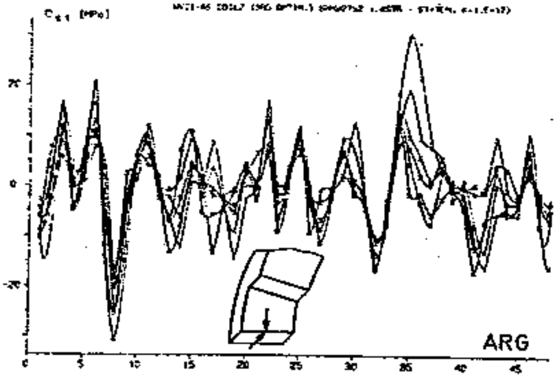

Fig. 8 Shear stress

3.4 Actual shear stress

The complex shape of the twisted coils requires a flexible conductor in order to avoid the spring back effect. Studies (BBC-Mannheim) have shown that such coils

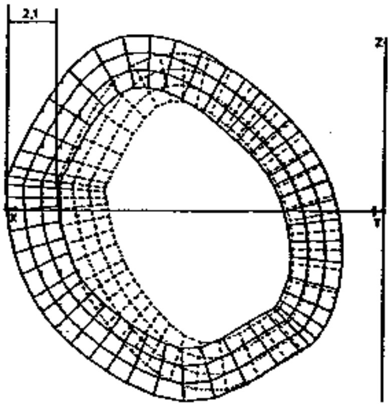

Fig. 10 Coil deformation (in mm)

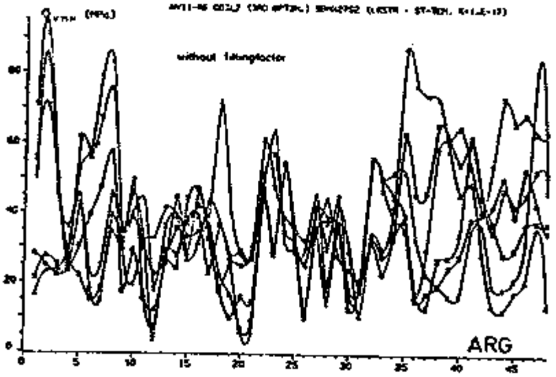

Fig. 9 Equivalent stress (von Mises)

can be manufactured by using stranded copper wires of prepressed squared cross-sections (10 mm x 10 mm) (fig. 11). The stranding of the individual copper wire leads to additional shear stresses if the flex is loaded with tension. Figure 12 represents schematically a part of the conductor (flex). The following considerations about the calculation of the shear stresses are obtained for a homogenious conductor which is elastically loaded /6/.

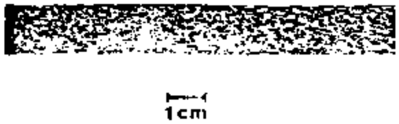

Fig. 11 Stranded, square-pressed conductor (flex)

Non detained lateral contraction:

$$\tau_N \approx \frac{\pi}{90} \cdot \hat{G} \left(\mathrm{arctg} \frac{\epsilon(1+\nu)}{(1-\nu\epsilon)/\mathrm{tg}\alpha + \mathrm{tg}\alpha(1+\epsilon)} \right) \quad (1)$$

Completely detained lateral contraction:

$$\tau_D = \frac{\pi}{90} \cdot \hat{G} \left(\mathrm{arctg} \frac{\epsilon}{1/\mathrm{tg}\alpha \; \mathrm{tg}\alpha(1+\epsilon)} \right) \quad (2)$$

With the notation:

$\hat{G}$ = average module of elasticity $\approx$ 27 000 MPa

ν = lateral contraction number ≈ 0.3

ϵ = strain ≈ 0.005 at $\sigma_T = 45$ MPa

α = stranding angle $\approx 80^0$

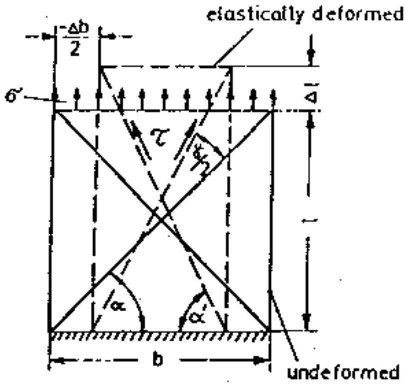

Fig. 12 Part of the stranded conductor (schematic)

The effective shear stress in the conductor depending on the stranding effect will be between the above mentioned limiting values:

$$\tau_e \approx (\tau_N + \tau_D)/2 \quad (3)$$

Finally the most unfavourable, actual shear stress is given for the two loading directions by: $\tau_{1/2\,I} \approx \tau_e + \sigma_{ST}$; $\tau_{1/2\,II} \approx \tau_e + \sigma_{TR}$ (4)

4. STRENGTH AND SAFETY MARGIN

As insulating material epoxy is assumed and the so-called Tsai-Hill criterion /7/, an extension of the von Mises criterion is used to evaluate the safety margin:

$$S_i = \left(\frac{\sigma_1^2}{\sigma_{1a}^2} + \frac{\sigma_2^2}{\sigma_{2a}^2} - \frac{\sigma_1\,\sigma_2}{\sigma_{1a}^2} + \frac{\tau_{1/2}^{\;2}}{\tau_a^2} \right)^{-1/2} \approx 1{,}3 \ldots 1{,}9 \quad (5)$$

For the copper conductor the structural change hypothesis (von Mises) was selected:

$$\sigma_{VMH} = \left(\sigma_1^2 - \sigma_1 \cdot \sigma_2 + \sigma_2^2 + 3\tau_{1/2}^{\;2} \right)^{1/2} \quad (6)$$

The safety margin is given by the ratio of the yield strength $R_{p\,0.2}$ to the actual stress σ_{VMH} (including the filling factor):

$$S_c = R_{p0,2} / \sigma_{VMH} \approx 1{,}9 \quad (7)$$

5. SUMMARY

Starting from the modular coils of WENDELSTEIN VII-AS, the winding current, the basic geometry and the support concept, the mechanical stresses resulting from magnetic volume forces and temperature rise are calculated with the STELLA-code. All forces except the centripetal ones sum up to zero over one field period.

The stresses in the coils are not larger than 105 MPa tension (filling factor = 0.7) and 25 MPa actual shear stress, depending on the coil shear and the internal conductor shear.

The complex coil shape requires a flexible conductor made of stranded copper wires prepressed and squared cross section. Safety margins for the coil materials (epoxy, copper) between 1.3 and 1.9 are obtained.

6. ACKNOWLEDGEMENT

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