15 TESLA SUPERCONDUCTING MAGNET*

J.C.Vallier
Centre de Recherches sur les Très Basses Températures
Centre National de la Recherche Scientifique
Grenoble, France

Abstract

A superconducting magnet which has been recently constructed using a mixed-winding of Nb-Ti and Nb3-Sn and designed to produce a field of about 15 Tesla with good homogeneity in a volume of several tens of cm^3 is described. The performance of the magnet has been studied at 4.2 K. Large instabilities in Nb3-Sn have been found, which make it necessary to vary the field of the magnet very slowly (about 7 G/sec in high field). The behaviour of the latter is strictly controlled for successive thermal quenches. The protection is assured by suitably chosen external resistances. A large fraction (85 %) of the stored energy is transferred.

I. Introduction

For several years now the Centre de Recherches sur les Très Basses Températures at Grenoble has made its own superconducting magnets for experiments which are being performed there in various domains. It has been necessary for these experiments to produce higher and higher magnetic fields. As a result the "Délégation à la Recherche Scientifique et Technique" (1) has recently authorized the study of a magnet capable of producing a field of 15 Tesla. This magnet has been made and rested at the above laboratory while a "Service de Champs Magnétiques Intenses" was being created at Grenoble. This service will eventually provide high magnetic fields in both Bitter and superconducting magnets, to which physicists needing such fields will have access.

II. The Magnet

The magnet is composed of an inner magnet made from Nb3-Sn and an outer magnet made from NbTi. The relative proportions of the two materials have been computed in such a way that their total cost is a minimum for a field of I5T having acceptable homogeneity. The dimensions of the Nb3Sn and NbTi magnets were computed at the same time. Hence in order to produce I5T in a magnet having a working diameter of 30 mm with an homogeneity of 1/1000 over a length of 5 cm along the axis, the calculation showed that the Nb3Sn magnet should produce 9T, the cost of the material being 150,000 F, and the NbTi magnet should produce 6T, the cost of the material being about 80,000 F.

In order to produce the same field in a magnet with a working diameter of 60 mm the total cost of the materials is about doubled (450,000 F). The contribution of the outer magnet to the full field increases from 6 T to 7,8 T while that of the inner magnet decreases (7,2 T).
Because the results of the calculation depend directly on it, the current density in the Nb3Sn ribbon has to be defined. And, since little was known of the characteristics of this material, a fairly small density (15000 A/cm^2 in a ribbon of external dimensions 10 x 0,1 mm) was chosen. It is evident that the calculation would give very different results for a current density in the Nb3Sn slightly larger or slightly smaller than the value chosen. The values of the other quantities which had to be defined for the calculation: working diameter (30 mm), maximum field (15 T) and homogeneity (1/1000), have already been mentioned. A homogeneity of 1/1000 was necessary because the magnet will later be used for magnetization measurements using an extraction method. The dimensions of the magnet are shown in Fig.1. The materials used are fabricated by Thomson-Brandt. The NbTi has a ten-strand structure: ten wires of NbTi are assembled together in a copper matrix. Each wire has a diameter of 210 microns and the material is delivered as a wire with a 1,5 mm square cross section. The ratio copper/superconductor is about 5,5.
The NbTi is close-wound. The use of a square-section wire complicates the construction of the magnet but gives an excellent filling coefficient (0,835). Cooling channels which are made using fibre-glass strips 5 mm wide and 0,4 mm thick are provided between every two layers. The different lengths of NbTi are connected electrically outside the magnet proper by indium solder in copper holders. The homogeneity is ensured by winding in such a way as to leave a circular trough around the centre of the magnet (see Fig.1). The Nb3Sn is in the form of a ribbon of width 10 mm and thickness 0,1 mm. Near the centre of the Nb3Sn magnet a THC3 ribbon, which is composed of three 0,025 mm thick Nb/Nb3Sn ribbons stabilized by a copper ribbon 0,025 mm thick, is used. Towards the outside of the magnet (see Fig.1) THC2 ribbon, which consists of two ribbons of Nb/Nb3Sn stabilized to two copper ribbons is used. The magnet is assembled on a suitably insulated stainless steel tube and consists of eight double pancake windings separated from each other by glass fibre spacers. Each double pancake comprises two pancakes wound in opposite senses on a copper former. Since copper formers of different thicknesses are used to obtain the required homogeneity, the internal diameter of the double pancakes near the centre of the magnet is slightly greater than that of those near the ends of the magnet.

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III. Protection of the Magnet

The working current densities in the two magnets and the large copper/superconductor ratio for the NbTi have been so chosen in order to control as closely as possible the quenching of the magnet. It was decided to limit the temperature reached at the hottest point in the magnet to a reasonable value (260-280°), and the potential differences between the ends of the windings (500-600V). However, since the energy used in the NbTi magnet to obtain a field of 5.5 T is of the order of 230 kJ, which is comparatively large, a great deal of care has been taken to protect this magnet. The classical method of protection described by Smith (2) was chosen. As soon as a normal resistive region appears, the magnet is isolated as quickly as possible from its current supply. In some situations this method enables a part of the energy stored in the magnet to be transferred to a suitably chosen receiver outside the cryostat. The problem to be solved was complicated by the fact that the two magnets were coupled magnetically and used together. The magnetic energies used in one or the other magnets were very different as were the copper/superconductor ratios of the materials from which they were made. It can be shown that in a magnet so constructed, the best solution is to protect the inner and outer magnets seperately.

Figure 2 shows the magnet and its associated electrical circuits. Each magnet has its own current supply and its own protection circuit. D1, K1 for circuit No.1, D2, K2 for circuit No.2. When in either circuit 1 or circuit 2 the appearances of a resistance is detected, the switches K1 and K2 are opened simultaneously. In the same figure are shown the resistances R_{e1}, R_{e2}, R_{b1}, R_{b2}. R_{e1}, R_{e2} are the resistances in which the stored energy is recuperated and have precisely calculated values. They are situated outside the cryostat. R_{b1}, R_{b2} have zero resistance before the magnets go into the normal state and represent the resistances which appear when either magnet 1 or 2 goes normal. To a first approximation the ratio between the resistance R_e and the resistance R_b (variable during the transition), which appears in its magnet, gives an indication of the fraction of stored magnetic energy which can be evacuated from the cryostat.

In practice the values of R_{b1} and R_{b2} are not known with any precision. But an upper limit for the heating can be obtained by calculating the rise in temperature neglecting them.

Suppose that K1 and K2 are open at the instant when a normal region is detected in one or other of the circuits. At this moment the respective currents are I_{o1} and I_{o2}. If M is the mutual inductance between the two magnets whose self inductances are L1 and L2 respectively, the magnetic energy

$$\frac{1}{2} L_1 I^2_{o1} + \frac{1}{2} L_2 I^2_{o2} + M I_{o1} I_{o2}$$

is converted into heat in the resistances $R1 = R_{e1} + R_{b1}$ and $R2 = R_{e2} + R_{b2}$.

The temperature (T_{F1}) of the hottest point in magnet 1 is a function of the integral

$$\int J_1^2 \, dt$$

taken between the moment when K1-K2 open and the time when the current becomes zero. J1 represents the current density in the magnet 1.

In the same way the temperature (T_{F2}) of the hottest point in the magnet 2 is determined by

$$\int J_2^2 \, dt$$

Since L_1 L_2 and M are known, the equations describing the response of the two circuits after K1-K2 are opened give the relations between T_{F1}, T_{F2}, R_{e1}, R_{e2}. The relations show that the maximum temperatures depend not only on the values of the external resistances but also on the ratio of the currents I_{o1} and I_{o2}. However it is adequate for our purposes to determine the time constants of the two circuits taking into account I_{o1}/I_{o2}.

It can be shown that **for efficient protection of** both magnets the current in the Nb3Sn magnet should be decreased as rapidly as possible while that in the NbTi magnet should be decreased very slowly. Thus there are two limits: for the Nb3Sn a too large potential difference can appear between the current terminals, while for NbTi the magnet may heat up excessively. Transfer of heat has been neglected in this calculation. In addition the processes occurring at the transition, which last only a few seconds, have been considered to be adiabatic. Furthermore the magnets have been supposed to quench simultaneously. This is obviously not true but the speed with which the current in that magnet which is not in the normal state is such that as soon as the switches K1-K2 are opened it goes into that state.

The detector of the quench plays an essential role in the system. It must work without fail otherwise the magnet may be destroyed. Consequently D1 and D2 each represent in fact two detectors. Since detectors connected in a "Wheatstone" circuit are insensitive to a rapid change in the current in one or other of the magnets, a circuit which detects the derivative of the current has been added. If the currents change too quickly the circuits are opened.

The fact that flux jumps occur frequently in the materials (Nb3Sn, NbTi) used has complicated the design of the protection system. The large amplitude voltage pulses lasting several tens of milliseconds associated with flux jumps may be detected by D1 or D2 and cause the switches K1 and K2 to be opened prematurely. In order to prevent this, the signal detected by D1 or D2 is analysed before this happens and the switches are only opened if the voltage detected exceeds a threshold value S for a time greater than T. T must be large compared to the duration of a flux jump, but K1 and K2 must not be left closed too long without risking damage to the material if the voltage detected is due to a magnet going normal and not a flux jump. Thus T in the two detectors is set at about 0.1 sec.

The detector curcuit is shown in Fig.3. The differential voltage measured is amplified and rectified. It is then compared to the threshold (S) and if it is greater than it a sawtooth generator is started whose voltage output is compared to a second threshold which represents T. If the output of the generator reaches T, K1 and K2 are opened. If the detected and rectified voltage remains larger than S for a time shorter than T, the sawtooth generator is reset to zero. If several flux jumps occur one after the other, the detectors may correlate them with a transition to the normal state and again open the switches K1 and K2 prematurely.

IV. Testing

The outer Nb-Ti magnet is energised first with a current of 240 A, (H/I = 0,0230 T/A) necessary to obtain the required field of 5.5 T at 4.2 K. Because of flux jumps, the rate at which the current is increased is limited to 5 A/min. The field of 5.5 cited above is the value along the axis, at the centre of the magnet. The critical field of the magnet working alone is slightly greater than this being 5.8 T (252 A) at 4.2 K. The Nb3-Sn magnet is then energised progressively. Flux jumps also occur frequently in this material and since it is only lightly stabilised, a flux jump may cause the magnet to quench for relatively small current densities. In practice, this happens for currents greater than 80 A corresponding to a total field of about 10 T. it is therefore necessary in order to obtain the required performance, to eliminate these flux jumps. This is easily done by increasing the current slowly. Our experiments show that the magnet quenches at 12 T when the rate of increase of the field is 15 G/sec. When dH/dt is 10 G/sec., the transition takes place between 13,2 - 13,6 T and when dH/dt is 7 G/sec., no transition is observed when the field is between 13,8 - 14 T.
At this point, the current in the Nb3-Sn magnet is 155 A. in order to limit the mechanical forces in the Nb3-Sn ribbon, this is the highest current which has been used at 4.2 K. However the field produced at 4.2 K is not necessarily the maximum of which the magnet is capable. In fact, tests have shown that the Nb-Ti magnet produces a field at 2K which is much larger than that obtained at 4.2 K. This is an intrinsic property of superconductors materials, but is often masked in the high current density materials employed in magnets, by instabilities in these materials. But, with a stabilised superconductive wire, such as those with a multistrand structure, the performance of a short specimen is greatly increased as is that of an actual magnet, when the working temperature is decreased from 4.2 to 2 K (We have recently built a magnet producing about 10 T at 2 K, using a wire made by IMI:61 filaments of 0,040 mm diameter).
The wires used in our 15 T magnet do not have a multistrand structure but they may be considered to be stabilised in view of the large quantity of copper incorporated in them. Although the flux jumps have a large amplitude, they do not lead to a quench. Thus it seemed preferable to try to increase the field produced by the outer magnet rather than to increase the current (155 A) at 4.2 K in the inner magnet. Tests of the Nb-Ti magnet showed an improvement in the performance at 2 K since the magnet was stable at 6.5 T whereas the critical field is about 7.2 T (as deduced from measurements made on a smaller magnet constructed from the same wire).
However at 2K, another problem arises because the liquid helium is in equilibrium with gas at a reduced pressure of 20 - 30 mm Hg. Hence when the protection circuits trigger, the gas may be ionised with dangerous consequences for the magnet. In spite of precautions taken to prevent this, ionisation of the gas was observed when the potential difference between each current terminal and the cryostat reached 400 - 500 V. But when a field greater than 14 T is produced at 2 K, the potential difference which appear when the magnet goes normal may be about 540 V. It is not safe, therefore, to operate the magnet at 2 K in helium in equilibrium with its vapour. A system has recently been described by Roubeau et al (3) which enables this normal behaviour to be modified. Using a simple device and the difference in thermal capacity between superfluid and normal helium, a normal helium bath whose surface can be in equilibrium with gaseous helium at pressure up to one or two atmospheres, may be created above the superfluid. This device should shortly be installed. Thus it is not yet possible to give a result for the field produced at 2 K.

V. Conclusion

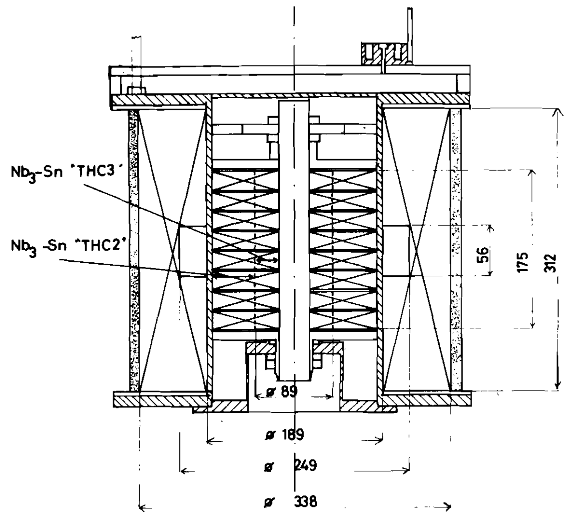
A hybrid Nb3Sn/NbTi magnet has been described. Measurements on it show that it can produce a field of 14 T at 4,2 K. A noticeable increase in the field produced by the outer magnet working at 2 K should give a better overall performance leading to fields of about 15 T. But, working at 2 K necessitates strict precautions against the ionisation of the helium. The calculations made regarding the protection of the magnet at the moment of thermal quenching have been confirmed by experiment and a large part (85%) of the stored magnetic energy may be transferred to external resistances when a quench does occur.

1. Etude et Réalisation d'un aimant supraconducteur 15 Tesla.
   Contrat DGRST 69-02-014.

2. P.F.SMITH, Rev.Sci.Instr. 34, 368 (1963).

3. M.N. BILTCLIFFE, P.E.HANLEY, J.B.McKINNON, and P.ROUBEAU
   Cryogenics, 44 (February 1972)

Fig 1



15 Tesla SUPERCONDUCTING MAGNET

External coil Nb - Ti — Inner coil Nb_3 - Sn

Self = 8,08 H — Self = 2,47 H

Mutual inductance 2,02 H

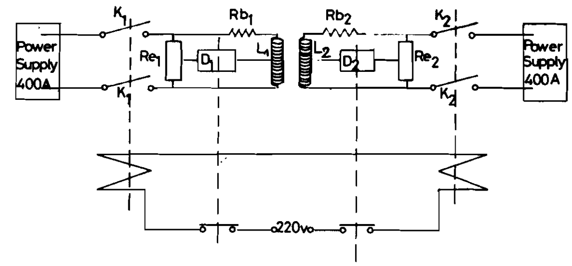


Fig 2

CIRCUIT DIAGRAM

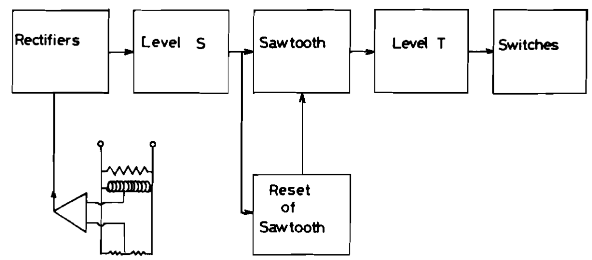


Fig 3

PROTECTION SYSTEM FOR THE COIL : BLOCK DIAGRAM