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ANALYSIS OF MAGNETIC FIELD MEASUREMENT RESULTS FOR THE AGS BOOSTER MAGNETS*

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SUMMARY

Magnetic field measurements have been made on nearly 200 conventional magnets that have been installed in the AGS Booster and its associated transfer lines. The measurements were intended to monitor the quality of the magnets being produced and to check the performance of each magnet before installation. The magnetic measurements effort led to certain improvements in the manufacturing process, which then subsequently produced very good, very uniform magnets. The integrated dipole fields of the 36 booster dipoles are uniform to 1.5 parts in ten thousand. The magnetic measurements indicate that the quadrupoles were manufactured to an accuracy of 3 ten thousandths of an inch, which is better than we can physically measure.

INTRODUCTION

At Brookhaven National Laboratory a Booster Accelerator is being added to the AGS complex.[1] All the magnets are in place and circulating beam is expected in a few weeks. The Booster is rapid cycling, is 200 meters in circumference, and is intended to 1.) quintuple the AGS proton intensity by injecting 2.25 GeV/c protons, and 2.) inject ions as heavy as gold into the AGS. Since high intensity is an important goal of the Booster, great care was taken in the design and fabrication of the Booster magnets. This note summarizes the results from the production testing of these magnets.[2]

The Booster and its associated transfer lines require about 300 individual magnets of about 30 distinct designs. Table 1 lists some of the parameters of the major magnet systems. Our goal was to measure every magnet. The lesson we learned is that systems can be developed to routinely and efficiently measure the important groups of magnets, but those that occur in small numbers or have very special measurement requirements frequently slip through the cracks.

THE BOOSTER DIPOLE

The Booster dipole is a curved 10 degree sector magnet. Table 2 gives the specified and the measured field shape. Figure 1 shows a typical field shape measurement.

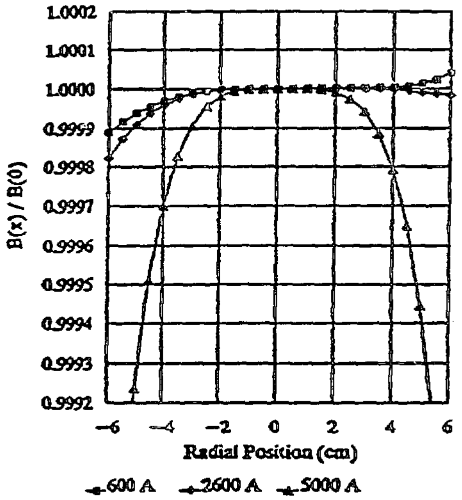

Figure 1. Magnetic profile, at 3 different currents, of a Booster dipole magnet taken over the entire length of the magnet. In this plot a quadrupole term and a sextupole term, equivalent to the average values of those terms in all the dipoles, have been removed, since they can be corrected for in Booster operation. The remaining field is good to one part in 10,000 over 10 centimeters at low field and over 5 centimeters at high field.

Of some interest is our degree of success in controlling the variation from magnet to magnet of the integrated dipole field strength. This was specified to have an rms variation of 1.5 parts in ten thousand. We claim to have achieved this. Three different sets of measurements were made on each dipole: 1.) A DC NMR measurement at the magnet center. These results were good to one part in ten thousand. 2.) A short (1 meter) rotating coil used in nine different positions to map the field. The results here are good to 3 parts in ten thousand and attest to the care of the technicians in placing the

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TABLE 1 BOOSTER MAIN MAGNET SYSTEMS

TYPE	DIPOLE	QUAD	QUAD	SEXT	
NAME	BMD	BMQL	BMQS	BMS	
NUMBER INSTALLED	36	24	24	48	
LENGTH	2.380	0.438	0.426	0.076	meters
GAP OR DIAMETER	8.255	16.510	16.510	16.510	centimeters
TURNS PER POLE	8	5	5	8	
Imax	5700	5700	5700	300	Amperes
POLE TIP FIELD AT Imax	13.5	8.4	8.4	2.1	kiloGauss

coil. 3.) A long coil measurement of the ramped field. These measurements gave us the integrated strength of the magnet, which is the number of interest for Booster operations and is the number we quote for overall magnet repeatability. The distribution of the results has a sigma of 2.7 parts per ten thousand. The system was designed to make absolute measurements on each magnet rather than doing comparative measurements of each magnet against a standard magnet. The ramping power supply needed periodic adjustments, which we believe were sufficient to affect the results at the level of a few parts in ten thousand as determined by periodic measurements of a standard magnet. Therefore, the number we quote, 1.5 parts in ten thousand results from some analysis and adjustment of the raw data. The point is that an accuracy of one or two parts in ten thousand is very hard and even when the manufacturing group achieves this accuracy by carefully controlling the length and weight of each magnet, demonstrating it by field measurement can still be a problem.

TABLE 2
RANDOM FIELD ERRORS IN THE BOOSTER DIPOLES

TERM	SPECIFIED TOLERANCE	MEASURED rms at 2600 Amps	UNITS
$\dfrac{\Delta\int B0 \cdot d\ell}{\int B0 \cdot d\ell}$	1.5	1.5	10^{-4}
B1/B0	2	0.91	10^{-5} cm^{-1}
B2/B0	5	0.89	10^{-4} cm^{-2}
B3/B0	7	0.14	10^{-6} cm^{-3}
B4/B0	1	0.01	10^{-6} cm^{-4}
B5/B0	1	0.06	10^{-7} cm^{-5}

The Booster will operate at up to 7.5 magnet cycles per second, which means that eddy currents induced in the vacuum chamber will contribute significantly to the magnetic fields, in particular to the sextupole term in the dipoles. A set of windings was designed to be installed on the vacuum chamber to carry a current to cancel the eddy current effects.[3] This current is driven by four turns wound around the dipole poles. This system has the advantages of canceling the sextupole at its origins, of decoupling the correction system from a dependence on vacuum chamber placement, and since it is entirely passive, of decoupling the correction system from a dependence on ramp rate settings. Figure 2 shows the measured induced sextupole as a function of the ramp rate with and without the correction coils connected. At a constant ramp rate the compensation is a remarkably good 99.5%. The compensating coil does produce higher harmonics, decapole, 14-pole etc., but the effects are small at the center of the magnet.

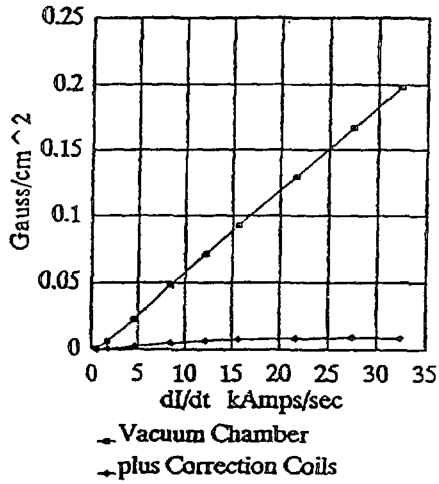

Figure 2. The measured induced sextupole field in a dipole as a function of ramp rate with and without the passive correction coils connected. Most of this sextupole is due to eddy currents in the vacuum chamber. The corrected sextupole field is less than the random allowed sextupole field.

THE BOOSTER QUADRUPOLE

The Booster uses two types of quadrupoles magnets, the horizontally focusing magnets being slightly shorter than the vertically focussing to compensate the horizontal focussing of the sector dipoles. Quadrant laminations are assembled into blocks and then the four quadrant blocks are assembled into a magnet. The initial assembly procedures produced blocks that were insufficiently rigid resulting in poor assemblies and very poor test results. The mechanical engineering staff very effectively solved the problem and produced a system that is now assembled rather like a watch. The result is a magnet that is very uniform from sample to sample. The controlling requirement was the uniformity of the integrated gradient, in meeting tolerances on that, the field shape automatically became very uniform from magnet to magnet. The same care in controlling block length and weight that was applied to the dipoles was applied to the quadrupoles. Table 3 summarizes the quadrupole results.

TABLE 3
RANDOM FIELD ERRORS IN THE BOOSTER QUADRUPOLES

TERM	SPECIFIED TOLERANCE	MEASURED rms at 2600 Amps	UNITS
$\dfrac{\Delta\int B1\cdot d\ell}{\int B1\cdot d\ell}$	6	1.6	10^{-5}
B2/B1	8	0.7	10^{-7} cm^{-1}
B3/B1	6	0.01	10^{-6} cm^{-2}
B4/B1	2	0.01	10^{-7} cm^{-3}
B5/B1	8	0.02	10^{-8} cm^{-4}

THE BOOSTER SEXTUPOLE

The Booster Sextupole was manufactured entirely by an outside vendor who delivered 52 completed magnets to us. Table 4 summarizes the magnet requirements and the measurement results. The magnet easily meets the stated specifications, and we suspect could have done even better with tighter control of the length and weight of the magnet cores.

TABLE 4
RANDOM FIELD ERRORS IN THE BOOSTER SEXTUPOLES

TERM	SPECIFIED TOLERANCE	MEASURED rms at 300 Amps	UNITS
$\dfrac{\Delta\int B2\cdot d\ell}{\int B2\cdot d\ell}$	9	3	10^{-3}
B3/B2	3	0.02	10^{-2} cm^{-1}
B4/B2	2	0.07	10^{-3} cm^{-2}
B5/B2	3	0.2	10^{-4} cm^{-3}

CONCLUSIONS

Our conclusions are that the booster magnets all meet specifications easily. Copper and steel magnets can be manufactured fairly readily to produce results uniform to the order of one part in ten thousand. However, to achieve these results each step of the process must be controlled rather carefully, in particular the length, weight, and gap of the magnet. Measuring to such good accuracy over a long period of time then requires very good equipment and carefully established calibration standards.

ACKNOWLEDGEMENTS

Many people contributed to the specification, design, construction, and testing of the booster magnets. The authors of the present note were solely involved in analyzing and monitoring the measurement results. As such they frequently raised nitpicking criticisms of the efforts of others and therefore would like to take this opportunity to congratulate them on a job well done.

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