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HIGH FIELD SUPERCONDUCTING MAGNETS FOR ACCELERATORS AND PARTICLE BEAMS*

J. Allinger, G. Danby, and J. Jackson†

ABSTRACT

Experience in designing precision superconducting magnets for fields up to 60kG will be described. Realizable construction tolerances and their impact on field accuracy is discussed. For dipole fields up to 60kG or more, rectangular coil window frame type magnets will be compared with circular or elliptical coil designs. In all cases, the same superconductor current density versus maximum field performance is assumed. The comparison will include field quality and correction required as a function of aperture size, stored energy, ampere turns required, and overall magnet size. In quadrupole design the impact of the allowed superconductor current density being roughly inversely proportional to peak field is severe. For gradients up to one Tesla/cm or greater, similar comparisons for different types of quadrupole construction is made.

I. INTRODUCTION

Considerable experience has been gained with superconducting magnets which utilize coils of rectangular cross section confined within iron window frames.^{1,2,3,4} These designs all employ a single auxiliary correction winding circuit to compensate for the effects of iron saturation. It is believed that magnetic fields comparable in precision and in predictability to that of conventional magnets can be obtained at all levels of excitation by utilizing the correction winding in a predetermined way. The scope of this paper is restricted to considerations of magnetic circuit design. A summary of performance is first given to establish relevance.

II. SUMMARY OF EXPERIENCE

Magnetic field measurements, internal and including end effects, of both 2m modules of the 8° system showed that a high degree of mechanical accuracy was maintained. The accuracy of measurement of multipole fields was $\sim 1 \times 10^{-4}$ of the dipole field at the search coil radius of 76% of the radius to superconductor. The integrated quadrupole normalized to the dipole was $\sim 1 \times 10^{-4}$ per cm. Higher multipole contributions due to winding or assembly errors were within the accuracy of measurement.^{1,2} Based on two units, the ability to construct large numbers of identical and predictable modules appears demonstrated to an accuracy within about a factor of two of that obtained in the construction of quality conventional magnets. This is, we believe, the best which has been reported to date for superconducting magnets. Because of the importance of this question, it is planned to measure more accurately the difference between the two units by simultaneous measurements. For completeness it must be noted there is a very small difference between the two 8° units, predictable by computer. This occurred for reasons which are not fundamental.¹ The absolute field uniformity, although it compares well with other superconducting magnets to date and is much better than required for its application, is not as good as that of the best conventional magnets. Improvements in the conceptual design will be described in Section III which should produce very uniform fields.

The 8° magnets also demonstrated that with the window frame design, high pressure prestressing during assembly is not necessary for accuracy and stability.

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Prestressing is commonly used to compensate for the greater shrinkage of the coil than of surrounding supportive cold iron during cooldown. With the rectangular window frame geometry, provided coil turns are constrained to move sideways only as coherent vertical layers, the coils will move outward under magnetic pressure and take a set against the supporting iron. Such coherent coil migration changes slightly the aspect ratio of the rectangular magnet aperture. Computations show this has a completely negligible effect on the magnet field. There will also be a differential shrinkage in the vertical direction. With the iron split on the horizontal midplane, the core can be assembled with a midplane space left between halves equal to the differential shrinkage. Upon cooldown the two halves come together, tightly constraining the coil and eliminating the differential.

High conductivity anodized and corrugated aluminum interlayer sheets provide a very efficient heat exchange with the helium coolant and ultrastability. This is in addition to providing electrical insulation and the coherent layer structure described above. The use of these sheets is unique to this design, and takes advantage of the fact that the field is almost vertical in the coil. All models of this type have shown extreme stability and excellent superconductor performance even when formvar coated rectangular composite NbTi conductor was used. A 1/2m long, full scale cross section model of the 8° magnets has operated to 50kG with extreme saturation because its return yoke was designed for 40kG. Portions of the coil experienced 57kG with a current density of $>90\text{kA/cm}^2$ in the coarse (75 micron) NbTi filaments, which is essentially short sample performance.¹ This magnet and the 8° modules were stable under test when charged or discharged in times as short as seconds, in spite of massive heating induced in the solid iron cores. Smaller laminated iron models have been completely stable, even with rise times to 40kG as short as 1/3 second.³ The time constant for dynamic effects is short, of the order of seconds, and is dominated by eddy currents in the stabilizing aluminum sheets.

A fundamental question relating to the practicality of superconducting magnets for primary beams or accelerators is their quantitative susceptibility to quenching. Results on the 8° magnets operating in a primary proton beam have demonstrated a large tolerance for absorbing accidental beam heat.^{1,2} This important question is being further studied. Experiments with various target materials and geometries are underway to determine experimental radiation heating and quench thresholds. This work in conjunction with detailed computations of radiation density, will provide a basis for predictions.

A related very important question is the speed of propagation of heat through the coil cross section

of a magnet with large stored energy which is undergoing a quench due to radiation heating or mechanical motion. Rapid transverse quench propagation can prevent large internal voltage generation and affect the number of turns safely allowed in a coil.

Low current conductors can form the basis for a magnet and dewar design with small heat loads.

Such basic parametric questions are strongly coupled to magnet circuit design. Preliminary observations indicate the present design is very favorable in this respect. As information is further developed for a variety of superconducting magnets, such questions will become clearer and will ultimately narrow the choice of magnets for a given application.

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The summary above emphasized results with coil designs which were developed as most appropriate in performance and economy for their purpose. Clearly all types of superconducting coils, with cabled or braided conductors, potted structures, etc. can be used with the window frame circuit. The small laminated model has been operated with a wide variety of conductors.

III. SECOND GENERATION DESIGNS FOR 40-45KG DIPOLES

A conceptual cross section of one quadrant of the 8° magnet, the first design of its type, is shown in Fig. 1. Below 22kG the high gap window frame has an extremely uniform field, modified only by the cooling channel cut from the iron above the dipole coil. The 1/2m model, built to develop winding techniques, was designed after the 8° magnets and had an improved computed field uniformity: everywhere constant to 1×10^{-4} for permeability μ large. Later designs, by adjusting the coil, iron and cooling channel surfaces, are even better and can give arbitrarily constant fields below saturation.

Saturation of iron in the pole regions commences at $B = 22$ kG, and produces aberration multipoles growing linearly proportional to $(B-22)$ kG. Table I, Column I shows this change at 4kG. The sextupole field ($r^4 \frac{3}{2} \frac{1}{\rho}$) is 4.8% of the dipole at 80% of radius to superconductor. The amplitudes of successively higher terms fall off rapidly.

TABLE I
Normalized Multipole Amplitudes for 40kG Magnet at 80% of Radius To Superconductor

	4kG-10kG Uncorrected	4kG Corrected w/Sextupole	4kG Corrected w/Multipole
$3\pm/10$	$+481.0 \times 10^{-4}$	0	0
$5\pm/10$	+31.5	+ 8.0	$+0.25 \times 10^{-4}$
$7\pm/10$	- 6.2	+ 2.0	+0.32
$9\pm/10$	- 1.5	-41.8	+1.74
$11\pm/10$	- 0.1	+ 6.9	-4.64
$13\pm/10$	- 0.3	- 1.5	+9.95

The midplane portion of the correction coil in Fig. 1 is a saddle coil like the dipole coil. Two simple race-track coils located top and bottom near the poles complete the circuit. All are powered in series, with j_A ampere turns alternating every 60° . (The dotted area $[+j_C A_B]$ is an alternate design to replace the midplane coil.) The amplitudes with the sextupole tuned to zero are seen in Column II. This requires at 4kG an excitation equal to 4.5% of the primary ampere turns. The correction coil, approximating a six wire air core sextupole, generates strongly $r^9 \theta$, the first odd harmonic of 3θ . This correction coil generated error is inherent in the design and is the dominant aberration. Other errors such as 5θ can be reduced by slight circuit refinements.

A second generation correction coil is illustrated in Fig. 2. The idea is to superimpose in concept several correction multipoles. These were then congealed into the simple correction shown which gives better correction than the "sextupole". The only practical complexity added is one small pair of flat racetrack coils. All elements are still in a single series circuit. In Table I, Column III are listed the multipole amplitudes present at 4kG with the sextupole tuned to zero using such a "multipole" coil. This reduced all lower order terms, especially 9θ . The error has been pushed up into $r^{12} \frac{1}{\rho}$ and other higher multipoles which should not effect the working aperture. (At 4kG on the horizontal midplane at 50% of radius to superconductor $\frac{\Delta B}{B} = 1 \times 10^{-5}$). At all field values the magnet is now sufficiently uniform on paper that

construction errors should determine performance. Finally, magnets of the 8° type, i.e., equal horizontal and vertical apertures of ~ 10 cm, are defined as 40-45kG because at this peak field the correction coil current density equals that of the primary dipole coil for reasonable cross sections.

IV. DESIGNS FOR ≈ 60 KG DIPOLES

It was decided rather than proposing a second generation 40kG magnet to proceed to design for higher fields. The window frame magnet circuit, with its extended dipole sheet approximation, rapidly improves in performance as the vertical gap is increased. The level of dipole saturation and of aberrations on the horizontal midplane at any field above 20kG drops off as a steep function of increase in vertical gap. As a result, the maximum usable field increases rapidly with gap. Consider, for example, the 8° magnets^{1,2} whose overall dimensions are 37.8cm high by 43.5cm wide, and which are inserted into a dewar of circular cross section. If the magnet height was made equal to the width, the vertical aperture could have been increased considerably while retaining adequate iron flux return. Experience has shown that the extra cost and labor for the increased coil height required would be a minor perturbation, resulting in only a small increase in magnet cost.

Fig. 3 shows the flux pattern of one quadrant of a 10cm x 19cm aperture 60kG design. Computations show that such a magnet has extremely small aberrations uncorrected at all fields except for sextupole. At 60kG this magnet has 1%/in. sextupole uncorrected and 10% more current than for $\mu = \infty$, in contrast to 2%/in. sextupole and 21% more current in the 8° magnets at 40kG.

The auxiliary correction coil consists of two Helmholtz pairs connected in series. Another feature of this design is that the field is everywhere lower in the dipole coil than in the aperture. The height overall need be no greater than the width. For example, Fig. 3 illustrates containment within a cylinder of nickel steel with radius determined by the horizontal midplane flux return. Such an idea would require no separate dewar vessel.

The group that constructed the 8° magnet is building a laminated core model to demonstrate dynamic effects, field uniformity, and high fields. This mockup model uses Tec shaped iron insertions to spread the two halves of an existing 90cm long core. The coil uses odd pieces plus used conductor with many splices. Thus, caution must be used in anticipating performance, particularly under high field stresses, but it should serve its purpose in any event. Fig. 4 shows the computed field uniformity at 50% of radius to superconductor for this model with a 6.35cm wide x 11.66cm high aperture. The maximum deviation from flatness ($< \pm 2 \times 10^{-5}$) at 30kG is due to $(r^4 \frac{1}{\rho})$. This extremely small error is basic and is the limitation imposed by using a single correction coil geometry at all fields. The first and second field derivatives also remain very small, even by the standards of conventional magnets.

V. COMPARISON OF RECTANGULAR AND CIRCULAR APERTURE DIPOLES AT 60KG.

It will now be shown that even if one made no use of the greater vertical height of the rectangular aperture magnet, which is an unnecessary restriction, there is no real penalty for realistic designs in stored energy or required ampere turns. Fig. 5 shows for a typical 8cm diameter to superconductor magnet the coil boundaries in the two cases. Both computed designs require 17kA/cm^2 in the coil package at 60kG. This is not a conservative rating for NbTi. It corresponds to ~ 1.5 cm overall coil thickness θ ; the more

familiar 40kG. (The dotted lines project for the cosine design $J = J_0 \cos \psi$, the equivalent constant $J = J_0$ coil area.) Comparing the rectangular magnet with the circular, the ampere turns are respectively $NI = 745$ vs. 821kA and the total stored energy $W = 210$ vs. 193kJ/m. The greater stored energy in the coil in the cosine case compensates for that in the extra height of the rectangular design, so that only 37% of the stored energy of the cosine magnet is in the aperture, vs. 82% in the rectangular case. The distances projected on the horizontal axes are to the iron boundaries (assumed round), and in both cases determined by a return yoke with $B=22$ kG. The rectangular magnet is $\sim 15\%$ smaller. External coil cooling requires horizontal space in the round magnet. This plus external coil support was assumed to use 1cm in Fig. 5. If this were reduced to 0.5cm, NI decreases by only 2.5% and W by 2.8%. However, for 60kG saturation contributes at $r = 4$ cm, 1% sextupole vs. 0.67% when the iron is 1cm away as in Fig. 5. Quite large sextupole correction coils are required which must be located inside the dipole coil.

Fig. 6 shows the effect of using a future advanced conductor such as Nb_3Sn , with double ($33\text{kA}/\text{cm}^2$) overall coil current density and with minimal 0.5cm external support and cooling. Now the circular magnet has NI 10% lower (652kA) and $W \sim 35\%$ lower (132kJ/m) than the rectangular. However, the heavily saturated iron produces 2.6% at the coil radius at 60kG for the round magnet, 2/3 as large as the 4% of the rectangular magnet. This requires a substantial correction coil at the inner coil radius. For the same useful horizontal beam aperture, the round magnet will have to grow larger, reversing its advantage in stored energy and required current.

Consider the effect of doubling aperture size in Fig. 5 from 8cm to 16cm, with J constant. The coil thickness and cooling space would remain almost unchanged. Except for a scaling factor the magnets would look like Fig. 6. Therefore, as apertures become larger, i.e., if iron moves relatively closer, the circular magnet could equal or surpass in saturation aberration the rectangular design, which changes more slowly with relative coil thickness.

The rectangular magnet has certain advantages for low fields. Fig. 7a shows 25kG designs with the $NbTi$ coil thickness scaled down to the same level of performance as at 40kG in Fig. 5. While its size advantage is very slight, the square magnet is an unsaturated window frame and can have in practice conventional magnet performance considerably less sensitive to current block motion than round magnets. Finally, Fig. 7b illustrates that for storage rings one option is to make long combined magnets. With the rectangular design, long racetrack coils on edge could thread the top magnet and return through the bottom with sagitta compensation easily included. Correction could also be provided by racetrack coils. For 25kG versions, external correction could suffice. Only study will tell if the simplifications compensate for the restriction on storage ring flexibility.

VI. QUADRUPOLE DESIGN CONCEPTS

The allowed aberrations for quadrupoles, provided the 4-pole symmetry is maintained, i.e., no construction errors are r^6 , r^{10} , r^{14} , etc. Control of only a few terms suffices to give high precision within a realistic beam aperture because of the large r dependence. Iron pole 40kG designs have been made with coil construction similar to the 8° dipole type wound into rectangular slots in the iron. A demonstration winding of one pole was made without difficulty for a

contemplated 20cm bore quadrupole. The impact of the critical current density $J_c \sim 5 \times 10^4$ for superconductors is severe on quadrupole design. For air core quadrupoles, the field continues to rise going into the coil. This limits J and for a constant G requires additional coil thickness and a corresponding increase in the peak coil field. The iron window frame design can reduce ampere turn requirements strongly even with large pole saturation, as well as reducing peak fields in the coil. Fig. 8 shows conceptually one quadrant of a 12cm bore design, requiring $J = 15\text{kA}/\text{cm}^2$ at 40kG ($G = 6.7\text{kG}/\text{cm}$). Although this is not an optimized design, computations show that with a single correction coil like the one sketched one can get very uniform gradients at all excitations. The dotted circle symbolizes the iron around a circular coil design where more ampere turns and higher coil peak fields will require a radially thicker coil. Thus, as in the case of dipoles, closely coupled iron can enhance the performance of quadrupoles.

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Fig. 1. Conceptual cross section of 8° magnet.

Fig. 2. 8° magnet with multipole correction.

Fig. 3. Flux pattern for 60kG dipole.

Fig. 6. Coil boundaries for rectangular and circular dipoles at 60kG with $J = 33 \text{ kA/cm}^2$.

Fig. 4. Computed field uniformity for 60kG dipole.

Fig. 7. Conceptual cross section of a 25kG dipole and a possible configuration for use in a storage ring.

Fig. 5. Coil boundaries for rectangular and circular dipoles at 60kG with $J = 17 \text{ kA/cm}^2$

Fig. 8. Conceptual cross section of high field quadrupole.