SUPERCONDUCTING MAGNETS FOR THE
200 GEV ACCELERATOR EXPERIMENTAL AREAS*

R.B. Meuser
Lawrence Radiation Laboratory
Berkeley, California

INTRODUCTION

The experimental areas of the 200 GeV accelerator provide an opportunity to realize a really large payoff from the use of superconducting magnets. Costs might be reduced because of the virtual elimination of the electric power and the systems necessary for delivering and dissipating that power. Further savings, and perhaps better physics, may result from the shortening of beam lines made possible by the higher magnetic fields.

A major part of the cost of an experimental area is associated with the dc magnets used for transporting secondary particle beams, and it is these magnets which are under consideration in this paper. If it is decided to make them superconducting, that decision must be made before large sums of money are committed for furnishing the electrical and cooling systems and other features of the experimental areas associated with conventional magnets. For the first of the three experimental areas planned, the decision must be reached by the fall of 1969. An early decision will furnish an impetus to the development of magnets suitable for that application.

The multitude of problems associated with superconducting magnets can be divided into two groups. The "priority program" comprises those items necessary for reaching a decision at an early date on whether to adopt conventional or superconducting magnets. The "nonpriority program" comprises the remaining items aimed at deriving the maximum benefit from superconducting magnets by continued improvement of the technology.

The priority program must include not merely the magnets but also the entire system associated with large numbers of magnets, and the interaction between that system and the performance of physics experiments.

To be acceptable, the superconducting magnet system must be economical. But, the economics will probably be rather different from a system of conventional magnets. At present it seems that the total capital cost of the superconducting magnet system will be higher than a system of conventional magnets. If initial equipment money is limited, this may mean that the superconducting system must be acquired at a slower rate. But a strong argument could be made for enhanced equipment funds to be traded off against lowered operating costs.

To be acceptable, superconducting magnets must be predictable, realiable, and easy to operate. If each of the 20 to 40 magnets on a beam had the characteristics of a temperamental laboratory device the physicists would find it intolerable. The optical properties must be at least as good as conventional magnets, and this requires careful design, precise conductor placement, and freedom from hysteresis effects. Short focal lengths and large acceptance angles may cause additional problems.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

Various conductor materials and forms and various winding configurations and methods should be investigated with emphasis on those which lend themselves to producing lots of, say, ten to twenty magnets. Cryostats must be designed to be compatible with magnetic shielding, to hold the windings and shields rigidly, and to minimize dead space at the ends. It is not clear that one has gained anything if to double the field available with conventional magnets one must use a cryostat having a length twice the effective length of the winding.

Cutting across all facets of the problem, and highest on the priority program, is the construction and operation of a beam line having as many beam transport elements as practicable. In addition to demonstrating feasibility of a system and providing both the opportunity and the necessity for solving some of the known problems it might provide answers to questions we do not yet know how to ask.

MAGNET REOUIREMENTS

As a part of a study of the refrigeration requirements a model of the experimental areas was developed, using as a basis the NAL Design Report, the various studies on experimental use, and discussions with various LRL and NAL personnel.[1] In order to determine the numbers of the various kinds of magnets required it was assumed that the bending and focusing power required for the various beams was supplied by modular superconducting magnets having the following characteristics:

Bending magnets:	35 to 40 kG in aperture
Quadrupoles:	30 to 35 kG at edge of aperture
Effective length:	1.75 m

These assumptions lead to a requirement for 254 magnets which may be grouped as follows:

Type:	
Quadrupoles	77%
Dipoles	23%
Radiation shielding:	
Probably required	53%
Probably not required	34%
Possibly required	13%
High fields useful for shortening beams:	
High fields useful	39%
High fields not useful (rf separated and neutrino beams)	61%

Sizes:
- Most quadrupoles have 4 in. diameter apertures
- A few 8 in. and 12 in.
- Most bending magnets require aperture widths of 8 in.

Magnetic shielding:
- Required for most magnets

1. M.A. Green, G.P. Coombs, and J.L. Perry, 500 Incorporated Report (1968).

Excluded from the list are a number of large spectrometer magnets, and the bubble chamber magnets. Also excluded are the hyperon beam magnets packed within the shielding near the targets.

For the latter the high fields attainable with superconducting magnets will probably result in shorter beam lines, and greater admittance solid angles. The shorter beam lines will result in greater particle fluxes and savings in shielding and real estate. The use of superconducting magnets for these applications has not been investigated in detail, and we are not yet in a position to list quantities, sizes, and kinds.

MAGNET DESIGN AND THE CURRENT DENSITY GAME

Most magnets will require magnetic shielding to minimize interaction between beam lines. The use of iron shielding enhances the field of a bending magnet by 5 to 10 kG and of a quadrupole by 2 to 5 kG. Iron shielding is the subject of a recent LRL study,[2] and Beth of Brookhaven has investigated the use of counterwindings to cancel the stray field.[3] Magnets with counterwindings can sometimes be made more compact than iron-shielded magnets, but the total amount of superconductor required is much greater. Nevertheless, they may find application where space is dear — close to targets, for example. Even a low-field iron-shielded superconducting magnet can be made more compact than the equivalent conventional magnet (unless one is willing to expend astronomical quantities of electric power on the latter).

Figures 1 and 2 illustrate the effect of current density, size, and field strength upon ampere-turn requirements for iron-shielded dipoles and quadrupoles, respectively. The ordinate is normalized to the current required for a thin winding having infinite current density. The necessity for high current densities for small high-field magnets, particularly quadrupoles, is apparent.

Current densities of more than 15 kA/cm^2 at fields of more than 60 kG have been obtained with NbTi in solenoids of the size of the beam transport magnets under consideration. In fact, however, no beam transport elements using NbTi have been completed. It is probable that twice the current density can be obtained by using fine-filament conductors, but it remains to be proved. Current densities of 40 to 60 kA/cm^2 at around 50 kG have been obtained in Nb_3Sn quadrupoles, somewhat too small for use at the 200 GeV accelerator, by Sampson and Britton at Brookhaven, and by others (G.E., British Oxygen) using substantially the Brookhaven configuration. No bending magnets using Nb_3Sn have been built of a size useful for the 200 GeV accelerator, but a small one at Brookhaven is well along.

If we adopt as a working hypothesis that Nb_3Sn costs twice as much as NbTi per ampere foot and that current densities of 15 and 40 kA/cm^2 are applicable to NbTi and Nb_3Sn, respectively, we find, using Figs. 1 and 2, the following crossover points.

---

2. R.B. Meuser, Lawrence Radiation Laboratory Report UCRL-18318 (1968).
3. R.A. Beth, Brookhaven National Laboratory, Accelerator Department Reports AADD-103 and AADD-110 (1966).

Field strength	Inside radius of winding (in.) Bending magnets	Quadrupole magnets
40 kG	< 1	1.9
55 kG	< 1	2.5

On this basis, Nb_3Sn wins the game for the smaller sizes and higher fields. However, many of the magnets for the 200 GeV accelerator application are larger than that for crossover at 55 kG, and for most of the magnets it is doubtful if there is any technical or economic reason to demand fields even as high as 55 kG. For many applications, however, the field strength, and therefore the current density, should be pushed as high as the state of the art will permit.

Clearly such numbers games as this are subject to many factors which cannot be accurately evaluated at present. We do not know how accurately present prices reflect actual production costs, or how the costs and production technology will be affected by time, quantity, or subsidization. Manufacturers are popping into and out of the field at frequent intervals, and prices sometimes vary by a factor of two between successive orders placed a few months apart. The cost of the conductor does not tell the whole story; it appears to this author that the costs of constructing a large number of Sampson-type Nb_3Sn magnets would be substantially less than for any of the magnets using NbTi now under construction, but if any of several alternative ways of building NbTi magnets worked out satisfactorily the picture could be reversed. It appears, therefore, that both Nb_3Sn and NbTi beam transport magnets should be pursued, and that in the end there will probably be some applications for which one is superior to the other.

THE LRL PROGRAM

Refrigeration

In the fall of 1966 the National Bureau of Standards undertook for us a study of the refrigeration problems.[4] The practicability and relative costs of a number of systems for supplying refrigeration were investigated.

In the fall of 1967, 500 Incorporated, a subsidiary of Arthur D. Little, Inc., was induced to undertake, at their own expense, a further study of the refrigeration system, and the results of that study have been recently published.[1] A summary was presented at this Summer Study by M.A. Green.[5]

It is convenient to treat the cryostat design and the refrigeration systems as separate problems, but in fact they interact quite strongly. For some systems the cost of the refrigeration system is insensitive to the heat load of the magnet cryostat, whereas other systems — for example, where many magnets are serviced from one

---

4. T.R. Strobridge, D.B. Mann, and D.B. Chelton, National Bureau of Standards, Boulder, Colorado, NBS Report 9259 (1966).

5. M.A. Green, these Proceedings, p. 293.

refrigerator or storage Dewar — are quite sensitive to the heat load of the cryostat. Although large transfer-line systems for liquid hydrogen are now commonplace, no such systems for helium have been built, and hence there has been little incentive to develop cheap and efficient ones. It would seem that a modest effort might result in such systems' becoming a reality, and this might change the complexion of the refrigeration system economics and the cryostat design.

Over-all Systems Studied

A preliminary study of the relative costs of conventional and superconducting magnets was presented at the Particle Accelerator Conference in March 1967.[6] The NBS study of the refrigeration problems, plus feedback from the industry, was used as the basis for estimating the cost of the refrigeration.

Over the next year we intend to continue developing a coherent picture of the superconducting magnet system. Operation of a superconducting beam line will be important to the development of that picture.

Magnets and Beam Lines

Early in 1967 we decided to attempt to build a beam transport magnet and install it on the beam line of an actual physics experiment as quickly as possible. There came to our attention the need for a solenoid capable of producing a $\int B_z dz$ of 140 kG·ft for an experiment at the 184-inch Cyclotron. The axis was to be horizontal and a 4 in. diameter clear warm bore was required. The construction of such a magnet would give us experience in all the aspects of the problems of a beam transport element except that the winding configuration would be different. It was agreed that we should build it, and design started in mid-year. The magnet has since been completed and is installed and operating. Its characteristics are, briefly, as follows[7]:

Conductor: Nb48%Ti, round wire, 0.015 in. diam core, 0.030 in. diam copper sheath.

Clear inside diam of warm bore	4.25 in.
Winding length	35.75 in.
Maximum field on axis	65.5 kG
Stored energy	200 kJ
Current density based on coil envelope	16.6 kA/cm^2

We started early in 1968 on a bending magnet model using 0.080 in. square NbTi conductor that was on hand. The procedure adopted was to wind flat double pancakes, race-track shaped, and then bend them over a cylinder. No potting or adhesive is used. Nine such double layers assembled on each side of a cylinder comprise the winding. A nonsuperconducting mock-up has been built to work out the fabrication techniques, and the winding of the superconductor has started. The winding has a 5 in. inside diameter, an over-all length of 15 in. A solenoid using the same conductor has operated at a current density of 14 kA/cm^2. With that current density the bending magnet model should produce a field of 30 kG without an iron return path. This is too small a magnet to be useful on a beam line, but it is intended to serve as a model for future magnets of a more useful size.

---

6. R.B. Meuser, IEEE Trans. Nucl. Sci. NS-14, No. 3, 372 (1967).

7. R.B. Meuser, W.H. Chamberlain, and R.E. Hintz, Lawrence Radiation Laboratory Report UCRL-18179 (1968). (To be published in Proc. 2nd Intern. Cryogenic Engineering Conference, Brighton, England, 1968.)

It is planned that a 6 in. aperture bending magnet be built by early 1969, to be followed by additional elements, and installed on a beam line at the Bevatron. A refrigerator for cooling these magnets has been purchased.

Fast and inexpensive winding techniques are made possible by the use of random-wound round wire. Complicated windings for motor and generator armatures and field coils and television deflection yokes, which are actually small bending magnets, can be wound in seconds. The space factor is poor — 50 to 70% — but by using small cores and a minimum of copper the over-all current density may still be acceptable. A small effort — one summer student — is being expended toward the utilization of this technique. Preliminary tests using inexpensive plaster and plastic winding forms have been promising, and somewhat better tooling is now being built.

Methods of winding round wire in a more orderly fashion are being contemplated by LASL and the British Oxygen Co. We have given some thought to the matter but have not yet devised a scheme that we feel will be satisfactory.

Pulsed Magnet Operation

To help gain an understanding of the effects produced during the turn-on of a superconducting magnet, some experimental work has been done with pulsed operation of solenoids. This was reported on at this Summer Study by Voelker[8] and Gilbert.[9]

8. F. Voelker, these Proceedings, p. 550.

9. W.S. Gilbert, these Proceedings, p. 1007.

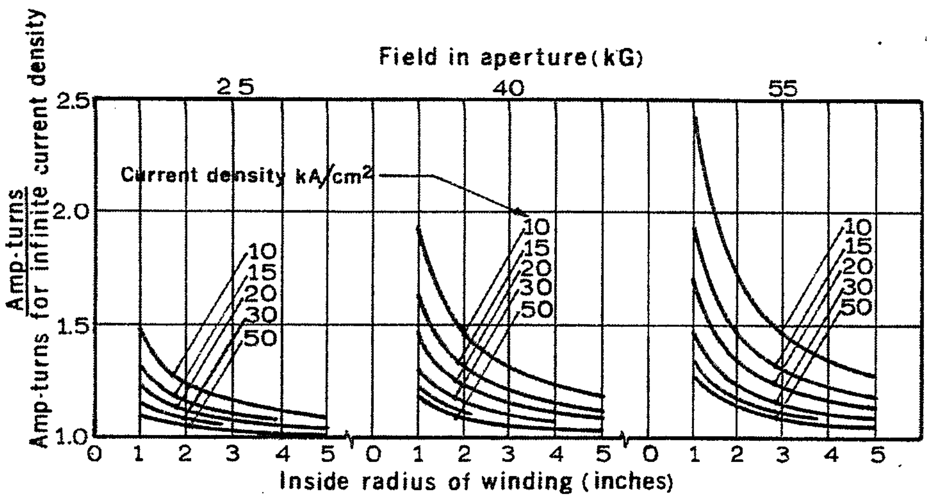

Fig. 1. Ampere turns required; bending magnets.

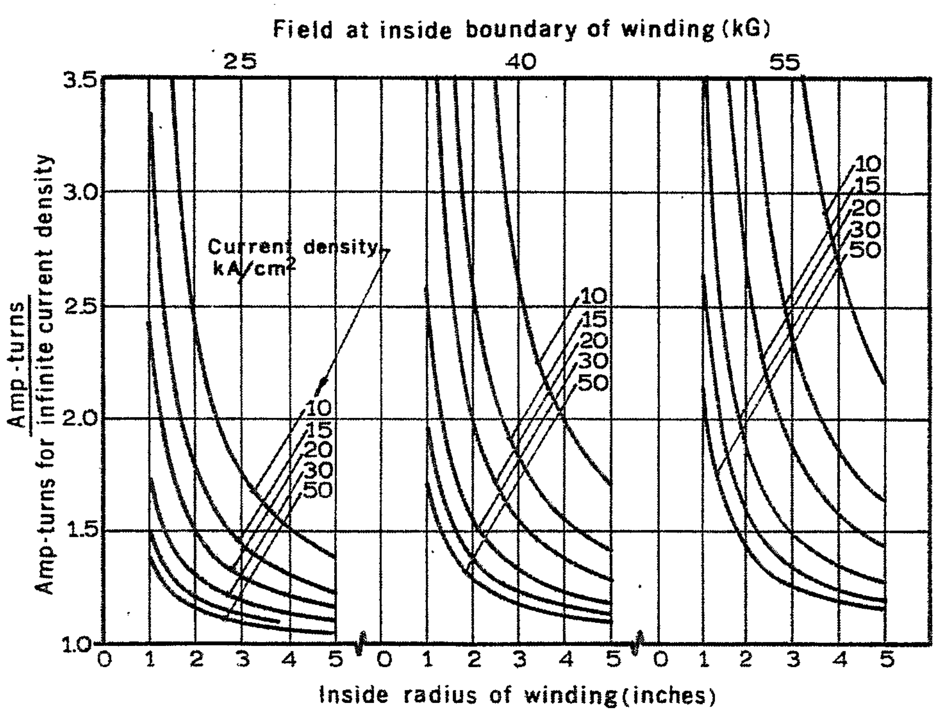

Fig. 2. Ampere turns required; quadrupole magnets.