THE SACLAY SUPERCONDUCTING PULSED DIPOLE "MOBY"

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Abstract

A pulsed superconducting dipole is being built at Saclay. It will give a field of 6 T in a bore of 100 mm with an homogeneity better than 10^{-3} in 50 % of the aperture. The current will be 1500 A and the minimum rise time 5 seconds.

This dipole has a cold iron shielding and will work in a horizontal cryostat. A considerable effort has been carried out to design this magnet as close as possible to an engineered version. Many parts are already delivered and the conductor has been tested on three solenoid coils.

I. Introduction

The development of superconducting pulsed magnets for synchrotron accelerators makes an increase possible by a factor 3 in magnetic field with regard to conventional magnets. The energy of existing synchrotrons could then be upgraded by a factor 3 just by replacing conventional magnets by superconducting ones, or new designed synchrotrons could have for the same energy a tunnel radius 3 times smaller.

The technology of such magnets is improving very fast but numerous problems still remain to be solved mainly when one has to go from the laboratory type magnet to the engineered designed magnet. That is the reason why a special effort has been made for MOBY to design as much as possible an engineered type dipole. Such parts as coils, iron shielding are very close to an industrial version. The horizontal working position is also very important. In fact going from this prototype to the industrial version should only be a problem of length. It is planned after the first magnetic measurements, to use a self-correcting field component device whose first tests are quite promising.[1]

II. Basic parameters

The basic parameters of MOBY except for the length could fulfil many of the requirements of a synchrotron accelerator dipole.

The central field has been chosen high : 6 T to try to push problems at their limits and to assess safety margin for operational magnets.

The main characteristics are listed on table I.

Central field	6 T
Coil aperture	100 mm
Rise time	5 sec
Operating current	1 500 A
Overall current density	15 000 A/cm^2
Magnetic length	50 cm
Coils losses (10 μ filament)	80 J/cycle
Iron shielding losses	60 J/cycle

The other main features of MOBY are on the one hand the location of the iron shielding very close to the coil and at helium temperature and on the other hand the choice of a totally epoxy impregnated coil cooled by means of copper heat drains.

Another important characteristic of MOBY is the type of winding which consists in using special form giving a constant turn perimeter per layer. This type of winding produces a stable mechanical location of turns and it is possible to build a whole pole with only one piece of conductor (no joint).

III. The conductor

An assembly of 24 composites is necessary to get the 1500 A conductor. The composites must be perfectly transposed to ensure equal current sharing, in addition they must be insulated from each other to avoid induced circulating currents. These currents would diminish the transport current and mainly they would increase considerably the losses in pulsed condition.

Having to choose between a cable and a braid which ensure both a good transposition, a hollow braid was finally chosen because at compaction it is easier to get a rectangular shape (4 x 2 mm), such a shape being more favourable to our winding process. The compaction is obtained by drawing the braid through a die. Braiding and mainly compaction are dangerous for the strands and several of them were broken on the two 800 meter pieces of conductor ordered, even with a rather poor packing factor ($\sim$ 50 %). Fortunately the actual needed length being only 600 m per pole (200 m extra length per pole were ordered for solenoïd tests) it has been possible to find 2 x 600 m lengths out of the 2 x 800 m with only one broken composite. Another drawback of the compaction process is damage on the composite insulation (p.v.a. 15 to 20 μ thick) and on a length of several hundred meters a few shorts occurred between composites.

The conductor overall insulation is made of a Terylene braid woven quite loose acting mainly as a spacer (0.1 mm). The braid is woven loose to make the impregnation of the conductor easier. The impregnation is carried out in our process just before winding.

Each of the 24 strands of the conductor is an I.M.I. composite 1 000/44 with a pure copper matrix.

Main characteristics of the conductor are listed on table II.

Conductor dimensions	4 x 2 mm
No of composites	24
Transposition pitch	60 mm
Packing factor	50 %
Composite diameter	0.44mm
Nb of filaments per composite	1 000
Filaments diameter	10 μ
Twist pitch	2 mm
Copper to superconductor ratio	1/1

In Fig. 1 a cross section of the composite is shown. On this photograph, the thickness of the insulation is not uniform around the wire, this effect is due to the twist pitch which can be felt along the wire and makes it move back and forth as it passes through the insulating guide.

A very compacted 24-strand braid trial is shown in Fig. 2 with an aspect ratio of about 3 (the actual braid has an aspect ratio of 2). Such a compaction rate deforms the strands very much and on this sample many breaks occurred so that a lower rate was taken for the actual braid.

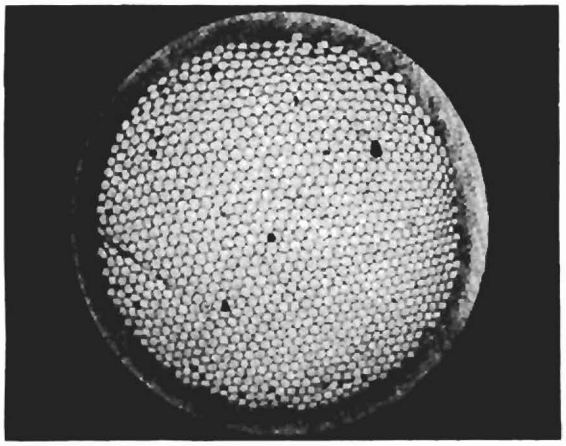

Fig. 1. 1000 filament composite of 10

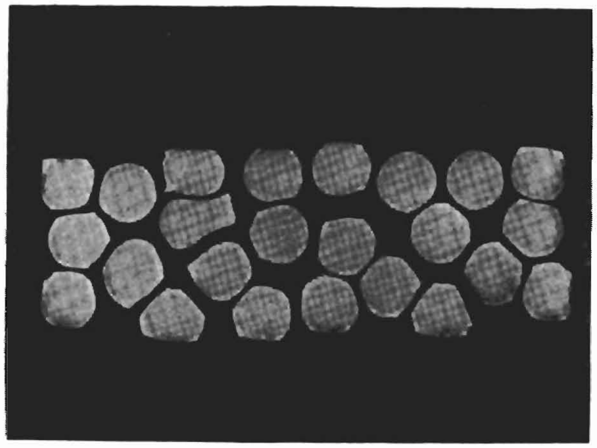

Fig. 2. Trial of braid compaction.

The whole conductor has been carried out by I.M.I.. The delivery involved also a dummy cable made of brass and was used to test the processes of braiding, compaction and mainly winding. Brass was chosen for its mechanical behaviour very close to the superconductor one.

IV. Coil and iron shielding geometries

a) Two dimensional problems :

The coil is the approximation of two overlapping ellipses. The shape is quite simplified for this prototype where the good field region with $\Delta B/B \leqslant 10^{-3}$ is limited to 50 % of the coil aperture.

The coil has a parallelogram shape with layers of conductors parallel to the horizontal plane.

Heat drains are stuck between layers to drive the heat from within to the inner edge of the coil where they protrude into the helium bath (fig. 3).

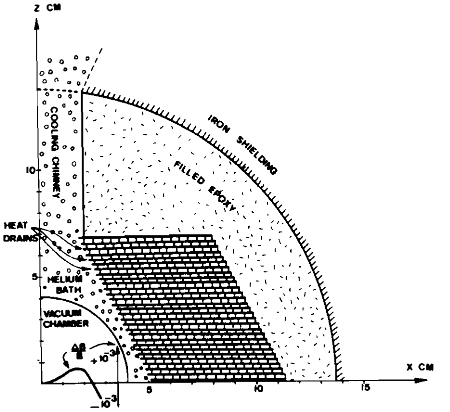

Fig. 3. Coil and iron shielding configuration.

It is possible while keeping the same type of winding with layers parallel to the horizontal plane to design coils giving a more homogeneous field.

One then chooses a shape more sophisticated than the parallelogram and one uses layers of drains with different thicknesses which give many parameters to adjust the field homogeneity. That is what has been done for the other dipole prototype ALEC whose construction is going on.

With this method of coil shaping the goal is not to make many field components equal to zero but to balance their effects in the horizontal median plane.[2]

The iron shield is circular and located at an inner radius of 137.5 mm. Its thickness is 20 cm and the average flux density is 2 T when 6 T is reached in the useful aperture. The homogeneity curve $\Delta B/B$ as a function of the radius in the horizontal median plane is shown in Fig. 3 along with the coil and iron shielding shapes.

Saturation effects were studied with the program MAGNET[3] up to a central field of 7 T. On Fig. 4 $\Delta B/B$ is shown as a function of the central field due to the saturation alone at different radius and in the median horizontal plane. Particularly at 70 % of the aperture the maximum $\Delta B/B$ is 2.10^{-4} occurring at 5.2 T for a field variation range 0 - 6 T. This effect is small even with a shielding so closely located.

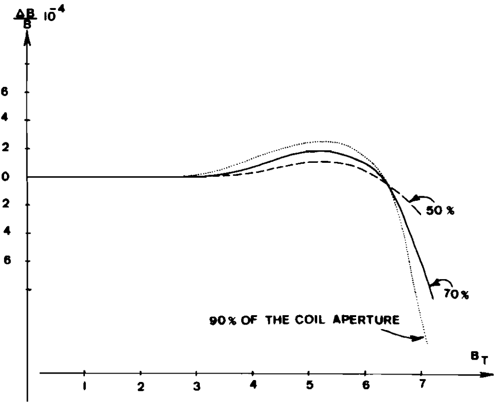

Fig. 4. Saturation effects

Saturation effects can be seen on field components such as :

$$B = B_o\ (1 + C_2 x^2 + C_4 x^4 \ \ldots + C_{2n} x^{2n} \ \ldots)$$

Coeff.	Any field $\mu = \infty$	5 T	6 T	7 T
$C_2\ m^{-2}$	5.06	5.21	5.26	4.84
$C_4\ .10^3\ m^{-4}$	- 7.31	-7.38	-7.49	-7.70
$C_6\ .10^6\ m^{-6}$	- 0.34	-0.34	-0.35	-0.35
$C_8\ .10^8\ m^{-8}$	- 0.98	-0.97	-0.99	-1.01
$C_{10}.10^9\ m^{-10}$	- 0.25	-0.23	-0.23	-0.24

b) Three dimensional problems :

Three dimensional problems must be taken into account to study the end effects on field integrals and to find the peak field value. Also for a magnet so short as MOBY, it is necessary to compute the three dimensional field if one wants to compare magnetic measurements with theory.

A three dimensional program has been made for the very particular end shape of MOBY (fig. 5).

Fig. 5. Coil end shape (brass model).

This program is able to take the shielding into account even with end plates but with $\mu = \infty$ (images method). The main results obtained so far are :

- The peak field is not located in the ends but in the straight parts, it is 5 % higher than the central field.

- Because of the short length the end effects are felt within the whole magnet and consequently it is possible to compensate the field integrals by changing the two dimensional shape.

V. The coil

The coil is built according to the method of equal perimeter of turns for a same layer. This type of winding, already used two years ago for OGA[4], enables to realize a winding very stable mechanically and to go from layer to layer by continuity with no need to cut the conductor. In addition using layers parallel to the horizontal plane results in a simpler mechanical structure needed in all cases to reach the required tolerances.

Another characteristic of the coil is to be totally epoxy impregnated and to be cooled by a mat of copper heat drains inserted between each layer and protruding at one end into the helium bath. The heat drains are made by winding a layer of formvar insulated copper wire on a large cylinder. A thin layer of epoxy is put to stick the wires to each other so that when the epoxy has cured one gets a sheet of parallel insulated copper wires which has a good thermal conductivity in one direction but is eddy current free under pulsed condition. In the coil the good thermal conductivity direction is set perpendicular to the turns directions, the positioning being made easier by the special winding technic because each layer surface can be developed into a rectangular sheet.

The coil is mechanically supported by its outer part, the inner part has no support and serves only for cooling.

The thermal behaviour of the coil in pulsed condition has been studied[5]. The point where the temperature is closest to the superconductor critical temperature is located on the internal layer of the coil where the heat drains protude into helium. Figure 6 represents two curves of temperature as a function of the horizontal axis for the peak field layer.

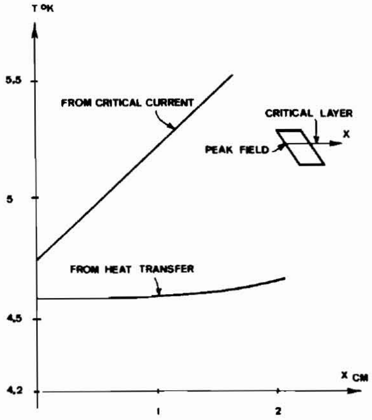

Fig. 6. Thermal behavior of the coil (peak field layer).

The upper curve is the critical temperature of the conductor which depends on the field and current. The lower curve is the temperature along the drain and depends on the superconductor losses (calculated for 6 T central field and 5 s rise time), the thermal contact between superconductor and drains, the thermal resistivity of the drains (drains diameter 0.2 mm, k = 7 W/cm^2°K) and the temperature drop at the contact helium-drain. It can be seen on Fig. 6 that for the operating field and rise time the safety marging is only 0.15°K.

As an order of magnitude for the above-mentioned parameters the peak thermal flux to transfer from the superconductor to the drains mat is 2.10^{-4} W/cm^2 and the peak thermal flux to transfer to the helium bath by the heat drains at their ends is 8.10^{-2} W/cm^2. Extensive studies are being made on the thermal behaviour of all these types of heat transfer.[6,7] The main part of the temperature rise comes from the drain to helium transfer (0.3°K). The rest of the temperature rise comes from the thermal contact between superconductor and drains (0.07° K) and along the copper heat drain (0.01°K).

The thermal contact of the sticking between superconductor and drain has been studied with filled and unfilled resins along with the behaviour of this contact under thermal shocks. It has been found that 1000 thermal shocks between nitrogen temperature and room temperature give an increase of 1.0% on the thermal resistance. Typically the interface thermal contacts are equivalent to a thickness of about 0.1 mm of epoxy resin.

The winding is made on a machine having a three-dimensional movement with impregnation of the conductor by making it pass through an impregnating machine just prior to set it on the coil former (fig. 7).

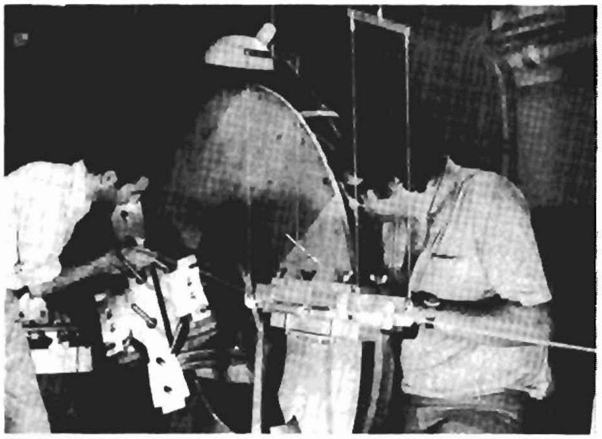

Fig. 7. Winding machine and impregnation of the conductor.

After a layer is completed the heat drain mat is set and a press is placed on it (fig. 8).

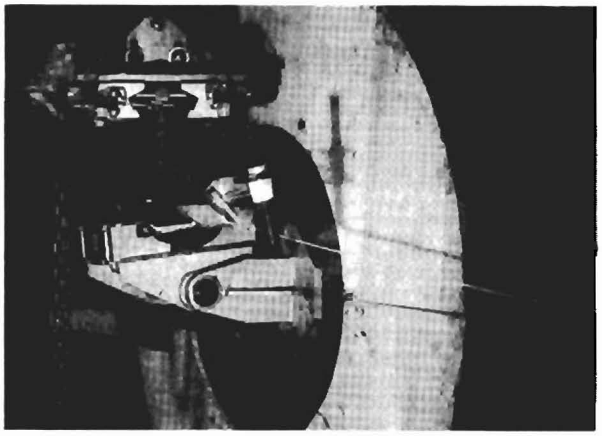

Fig. 8. Press being set up on the winding.

The press is then tied up by means of the tie rods up to reach calibrated wedges whose dimensions are the theoretical thickness of the coil for the concerned layer. The width of the coil is obtained by another independent type of wedges. (fig. 9).

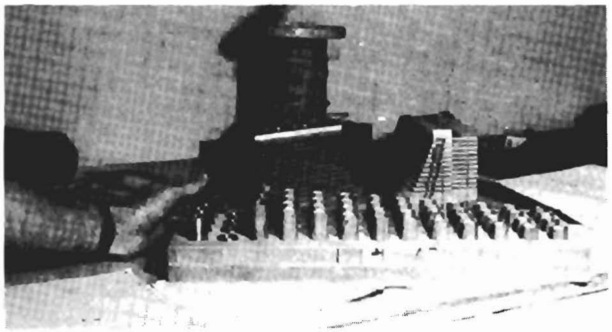

Fig. 9. Calibrated wedges (thickness and width).

The press can be heated to accelerate the curing of epoxy. The epoxy being hard enough another layer is wound and so on. With this method no error can be accumulated on dimensions.

To get the ends of the drains in contact with helium a "false turn" is wound between the inner coil former (which is removed after winding) and the first turn. This false turn made of plastic material can be removed or machined so that heat drains protrude or reach just the coil inner surface level.

A brass model (fig. 10) has been carried out with this technic and theoretical dimensions were obtained within ± 0.1 mm for the thickness of the coil (which is the more severe tolerance).

Figure 11 shows a cross section of this coil. On the left side of the magnified part of the view the false turn, not yet removed, can be seen.

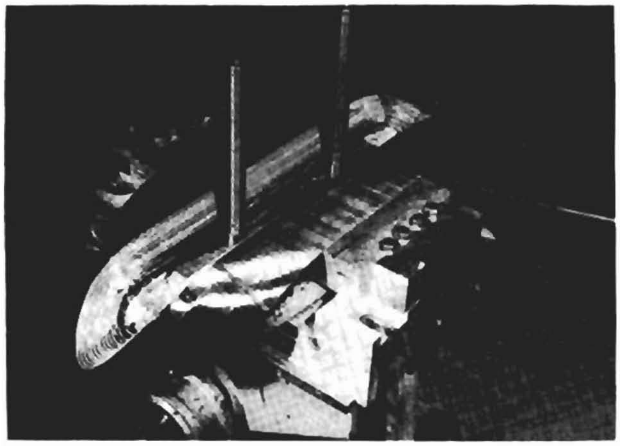

Fig. 10. Completed brass coil (still on winding machine with coil inner former removed).

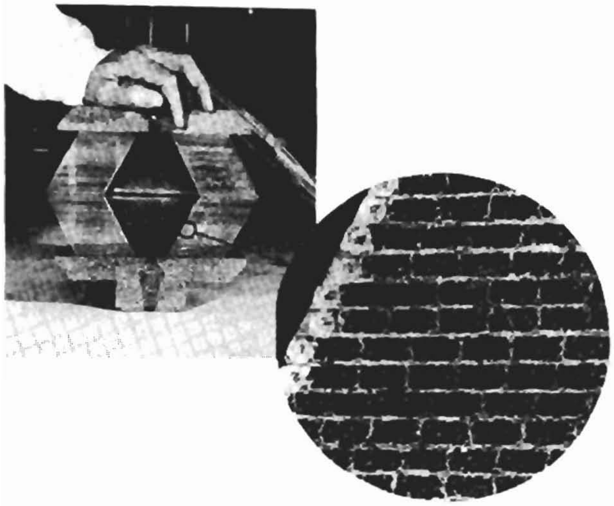

Fig. 11. Brass coil cross section.

This winding technic can applied to a vacuum impregnated coil. The same process can be kept just by not impregnating the conductor but by putting on its surface a thin layer of thermosetting material to keep the conductor in place during winding. The coil being completely wound can be vacuum impregnated afterwards.

VI. Iron shielding

The iron shielding has a circular shape with a 275 mm inner diameter and a 675 mm outer diameter. It weighs 1.7 tons. It is made of laminations stacked with a pressure of 140 N/cm2.

The stacking is contained by a mechanical structure made of stainless steel bars located around the outer diameter and screwed at their ends on stainless steel end plates. The laminations are low losses silicon steel 0.35 mm thick, (losses given by manufacturer are 1.1 W/kg for a.c.50 Hz current and 10 kG peak field).

Figure 12 shows the iron shielding with the brass coil model located inside the bore.

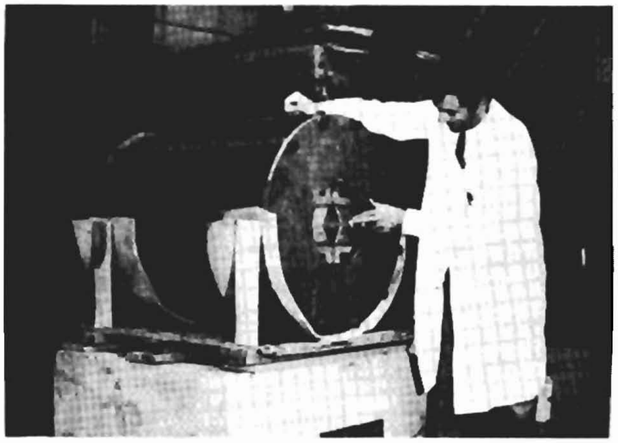

Fig. 12. Iron shielding.

The helium circulation on the inner coil surface where the heat drains protude is made by natural convection by means of chimneys through the stacking.

These chimneys are obtained by punching an upper and lower gap on some laminations of the stacking. Figure 13 shows the shielding position inside the cryostat and the cooling chimneys.

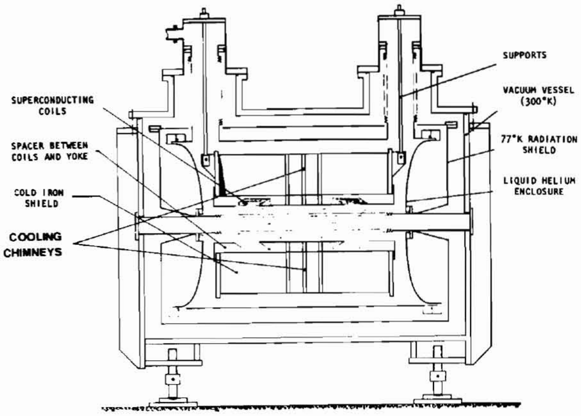

Fig. 13. Schematic view of the magnet mounted in its cryostat.

The shielding is also used to contain the bursting forces of the coils. Positioning the coil inside the shielding is a difficult problem by reason of their different thermal contractions and the required tolerances (0.2 mm). The coil shrinking more than the shielding one thinks to mount the coil in the shielding under stresses at room temperature and then to cast a thin layer of filled epoxy resin between the outer diameter of the coil (which has been made round by fiber glass epoxy spacers) and the inner diameter of the shielding. The trouble with this method is that it is practically impossible to take the magnet apart. This process is not completely frozen and one is studying a way of replacing the final casting of epoxy by a material which would be soft at room temperature. It would then be possible to put the magnet into pieces.

VII. The cryostat

The cryostat is classical with nitrogen shielding and is designed to have the dipole working position horizontal. It is schematically shown on Fig. 13. For this first prototype it has been designed so that it is very easy to put the magnet inside as well as to take it out. For that reason the vacuum tank presents an horizontal joint and is rather encumbering. The useful aperture is under vacuum and cold, separated from the helium by the wall of the inner tube which is the only part of the cryostat within magnetic field. In order to diminish the eddy current losses a corrugated tube made of stainless steel 0.4 mm thick is used. Corrugations take place between an inner diameter of 63 mm and an outer diameter of 81 mm. They make the current lines longer and increase the apparent electrical resistivity. In our special case the losses are 5 times smaller compared to a smooth tube 0.4 mm thick with the same average diameter (72 mm).

The magnet is suspended by means of two rods cooled by helium gas. The magnetic axis alignment can be made from outside in adjusting the upper rod positions after the field map has been measured.

VIII. Solenoid test coils of the conductor

In order to try the conductor as well as the impregnation technique and the way of cooling chosen for MOBY, three solenoid coils were wound and tested. These solenoïds were made from the extra lengths of the MOBY conductor. Each of them used 90 meters of conductor, and could reach a field of 6.5 T for a current of 1700 A (6 kJ stored energy). One of them is shown on Fig. 14, where the heat drains can be seen protruding one side.

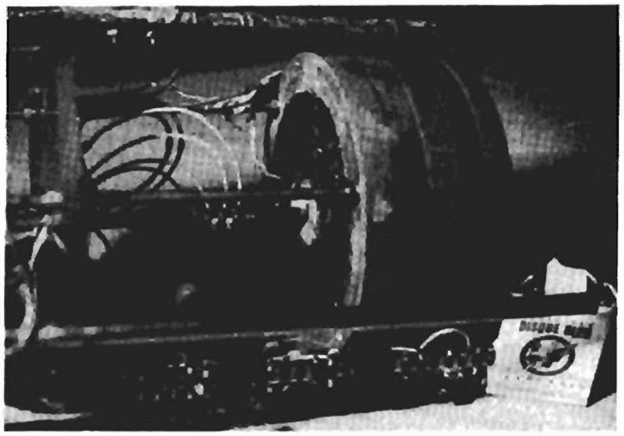

Fig. 14. Solenoïd test coil.

- The first solenoid was impregnated with a filled epoxy resin (Stycast 2850 FT Emerson and Cuming) and reached its critical current at slow rise time. Huge losses were measured at faster rise times

(25 times the calculated losses for 1 s rise time !) and we got also big degradation (degradation = (Is - Ic)/Is where Is = short sample current and Ic = coil current). One found that the epoxy filler (alumina powder) was very abrasive and had damaged the strand insulation during winding so that most of them were short circuited and gave the unexpected big losses.

- The second solenoid was impregnated with an unfilled resin (Epikote 828 Shell) and we got only a few shorts. (It is almost impossible to avoid them at 100 %). One got the expected losses but a degradation of 45 % even in slow rise and the reasons were not clearly understood. Bad impregnation was finally supposed and one made a third solenoid.

- The third coil used the same epoxy resin and the impregnation was made very carefully. The coil degradation was 49 % for any rise times but the losses were correct. One then had the idea to measure the individual currents of the 24 strands by means of resistances series connected. These resistances do not only enable to measure the currents but they tend to make them all equal. The coil degradation was then 75 %. All currents were measured in d.c. condition and two were found 20 % smaller than the others. By disconnecting these two "bad strands", the 22 remaining strands reached their critical current after a little training even in fast rise time (3 sec). In fact the two bad strands were broken and their measured current passed through a few shorts.

It has not been possible to check the second solenoïd which was no more available with the same method but probably its bad behaviour can be explained by the same reason (the extra conductor length of MOBY had several strands broken).

One thinks such a behaviour should not have happened with broken strands if the strands insulation had been perfect.

This experiment seems to prove that the assembly of insulated strands can be very dangerous if some shorts occur. Maybe a better way of assembly would be to put between strands a resistive barrier high enough to limit the losses but small enough to allow smooth sharing of currents between strands along the conductor if necessary (break, transition of one strand, etc...). The good behaviour at low rise of the first solenoïd, where all strands were short circuited, has shown the better stability of a conductor with possibility of "smooth current sharing".

IX. Present status

The conductor was delivered six months ago and the delay of the project is due to the bad results of the two first solenoid tests. Now the winding is in progress.

The iron shielding is completed. The main parts of the cryostat are also completed and first low temperature tests are in progress.

First test is now planned for the end of the year.

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