Fiducialization of Magnets for the MIT-Bates SHR*

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Abstract

The 190 m circumference South Hall Ring (SHR) and Injection Line contain 94 quadrupoles for which the design position tolerances are ± 100 μm, transverse and vertical. About half of the error budget on this tolerance will be used in fiducialization, the relating of the magnetic axes to the positions of survey targets fixed to the magnet. The system we are developing uses the SLAC Industrial Measurement System (SIMS) while the magnetic properties are being measured on a harmonic analyzer. The usual step of relating the magnetic axes to the mechanical axes is bypassed in this system, but this relationship will be measured for a subset of magnets as a check of systematics. Results of the fiducialization of over 20 quadrupoles are presented.

1 Introduction

The SHR, scheduled to be commissioned in 1992, 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 ref. [1].

The quadrupoles for this new facility follow the design of booster ring quadrupoles for the Advanced Light Source under construction at the Lawrence Berkeley Laboratory. The laminated iron yoke consists of two identical cores joined at the horizontal midplane. Mechanical imperfections in these cores result not only in non-circular apertures but also in apertures whose profile is a function of position along the magnet axis. While these imperfections have not been large enough to produce unacceptable magnetic properties[2], they are too large to ignore when fiducializing the magnets. Figure 1 shows the mechanical asymmetry of the aperture at one end of the magnet for the 128 new quadrupoles obtained for this project.

An integral part of our fiducialization system is a Harmonic Analyzer (HA) which is used for magnetically measuring the quadrupoles and is briefly described in reference[2]. It mainly consists of a rotating ceramic bobbin with an angular encoder, a support structure holding the bobbin, a V/f converter and five micrometers for aligning the bobbin relative to the magnet.

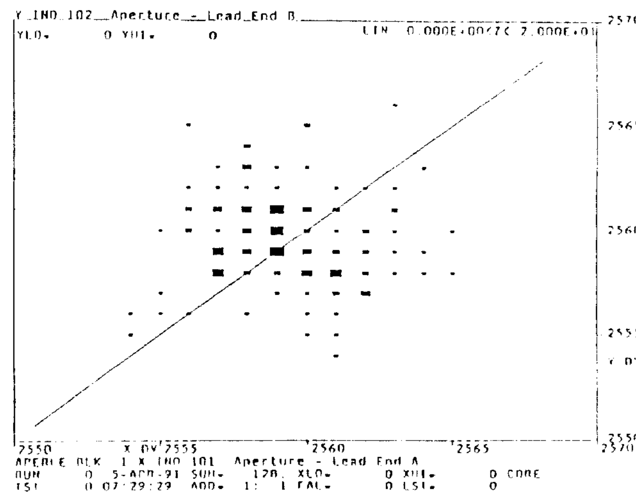

Figure 1: Scatter plot of one pole gap diameter (measured diagonally between the pole tips) versus the other at the same end of the quadrupole. The smallest rectangle represents one quadrupole. The gap diameters have been binned in one mil (0.001 inch) steps. Quadrupoles whose data lie on the diagonal line have circular bores.

The original plan was to fiducialize the quads in two steps, the first of which was to relate the magnetic axis to the mechanical axis. However, the elliptical apertures did not permit defining the mechanical axis with a simple centering spindle. We have removed the requirement of determining the mechanical axes of the magnets by fiducializing the HA (measuring the distance from the bobbin axis to fixed survey targets on the bobbin support) and then measuring the distance from these targets to the ones attached to the quadrupole.

The survey measurements are made with SIMS[3], a highly automated triangulation system using electronic theodolites viewing survey targets on the object as well as on the ends of a precision scale bar. Observations are made from typically three or more theodolite locations. In the data analysis, the bobbin axis is assumed to be coin-

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cident with the quadrupole axis when it measures a zero dipole component; pitch and yaw are fixed by use of the alignment spindle. Since the HA is insensitive to absolute roll, the roll is nulled by mechanically leveling the magnet using a precision bubble level. Our current procedure for fiducializing the SHR quadrupoles consists of the following main steps:

- Install magnet on the HA table, level, and mechanically align the magnet,
- Null the dipole term measured by HA,
- Make angle observations of survey targets on the HA table, on the magnet and on the scale bar using SIMS,
- Analyze data using bundle adjustment software [4] in SIMS.

2 Procedure

2.1 Nulling the Dipole Term

After installing a quadrupole on the HA, the roll, whose tolerance is 1 mr, is nulled by mechanically leveling the magnet using a precision bubble level and an "integrator plate", which averages over the uneven features (irregular laminations, paint) on the top surface of the magnet. Then the magnet is mechanically aligned by replacing the coil assembly with a precision-ground shaft (alignment spindle) held with the same fixtures that hold the coil assembly. The shaft location is then adjusted with precision micrometers (1 μm resolution) that support the structure holding the alignment spindle. The micrometers are adjusted until phenolic cylinders sliding on the alignment spindle easily slip into the aperture of the quadrupole. At this point, the quadrupole is considered to be mechanically aligned. The alignment spindle is removed and the coil bobbin is mounted, the quadrupole is energized, and the dipole component of the field is measured. The micrometers are then adjusted to minimize the real and imaginary dipole components in an iterative fashion. This procedure is considered complete when micrometer movements for further reduction are less than $\sim$10μm; at this point the micrometers, which had been initially zeroed, read how far the magnetic center is from the mechanical center.

2.2 Theodolite Setup and Angle Observations

With the help of simulation, three theodolite locations surrounding the HA were chosen such that a maximum sensitivity to both vertical and transverse components of the survey targets on the quadrupole could be achieved. Later we added a fourth theodolite at a location close to the beam axis of the magnet, and relocated the third one to further improve our transverse sensitivity. There are a total of eleven (11) survey targets, five on either end of the support structure holding the bobbin and one in the middle of the HA table. There are also several survey targets on the surrounding walls. Figure 2 shows our fiducialization setup. Before fiducializing any quadrupole we had to fiducialize the HA table relative to the axis of the bobbin; we refer to this process as a "calibration" run, which is described below.

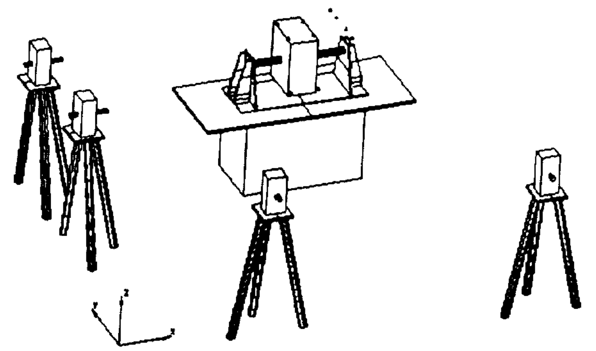

Figure 2: Isometric view of Fiducialization setup for SHR quadrupoles. The survey targets are indicated as dots, the magnet is the rectangular box with the bobbin going through its axis. The four tripods are bolted to the floor.

2.2.1 HA Calibration

The calibration run had to be done once, and may be repeated a few times during the course of several months as a systematic check, when all quadrupoles are being fiducialized . It was done with the bobbin removed and no magnet mounted. The coordinates of all survey targets on the HA were measured in a coordinate system (XYZ) with the X axis being the axis of the bobbin (magnetic axis of the quad), the Y axis in the horizontal plane and the Z axis in the vertical direction. Two precision machined fixtures were fabricated and installed in place of the bobbin on the support structure which holds the ends of the bobbin. These fixtures have drill bushings at both ends, and hold four survey targets all lined up on the axis of the bobbin. In the calibration measurements, for maximum transverse sensitivity, we also added a fifth theodolite location (not shown in the figure) with an optical axis very close to being on the axis going through the four targets on the fixtures (axis of bobbin). Using SIMS and two Kern [5] electronic theodolites at a time, all targets were viewed four times (two forward and two reverse) from all five locations. Also viewed from each theodolite location were two survey targets, one at each end of a calibrated scale bar [6]. A least squares analysis (bundle adjustment) of the data gave the coordinates of survey targets relative to the location of one of the theodolites ("control theodolite"); the coordinates were then transferred from the control theodolite location to the XYZ coordinate system defined above. The origin of XYZ system is defined to be at one end of the bobbin.

2.2.2 Quadrupole Fiducialization

After a quadrupole is installed and leveled on the table, and after the dipole field is nulled, the fiducialization can begin. There are a total of six targets on the quadrupole, four on top and two on fixtures attached to the mounting brackets for the magnets. The center of these two temporary targets define the ends of the magnet (Figure 2) along the beam; the midpoint of these two targets defines the mechanical midpoint of the magnet. From the four theodolite stations, a total of nineteen targets (including the scale bar ends) are viewed four times each, two forward and two reverse. Presently, it takes just under two hours to shoot all targets and this time may be further reduced as we gain experience.

2.3 Data analysis and results

The coordinates of the eleven survey targets on the HA measured in the calibration run implicitly contain the coordinate system of interest (XYZ). Keeping these coordinates fixed and doing a bundle adjustment in SIMS, the data for each magnet are analyzed. With a total number of 76 angle observations from four theodolite stations, one distance (the scale bar length), and six unknown object points on the quadrupole, we typically have 66 degrees of freedom, and a typical reference standard deviation (χ) of 0.7 . The coordinates of the unknown points (magnet targets) and their associated errors are calculated in the XYZ coordinate system. Since the origin of XYZ coordinate system is not at the midpoint of the magnet, a simple translation in X of all coordinates is needed. This is done by translating all X coordinates by an amount equal to the average of the X coordinates of the two survey targets at each end of the magnet.

Table below shows typical results from a SIMS run on one of the SHR quadrupole(#58). The letters A, B, C and D refer to survey targets on top of quad; these four targets will also be used for installation of the magnet in the ring tunnel. The "IN" and "OUT" refer to the temporary targets at both ends of the magnet. We should note that the errors SX, SY and SZ given in this table are smaller than $60\mu m$, $50\mu m$ and $40\mu m$ respectively. After fiducializing about twenty quadrupoles, we are in the process of doing a series of systematic studies which include both the calibration process as well as the production measurements. For instance, we have re-calibrated the table and the results were consistent with the first calibration. We are also repeating an earlier fiducialization measurement on a single quadrupole to better understand the statistical and systematic errors.

Final object point coordinates (mm)

Target	X	Y	Z
Q058A	305.768	134.066	299.985
Q058B	560.325	133.622	300.299
Q058B	560.325	133.622	300.299
Q058C	560.444	-133.518	300.539
Q058D	305.849	-133.349	299.976
Q058IN	292.919	-299.303	-270.729
Q058OU	572.650	-297.452	-221.187

Final object point standard errors (mm)

Target	SX	SY	SZ
Q058A	0.056	0.048	0.036
Q058B	0.057	0.050	0.037
Q058C	0.054	0.047	0.034
Q058D	0.053	0.044	0.033
Q058IN	0.052	0.044	0.037
Q058OU	0.054	0.047	0.038

3 Conclusion

We have developed a procedure for fiducializing all 128 SHR quadrupoles using SIMS and a harmonic analyzer system used for magnetic multipole measurements. The process has been optimized and the errors are within our total error budget of $\pm 100\mu m$, transverse and vertical. The procedure developed for the quadrupole magnets can also be used for fiducializing the 32 new SHR sextupoles. For all other SHR magnets, our plans are to fiducialize them with SIMS and a mapping table (described in reference [7]) which is used for grid measurements of magnetic field.

References

[1] J.B. Flanz et al., Proceedings of the 1989 IEEE Particle Accelerator Conference, March 20-23, 1989, p.34.

[2] J.D. Zumbro et al., Proceedings of the 1991 IEEE Particle Accelerator Conference, May 6-9, 1991.

[3] A PC-based acquisition and analysis software system developed at SLAC for tri-dimensional survey and bundle adjustment.

[4] Bundle Adjustments and Tri-dimensional Coordinate Determination, SLAC-PUB-4717.

[5] Models E2 and E2-I,**KERN**SWISS, Aarau, Switzerland.

[6] Model # 803M, Invar scale kit, Brunson Instrument, Kansas City, Mo.

[7] M. Farkhondeh *et al.*, Proceedings of the 1991 IEEE Particle Accelerator Conference, May6–9, 1991.