LCT-Coil Design: Mechanical Interaction Between Composite Winding and Steel Casing Under Various Test Conditions

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Finite element computations for the structural design of the large superconducting toroidal field coil contributed by EURATOM to the Large Coil Test Facility (LCTF) at ORNL, USA were performed at KfK, using the ASKA code. The layout of the coil must consider different types of requirements: Firstly, an optimal D-shaped contour minimizing circumferential stress gradients under normal operation in the toroidal arrangement must be defined. Secondly, the three-dimensional real design effects due to the actual support conditions, manufacturing tolerances etc. must be mastered for different basic operational and failure load cases. And, thirdly, the design must stand a single coil qualification test in the TOSKA-facility at KfK, Karlsruhe, FRG, before it is plugged into the LCTF.

The emphasis of the paper is three-pronged according to these requirements:

i) the 3D magnetic body forces as well as the underlying magnetic fields as computed by the HEDO-code are described.

ii) the mechanical interaction between casing and winding as given elsewhere in terms of high stress regions, gaps, slide movements and contact forces for various load cases representing the LCTF test conditions is illustrated here by a juxtaposition of the operational deformations and stresses within the LCTF and the TOSKA.

iii) Particular effects like the restraint imposed by a corset-type reinforcement of the coil in the TOSKA test facility to limit the breathing deformation are parametrically studied.

Moreover, the possibility to derive scaling laws which make essential results transferable to larger coils by extracting a 1D mechanical response from the 3D finite element model is also demonstrated.

Some remarks on the mechanical anisotropy of the composite winding, which according to our knowledge at the time of writing can only marginally influence the global stress situation, conclude the paper.

1. Introduction

The development of the large superconducting toroidal field coil which will be contributed by EURATOM to the Large Coil Test Facility (LCTF) at ORNL / 1 / is now entering the manufacturing phase. The technical management is provided by KfK, the detailed design and production was contracted to Siemens and Krupp, FRG.

The purpose of LCTF is to simulate Tokamak conditions by a hexagonal arrangement of six large toroidal field coils / 1 / (Fig. 1). Prior to the shipment to Oak Ridge, the European LCT-coil will be pre-tested in the free-standing single coil test facility TOSKA (Fig. 2) at Kernforschungszentrum Karlsruhe / 2 /.

As the design of the coil was optimized for the test conditions specified for the hexagonal arrangement - progress in this direction was reported in a series of status reviews / 3,4,5 / - there is little wonder that the particular situation of the single coil test can imply more severe conditions regarding the mechanical strength.

This paper describes the influence which the design features and these different test conditions have on the mechanical behavior of the coil.

2. Magnetic Field and Body Forces

The 3D body forces within the winding are strongly influenced by the geometric shape of the coil contour and of its cross section and by the spatial arrangement of other coils contributing to the common magnetic field. For the hexagonal configuration (Fig. 3) of the LCTF, the cross section was taken as rectangular, and the D-shape of the contour was then iteratively optimized to fulfill a constant hoop stress criterion based on a 1D theory for filament stretch. The optimization procedure is described in / 6,7 /. It is quite plausible that the magnetic self-field of a free-standing single coil differs from that of a solenoid only by a distortion of the symmetry induced by the optimized D-shape alone (Fig. 4). In the toroidal arrangement the resulting magnetic field depends also on the positioning of all coils as well as on their relative magnitudes of electric current (Fig. 3). Moreover, in contrast to the single coil field, which yields selfequilibrating body forces, there is a net force resultant pointing radially inward in the hexagonal configuration / 7 /.

Therefore, a thorough 3D finite element analysis is necessary to evaluate the sensitivity ("vulnerability") of the 1D-shape-optimized coil to the mechanical effects introduced by the support conditions, the mechanical interaction between coil and casing, the anisotropy of the composite winding etc. Relevant results were given in two comprehensive papers / 8,9 / with particular emphasis on the multiple load case design requirements and on the complete description of the pertaining magnetic body force distributions.

3. Mechanical Behavior within TOSKA and LCTF

The dominating effect of the magnetic loads is a breathing behaviour of the composite winding (as described in / 7,8,9 /), which tends to approach a circular form. In the hexagonal arrangement the coil is simultaneously pushed radially inward against the central bucking post of the LCTF. The net effect of the combined influence of the support reaction forces along the almost straight inner leg and the stretching forces pointing radially outward along the coil contour is a relatively smooth breathing. The inner bore dimensions are increased everywhere along the contour, showing a plausible buildup of the increase from the inner to the outer leg (Fig. 5). In the TOSKA facility, however, due to the lack of the centering force, the curvature change of the inner leg is remarkable (Fig. 5). Besides a decrease of the vertical bore dimensions this gives rise to the highest stresses within the entire load case catalogue in this part of the contour. Therefore a corset structure (Fig. 6) was considered to restrain the deformation during the TOSKA tests. Fig. 7 shows the useful influence of this device, which is given quantitatively in table I. Fig. 8 gives a comparison of the winding stresses for the LCTF and the TOSKA test conditions. The smoothness of the LCTF curves is destroyed under the nonoptimal TOSKA conditions. Increasing the corset stiffness alleviates the peaks at $\varphi \simeq 75^{\circ}$, but it pushes the inner leg peak upwards, thereby limiting the feasible range of rod stiffnesses to 10 k ($k = 2.43 \cdot 10^{8}$ N/m = individual rod stiffness). This load diffusion effect (marked "K" in Fig. 8) is more proncounced for the normal contact forces between casing and winding (Fig. 9). In the limit case (10 k) the inner leg peak reaches the level of the support-induced LCTF reaction force! Figs. 8 and 9 show clearly that the sensitivity to load diffusion effects is greater for the inner leg (compared with the outer leg) and that the casing "suffers" more from these effects than the winding.

4. Asymmetric Loading

Apart from the contour optimization for normal operation under in-plane loading, several combinations with two basic out-of-plane load distributions must be considered in the design process / 4,8 /. The transverse loading due to a faulting neighbour (LC3 in Fig. 10) and the overturn moment loading under the pulsed poloidal field (LC4 in Fig. 10) are typical for Tokamak arrangements. For the body force distributions expected within the LCTF the mechanical interaction between casing an winding in terms of high stress regions, gaps, slide movements and contact forces was thoroughly discussed elsewhere / 9 /. Here we show that the extraction of simplified 1D curves describing the salient deformation features of D-shaped TF coils (Fig. 10) from our 3D results is possible. This capability of setting up scaling rules is promising for the preliminary design of future Tokamak reactors, like the INTOR/NET design study / 10 /, where existing knowledge about coil mechanics must be transferred to larger coils in a condensed form. The condensation to 1D modelling is mandatory because a full 3D finite element study is too time-consuming and cumbersome in the early preliminary design stage.

5. Conclusions

The main conclusions from our results are: A thorough finite element analysis reveiling 3D effects is indispensable for the global design of large toroidal coils. The optimization covers special situations like the free standing test or non-symmetric loadings. Our model is a good basis for deepening the insight into coilmechanics in two directions: 1) more detailed analysis of local effects (high stress regions, conductor cluster, winding anisotropy etc.) as currently performed at KfK and the manufacturers and 2) derivation of scaling rules for the preliminary design of larger coils. The influence of the winding anisotroy on the stresses is only marginal compared with that of the corset (see Appendix).

6. References

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Table I: Influence of a restraining corset

		Rod Stiffness Factor				
		0 k	1 k	2 k	10 k	
Maximum	F	147.1	96.3	85.1	73.1	N/mm^2
Equivalent	S	142.0	100.7	91.0	80.7	
Stresses	W	92.5	78.8	75.5	86.4	
Tension Force within 1 rod		-	465.9	694.4	1208.6	kN
Max. Increase of horizontal bore width		3.57	2.57	2.20	1.54	mm

1 k = $2.43 \cdot 10^8$ N/m; F = front plate, S = side wall, W = winding

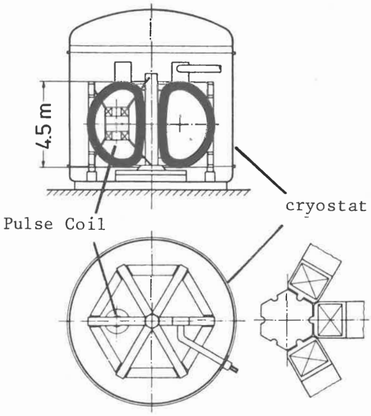

Fig. 1:
Schematic of the Large Coil Test Facility /1/.

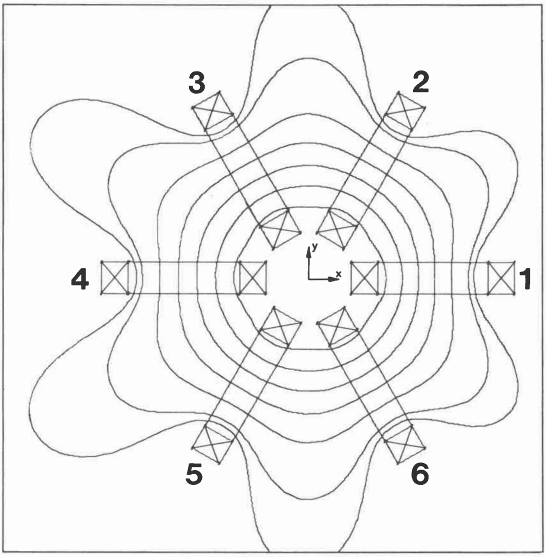

Fig. 3: Magnetic Field in the LCTF Arrangement
1 = 100 %, 2 to 6 = 80 % of nominal current

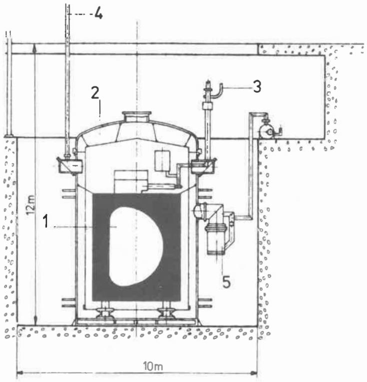

Fig. 2:
Schematic of the TOSKA Test Facility /2/ (1 = LCT-Coil, 2 = Vacuum Containment of 175 m^3, 3 = Electric Power Supply, 4 = Helium Supply, 5 = Vacuum Pump)

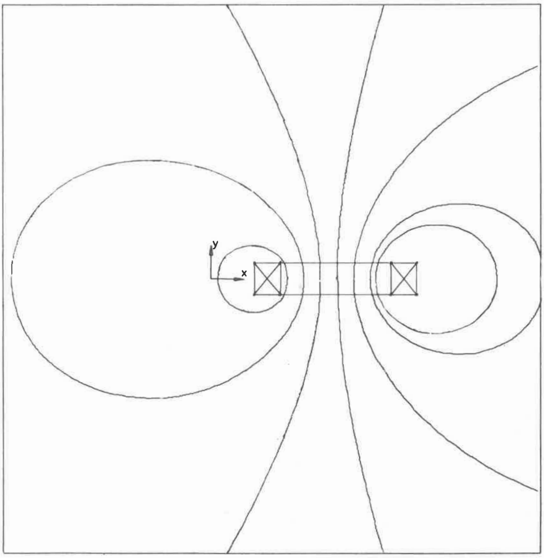

Fig. 4: Magnetic Field in the TOSKA Test Facility

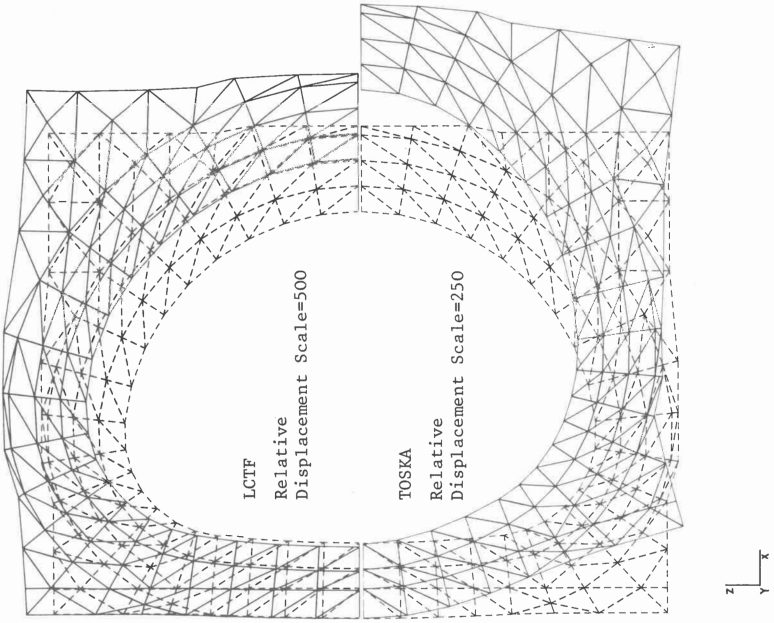

Fig. 5: Comparison of the Breathing Mode Deformations within LCTF and TOSKA

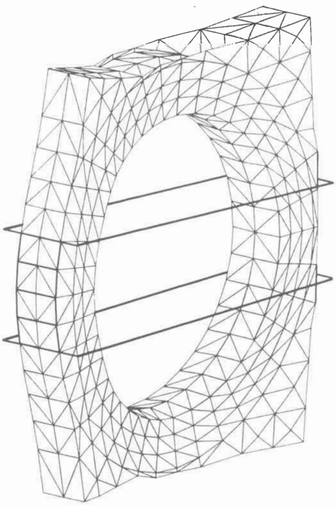

Fig. 6:

Finite Element Model of Coil and Corset for the TOSKA Test

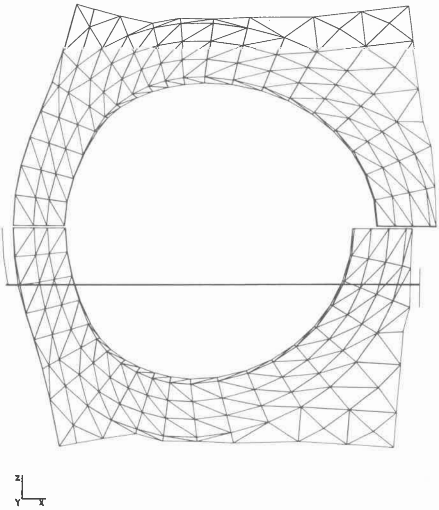

Fig. 7: Influence of the Corset on the Breathing Deformation

(Relative Displacement Scale = 250)

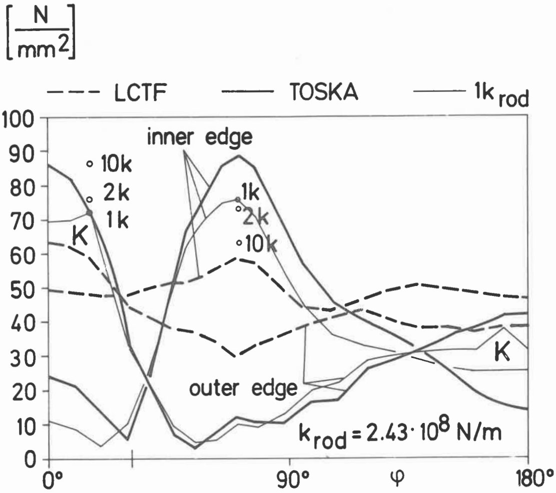

Fig. 8: Equivalent Stresses within the Coil Winding

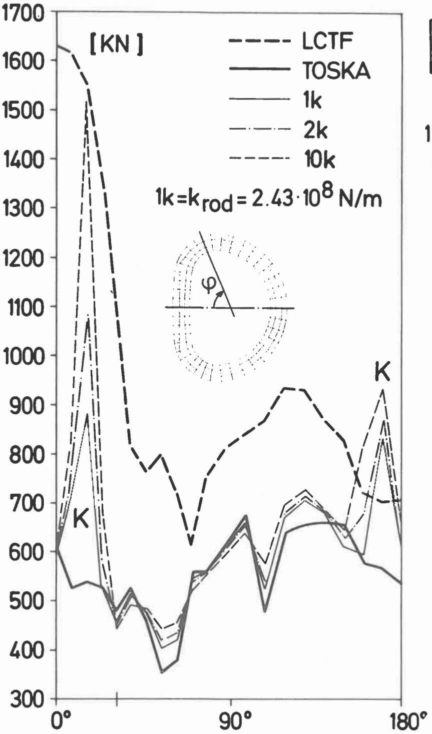

Fig. 9: Contact Forces Between the Winding and the Casing along the Outer Edge

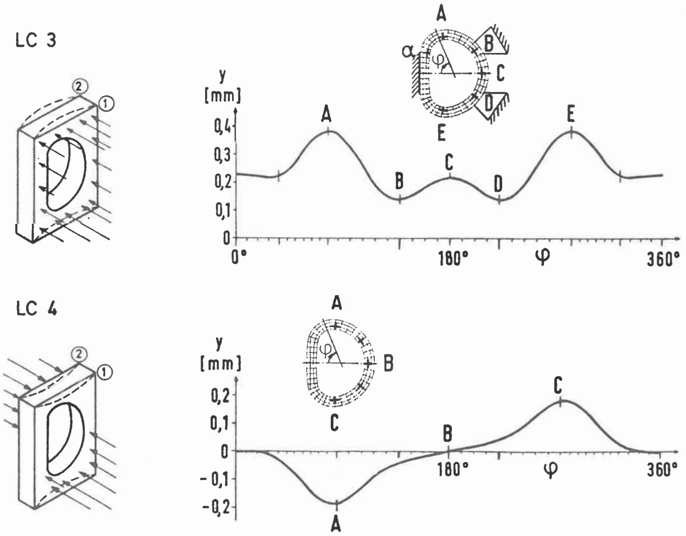

Fig. 10: Asymmetric Loading within the LCTF: Axial Displacement of Cross Section Centroids

Appendix: Mechanical Anisotropy of the Coil Winding

A comparison between the most important stress results for an isotropic and an anisotropic (transverse isotropy) elasticity matrix for the coil winding is given in table II for normal operation in the LCTF.

Table II: Comparison of Stress Results

		isotropic	anisotropic
Elastic Modulus (N/mm^2) in the Winding (Casing: $2.1 \cdot 10^5$)		$1.2 \cdot 10^5$ Poisson Ratio ($\nu = 0.25$)	E(6,6) symmetric matrix, where $E(1,1) = 1.35 \cdot 10^5$, $E(2,1) = E(3,1) = 1.94 \cdot 10^4$, $E(2,2) = E(3,3) = 3.57 \cdot 10^4$, $E(3,2) = 1.27 \cdot 10^4$, $E(4,4) = E(6,6) = 8 \cdot 10^3$, $E(5,5) = 4.62 \cdot 10^4$
Maximum Equivalent Stresses (N/mm^2)	F	78	87
	S	79	85
	W	64	70
Maximum Shear Stress Components (N/mm^2)	(xy)	1.4	2.2
	(yz)	4.4	8.9
	(zx)	4.9	4.9

F = Front Plate, S = Side Wall, W = Winding

Remarks: The transverse isotropic elasticity matrix is an "educated guess" derived from widely accepted mixture rules for similar composites. Complete experimental evidence of this data at 4.2 K temperature is not yet available.

The equivalent stresses are generally higher with anisotropic input. However, not all cartesian stress components show the same behavior. This is plausible because with the used transverse isotropic elasticity modulus the coil winding is strengthened in the circumferential direction and weakened in the transverse direction. This leads to higher (lower) hoop stresses in the winding (casing rings). The axial stress is reduced in the winding and increased in the casing rings. The (xy)-transverse shear stress in the cable and the radial interpancake (yz)-shear stress are increased, and the interlaminar (zx)-shear stress remains approximately constant. The higher values of the anisotropic shear stresses are not dangerous, however, because they remain below 10 N/mm^2 under operational LCTF loading.