

Structural Analysis of Large Nonplanar Coils for Fusion Experiments

U.B. Brossmann, S.B. Mukherjee

Max-Planck Institut für Plasmaphysik, D-8046 Garching, Germany

SUMMARY

Modularity is most probably an essential prerequisite for a fusion reactor. Toroidal field coils for fusion experiments (e.g. with reactor dimensions) can therefore be of nonplanar shape. This allows vertical fields to be superimposed in the case of a tokamak system, and helical fields in the case of a stellarator system without additional coils.

However, because of their toroidal deviation nonplanar coils are subjected to additional mechanical stresses (tension, compression, shear) by the magnetic forces compared with planar coils. On the other hand, all three-dimensional forces and moments acting on an individual coil and all interactive forces and moments between adjacent coils have to be supported within a complex structure.

The present report summarizes a mechanical stress analysis, with the optimization of the support regions and a survey of different support systems. In an engineering study the WENDELSTEIN VII-AS coil system was scaled up to reactor-size dimensions. Typical parameters are: major plasma radius 20 m, radial coil thickness 1.12 m, lateral coil thickness 0.7 m, average minor coil radius 4.8 m, field at conductor ≈ 9 T, average field on the plasma axis 5.3 T.

Force components and mechanical stresses acting at the coil cross-section are calculated for the individual coils by means of the EFFI and three-dimensional SAP V 2 codes. The support regions are simulated by boundary elements acting normally on the coil surface.

A FORTRAN optimization program has been written and combined with the finite element code to find an optimum support system. Two types of support concepts for a coil are described in this paper and compared. The first one is a standard front-support together with the lateral support. The second one is a newly developed ring support. With the ring-type support concept, a coil is held from inside and laterally. The finite element computations are carried out for a particular coil using above two support concepts.

Typical values of the maximum volume forces are 1.3 MN/m^3 , 70 MN/m^3 and 90 MN/m^3 in the poloidal, toroidal and radial directions, respectively.

With the front support the maximum values of the various stresses are tensile stress 580 Mpa, critical shear stress 120 Mpa and compression stress 170 Mpa. Using the ring-type inside support system a considerable reduction of the stress values can be achieved. (Tensile stress 13 MPa, shear stress 2 Mpa and compression stress 25 Mpa).

The present preliminary design of the coil and inside support concept is realized by using inner support plates and Bitter-type conductor plates.

1. INTRODUCTION

Preliminary design studies of large, nonplanar coils for fusion experiments were aided by finite element analyses of the coils, including the support conditions. Some work performed at IPP is outlined in this paper. The numerical results are intended as illustrative examples rather than final design data.

For the coil system, a version of the coil set of the WENDELSTEIN VII-AS advanced stellarator /1/ scaled up to reactor dimensions (large, nonplanar coils), an engineering study was conducted to evaluate mechanical stresses using different support concepts. The system considered is not yet optimized for reactor application. Typical parameters are presented in Table I. A schematic representation of the coil configuration of one period is shown in Fig.1. Within one field period (coil 1 up to coil 10) the toroidal and vertical forces on the coils are balanced. The most unfavourably loaded nonplanar coil 1 was used for the stress analysis, which includes computation of magnetic forces, mechanical stresses and deflections. This coil has a wide lateral deformation and a high magnetic field at the inner edge. The finite element stress analyses were done for an average magnetic field $B_0 = 5.3$ T on the plasma axis. The supporting structure was simulated by the boundary spring elements.

The present paper reviews the status of the engineering study for developing support concepts of large nonplanar coils. More extended computations for studying unconventional kinematics of the coupling coil and casing (friction, padding) and anisotropic coil behaviour are to be done.

2. PROGRAM SYSTEM

The STELLA /4/ program system is being used for computing magnetic fields, forces, inductances, mechanical stresses and deflections of nonplanar coils. A detailed flow chart is shown in Fig. 2. The program system consists of nine main programs. SPULPRO determines the geometry of the coil system and subdivides a coil into macroelements. These subdivisions are too rough for the calculation of volume forces and mechanical stresses, and so MESHGCE makes further discretization of macroelements into small general current elements (GCE). The PLOT program is for plotting the coils with the macroelement or microelement subdivision. The core of the STELLA program system consists of the EFFI /2/ and SAP /3/ program. With the EFFI program the magnetic fields, forces and inductances can be calculated for general three-dimensional current distributions. The magnetic volume forces calculated with EFFI are needed as input for the SAP finite element program. FENGGEN also generates nodal coordinates and element descriptions as input for SAP V and SHAPE. SHAPE converts the volume force for an element into its nodal forces and the data are fed into SAP V. The boundary elements are generated by BELGEN. Global stresses are converted into local stresses by the COPLOLOS program.

3. COIL SHAPE AND MAGNETIC FORCES

For the development of the nonplanar coil set /5/ a known advanced stellarator configuration was chosen as initial magnetic topology. This configuration has a plane non-circular magnetic

axis and five field periods. From the surface current pattern of this topology the coil system of WENDELSTEIN VII-AS is generated and scaled up to reactor dimensions (Fig. 1). The 3 D electromagnetic forces arising within the coil during normal operation are calculated by means of the EFFI code. These computations include the two basic contributions: the self force of the individual coils and the interactive force between different coils. These volume force components F_P , F_S and F_R are plotted in the Figs. 3, 4 and 5 for the six general current elements of the cross-section of the coil and as a function of the poloidal coordinate of the coil (ARG). These force plots help to decide a coil support concept. Fig. 6 illustrates schematically the force components F_P , F_S and F_R in the poloidal, toroidal and radial directions for one volume element (= GCE).

The poloidal and toroidal force components F_P and F_S depend on the lateral (toroidal) deformation of the coil. Small deformations give force values for F_P and F_S of nearly zero. Under large deformation (coil 1) the maximum value of the poloidal force F_P reaches 1.3 MN/m^3 (Fig. 3) and the toroidal force F_S varies greatly with the poloidal coordinate between $\pm 70 \text{ MN/m}^3$ (Fig. 4). This force component F_S alone tends to deform the coil into larger toroidal deviation. Fig. 5 illustrates the radial force component F_R . The innermost filaments (1,4 and 2,5) feel a force acting towards the outside (+) of the coil, while the outermost filaments (3,6) feel a force acting towards the inside (-). Typical values of the maximum volume forces are $+ 90 \text{ MN/m}^3$ and $- 20 \text{ MN/m}^3$.

Acted on by all three force components F_P , F_S and F_R each of the nonplanar coils tends to spring back into a plane.

4. FINITE ELEMENT ANALYSIS

For the static analyses of the coils the SAP V 2 code was used. The finite element model of the coil consists of 288 elements and is shown for coil 1 in Figs. 7 and 8. Each element is three-dimensional and isoparametric and has 21 nodes. The support regions of the coil are simulated by boundary spring elements set normally on the coil surface at its nodal points.

4.1 Coil support

Nonplanar coils are usually sensitive to support conditions and the stresses response accordingly on how the coils are being supported. Among the different support system considered, the two plausible concepts are discussed below.

In the first support concept the coil is supported at the front to take up the centering force and laterally to transmit the toroidal forces and tilting moments. This front support concept is shown in Fig. 7, the shaded areas being the supporting regions.

The second support concept features a ring-type supporting structure /6/ for holding the coil from inside in order to allow the radial forces concentrated at the innermost windings to be transmitted directly into the support structure. A lateral support helps to stop the toroidal forces and tilting moments. The inside support is indicated in Fig. 8 by the shaded areas.

4.2 Mechanical stress analysis

The finite element calculations are done with the same nodal forces for both of the above-mentioned concepts and use an isotropic idealization with elastic moduli $E_{xx}=E_{yy}=E_{zz}=1,5 \times 10^{11}$ N/m² (1:1 mixture of copper and steel). This idealization of the coil material will make the coil too flexible to bending, which is significant in nonplanar coils, and so the results are rather conservative.

The Poisson ratios are $\nu_{xy}=\nu_{xz}=\nu_{yz}=0.3$ and the shear moduli $G_{xy}=G_{xz}=G_{yz}=3.8 \times 10^{10}$ N/m². The stress values at the center of an element were obtained for comparison.

Figures 9, 10, 11 and 12 show the tensile stresses σ_T and the critical shear stresses σ_{ST} for both support concepts. The stresses are plotted over the poloidal coordinate ARG, which is the number of the cross section of the coil on which the 6 stress output locations lie (Fig.9). The number of the poloidal coordinate ARG increases if one follows the direction of the arrow shown in Fig. 9.

With the front support system, the tensile stress σ_T varies greatly except at the front support region (Fig. 9), where a homogeneous stress value of 160 Mpa occurs along this region (ARG from 18 up to 30). This average stress value will be enlarged up to values of 580 Mpa by superimposed bending moments outside the front support area. The critical shear stress σ_{ST} rises to maximum values of 120 Mpa at ARG 6 (Fig. 10) because the bending moments in the coil change their directions by 90° at this cross section (M_{radial} into $M_{lateral}$).

For the inside support the tensile stress σ_T (Fig. 11) is nearly homogeneous around the coil (magnified ordinate) and rises to maximum values of 13 Mpa. The critical shear stress σ_{ST} (Fig. 12) is very low and amounts to only 2 Mpa because of the reduction of significant bending moments.

Figures 13 and 14 illustrate the deformation of the coil in normal operation and with each of the support concepts. With the front support the deflection is about 60 mm (Fig. 13), which is reduced nearly 200-fold by using the inside support concept (Fig. 14).

With an increasing magnetic field the front support tends to produce stresses superimposed on by bending stresses which may be rather high. The inside support together with the lateral supports have the advantage of reducing the unwanted bending stresses, thus affording a much higher safety factor and endurance limit than would otherwise be possible /7/.

5. CONCEPTUAL DESIGN

The nonplanar coil design for a front support concept is virtually conventional and can be made by winding techniques i.e. using a flexible conductor (spring back effect). For the inside support concept the radial coil forces can only be transmitted by using predeformed Bitter-type plates. In the presented preliminary design (Fig. 15) this is realized with an explosively bonded, if necessary cold-worked, copper-austenite compound /8/ and insulated inner support plates, all connected by bolts or clamps. The inner support plates decrease the space between the coil and plasma and may find application for inside components. The manufacture of such coils and casings could entail an added degree of difficulty compared with the winding techniques. But the advantage of lower mechanical stresses in a coil justifies the higher expenditure for design and production.

6. CONCLUSION

These finite element calculations and the conceptual design are necessary and suitable for the preliminary analysis of large nonplanar coils. With simplifying assumptions, the mechanical stresses and deflections gave a first identification of design problems under realistic mechanical support conditions. For a final judgement more refined modelling of the coil and casing are required. Future efforts will therefore concentrate on the sliding and padding effects between coil and casing and on the anisotropic behaviour of the coil material.

7. ACKNOWLEDGEMENT

The authors are grateful to H. Gorenflo, O. Jandl and E. Springmann for their valuable suggestions and helpful organization and management of the system of numerical codes involved.

REFERENCES

- /1/ BROSSMANN, U. B. et al: "Concept of an Advanced Stellarator" Proc. of the 9th Int. Conf. on Plasma Physics and Contr. Nuclear Fusion Research, Baltimore, USA (1982)
- /2/ SACKETT, S. I.: "EFFI-A code for calculating the electromagnetic field, force and inductance in coil systems for arbitrary geometry", Lawrence Livermore Laboratory, Report UCRL-52402 (1978)
- /3/ SAP V (2) - "A structural analysis program for static and dynamic response of linear systems" User Manual, University of Southern California, Dept. of Civil Engineering, Los Angeles (1977)
- /4/ CORENFLO, H. et al: "STELLA-A computer program system for calculating magnetic fields, forces and mechanical stresses for twisted stellarator coil systems", Max-Planck-Institut für Plasmaphysik, Garching, Interner Bericht No 27 (1980)
- /5/ RAU, F. et al: "Vacuum magnetic field and modular coil system of the advanced stellarator WENDELSTEIN VII-AS" Max-Planck-Institut für Plasmaphysik, Garching, IPP 2/259 (1982)
- /6/ MUKHERJEE, S. B.: "Ring-type support concept for twisted coils (FE-Simulation)", Max-Planck-Institut für Plasmaphysik, Garching, IPP-Bericht (in preparation)
- /7/ BROSSMANN, U. B. et al: "Computational aspects for a modular stellarator fusion reactor magnet", Proc. of the 12th Symposium Fusion Technology, Volume 2, Jülich (1982)
- /8/ HAUBENBERGER, W. D.: "Bitter-type magnet plate design with compound conductor of ultrahigh mechanical strength", Proc. of the 9th Symposium on Engineering Problems of Fusion Research, Chicago, USA (1981).

Table I. Typical design parameters

Major plasma radius	20 m
Average minor coil radius	4.8 m
Radial coil thickness	1.12 m
Lateral coil thickness	0.71 m
Field at the conductor	>9 T
Average field on the plasma axis	5.3 T
Gross current density	$1,33 \times 10^7 \text{ A/m}^2$

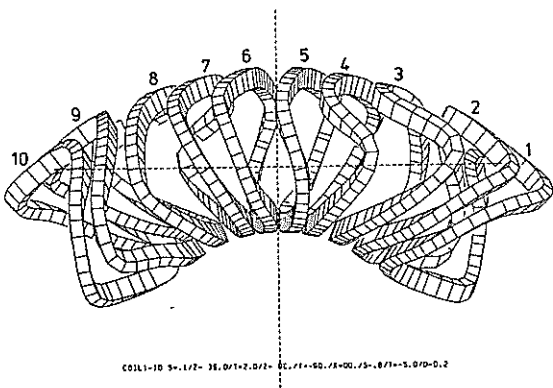


Fig. 1 Top view of one period of the nonplanar coil set

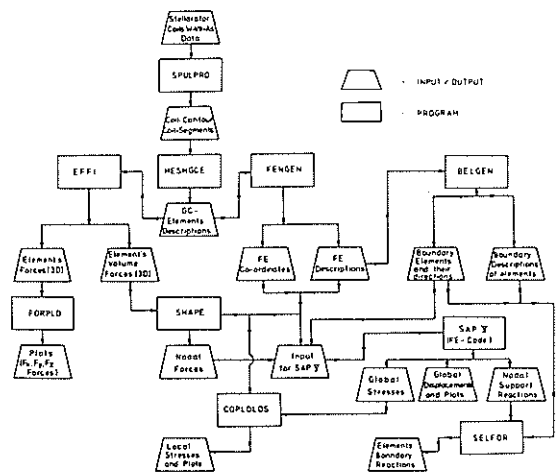


Fig. 2 Detailed flowchart of the Program system STELLA

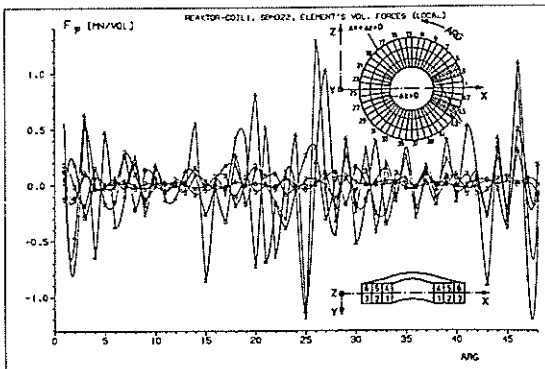


Fig. 3 Magnetic forces per volume element in poloidal direction MN/m^3

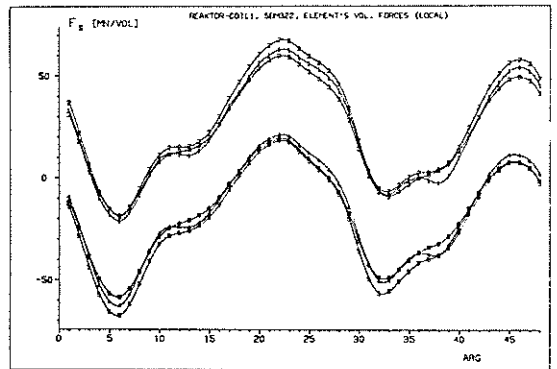


Fig. 4 Magnetic forces per volume element in toroidal direction MN/m^3

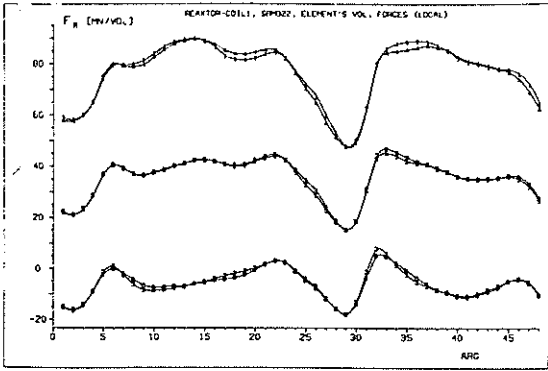


Fig. 5 Magnetic forces per volume element in radial direction MN/m³

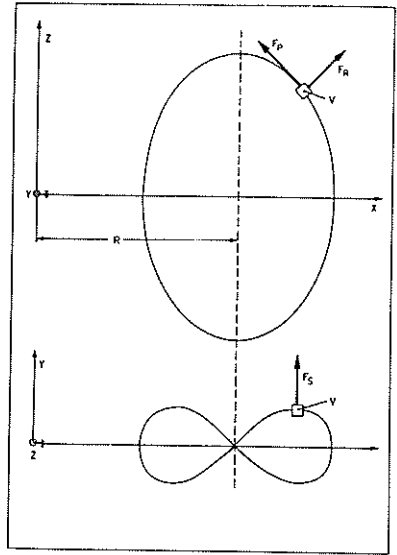


Fig. 6 Magnetic forces acting on a volume element of the coil (schematic)

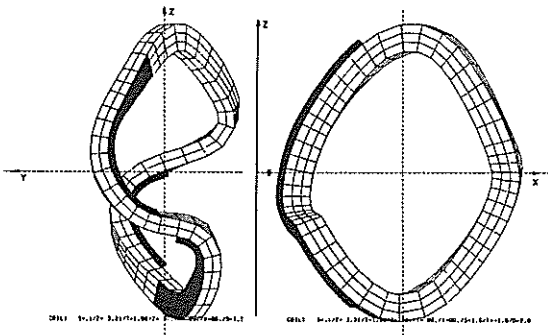


Fig. 7 FE-subdivision and front support concept

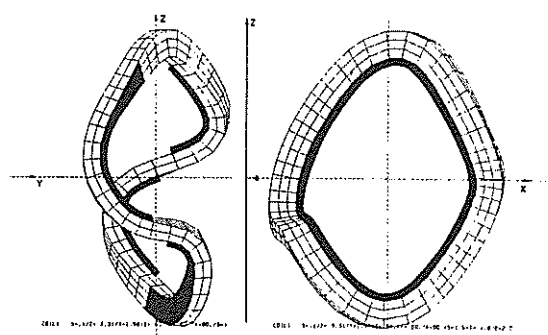


Fig. 8 FE-subdivision and inside support concept

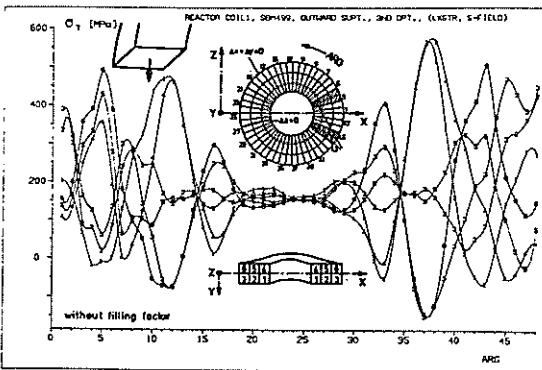


Fig. 9 Tensile stress, front support

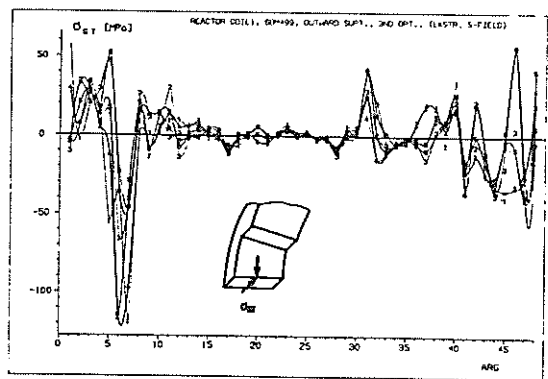


Fig. 10 Shear stress, front support

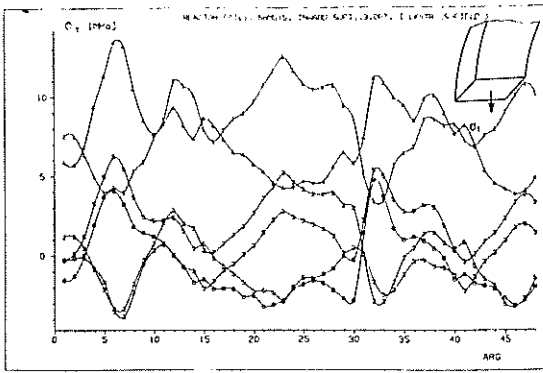


Fig. 11 Tensile stress, inside support (without filling factor)

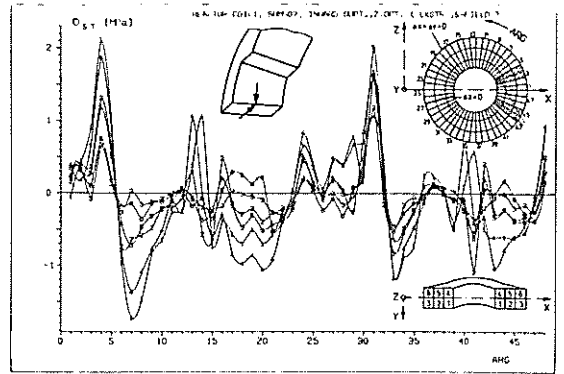


Fig. 12 Shear stress, inside support

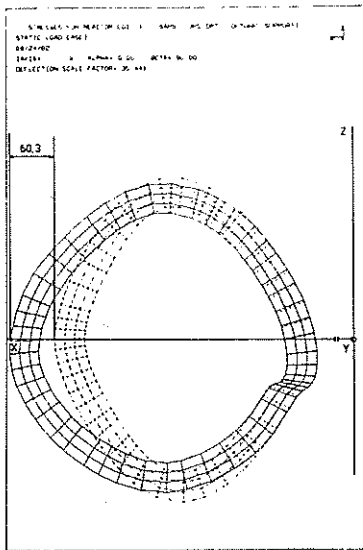


Fig. 13 Coil deformation front support mm

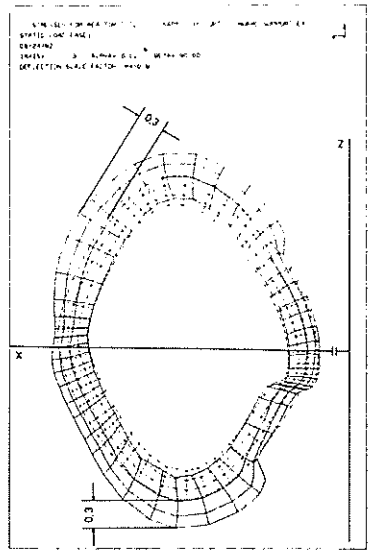


Fig. 14 Coil deformation inside support mm

Fig. 15 Conceptual coil design (schematic)

