THE INTEGRATED CRYOGENIC - SUPERCONDUCTING BEAM TRANSPORT SYSTEM PLANNED FOR MSU*

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Summary

Approximately 100 superconducting beam transport magnets will be constructed and coupled to an integrated system for distribution of liquid helium and liquid nitrogen. The economics of the superconducting magnet designs and some of the options for the cryoenic distribution system are discussed.

Introduction

The National Superconducting Cyclotron Laboratory at Michigan State University will consist of two coupled cyclotrons and associated experimental equipment for basic research in nuclear science using medium energy heavy ion beams. The maximum magnetic rigidity of the beams extracted from the superconducting accelerators will be 1.6 GeV/c. In this paper we discuss the plans for construction of superconducting beam transport magnets and the associated cryogenic system.

At the present time the K=500 cyclotron is completed and is being used as a stand-alone accelerator for research with temporary experimental facilities. The K=800 cyclotron, and phase II experimental facilities are currently under construction with planned completion dates in 1985. In the phase II floorplan shown in figure 1 the two cyclotrons, their coupling line, the beam transport system, several experimental stations including a high resolution superconducting spectrometer, and a 200 l/hr liquid helium refrigerator can be seen.

The beam transport system, including the cyclotron coupling line, will consist of about 70 superconducting quadrupoles and 15 superconducting dipole magnets. The economic considerations which led to the choice of superconducting magnets and the particular designs chosen are presented below. Alternative plans for the cryogenic distribution system are also discussed.

Superconducting Magnets

We concluded some time ago that low field (1.7 T), low current (10-50 amp), iron-dominated, potted coil superconducting magnets are the most economical for our application.[1] A beam transport line based on this type of magnet was built and tested several years ago at Argonne[2]. The low field "superferric" magnets[3] being considered for the high energy "desertron" accelerator are justified by similar economic arguements. Below we first compare low-field and high-field superconducting magnets and then superconducting vs. conventional copper coil magnets.

Low Field vs. High Field

A dipole magnet must have a certain integral of field times length, B x L, for a given angle of deflection. We also assume the beam requires a certain magnet aperture width, w, and gap, g, and that an iron yoke must be used to return the magnetic flux, B x w x L, to keep down external magnetic fields. Now compare the two dipoles shown systematically in figure 2, one operating at field B_o with length L_o and the other $2B_o$ and $L_o/2$. The higher field magnet requires an iron yoke of about 1.5 times the mass of the low field one. Similarly, for fixed current density in the conductor, the total length of conductor required would be approximately independent of B, but the higher peak field would reduce the allowable current density necessitating approximately twice the conductor. This is exacerabated by the facts that for fixed B x L, the total energy stored

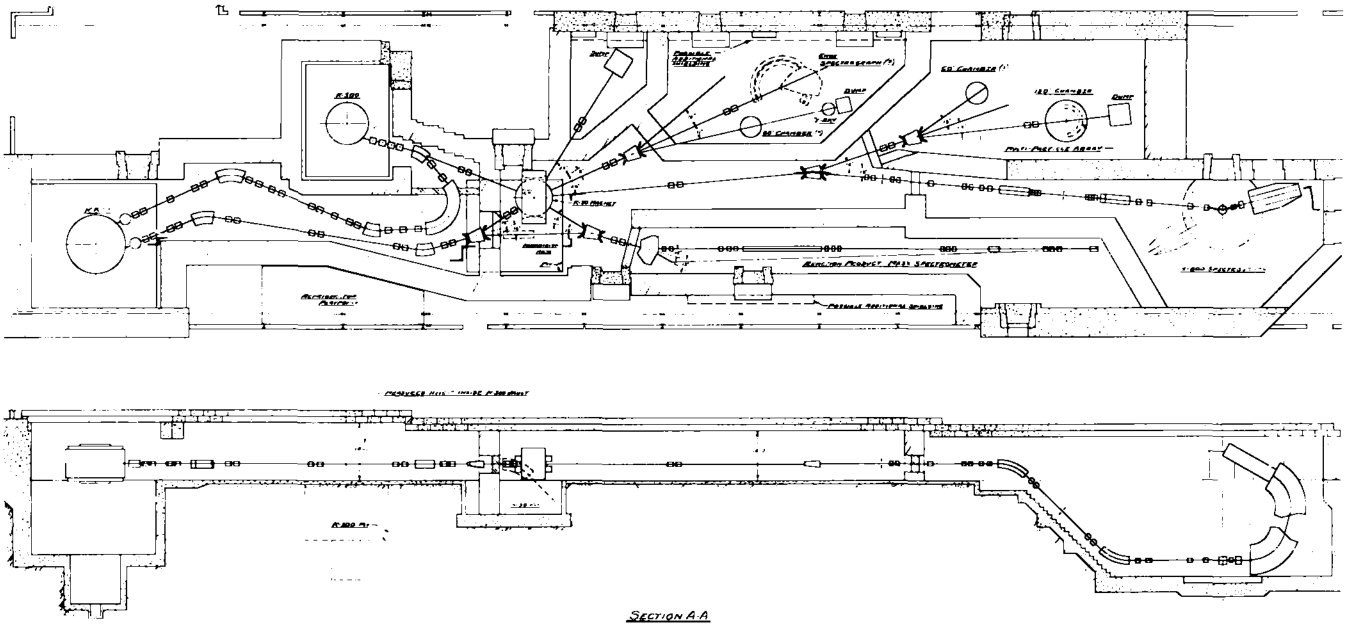

Fig. 1. The planned layout of the accelerators and experimental areas for NSCL Phase II. The two cyclotrons, the beam transport system, and the high resolution spectrograph all use superconducting magnets.

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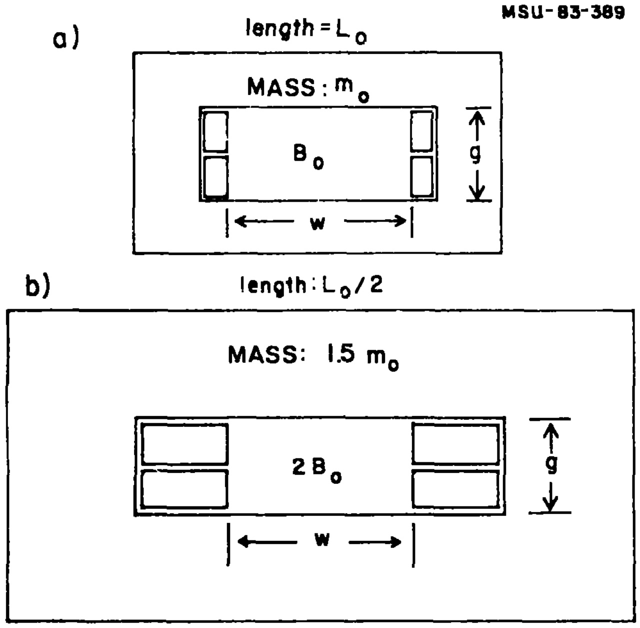

Fig. 2. a) Schematic section of a magnet of length l_o and operating at field B_o. b) Magnet with same aperture but with length $l_o/2$ and field $2B_o$ (constant Bxl). Because of the return yoke magnet (b) weighs about 50% more than (a).

TABLE 1

Cost Comparison for Quads, 14" Long, 5" Inside Diameter and 6 kG/in

Superconducting			Conventional (3000 A/in^2)	
Construction:				
Iron	@ \$1.5/lb 300 lbs	0.5 k\$	3,900 lbs	6.0 k\$
Conductor	@ \$0.02/ft 50,000'	1.0 k\$	385 kg @ \$20/kg	8.0 k\$
Power Supply	15 A, 10V	0.5 k\$	46 kW	10.0 k\$
Cryostat, Bobbin, Winding, Assembly		4.0 k\$		
Cryogenic Plumbing		4.0 k\$		
Refrigerator (fraction of larger system) 0.5 W		2.5 k\$		
SUB TOTALS		12.5 k\$		24.0 k\$
Operational Costs (10 Years, Electricity @ \$0.05/kwh)				
Electricity (ref 0.5 kW)		2.0 k\$	P.S. (10% duty factor)	
Maintenance		.5 k\$		
Cooling Water			9 gal/min	1.5 k\$
Liquid Nitrogen		1.0 k\$		
SUB TOTALS		3.5 k\$		21.5 k\$
TOTAL (per device)		16.0 k\$		45.5 k\$
TOTAL (70 devices)		1120. k\$		3185. k\$

in the magnet scales approximately as B, U ~ B^2 x L x w x g, and the force per unit length on the conductor bundle scales as B^2. Magnets with lower stored energy can generally be run at lower currents because of less severe quench protection requirements. Low current operation is desirable because of the less expensive power supply and lower heat leak associated with the magnet leads.[4] Less force on the coil simplifies the coil support structure and reduces stresses within the coil.[5] Our conclusion is that low field, low current superconducting magnets are physically very compact and cryogenically very efficient and are, therefore, a good choice for a beam transport system if space permits the extra lengths implied.

Superconducting vs. Conventional Magnets

The use of superconducting magnets for the beam transport system show in figure 1 is much more important for the quadrupoles than for the dipoles. For the large number of experimental stations planed for the relatively small building, fairly strong gradients are required in the quadrupoles. We are planning 5" ID x 14" long quadrupoles with gradients of 6 kG/inch. Rough estimates of the costs of superconducting and conventional versions of such a quadrupole are presented in table 1. The superconducting devices are about a factor of two cheaper to build and a factor of ten cheaper to operate, leading to an estimated net total savings over a 10 year period of over two million dollars.

For the dipoles we estimate that the initial costs of conventional magnets would be about 1.5 times that of superconducting, while the 10 years operational cost (with 10% duty factor for the conventional and 100 % for the superconducting) would be about three times more for the conventional. The net total savings in this case over a 10 year period is estimated to be 0.3 million dollars.

A proportionate cost of the central liquid helium refrigerator per device has been included in the above cost estimates, but the cost of constructing cryogenic transfer lines for liquid helium and nitrogen to these devices from the central location has not been included. However, it is evident that even the most sophistocated of the options envisioned for this system (see below) will be significantly less costly than the savings indicated above.

Magnet Designs

We have investigated various geometries for the quadrupole magnets including the Panofsky-type used in reference 2, coil-dominated cos (2θ) types, and iron-dominated hyperbolic styles. A version of the latter has been chosen as the most suitable for our application and a prototype is currently under construction. The two-dimensional magnetic field calculations for this design is shown in figure 3. The coil boundaries are straight lines, but tilted to approximate the ideal hyperbolic shapes. The 300 pound cold-iron structure consists of a cylindrical yoke and 4 numerically machined pole tips. The superconductor in the prototype will be 0.012" diameter NbTi wire with a 5:1 copper to superconductor ratio. It is designed to have a gradient of 7.3 kG/in at an operating current of 12 amps.

There are several ±16 degree switching magnets shown in figure 1. A prototype for these magnets is also currently under construction.[1] It is a compact trapesoidal superconducting H-frame dipole. The two dimensional calculation for a section of this magnet is shown in figure 4. This is a warm-iron magnet weighing less than 2 tons and having a 1/2" x 1" cross section potted coil mounted in a stainless steel bobbin. The tapered slot in the base of the pole tip has been introduced to keep the magnetic field profile flat over a wider dynamic range.

The long curved dipoles shown in figure 1 could be either long curved versions of the warm-iron H-frame switching magnets or curved cold-iron window-frame magnets. The final decision on this is pending experience with the prototype magnets mentioned above and an assessment of the inconvenience associated with

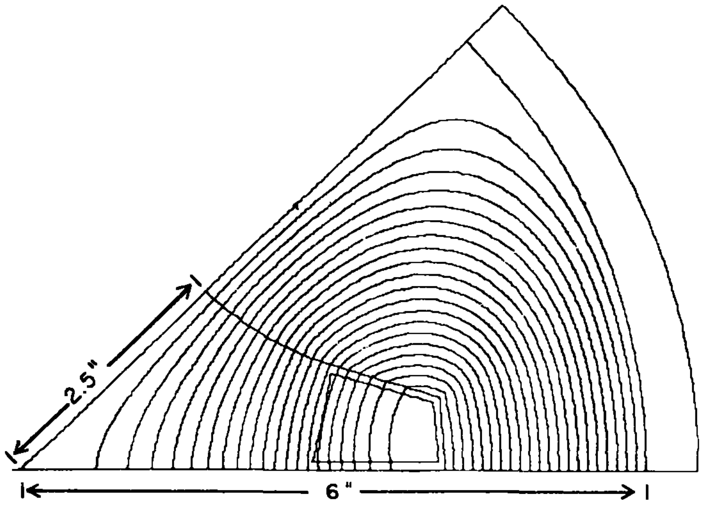

Fig. 3. Two dimensional calculations of the field of a superconducting quadrupole. The iron pole tip is hyperbolic and the edges of the coil are straight-line approximation to hyperbolas.

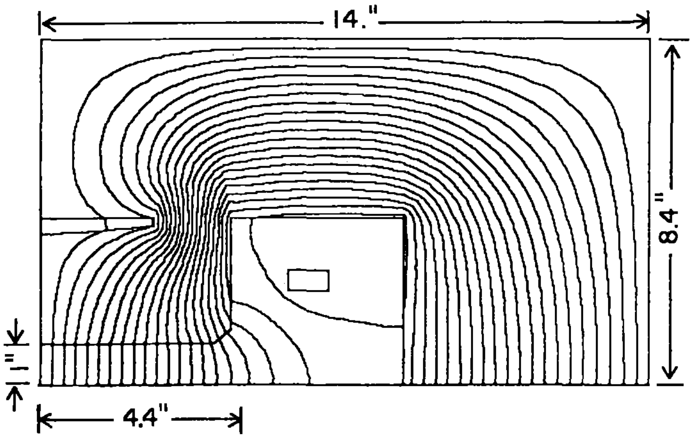

Fig. 4. Two dimensional calculation of the field of a compact warm-iron superconducting dipole. The tapered groove in the base of the pole tip helps to increase the useful dynamic range of the magnet.

with the cool down of cold-iron dipoles.

Cryogenic Distribution System

A prototype continuous flow cryogenic distribution line has been built and is successfully delivering cryogens to the K500 cyclotron cryostat and, in parallel, its vacuum cryopanels. Based upon this experience, a continuous flow system is being designed and cost estimated for the beam lines. An alternative distribution system for batch delivery of He and LN_2 to the beam line magnets is under study. Initial cost, operational convenience, reliability, cryogenic efficiency, cool-down procedure and quench-recovery considerations must all be properly weighed. It is planned that a prototype section of superconducting beam lines will be built and tested before proceeding with the final design.

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