AGS BOOSTER PROTOTYPE MAGNETS*

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ABSTRACT

Prototype magnets have been designed and constructed for two half cells of the AGS Booster[1,2] The lattice requires 2.4m long dipoles, each curved by 10°. The multi-use Booster injector requires several very different standard magnet cycles, capable of instantaneous interchange using computer control from dc up to 10 Hz.

INTRODUCTION

This report describes the design of the prototype magnets for the BNL Booster, carried out by a pre-project "Task Force". The Booster Project is now funded and construction is underway by a BNL Accelerator Development Department production team. This description of magnet characteristics developed by the "Task Force" outlines the basic features of the current design.

Dipole and Quadrupole Design Considerations

The requirements of high precision field quality from 1Hz (heavy ions and polarized protons) to 7.5Hz (high intensity protons), plus cost considerations influenced the design.

	Dipole	Quadrupole
Number	36	48
Gap/Pole Diam.	3.25″ (8.255 cm)	6.5″ (16.5 cm)
Useful Aperture of Pole Diam.	2.75″ × 6″ (ellipse)	6.1" (circle)
B/I (low B)	2.436 kG/kA	1.624 kG/kA
B/I (high B)	2.320 kG/kA	1.547 kG/kA
B (200 MeV) (protons)	1.56 kG	1.04 kG (pole tip)
B (1.5 GeV) (protons)	5.46 kG	3.63 kG
B_{min} (heavy ions)	~ 0.6 kG	~ 0.4 kG
B_{max} (heavy ions)	12.74 kG	8.4 kG
LB	94.5″ (2.40 m)	21″ (0.53 m)

Table 1 - Dipole and Quadrupole Magnet Parameters

The gap height choice dominates the dipole magnet and power supply costs. The gap is based on space charge requirements, scaled from the AGS. Fig. 1 shows the dipole cross-section. The 2.4 m long curved dipole magnets have a total sagitta of 2.060" (5.23cm). Straight magnets would cost considerably more and have greater stored energy. For 7.5 Hz operation this would require a considerably more expensive power supply to excite the required $\frac{dB}{dt}$ = 95 KG/sec and 63 kG/sec in the dipoles and quadrupoles respectively. The pole width was minimized to 10"(25.4 cm) = three gaps including edge bumps - to provide the required large good field region and dynamic range with minimum stored energy. H magnet design provides the most compact and symmetric dipole, thereby minimizing effects of iron permeability with minimal remnant fields. The magnet is short enough that simple racetrack coils can be inserted from one end and intermittent internal coil support can be adjusted from each end. This permits use of a single piece lamination which is much cheaper and more accurate. The open horizontal mid-plane (Fig. 1) provides space on either side of the gap for special purposes, such as injection and ejection.

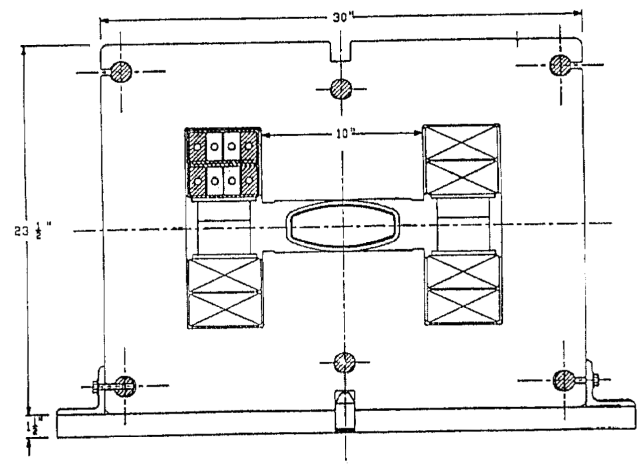

Figure 1 - Dipole Magnet, Cross-Section

The coils have 4 pancakes with only 16 turns total, for low inductance and low voltage at 7.5 Hz. The conductor width, 1" is the largest that could be practically bent to the required corner radius. The large conductor height, 2" was chosen to increase turn area and minimize power requirements.

The dipole design as computed has $\lesssim 1 \times 10^{-4}$ multipole aberrations at any field over the working aperture required by the lattice. The following factors will dominate aberrations: (i) Construction errors (ii) Magnetization will give significant field errors. Randomization of all the dipole steel should make these identical unit to unit to high precision. (iii) Eddy currents will also give field errors. Those in the magnet itself should have very small unit-to-unit variations. The design and construction choices have all been made with the central goal of reducing these to a minimum. Single piece H-form laminations have many advantages. There is a minimum yielding of steel (internal stress relief) following punching. The horizontal midplane parting surface is eliminated with its associated assembly errors and shorting of laminations. Four-fold rotational stacking and shuffling provide complete averaging of steel magnetization and rolling direction inhomogeneities and punch and die errors. The lamination pole faces were flat and parallel to ± .001". During block construction alignment was established by supporting the lamination on its pole surface in the stacking fixture. This plus four-fold rotation greatly reduces odd multipoles, normal and skew quadrupoles and octupoles, etc. This is evidenced by the very accurate prototype field measurements. Reducing horizontal dipole, and higher multipole field errors to an absolute minimum is very desirable for polarized proton operation and for large dynamic aperture with very high intensity space charge loaded beams. The laminations for a dipole were assembled and glued into 5 blocks each with a 1° wedge on both ends. The

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wedges were made simply by shearing standard one-piece laminations. The inside surfaces of the stacking fixture end plates are machined to fully surface support the 1° wedge of sheared laminations on each end of a block. The glued wedge thus becomes an integral part of the magnet core block. The fifth block was split into two halves after fabrication. The parting surfaces at the split become the two ends of the magnet. The total core is sandwiched between stainless-steel end plates. The one-piece laminations make an extremely rigid magnet core. It is self-supporting with negligible sag provided the total assembly of blocks is maintained under compression.

For the prototypes, six tension rods hold the five blocks together to make full magnets. A non-ferrous base plate with pins provided accurate horizontal location. An existing sub-base plus shimming provided vertical alignment (elevation, roll and pitch). The individual blocks were clamped to the base plate on either side to inhibit vibration. Alternative techniques for assembly of coreblocks, e.g. welding, are being considered for final production.

The magnet is very insensitive to coil location making possible economical coil construction. The computed field change for a 0.10 inch vertical coil movement gives $\Delta B/B < 1 \times 10^{-4}$, over the entire beam aperture. Horizontal coil movement results in even smaller $\Delta B/B$. The coil construction tolerance is ± 0.015 in., six times smaller. The pole steel of the pure dipole magnet circuit screens the coil from the aperture high-field region, which only sees low fields and forces. At 12 kG (1Hz) each 8 turn half coil has F_{radial} = 18 lbs/linear inch outwards and $F_{vertical}$ = 46 lbs/inch away from the horizontal mid-plane. For 7.5 Hz operation (5.46kG) F_{radial} = 3.7 lbs/inch and $F_{vertical}$ is 9.3 lbs/in. These small forces make control of vibration at 7.5 Hz easy: The magnets show no significant noise or vibration. [1 lb/in. = 17.9 kgm/m].

Eddy currents are a concern with 7.5 Hz operation. These are primarily induced in the vacuum chamber. The dipolar symmetry of the main field eliminates quadrupole or octupole eddy current fields. The location of the coils results in negligible field perturbation in the aperture from eddy currents in the coils. Calculations at 200 MeV and 10 Hz (the worst case) show $\Delta B_{eddy}/B_o < 1 \times 10^{-4}$ anywhere in the aperture.

At the magnet ends, there are fields perpendicular to the thin dimension of the laminations. The effect of a beveled end shape on the static field, and the effect of the eddy-current time constant and amplitude on the dynamic field and on heating losses, are being studied and optimized. Silicon steel is superior for ac excitation in general, particularly in ends. Its narrow magnetization loop is attractive because the Booster has to provide on short notice very different magnet cycles, with resulting differences in magnetization.

Dipole Field Quality

The computed good field region at injection fields extends essentially over the entire beam aperture: except at $x \cong \pm 3$ inches, $\Delta B/B_o < 1 \times 10^{-4}$ (See Fig. 2). Note that the die set was fabricated for punching 0.062" thick steel. Agreement with experiment is excellent. The 0.025" silicon steel stamped with the same die, clearly had some distortion which the four-fold rotation converted into a sextupole-like small error. This is of interest, but not relevent to final production. The one piece laminations produced very accurate magnet blocks. The blocks (Fig. 2) were not distinguishable from one block to another. No quadrupole is observed; i.e. no side-to-side variation over 6 inches. When the level of the magnet was defined by the top surface of the blocks, the horizontal field B_x was measured $\le \frac{1}{2} \times 10^{-4}$.

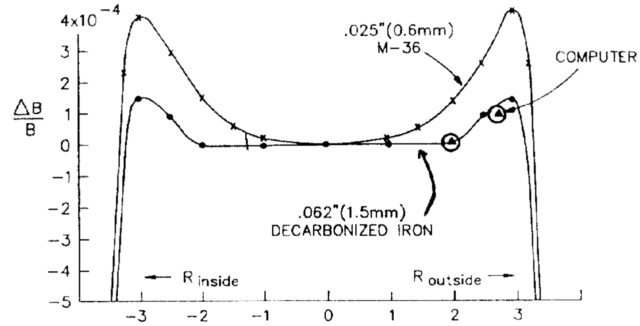

Figure 2 - Bus. Radius at 5.46 kG (1.5 GeV)

Magnetization and eddy current effects were found to be almost pure dipole, greatly easing servo problems. Sextupoles and other aberrations are less than 1×10^{-4} across the entire 6" aperture for a M-36 silicon steel block, pulsing from very slow cycles up to 80 kG/sec. For the 7.5 Hz proton cycle the dipole deviation from linearity with I during the rise is 4 gauss due to magnetization. Stacking should reduce the dipole to dipole deviation to a very small residual. Eddy currents contribute only 0.25g ± .13g to the rising field at 80 kG/sec. In the case of the 0.062" decarbonized iron lamination measurements, the magnetization is twice as great, and the eddy currents are 17 times as large. Scaling for resistivity and thickness predicts 20 times larger, in good agreement. This steel will not be used in production (it was available free).

By 12 kG the "good field" region shrinks to ≈ ± 1", equal to lattice requirements. The computed change in field uniformity $\frac{\Delta B}{B}$ on the horizontal midplane is shown in Fig. 3 and the multipole content is tabulated in Table 2. For 12 kG, at x = 1 inch the deviation is only 1.2×10^{-4} and almost pure sextupole which can be corrected. Ten-pole and higher moments are very small at all field levels. Note that for a 4% change in B_o, 12.5 to 13 kG, the sextupole change is 0.6×10^{-4} at x = 1 inch. This very small sextupole variation quantifies the tolerance on magnet packing factor: the design goal of 2×10^{-3} variation is 20 times smaller, so packing factor should affect only B_o, the central field, not unit to unit multipole content.

The dipole saturation is ~ 3% at 12 kG and about 5% at 12.74 kG for 100% packing factor and typical steel. For B=12kG, a 0.4% change in central field results from a 1% change in packing factor. The design tolerance on packing factor of 2×10^{-3} will result in $\sim 8 \times 10^{-4}$ parts change in the dipole field.

B_n/B_o \ B_o	1.6kG *	10kG	11kG	12kG	12.5kG	13kG
B_2/B_o	1.6	-0.314	-0.545	-1.042	-1.466	-2.032
B_4/B_o	0.2	-0.038	-0.076	-0.161	-0.229	-0.307
B_6/B_o	0.1	-0.003	-0.008	-0.015	-0.018	-0.019
B_8/B_o	0.1	-0.001	0.000	0.000	0.000	0.000
B_{10}/B_o	0.0	0.000	0.000	0.000	0.000	0.000

Table 2 - Dipole Multipoles

* In this column B_{inj} = 1.6kG multipoles are expressed in ppm. In the other five columns, multipoles are expressed in units of 10^{-4}. All are at x=1 in., y=0.

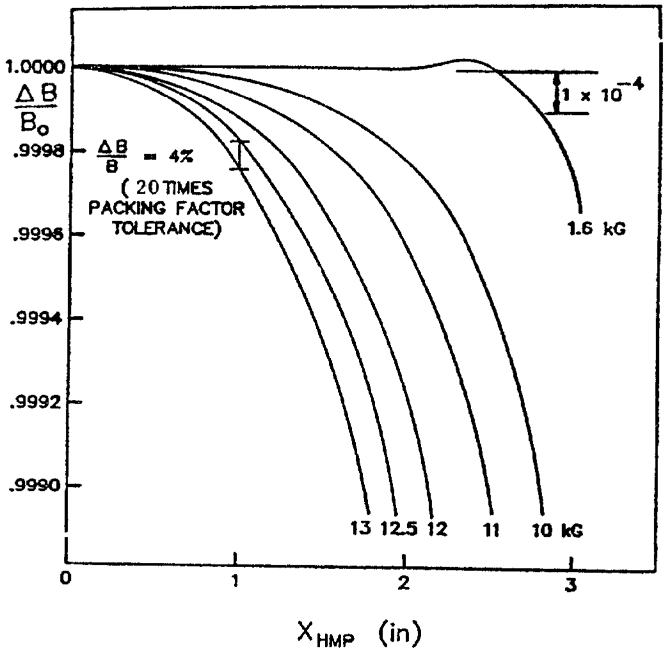

Figure 3.

Shrinkage of good field region with increase in B.

Quadrupole Properties

A high current, compact quadrupole design with a small total coil cross-section gives low inductance and voltage for 7.5 Hz operation. [Fig. 4]. Simple 5 turn racetrack coils with large area conductors are used, located out of the high field region. This results in small coil forces. Conductors at considerably larger radius than the pole tip reduce end-effect aberrations due to coil errors. The quadrupole field is iron-dominated and very insensitive to coil location or coil eddy currents. The low field, B_{max} = 8 kG, permitted straight poles. The pole tip shape is based on a National Synchrotron Light Source design.[3] Each pole is fabricated separately and precisely aligned for four-fold symmetry using doweled end support rings. The ratio of quadrupole length to aperture diameter is small ~ 3:1.

End effects will be studied with shaped ends to minimize end-generated multipoles and $\dot{B}$ effects. With the end design chosen, precision integral and internal (2D) magnetic measurements will be made. These will be used in computer calculations of modifications to the internal (2D) pole profile so that the internal multipoles are equal in magnitude and opposite in sign to those in the ends. Previous experience assures that this modification will be minor. The pole face portion of the die is changeable to accommodate this.

For a particle at constant radius the integrated value (60/20) (measured by a long search coil) will be made exactly zero. The integral of higher multipoles will be reduced if necessary. This impulse approximation is extremely good even for real particles in the Booster, since $\sqrt{\beta}$ varies very little over the short length of the quadrupoles. The aperture field is insensitive to eddy currents in the coils at 7.5 Hz. The open horizontal mid-plane between the coils gives space for injection and extraction.

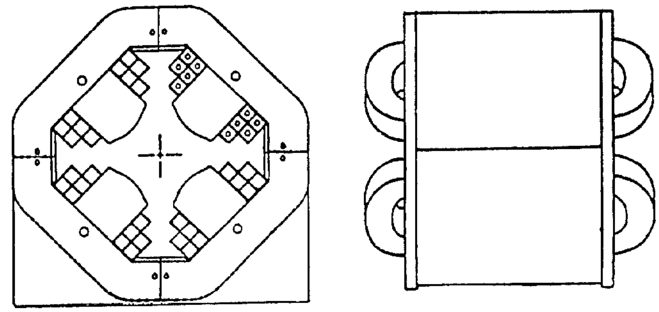

Figure 4 - Quadrupole Magnet

The dipoles and quadrupoles have identical currents at the nominal Booster tune ν = 4.83 and the B/I and G/I saturation has been matched. For quadrupoles allowed multipoles are important at injection fields where r=3" of good field is required. Computer results show small changes from low to high fields, where roughly 1/3 the good field aperture is required. These terms 60/20, 100/20, 140/20 then decrease by ~ 3^4, 3^8, 3^{12} respectively and become completely negligible.

TERM	POLES	LONG COIL	INTERNAL COIL	Δ ENDS
60/20	12	$+51.3\times10^{-4}$	-11.6×10^{-4}	$+63\times10^{-4}$
100/20	20	$+10.8\times10^{-4}$	$+9.6\times10^{-4}$	$+1.2\times10^{-4}$
140/20	28	0	$+0.6\times10^{-4}$	-0.6×10^{-4}
30/20	6	2.0×10^{-4}	2.2×10^{-4}	0
40/20	8	4.4	2.9	1.5×10^{-4}
50/20	10	0.7	0.4	0
70/20	14	0	0.4	0

Table 3 - Preliminary Quadrupole Measurements, r=3"

These results are with a square pole end, which will be studied before a shaped end. Then the pole profile will be modified to make the "integrated" allowed terms zero.

The only error terms show 2 x 10^{-4} sextupole and twice that much octupole. Better pole fabrication tooling is planned, although the results are acceptable. Note that the field integral of the quadrupole at r=3" is ~ 1/8 of that of the dipole, so a standard of $\frac{\Delta B}{B} \leq 1 \times 10^{-4}$ for dipoles permits larger deviation tolerances in quadrupoles. Eddy currents due to the circular vacuum chamber, laminations, coils and $\dot{B}$ end fields are all four-fold. No octupoles, sextupoles, etc., are induced.

Finally, field monitoring transducers in extra series quadrupoles and a dipole will provide feedback for tracking of magnets. The very small sextupole and other aberrations caused by magnetization and coil and lamination eddy currents reduce the complexity greatly, to a pure dipole and quadrupole field tracking. Eddy currents in vacuum chambers will no doubt complicate this and dominate the problem.

REFERENCES

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2. Booster Design Manual, 1986.
3. J. N. Galayda, H. Hsieh, Private communication.