A 1 T, 0.33 M BORE SUPERCONDUCTING MAGNET OPERATING WITH CRYOCOOLERS AT 12 K

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Abstract-**The application of small cryocoolers for cooling a superconducting magnet at 12 K has important advantages especially for small and medium sized magnets. A simple construction and a helium free magnet system is obtained. The demonstration magnet developed is a six coil system with a volume of 75 L and can be regarded as a 1:3 scale MRI magnet. With a current of 100 A, a 1 T central field is generated with a maximum of 1.9 T in the windings. The magnet consists of six coil formers and five aluminium spacing rings, providing easy service and disassembly. The superconductor, a 0.6 mm diameter Nb_3Sn wire, is wound on the thin walled stainless steel coil formers after which the coil is heat treated and vacuum impregnated. Afterwards, the coil system is assembled and the electrical and thermal connections are made. This paper describes the development of the superconducting magnet.**

I. INTRODUCTION

A cooling system that is based on thermal conduction in solids solely has obvious advantages. Similar systems have been proposed e.g. in [1] one of the first descriptions and concepts of such a magnet system is published, in [2] and [3] magnets cooled by cryocoolers which were actually build and tested are described. In order to investigate the properties of these class of systems, and the requirements necessary to build them, we have developed a magnet system which has the qualities present in similar magnets. Investigations are carried out on the following subjects. A major demand is that the system can be built in a reliable way against acceptable costs. This has consequences for the primary production technology i.e. is the magnet wound first and then reacted, or is it preferable to do it in the opposite way. The lowest temperatures reached by "off the shelf" cryocoolers is 8 K so that the magnet has to operate at a temperature of at least a few kelvins higher in order to have a sufficiently current density margin. In this case our goal is 12 K.

Also important is the way in which the thermal connections between the cold heads and the magnet are made, especially the position of the cold heads in relation to the magnetic field generated by the magnet. The field in the vicinity of the driving motor of the cold head is 0.03 T. In [4] it is shown that this value is safe. Other items are conduction cooled current leads, a high accuracy winding technique and the electromagnetic stability of the Nb_3Sn conductor at 12 K. The magnet construction and lay out are described first.

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II. CONSTRUCTION OF THE MAGNET

Cryocoolers of moderate size, in comparison with the magnet dimensions, have cooling capabilities of a few watts at their second stage of the cold head. The dominating heat load at this temperature level is brought in by the current leads. For this reason the magnet current must be kept at a low value so that thinner leads can be used resulting in a lower heat load on the cold head. An optimized pair of copper leads, thermally anchored to the first (50 K) and second stage (10 K) of the cold head, has a heat load, at the 10 K stage, of 1 W per 100 A magnet current. A lower magnet current results also in a higher required number of turns and therefore in a higher inductance and a reduced current decay rate in the persistent mode. To meet the demands on wire handling, current carrying capacity and commercial availability a 0.6 mm diameter Modified Jelly Roll Nb_3Sn wire from Teledyne Wah Chang Albany (TWCA) will be applied in the magnet. Moreover a few coil sections will be built using a Nb_3Sn tape conductor in order to investigate the properties of this type of conductor in relation to MRI magnets too.

To minimize the risk of damaging the wire during the coil winding process, the choice has been made to wind first and to react afterwards. As a consequence the materials used in the construction must withstand the maximum reaction temperature of 1000 K.

An outline of the magnet system design is shown in fig. 1. The magnet is a six coil system optimized to have a field homogeneity of 10 ppm in a sphere with a diameter of 150 mm. The main characteristics of the coil system are collected in table 1. The coil formers are made of stainless steel 304 and are, after the reaction process, fitted with an aluminium 1100 strip on the outside. This strip is connected to 12 axial, radially distributed, alu 1100 strips which come together at both sides of the magnet on two heat collecting rings. One ring is thermally connected to the two cold heads successively with an alu 1100 prismatic bar and a flexible copper braid. The thermal interconnections are made by screwing the parts together with an indium layer in between.

The magnet itself consists of a stack of the six coils and five spacer cylinders held together with four tension rods. A modular system was designed because of the more flexible experimental possibilities and to prevent that one damaged coil makes the whole magnet unusable.

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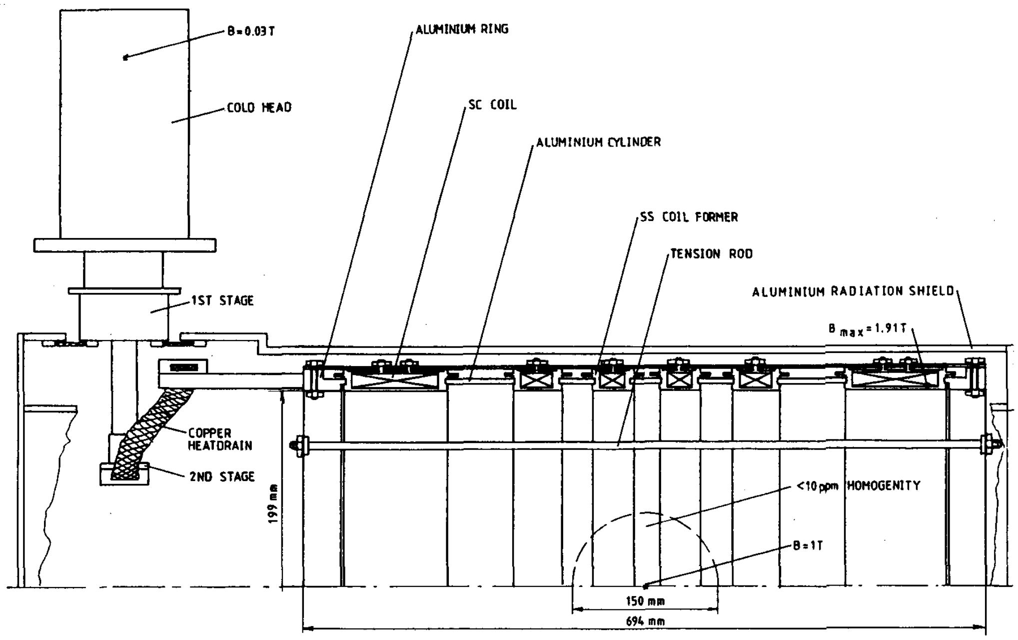

FIG. 1. Lay out of the magnet system.

TABLE 1
Main characteristics of the coil system

Type:	six coil MRI system
Bore:	400 mm
Length:	600 mm
Outer diameter	430 mm
Warm bore:	330 mm
Inductance:	10.72 H
Operating current:	100 A
Stored energy:	53.6 kJ
Nominal field:	1.00 T
Peak field:	1.91 T
Conductor type:	0.6 mm Nb_3Sn with 50-52% Cu
Conductor length:	9.25 km
Total number of turns:	7098
Cold mass:	61 kg

III. THE WINDING AND PRODUCTION PROCESS

Each of the six coils is separately made and then stacked together. The construction of one coil is shown in fig. 2, in this case one of the two mid coils. The stainless steel coil former is provided with a 0.25 mm thick boron nitride coating on the surfaces of the winding space. The boron nitride prevents the impregnated winding to stick to the coil former avoiding shear stresses in the interface winding/coil former. This is the floating coil concept. Shear stresses in these areas can cause premature quenches as is described in [5] and [6].

In order to practice the winding process a small test coil is made exactly according fig. 2 except for the winding diameter which was 40 mm in stead of 400 mm. At first we have tried to wind orthogonal cyclic but the tolerances on the wire diameter are too demanding to apply this winding process properly with a satisfying accuracy. The number of turns per layer varied from 25.6 to 28.2 while the deviation in layer thickness was ±0.25 mm. This is due to the fact that the wire is insulated with a relatively flexible glass braid so that it is practically impossible to get a regular winding package.

A good improvement appears to be when between each layer a 25 μm thin copper foil is placed. The number of turns per layer is for all the layers 32.0 windings while the layer thickness has an accuracy within 0.05 mm. This copper foil also improves the heat conductivity in the winding package. Each wire cross section has a position right above a wire from the previous layer while the former process has a triangle shaped winding structure. In the orthogonal cyclic process the filling factor of the coil former is 0.82. The latter process has a filling factor of 0.68. These factors include the wire insulation.

When the winding is completed the ends of the conductor are fastened to the copper terminals on both sides of the coil former and the prescribed heat treatment is carried out. When this is finished an

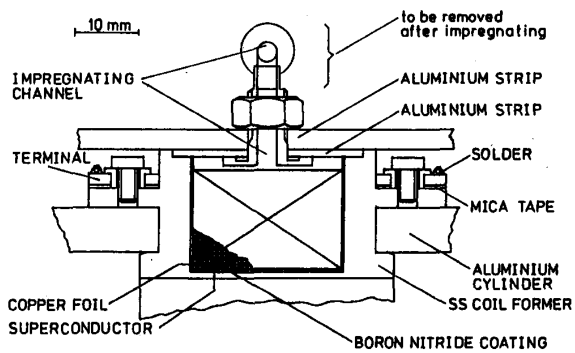

Fig. 2. Construction of one coil section.

alumininium strip is fitted on the outside of the coil. This strip contains twelve small hollow threaded bars which are on the outside connected with each other with tubes. Through these tubes and bars the epoxy resin flows during the vacuum impregnating process.

The epoxy resin used is a combination of the CIBA resin harder and accelerator: MY 740, HY 906 and DY 062. This system has at the processing temperature of 55°C a pot life of six hours. After the resin has been cured the bars on the aluminium outside cover are stripped from their top, with this removing the epoxy filling channels. The threaded pins are still at their positions and are being used as connection taps for the twelve aluminium heat drain strips.

IV. A MODEL COIL

Before starting to wind the 400 mm diameter coils a smaller coil is wound, heat treated and vacuum impregnated. The heat drain construction is the same as that which shall be applied in the magnet depicted in fig. 1. The test coil has the same structure as the coils to be build, except for the boron nitride coating which is not present in this case and the electrical connection to the current leads. The way in which the coil is fitted in the cryostat is shown in fig. 3 and 4. The cryostat is the same one as that will be used for the 400 mm coils. The test coil is cooled by means of two cryocoolers. In fig. 4 the copper braids which are connecting the cold heads to the radiation shield and the test coil are clearly visible. After cooling down a temperature distribution settled which is shown in fig 3. The test coil has reached its equilibrium temperature within four hours while the shield, with a weight of 40 kg, is at its end temperature in 36 hours. The dimensions and other data of the test coil are collected in table 2.

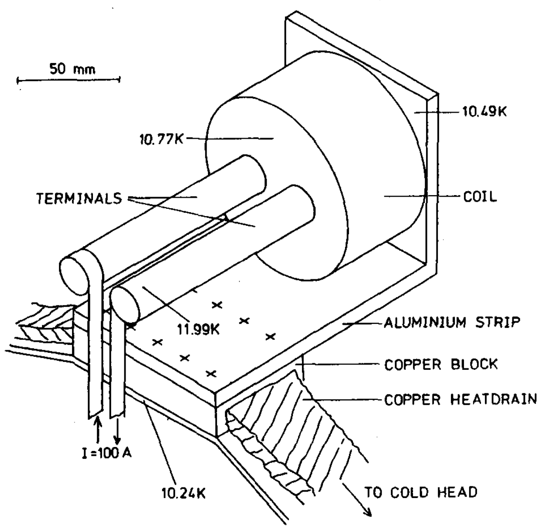

Fig. 3. Lay out and heat drains of the test coil. The temperatures are within ±0.05 K accurate

TABLE 2
Test coil data.

Inner diameter:	40.0 mm
Outer diameter:	70.8 mm
Length:	24.3 mm
Wire diameter:	0.6 mm
Filaments:	≅1530
Matrix:	50-52% copper
Insulation:	glass braid
Process:	Wind & React
Supplier:	TWCA
Number of turns:	627
Max.-field constant:	17.9 mT/A
Cold mass:	4 kg

V. RESULTS

The test coil was first mounted in a LHe cryostat in the bore of a 16 T magnet. The quench current is measured as a function of the magnetic field. The results are shown in fig. 5. The field is the maximum field in the windings including the field generated by the test coil itself. There are ten training quenches necessary before the specified current is reached. These training quenches are numbered 1 to 11 in fig. 5. The specification from the wire supplier is marked with a plus sign. This is the point where Ic=250 A and B=9 T. At fields below 7 T the coil suffered from premature quenches. The origin of these quenches is not exactly known. It is possibly a stability problem. When the theory of Wilson [7] about flux jump stability is applied to the test coil indeed a stability boundary at 7 T and 4.2 K is found. Measurements, covering the field range from 0 T to 16 T at 4.2 K on a short sample, showed however no instabilities. These measurements are not treated in this paper.

The quench current measurements were continued by installing the test coil into the cryocooler cryostat according to fig. 3 and fig. 4. In this case there is no external field present. A heater is fitted at the position where the aluminium strip is connected to the copper block as in fig. 3. In this way temperatures covering the range from 11 K to 17.5 K can be established.

The quench current as a function of the temperature is shown in fig. 6. The maximum magnetic field is proportional to the current and is also indicated in fig. 6. In the coil a maximum temperature gradient is

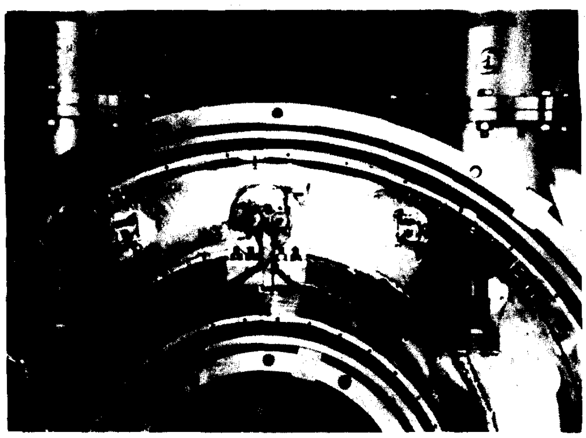

Fig. 4. Test coil assembly in the cryostat.

present of 0.3 K. The leads are at a higher temperature level due to minor effective heat drains. No instabilities were measured in this case. The quenches can also start in the leads where the temperature is higher while the field is smaller than in the coil. Or they can be originated in the coil where the situation is the opposite.

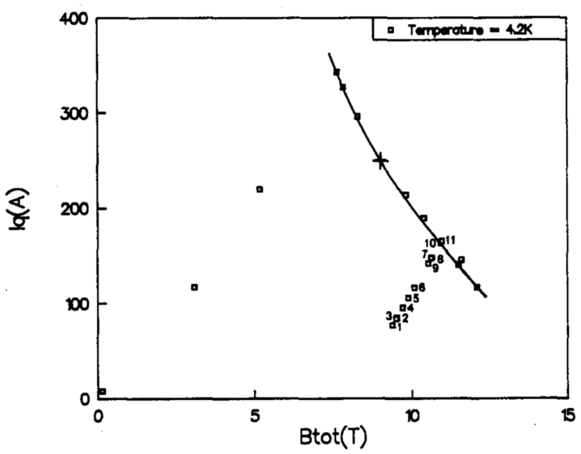

Fig. 5. Quench currents of the test coil versus the peak field in the coil at 4.2 K.

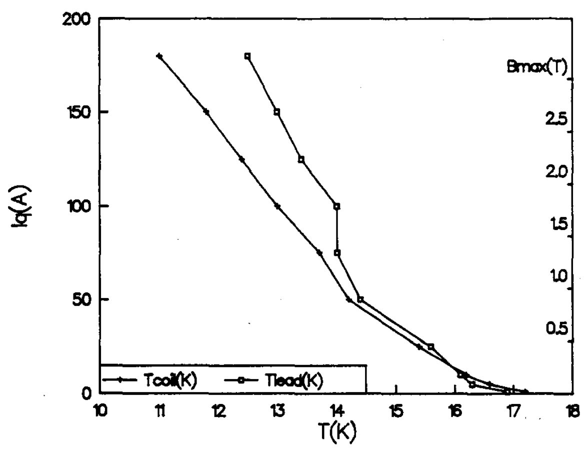

Fig. 6. Quench currents of the test coil versus the coil- and lead temperature without external field.

VI. CONCLUSIONS

A demonstration model magnet is developed in order to investigate the possibilities of building conduction cooled magnets which are medium sized and operate at a temperature of 12 K. On the basis of a smaller test coil it is shown that the production process following the steps winding, heat treatment, vacuum impregnating and after that making the thermal and electrical connections, yields a magnet which satisfy the specifications. The winding of the magnet can be performed in an accurate and predictable way when between the layers a 25 μm thin copper foil is wound.

At 4.2 K instabilities occur below fields of 7 T. The origin of this is not yet clear.

At the operating temperatures of the demonstration magnet of 12 K the test coil reached after a few training quenches its nominal current.

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