THE USE OF SUPERCONDUCTING MAGNETS IN SPECTROGRAPHS AND BEAM TRANSPORT SYSTEMS*

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Superconducting magnets are being designed and constructed at the NSCL for use in the beam transport system and in a large magnetic spectrograph. Cost studies indicate that it is more economical to use superconducting magnets than conventional magnets in these applications, both in the initial construction and in operation. Some of the magnets are described below.

Introduction

With the completed K=500 superconducting cyclotron at the NSCL and the four other superconducting cyclotrons under construction around the world, superconducting magnets have obviously begun to play an important role in cyclotron technology. At the NSCL we are also extending this role to the beam transport system and some of the experimental apparatus. Cost studies presented below indicate that with efficient magnet and cryogenic design this is the most economical solution for high rigidity beam transport systems and magnetic spectrographs.

In the NSCL coupled superconducting cyclotrons the maximum magnetic rigidity of the extracted beams will be 1.6 GeV/c. In the floorplan shown in figure 1 are the two cyclotrons, their coupling line, the beam transport system, several experimental stations including the high resolution k = 800 magnetic spectrometer, and the 200 ℓ/hr liquid helium refrigerator. The beam transport system, including the cyclotron coupling line, will consist of about 70 superconducting quadrupole and 15 superconducting dipole magnets. A preliminary report on this beam transport system has been presented previously[1]. More detailed descriptions of the prototype superconducting quadrupole are presented in paper B16 in these proceedings. The magnetic spectrograph will use two large superconducting quadrupoles and two 75 ton superconducting dipoles[2]. A more detailed view of the preliminary mechanical design of the spectrograph is given in figure 2.

Cost Considerations

General

Simple scaling laws applied to cyclotron magnets explain the tremendous cost savings resulting from the use of superconducting magnets in cyclotrons. For a cyclotron of given k-value the total magnetic flux scales inversely with the magnetic field strength, so that high field superconducting magnets are much less massive than the corresponding conventional cyclotron magnets. The first generation superconducting cyclotrons at NSCL, Chalk River, Milan, and Texas A&M will be developing the techniques necessary for the everyday use of the superconducting technology.

On the other hand, the scaling laws for beamline and spectrograph magnets are quite different from those for cyclotrons. For magnetic spectrographs the first order resolving power is directly proportional to the integral of magnetic flux enclosed by the beam

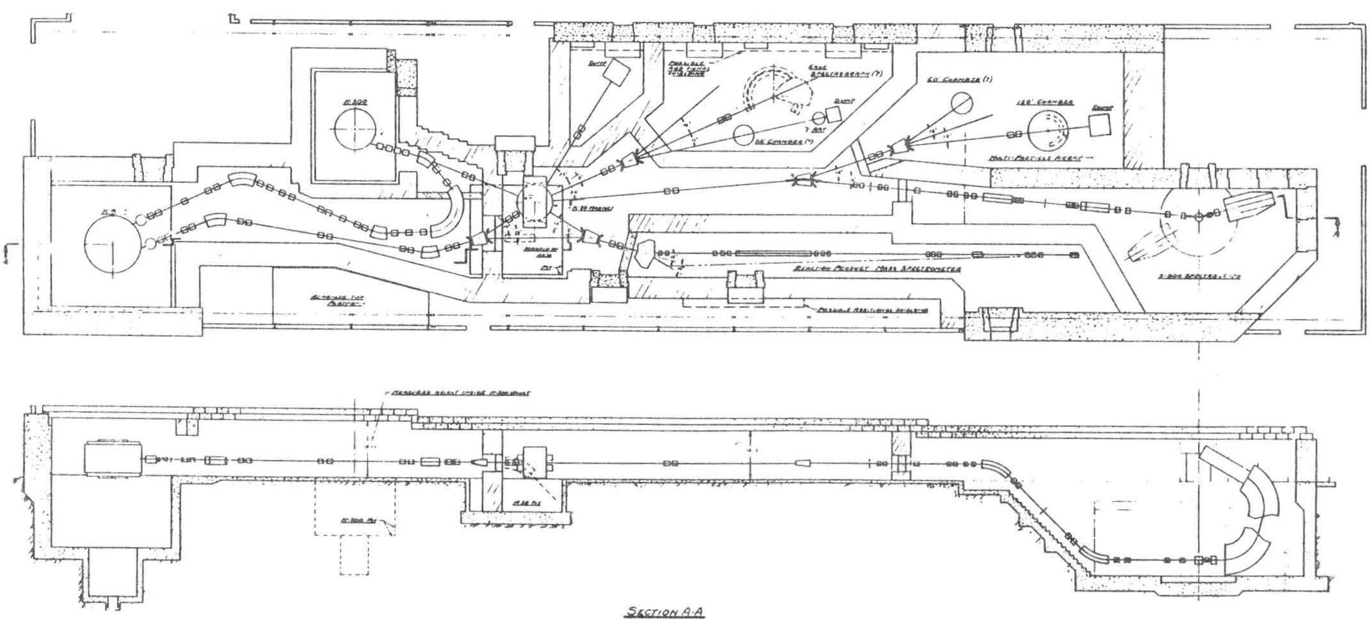

Fig. 1. The NSCL phase II floorplan involves about 100 superconducting magnets and an associated system for distribution of liquid helium and liquid nitrogen.

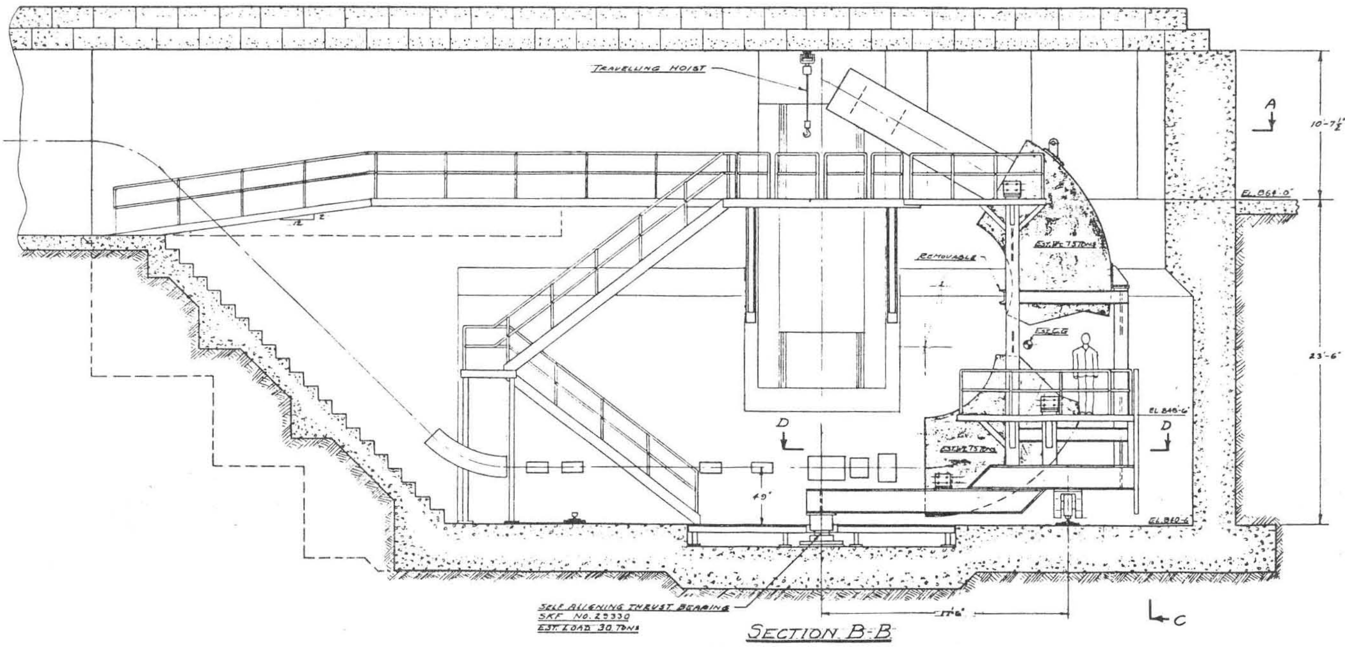

Fig. 2. A preliminary drawing of the k=800 superconducting spectrograph.

envelope, and hence using higher magnetic field does not reduce the mass of the magnet unless the idea of using iron to return the magnetic flux is discarded. Similarly, as is pointed out below, beamline magnets which require a given value of $\int B \cdot d\ell$ for a given bend angle, tend to be more massive at higher fields. Iron-free spectrometer and beamline magnets pose other problems and will not be considered in this paper. High-field spectrographs and/or beamline magnets may be the choice at very high momenta where space considerations dominate or in dealing with short-lived secondary particles such as pions or kaons where path-length considerations dominate.

In this paper, however, arguments are presented in favor of using low-field (~1.5 - 2. T) superconducting magnets in spectrographs and beamlines for beam rigidities nominally in the range from 1 to 10 GeV/c. At lower momenta the use of conventional magnets is relatively more economical, while at higher momenta space considerations may lead to the choice of higher field superconducting magnets.

The NSCL seems to be the perfect laboratory in which to develop and evaluate extensive use of superconductivity in beamlines and spectrographs for conventional nuclear physics. The Phase II beam momenta will be relatively high, 1.6 GeV/c, and the laboratory already has magnet design capability and cryogenic expertise.

Our goal is to make the beamline and spectrograph magnets very efficient cryogenically and very reliable in operation. We anticipate that these magnets will make a relatively minor perturbation on the laboratory's refrigerator, using less than 25% of its total capacity, leaving over 75% for the two cyclotrons.

Pioneering work on superconducting magnets appropriate for beam transport was carried out by John Purcell and co-workers at Argonne[3]. We have tried to build on their experience whenever possible.

In the cost comparisons given below not all aspects of either superconducting or conventional systems are mentioned explicitly. For example, offsetting costs such as the space required for the helium refrigerator and compressors compared with the space required for a low conductivity cooling water system and large power supplies for the conventional system have been omitted. The comparisons are primarily between items which are significantly different in the two cases.

Before beginning the more detailed comparisons it is interesting to first consider the intrinsic cost of superconducting wire compared with conventional copper wire. The superconductor purchased for the k=800 spectrograph is 0.128" x 0.078" in cross section, is 7% NbTi and 93% Cu, will operate at 500 A or 50,000 A/in^2, and cost \$0.50/ft. Copper conductor to carry the same 500 A at a typical current density of 3000 A/in^2 would also cost about \$0.50/ft. This illustrates that in both cases it is not the conductor itself which is very important, but it is the cost of the fabrication or packaging which dominates.

In what follows below we will attempt to answer the basic question "How can superconductivity help?" For beamlines and spectrographs the answers fall into four main categories: a) reduced initial cost through cheaper steel, cheaper coils, and cheaper power supplies, b) reduced cost of operation through lower utility cost, c) the possibility of higher gradients in quadrupoles, and d) the possibility of larger gaps in dipoles for relatively small incremental cost.

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 schematically in figure 3, 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 approximately 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. (At fields above 2 T the amount

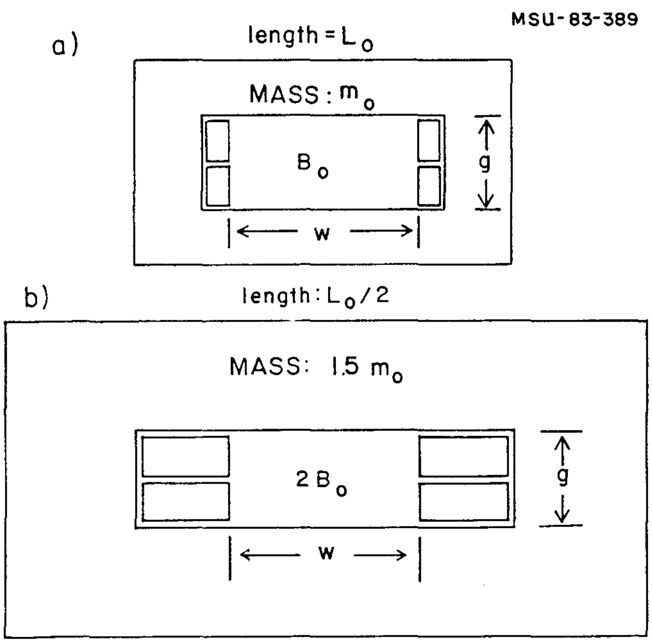

Fig. 3. This figure is intended to illustrate the advantages of low field superconducting magnets. For the momentum ranges of interest at the present time in nuclear physics, about 1-10 GeV/c, the constraints of magnet size and/or length are not usually severe. For example, the ±16° switching magnet discussed below for 1.6 GeV/c operates at 17.5 kG and is only 0.8m long. Increasing the field to 35 kG and decreasing the length to 0.4m would greatly increase the cost and complexity of this magnet. The higher field magnet would require more iron and over twice as much superconductor, and it would also be more difficult to maintain good field quality over a wide dynamic range.

of conductor required increases even more rapidly because the iron saturates.) This is exacerbated by the facts that for fixed B x L, the total energy stored in the magnet scales approximately as B, $U \sim B^2 x L x w x g$, 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

Given the justification that low-field superconducting magnets would be more economical for us than high-field ones, it remains to be shown that a particular low-field superconducting magnet is better than a corresponding conventional magnet. In this subsection we do this for the particular designs which we currently have under construction. More details of the actual designs are given in the next major section of this paper.

Beamline magnets. The high current densities ($\geq$10,000 A/cm^2) made possible by superconducting wire allow the design of very compact high-gradient beamline quadrupoles. Our design has a 10 cm diameter clear warm bore and a nominal gradient of 2.4 kG/cm. Although these high gradients are not necessary everywhere in our transport system, they are especially useful in the cyclotron coupling line and in the spectrograph beam analysis system. Actually for the beam transport system the use of superconducting quadrupoles is economically much more important than the use of superconducting dipoles. This is partly because the use of the higher current density is intrinsically more beneficial in the quadrupole design and partly just because of the large number of quadrupoles required.

TABLE I

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

Superconducting Construction:			Conventional (3000 A/in^2)	
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)	20. k$
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$

A cost estimate comparison between our superconducting quadrupole and a preliminary design for an approximately equivalent conventional quadrupole is presented in Table I. We conclude that the superconducting version will be approximately a factor of two less expensive in initial cost, due to a large extent to the much more costly power supply required for the conventional model. (In our case, we could save about 10% on the total cost of the conventional quadrupoles by sharing power supplies since no more than 80% of the quadrupoles would be in use at one time. However, this difference is less than the uncertainty in the power supply cost estimates and the amount of possible power supply sharing would vary considerably from Lab to Lab.)

Also indicated in Table I is the approximately factor of 6 difference predicted in the operating costs of the two types of magnets. This assumes a 100% duty factor for the superconducting and a 10% average duty factor for the conventional quadrupole. The 10% is an estimate of the combination of time on and operating power level factors. The number could clearly be much larger in some applications and is also subject to large year-to-year fluctuations. The number listed under maintenance of the superconducting quadrupole is primarily an estimate of its share of the cost of operating and maintaining the large refrigeration system of the laboratory.

For the beamline dipoles we estimate that the initial cost of conventional magnets would be about 1.5 times that of superconducting, while the 10 year 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.

Thus, for the beamline as a whole the use of superconducting magnets is estimated to yield a net savings to the laboratory over a 10 year period of over $2 M total or an average of over $200 k per year. For beamlines at higher momenta the savings should be even more substantial.

Spectrograph Magnets. The special features of the design of the k=800 magnetic spectrograph which are made possible by the use of superconducting magnets are: a) a strong, large-aperture quadrupole (2.1 T pole-tip field and 20 cm aperture) as the first magnetic element to help in achieving both large solid angle and high resolution; b) relatively large gap dipoles (15 cm) without excessive power dissipation, and c) relatively light-weight dipoles through the use of small superconducting coils and fairly saturated iron yoke.

A rough cost comparison between corresponding components of the two superconducting dipoles and comparable conventional-conductor dipoles is given in Table II. The conventional dipoles require about 50% more iron because of the much larger space required for a copper coil and the fact that the yoke must be run much less saturated to avoid excessive power consumption. The net savings for the two dipoles of the spectrograph is estimated to be about $600 k over a ten year period. If the dipoles were run at a useage ratio of greater than 20% the savings would be larger, about $100 k additional for each 10% increase in duty factor.

TABLE II

Cost Comparison for Two Spectrograph Dipoles

Initial	Superconducting	Conventional
Steel	$450 k (150 tons)	$675 k (x1.5)
Coils and Cryogenics	$217 k	$450 k (15 tons @ $15/lb)
Power Supplies and Protection	$40 k	$100 k (2x100 kW)
Supports	$50 k	$75 k
	$ 757 k	1300 k
Operational Costs (10 Years, Electricity @ $0.05/kW-hr)		
Electricity	$80 k (refr. at 100%)	$200 k (at 20%)
Maintenance	$20 k (Refr. main.)	
	$100 k	$200 k
TOTALS:	$857 k	$1500 K

It is hard to estimate the monetary savings made possible by using the high pole-tip field superconducting quadrupole in this spectrograph design. Replacing this quadrupole with a conventional one, limited to about 10 cm aperture and 1.0 T pole-tip field, would reduce the spectrograph solid angle by a factor of four (from 20 msr to 5 msr). To keep both the large solid angle and high resolution features of the present design while using conventional quadrupoles would require large drift distances and, therefore, would result in a much larger and more massive spectrograph. The cost of such a device would be prohibitive.

Cryogenics. The costs of the refrigerator and cryogenic plumbing are included in the above cost estimates for the superconducting magnets. These cost estimates are based on an estimate of a pro-rated share of the NSCL 200 ℓ/hr liquid helium refrigerator (total cost including accessory cryogenic plumbing about $900 k or about $4.5 k per ℓ/hr). Smaller units would be relatively more expensive per unit refrigeration capacity, while larger units would be less expensive. The operating costs for superconducting magnets include the electrical power useage of the refrigerator (about 1 kW electrical power per W of cooling at 4.2 K), the operating and maintenance of the refrigerator, and the purchasing of liquid nitrogen (about $0.07/ℓ). The power supplies for the superconducting magnets are much smaller than the corresponding ones for conventional magnets, and hence should require significantly less maintenance. Also the maintenance cost which are required for the liquid helium refrigerator are partially compensated by savings on the maintenance which would be required for a large cooling-water system for conventional magnets.

An additional advantage of having a system for distributing liquid helium and liquid nitrogen around the laboratory is their availability for cryopumping applications. Cryopumping with liquid helium is an economical way to provide high speed vacuum pumping for beamlines and experimental apparatus, especially large volume scattering chambers.

Magnet Design

General

In choosing the design for superconducting beamline and spectrograph magnets, there are many parameters and options to consider, e.g. current density, operating current, quench protection, cryogenic efficiency and operating convenience. Detailed consideration of all the choices is beyond the scope of this paper. Here we will mainly describe some aspects of the superconducting magnets currently under construction at the NSCL, after a brief statement of some of the general principles which led us to these designs.

For reasons stated above we have chosen low-field (1.5 - 1.75 T) magnets for both the beamlines and spectrograph. Both use iron to return the magnetic flux, but the iron is run more saturated than in conventional magnets because ampere-turns are relatively much cheaper in superconducting magnets. Of course, this results in larger than normal fringing fields (~100 G or more near the return yokes), but we feel that this is tolerable.

For each magnet the operating current has been chosen as low as is practical considering its stored energy and quench properties. For a given amount of stored energy quench calculations were carried out to determine the lowest reasonable current at which the various magnets could be safely operated. Our smallest magnets, the beamline quadrupoles, are designed for a very low current, 12.5 A, while our largest magnets (except for the cyclotrons), the spectrograph dipoles, are designed to operate at the relatively low current of 500 A.

For our small magnets for the beamlines, both quadrupoles and dipoles, the stored energies and forces on the coils are low enough to permit designing them with simple epoxy-potted coils with operating current densities between 10,000 and 20,000 A/cm^2.

These coils will quench if any piece of conductor moves, i.e. they are not cryostable. However, these magnets are predicted to quench fast enough and have low enough stored energy so that they do not require external dump resistors or fast-dump switches. The coils themselves absorb the energy dissipated in a quench. Examples of quench calculations for the beamline switching magnet are given below. Even though these magnets are predicted to be unharmed by quenches, quenches should occur only rarely, in order to not adversely affect beamline operations. To help reduce quenches the maximum operating currents in these magnets are only 60-70% of the short sample limits of the superconducting wire. It is also predicted that there is sufficient cooling of the coils by liquid helium to prevent quenching due to rather large loads due to neutron and gamma radiation.[6] (Radiation levels as high as 10^6 rad/hr may occur in a magnet if it is located immediately downstream of a beam stop.)

For the seventy-five ton spectrograph dipoles the deflections due to the magnetic forces on the coil are predicted to be much larger; the coils are large and more complicated in shape, with negative curvatures. Hence we have chosen to use low current density (~4000 A/cm^2), cryostable coils for these magnets. Because of the larger stored energies in these magnets (1 MJ per dipole), they will have dump resistors and dump switches for protection in case it is ever necessary to reduce the current quickly.

Beamline Quadrupoles

Details of the magnetic and cryogenic design of these magnets are given in a separate paper, B16, of these proceedings. Because of the large number (70) of these magnets in the beamline, great emphasis has been placed on achieving a design with high magnetic field quality, simple construction and excellent cryogenic efficiency. It is also important that this magnet be highly reliable and easy to operate. A prototype is currently under construction and should be completed and tested this year to see if any design changes will be necessary before going into production of the remaining quadrupoles.

The testing of this prototype quadrupole will also involve evaluating a prototype section of cryogenic beamline. It involves three devices connected as indicated schematically in figure 4 to test cool-down times, helium and nitrogen boil-off rates, magnet training, quench effects, and magnet field quality.

Beamline dipoles

The beam transport system shown in figure 1 uses five standard ±16° superconducting switching magnets. We are currently building a prototype of this magnet to evaluate the magnetic and cryogenic design. A schematic view of this design with its main components labelled is given in figure 5. In addition to the components shown in the figure there will be a cryostat with reservoirs for liquid helium and liquid nitrogen above the magnet. A POISSON calculation of the magnetic field of this H-frame design is shown in figure 6. The gap behind the pole tip helps to maintain good field uniformity from 1.0 to 1.75 T. It has a potted coil which runs at a current density of 17,000 A/cm^2 at a maximum operating current of 100 A. Small versions of these coils have been wound and tested at current densities up to 50,000 A/cm^2. The 6500 lb warm-iron yoke is run fairly saturated and is tapered both horizontally and vertically so that it is saturated equally at both the narrow and wide ends.

The stored energy in this magnet at peak field is only 35 kJ, but since its two coils are thermally isolated and are electrically in series, most of this energy will be dissipated in one of the coils during a quench. However, calculations with a code from Harwell[7] predict a hot spot temperature of less than 150 K. As indicated in figure 7 the calculated quench propigates very quickly so that an external dump resistor is of little use. More details of this magnet design and these quench calculations are given in reference 8.

Spectrograph Quadrupoles

The first quadrupole of the S800, indicated as Q_y in figure 8, requires a 20 cm diameter aperture, a pole tip field of 2.1 T, and is 40 cm long. This quadrupole is not designed in detail so far, but POISSON calculations indicate that it can be constructed using a square Panofsky-style gemoetry[9]. This will yield a peak field in the conductor at the corner of about 3 T, but Panofsky quadrupoles of this size and operating at such field levels have been constructed and successfully operated[10,11]. As mentioned above, it is this magnet for which superconductivity is most essential, due to its high pole-tip field.

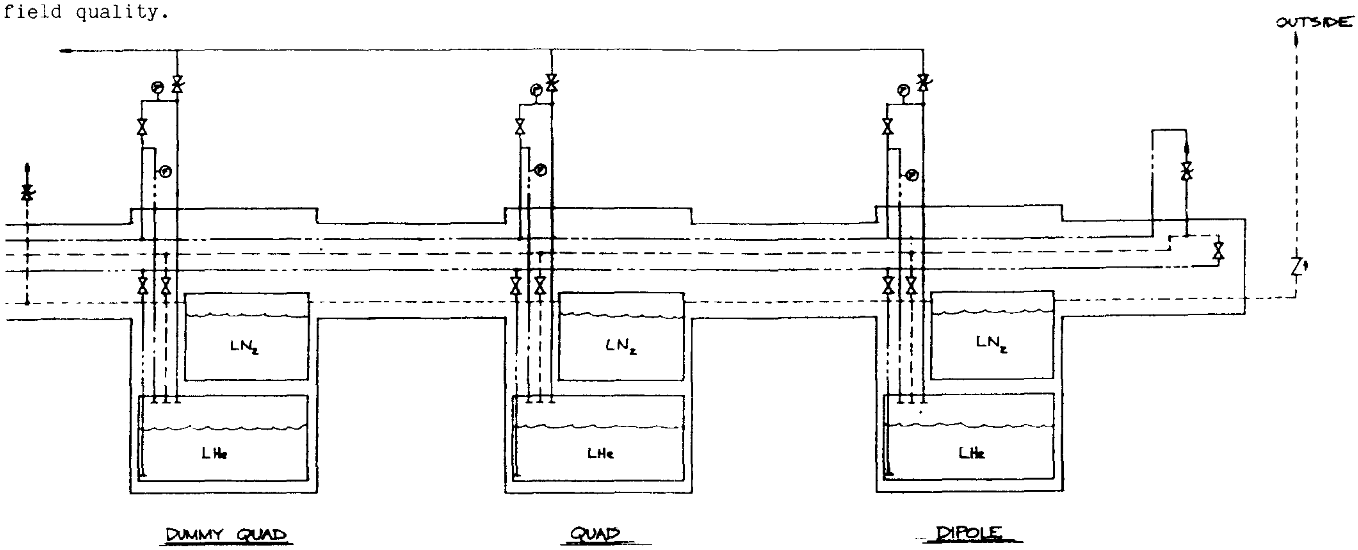

Fig. 4. Schematic diagram of the prototype cryogenic beamline.

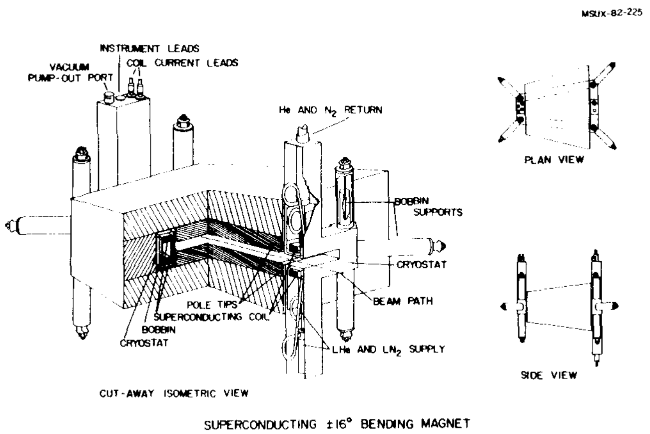

Fig. 5. Schematic drawing of the prototype ±16° superconducting switching magnet.

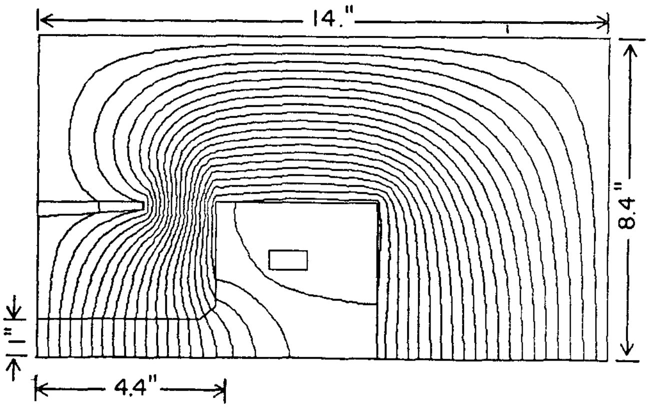

Fig. 6. Two dimensional POISSON calculation of a section of the ±16° switching magnet.

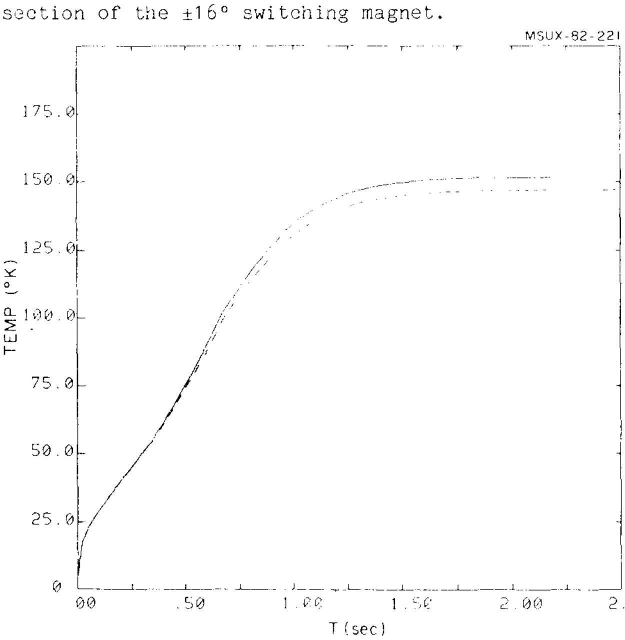

Fig. 7. Calculation of the hot spot temperature in the coil of the ±16° switching magnet as a function of time following the initiation of the quench. The solid line is for the case with no external dump resistor while the dashed line corresponds to switching in a dump resistor at the start of the quench.

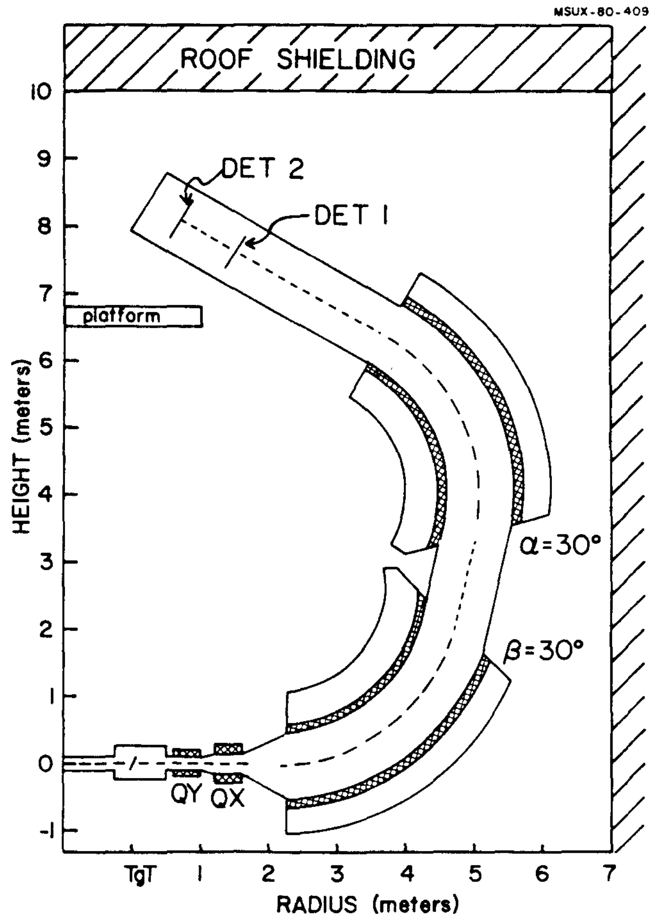

Fig. 8. Schematic view of the k=800 spectrograph showing the two superconducting quadrupoles and two superconducting dipoles.

The second quadrupole, Q_x in figure 8, has a much lower pole-tip field requirement (1.0 T), but is rectangular in cross section (17 cm x 35 cm). Hence, it will be convenient to make this a Panofsky-style quadrupole with a 2:1 aspect ratio.

Spectrograph Dipoles

The S800 uses two 75 ton superconducting dipoles as indicated schematically in figure 8. An expand-view section of one half of one of these H-frame dipoles showing the pole tips, main coils, trim coils, bobbin and cryostat is shown in figure 9. The results of POISSON calculations for this magnet showing the effects of the filter gap behind the pole tips and the trim coils are given in reference 12. This spectrograph has a k-parameter of 800 for the central ray at a nominal dipole field of 1.5 T, but the field profile is calculated to still be reasonable to approximately 1.6 T. The forces on the coil are also calculated to be tolerable up to this field level.

The steel for these dipoles has been machined and received at the NSCL. The stainless steel bobbins for the coil have also been manufactured. The details of the coil winding scheme are currently being finalized. Each of the four coils will consist of 270 turns of 0.128" x 0.078" superconducting wire. The most difficult aspect of the coil winding will be associated with the negative curvature on one side of the dipole. The coil will be wound with very little

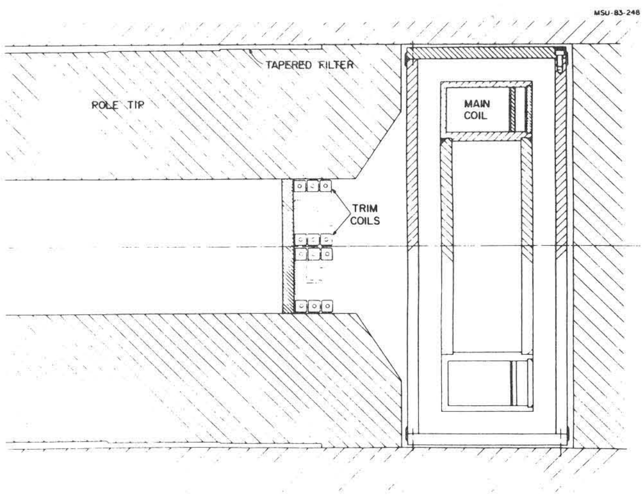

Fig. 9. Enlarged view of a section of the dipole of the S800 illustrating the beam vacuum chamber, pole tips, cryostat, coils, and coil bobbin.

tension, held in place turn by turn with clamps, and finally kept under external pressure by springs. Because of the low magnetic field, the magnetic forces on this coil are fairly small, less than 200 pounds per inch.

Summary: Pros and Cons

In this paper we have briefly described the designs of several low-field superconducting magnets which are being built for the beamlines and spectrograph at the NSCL. Cost studies have indicated that these magnets are less expensive than conventional ones, both in construction and operation. They also have additional advantages. The S800 solid angle is about a factor of four larger than would have been possible within our budget with conventional magnets. Ampere-turns are relatively inexpensive, making it economically feasible to use larger magnet gaps and also to save significantly on the mass of steel in the yokes. Also larger gradients in the beamline quadrupoles give shorter focal lengths and, hence, more beam transport options within a given amount of building space. A side benefit associated with the cryodistribution system is the availability of liquid helium for cryopumps in the experimental areas.

The disadvantages of such extensive use of superconducting magnets are primarily associated with learning the technology. While the material costs for the superconducting magnets are significantly less than for the corresponding conventional ones, the assembly is intrinsically more intricate. High quality welding and careful leak checking are essential. In operation, expertise in refrigerator operation and maintenance must be developed. At the NSCL the cyclotrons already demand the presence of this technology. Hence, this is the ideal place to use superconducting technology also in the beamlines and experimental areas. We feel that at higher beam momenta the potential economic savings are even larger, so it is important to begin now to develop the necessary designs and techniques which will be essential later.

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