MAGNETIC CIRCUIT CONSIDERATIONS FOR HIGH FIELD MAGNETS*

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Abstract

The iron window frame approach to high field dipole magnet design is described. This approach approximates the dipole field between extended parallel current sheets. Very high field uniformity is possible at all obtainable excitations, provided an auxiliary correcting coil circuit is used above ~ 20kG. Two-dimensional field computations using known permeability data are used for precision optimization of the circuit design. Comparisons of computed fields with model magnet experimental results are given. Some calculations of high field iron core quadrupole properties are also briefly considered.

I. Introduction

A high field dipole (i.e. ≥ 40kG) employing a rectangular coil cross section surrounded by iron of sufficient thickness to shield against large external field leakage has various attractive features in applications where the vertical aperture can usefully be equal to, or greater than, the horizontal. Basic parameters of saturation and aberrations were first explored by the use of very simple models excited to fields ≥ 40kG and cooled by immersion in LN_2. Subsequent model studies have been made with both high purity aluminum and superconducting coils.[1,2,3] Circuit design has been refined by the use of precision field computations.

An auxiliary correcting coil circuit which carries up to several percent of the ampere turns of the primary dipole coil is required. This corrects for sextupole aberration, with other aberrations being more than one order of magnitude smaller. For many particle beam applications the auxiliary coil requirement is a modest inconvenience. However, for some precision applications, and certainly for accelerators, available control of widely distributed sextupole is in itself attractive. In fact, it is essential in any case. High current density, relatively small aperture dipoles such as are considered for superconducting accelerators, have difficult positional tolerances on conductor location, both during construction and in operation. The window-frame magnetic circuit considered herein is relatively straightforward to construct, and has other operational advantages. These features have been considered further in various other works[3,4,5] and in companion papers in these proceedings[6,7].

Magnetic field computations have been made using the TRIM program, and also using LINDA.[8,9] Such programs have necessarily complex convergence criteria, and are often used with difficult boundary conditions. They can give extremely accurate field descriptions if used with discrimination. TRIM, with its triangular mesh generation, is extremely flexible. However, in those problems where comparison has been made, essentially exact agreement between results of both programs has occurred. An early model magnet was deliberately made with a complex field shape involving irregular saturation of a pole to test computations under diffucult circumstances. The computations showed agreement with experiment to the level of 1×10^{-3} parts, which was approximately the accuracy of the experimental data.

II. Development of Magnetic Circuit for a 3-in. Diameter 40kG Superconducting Dipole

A small model magnet which has been studied extensively is shown in Fig. 1. This contains within the rectangular iron window the primary dipole coils, as well as the three windings which are connected in a single series circuit to give approximately an air core sextupole. The small rectangles marked 1 through 9 denote field measurement search coils. An existing laminated iron core and existing superconducting wires were used so that while the geometry of the model was somewhat distorted, it nevertheless has served as a test of circuit design.

Figure 2 shows the effect of saturation on the dipole field as a function of excitation current. The field is divided by the current and is normalized to unity for infinite permeability. The agreement between the TRIM computations and experiment is excellent. Figure 3 shows for several search coil locations, which are indicated on Fig. 1, the measured magnitude of the field deviations caused by saturation as a function of excitation. This illustrates why a simple excitation function for a single correcting circuit can give excellent field quality at all excitations. In an earlier work, the agreement between calculations and experiment for this model is described.[5] Field deviations of several percent, as well as their corrections were measured. Agreement with predictions was itself good to a few percent of the deviations. Considering the very small size of the model, and immediate proximity of search coils to the conductors, it was judged that the computations agreed to the accuracy of the measurements.

The internal consistency of the computations for a large bend superconducting magnet using the TRIM program show accuracies of 1×10^{-4} or better. That is, the superposition of different correction coil multipolarities, as well as varying amplitudes for these multipolarities, behaves very predictably at low fields and fields

*Work performed under the auspices of the U.S. Atomic Energy Commission

up to 40kG. This permits a perturbation approach to accurately converge on a design using the results of a few parametric calculations as a starting point.

To predict an actual magnet beyond $\sim 1 \times 10^{-3}$ parts absolute accuracy requires a detailed knowledge of iron used, its packing factor, permeability variations in operating at 4°K, etc. In fact, however, it is not necessary to know these quantities in great detail to produce an accurate magnet. Any good magnet iron satisfies the high permeability low field design requirements. For high fields, saturation is an asymptotic property commencing at $\sim$ 20kG. Slight variations in iron saturation properties simply shift the curves, for example, either to the right or the left on both Figs. 2 and 3. As a result, a calculation giving a certain dipole saturation and aberration content at say 38kG may apply to an actual operating magnet at 38.8kG, but the design is unchanged. This basic property of estimation, plus the fact that variational change is accurately predicted by computations, permits design to the 1×10^{-4} level of accuracy. If the magnet iron is slightly different than assumed, one will simply get the same optical properties at a slightly different absolute field.

A magnet for 8° deflection of 30 GeV/c protons is under construction. This consists of two 6-ft long modules. The semi-warm bore beam pipe is a 3.0-in. o.d. stainless steel tube with 1/16-in. wall thickness. This permits $<$1/4-in. of insulation between the beam pipe and a 3.475-in. i. d. tube operating at 4°K, on which the superconducting coil structure is constructed. Details of this magnet are included in a companion paper[6], and in an earlier publication[5]. Figure 4 shows a cross section of the 8° magnet. A 20-in. long prototype of essentially identical cross section has been undergoing tests.

The relative saturation of the dipole field as a function of excitation is shown to $\sim$ 40kG in Fig. 5. The magnet performs slightly better than the computations by $\sim$ 1kG. This is in large part because a low carbon steel is used in the magnet, while the computations are for M-36 silicon steel which has a lower magnetization value at saturation. By $\sim$ 40kG the shift of the two curves is decreasing. This occurs because the field is measured over a few inches at the center of the magnet, and this short model is commencing to have no flat two-dimensional region at the highest fields. Time has not yet permitted recalculation with more realistic permeability so that Fig. 5 would show the excellent agreement shown in Fig. 2 as discussed above, however, this is not really necessary.

In Table I, the multipolarities obtained at approximately 19, 32, and 38kG are given. The numbers are the amplitudes of the radial components of the field multipoles present at the measurement radius of 1.513-in. This is slightly larger than the o.d. of the warm bore tube to be used, and is .36-in. from the nearest superconductor. That is to say, the measurements are taken at 80% of the radial position of the nearest superconductor. The field amplitude is given normalized to the dipole field amplitude. The terms in Table I include those allowed by the symmetry of the magnet. Only odd multipoles are present in a magnet of four identical quadrants. All even harmonics should ideally be zero, but small even terms have been measured as is discussed in a companion paper.[6] Note that the comparison of experimental and computed 3θ (sextupole) results involves the actual magnet iron permeability mentioned with respect to Fig. 5 and earlier discussion. In fact, the exact sextupole excitation needed can be tuned always to completely remove 3θ. Tuning out the small remaining sextupole has a completely negligible effect on higher multipoles. For example, in Table I the 32kG run had a much larger current misadjustment than the other two runs. Adjusting the sextupole to zero; i.e.,-.392%, affects the other multipole amplitudes by $<1 \times 10^{-4}$. On the basis of these preliminary runs, one can now predict very accurately the auxiliary coil current to match any dipole coil current. Future data thus would be taken with 3θ zero.

The variation of these multipole terms with r is indicated in the Table as well. For example, 9θ decreases as the 8th power as the radius decreases. A positive sign for a multipole indicates it is in phase with the poles of the dipole. A negative sign indicates a multipole 180° out of phase with the poles of the dipole.

The computer calculations were originally done using the identical dipole coil and auxiliary coil currents as in the experiment. The dipole current was then slightly reduced in computations until the same 3θ amplitude was obtained as in the experiment; i.e., the same fractional saturation for the iron of the magnet and for the calculation. In fact, at 32kG where the 3θ setting error is largest, the resulting reduction in the dipole current agrees exactly with the displacement in currents between the experimental and computed dipole field at the same level of saturation shown in Fig. 5.

The 38kG experimental data has almost the exact auxiliary correction current required, the 3θ error being 2×10^{-4} parts. This occurs because the lower field data, taken earlier, could be used to predict the correction. In this case no adjustment was attempted since the results agree to high accuracy. The corrected auxiliary current column gives the computed results for complete sextupole correction.

Consider next the 5θ term. This varies as r^4, and is the largest aberration present, increasing from $+5 \times 10^{-4}$ parts at low fields, to $+8 \times 10^{-4}$ parts at high field. However, this is as expected and was present in the calculations. The agreement is good to 1×10^{-4} parts. The important point is that the 8° magnet and later designs will have the 5θ term reduced to $\sim$ 1/3 these values over the entire range of excitation. One should note that the diamagnetic effects due to trapped flux in the sextupole coil will have predominantly 5θ symmetry, and is not included in the computation. As discussed in a companion paper, we are estimating that the diamagnetic effect amounts to $\sim 1 \times 10^{-4}$ parts at 18kG and correspondingly less at higher fields.

The 7θ term is everywhere less than 3×10^{-4} parts, and again is in excellent agreement with the computation. The 11θ term is everywhere a few parts in 10^4 and varies as r^{10}. It will be of no consequence in the working aperture of the magnet.

The large 9θ term present at higher fields is due to the simplicity of the essentially air core sextupole correcting coil. This term is the first odd harmonic generated by a sextupole winding. As a result, by 40kG the precision field region (arbitrarily defined as $\leq 1 \times 10^{-4}$ parts of 9θ) is reduced to $\sim$ 1-in. radius. It should be noted that the 8° magnetic field quality is completely adequate for its beam transport application. However, a slightly modified design has now been made which will considerably reduce the 9θ amplitude if it is necessary for other applications. This pushes the dominant multipole error higher in power. Note that the amplitudes of the computed 9θ term are $\sim$ 20% larger than the experimental values for all three fields given in Table I. At 19kG the excitation of the auxiliary coil, which is the cause of the 9θ aberration, is very small and the difference between experiment and computer is $+ 1 \times 10^{-4}$ parts. The difference between experiment and saturation at 32 and 38kG is proportional to the auxiliary coil current. Due to the high multipolarity of the 9θ term, and the limited number of points used in the harmonic analysis (measured every 10°), there is a small systematic error in the experimental coefficients. As a result, the disagreement between computations and experiment by 5×10^{-4} parts and 9×10^{-4} parts respectively at 32 and 38kG is spurious in these preliminary measurements.

III. Quadrupoles

The first applications offering major advantages from the use of superconducting magnet properties for the experimental high energy physics program at the Brookhaven AGS require relatively large bend dipoles. For future accelerator considerations, dipoles even more strongly dominate the economic aspects. Higher gradients than are attainable with conventional quadrupoles are a nice option however, and in fact, soon will become necessary. The higher field symmetry of quadrupoles makes design easier, at least conceptually. In an earlier work, Table III and Figures 5 and 6 illustrated a conceptual design for an iron pole quadrupole.[4] The coil cross section used was excessive in area in terms of the high current densities attainable with superconductors so performance could be improved. Nevertheless, a very simple quadrupole design suffices, using coils of rectangular cross section. The preliminary calculations gave extremely constant gradients with the aid of a single auxiliary coil.

Whether this approach is preferable in general compared to air core quadrupoles has not as yet been developed. However, it does have at least some attractive mechanical features. In the case of the dipole, the auxiliary sextupole coil offers the considerable advantage of available and controllable distributed sextupole field. For the quadrupole, however, an auxiliary coil does not obviously offer any optical benefits in return for its complexity. Greater saturation of poles will also occur. As a result, even though this multipole approach to producing a quadrupole magnet has some strong parallels to the dipole work described herein, it will require considerably more work to ascertain its merits compared to more conventional air core designs.

IV. Conclusions

It is clear that by the use of computational aids one can predict the magnetic fields of superconducting magnets "on paper" to a level approaching at least 1×10^{-4} parts.

The magnetic circuit ideas used in this work, and which are still undergoing refinement, can produce efficient high field magnet designs suitable to large scale usage. The magnetic field qualities already obtained compare very favorably with those of conventional magnets.

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TABLE I

Comparison of Experimental and Computed Harmonic Coefficients for the 20-in. Magnet as a Function of Field

B_o(kG)	Harmonic Coefficients	Experiment	Computer	Computed† for 3θ/1θ=0	Δ(Exp.-Comp.)
19.1	3θ/1θ (r^2)	-0.039 %	-0.039%	0.0	0.0%
	5θ/1θ (r^4)	+0.033	+0.045	+0.041	-0.012
	7θ/1θ (r^6)	+0.025	+0.026	+0.026	-0.001
	9θ/1θ (r^8)	-0.041	-0.049	-0.049	+0.008
	11θ/1θ (r^{10})	+0.015	+0.003	+0.003	+0.012
32.3	3θ/1θ	+0.392 %	+0.392%	0.0	0.0 %
	5θ/1θ	+0.065	+0.051	+0.071	+0.014
	7θ/1θ	-0.021	+0.001	+0.008	-0.022
	9θ/1θ	-0.244	-0.293	-0.285	+0.049
	11θ/1θ	-0.031	-0.047	-0.045	+0.016
38.3	3θ/1θ	+0.018%	0.0 %		+0.018%
	5θ/1θ	+0.070	+0.078		-0.008
	7θ/1θ	+0.023	-0.011		+0.033
	9θ/1θ	-0.306	-0.394		+0.088
	11θ/1θ	-0.033	-0.050		+0.017

† Computed results for correction coil "tuned" to give 3θ/1θ=0.

Note: The harmonic coefficients were measured and computed at r = 1.513 in. which is 80% of the radial position of the nearest superconductor.

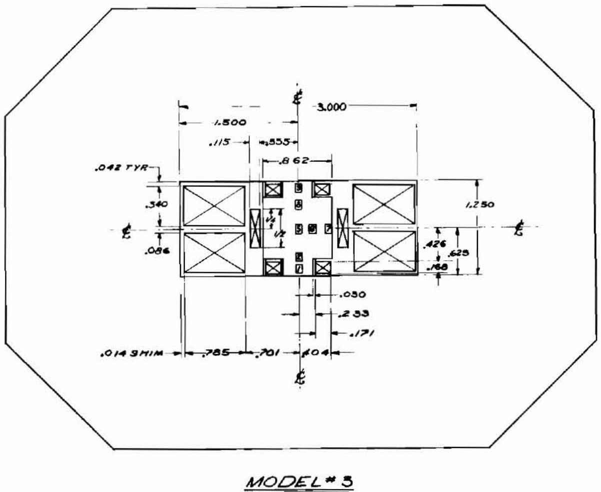

Fig. 1. Model Magnet #3 showing Correcting Coil and Field Measurement Coils

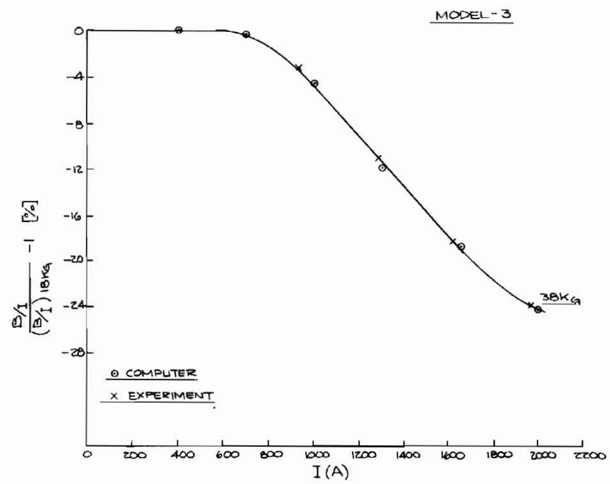

Fig. 2. Saturation Effect on Dipole Field for Model #3.

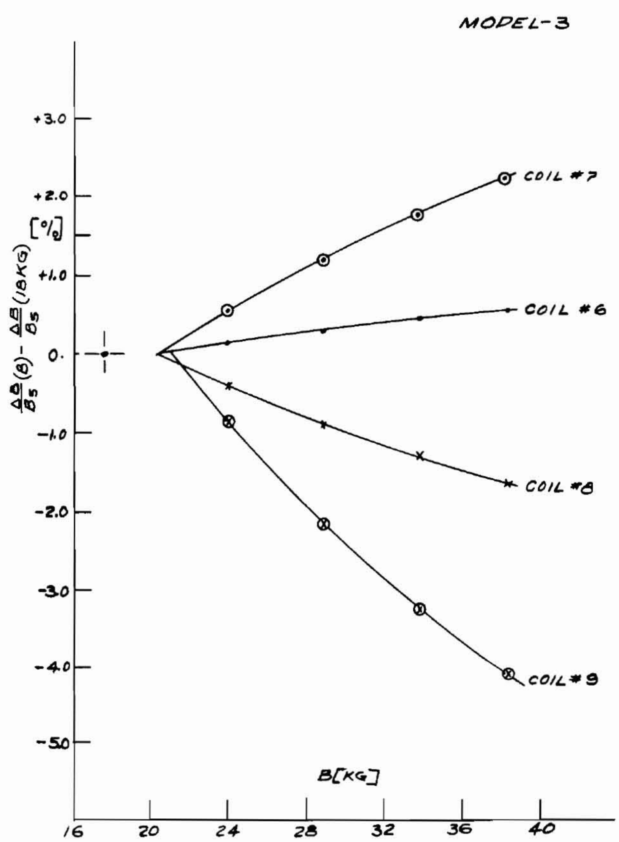

Fig. 3. Field Deviations caused by Iron Saturation in Model #3.

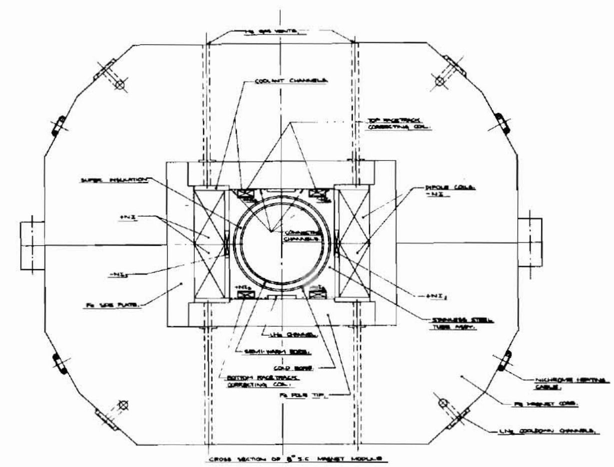

Fig. 4. Cross-section of 8^{o} Magnet.

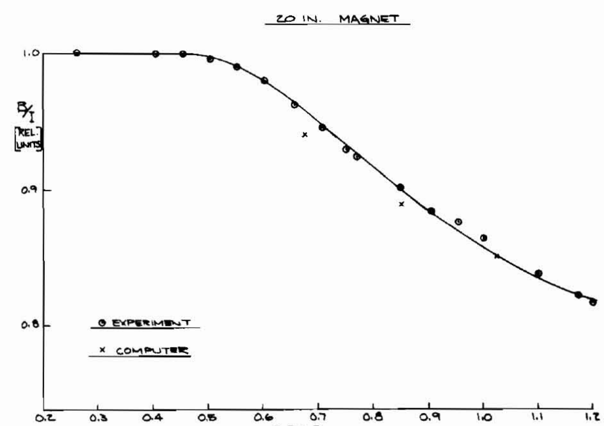

Fig. 5. Relative Saturation of Dipole Field for 20-in. Prototype Magnet.