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DESIGN AND TESTING OF A DUAL 8-T 380-mm/12-T 220-mm SPLIT SUPERCONDUCTING SOLENOID FOR ORNL*

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MASTER

Abstract. A superconducting high field magnet facility has recently been prepared for operation at the Oak Ridge National Laboratory (ORNL). The facility consists of a background NbTi coil and an insert coil made of Nb_3Sn tape. The background coil produces an 8-T central field, with a peak field of 8.8 T, in a bore of 380 mm and contains radial access ports of 67-mm diam. The insert in conjunction with the background coil produces a central field of 12 T, with a peak field of 13.5 T, and provides radial access ports of 67-mm diam. Details of magnet design both for the background coil and insert coil will be presented. The protection scheme will be discussed and test results will be given.

INTRODUCTION

With the anticipated application of superconductivity in large machines for fusion,[1] magnetohydrodynamic (MHD), and like devices, existing short sample testing facilities are simply not adequate for the job. The conductors may be rated at 10,000 - 30,000 A in a magnetic field of 8 T or even 12 T. In addition, one would like to test more than just short sample critical current. Some measure of the stability margin should be obtained on a full-scale conductor at the rated field prior to building an expensive device.

To meet these needs, we at the Oak Ridge National Laboratory (ORNL) have assembled a test facility using a conductor originally purchased for another experiment and wound into an 8-T coil that was built to demonstrate several aspects of coil winding. An insert coil was purchased in industry to provide 12 T in conjunction with the ORNL 8-T coil. The system may be operated either vertically for testing helical coils or horizontally to accommodate short straight samples of conductor. Together with the 30,000-A supply and refrigerator at ORNL, this system will provide a great deal of information on short samples of full-size conductors.

Details of the design, construction, and preliminary tests comprise the balance of this paper.

BACKGROUND COIL

General

The background coil was designed to be used alone as an 8-T facility as well as to provide a significant portion of the ampere turns for the 12-T operation. Magnet parameters are summarized in Table I.

Table I. Background coil parameters

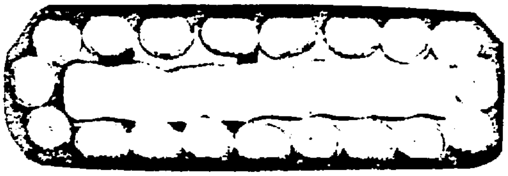
Bore	380 mm
Central field	8.0 T
Peak field	8.8 T
Peak field in bore	8.6 T
Radial access ports	67-mm diam
Outside diameter	1.0 m
Overall length	0.8 m
Conductor	10.0 mm by 3.0 mm compacted cable
Operating current	2150 A
Number of turns	2850
Stored energy	6 MJ
Average current density	5100 A/cm^2
Total weight	2000 kG

Coil Design

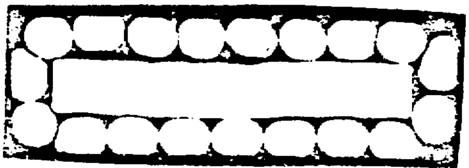
The magnet consists of two essentially identical coils; each winding has a 404-mm inside diameter, a 808-mm outside diameter, and a length of 299 mm. The windings are spaced 89 mm apart to allow for the 67-mm radial ports. This coil arrangement leads to a central field of 8.0 T at a uniform current density of 51 A/mm^2 over the winding space. Peak field in the winding for this condition is 8.8 T.

Conductor

The conductor was produced by Intermagnetics General Corporation (IGC) and is in two grades. The low field grade comprises the bulk of the conductor and was originally produced for the Large Coil System (LCS) experiment.[2] The high field grade was purchased separately for this coil. The short sample ratings are 1800 A at 8 T for the low field materials and 2550 A at 9 T for the high field conductor. Both conductors are made by cabling strands of NbTi/Cu composite wire around a rectangular core along with extra copper strands, which provide more stability. Figure 1 shows a cross section of both conductor grades.



HIGH FIELD CONDUCTOR



LOW FIELD CONDUCTOR

Fig. 1. Cross section of low and high field conductors in 8 T background coil.

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Winding Technique

Layer-cake Design. In order to avoid the need to bring our lead through the flange in a layer winding and to avoid the many joints required in a pancake winding, the two techniques were combined in what we call the layer-cake winding. Essentially, it is a layer winding with a single pancake at the low field end to bring both conductor leads to the outside of the coil. This winding operation is illustrated in Fig. 2.

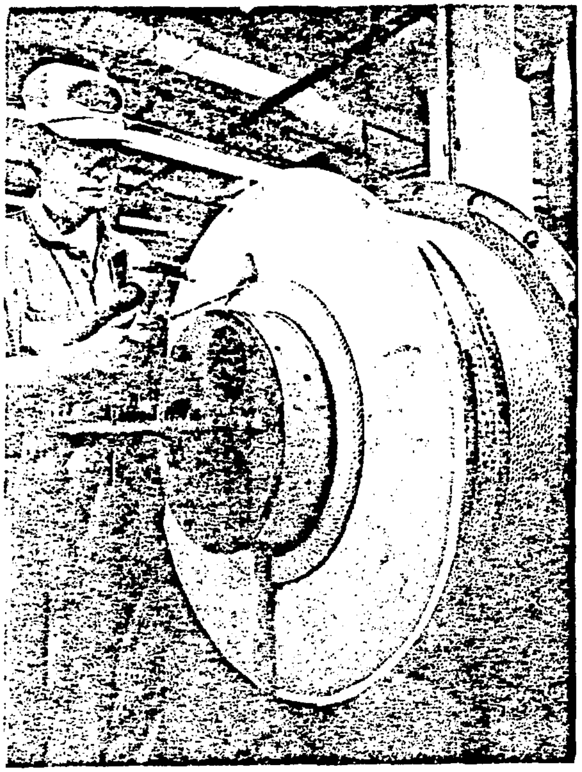

Fig. 2. The "layer cake" winding configuration used in 8 T background coil.

Grading and Splices. Two conductor grades were used with a grading splice occurring in the 11th layer in the layer part of the winding and in the 9th turn of the pancake section. The splices were made by peeling back the cabled outer conductors and forming a soldered joint in the copper cores. Figure 3 shows the joint in preparation. After the cores were soldered, the superconducting strands were soldered back to the cores. However, instead of cabling around the core, they were simply laid straight along the core. The strands alternated from the high and low field sections so that current transfer could occur along the entire length of the joint between adjacent strands. The copper strands from the low field section were cut off and discarded. Then, the eight composite strands from the low field conductor and eleven strands from the high field section were interleaved in the joint. Tests showed a joint resistance less than 10^{-8} ohms in a 7 T field and a higher mechanical strength than the parent material.

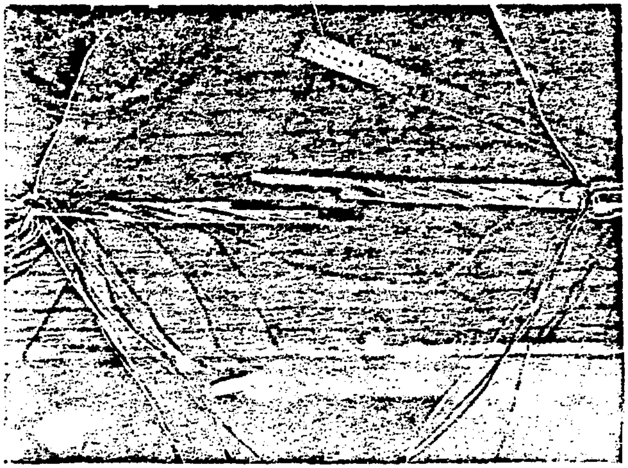

Fig. 3. Splicing joint used in 8 T background coil.

Assembly

The coils were wound on stainless steel bobbins with only one end flange, which faced toward the center of the magnet. The central spacer was made of thick aluminum into which the 67-mm ports were machined. End flanges of 50-mm-thick aluminum plates were placed on the outside ends, and the entire unit was assembled with 20 aluminum tie rods. Figure 4 shows the final coil as assembled. The heavy aluminum end flanges are not attached to the bobbin so that upon cooldown thermal contraction of the tie rods will tighten the winding as it pulls the end flanges together.

Fig. 4. 8 T background coil fully assembled.

Protection and Power Supply

A protective resistor of 0.25 ohms was connected directly across the coil. In the event of a quench, a series circuit breaker disconnects the power supply, discharging the magnet through the resistor at a terminal voltage of just over 500 V.

The electrical system consists of a 3000-A, 10-V SCR type power supply with a protective diode across the output terminals, a series dropping resistor rated at 5 V and 2200 A to allow faster field decrease, a series circuit breaker, and the parallel combination of magnet and protective shunt. The power supply is operated in a voltage controlled mode. This mode is more stable than current control for this type of supply although it requires continual adjustment to maintain a constant ramp rate.

Test Results

The first successful test of the background coil was performed in September 1980. Two previous tests were curtailed before attempting to energize the magnet because of difficulties with the cryogenic system. At a current of 2150 A, a magnetic field of 8.6 T was measured just inside the bore corresponding to a central field of 8.0 T.

The coil showed no evidence of training or instability during the test and was not quenched. It was repeatedly dumped to test the protective circuitry up to about one-half the full field. At the highest field the breaker seemed to have more arcing than expected. Circuitry to reduce this arcing has been designed and will be evaluated on the next test.

INSERT COIL

General

The characteristics of the 4-T IGC insert magnet are given in Table II. The magnet is constructed in the modular fashion typical of high field IGC Nb_3Sn tape-wound magnets.[3] For a central field of 12 T in the combined magnet system, the peak field at the windings of the insert magnet is 13.5 T. This is well within the field range of application for the Nb_3Sn tape in high field solenoids.[4] The peak stress in the windings is 220 MPa. High strength windings are readily fabricated by co-winding stainless steel with the superconducting tape. The individual pancakes, or disks, of the windings are separated by insulating spacers containing cooling channels. The winding depth of the insert is 56 mm. Tape insert magnets usually exhibit stable operation and relatively fast ramp capability, probably as the result of adequate helium bubble clearance from the short cooling channels in addition to the stabilizing effect of the outer magnet field.

The bore diameter of the insert is 211 mm. The insert magnet is constructed as two nominally identical coils, each with its own mechanical structure and electrical terminals. A radial access port of 67-mm diameter is formed by easily removed midplane spacers, making the insert magnet a variable gap split.[5]

Stored Energy

The incremental field is achieved at a current of 149 A. The stored energy in the insert magnet alone is a modest 0.21 MJ. The mutual energy in Table II includes the mutual energy associated with both the inner and outer magnets. With the stored energy of the outer magnet the total system stored energy is 7.5 MJ.

Table II. Insert magnet characteristics

Clear bore	211 mm
Outside diameter	376 mm
Length	489 mm
Clear radial split	67 mm
Incremental field	4.0 T
Total central field	12.0 T
Maximum field-on-windings	13.5 T
Current	
Inductance	149.0 A
Self	19.1 H
Mutual	3.1 H
Energy	
Self	0.21 MJ
Current Density	8940 A/cm^2

Protection

High field IGC Nb_3Sn tape magnets are typically made self-protecting through the use of resistive shunts across subdivisions of the windings. The protection of an insert magnet powered separately from the outer magnet must include the possibility of inductive energy transfer in the case of quench or discharge of the outer magnet. In the present case, heaters have been provided to initiate a quench of the inner magnet in the event of a quench of the outer magnet. The relatively short time constant of the inner magnet ($\sim$2 s) compared with that of the outer magnet ($\sim$10 s) assures the lack of energy transfer.

Stability and Test Results

The insert magnet was designed to be stable in the background field of the outer magnet. Initial stand-alone tests of the inner magnet have been performed to check continuity of the windings, joint resistance, and operation of the protection system. In these initial tests, the maximum current was limited to approximately 148 A by magnetic instability in the end modules. Figure 5 shows the 12-T insert after winding and prior to the application of its protective cover.

SYSTEM ASSEMBLY

To test the system in 12-T operation it is necessary that the two magnets be firmly coupled mechanically. A calculation shows that if the insert quenches in such a way that current is diverted into the protective shunts starting at one end of the insert extremely large decentering forces, as high as 220 kN (50,000 lb), could exist. It is not advisable to attempt to contain these forces by means of support from the top flange because of buckling possibilities and because of the additional heat leak involved in such a large structure. Consequently, we arranged the two magnets such that they could be locked together through the winding structure. The insert was fitted with a flange to mate with the top of the winding bobbin of the background coil and a set of cams mating with the lower edge of the bobbin. The cams can be actuated from outside the dewar so the insert coil can be inserted or removed while the background coil remains cold. Figure 6 shows the two coils as they were being prepared for final tests.

CONCLUSION

With the final testing of the system up to 12 T, we will have demonstrated an extremely versatile system for evaluating large superconductors. This

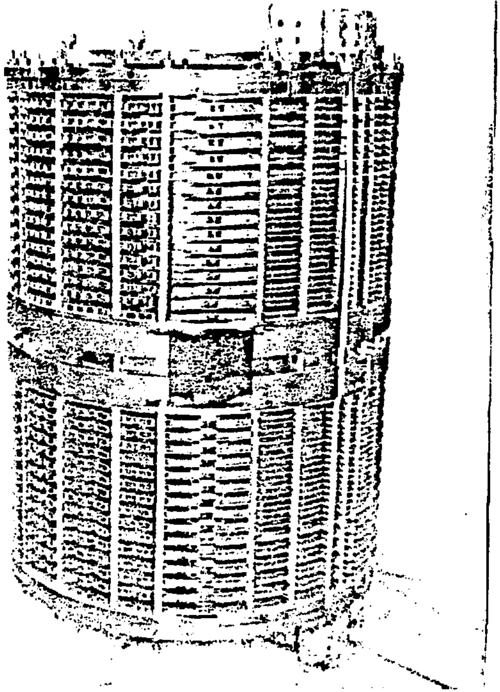

Fig. 5. The 12 T insert coil prior to the application of its protective cover.

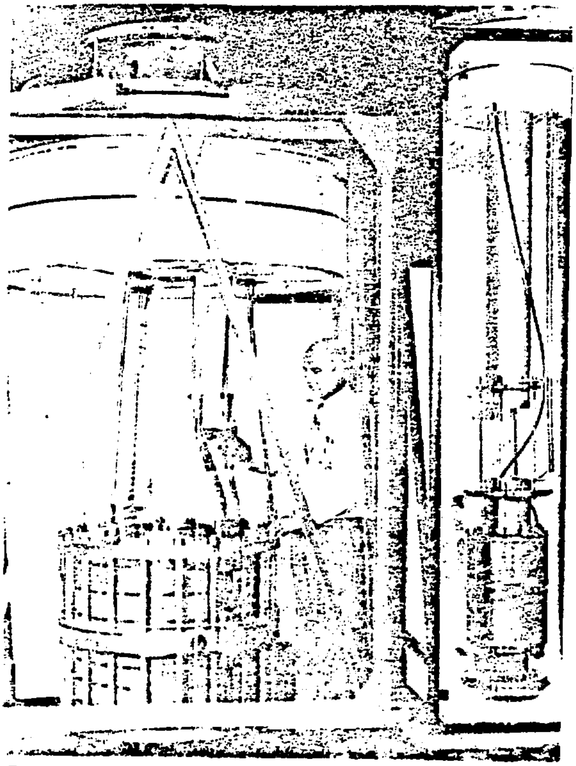

Fig. 6. Insert and background magnet ready for final testing.

test is scheduled for the immediate future (having been delayed somewhat by the pressure of other activities at ORNL). The successful testing of the individual components gives us a high degree of confidence in the ultimate success of the system.

The system will accommodate helical coils of 380-mm outside diameter at 8.6 T and 210-mm outside diameter at about 12.5 T when used in vertical orientation. With horizontal mounting, a high field region of nearly 500 mm is available at 8 T and of 250 mm at 12 T for short straight sample tests. For measuring the stability margin, heaters may be installed and the effect of adjacent turns modeled with dummy conductor within the 67-mm access port.

ACKNOWLEDGMENTS

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