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TEST OF A MODEL COIL OF "TORE SUPRA"

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Inside the qualifying test programme, supporting the "Tore Supra" Tokamak design, a reduced scale model of coil was fabricated by an industrial firm and fully tested. This model coil is provided with the same features as those retained for the complete magnet and is built according to the same design; in particular the Nb-Ti mixed matrix monolithic conductor is cooled by a pressurized superfluid helium bath, supplied from a model of the envisaged complete cryogenic system. Three main objectives have been assigned to this test: operation of the cryogenic system, stability of the superconductor winding under high mechanical stresses, mainly shear, and simulation of coil quench conditions. For this purpose, the model coil (outside bore 0.8 m) is located inside a 4 T magnet, an hydraulic jack applies a 1 MN force along a coil diameter. Operation of the model coil has been found highly stable, under the conditions of applied field and forces, a coil transition can be induced by an electrical heater only when the superfluid bath temperature is close to Tλ. The 1.8 K cryogenic system provides a useful calorimetric measure of total losses induced inside the winding; its operation has been quite simple and reliable, permitting a sure extrapolation to a much larger size.

Introduction

The EURATOM-CEA Association is proposing a medium size Tokamak with superconducting toroidal field coils. The conceptual design of "Tore Supra", initiated in 1977, was presented at the PITTSBURG Conference[1]. We have considered a new option with a larger plasma radius 2.25 m, with the same value of the magnetic field 4.5 T and only 18 coils, instead of the previous 24 coils, the stored magnetic energy reaches 500 MJ. The coils use a NbTi monolithic conductor, cooled by a pressurized superfluid helium bath.

Before approval of construction it was necessary to define and carry out a programme of technical tests. This programme has started at the beginning of 1978; it includes a reduced scale model of the toroidal field coils fabricated by an industrial firm. This model coil has been tested with regards to cryogenic, mechanical and magnetic aspects.

Model coil description

As explained previously the conditions requested for the coils were: an average current density inside windings around 50 A/mm^2 with a maximum field value of 9 T and no quench under any field variations including plasma current disruptions (0.8 T parallel and 0.3 T perpendicular to the conductor with a time constant of 20 ms). These conditions lead to the choice of a small size conductor and a good thermal contact, without insulation, to a large volume of pressurized superfluid helium at 1.8 K and at atmospheric pressure.

The rectangular monolythic conductor is made of a double stack according to the formula :

$$((\mathrm{NbTi},\ \mathrm{Cu}_1,\ \mathrm{CuNi})_m\ \mathrm{Cu}_2)_n,\ \mathrm{Cu}_3.$$

with the following percentage in volume 25 NbTi, 63 Cu, 12 CuNi.

Other characteristics are listed in table I.

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TABLE I
Characteristics of the conductor

Dimensions	2.5 x 5.6 mm^2
m x n	180 x 60
Twist pitch	35 mm
Diameter of filaments	20 µm
Working current at 9 T	1400 A

Five firms were contacted to produce units of 600 m of this conductor (the length of a double pancake for "Tore Supra"), two units have been used to realize the model coil.

The conductor is wound on the narrow plane to form double pancakes. Helium channels with a depth of 1.8 mm, are provided between pancakes with spacers, the liquid helium wets 75% of the conductor large face. The enthalpy of the superfluid helium between 1.8 K and Tλ= 2.17 K is equal to 0.29.10^6 J/m^3 of liquid. This enthalpy is noticeably larger than the total losses inside the conductor, which stay in the range of 5.10^4 J/m^3 of conductor. The volume of the superfluid helium adjacent to the conductor insures also the stability conditions of the conductor as shown later.

In order to test the model coil inside an existing solenoid its scale has to be reduced to less than half size of the final toroidal field coils. Table II gives the main parameters of the model coil.

TABLE II
Parameters of the model coil

Number of double pancakes	9
Number of layers per pancake	20
Number of turns per coil	360
Average coil radius	0.34 m
Conductor weight	120 kg

Figure 1 shows a view of the coil. The winding is enclosed inside a thin wall, electrically insulated box, which contains the superfluid helium. A strong stainless-steel casing is put over and welded; it is separately cooled at 4.5 K through special pipes. A specially good thermal insulator at low temperature has been developped.

The casing restrains a large fraction (2/3) of all the electromagnetic forces applied on the coil and puts, after cooling down, the whole winding under compression.

Objectives of the model coil testing

Three objectives are assigned to this experiment: operation of the cryogenic system, stability of the conductor, simulation of quench conditions.

The cryogenic system is for the model coil very similar to what is designed for each coil of the full torus. This global test qualifies at once the whole technology involved with pressurized superfluid helium.

The effect of mechanical stresses as high as expected during operation of the full torus can be applied to the model coil (tensile stresses but also shear stresses); the stability of the superconductor can be observed under theses conditions.

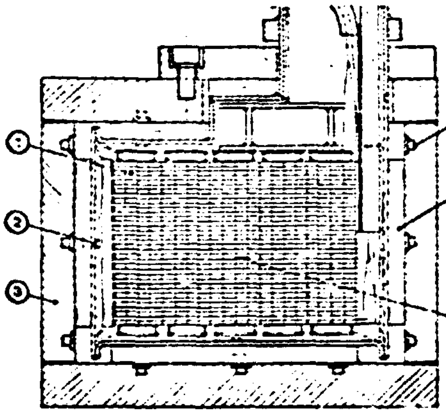

Fig.1 - View of the coil.

1	conductor	4	helium I pipes
2	helium II box	5	alumina polyimid insulator
3	casing	6	heater

The model coil arrangement permits to follow propagation of an induced normal zone. Information will allow to determine the protection scheme.

Experimental arrangement

A single coil does not provide simultaneously characteristics of the full torus, such as magnetic field value, stored energy per unit conductor volume, stresses in the winding. The retained arrangement permits to come close to the real values for these parameters.

The main components of the experiment are enclosed in a 1.5 m bore cryostat: the model coil is horizontal, in the middle plane of the available "BIM" magnet. The position of the coil is not important as long as the superfluid helium cooling is considered, but comes to play during the quench development. The figure 2 shows the cryogenic circuit scheme. The pressurized superfluid helium is cooled through a heat exchanger by evaporation of liquid helium introduced through an expansion valve and pumped by rotary pumps. A long pipe (7 m) simulates geometrical conditions prevailing in the complete torus. A safety valve (large aperture but low heat conduction) can be actuated by pressure measurement.

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 hydraulic 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 figure 3 shows the jack into the coil.

Experimental conditions permit to approach the behaviour of a full scale toroidal field coil during a quench. This can be obtained when discharging in series the model coil and the large "BIM" magnet (10 MJ); a quench is started inside the coil with a small heater.

The number of measurements inside the coil winding is reduced to three voltage taps. A heater (4 x 7 mm^2) is located between the conductor and a spacer; a stainless steel ribbon 25 μm thick is insulated from the conductor by a 20 μm layer of kapton. Strain gages and capacitive displacement tranducers are placed on the casing. Helium pressure in the superfluid circuit is measured by deformation of a 2 mm stainless steel membrane.

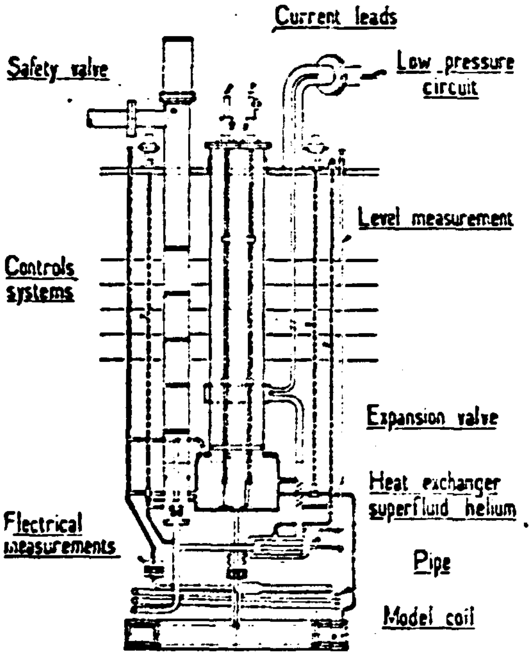

Fig.2 - Scheme of superfluid helium circuit.

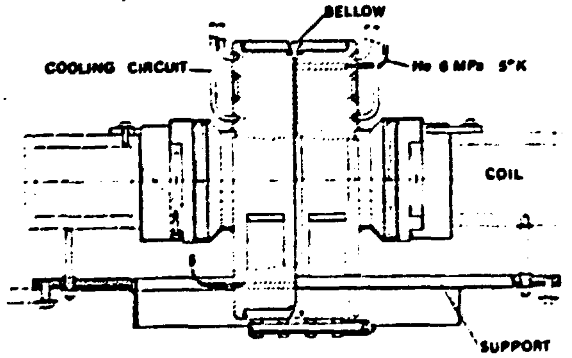

Fig.3 - View of the hydraulic jack. (1 MN force)

Operation of the He II system

The refrigerating circuit, of the Joule Thomson type, is equipped with two roughing pumps, 200 m^3/h each.

The refrigerating capacity available at the evaporator, where the saturated liquid helium boils at a pressure between 10 and 20 torrs, can reach 8 W at 2.16K and 3 W at 1.8 K. In fact, this refrigerating capacity is a direct function of the helium flowrate which can be adjusted by an expansion needle valve. For a given flow rate, the temperature of the bath can be further adjusted by applying heat to the He II bath by means of an electronic temperature controller.

The filling of the model coil circuit with 14 liters of helium, then cooling to below 4.2 K does not set any particular problem. To cool from 4.2 K to 2.16 K, 13.7 kJ must be removed. With a flowrate of 3100 l/h NTP in the refrigerating circuit, giving useful powers of 3 W at 4.2 K and approximately 1.7 W at 2.17 K, the time required is 90 minutes. Cooling from 2.16 K to 1.8 K corresponds to an energy of 3.5 kJ and with the same flowrate of 3100 l/h the time required is about 30 minutes.

Filling was accomplished in spite of the geometry of the circuit which purposely comprises high and low points and a liquid feed line that does not run directly through the cold source. A wide choice of cryostat geometries is possible due to the use of superfluid helium.

By operating at constant temperature, heat losses of the helium II circuit can be evaluated. For instance, for a temperature of the bath of 1.84 K obtained with a pump flowrate of 2.24 m^3/h NTP, corresponding to a power of 2.2 W, the controller dissipates a power of 0.8W. The heat losses under these conditions are evaluated at 1.4 W. The predominant term, evaluated at 0.6 W, is due to the conduction of the insulating spacers between 1.8 K and 4.2 K. Other losses are mainly due to : the measurement wires on the 1.8 K circuit, in particular the coaxial wires for the pressure measurements; the sealed feed throughs for the current supply lines and thermal leakage at the safety valve.

For a full scale coil, the losses due to conduction of the spacers will be increased tenfold, whereas the other losses will be unchanged.

The experimental conditions (temperature and pressure) can be chosen independently in the temperature range 1.8 K to 2.16 K and pressure range from 0.1 to 0.3 MPa.

The temperature controller which holds the temperature at a constant value can be used with advantage to measure losses in the coil. Heat is diffused in the superfluid helium sufficiently rapidly so that any heat released anywhere in the bath results in a variation in the heating level controlled by the temperature controller. Figure 4 shows a recording of the heating power and of the current in the coil as a function of time. The heat released on energizing or discharging the coil can be measured by integration of the signal from the temperature controller. For the geometry considered, the sensivity of the measurement is 2 J (for a minimum power of 0.5 W), while the maximum permissible energy is some 2 kJ.

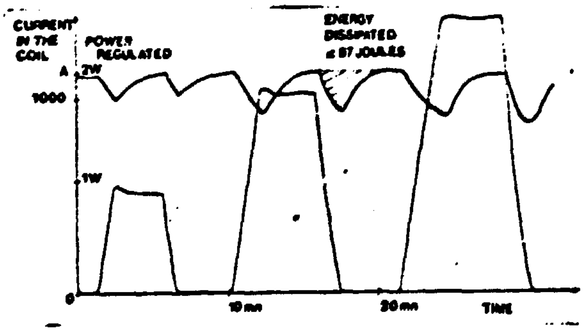

Fig.4 - Losses measurement by cryogenic method.

Stability of the conductor

If energy is suddenly released in a small region of the winding, the conductor will become locally normal if the critical temperature is exceeded. Reliability requirements demand that the whole length of conductor does not quench under normal operational conditions. The cooling must prevent the propagation of the normal zone and recovery to the superconducting state must occur. The goal of the stability tests performed in the model coil was to get experimental evidence of dependability of the choices regarding the conductor and the cooling. Recovery after a transition to normal state induced by a rapid local energy release up to 10^5 Jm^{-3} over 1 cm of conductor is required.

A small heater, located between a spacer and the conductor, deposits a known quantity of energy into the coil. After the energy is introduced in a few milliseconds, the evolution of the normal zone is monitored by measuring the voltage across the various voltage taps as a function of time. The maximum recovery normal zone length is about 10 cm, neglecting the zone of current sharing. Propagation can be induced by a 0.5-J pulse only when the superfluid bath temperature is close to T_λ (for currents less than 1500 A and fields less than 4 T). Figure 5 shows recovery currents as a function of magnetic field.

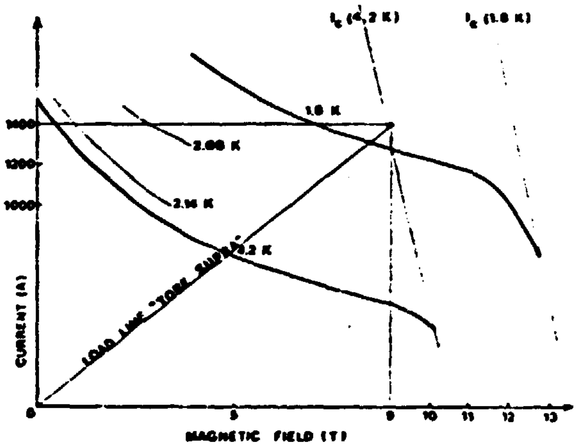

Fig.5 - Recovery currents versus field for 2-J heat pulses.

——— small test solenoids
——— model coil

Besides these points, we have plotted results of previous experiments which have been performed on a series of smaller test solenoids as described in[2]. These experimental results as well as measured time scales and normal zone lengths can be recovered from a one dimensional numerical model making use of the heat transfer properties of superfluid helium.

A set of experiments have been performed to control the stability of the conductor under mechanical stresses. In these tests the maximal value of the magnetic field was 5.8 T and the force applied to the coil by the hydraulic jack 1 MN providing tensile stress inside the conductor and shear stress of 10 MPa across the epoxy resin bonding[3]. For these conditions representative of those appearing inside the full toroidal magnet no transition appears in the oil and no detectable voltage was observed between the external coil connections at any time. Eventual anelastic losses could have been measured with previously described calorimetric method; if any, they were always smaller than sensitivity limit of the apparatus.

In conclusion, the experimental and theoretical studies show that the conductor design and the cooling method envisaged for "Tore Supra" should insure stable working conditions for the toroidal field magnet.

Quench conditions

For this purpose the "BIM" polarizing magnet and the model coil are series connected; with 1200 A, according to Fig.5, coil transition can be initiated by the 2-J pulse heat if the bath temperature is closed to T_λ. Along time, three phases of propagation of the normal zone can be observed: first along the conductor starting from the heated zone, with a very low velocity (0.2 m/s), then across the turns of the same pancake, followed by transition from pancake to pancake.

Figure 6a shows current versus time for the experiment described. The transition is initiated at $t = 0$. The pressure in the Helium II circuit is plotted on the same figure, it rises quickly inside the closed system during the transition development and decrease after opening of the safety valve.

Figure 6b gives the power dissipated inside different double pancakes versus time. The bump on these curves correspond to the valve opening, expansion momentarily lower the temperature. It is important to notice that the bottom 4 double pancakes never transit, heat transfer by convection from hotter parts vertically downwards being insufficient. However, the situation will be quite different in the torus where the coils are vertical: propagation will induce transition of the whole coil. During this test, 167 kJ were dissipated inside the coil, the average temperature reached inside the different transited pancakes varies from 45 K to 60 K, which correspond to 77 kJ of the enthalpy, approximately half of the dissipated energy.

The energy balance during the process can be written :

$$\int_0^t RI^2 dt - v\int_0^T c dT = E_{exchanged}$$

The first term refers to the Joule energy dissipated inside the conductor, the second the energy needed to heat the conductor and spacers. The difference is the energy exchanged with helium.

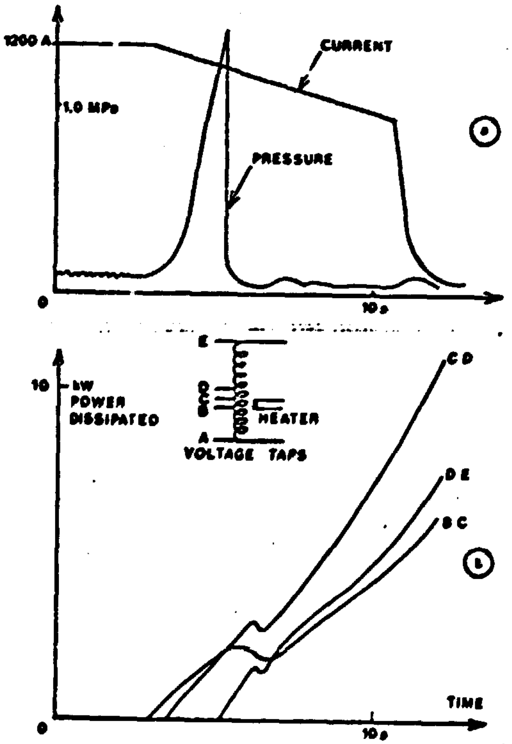

Fig.6 - Development of the quench.

a) current and pressure
b) mean power per double pancake

Figure 7 shows these three quantities versus time. The exchange is seen to be reached zero after about 10 s. From this point an adiabatic heating of the conductor occurs. For each double pancake the power exchanged with helium is about 2.5 kW and varies little throughout the process.

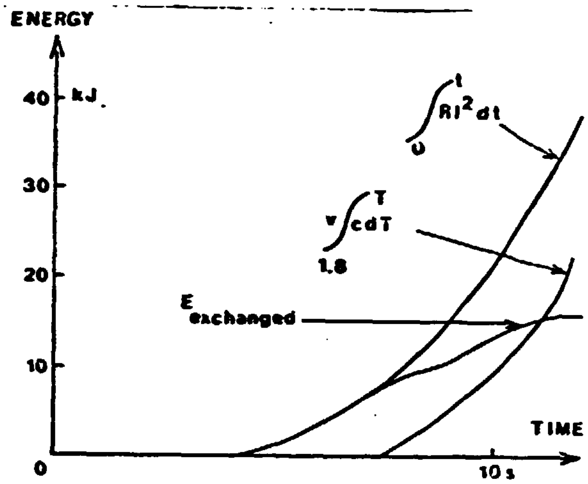

Fig. 7 - Joule, thermal and exchanged energies during the quench. (per double pancake).

Conclusions

Operation of this model coil has been found highly stable. The coil design and the retained manufacturing methods have proved a mechanical strength good enough to support the prevailing stresses in a reversible manner: no training was observed. More, coil transition can be induced by a local heater only when the superfluid helium temperature was quite close to T λ.

The cryogenic system has operated reliably, and can be enlarged to meet the full toroidal magnet requirements wihtout new problems to be expected. Thus, the fabrication of the superconducting toroidal field coils for "Tore Supra" can be undertaken on the present design without further development works.

References

1. R. Aymar et al.- "Conceptual design of a superconducting Tokamak: TORUS II Supra". IEEE Trans. on Mag 15 (January 1979). no 1 p 542
2. C. Claudet et al.- "Superfluid helium for stabilizing superconductors against local disturbances". IEEE Trans. on Mag. (January 1979).
3. R. Aymar et al.- "Manufacture and test of a TORE SUPRA model coil". 11th SOFT, Oxford (September 1980)