MISALIGNMENT EVALUATION OF SUPERCONDUCTING MAGNETS IN THE RELATIVISTIC HEAVY ION COLLIDER [*]

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Abstract

In this paper, we first present the procedures for aligning and installing RHIC superconducting magnets, and then discuss the effects and compensation methods for the remaining misalignments.

1 INTRODUCTION

In the Relativistic Heavy Ion Collider (RHIC),[1] two ion beams of various species will be accelerated and stored in their separate rings for 10 hours at 100 GeV/u. The requirements on magnet alignment and field quality[2] are most stringent during the low β^* storage of gold ions (when the beam emittance is large due to intra-beam scattering), and during the operation of polarized protons.

The RHIC magnet system[1] consists primarily of superconducting dipoles and corrector-quadrupole-sextupole (CQS) assemblies for guiding, focusing, and correcting the beam in the regular arcs of the ring. A significant complement of special magnets, including the triplet assembly, is also required for steering the beams into collisions at the six interaction regions (IR). The challenge in magnet alignment has been to assemble multiple magnet components (cold masses) into a common cryostat, so that their magnetic centers and orientations have ideal values when they are cooled down to the operating temperature of 4.5 K. The rigid composite cold mass must be free to shrink and expand longitudinally during thermal cycling. At the same time, the transverse motion must be strictly constrained.

2 ARC REGION CQS ASSEMBLY

Each arc region of the twelve RHIC sextants consists of eleven FODO cells. Each FODO cell consists of two dipoles and two CQS assemblies (Fig. 1). The alignment of a CQS assembly consists of several steps. First, each CQS cold mass is measured at room (warm) and superconducting (cold) temperatures to determine its magnetic field angle and center offset with respect to the cold mass fiducials. This field quality data[2] is transferred into the RHIC database and analysed by studying the trends, statistics, and expected value comparison using the computer program MAGSTAT. Then, after all three individual cold masses have been accepted by the Magnet Acceptance Committee (MAC) and assembled into their cryostat together with the beam position monitor (BPM), the CQS assembly is surveyed with either colloidal-cell optical[3] or stationary-coil pick-up (antenna) techniques to locate the magnetic centers of the components relative to the cold mass fiducials, and the externally accessible cryostat fiducials. This survey data is transferred into the database and analysed using the computer program SURVSTAT. Finally, after the entire assembly is remeasured and accepted by the MAC, it is installed into the ring and positioned using both cold mass and cryostat fiducials.

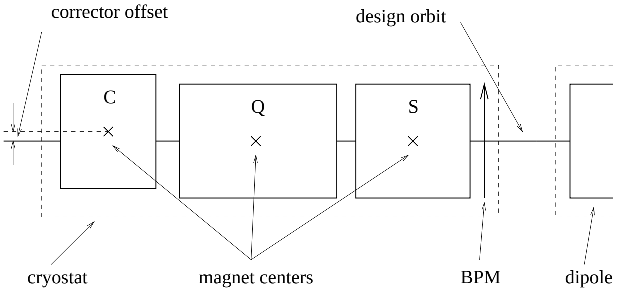

Figure 1: Schematic layout of the CQS assembly.

2.1 *Cold Mass Field Quality*

Table 1 shows for 262 dipole, 380 quadrupole, 300 sextupole, and 431 corrector cold masses the mean and standard deviation (S.D.) of the magnetic centers relative to the mechanical centers, and the integral field angle relative to the base. The systematic roll, and possibly the systematic vertical offset in the quadrupole, is due to the field from the current leads.

Table 1: Statistics of dipole and CQS magnetic integral field angle, horizontal (H), and vertical (V) center offsets.

Quantity	H/V	Units	Mean	S.D.
Dipole field angle[a]		[mr]	-0.8	0.7
Quad. field angle[a]		[mr]	-1.7	0.3
Sext. field angle		[mr]	-0.3	0.7
Corr. field angle[b]		[mr]	-4.5	3.9
Quad. center offset	H	[μm]	14	61
	V	[μm]	110	64
Sext. center offset	H	[μm]	15	88
	V	[μm]	28	34
Corr. center offset[b]	H	[μm]	70	80
	V	[μm]	50	100

a) To be corrected during CQS ring installation.
b) Dipole layer of the corrector only.

2.2 *Cold Mass Alignment*

The CQS components need to be aligned with each other so that their magnetic centers are on a straight line. “Springs”

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made of G-10 plastic, installed in the support posts, push the cold mass transversely while allowing free longitudinal motion. Initially, special welding strips are applied on the CQS shell to assure that the relative mechanical centers of the individual cold mass are aligned within 0.25 mm. Subsequently, the welding sequence is carefully choreographed to balance "curling" distortions against each other.

A crucial issue in CQS alignment is to accurately locate the magnetic centers of the cold masses after they are fully assembled. In early CQSs, the colloidal-cell technique was used to locate the transverse quadrupole field center with respect to the external fiducials. In recent CQSs, the antenna technique is used to locate the centers of quadrupole, sextupole, and multi-layer corrector. The measurement is done at several locations along the longitudinal axis with an estimated error from 0.05 to 0.1 mm. As shown in Table 2, the difference between optically and mechanically measured quadrupole centers is mostly caused by the final welding of the cover plates after the mechanical measurement is performed. The straightness of CQS is indicated by the corrector and BPM offset (Fig. 1) from the design trajectory. Fig. 2 shows the assembly learning curve, where the most significant improvement was achieved by using more symmetric welding patterns.

Table 2: Measurement statistics of CQS cold mass center position and straightness.

Quantity	H/V	Units	Mean	S.D.
Quad. center difference	H	[μm]	35	157
(Antenna−Mechanical)	V	[μm]	18	72
Quad. center difference	H	[μm]	62	276
(Colloid−Mechanical)	V	[μm]	−39	148
Corrector offset	H	[μm]	−150	605
	V	[μm]	4	412
BPM offset	H	[μm]	145	335
	V	[μm]	100	277

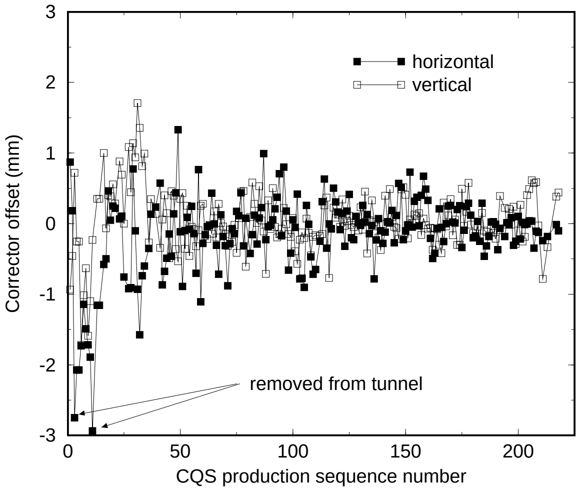

Figure 2: CQS corrector offset from the ideal orbit.

2.3 *Ring Installation*

The CQS assembly is installed and surveyed into the ring by centering the quadrupole and sextupole on the design beam orbit. The orientation is chosen to compensate the quadrupole magnetic field angle deviation. With preliminary installation and survey, Table 3 shows the deviation of the actual position from the ideal position, both in the RHIC global coordinate system (North, East, and Elevation) and in the beam system, which results from the limited accuracy in installation, survey, and center evaluation. The S.D. in offsets can be reduced to about 0.3 mm by a second round survey adjustment ("smoothing").

Table 3: Preliminary installation offsets (mean±S.D.) of 77 arc CQSs and 88 arc dipoles.

Direction	Units	arc dipole	CQS element
North	[mm]	-0.1 ± 0.6	0.0 ± 0.6
East	[mm]	-0.1 ± 0.5	0.0 ± 0.7
Elevation	[mm]	-0.1 ± 0.7	-0.2 ± 0.5
Radial	[mm]	0.1 ± 0.4	0.0 ± 0.4
Vertical	[mm]	-0.1 ± 0.7	-0.2 ± 0.5
Longitudinal	[mm]	0.0 ± 0.6	0.1 ± 0.4

2.4 *Effects of CQS Misalignments*

The closed orbit error produced by the quadrupole center S.D. of 0.5 mm (Table 3) requires a correction by dipole correctors with a rms current of about 3 A at top energy. The sextupole center S.D. of 0.5 mm produces[4] a beta wave $|\Delta\beta/\beta|$ of about 20%. These undesired effects can be significantly reduced after the "smoothing" position adjustments.

Since the quadrupole roll has been individually compensated to minimize the skew component, the sextupoles are aligned with systematic and random roll of 1.4±0.7 mr. This roll produces a skew sextupole component ($a_2 = 0.2 \pm 0.1$) which is small compared with that of the arc dipoles ($a_2 = -1.1 \pm 0.2$).[2]

Correctors with large misalignments (Fig. 2) can generate serious feed-down harmonics. Two early CQSs with corrector offsets larger than 2 mm have been removed from the tunnel, and were later verified to be noticeably bent. Correctors with large roll in their dipole or quadrupole layer (more than 15 mr) have been designated as spare magnets. For all the magnets, the effect of longitudinal center offset (Table 3) is insignificant.

3 ARC REGION DIPOLES

Arc region dipoles are installed with a deliberate offset[5] of 1.3 mm, radially outward, to compensate for a systematic sagitta error from manufacturing. Arc dipoles are also aligned individually to compensate for the magnetic field angle deviation (Table 1). The deviation of the actual position from the ideal position is shown in Table 3. The resulting reduction in physical aperture is insignificant.

4 IR TRIPLET ASSEMBLY

The IR triplet cryostat contains two dipoles, six quadrupoles, and six four-layer corrector packages in the two rings (Fig. 3). The requirements[6] on magnet alignment become stringent during low-β^* storage ($\beta^* = 1$ m) when the beam size at the triplet is large ($\beta \approx 1400$ m). Techniques developed during CQS assembly become highly beneficial.

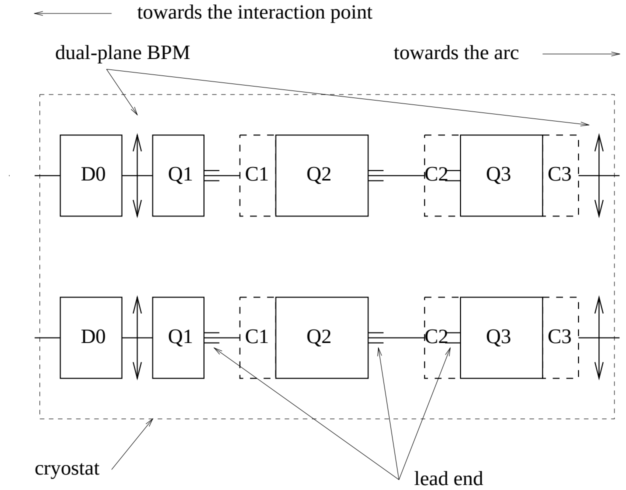

Figure 3: Schematic layout of the triplet assembly, showing the dipoles (D0), quadrupoles (Q1, Q2, and Q3) and their lead-end orientation, triplet correctors (C1, C2, and C3), and dual-plane BPMs of both rings.

In order to achieve high alignment accuracy, special measures are taken during triplet assembly. First, the various layers of corrector coils are shimmed at the pole position during construction to minimize the relative field angle deviation between the layers. Since only two IRs are designed to operate at low β^* of 1 m, the C and Q units are then sorted based on the cold measurements, selecting the "golden" candidates for these two IRs while minimizing the relative center offset between C and Q cold masses. During the corrector-to-quadrupole attachment, adjustment is made to minimize the relative center offset and relative roll between the two units. The finished CQ units are measured using the antenna technique to locate their magnetic centers with respect to the cold mass fiducials. Finally, the CQ packages are aligned using these fiducials and assembled together with D0 dipoles in their common cryostat in the ring. After the IR triplet assembly is completed, it can only be adjusted as a rigid body to optimize the center offsets of the quadrupoles, provided that the antenna technique is used to locate in the ring the centers in the cryostat.

The cumulative errors from each step together with the complication caused by the neighboring warm-cold transition make an accurate alignment a challenging task. Table 4 shows the effects of given misalignments of the magnets, and the amount of correction needed. Effective closed-orbit correction using the triplet dipole correctors, which are highly effective due to their high β locations, is essential to successful operation during storage. Fortunately, since the betatron phase advance is small across the triplet region, it is possible to use the two (horizontal and vertical) dipole correctors to correct the closed orbit error produced by the misalignment of the magnets in the triplet.

Table 4: Effects of transverse offsets and rolls of the dipole (D0) and quadrupole (Q2) in the triplet from the design trajectory during $\beta^* = 1$ m storage.

Name	Offset or roll	Effects	Corrector needed
D0	0.5 mm	2% aper. reduc.^{a}	
	0.5 mr	$\Delta x_c = 1.3$ mm ^{b}	a_0/b_0 at 1 A
Q2	0.5 mm	$\Delta x_c = 23$ mm ^{b}	a_0/b_0 at 13 A
	0.5 mr	$\Delta Q_{min} = 0.026$ ^{c}	a_1 at 7 A

a) Reduction in good field radius of 30 mm.
b) Closed orbit offset at arc section with $\beta = 50$ m.
c) Minimum tune split due to linear coupling.

5 CONCLUSIONS

The challenging requirements on the superconducting magnet alignment in RHIC are painstakingly met by a joint effort between the Accelerator Physicists, magnet builders, surveyors, and installers. An accurate location of the magnetic center using colloidal-cell and antenna techniques is essential. The IR triplet correctors are crucial for successful field quality[7] and misalignment compensation during storage.

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6 REFERENCES

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