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HIGH PRECISION SUPERCONDUCTING MAGNETS*

J. Allinger, G. Danby, J. Jackson, A. Prodell
Brookhaven National Laboratory
Upton, New York 11973

Summary

Window-frame type superconducting dipole magnets have demonstrated accuracy and predictability of fields which compare well with the best conventional accelerator-type magnets. Precision measurements were made on the two series powered 2 m long 4 T modules comprising the 8° bending magnet at BNL after two years of beam operation including several dozen beam induced quenches. The integral field of the two units is identical to measurement accuracy, $\leq 1 \times 10^{-4}$ parts at $\sim$ full aperture, for all multipoles except quadrupole. Random quadrupole terms of $G/B = 6 \times 10^{-5}$ cm^{-1} or 2×10^{-4} parts are present. A 1 m long 6 T model of more advanced design shows pure dipole field, at all field levels, to 1×10^{-4} parts, using a single correction coil with predetermined excitation. The field shape at $\sim$ 0.5 T/sec rise rate is identical to dc. The advantages of the extended current sheet coil construction are discussed. Results will be compared with computer simulations of construction errors. Suitable conceptual designs of compact 6 T dipoles and of quadrupoles applied to a 1 km accelerator lattice will be presented.

I. Introduction

Prior to the advent of superconductivity, builders of accelerators and particle beams utilized magnetic fields which could be essentially determined by iron pole surface contours to great precision. Predictable deviations typically of the order of one percent over the operating range of the magnets, occurred in the field shape due to variable permeability. This aberration contributed to the need for correction devices.

Superconductivity offered the promise, attractive to any physicist, of building linear "air-core" magnets where detailed placement of small elements with current density, J, exactly determined the field shape, with iron playing no part or at best a minor shielding role. This concept forms the basis of the superconducting "cosine θ" magnet circuit designs which are almost universally being considered. In practice, however, there is considerable deviation from this ideal because of the large diamagnetic properties of superconductors, eddy currents, constraints due to practical coil construction, support and cooling requirements, etc. In addition, superconductors can abruptly make a transition to the normal state, triggered by various small sources of heat, with a sensitivity dependent in a complex way on the parameters J, B, and temperature T as well as on macroscopic cooling properties of the magnet. For a fixed T, the intrinsic $J_{max} \times B_{max}$ of the superconductor is almost constant, so the coil cross sectional area requirements increase at least as the square of the peak field. For small aperture magnets where $J \times B$ limitations are most severe, an intermediate design is widely used where "cold" iron closely surrounding the coil provides not only much of the massive support required, but also contributes significantly to the B_{max} obtained, so that $J_{max} \times B_{max}$ in the superconducting strands is reduced. Iron saturation contributes a systematic aberration, typically $\sim$ 1/2% at peak fields. Other magnet designs have the iron located sufficiently remote that, even at maximum fields, no saturation occurs. This in practice often leads to a "warm iron" design. For efficient small magnets, this design puts greater $J_{max} \times B_{max}$ demands on the superconductor.

Efficient and economical magnets should have the coil occupying as small a cross sectional area as possible compared to the aperture cross section so that the ampere turns NI and stored energy W are primarily dedicated to the useful aperture region, and only secondarily to the coil region and beyond. How close to the "short sample" $J \times B$ limit superconductors can be operated in large systems is ultimately determined by operating experience. A "rule of thumb" sometimes used is that a magnet theoretically capable of 5.0 T is defined as operational at 4.0 T. Thus $(J \times B)\ 4.0/(J \times B)\ 5.0 = (0.8)^2 = 0.64$. This vital question of superconducting reserve will be considered further in a companion paper[1] discussing the related subjects of magnet stability and cooling. The required current density and assumed thermal reserve Δ T below quench threshold dominates the design of efficient magnets for very high fields.

The window frame magnet circuit provides an alternate design utilizing two extended parallel plane current sheets to generate a dipole field. The current sheets terminate in a surrounding iron "window frame" of sufficient thickness that iron saturation occurs only in the immediate vicinity of pole surfaces. This circuit is more efficient in its use of ampere turns, but produces larger systematic aberrations due to iron saturation.

This approach was applied first to the two, 2 m long, 4 T modules of the 8° bend magnet which has operated for over three years in the primary proton beam line at the AGS.[2,3] This magnet has an aperture width, w = 10 cm, between the coil sheets and an aperture height, h = 10 cm, between the iron pole surfaces. Using its single predetermined saturation correction coil, a magnetic field design uniformity, $\Delta B/B \simeq 1 \times 10^{-3}$, over the entire beam aperture is produced at 4 T. This is good by superconducting magnet standards and more than adequate for the purpose. The important feature which will be explored later is that the construction errors are very small in the window frame design. Refined designs improved the field uniformity by almost a factor of ten[4] without significant increase in construction complexity.

It was recognized that the ratio of magnet aperture height to width, h/w, of the 8° magnet could have been increased from unity up to $\sim$ 1.8 and the magnet still would have fitted within a circular cylinder defined by the original width on the horizontal midplane. This would have added very little to cost. The stored energy would increase less than linearly with h/w and the effect of iron saturation on excitation and aberration would decrease quadratically. A 6 T version was designed which with a single correction coil gives fields uniform to $\Delta B/B \simeq 1 \times 10^{-4}$ over its entire beam aperture[†] at all field levels.[4]

Furthermore, because of the considerably extended sheet symmetry and geometrical simplicity, the magnet is quite free of the small but high order multipoles generated by discreet coil blocks. In this respect, it is more similar to conventional pole surface magnets whose aberrations appear only in low order multipoles.

II. Magnet Circuits for 6 T Magnets

Calculations have been made comparing windowframe magnets with circular 6 T cosine θ type magnets using "cold" iron support with the same horizontal aperture width to the superconductor in each case.[4] These calcu-

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[†] In this paper, beam aperture is defined as 75% of the horizontal distance to the superconductor.

lations were done both for NbTi and for more advanced superconductors. Comparing ampere turns, stored energy and overall magnet size, there is no penalty for an almost double vertical aperture in the rectangular magnet. This result, applying equal J × B constraints in both cases, comes about because high fields can be attained with the windowframe circuit with less stored energy in the coil. Furthermore, these calculations did not take advantage of the fact that the rectangular magnet, with the field rising through the coil layers like in a solenoid, lends itself more naturally to a graded conductor with J larger on the outside. This is illustrated later. Saturation produces a sextupole which grows linearly staring above 2.0 T and reaching 2.25% by 6 T at beam aperture before correction.

Note that a relatively efficient cold iron 6 T cosine will have ~ 1 % saturation sextupole,[4] considerably more than at 4 T. Of course, the iron can be more remotely coupled, leading to smaller saturation. However, this puts much greater demands on the coil, leading to a very thick coil radially and an inefficient magnet. The same magnet size, stored energy, and ampere turns devoted to a larger version of a magnet with appreciable iron saturation at the highest fields would produce a larger useful aperture over most of its excitation range.

Figure 1 shows a 1 m long, 6 T windowframe magnet. This was called the "model T" because of the improvised nature of its magnet iron, using tee shaped inserts in an existing iron core. The dipole coil and the series aiding Helmholz correcting coil were made with leftover conductor from the 8° magnet. The coils were plain racetracks, since the problem of forming saddle coils was solved without difficulty in the 8° magnet construction. The purpose of the model was to demonstrate high fields, field uniformity, and quench propagation. A matrix of harmonic measuring search coils was buried in the aperture. Table 1 shows the magnet design parameters. The magnet has operated to 6.25 T, at fully 100% of thermal runaway short sample.

TABLE 1

60kG Model "T" Dipole Magnet Parameters

Magnet Length	1 m
Iron Gap Height	11.66 cm
Magnet Field Intensity	60kG
Ampere Turns, Dipole Coil	587,250
Ampere Turns, Series Aiding Correcting Coil	46,375
Current, Dipole Coil	1350A
Current, Correcting Coil	265A
Current Density, Dipole Coil Conductor	3.66×10^4 A/cm^2
Current Density, Correcting Coil Conductor	2.82×10^4 A/cm^2
Stored Energy	~ 137kJ
Inductance, Dipole Coil	0.150h

III. Precision of Fields

Superconducting magnets, even if arbitrarily accurate on paper can be subject to very large forces and force gradients due both to the very high magnetic fields and to the interference fits commonly used. These act on combinations of metals and insulators with dissimilar thermal shrinkage coefficients. For applications requiring high accuracy and identity of units, this is more of a problem than for conventional magnets. The treatment of this problem normally is to assume such motion as a "random walk" of conductor placement. This effect fortunately is helped by rms type statistical averaging.

Another effect which may be more serious is motion in response to forces. Variations of materials properties, in magnet assemblies, and in magnet use, will also statistically occur and these will affect the response to the actual forces generating an ensemble of motions occupying a more limited part of the harmonic spectrum than a random walk. This will preferentially produce the lower order normal and skew oriented multipoles.

The windowframe circuit magnet appears to have unique features for producing very precise, identical magnets. The winding of the layers is analogous to winding a solenoid. Layers are wound continuously from top to bottom as a single entity. The horizontal midplane exists only as a point of symmetry with no significance to the winding. The shape of the field permits the insertion of a spacer extending the full layer height and over the length of the magnet between each layer. The coil, typically 6 to 10 layers of conductor with interlayers of Al spacers, is pushed outward and constrained to respond as a single coherent block. Preloading is not used. After cooldown, the coil has typically 0.1 mm clearance in both planes within the iron windowframe. The joining of the top and bottom iron pieces at the horizontal midplane can be arranged to close the 0.1 mm vertical clearance after cooldown. Horizontally, the coil is free to take its set, having negligible effect on the field shape.

Coil positional errors at ρ/ρ_{sc} = 75% were simulated on the computer for a design very close to the "model T".

(1) An outward compression of the coils of 0.1 mm on each side, i.e. about what will occur, produces a minute sextupole b_3/b_1 $(3\theta/1\theta) = 2.4 \times 10^{-6}$ at 1 T, increasing only to 2.8×10^{-6} at 6 T. This negligible change verifies that precompression is unnecessary.

(2) A non-uniform compression of the coil next to the aperture by 0.1 mm on one side at the top and on the other side at the bottom (i.e. inner sheets parallel but tilted) had no observable effect.

(3) An unequal coil aperture width, i.e. 0.1 mm wider at the top than at the bottom produces a very small skew quadrupole $a_2/b_1 = 8 \times 10^{-6}$ at all fields. These examples illustrate that smooth distortions of the coil block as a whole or, strictly speaking of individual layers, have an extremely small effect. This constraint automatically applies to horizontal motion. Computations show for vertical motion that for continuously wound layers with tight insulation thickness tolerances, it is highly improbable that vertical space variations will combine to give large aberrations, such as, for example, will occur with coils separated on the horizontal midplane with even tight tolerances. During winding, each layer is made very tight within its predetermined height by the insertion of 2 very thin shims. These are "stacked", aided by the computer error calculations, so they have a mutually cancelling effect to high accuracy.

Table II shows how well the 8° magnets compare after > 2 years of operation, with approximately 50 deliberately induced or operational quenches. Harmonic analysis with simultaneous long rotating coils at a radius just clearing the beam pipe show identity of the units to measurement accuracy at all field levels except for skew (a_2) and normal (b_2) orientation quadrupoles. Individual unit measurements show random quadrupole of 2×10^{-4} parts ($G/B = 6 \times 10^{-5}$cm^{-1}). All higher multipoles show identity of the magnet units to measurement accuracy which is ~ 1×10^{-4} for low multipoles, even better for higher moments.

TABLE 2

$\left[\int B\cdot ds_{\text{UNIT 1}} - \int B\cdot ds_{\text{UNIT 2}}\right] / 2b_1$ FOR 8° MAGNETS MEASURED AT FULL BEAM APERTURE

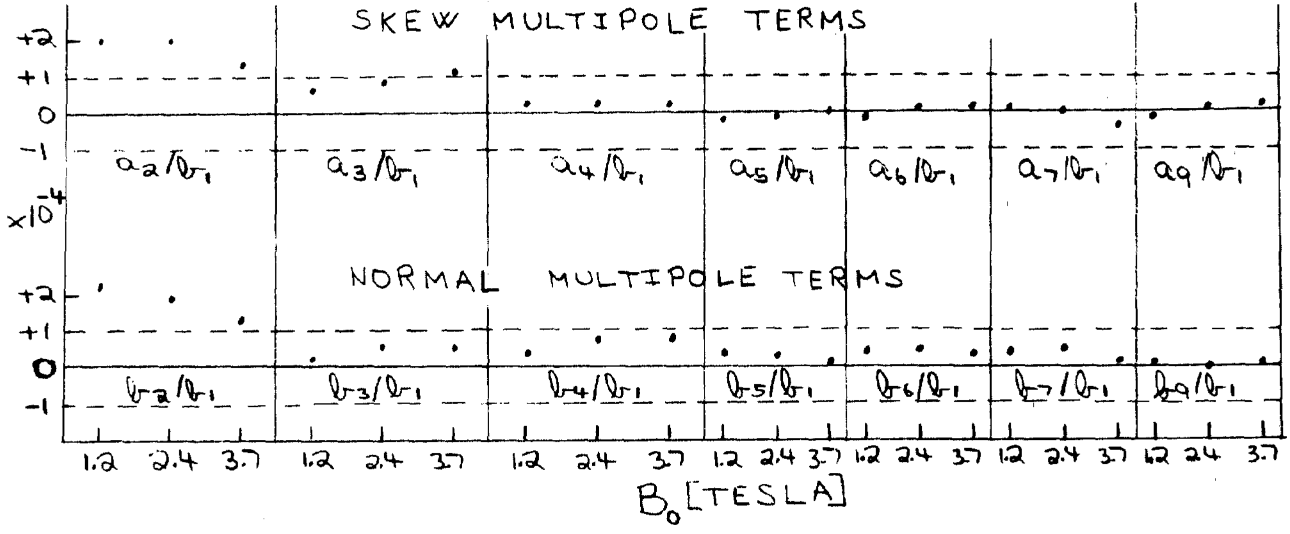

TABLE 3

"MODEL T" MULTIPOLE FIELD TERMS RELATIVE TO DIPOLE TERM (b_1)

	B	b_1	a_2	b_2	a_3	b_3^*	a_4	b_4
RUN I	20 kG	+100.0%	-0.02%	+0.01%	-0.04%	-0.25%	-0.07%	-0.04%
	40	+100.0	-0.01	+0.01	-0.05	-0.06	-0.06	-0.05
		Run I initial run, terminated at 45 kG with no quenches.						
		Run II is the second cooldown with the magnet "pre-trained" to 61 kG.						
RUN II	20 kG	+100.0%	-0.01%	0.00%	-0.04%	-0.27%	-0.09%	-0.03%
	40	+100.0	-0.02	+0.01	-0.02	-0.05	-0.07	-0.04
	45	+100.0	-0.02	0.00	-0.02	-0.23	-0.07	-0.04
	50	+100.0	-0.02	0.00	-0.03	-0.19	-0.07	-0.05
20 kG - 20 kG (Run I)		0.0%	+0.01%	-0.01%	-0.00%	-0.02%	-0.02%	+0.01%
40 kG - "		0.	0.00	0.00	+0.02	+0.20	0.00	0.00
45 kG - "		0.	0.00	-0.01	+0.02	+0.02	0.00	0.00
50 kG - "		0.	0.00	-0.01	+0.01	+0.06	0.00	-0.01

NOTES: 1) The field multipoles were measured at a radius equal to 75% of the radius to the superconductor.
2) The absolute accuracy of the data is ~ 0.1%, while the relative accuracy is 0.01%.

*The b_3 term (normally oriented sextupole) can be "tuned" to zero.

The "model T", 6 T magnet, because of the constraints of using fixed preinserted measurement coils as distinct from movable coils, can only give absolute accuracies of approximately 0.1% for the multipole content. This is determined by analyzing subsets of the data at a given field. However, relative change in the field shape from 2 T to high fields and from before to after first excitation to high magnetic fields can be determined to $\sim 1 \times 10^{-4}$ parts.

Table III gives the constancy of the field at all field levels, as predicted by the computations, to be $\sim 1 \times 10^{-4}$ parts measured at 75% radius to superconductor in this very small aperture model. Higher multipole terms are completely negligible. While not directly shown to high accuracy by the data, the windowframe magnet circuit is ideal for providing very uniform fields below saturation. The large gap aspect ratio, $h/w \sim 1.8$, creates a much better situation for iron remanence than exists for conventional magnets. Furthermore, magnetization and diamagnetic effects which occur in the superconducting current sheets return their flux through the surrounding iron, not the aperture. Thus the remanent field (obtained by current reversal) is very small and such magnets can be used even at quite low field levels. Reversal at 2 T showed identity except for a sextupole of $2 \pm 2 \times 10^{-4}$ T.

4. Future Designs

The window frame design lends itself to small, efficient, very high field magnets. Smallness increases the field precision problem. The evidence, particularly the identity of the 8° magnet units which compares favorably with the best of conventional magnets, supports the case for the unique, practical, construction features.

Figure 2 shows a conceptual design for a 4.5 T operational field magnet. This is quite conservatively designed. The conductor would be capable of 40% higher field if the iron yoke thickness was adequate. If the conductor were operated at 100% of short sample, the magnet and dewar cross sections could be reduced by ~ 16% in diameter.

Figure 3 shows again a conceptual design for a 6 T operational field. The coil field reserve is above 25%

in this case. If this conductor were operated at 100% of short sample, i. e. with zero thermal reserve, the magnet and dewar cross sections could be reduced by ~ 10% in diameter. The basis for these conductor choices is discussed in a companion paper.[1]

Table 4 lists the parameters of the 4.5 T and 6 T designs. (The flux pattern for these designs is illustrated in Fig. 3 of reference 4.) No magnet correction coil was shown. For internal correction, this can be accomplished in three ways: (1) A series aiding Helmholtz coil (Model T), (2) sextupole type coil (8^c magnet), (3) correction applied using outer coil layers only. For an accelerator, external correction may be used. For a typical machine lattice, with ρ = 1 km, a sextupole strength of 39% of the total distributed magnet sextupole located at the horizontal focusing quadrupoles is required for excellent correction of tune shift in first order. This is quite reasonable.

It should be noted that magnets can be biased to introduce sextupole at low fields. Where this is acceptable, the magnitude of the maximum correction field required is reduced to ~ 25% of the unbiased case.

TABLE 4

Graded* Superconductor Window Frame Magnet Parameters

Magnetic Field Intensity	45	60kG
Iron Gap Height	8.13	9.14 cm
Aperture Height	7.54	8.14 cm
Aperture Width	4.45	4.45 cm
Dipole Current (Typical)	1600	1600A
Ampere Turns (Dipole Coil)	302.4	475.2 kA-T
*J in Dipole S.C. only	68.5	68.5 kA/cm^2
Stored Energy	50	126 kJ/m
Inductance (Typical)	.035	.102 H/m

*The dipole coil consists of ≤ six layers of superconductor in the 4.5T case and ≤ 9 layers in the 6T case. The outermost layer in the low field area is made from smaller superconductor series connected to the remainder of the coil conductor.

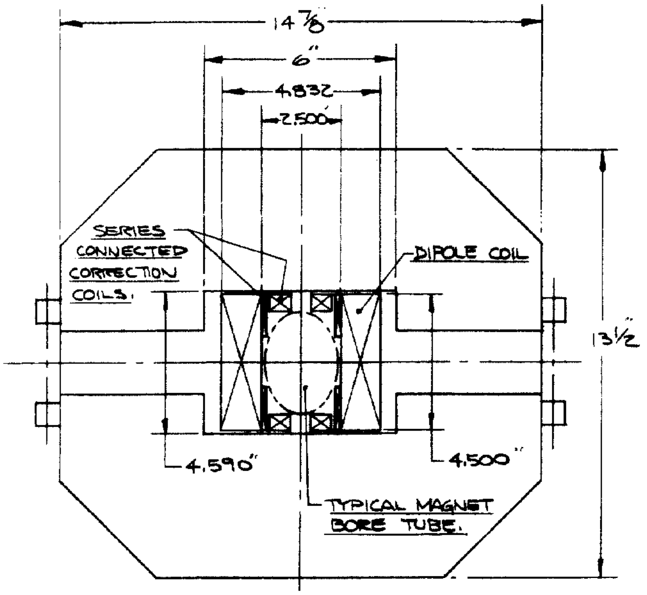

Fig. 1. Model "T" One Meter 60 kG Dipole Magnet

Related quadrupole designs up to B_T = 4 T have been briefly described.[4] If matched to the small aperture dipoles of Figs. 2 and 3, they have in principle smaller outer diameters, producing very high gradients even for modest B_T values.

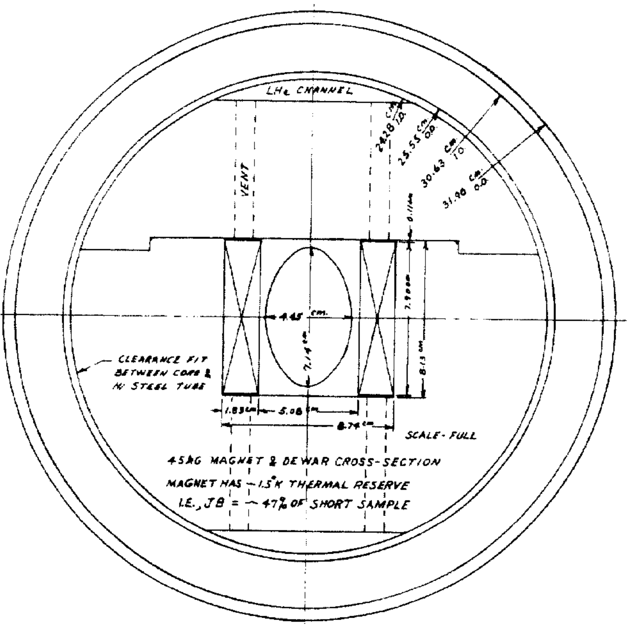

Fig. 2. Conceptual Design for 4.5 T Magnet

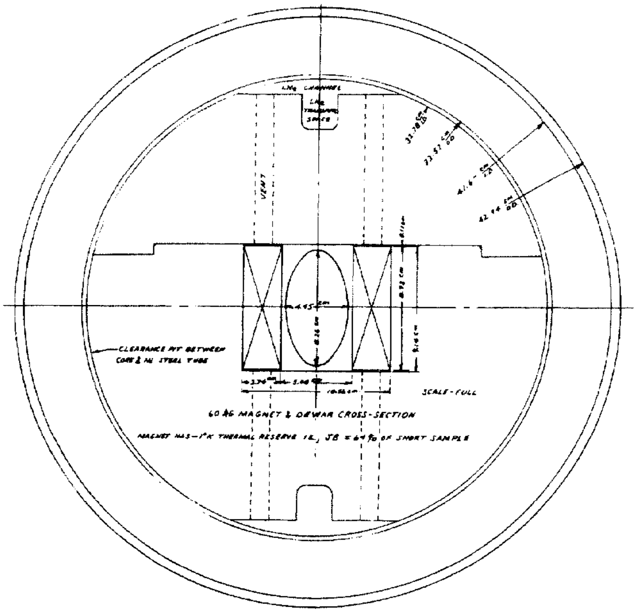

Fig. 3. Conceptual Design for 6.0 T Magnet

References

1. "Ultra Stable High Field Superconducting Dipoles", J. Allinger, et al. elsewhere in these proceedings.
2. J. Allinger, et al. Proc. IXth Intl. Conf. on High Energy Accelerators, SLAC (1974).
3. J. Allinger, et al., IEEE Trans. Magnetics MAG-11, No. 2, p. 467 (1974).
4. J. Allinger, et al., IEEE Trans. Magnetics MAG-11, No. 2, p. 463 (1974).