Magnetic Measurement, Fiducialization and Alignment of Large Dipoles for the MIT–Bates SHR*

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Abstract

The South Hall Ring (SHR) lattice uses sixteen large dipoles originally designed for the Princeton-Pennsylvania Accelerator. These 3.6m long, 30 ton dipoles have bend radii of over 9 meters and gaps of only 7.6cm. The requirement that the four dipoles be powered in series, as well as other restrictions, resulted in magnetic and mechanical alignment tolerances which are very demanding for magnets of this size and shape. Two independent methods were used for measurement of the field integral along the design orbit. Field integrals were measured on all dipoles using a long coil excited by ramping the field. On four dipoles, the integrals were also measured using Hall probes moving along the design orbit. The techniques and results will be presented. The fiducialization of these dipoles was accomplished using precision-machined fixtures and the SLAC computer-aided Industrial Measurement System. Position corrections due to different measured effective lengths of these magnets will be discussed, and details of fiducialization and alignment will be presented.

1 Introduction

The 190 meter circumference SHR, currently under commissioning, will be a high intensity pulse stretcher facility providing high quality cw electron beams with energies between 0.3 and 1.0 GeV. It can be operated in storage mode for internal target experiments and in extraction mode for more conventional experiments. A detailed description of the ring is given in [1].

The 360 degrees of bend in the ring are provided by 16 C-profile laminated dipole magnets, each 3.6m long with a 7.6cm gap and a nominal n value of 1/2; one such magnet is shown in figure 1. The yoke of each magnet consists of c-shaped laminates of high μ steel with the pole tip field defined by crenelated laminated pole blocks each 2 inches wide. The gap is determined by a vertical spacer plate separating the upper and lower pole pieces; the upper pole pieces are forced onto the spacer plate by pressurized hoses. A ± 2.2mr relative pole tip inclination produces an $n = 1/2$ magnet. The pole blocks introduce some small gap variations along the length of the magnet resulting in field variations of $\pm 0.07\%$ from block to block. The design requirements and magnetic tolerances for these dipoles are summarized in Table I.

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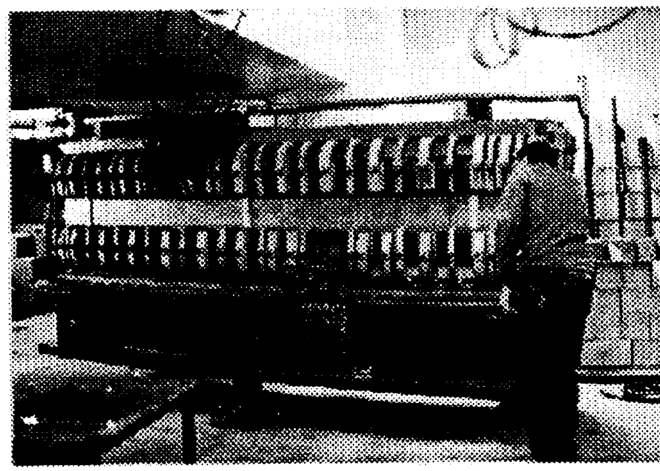

Figure 1: One SHR dipole.

Table I
Magnetic Tolerances

Quantity	Value	Tolerance
Effective length	3.591m	1mm
Gap	7.6cm	0.75mm
Bend angle	22.5deg	0.1mr
Eff. Field Boundary	–	1mm
Field settability		10^{-3}
Field stability	long term	10^{-4}
Field stability	short term	10^{-5}

The tolerance on the effective field length is very tight because the beam passes through these dipoles many times and the effective field length enters the overall circumference of the ring which has a tolerance of 5mm. Each of these dipoles has been magnetically measured, fiducialized and aligned.

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2 Magnetic Measurements

After extensive studies two measurement techniques were developed: stepping a Hall probe along the design orbit to produce a field map, and measuring the EMF induced by a ramped field in a coil centered about the design orbit. Two-dimensional field maps with the XZ table provided the $\int B \cdot dl$ along the beam trajectory, n value, and an indication of field variations in the uniform region. The long coil measurement determined the effective length along the nominal beam path.

2.1 XZ Table Measurement

A two-dimensional mapping table (on loan from NIST) was developed for field measurements using temperature-compensated Hall probes at predetermined points on a plane [8]. Two axes of motion of the table are instrumented and controlled by computer via CAMAC; the vertical axis is controlled manually by a micrometer stage.

The dipoles are so long that the table had to be placed at each end of the magnet. Field maps were made using a long arm holding two Hall probes separated by 54cm, and a complete map of a dipole required joining the four measurements from the two Hall probes from each end of the magnet. This required a good cycling procedure for the magnet, a stable power supply, and an overlap in mapping points of the two probes. The XZ table origin was related to a reference point in the magnet; we chose the intersection of the design orbit with a line parallel to the first lamination in the end pole block. This point was optically referenced using a precision machined fixture holding a survey target. The same fixture was used in the fiducialization of the magnet. The transverse origin was determined using a magnetic blade attached to an aluminum block of precise length with its end registered against the inner land of the upper pole tip. Radial field maps confirmed the design n value of 1/2; the higher multipoles were consistent with zero in the uniform field region and had high values near the pole faces at each end of the magnet.

2.2 Long Coil Measurements

All 16 dipoles were magnetically measured using the long coil. The long coil consists of an arc-shaped aluminum plate with an arc length equal to the physical length of the magnet arc plus 10 gaps, with grooves for the closed loop signal wires. When installed in the magnet for measurement, the long coil form positioned a flat coil of width 2.055 ± 0.004 inches on the midplane, centered about the design orbit. As the current was ramped from 0 to a set point (or from a set point to 0), an EMF was induced in the coil; magnetic flux or the time integral of the induced voltage $\Phi = \int V dt$ is proportional to the area of the coil and the change in the field,

$$\int V \cdot dt = \int_{B=B_i}^{B=B_f} A \cdot dB = W \cdot L_{eff} \cdot (B_i - B_f)$$

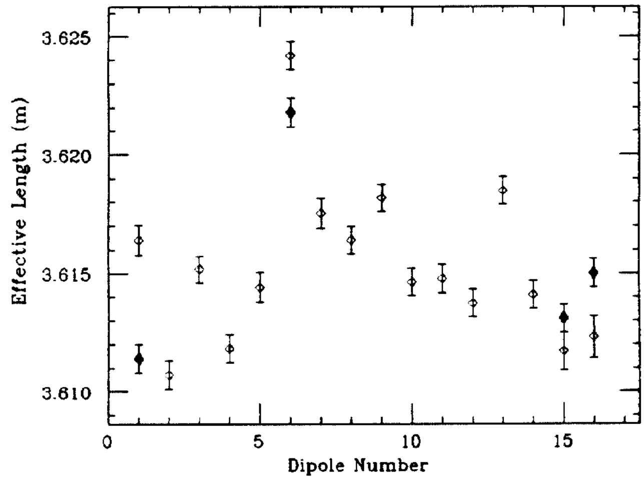

Figure 2: Effective field length for each dipole (solid points are XZ results, open points are Long Coil results).

where W is the average width of the coil and L_{eff} is the effective magnetic length of the magnet. The 6 turns of wire in the coil produced a 5 mV signal for a 5 Amp/sec ramp. The field on the design orbit was measured at one location by two NMR probes inserted in a machined slot in the form. Prior to each measurement, the Dymec 2401-A Integrating Digital Voltmeter was calibrated.

The largest uncertainty in determining the effective length was the uncertainty in the average width of the coil, resulting from variations in the placement of the wires in the grooves.

2.3 Results and Comparison of the Two Methods

The XZ maps were more time consuming than the long coil measurements and required complicated off-line analysis for deriving the integrated field. The XZ map was used for absolute measurements while the long coil, due to the uncertainty in the absolute value of the coil width, was used for relative measurements of the magnets. Figure 2 shows L_{eff} for all 16 dipoles for both techniques.

The absolute value of the field integral was measured with the XZ table to 5×10^{-4} to 1×10^{-3} depending primarily on the Hall probe scale used (in other words, depending on the magnet current) and the absolute value of the effective length was measured to 3×10^{-4}. Field integrals were measured at 4 currents corresponding to a range of beam energies between 0.3 and 1.1 GeV. The absolute and relative uncertainties in the long coil measurements of the effective length are 8×10^{-4} and 3×10^{-4}. A polynomial fit to the NMR probe field as a function of magnet current for the long coil data sets produced coefficients which are used by the SHR control system to set the magnets for a given beam energy; the control system also takes into account the varying bend radii $\rho = L_{eff}/(\pi/8)$ of the magnets.

3 Fiducialization

In the fiducialization process, the magnetic and mechanical axes of each magnet were related to five fixed fiducial targets on top of the magnet. Precision fixtures holding survey targets on the midplane were positioned on the pole tip at the edge of last lamination block at either end of the magnet such that one of the targets in each fixture was on the design orbit. We defined the midpoint between these two targets as the magnet origin.

For fiducializing all SHR magnets we used the SLAC Industrial Measurement System (SIMS) [2], with two Kern electronic theodolites. With the help of simulation software, six theodolite locations surrounding a dipole were chosen to achieve maximum sensitivity to both vertical and transverse locations of the survey targets on the magnet and on the design orbit.

The SIMS bundle adjustment software [3] generated the coordinates of magnet targets, fixture targets, targets on either end of a calibrated invar rod [4], and some auxiliary targets with respect to the coordinate system of one of the theodolites positioned close to the center of the magnet. A coordinate transformation from the theodolite system to the origin of the magnet was performed using software from the SLAC Alignment Group. The coordinates of the five fixed targets were stored for the next step, alignment.

The magnet origin found in the fiducialization procedure must be adjusted to account for the different measured effective lengths of the magnets. Each magnet must be positioned such that an electron of the proper energy is bent by 22.5° and its path intercepts the fiducialization targets on the design orbit. Thus, a suitable axis for these dipoles is a line connecting the effective field boundaries of the magnets which are by requirement on an arc of subtended angle $\frac{\pi}{8}$. A transverse shift of this axis is necessary because the effective field boundary is further outside the magnet than the design value.

4 Alignment

For the SHR survey and alignment [6], we adapted a computer-assisted database survey and alignment system from SLAC [7] which provided sufficient redundancy and error analysis did not require extensive experience with optical tooling techniques. The main steps are:

1. Survey of the network of SHR floor monuments,
2. Calculation of ideal coordinates of magnet survey targets,
3. Integration of 1) and 2) into a database, and
4. Alignment of magnets using the database and intersecting sight lines of electronic theodolites.

The SHR has a network of over 80 floor monuments whose locations in the ring coordinate system are part of the database. The ideal coordinates of survey targets on a magnet in the ring coordinate system are achieved by merging the TRANSPORT output of magnet location and the result of the fiducialization. A magnet was positioned to within a few centimeters of its ideal location using conventional methods, then precisely aligned using the monuments and the database. A Wild N3 optical level, 2m survey rod and a network of elevation rivets were used to level and set the magnet at its ideal height. With two theodolites positioned precisely on monuments at optimum locations near a dipole, the CLASH interactive software from SLAC [5] calculated the direction to point the theodolites for each target. In an iterative process, the theodolites were set to the direction for each target, and the magnet moved until that target was at the intersection of the two lines of sight; then the height of the magnet was corrected. In the end, all five targets were within 1/4mm of their ideal positions.

5 Conclusions

We have developed and executed procedures for precision magnetic measurements and survey and alignment of 16 very large dipoles for the SHR. The results of the magnetic measurements have been implemented in the ring control system. The success of the measurements and the alignments was confirmed by a successful storage of the beam on the first day of commissioning, for a time limited only by energy losses due to synchrotron radiation, as the cw RF cavity was not installed.

References

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