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Argonne National Laboratory

A LARGE, HIGH-FIELD, SUPERCONDUCTING MAGNET SYSTEM

by

C. Laverick and G. M. Lobell

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Central Shops

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	4
INTRODUCTION	4
CABLE TYPES	5
MAGNET DESCRIPTION	6
OUTSIDE COILS	8
Intermediate Coil	8
Inside Coil	9
DESIGN CRITERIA	9
TESTS OF 18-in. SYSTEM	10
TEST OF COMPLETE SYSTEM	11
FUTURE PLANS	13
CONCLUSIONS	14
ACKNOWLEDGMENT	14
REFERENCES	15

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Cable Types Used in Magnet.	5
2.	Schematic Diagram of Nested Magnet System	6
3.	Completed Magnet Showing Nested Coils.	7
4.	Component Parts of the Magnet System	7
5.	Individual Coil Voltages during a Transition to the Normal State	13

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Details of Magnet Performance.	6
II.	Test Summary.	12

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ABSTRACT

A superconducting magnet system composed of three separate, easily removable, nested solenoids is described. The outer two solenoids are split-coil systems so that particle beams can be directed through the magnet when these sections are used to provide the magnetic field for a helium bubble chamber. Magnetic fields of 67, 42, and 17 kG have been achieved in winding diameters of 7, 11, and 18 in., respectively. The results indicate that the system is capable of operation at fields in excess of 70 kG.

The magnet is wound from various types of superconducting cable. Some of the considerations governing the choice of cable types and magnet design are presented.

The tests carried out on the magnet system are described, and the test results are discussed.

INTRODUCTION

The outer sections of the present superconducting magnet system were designed and constructed for use with a 10-in.-ID helium bubble chamber.⁽¹⁾ The magnet has been operated with a central magnetic field of 67 kG in a winding diameter of 7 in., and higher field strengths can be attained. No damage was observed after eight transitions to the normal state had occurred.

The system was subsequently operated to transition in helium vapor at 32 kG without damage. This transition was induced by deliberately increasing the charge rate. A more recent experiment in this laboratory with a smaller coil of this type demonstrated that when the coil was operated in vapor the transition current was only 3% less than when the coil was operated in liquid helium.

Five different types of superconducting cable were used in the coils so that maximum information could be obtained from one test.

CABLE TYPES

Many different cable configurations are possible.⁽²⁾ In the past year, we have concentrated upon stranded conductors and have experimented with several configurations in more than 30 different solenoids. Multiple stranding provides several parallel superconducting paths. This reduces the probability of a large reduction in current-carrying capacity due to faults in any one length of wire. The number of superconducting joints in a large system can be reduced considerably, or even eliminated, when cable is used. The cables carry considerably higher currents than the individual strands, and fewer turns are required for any given coil. These properties lead to a considerable reduction in winding time for a given coil, while the enhanced mechanical strength results in greater ease in handling. The inductances of large, multiple-strand coils can be made low.

Separately insulated, 0.010-in.-OD, copper-coated, superconducting strands with 0.00075 in. of copper in the radial thickness have been used in the construction of most superconducting coils. The thickness of the insulating coating has usually been 0.001 in. In the cable types chosen, copper coatings of 0.0015- and 0.002-in. thickness have been used so that each superconducting strand has enhanced electrical stability.⁽³⁾ The conductors are then stranded together without electrical insulation between individual strands, so that the copper coatings are interconnected. Indium impregna-

tion interconnects the copper coatings and prevents their deterioration through oxidation. Partial nylon insulation of 0.002-in. thickness is stranded around the completed cable. Higher current-carrying capacity can be obtained by using greater thicknesses of copper, and this copper can be stranded around the finished cable and impregnated with indium to provide a better electrical connection to the cable.

137-1210

Fig. 1. Cable Types Used in Magnet

The cable types used in the present magnet are shown in Fig. 1. Their locations in the system are shown in Fig. 2. The maximum current-carrying capacities obtained for each cable during the operation of the magnet, and the corresponding average current densities in each winding, are listed in Table I. The currents obtained compare favorably with those obtained for small- or medium-sized superconducting

magnets at the same magnetic fields. The cable types chosen have provided a good thermal environment for the superconductor and have enhanced the electrical stability of the superconductor.^(2,3)

137-1211

Fig. 2. Schematic Diagram of Nested Magnet System

Table I
DETAILS OF MAGNET PERFORMANCE

Winding Designation	Winding ID, in.	Winding OD, in.	Winding Length, in.	No. of Turns, N	Field Constant, Gauss / Amp	Max. Current, Amp	Packing Factor λ , %	Average Current Density, Amp/cm ²
Inside (7-in.-ID)	7.175	10.675	10.875	6225	216	119	15.4	6037
Inner (11-in.-ID) Intermediate	11.08	15.62	4.875	1363	76	283	13.5	5404
Outer (15-in.-ID) Intermediate	15.77	17.44	4.875	1800	88	134	24.26	9188
Outside (18-in.-ID) Uncoated	18	24.125	4.6	1952	40	211	7.6	4532
Outside (18-in.-ID) Coated	18	24.5	4.625	1846	38	245	7.0	4851

MAGNET DESCRIPTION

A schematic diagram of the assembly is presented in Fig. 2, and the assembled magnet is shown in Fig. 3. The top clamping plate is removed in Fig. 3 to show the spaces that permit liquid helium to flow into the magnet through the holes in flanges. The lengths of the cables that form the power joints can be seen as they are led to the outside of the magnet from the various coils. These joints are approximately 20 ft long and are wound around the windings of the outside coils after sufficient insulation has been applied.

210-990

Fig. 3. Completed Magnet Showing Nested Coils

The component parts of the magnet system are shown in Fig. 4. A small $\dot{B}$ coil (smallest coil) is shown, in addition to the component coils, and this is mounted at the center of the system. The lengths of lead which form the power connections can be seen with each coil.

210-980

Fig. 4. Component Parts of the Magnet System

The interlayer mesh (see Fig. 2) allows helium to permeate the coils and provides automatic interlayer shunting when transition to the normal state occurs. Holes in the stainless-steel flanges and slots in the inside flange insulation permit the liquid helium to flow into the coils. This type of construction allows rapid cooling since temperature equilibrium is rapidly established throughout the coils when it is plunged into liquid nitrogen.

Outside Coils

The interlayer mesh for the outside coils (see Fig. 2) consists of one layer of 0.013-in., No. 30, stainless steel wound around one layer of 0.069-in., No. 6, stainless steel.

A winding tension of 50 lb was used. The cable acts as its own support structure when the magnetic loads are applied. The coils were wound at packing factors of 7.6 and 7.0%, respectively (see Table I).

The two outside coils were tested as a separate assembly. The incomplete outside layers were displaced axially 2 in. by the action of the magnetic forces during the test. This demonstrates the stability achieved by the use of the extra copper coating, since no deterioration in electrical performance occurred when this movement took place. Coils wound from superconductors with thin copper coatings around them and even short lengths of some superconducting wire tend to operate at prematurely low currents if movement occurs.^(3,4)

Intermediate Coil

The intermediate coil contains two windings (Fig. 2). The cable of the inner, 11-in.-ID, winding contains 14 HI-120 superconducting strands. HI-120 is a niobium-titanium wire manufactured by Westinghouse. The shape of this conductor (see Fig. 1) makes it ideal for use where high loads are anticipated. The large number of strands ensures a current-carrying capacity equal to that of the outer coils in high magnetic fields. The winding had a packing factor of 13.5%.

Wire from Supercon, a division of National Research Corporation, was used in the outer 15-in.-ID Nb-25% Zr winding. Two separate pieces of cable were joined, using a 20-ft lap with indium impregnation and copper coating to form one length of cable. Each piece contained two broken superconducting strands and a damaged length of about 100 ft with only six conductors. The damaged regions were repaired by use of extra lengths of superconducting cable and by the technique employed for making the cable containing 14 HI-120 strands. This winding was wound with a packing factor of 24%.

Inside Coil

The cable on the inside coil contained six HI-120 strands and was wound as a single length on a titanium form. Three separate lengths of cable were used and were joined together using a 20-ft lap and the same technique as described in the paragraph directly above. The interlayer insulation consisted of 0.013-in.-thick stainless-steel mesh and 0.002-in.-thick Mylar. Details of construction can be seen in Figs. 1, 2, 3, and 4. The packing factor was 15%.

DESIGN CRITERIA

Four concentric windings were used in this design, with the inside and outside windings on separate forms. The variation in current-carrying capacity of the superconducting wire with magnetic field can be better utilized by operating each layer at different currents. The original plan had been to use only unbroken lengths of cable so that persistent-current switches could be used and no superconducting joints would be present. Accidental breakages in manufacture eliminated this possibility. Cable-splicing techniques were used as a result of experiments in this laboratory to obviate the need for making many superconducting joints outside the coil system and to permit the use of joints that could be wound directly into the coil. This simplified the construction problems.

An attempt has been made in the design to provide good cooling by permitting the liquid helium to penetrate the windings. A high degree of mechanical stability has been achieved by winding at high tension. The use of a large amount of copper coating around the superconductor, where possible, limits the rate of propagation of the superconducting to normal transition region and can, if adequate, prevent the propagation of a normal region.^(2,3) This can be seen from the results reported here.

The use of stainless-steel mesh as layer-to-layer insulation, together with the partial nylon wrap on the cables, provides automatic shunting when superconducting-to-normal transitions occur, and eliminates the need for elaborate protection schemes. The magnet design criteria have been discussed in more detail elsewhere.⁽²⁾ Compressive loads in excess of 100 tons are exerted axially on the inside flanges of the split-coil system. These loads are transmitted through the windings so that space-consuming support structure is eliminated. The outside of each coil was wound with Mylar binding tape and nichrome wire to prevent movement of the outside layers.

Operating costs for superconducting magnets can be made low. The cost of testing large magnet systems can be high if superconducting-to-normal transitions occur and cause the energy of the magnetic field to be

liberated in the liquid helium. In the present system, more than 300 liters of liquid helium can be evaporated when a transition occurs. Magnets can be fabricated in which normal regions can be induced and removed without any large dissipation of energy, merely by reducing the coil current slowly until the normally conducting region disappears. The outside section of the present system acts in this way. This is due to the combination of good cooling and a sufficient thickness of copper. The inner layers of the present magnet system would have to be wound with lower packing for the system to be completely stable. It was believed that the gain in current would not compensate for the loss in packing factor in a magnet of this size, so that there would be an overall loss in the attainable magnetic field. The present magnet dimensions are fixed because of its intended use with an existing bubble chamber and because of the size and shape of the magnet enclosure. Designs providing more space for the magnet would permit this construction technique to be used, even in a magnet of the same bore.

TESTS OF 18-in. SYSTEM

A preliminary test of the 18-in.-ID coil system was carried out. The windings in one coil were accidentally damaged before the test when a drill chuck penetrated a cooling hole in one flange. The end turns of four consecutive layers were damaged in this region, and some superconducting strands were broken. An attempt was made to repair the damage without unwinding the coil, and the coil was operated in this condition during the test series.

The first transition occurred with the two coils in series at 211 Amp. The central field was 17 kG, and the maximum field at the wire was 25 kG. No propagation of the transition region occurred. No change in series current or rate of change of the central magnetic field was observed. The presence of the normal region was detected by monitoring the charging voltage across each coil. When the normal region developed, the charging voltage across the damaged coil doubled, while that across the undamaged coil decreased to zero. The charging voltage across the two-coil system during this test was 74 mV. The normal region was removed by reducing the series coil current until the indicated charging voltage across each coil was zero. The series current could then be raised to a slightly lower current than previously for continuous operation of the system in the superconducting state.

In later tests, self-propagation of the transition region did occur in the undamaged coil when the coils were operated with a series current of 175 Amp and an additional current of 70 Amp through the undamaged coil alone.

In a third test, the transition occurred for a series current of 198 Amp and an additional current of 44 Amp in the undamaged coil alone.

Higher operating currents may have been possible at lower charging voltages. This test showed that the coils could be operated at maximum currents of 211 and 245 Amp, respectively, for a central magnetic field of approximately 17 kG and a maximum field of 25 kG at the wire.

TEST OF COMPLETE SYSTEM

The main consideration in the test was to obtain the maximum amount of information for the expenditure of a fixed amount of helium, rather than to operate the system until maximum field had been attained and optimum operating conditions had been determined precisely for each coil. Operation of the system was made more difficult because the power supplies available for the test did not permit individual operation of each coil.

The system was operated continuously for 4 days and was charged in times of 6 to 12 hr to avoid premature transitions and consequent loss of liquid helium. Sufficient warning of a transition could be obtained so that a Visicorder could be used to monitor the charging voltages across the individual coils and could be switched to high-speed recording when a transition occurred. This method of operation was found to be simpler and more convenient than using a multichannel tape-recorder system, which is necessary when no warning of an impending transition is given.

The central magnetic field in the system was monitored continuously in three different ways. The measured results were compared with the calculated central magnetic field obtained using the measured value of coil current, the number of turns on the coil, and the coil dimensions. The measured and calculated magnetic fields were in good agreement with each other. The measurement techniques involved continuous integration of the output of a $\bar{B}$ coil at the center of the system, continuous measurement and digital display of the output voltage from a Hall probe, and occasional measurement of the central magnetic field with a pull coil and flux meter.

A test of the complete system was carried out without repairing the damaged 18-in. coil. The outer windings of the 18-in. coils had been displaced during the previous test, so they were bound tightly with Mylar stretch tape and nichrome wire to hold them in position and insulate them, before the joints from the inner coils were wound around them.

A different electrical circuit was used for each charging of the system to a transition. The reason for this was to attempt to ascertain the appropriate current-carrying capacity of each winding with reasonable currents in each of the other windings. The test summary (Table II) gives details of the currents in each winding and the corresponding central magnetic field for each transition in liquid helium. In almost every case in which a transition occurred during this test sequence, the charge rate in the coil that

initiated the discharge had been increased immediately before the transition. More experience with the system is necessary to attain the highest operating current in each winding and the maximum central field.

Table II
TEST SUMMARY

Test No.	Central Field, kG	Separate Winding Currents, Amp				Reason for Transition	Object of Test
		7-in.-ID	11-in.-ID	15-in.-ID	18-in.-ID		
1	58	100	241	100	193	Charge rate on 11-in. winding increased too quickly	General check of system and of technique for charging with inadequate power supplies
2	31	Not energized	134	134	134	15-in. winding driven to transition	Check for operating range of 15-in. winding
3	42	Not energized	284	92	154	11-in. winding driven to transition	Check for operating range of 11-in. winding
4	40	Not energized	205	119	179	Increased charge rate in 11-in. winding	Attempt to set windings at reasonable operating currents
5	67	119	256	97.5	198.5	Changed to high charge rate in 7-in. winding	Check for operating range of 7-in. winding at high field

NOTE: A number of less significant tests are not reported. The system was finally operated twice to transition in helium vapor at magnetic fields of 30 and 32.8 kG, but the transitions were deliberately induced by increasing the charge rate.

When the complete system is energized, the magnetic field at the inside windings of the 18-in.-ID coils is less than when this coil is energized alone. A logical next step in the test sequence would have been to determine the operating limit for the outside coils with the whole system operating at high field before operating the system at the maximum field possible in each bore. The test was discontinued because the extra information was not sufficient to justify the additional expenditure of liquid helium.

The test results (Table II) indicate that with greater operational experience, higher magnetic fields should be attainable. An additional magnetic field should be generated when the damaged outside coil is repaired.

The method of determining which winding has initiated a transition was based on examination of the Visicorder record. An example is shown in Fig. 5, in which a portion of the Visicorder record for the 67-kG transition is shown. The duration of the disturbance is also recorded. The voltages across the coil during the transition were of the order of 10 to 15 V. The record is complicated by the fact that most of the coils are connected in series (Table II, Test 5). The resulting coil voltages are the result of this combination of series electrical connection and inductive interaction.

137-1209

Fig. 5. Individual Coil Voltages during a Transition to the Normal State

Approximately 30 sec before the zero time marker of Fig. 5, a partial transition occurred in the 11-in. winding, but the system recovered. The sudden changes in all coil voltages led the operator to assume that the disturbance had occurred in the 7-in. winding, since this was the coil current being increased at that time. The initial portion of the trace for the 7-in. winding in Fig. 5 shows a reduction in coil charge voltage which was due to reducing the charge voltage quickly to zero to compensate for the previous disturbance. At this time, the disturbance had clearly been balanced out. This sudden change caused a transition in the 7-in. winding, which began to discharge; approximately one second later, the 11-in. winding began to discharge. This induced voltages of opposite polarity in the other coils, which then began to discharge because they were connected in series electrically with the 11-in. winding in which the transition was causing the current to decrease.

FUTURE PLANS

The present magnet was designed as an experimental high-field magnet to obtain design information and information on the properties of the large volume of superconducting material involved. The magnet has provided information on the operation of five different cable types and four different types of winding construction while being acceptable for operation in a bubble chamber.

A future design would be based upon this information. An attempt would be made to improve the system stability and to arrange the windings so that each would carry approximately the same current at the highest field. In this way, series operation with only two power leads would be possible, and persistent-mode operation could be easily accomplished. The system could be operated at 60 kG in 11 in. and 80 kG in 7 in. by increasing the average current densities in the inside and outside coils. This can be accomplished by increasing the packing factor.

The current densities in the outside windings can also be increased by using additional copper and by winding with the same packing factor.

Experiments with smaller coils in this laboratory have demonstrated the feasibility of this approach. Currents in excess of 600 Amp have been obtained with shorter lengths of the same cable as that used in the outside windings at similar magnetic fields. The small coil used for these experiments was 6 in. long and 4 in. ID, and generated a central field of 12 kG for 600 Amp.

CONCLUSIONS

Large superconducting magnets are economically feasible and can be operated at currents that compare favorably with the short-sample characteristics of the materials involved. Undesirable large-coil effects and split-coil effects can be reduced or eliminated by good engineering design.

Satisfactory power connections can be made to superconducting cable. Cable lengths can be connected together so that the resistance between them is less than 10^{-8} Ohm, and these connections can be wound directly into high-field coils.

The use of multistrand conductors insures low inductance, high mechanical stability, and good current-carrying capacity in each strand. These high-current conductors speed and facilitate the problems of coil construction and testing.

Coil windings can withstand compressive loads in excess of 100 tons without deterioration. This eliminates the need for separate load-bearing material in the coil.

Information based upon studies of small coils can be used as a basis for the design of large coils.

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REFERENCES

1. Pewitt, E. G., et al., The Hydrogen-Helium Superconducting Magnet Bubble Chamber, 1964 International Conference on High Energy Physics, Dubna, U. S. S. R.
2. Laverick, C., Progress in the Development of Superconducting Magnets, invited paper to July 1964 Summer Meeting of the American Physical Society, to be published in Cryogenics.
3. Laverick, C., The Performance Characteristics of Small Superconducting Coils, Advances in Cryogenic Engineering 10, 1965.
4. Laverick, C., Experimental Studies on the Current-carrying Capacity of Niobium-Zirconium Wire under Conditions of Fixed and Swept Magnetic Field, Advances in Cryogenic Engineering 9, 1964.