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A SUPERCONDUCTING IRON-DOMINATED QUADRUPOLE FOR CEBAF

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Abstract

The present design for the high-resolution spectrometers at CEBAF requires a front quadrupole (Q0) that has a gradient x length of 6.8 T with a "good field" aperture (1x10^{-8} uniformity in gradient) of 16 cm radius. A room temperature design was found too power hungry and interfered with the beam. Engineering and construction of a small cos 2θ magnet was considered to be quite expensive. A Panofsky design was not considered due to the extreme sensitivity of the field quality to errors in conductor placement. A conformal mapping of a window-frame dipole into quadrupole geometry worked well at NSCL[1]. A conceptual design has been developed with the following characteristics; physical length (total)=1.2 m; iron length=1.1 m; iron outer dimensions=54 cm x 80 cm; peak gradient= 6.2 T/m; pole radius=20 cm; " Good field" radius=16 cm; coil peak field=1.5 T; conductor=1 mm diameter; Cu/NbTi=7:1; current=400 A; turns=250/quadrant; stored energy=50 kJ.

Introduction

Designing the quadrupoles for the CEBAF focussing spectrometers has proved a non-trivial task. One of the designs presently under consideration[1] is that of a superconducting cos 2θ concept with a 1 m coil diameter and 1.5 m long; peak field is around 2 T. There is an iron return yoke around the magnet. Clearly this is a formidable object both structurally and financially. A different, seemingly simpler and cheaper design is the topic of this paper. This magnet is iron-dominated, ie. it has iron poles, but uses superconducting coils; the iron is cold. The design, construction, and expected performance of the magnets are presented below.

Design Procedure

Magnetic Design

One is driven to superconducting designs for magnets by fields high enough to cause iron saturation and/or power costs. While there have been several approaches to the problem of superconducting dipoles, superconducting quadrupoles have seen only two designs until relatively recently. These are the " cos 2θ" and "Panofsky" de signs. The former is essentially the only design used for accelerator applications and has been developed to a high state by many groups all over the world; all have had bores of less than 20 cm. The latter was initially constructed by Purcell's group at Argonne National Lab. for the ZGS[2]. These small bore ($\sim$10 cm I.D.) magnets were simple to build as they used an easily machined iron " box" around random-wound coils made of small diameter wire. Saclay[3] and KEK[4] later built larger aperture " Panofsky's", but they experienced a great deal of difficulty. A notable point of distinction between both of these magnets and the ANL magnet was the larger conductor and discrete turn-by-turn winding in the large magnets versus the above mentioned small conductor which was random-wound in the ANL magnet. Some of the problems experienced in the larger magnets could possibly have been corrected with an improved bracing of the coils and/or a change of epoxy type.

A third type of superconducting quadrupole was developed at Michigan State University for the NSCL beamlines[5]. It differs from the other two in that the field shaping is done primarily by iron poles; in this sense it more closely resembles "classical" iron-dominated quadrupoles but with some important differences. A sketch of an octant of this design is shown in Fig. 1. The fraction of useful bore of this magnet is quite good when compared to resistive magnets. Mathematically this performance can be understood by conformally mapping this and the standard geometries into equivalent dipoles. One finds that the standard design maps to an ill-formed " H" dipole while the new design maps to a " window-frame" dipole. The field in a window-frame dipole is uniform up to the edge of the conductor; thus a conformal mapping of it into a quadrupole would give a magnet good up to the edge of the conductor. This is not true for the " H" magnet; typically, 1 to 1 1/2 half-gaps are lost inside of the pole edge with a commensurate loss in the mapped quadrupole. Resistive coil magnets are forced into the mapped "H" geometry by virtue of the large number of amperes-turns needed by the typical magnet and the limited current density available with copper, ie. the magnets simply need the space to get all the ampere-turns packed in. Peak pole fields are also limited by saturation of the pole root. The pole does not grow in cross-section to accomodate the additional flux which enters it with increasing radius; in some magnets the

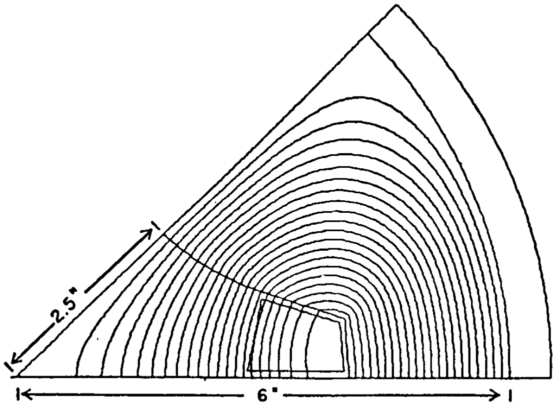

Figure 1: Octant of NSCL beamline quadrupole with field lines.

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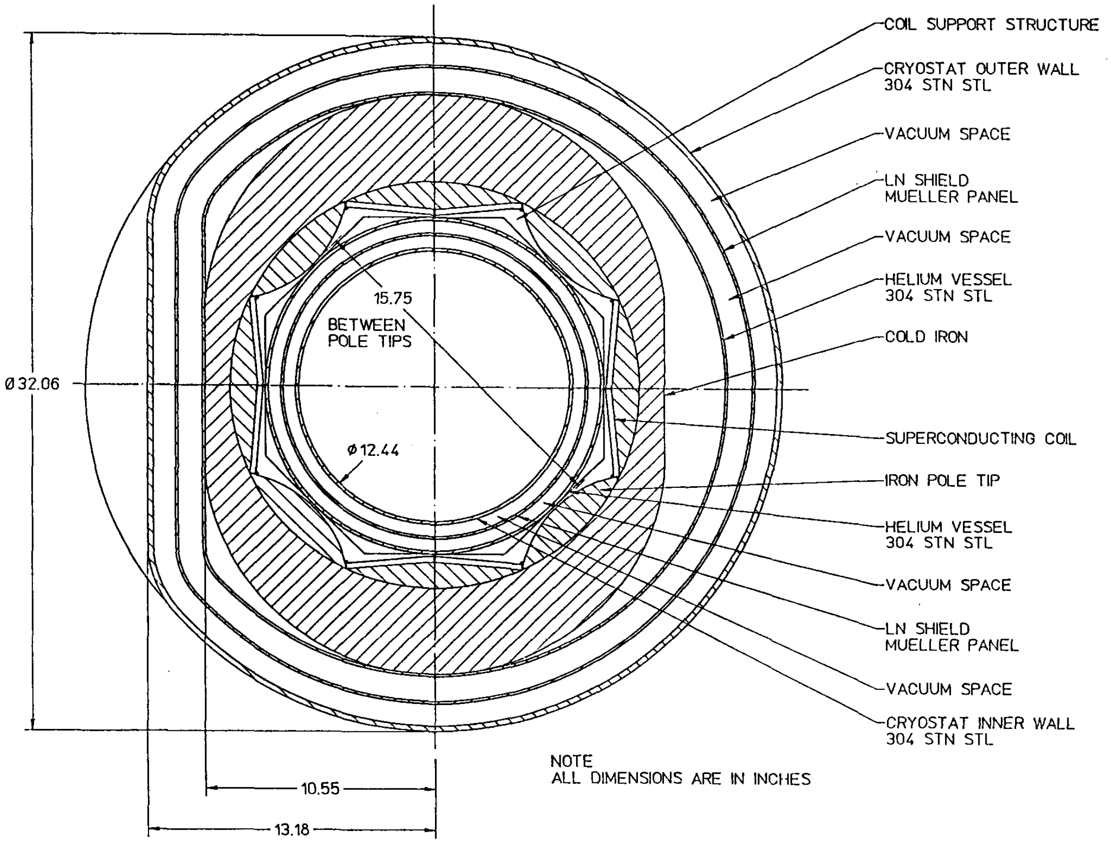
cross-section even decreases in order to permit a large coil to be used. The mapped window-frame magnet does not suffer from this handicap since the pole cross-section increases until the return iron is reached. If the conformal mapping were carried to its full analogy, the coil surface would be hyperbolic and the current density would not be uniform. As an accurately non-uniform current density would be difficult to achieve, the nonuniformity is compensated for by repositioning the exposed surface of the conductor; simultaneously, the face was simplified to a flat surface which is easier to manufacture than the "perfect" hyperbola. The angle of the surface was adjusted until the field reached an optimum quality. The coils are random-wound in a wet lay-up procedure with an ingeniously simple winding table; *2000 turns of 0.4 mm conductor are put on a coil* in one 8 hour shift. The iron for the magnet is machined with numerically controlled machines. The magnet proved to be inexpensive and straightforward to build. By having the field shaped primarily by the iron, it also escaped the bane of most superconducting quadrupoles, ie. conductor misplacement.

The initial need for such a magnet for CEBAF came in the front quadrupole for the HRS[2] spectrometer system. There is a premium put on the extent of the median plane dimension for this magnet as it sets the minimum scattering angle for the spectrometer. A resistive option was investigated and it was found that it would be a 0.4 MW magnet and would interfere with the beam at the desired scattering angles. It was felt that a down-sized version of the cos 2θ magnets would be prohibitively expensive. The MSU "cold-iron" magnet held promise of inexpensive construction and good field performance. A design has been developed following the same design procedures but aimed at the more ambitious goal of having the coil at the same radius as the pole. To date the magnetic study has been done with the the POISSON suite of two-dimensional magnetostatic codes; end effects will be studied in the future with the three-dimensional magnetostatics code TOSCA. As at MSU, small gaps were left at the top and bottom of the coil for manufacturing and assembly ease. The initial study was for a magnet with a "good" field region with a radius of 16 cm. "Good" field is, of course, an subjective goal. The specific goal of this study was a fractional deviation from a "perfect" quadrupole field of no more than $5\text{x}10^{-4}$. A cross-section of the magnet at the present stage of the design is shown in Fig. 2. This magnet achieves fractional deviations of $2\text{x}10^{-4}$ for



NOTE
ALL DIMENSIONS ARE IN INCHES

Figure 2: Cross section drawing of current state of design of the cold-iron quadrupole. Iron is assymetric to meet constraints on space in the horizontal plane.

gradients of 6.2 T/m and below, as shown in Fig. 3; at 7.4 T/m (1.5 T pole tip field, which is 1.5 times the nominal 1.0 T for "conventional" quadrupoles) the deviation is less than 3×10^{-4} in the desired aperture. The Fourier decomposition is outlined in Table 1.

Table 1

Fourier Decomposition of Quadrupole Field*

n	B_n**
2	990.8
6	-3.9
10	3.5
14	1.5

* At 16 cm nominal warm bore radius of magnet shown in Figure 1.

** $B(r) = \Sigma B_n(r/16)^n$; r is in cm.

Two types of trimming have been tried for this magnet. One is the inclusion of a "skew" winding. This is a coil which gives a quadrupole field rotated by 45° relative to the primary field; such a coil can be used to correct for rotational misalignment of the magnet. It was modeled with the following procedure: (1) the "normal" geometry was rotated until the centerline of the pole lay on the axis; (2) the first 45° above the median plane was then modelled with LATTICE; (3) a number of current filaments were placed on a cylinder of 18 cm radius; (4) POISSON was run in the infinite permeability limit; (5) the number and angular positions of filaments were varied to achieve optimal field quality. Table 2 presents the Fourier decomposition of the field at the nominal 16 cm radius aperture for a magnet with four filaments in each quadrant; the filaments are placed $\pm6°$ and $\pm24°$ relative to the centerline of each pole. The 28-pole term is the largest error term and represents 10% of the quadrupole field. The skew quadrupole would be used to correct for a misalignment of the median plane of the magnet and the median plane of the spectrometer; as this alignment should be achievable mechanically to about 1 mrad, the skew quadrupole strength would be less than 0.001 of the primary strength. Thus, the skew 28-pole would be less than 0.0001 of the primary quadrupole field at the warm bore radius and would rapidly become less; this is well within the goal for this study. Multipoles superimposed on the quadrupole might be needed in some optical systems. A sextupole was investigated here as a proof of principle. The procedure was similar to the skew quad except the entire half of the magnet above the median plane had to be modelled; 12 filaments were used to achieve acceptable field quality. In this study, finite permeability was used with the magnet energized to the 6.2 T/m which corresponds to the field needed for one of the proposed spectrometers. The magnet was run with the sextupole filaments activated and with them deactivated. A Fourier analysis of the field was done in both cases; the Fourier amplitudes were then subtracted in order to get the net effect of the sextupole. The results are given in Table 3. The fractional field error is on the order of 1%. The procedure gives a respectably good sextupole considering it is constructed of only a few strands of conductor. Not surprisingly, it was found that increasing the radial position of the filaments improves the field quality as this moves these singularities in the field further from the point of observation.

Table 2

Fourier Decomposition of Skew Quad Field*

n	B_n**
2	98.6
6	-1.4
10	1.7
14	10.0
18	-0.00037
22	6.2
26	-2.4

* At r = 16 cm

** $B(r) = \Sigma B_n(r/16)^n$

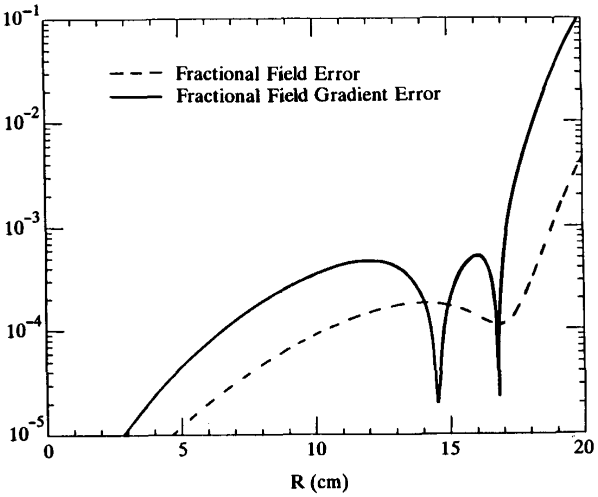


Figure 3: Fractional deviations of the magnet shown in figure 2 from a perfect quad. Results are shown for both field and gradient.

Table 3

Fourier Decomposition of Sextupole Field*

n	B_n**
3	82.6
5	-3.0
7	-1.6
9	0.024
11	1.41
13	-0.019

* At $r = 16$ cm; values presented are after subtraction of terms present when only the quadrupole is energized.

** $B(r) = \Sigma B_n(r/16)^n$

Cryogenic Design

These magnets are fairly straight-forward in terms of conductor and cryogenics. Table 4 presents the numbers for a 1.1 m long magnet with a 20 cm pole radius (16 cm warm/useful bore radius) and a 6.2 T/m gradient. Calculations with the venerable code QUENCH indicated a 400 A conductor would limit the induced voltage in a quench to 800 V if an external dump resistor was switched in when the internal voltage reached 5 mV. Conductor with this current capability is available with a 1 mm diameter; such a conductor would still permit the coil to be made in a random-wind, wet lay-up procedure as with the MSU magnet. This will keep the cost low relative to working with discrete placement of large conductor. This conductor is also suitable for the trimming coils as they would have acceptable strengths with a single strand used for each of the filaments used in the modelling.

Mechanical Construction

Although all the mechanical details have not been worked out, particularly the details of the cryostat, many of the main features have been addressed. The yoke would be made of two halves which are dowelled before the final machining of the circular bore. The poles, along with the iron pieces immediately outside the coils, are machined as separate pieces; the coils are made with a random-wind, wet lay-up procedure, as mentioned earlier. The quality of the field is primarily determined by relative positioning of the inner surfaces of the poles relative to the coils; symmetry is, of course, critical. In order to achieve the desired relative positioning without exorbitant cost or risk, a fixture within the aperture of the magnet seems to be optimal. This fixture would best be made with its exterior a direct "mold" of the desired surface upon which the components should lie. However, the need could be removed with some ancillary fixtures to guarantee the orientation of the poles with respect to the fixture. The choice between the two procedures awaits a more detailed cost study. The assembly procedure would have the poles, coils, and coil back-up iron placed on the fixture; they would then be held in place with a pin through a stainless steel ring on each end of the structure into each component; the rings would then form the final constraint on relative motion of the parts. The yoke would be split into its two halves and the halves reassembled around the "core". The rings which connect the "core" pieces would then be attached to the yoke, thereby fixing the "core" to the yoke. The assembly is then placed in its cryostat with all the appropriate leads and diagnostics. The helium temperature bore tube would itself be the most likely spot to mount any corrector coil turns.

Table 4

Physical Parameters of Present Q0 Design

Physical length (total):	1.3 m
Iron length:	1.1 m
Iron outer dimensions:	54 cm x 68 cm
Peak gradient:	6.2 T/m
Pole radius:	20 cm
"Good field" aperature radius:	16 cm
Coil:	
Peak Field:	1.5 T
Conductor:	1 mm dia.
Cu/NbTi:	7:1
Current:	400 A
Turns:	250/quadrant
Stored energy:	50 kJ
Winding technique:	random wind, wet lay-up

Summary

The design described above for a cold-iron, superconducting quadrupole appears to be a less expensive, lower-risk, higher precision alternative to cos 2θ quadrupoles. Its limitation lies in the iron poles, ie. it starts to have poor field if the iron is saturated. However, the iron limitation is 50% higher than in resistive magnets because optimal use of the iron geometry is achieved by the full exploitation of conformal mapping to understand the field performance and thereby have a much extended range of application.

References

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