DESIGN AND CONSTRUCTION OF A LOW CURRENT, CRYOGENICALLY EFFICIENT BEAM LINE QUADRUPOLE*

A.F. Zeller, J.A. Nolen, M.J. Dubois, J.C. DeKamp and R.T. Swanson
National Superconducting Cyclotron Laboratory Michigan State University East Lansing, MI 48824

Abstract

A superconducting quadrupole with a 12.7 cm bore has been designed and is under construction. It uses a hyperbolic pole to shape the field for gradients up to 28.8 T/m with a gradient uniformity of 0.1% at the warm bore radius of 5 cm. A maximum operating current of 12.5 A makes it possible to achieve an estimated liquid helium consumption of 0.1 l/hr so that a 25 l reservoir permits refilling weekly.

Introduction

The beam transport system for the 1.6 GeV/c NSCL Phase II beams will use many superconducting magnets, including approximately 70 superconducting quadrupoles. Because of the large numbers involved, we are developing a quadrupole which is to be highly reliable as well as cost efficient, both in construction and operation. Great emphasis has been placed on cryogenic efficiency. The design of a prototype, which is currently under construction, is described in this paper.

Choice of Magnetic Configuration

Three types of quads were considered: 1) Panofsky[1] 2) intersecting circle approximations to cos 2θ, and 3) hyperbolic iron pole tips. The Panofsky style[2], was a serious candidate, but suffers from two problems: The field in the corners of a square quad is $\sqrt{2}$ times the field at the "pole" which means that the superconducting wire parameters are dominated by a region of "wasted field". Also two Panofsky quads which have been built and carefully mapped[3,4] have achieved the desired field uniformity only by very careful construction, assembly, and attention to where each individual wire is placed. Thus, while we may use Panofsky quads for rectangular or very large aperture quads[5], we have not chosen this style for the beamline magnets.

Small diameter cos 2θ quads which produce highly uniform gradients of up to 50 T/m have been built at Fermi lab[6], and many other places. However, these designs have mostly used conductor in the form of flat cable which requires high current operation (1-5 kA). Vapor-cooled current leads for 1000 A require 2.8 l/hr, of LHe boil off, so 70 quads would use all the 200 l/hr capacity of our refrigerator. Additionally, the cost of the high current power supplies would be prohibitive. We have calculated low current quads which use two offset circles of current ("sliver quads") to approximate the required current density and shape. While quads of highly constant field gradient can be designed, they depend critically on exact wire placement.

Since it is easier to shape iron than complicated coil bundles, we have settled on a design which shapes the field primarily with iron pole tips. We know that a window-frame dipole, in the infinite permeability limit, produces a perfect field up to the coil, and such a dipole conformally mapped into a quadrupole is also perfect. The result is a hyperbolic iron pole tip and a coil which also has a hyperbolic cross section and a current density which varies with radius. The superconducting quadrupole which we are building is an approximation to such a mathematically perfect device.

Field Calculations

Conventional water-cooled copper coil quadrupoles have been used for many years, but the problem of getting enough conductor into the space available has limited their use to low gradients and/or small apertures. With conventional quadrupoles the peak magnetic field is often much larger than the pole tip field. However, superconducting coils, operating at densities up to 50 times larger than water-cooled copper coils permit much more compact designs with correspondingly lower peak fields. Starting with a hyperbolic-shaped pole and coil, a design was found in which the coil cross section is a straight line approximation to the hyperbolae and the current density is a constant. The resulting iron and coil cross sections and calculated field lines are shown in figure 1 for a 12.7 cm inside diameter quad. These

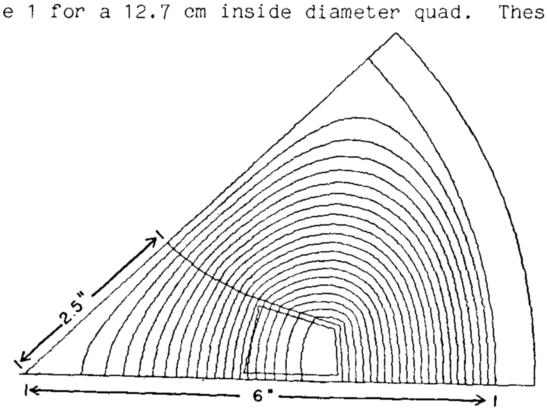

Fig 1. Field lines calculated for a cold-iron superconducting quadrupole (One eighth of the quadrupole is shown.)

calculations were done with the two dimensional code POISSON[7] and, therefore, do not include estimates of the end effects on the integral gradients. The final radial position of the coil represents a compromise between small radii to mimimize peak fields in the conductor and larger radii to reduce sensitivity to details of coil shape and wire placement. In this design the peak field in the conductor is about 1.25 times the pole tip field. Figure 2 shows the uniformity of the gradient calculated for the infinite permeability assumption and for several

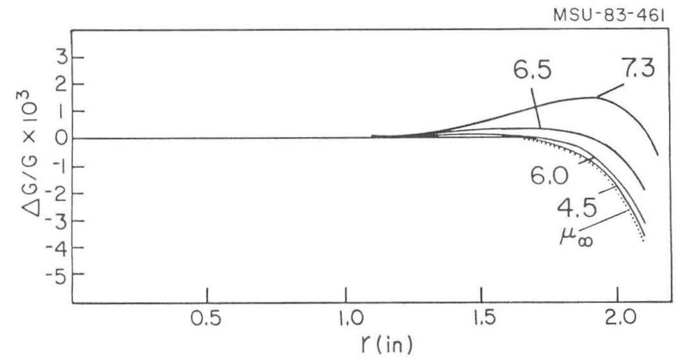

Fig. 2. Deviation of the gradiant from the central gradiant in parts per thousand as a function of radius for the infinite permeability and several finite permeability field levels.

gradient levels assuming a realistic permeability curve. Beyond 7.3 kG/in (28.8 T/m) the field quality rapidly deteriorates as the poles saturate. Only at the highest fields does the gradient deviation vary by

TABLE 1

Harmonic components of the field at a radius of 5 cm for several gradients. The numbers are defined by $B_N/B_{QUAD} \times 10^4$. N is the component whose radial dependency is given by $(1/r)^{(N-1)}$. λj is the current density in the coil at the given gradient.

G (kG/in)	G (T/m)	λj (A/cm^2)	N=6	10	14	18	22	Sum
$\mu=\infty$			1.0	-0.8	-0.7	-0.3	-0.1	-0.9
4.5	17.7	5400	1.2	-0.8	-0.7	-0.3	-0.1	-0.7
5.0	23.6	7300	1.4	-0.5	-0.7	-0.3	-0.1	-0.2
5.5	25.6	8000	2.5	-0.1	-0.7	-0.3	-0.1	1.3
7.3	28.8	9100	4.6	0.9	-0.7	-0.3	-0.1	4.5

over 0.1 % at a 5 cm radius. Table 1 lists the multipole components of the field in part in 10^4 calculated at a 5 cm radius relative to the quadrupole component, where the design has been optimized for 23.6 T/m. Small changes in coil placement and/or shape do not produce large changes in the calculated properties. A photograph of the machined yoke (1020 steel) and low carbon (1003 steel) pole pieces is shown in figure 3. The entire magnet will be operated at liquid helium temperature.

Superconducting Parameters

In order to keep the helium usage as low as possible, a very low operating current (12.5 A) has been chosen. Although this results in a large inductance, the corresponding savings in helium consumption and reduced power supply cost is very attractive. Quench calculations for these potted coils indicate that they are still conservatively designed. This is mainly due to the low stored energy and short coil length. The magnet, conductor, and coil characteristics are summarized in table 2 and a schematic drawing of the complete quad showing main features is given in figure 4. A semi-automatic winding table for these large-turn-number, wet-wound coils is currently being developed.

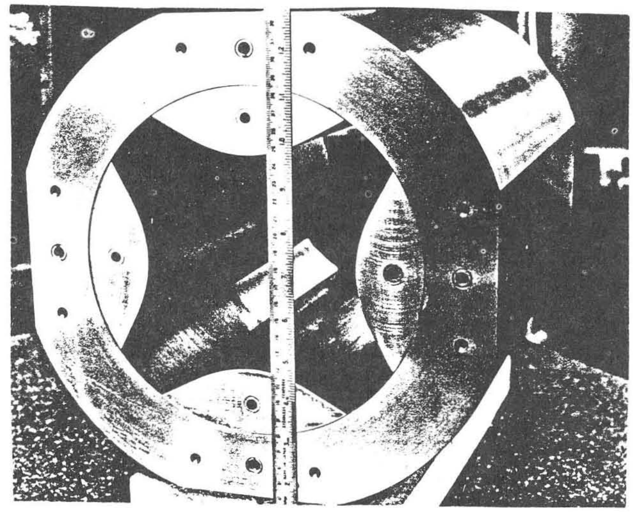

Fig. 3. Photograph of the steel yoke and pole tips of the superconducting quadrupole prototype. The yoke is 30.5 cm O.D. by 35.6 cm long.

TABLE 2

Magnet	
Pole tip diameter	12.7 cm
Warm clear bore	10 cm
Length of iron	35.6 cm
Outside diameter of yoke	30.5 cm
Iron weight (cold)	145 kg
Wire (NbTi)	
Diameter	0.3 mm
Cu:SC	6:1
I_{crit} @ 2T	18 A
Turns per coil	3740
Coil at 28.8 T/m Gradient	
Operating current	12.5 A
Stored energy	6250 j
Inductance	77 h
Helium gas to cool leads	5 g/hr

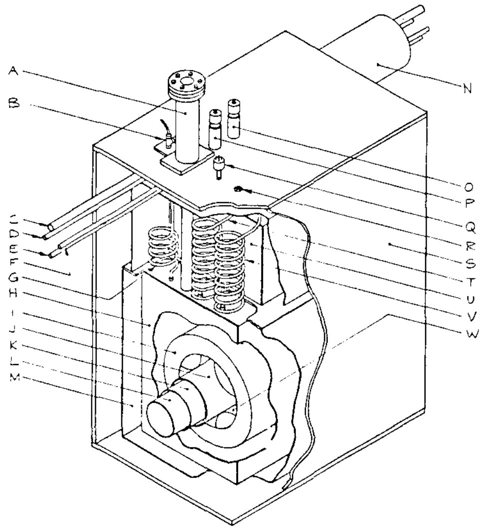

Fig. 4. Schematic drawing of the superconducting quadrupole showing parts indicated by the following letters: A - Rupture disk port, B - Instrumentation and coil lead feed-thru, C - 300 K He return line, D - LHe supply line, E - LN supply and return, F - Cold He gas return, G - Vapor cooled coil and instr. leads, H - LHe reservoir, I - Magnet iron, J - Inner cryostat wall, K - 77 K inner shield, L - Warm bore beam tube, M - 77 K radiation shield, N - Transfer line vacuum jacket, O - LHe supply valve, P - Cold He gas return valve, Q - Vacuum transducer, R - Thermocouple feed-thrus, S - Vacuum box, T - Cold He gas return, U - LN reservoir, V - LHe supply, W - Coil space (coil not shown). The room temperature vacuum box (S) is 48 cm wide, 66 cm long, and 88 cm tall.

Cryogenic Parameters

To minimize the overall LHe load on our refrigeration system, and to cryogenically decouple devices during operation, a batch-fill mode of operation will be tested (see paper on cryodistribution system by Dekamp et al at this conference). The break-even point over a continuous flow system requires a minimum of one week between LHe filling. In order to fulfill this condition, and to keep the reservoir a resonable size, careful design and construction is required. It was decided that a 25 l dewar was the practical limit for both LHe and LN. Calculated heat leaks are listed in table 3. Note that the vapor-cooled current leads are not listed since the cryostat evaporates enough helium to cool the leads. The leads, a type suggested by John Purcell[8], consist of nine strands each of 0.01" diameter formvar insulated superconducting wires. All 18 wires for the two leads plus the instrumentation wires (the same type conductor), are twisted together to form a single vapor-cooled bundle sealed into a long stainless steel tube (feature G in figure 4).

Table 3

Calculated heat loads for the quadrupole cryostat (l/hr)

ITEM	LHe	LN
Support links	0.015	0.002
Rupture disk & tube	0.029	0.002
Feed lines	0.008	0.001
Radiation	0.028	0.084
Total	0.08	0.09

Conclusions

We believe that production-model quads of this type can be built for about 10 to 15 thousand dollars each. Testing of the prototype will begin this summer.

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