Investigation of the mechanical properties of the Euratom LCT coil by tests under different boundary conditions

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1. INTRODUCTION

The increasing size of supcerconducting magnets for fusion and other application requires a careful design of the mechanical support structure to avoid expensive overdesign or damage. An encouraging progress was made in this field during the last ten years. Requirements of the Large Coil Task, a program to develop superconducting magnets suitable for TOKAMAKS, made it indispensable to transfer the already existing calculation of the finite element method (FEM) to the field of superconducting magnet technology. There are some conditions which require an additional effort and extension of the FEM models for the usage in this field. As a consequence of the operation at low temperatures material data must be available over the whole temperature range. The winding and the conductor of superconducting coils is a sophisticated composite with orthotropic material properties which have to be determined by suitable detailed FEM models and which have to be also checked by measurements on test samples of the winding pack. In most cases an additional structure of stainless steel or fiberglass reinforced epoxy is necessary to support the winding pack. Therefore a suitable model representing the elastic properties of the mechanism of force transmission has to be introduced in the FEM calculations. The mechanical measurements on a superconducting coil confirm or show weak points of the model and close therefore existing gaps. The Euratom LCT coil is equipped with sensors (strain gauges rosettes, displacement transducers) to analyse local and global structural mechanical behaviour. The spectrum of load cases applied during the testing with partly varying boundary conditions offers an excellent experimental frame to elucidate hidden uncovered model problem areas.

2. TEST CONDITIONS AND RESULTS

The D-shaped Euratom LCT coil was tested as a free standing single coil in TOSKA 1984, as a single coil and in six coil toroidal arrangement in the International Fusion Superconducting Magnet Test Facility (IFSMTF) in Oak Ridge 1986.

2.1 The TOSKA single coil test

The single coil test in TOSKA stimulated improvements of the FEM model and introduction of more realistic overall material data which brought a better agreement with the measurements. The azimuthal dependence of the radial Young's modulus in the winding showed excellently the impact of manufacturing procedures on the overall

material data, A. Maurer et al. (1985). In a second attempt some improvements were introduced in the model. In the runs during the design phase some elements of the structure were omitted to simplify the model and to save computer time. All structural elements which could contribute to the stiffness were modeled (flange of the coil case, dome box, pretension of the flange bolts). The modelling of the dome box showed a stronger impact on the stiffness of the coil and reduced the difference between measured and calculated vertical overall deformation to about 20%. The other changes contributed to stiffness only in range of percents and were negligible, A.Maurer et al. (1986).

The analysis of the results of the TOSKA-Test brought some improvements in the FEM but showed also clearly that the used instrumentation reached its resolution. Some additional instrumentation would be necessary to get more detailed knowledge.

2.2 The test in the IFSMTF

In IFSMTF in Oak Ridge the coil was clamped together with five other coils against a central bucking post. The lateral support of the coil was carried by a nose at the front part of the straight section of the D which fitted into a grove in the central bucking post. The outer legs (curved part of the D's) were supported against lateral forces by an upper and lower torque ring around the torus (Fig. 1).

In every series of tests every coil could be operated as a test coil. In this position it were assigned more channels of the data acquisition system than in a background position expecially for structural mechanical measurements.

The test series were:

- Single coil test,
- Test in a toroidal configuration up to 8 T (Standard I),
- Test in a toroidal configuration up to 8 T (Standard II) with an external pulsed field with components perpendicular to the toroidal field.

The Euratom coil ran in 1986 successfully as the first one of the six coils through all the three test series. When all coils are through the test series mentioned above some "Extended tests" are planned which explore the upper operation limits. In these tests the forces will be nearly doubled compared to the tests described before.

The overall stress loading was reduced considerably if the coil was clamped against the central bucking post with a local stress increase in the clamping area. The operation in a toroidal configuration was the case for which the coil was designed with a minimum of bending forces. The overall compression force of the coil to the central bucking post reached in this load case about 40MN.

The different ampere-turns of the coils led to the consequence that the torus could only be symmetric in forces or field. For a symmetric field torus at 8 T already considerably out-of-plance forces had to be carried by the Euratom coil which was positioned between a coil with highest (Westinghouse) ampere-turns and a coil with the lowest ampere-turns (Swiss), S. Shen et al. (1986). The calculated out-of-plance force was 10 MN for this load case. This was already about 36% of the out-of-plance load, if one coil had no current and the other 5 had 100% of its rated current. For the Euratom Stand I test the current distribution was optimized so that the out-of-plane force was a minimum of about 0.6 MN.

Additional out-of-plane forces were generated by the perpendicular pulsed field components with about 0.15 T at the inner contour of the coil. The moments around the horizontal coil axis were about 2.45 MNm.

3. INSTRUMENTATION

The coil was equipped with 12 strain gauges rosettes (only 9 were connected to the data acquisition system during the test in the IFSMTF). The principal strains, the direction of the principal strain axis and finally the von Mises stresses were calculated according to

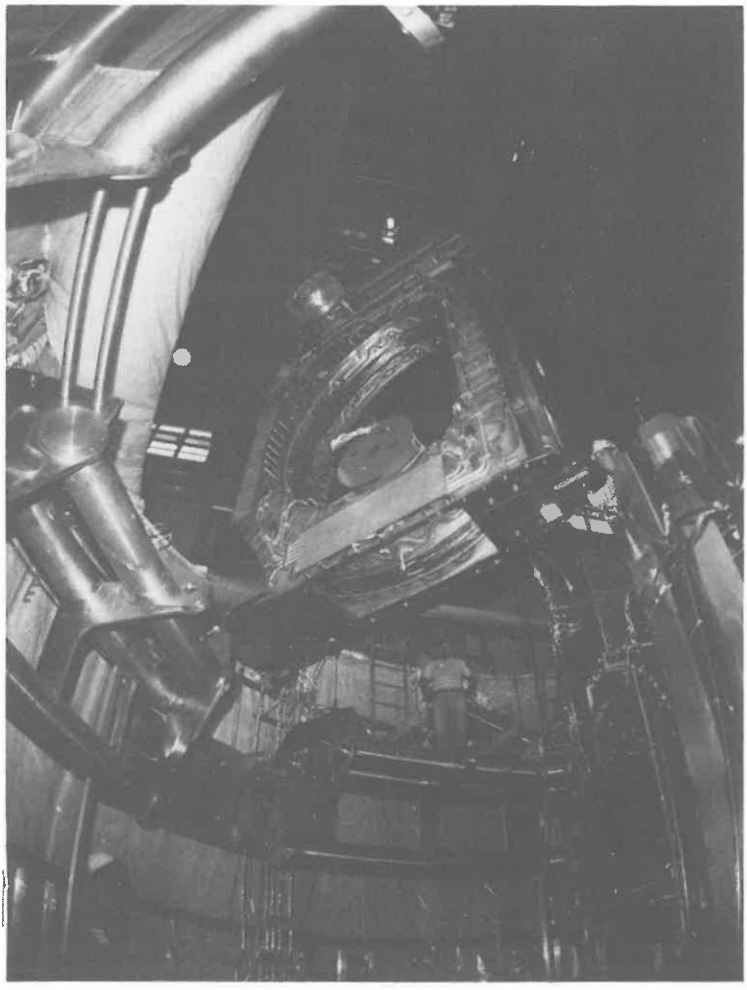

Fig. 1. The Euratom LCT Coil during the installation in the IFSMTF. On the left hand side the central bucking post with its groves is visible. On the right , the upper torque beam with its beams and its gaps for acceptance of the coils are visible.

Principal stresses

(1) $\sigma_i = [E/(1-\mu^2)] \cdot [(\varepsilon_i + \mu\varepsilon_j)]$ $\quad i = 1,2;\ j = 2,1;$

$\mu = 0,3$; $E = 2,1 \cdot 10^{11}$ N/m^2 for stainless steel DIN 1.4429 at 4.2 K.

Von Mises stresses

(2) $\sigma_{VM} = \sqrt{\sigma^2_1 + \sigma^2_2 - \sigma_1\theta_2}$

The force transmission and stiffness of the winding were investigated by measuring the gap between winding and case with displacement transducers. In the TOSKA test the

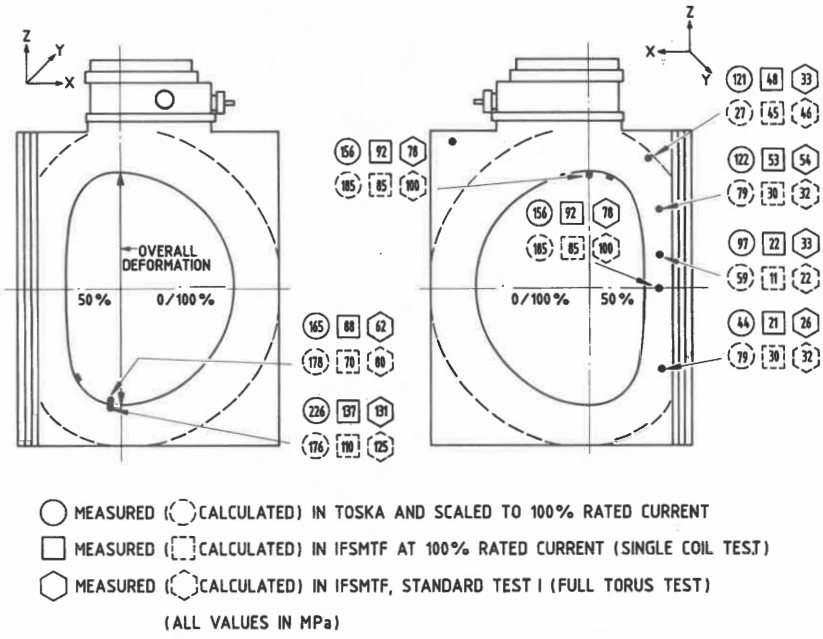

Fig. 2. The measured von Mises stresses for the different test compared with the FEM calculation.

vertical overall deformation of the coil was measured. Such equipment could not be installed in the IFSMTF, because the coil bore had to be free in order to move the pulse coil system through the bore.

4. DISCUSSIONS

The material data and the FEM model were improved according to the knowledge derived by the TOSKA experiment. The load cases in the IFSMTF were already investigated through the design phase of the coil, A. Maurer (1981). A repetition of the runs would be very expensive with implementation of all the changes (azimuthal dependence of the radial Young's Modulus, dome box, unsymmetric ampere-turns). Further a considerable amount of time would have to be spent to implement in the model all improvements of the NASTRAN code. In order to avoid this excessive expense the calculated values for the IFSMTF were taken from calculations performed during the design phase. For all three tests (TOSKA, IFSMTF single, toroidal without pulsed field) the measured and calculated von Mises stresses were compared (Fig. 2)

The results can be summarized as follows:

- The TOSKA load case (free standing single coil) showed the highest stress level as expected. The deviation between calculation and measurement is relatively large. Attempts to find explanations were not successful. Big discrepancies can be explained by local properties (weld seam: left corner outer D contour, side plate lower apex).
- The single coil (IFSMTF) showed a considerable reduction of the stresses at the measured points; roughly all are in fair agreement with their calculations. It has to be

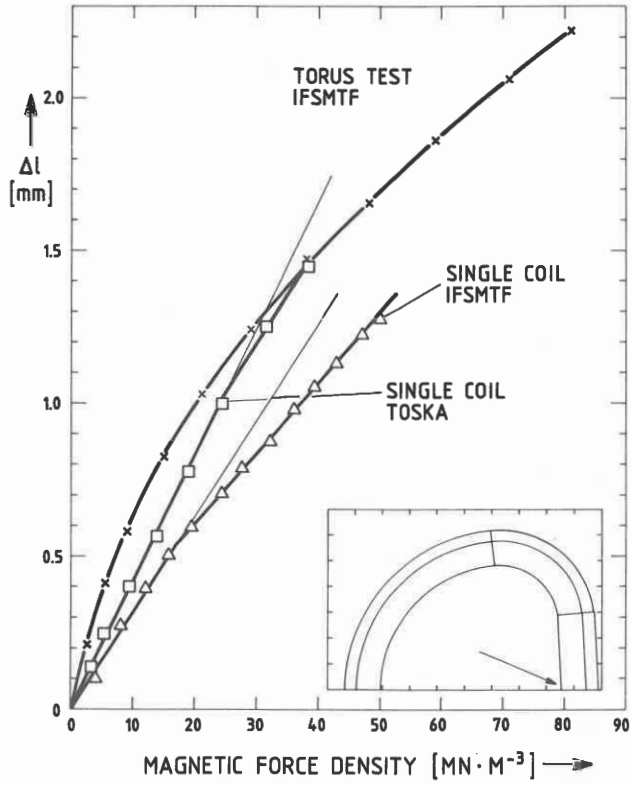

Fig. 3. The gap between winding and case for the different tests as a function of the averaged volume force

taken into account that at the clamping area the local stresses are much higher but there was no instrumentation installed for measuring.

- The test in toroidal configuration (IFSMTF) showed nearly the same stress levels like the single coil test.
- The symmetry of the stresses was given approximately in the appices but not in the straight section of the D. In the upper half the measured stresses were higher than in the lower half.
- The directions of the principal strain kept their direction nearly for all load cases.
- The test in toroidal configuration with an external pulsed field could not be analyzed because of the low scan rate for the rosettes.

Besides the strain measurement the gap between winding and case in the central plane of the straight section was investigated. To compare all local cases the averaged magnetic volume force density was chosen (Fig. 3). The volume force density is considerably higher for the torus and therefore the winding experiences the highest compression. There is no linear correlation for this load case what is not easy to understand. The differences could have its origin in the case deformation which is always superimposed.

The displacement transducers at the side plates showed no global movement of the winding in the case as well under the out-of-plane forces of 10 MN as under pulsed field operation. All measured displacements could only be explained as local elastic properties. The measured gaps were < 50 µm and therefore also smaller than those derived by FEM calculation ~ 200-250 µm.

5. CONCLUSIONS

Four different local cases were experimentally investigated and compared with the finite element calculations. The extensive investigation of the TOSKA load cases demonstrated the limits of the model and the resolution of the instrumentation. The tests in the IFSMTF were in sufficient agreement with its FEM calculation, even though these calculations were performed during coil design. The biggest deviations were again observed in the straight section of the D. The winding showed no global movement under out-of-plane loads applied up to now.

The excellent mechanical properties of the coil correspond up to now the expectations. The mechanical rigidity is also confirmed by the electrical stability and the necessary low cooling power during operation.

6. ACKNOWLEDGEMENTS

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REFERENCES

Maurer, A., Ulbricht, A., Wüchner, F. 1985. Effect of azimuthal dependence of radial Young's modulus on the mechanical behaviour of the European LCT coil. Proc. 9th Int. Conf. on Magnet Technology, Zürich Sept. 9-13, 1985 Switzerland p. 428-431

Maurer, A., Ulbricht, A. , Wüchner, F. 1986. Proc. 14th Symp. on Fus.Technology, Avignon Sept. 8-12, 1986

Shen, S.S. et al. 1986. First results of the full array LCT coil tests, Proc. Appl. Superconductivity Conf. Baltimore Sept. 28 - Oct. 3, 1986

Maurer, A. 1981. Structural Analysis (Siemens) of the Euratom Coil for the Large Coil Task. Proc. of MT-7, IEEE Trans. on Magn., MAG-A15), 2097-2100, Sept. 81