Control of Roll in Fiducialization of Quadrupole Magnets for the MIT–Bates South Hall Ring*

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Abstract

The South Hall Ring (SHR) requires for all 94 quadrupoles in the lattice a roll tolerance of less than 2mr. An important step in achieving this tolerance is the fiducialization: the relating of the magnetic axes to the position of the survey targets fixed to the magnet. The fiducialization procedure which we developed involved a harmonic analyzer system and the SLAC Industrial Measurement System. After fiducialization and database generation had been completed for over 1/3 of the elements, and after the precision installation had begun, we noticed a random roll well outside the tolerances. The roll had been overlooked partially because the harmonic analyzer system is insensitive to rotations about the coil axis. We were able to overcome the problem through software by developing an extensive algorithm and regenerating the database without a need for refiducialization. This correction process for both the roll and the pitch will be presented.

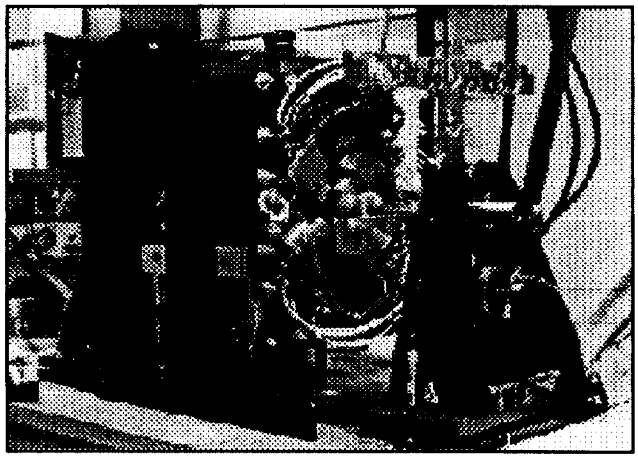

Figure 1: A photograph of the Harmonic Analyzer table with a quad mounted for magnetic measurement and fiducialization.

1 Introduction

The 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 ref. [1]

The SHR quadrupoles follow the design of booster ring quadrupoles for the Advanced Light Source 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.

The critical tolerances for the quad positioning are the transverse (XY plane) tolerances of 0.1mm element-to-element and a rotational roll tolerance of 0.1 deg (1.7mr). Rotational misalignment of quads will mix the X and Y components of the field, coupling the phase space in the two planes. The specified tolerance should assure that this coupling is less than 10% .

During the initial precision survey and alignment of the quadrupoles [2] in the injection line area, the presence of a random but significant roll and pitch was detected. The problem was soon traced to an oversight in the fiducialization of the quads and usage of a Harmonic Analyzer system which is insensitive to small rotations (a photograph of the table with a quad is shown in Fig. 1). In this report we will describe the issues relevant to the control of the roll and will present solutions to overcome the roll problems as encountered.

2 Fiducialization and Rotation

A detailed description of the fiducialization of these quadrupoles is given in ref. [3] and a schematic of the setup with four Kern theodolite locations is shown in Fig. 2. However, a brief summary of it is given here with an emphasis on the rotation issue. An integral part of this fiducialization system was a Harmonic Analyzer (HA) which was used for magnetically measuring the quadrupoles and is briefly described in ref. [4]. It consists of a rotating

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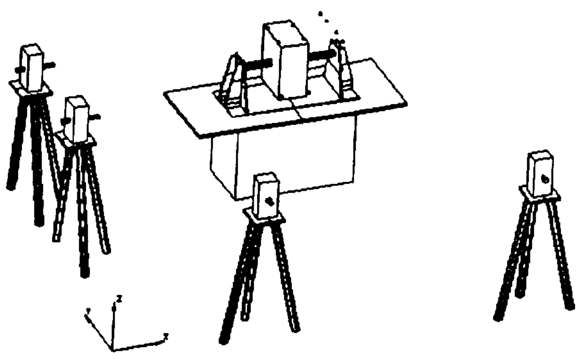

Figure 2: Schematic diagram of quad fiducialization setup.

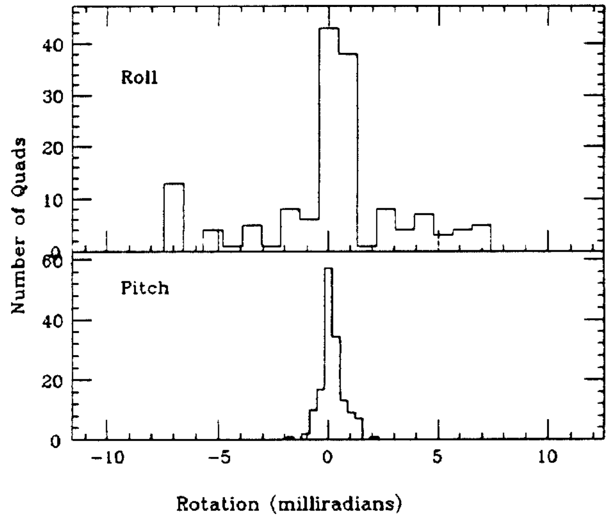

Figure 3: Statistical results of Roll and pitch of the HA table and the quads in the database.

cylindrical ceramic bobbin with wire coils wound on it, a moveable support table holding the bobbin and survey targets, and five micrometers for aligning the table supporting the bobbin relative to the quad. The quad is supported by three posts mechanically isolated from the bobbin support.

To position the magnet on the HA for the magnetic measurements and fiducialization it was first necessary to level the magnet using the three support posts. A precision bubble level was placed on a heavy steel plate (approximately 30 cm square) resting on a thin foam pad which "integrated out" the small surface irregularities of the laminated yoke. It was earlier determined that the top surface was parallel to the mechanical midplane within the needed tolerances. After the magnet had been leveled, the bobbin axis was positioned to coincide roughly with the mechanical axis of the quad. An alignment shaft with custom spacers replaced the bobbin for this operation. The magnet was then energized and the measured dipole component was nulled by fine-tuning the position of the bobbin, being careful to adjust the positioning micrometers such that the axis was only translated and not rotated about any axis.

We also fiducialized the HA table relative to the axis of the bobbin; this one-time survey measured the coordinates of all 11 survey targets affixed to the table relative to the axis of the bobbin as described in ref. [3]. These measured coordinates are fixed relative to the gravity vector as long as the HA micrometers are left alone or changed for only translational movement of the bobbin.

The quad fiducialization was done with the SLAC Industrial Measurement System (SIMS)[5] using a total of four theodolite locations viewing the 11 targets on the HA table, the quad survey targets and the end targets on a precision invar scale bar. A bundle adjustment [6] with the coordinates of the 11 table targets (measured in the table calibration) as input produced a set of coordinates for the quad targets in the bobbin coordinate system. As described above, the bobbin axis is adjusted to coincide with the magnetic axis of the quad.

An oversight occurred during the rough mechanical alignment of the bobbin in which random table rotations well outside the tolerances were introduced. This occurred in the process of making the custom spacers fit into the quadrupole aperture by randomly changing the micrometers. Since the HA with a long bobbin extending well outside the fringe field regions is insensitive to roll or a small amount of pitch, the subsequent magnetic measurement and dipole minimization could not detect the rotation of the HA table relative to gravity and the quad.

The oversight was discovered after about 1/3 of the quads were measured and installation began. All quads were installed at the proper survey target heights, but for some, the precision bubble level reported significant amount of pitch and/or roll. These random rotations were as large as 10 mr, well outside the rotational tolerances. Figure 3 presents a statistical analysis of the roll and pitch for nearly all 128 quadrupoles; the roll is typically larger than the pitch. We were able to correct these undesirable rotations by correcting our database without any need for refiducialization. This was possible, primarily because direction of the gravity was implicitly defined by the vertical angles of the theodolites which were recorded in each fiducialization file.

3 Control of Roll and Pitch

After the source of the rotation problem was detected we added a procedure for ensuring that during each quad measurement, the HA table orientation relative to the gravity vector was the same as it was during the one-time table fiducialization. We reconstructed this orientation by making the relative differences between the vertical coordinate of the table targets exactly the same as they were in the calibration file. We then installed a ground plate with three point contact on a flat region of the table, leveled

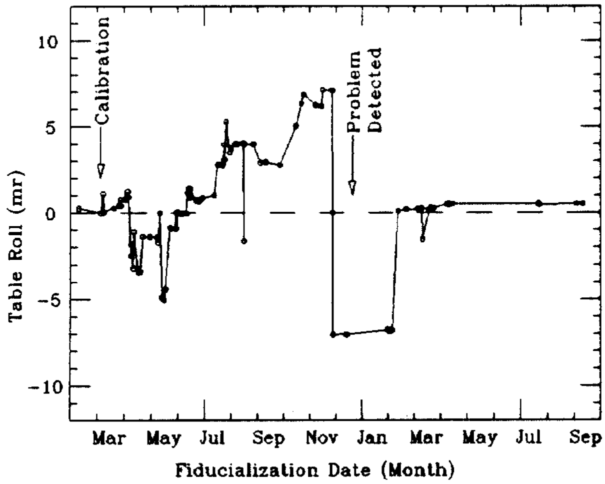

Figure 4: Roll of the HA table as a function of time of quad fiducializations between 1990 and 1992.

the plate with a precision level and permanently attached it to the table. Prior to each quad fiducialization, the plate was leveled with a precision level, thus ensuring the correct orientation of the table. However, there always were some residual rotations which were corrected in the software.

When the surveying part of the fiducialization of a quad was completed, the coordinates of the quad survey targets were determined in the table coordinate system by using the survey data and by keeping the calibration coordinates of the 11 table targets (control coordinates) fixed; this step assumes that the table orientation stayed unchanged since the calibration. Since the quads were leveled during the survey, any residual rotation of the table introduced during the mechanical alignment manifested itself as a rotation of the quad in the opposite direction. Denote the coordinates of the i^{th} survey target on the quad in the table "object" coordinate system as $X_o = (x_o^i, y_o^i, z_o^i)$ and the amount of rotation as R(oll) and P(itch). In order to determine the true orientation of the table, we performed a bundle adjustment in the "local" coordinate system of the control theodolite and calculated a set of coordinates for each quad survey target denoted as $X_l = (x_l^i, y_l^i, z_l^i)$. Using a 9-parameter coordinate transformation from SLAC between these two sets of coordinate systems we calculated the transformation matrix including R and P angles. The rotation angles always were determined with no ambiguity to better than 0.01 degrees. Figure 4. shows a history profile of the the table rotation during the period between 1990 to 1992.

The correct coordinates of the quad targets in the quad system X_o^c were then calculated by a rotation matrix Γ =[R][P] with [R] and [P] the normal 3×3 rotation matrices:

$$X_o^c = \Gamma X_o$$

with

$$\Gamma = \begin{pmatrix} \cos P & 0 & \sin P \\ +\sin R \sin P & \cos R & -\sin R \cos P \\ -\cos R \sin P & \sin R & \cos R \cos P \end{pmatrix}$$

The process was automated by a Fortran code which manipulated the coordinate database and performed all the transformations.

4 Commissioning Results

The SHR is undergoing its completion and commissioning phase. In March of this year and on the first day of commissioning of the ring lattice, electron beams were stored for as long as 20 ms which corresponds to over 30,000 turns before it was lost due to synchrotron radiation loss with no RF cavity in the ring. With one turn injection, beam currents as high as 40 mA were stored later, meeting the design goal for 1–turn injection.

5 Conclusions

We have developed and executed a comprehensive survey and alignment program for controlling the roll and pitch of the SHR quadrupoles. The residual rotations were nulled by correcting the coordinate database, which was based on a fiducialization of individual quads using a harmonic analyzer table insensitive to small rotations. The database correction process was automated and the alignment of all 94 SHR quads has been completed to $\sim \pm 0.25$mm. The initial commissioning of the beam verified the success of the handling of the roll.

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