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MANUFACTURE AND MECHANICAL TEST OF A "TORE SUPRA" MODEL COIL

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ABSTRACT

Inside the qualifying test programme, supporting the Tore Supra Design, a reduced scale model of a B_T coil was fabricated by a large industrial firm. This model coil is provided with the same features as those retained for the complete magnet.

Tests of this model coil have been carried out in such a way that most of stresses which will arise in Tore Supra windings are simulated ; simultaneously its cryogenic supply is fully representative of the system retained for the complete machine.

Operation of the model coil has been found highly stable ; under the conditions of applied field and forces a coil transition could be triggered, by an electrical heater located inside the coil, only when the temperature of the superfluid helium bath was close to T_λ. Thus design and manufacturing techniques have been qualified satisfactorily to proceed to the next step : fabrication of the superconducting B_T coils of Tore Supra.

I. OBJECTIVES

Two main objectives have been assigned to the model coil [1] [2] :

- to check the feasibility of the manufacturing process retained for the superconducting coils of Tore Supra,

- to investigate the behaviour of the winding and cryogenic system when magnetic field, mechanical stresses and heat input are applied simultaneously.

II. EXPERIMENTAL ARRANGEMENT

The coil cross section can be seen in fig. 1. The superconductor winding is cooled by heat transfer (with no mass motion) through a 1.8 K pressurised superfluid helium bath enclosed inside a thin casing ; a thick steel casing, cooled by normal helium flow at 4.5 K, gives most of the strength. Main coil characteristics are included in table I.

Fig.2 shows a general view of the experiment. The main components are enclosed inside a 1.5 m bore cryostat. The pressurised superfluid helium bath is cooled down through a heat exchanger by evaporation of liquid helium introduced through an expansion valve and pumped by two rotary pumps ; a 7 m long pipe simulates the conditions of supply of Tore Supra. A biasing field of 4 T from the BIM magnet can be added to the self field of the model coil (2.4 T) : in these conditions, the tensile stresses prevailing in the torus can be reached, even if the maximum field value is not as high. Shear stresses between coil turns existing in the full torus, will be simulated by a jack applying 1 MN along a coil diameter. This jack works with helium at 5 K and a pressure of 6 MPa, introduced into a small volume one corrugation bellow.

The coil is provided with :

- small heaters bonded to the superconductor under spacers,
- three voltage taps located on the central double pancake,
- four strain gauges bonded on the polyimide alumina chocks located between the thin and thick casings,
- fifteen strain gauges arranged on the thick casing as shown in fig. 5,
- nine capacitive displacement transducers.

III. MANUFACTURING PROCESSES AND TESTS OF THE COMPONENTS

The model coil has been fabricated by a large industrial firm (Alsthom Atlantique, Belfort) using components, manufacturing processes, methods and means which will be used for the manufacturing of the complete set of coils for Tore Supra. Its overall size was imposed by the inside bore of the 4 T BIM magnet available at Saclay.

The design of the toroidal field coil of Tore Supra takes into account the cooling process using pressurized superfluid helium and the losses induced by the large magnetic field changes which occur during plasma disruption. These considerations have led to a coil fabricated with a bare conductor which allows an efficient heat transfer to the superfluid helium. The conductor size (2.5 x 5.6 mm^2) is a compromise,being small enough to reduce varying field losses and large enough to be used as a monolith, providing a mechanically strong winding.

Double pancake winding instead of layer winding has been chosen in order to have all electrical connexions located at low field values. Spacers set between pancakes determine the thickness of cooling channels. A 0.3 mm thick preimpregnated ribbon laid between turns insures electrical insulation and turn to turn bonding. The whole coil, which looks like a kind of honeycomb structure, becomes stiff after polymerisation and behaves as a solid body provided with a large amount of superfluid helium evenly distributed and in close contact with the superconductor. The bonding between components plays therefore a major role in attaining this objective. Conventional impregnation techniques cannot be used ; therefore a solution extensively using epoxyresin preimpregnated ribbon had to be worked out. Many tests have been performed on different patterns of small straight bars fabricated with this bonding process and the results are shown in fig. 3.

Spacers

An electrical test is performed on each spacer just after curing - 500 volts are applied between two flanges during 10 seconds - no breakdown was observed during these tests. The measurements of the thickness performed on 160 spacers are included in the range 1.37 - 1.49 mm.

Double pancakes

Shape and dimensions of each double pancake are determined by the rigs which have been used for winding and polymerisation. The utmost dimensions measured on the 9 double pancakes are : thickness 6,8 - 6,9 mm, external diameter 805,3 - 806,1 mm, internal diameter 568,35 - 568,85 mm.

Assembling of the coil

After polymerisation each double pancake is mounted in a dedicated rig with spacers laid in between, then the whole coil is tightened axially in order to compress the preimpregnated material and to insure effective bonding between the double pancakes. The polymerisation under controlled atmosphere and the soldering of connexions between adjacent pancakes are achieved simultaneously in one heating cycle. The winding is then electrically tested up to 1800 V with a pulse generator and geometrical measurements performed.

Radial glass epoxy chocks and ground insulation made with nested shells are then set up (always with 0.3mm thick preimpregnated tape laid in between) inside the previous assembly rig, compressed, electrically tested and polymerised. The measurements performed on the ground insulation give : thickness 93,19 - 93,42 mm, external diameter 829,88 - 830,1 mm, internal diameter 553,68 - 554,07 mm.
After mounting and welding of the thin SS casing, its tightness has been carefully tested first by pressurising the casing up to 2,5 MPa in order to open up possible hidden cracks then by a helium test. The insulation between the winding and the thin SS casing was tested up to 5 kV just before welding.

The setting-up of the polyimid alumina chocks which insure the thermal insulation between the thin casing containing the superfluid helium and the thick casing must be carried out carefully in order to get an efficient transfer of the forces from the winding to the thick casing. For this purpose these chocks were coated with 0,3 mm thick preimpregnated ribbon whose compressibility (about 0,1 mm) allows compensation of small differences.

The flanges and rings of the thick SS steel casing have to be mounted simultaneously. As already mentionned, this casing is designed to support all electromagnetic forces, this means that loseness in any direction will have to be eliminated. While hooping of internal and external rings were performed, the flanges were put in position and pressed by a rig in order to keep the winding in compression in any direction. Before withdrawing this rig, the flanges and rings were attached by spot welding.

The electron beam welding carried out on the external ring and the coated electrode welding of the internal ring which follows both produce a significant amount of pressure on the winding.

During these operations, ten strain gauges were monitoring the stresses (6 of which were bonded on the SS casing and 4 on the thermal insulation chocks). After hooping of the two rings an average radial compression about 10 MPa results. After the welding operation with electron beam the radial stress on the winding increases by 6 MPa on its outer edge and 1 MPa on its inner edge. Again after the welding with coated electrode the pressure increases by 8 MPa on the outer edge and 4 MPa on the inner edge.

Measurements performed during the cooling down phase have pointed out that the radial compression on the winding has increased by about 8 MPa. The precision on this figure is low because of the apparent strain of the gauge. This is always difficult to know even if test gauges bonded on separate bars and only submitted to their own thermal deformation are used as reference. This kind of measurement becomes still more difficult below 20 K because the apparent strain varies very rapidly from this point.

IV. MAIN EXPERIMENTAL RESULTS

The main goal of the experiments reported here was to test the stability of the superconductor winding operation under the stresses prevailing in the full toroidal magnet of the Tore Supra. These stresses were simulated by adding to the load coming from the self field of the model coil (2.4 T max.) those resulting from a biasing field (4 T) and from a 1 MN hydraulic jack.

Secondary goal was to assess experimentally how the loads applied to the winding are transmitted to the strong casing. In the actual case of the very anisotropic mechanical characteristics of the winding, as measured on small samples (fig. 3), and under the large initially existing compression, previously described, this transfer can takes place :

- partly by radial pressure through the chocks located at the outside perimeter,
- partly by friction and shear through the chocks set between the winding and the case flanges.

Results from the numerical stress analysis of a finite element model of the casing (170 nodes and 34 elements), using various transverse stiffnesses to simulate the winding, were fitted to a limited number of measured stress values : those obtained from strain gauges bonded or welded on the outside surface of the thick casing and on some polyimid alumina chocks (radial pressure).

Tests performed with electromagnetic forces only

Tests have been performed at several levels of the background field produced by the BIM magnet. The current inside the winding of the model coil has been raised step by step up to its nominal value of 1400 A which represents an average current density of 100 A/mm^2 inside the conductor. Most of the measurements have been performed with a background field of 3.6 T and a current in the model coil of 1300 A (fig. 4). The distribution of stresses is shown in fig. 6 and 7. In this case the normal force through a cross section of the casing reaches about 420 kN that is to say 2/3 of the total 640 kN load. The remaining 1/3 is therefore withstood by the winding and to a smaller extent by the thin casing. The 420 kN load supported by the thick casing results half from the radial pressure applied by the winding on the external ring and half from friction between the sides of the winding and the flanges of the thick casing. Main stress values are listed in table II ; the average shear stress on the bonding of spacers to pancakes, a particularly important parameter, has a safe value.

Experiments adding load from the jack

In addition to the electromagnetic force previously mentionned, a force of about 1 MN has been applied along a diameter of the coil by a jack working at 5K. The aim of this test was to check the behaviour of the winding, when shear stress of about 10 MPa is applied between turns. The winding being unaccessible to direct measurement, modelization and numerical calculations have again been used to obtain an estimation of shear stress between turns. Calculations were performed separately for the winding and the SS casing, then combined with experimental measurements to obtain self consistent results. The average stiffness ratio between the SS casing and the winding measured and calculated give about the same value : 15. Main stresses are again listed in table II : normal stresses reach in this case higher values, shear stress across copper-epoxyresin bonding being everywhere around 10 MPa.

Stability of operation of the superconducting winding

During the previous tests, operation of the superconducting coil was monitored through voltage measurements across the current leads, and thanks to the 1.8 K cryogenic cooling system, through a calorimetric assessment of eventual energy losses dissipated inside the coil [3].

Even when the superfluid helium bath temperature was close to T_λ, no training was observed, and none of the previously described tests induces any quench or voltage across the coil leads. Eventual anelastic energy losses, if any, were smaller than the sensitivity limit of the calorimetric method (a few tenths of a joule).

More extended information concerning the superconductor and cryogenic system operation are available elsewhere [3] ; however two results need to be reported, being related to the coil fabrication :

- the heat dissipated by the 8 soldered connexions between pancakes is negligible and lower than the sensitivity limit of power measurement,
- the heat conduction through the polyimid alumina chocks was found close to the value expected from sample measurements ($\leq$ 0.7 W between 2 K and 4.2 K).

V. CONCLUSION

Operation of this superconducting coil, reduced scale model of those envisaged for the Tore Supra toroidal magnet, was found highly stable under truly representative stresses. Mechanical design and fabrication methods and tolerances are thus considered satisfactory ; measurements have assessed that :

- the winding is kept in compression under any circumstance,
- shear and compression act simultaneously to transfer loads from the winding to the casing,
- a shear stress level of 10 MPa across copper-epoxyresin bonding is safe and does not lead to any harmful anelastic losses.

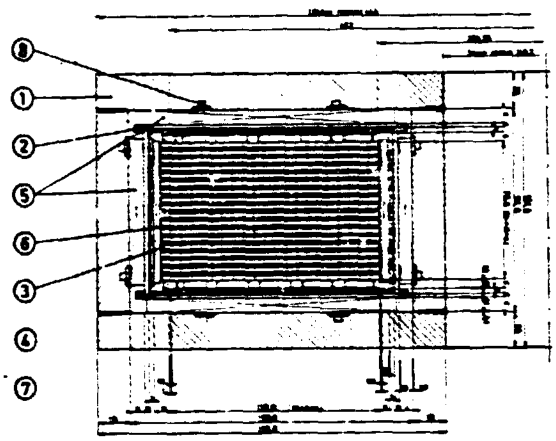
Simultaneously, coil components have been built at an industrial scale and thoroughly tested ; auxiliary systems - cryogenic, coil protection - have been experimented at a significative level. Fabrication of the large TF coils of Tore Supra can thus be undertaken with the present design and without any further development.

References

[1] "Conceptual design of a superconducting Tokamak : Tore Supra" (10 th SOFT - Padova 1978).

[2] "Tore Supra" - EUR-CEA-FC-1021 (1979).

[3] "Test of a model coil of Tore Supra" (Applied Superconductivity Conference - Santa Fe 1980).



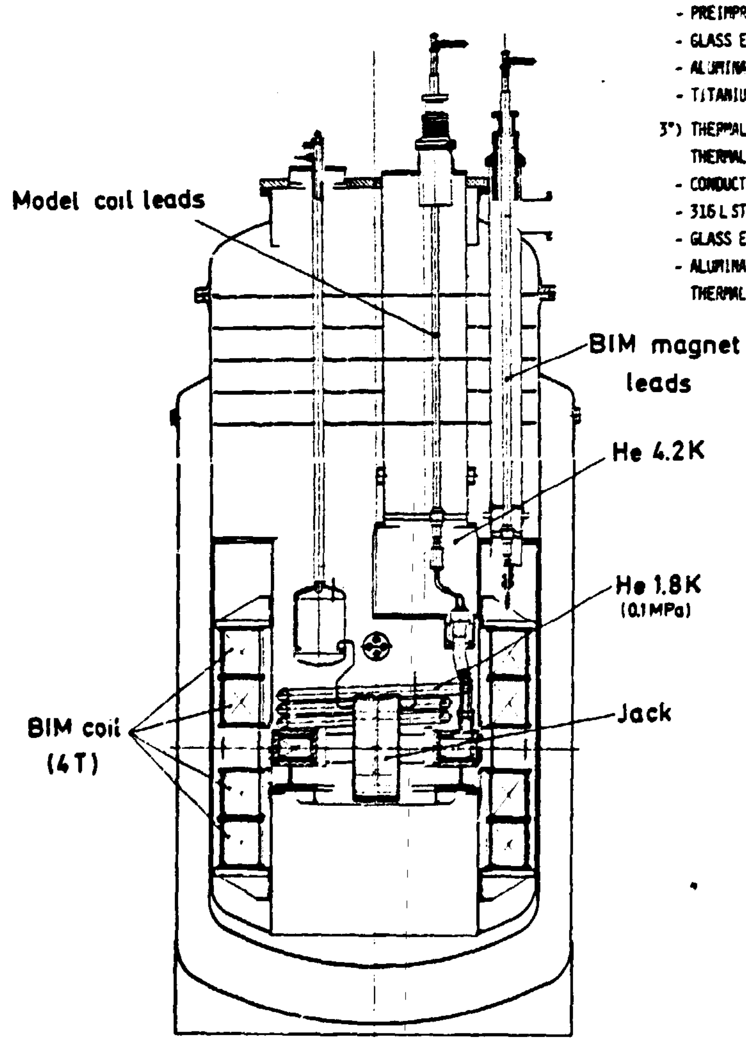
1 Stainless steel thick casing (316L)
2 Stainless steel thin casing (316L)
3 Superconductor (Nb Ti)
4 Spacers
5 Polymid alumina chocks
6 Glass epoxy chocks
7 Insulation glass epoxy layers
8 Liquid He cooling channels (4K)

Fig.1 MODEL COIL CROSS-SECTION

TABLE I : MAIN CHARACTERISTICS OF THE MODEL COIL

1°) MAIN DIMENSIONS	(AT 290 K)
OUTER RADIUS	444 mm
INNER RADIUS	[illegible].2 mm
MEAN RADIUS	345 [illegible] mm
HEIGHT	147.6 mm
CONDUCTOR CROSS-SECTION	2.5 mm x 5.6 mm = 14 mm^2
NUMBER OF TURNS BY PANCAKE	20
NUMBER OF DOUBLE PANCAKES	9
TOTAL CONDUCTOR CROSS-SECTION	5000 mm^2
THICK CASING CROSS-SECTION	11 000 mm^2
2°) MECHANICAL CHARACTERISTICS	(AT 4 K)
YOUNG'S MODULI	
- SUPER CONDUCTOR	130 GPa
- 316 L STAINLESS STEEL	210 GPa
- PREIMPREGNATED RIBBON (⊥ TO LAYERS)	15 GPa
- GLASS EPOXY CHOCKS (// TO LAYERS)	40 GPa
- ALUMINA POLYIMID CHOCKS	19 GPa
- TITANIUM SPACERS	100 GPa
3°) THERMAL PROPERTIES	
THERMAL CONTRACTION FROM 290 K TO 4 K	
- CONDUCTOR	2900 $\mu\varepsilon$
- 316 L STAINLESS STEEL	3060 $\mu\varepsilon$
- GLASS EPOXY (// TO LAYERS)	1650 $\mu\varepsilon$
- ALUMINA POLYIMID CHOCK	3500 $\mu\varepsilon$
THERMAL CONDUCTION AT 4 K OF ALUMINA POLYIMID CHOCK $\leq 10^{-2}$ $W.m^{-1}.K^{-1}$	

BIM TEST FACILITY



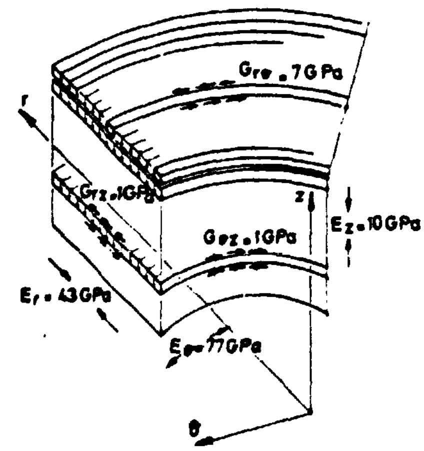


fig.3. YOUNG'S AND COULOMB'S MODULI OF THE SUPERCONDUCTING WINDING

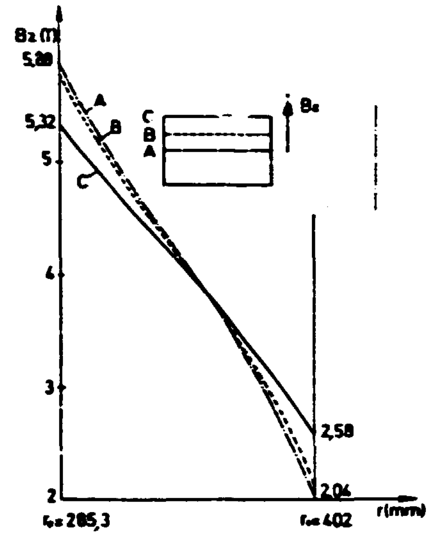


fig.4. MAGNETIC FIELD INSIDE THE WINDING

BIM 3,6 T . MODEL COIL 1300 A

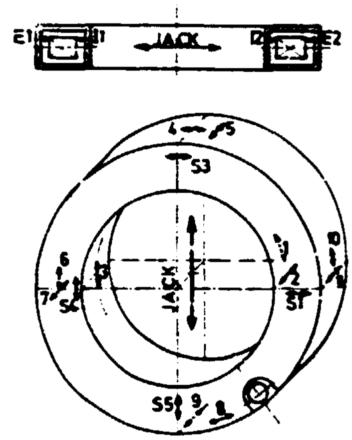


fig.5. STRAIN GAGES LOCATION

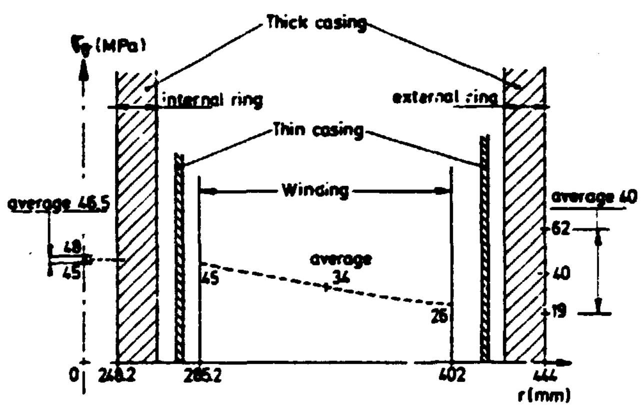


Fig 7. STRESS DISTRIBUTION IN THE COIL CROSS-SECTION ALONG A RADIUS (B only)

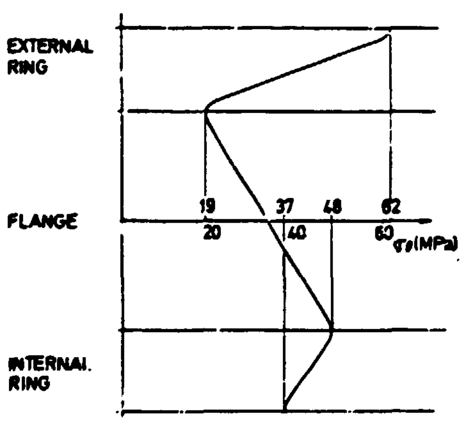


fig.6. STRESSES IN THE SS CASING UNDER ELECTROMAGNETIC FORCES BIM MAGNET 3,6 T + MODEL COIL 1300 A

TABLE II : STRESSES IN THE COIL

1°) AVERAGE INITIAL STRESSES	
RADIAL COMPRESSION ON THE WINDING	
AFTER HOOPING :	10 MPA
AFTER WELDING :	16 MPA
AFTER COOLING DOWN	24 MPA
2°) STRESSES ADDED DURING THE TESTS	
A) UNDER ELECTROMAGNETIC LOAD : BACKGROUND FIELD	3.6 T
+ MODEL COIL	1300 A
RADIAL COMPRESSION IN THE WINDING	13 MPA
AVERAGE TENSILE STRESS IN THE CONDUCTOR	34 MPA
SHEAR STRESSES BETWEEN PANCAKES	10 MPA
(ON THE TITANIUM SPACERS)	
AVERAGE TENSILE STRESS IN THE THICK SS CASING	38 MPA
MAXIMUM TENSILE STRESS IN THE THICK SS CASING	62 MPA
B) ADDITIONNAL STRESSES UNDER JACK LOAD	
MAXIMUM TENSILE STRESS IN THE CONDUCTOR	70 MPA
MAXIMUM SHEAR STRESS BETWEEN TURNS	10 MPA
MAXIMUM TENSILE STRESS IN THE THICK SS CASING	147 MPA