SOME SUPERMAGNET DESIGN CONSIDERATIONS*

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Abstract

The practicability of medium-sized superconducting magnets has been demonstrated by the performance of the ANL 67 kG seven inch magnet system. This paper summarizes the design factors for that magnet, with special emphasis upon their implications for very large magnets. Various techniques for obtaining satisfactory current densities at a high level of stability and reliability are discussed. The clear implication of the results up to now is that very large supermagnets are indeed practical from a technical standpoint. The economic factors which must be carefully studied in order to establish the over-all practicality of large supermagnets are discussed.

Introduction

In early superconducting magnets the current carrying capacity of the superconducting material was found to be considerably less than that anticipated from tests with short samples of the material.[1] These degradation effects are now better understood and techniques for reducing or eliminating them have been developed.[2, 3] General design techniques for superconducting magnets have been developed[2, 3] and have been applied to the design and construction of a number of recent superconducting magnet systems.[4] The successful operation of these magnets at reasonable values of current has demonstrated the soundness of the design criteria.

The operation of currently available superconductor materials at their highest current densities requires the provision of a favorable thermal environment and adequate electrical shunting to reduce the probability of a superconducting to normal transition and subsequent propagation of the normal region. Limitations in current carrying capacity due to relative movement of superconductor turns are gradually eliminated as superconductor electrical stability is increased. Stranded superconducting cable can be used to provide multiple parallel conducting paths and facilitate magnet construction. Application of these ideas can result in the provision of large supermagnets of reasonable cost in which self propagation of a superconducting to normal transition region is eliminated.

As a specific example of the application of these ideas in working supermagnets, we discuss in the next section the Argonne "seven-inch" magnet system.

The second part of this paper considers the economic factors involved in the design of very large supermagnet systems. Appropriate emphasis must be given to the "system" aspect of the problem, since a large fraction of the cost of almost every magnet system, conventional or superconducting, represents items other than the coil material.

ANL Seven Inch Magnet

The ANL 67 kG seven inch I. D. system was designed and built for use with a bubble chamber and has been described in detail elsewhere.[4] It is composed of three concentric magnets which can be used separately or in combination (see Fig. 1). The magnet was wound from various types of cable (see Fig. 2) so that information on the performance characteristics of large coils using these cable types could be obtained. A large number of cable types had been tested in coils prior to the construction of the large system to ascertain the performance characteristics of several types of cable design and winding construction.

The results obtained from the operation of this magnet system are given in Table 1 and demonstrate the practicability of magnet systems of substantial size at reasonable current levels.

The inside coil was wound using six copper coated Westinghouse HI 120 (Niobium Titanium) superconductors stranded about a center copper conductor (see Figs. 1 and 2). The coil operated at a maximum current of 119 amperes for a central magnetic field of 67 kG in the system. These results approach the short sample characteristic for the material used and are believed to demonstrate the effect of magnetic field stabilization. The phenomenon is well known in Nb_3Sn high field magnets.[5]

The 11 inch I. D. 14 conductor HI 120 winding was wound with a lower packing density than the inside winding since copper conductors were wound about the 14 superconductor strands. The cable was operated to the transition region for a current of 284 amperes and a central magnetic field of 42 kG in the 11 inch magnet. This corresponds to a current of approximately 20 amperes per superconducting strand for a maximum field of almost 50 kG at the wire. The average short sample current carrying capacity of the material at 50 kG lies between 27 and 37 amperes. This result would appear to indicate that the amount of copper used on this material for this winding construction was not sufficient to give maximum electrical stability while the magnetic field at the outermost winding sections was too low for magnetic field stabilization.

The 15 inch I. D. Nb 25% Zr winding carried a current of 19 amperes per superconducting strand when the 11 inch I. D. system was operated at a central field of 31 kG. This current is considerably lower than the short sample characteristic for the maximum field at the winding although the average current density in this coil (see Table 1) was considerably higher than that elsewhere in the coil system. The cable was not impregnated with indium and the winding construction was less porous than that of the other windings.

The current carrying capacity of the outer 18 inch I. D. coils was almost double that of the 15.8 inch I. D. winding but extra copper was used around the cable (see Figs. 1 and 2) and the winding construction was open to allow liquid helium to penetrate the coil. The 18 inch I. D. split coil system had been operated separately at a central field of 16.7 kG at a cable current of 245 amperes. This current is rather less than the short sample current carrying capacity for the maximum magnetic field at the wire.

The 18 inch I. D. system can be operated in the transition region, with some of its superconductor driven into the normally conducting state, without self propagation of the normally conducting region. The coil current is carried by the shunt copper around the normally conducting region when this occurs. The system can be made fully superconducting again by decreasing the coil current until the normally conducting region disappears and the voltage across the coils is reduced to zero.

Several other magnets have been operated at ANL using a basic seven conductor cable identical to that used in the 18 inch I. D. coils. Various types of winding construction and different copper thicknesses were used. Some coils were wound from heat treated wire. It was observed, as expected, that increases in current carrying capacity and in the stability of the system when operated near or at the point of transition from superconducting to normal region were obtained when the design changes increased the efficiency of the liquid helium inter-layer cooling system or the amount of copper around the superconductor.

This program is aimed at maximizing the current density, stability, and over-all practicality of large supermagnets, and the detailed results and design procedures will be reported elsewhere.

Economics

The techniques described above seem to be applicable to d. c. supermagnets of almost any size. It is essential to obtain realistic cost estimates for such magnets. Because of the well known uncertainties involved in cost estimates, we start by considering approximate cost data for two existing magnet systems, as given in Table 2. These magnets are similar in size and field strength; one is conventional[6] and the other is a superconducting magnet.

Three additional important points to be considered when comparing the costs listed in Table 2 are as follows:

1. The high field strength biases the situation in favor of a supermagnet.
2. The operating cost of a supermagnet (liquid helium consumption) is by no means negligible even though the power dissipation is almost zero.
3. Very different types of engineering effort are required for the two cases and, so, engineering costs are not included.

The engineering costs which would be necessary for duplicating or improving either of these two magnet systems would probably be comparable. This seems reasonable because the engineering effort required for the design of the more complex supermagnet system is probably comparable to the effort required to design the very large power supply and cooling equipment installation needed for the copper magnet.

Generalizing from the cost data of Table 2, as well as from other design studies which have been made for larger magnets, we reach two important conclusions:

1. The initial capital costs of existing supermagnet systems are usually less than those of conventional magnet systems of comparable performance. With reasonable progress in fabrication and design techniques as well as a likely reduction of superconducting material costs, this favorable capital cost position of supermagnets may soon apply to almost all types of large d.c. magnets.

2. The operating cost for providing the low temperature environment for existing supermagnets is currently comparable to or greater than the power cost that is saved. Hence, in order to realize the substantial potential economies on operating cost, very careful attention to the cryogenic engineering aspects of supermagnet design is required. Up to now, the main engineering and development effort on supermagnets has been focussed on coil design. A comparable effort must now be devoted to such cryogenic matters as optimizing dewar design, minimizing the heat leak along the electrical leads, and most important of all, developing economical and reliable sources of refrigeration at liquid helium temperature.

A further consideration which relates to both the practicality and economics of supermagnets is that of the reliability of the entire system. Even conventional copper magnets have been known to exhibit unreliability! Some of the usual causes are shorts or other coil malfunctions (sometimes caused by magnetic forces), accumulation of unwanted matter in the cooling system, and instabilities or malfunction of the power supply.

A similar variety of problems can arise for supermagnets. More operating experience with supermagnets of substantial size is required for a careful evaluation of the reliability question. Two advantages which should help in reaching satisfactory reliability are the lack of thermal stresses during operation and the high mechanical strength of the Nb-Zr alloys. A problem which plagues many kinds of cryogenic apparatus is the thermal stress involved in the cooldown from room temperature. The overall reliability which has already been reached with very large-scale low temperature machinery (liquefiers, dewars, rockets, etc.) indicates that the problem of making reliable superconducting magnets will soon be solved.

Conclusions

The size range over which superconducting magnets form a practical and advantageous alternative to conventional d.c. magnets is continuing to grow. The satisfactory performance of the ANL seven inch magnet has demonstrated that high current density, satisfactory stability, and ease of fabrication are all attainable, and further development work now underway is opening new avenues for improved performance and economy. In order to minimize the operating cost of these magnets, an intensive program of cryogenic design is required.

References

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TABLE 1

DETAILS OF MAGNET PERFORMANCE - 67 kG Seven Inch I. D. System

Coil Designation	Winding I. D. in.	Winding O. D. in.	Winding Length, in.	No. of Turns N	Field Constant Gauss/Amp.	Max. Current Amp. Per Cable/Per 0.010 inch Strand	Packing Factor λ	Max. A/cm^2
Inside (7-in. -ID)	7.175	10.675	10.875	6225	216	119/20	15.4	6037
Inner (11-in. -ID) Intermediate	11.08	15.62	4.875	1363	76	283/20	13.5	5404
Outer (15-in. -ID) Intermediate	15.77	17.44	4.875	1800	88	134/19	24.26	9188
Outside (18-in. -ID) (Uncoated)	18	24.125	4.6	1952	40	211/30	7.6	4532
Outside (18-in. -ID) Coated	18	24.5	4.625	1846	38	245/35	7.0	4851

TABLE 2

MAGNET SYSTEM COSTS (Approximate)

	ORNL Seven Inch 65 kG Copper Magnet (Ref. 7)	ANL Seven Inch 67 kG Superconducting Magnet
Coil (Material)	\$ 5,000	\$ 70,000
Coil (Fabrication)	10,000	30,000
Power Supply System	150,000 (3.5 MW)	10,000
Water Cooling System (Including cooling tower)	140,000	---
Dewar (and accessories)	---	30,000
Capital Cost (Engineering Excluded)	305,000	140,000
Operating Cost	*\$20/hour (at 0.6 ¢/kW hour)	\$20/hour (at \$5/liter of liquid He)

*NOTE: Oak Ridge costs at special low rate 0.4 cents/kW hour.
ANL costs 0.8 cents/kW hour.

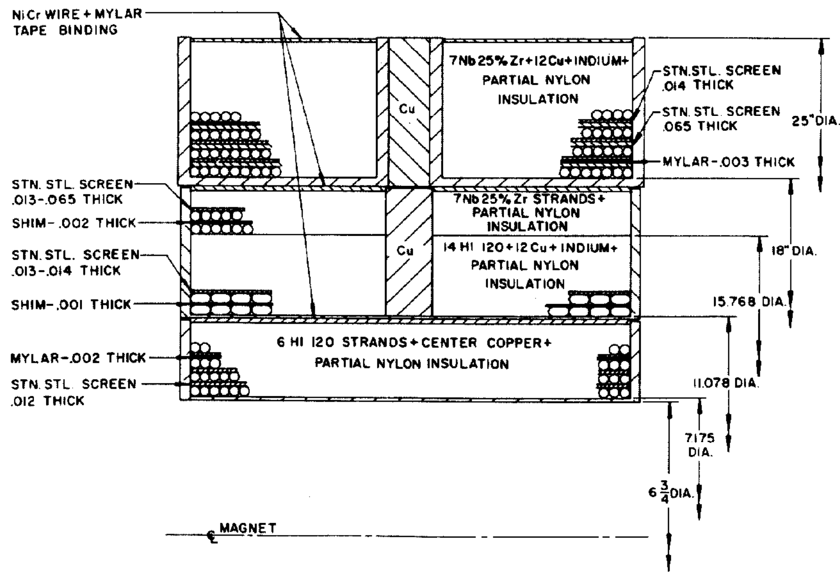

Fig. 1 - Schematic of Magnet System.

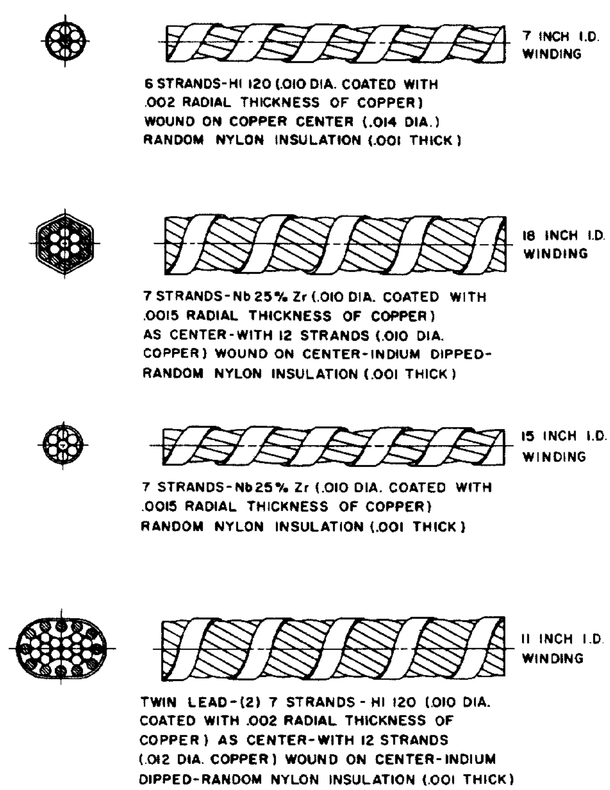

Fig. 2 - Cable Types Used in 67 kG Magnet.