Effects of CQS and Dipole Misalignments in RHIC

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Abstract

This report summarizes a study on Corrector-Quadrupole-Sextupole (CQS) and dipole misalignments based on recent survey measurements. The misalignment of the individual elements in the CQS assemblies is found to be able to cause significant undesired effects if proper measures are not adopted. The CQS assemblies should continue to be aligned, during installation, such that the magnetic centers of the quadrupole and the sextupole are on the design trajectory of the beam, and that the integral field angle of the quadrupole is zero. The center offset and roll of the corrector should be limited below 2 mm and 20 mrad, respectively, to provide satisfactory decapole and octupole corrections in the future.

1. INTRODUCTION

Preliminary survey measurements indicate significant offsets in the beam-pipe and corrector magnet center positions from the design trajectory of the beam for both CQS assemblies and arc dipole magnet (DRG). We studied possible installation schemes and estimated the effects of misalignment on the nominal operation of RHIC. This report summarizes the results for both CQS (Section 2) and arc dipole (Section 3). The conclusion is given in Section 4.

2. CQS MISALIGNMENT

The CQS cryostat contains a one or four layer arc corrector (near the lead end), an arc quadrupole, and a sextupole (near the non-lead end) components. For the first 65 CQS assemblies installed in the RHIC tunnel and recently surveyed at room temperature, Fig. 1 shows the horizontal and vertical offsets of the beam pipe center from the ideal beam orbit at both the lead (corrector) end and non-lead (quadrupole) end. The quadrupole center

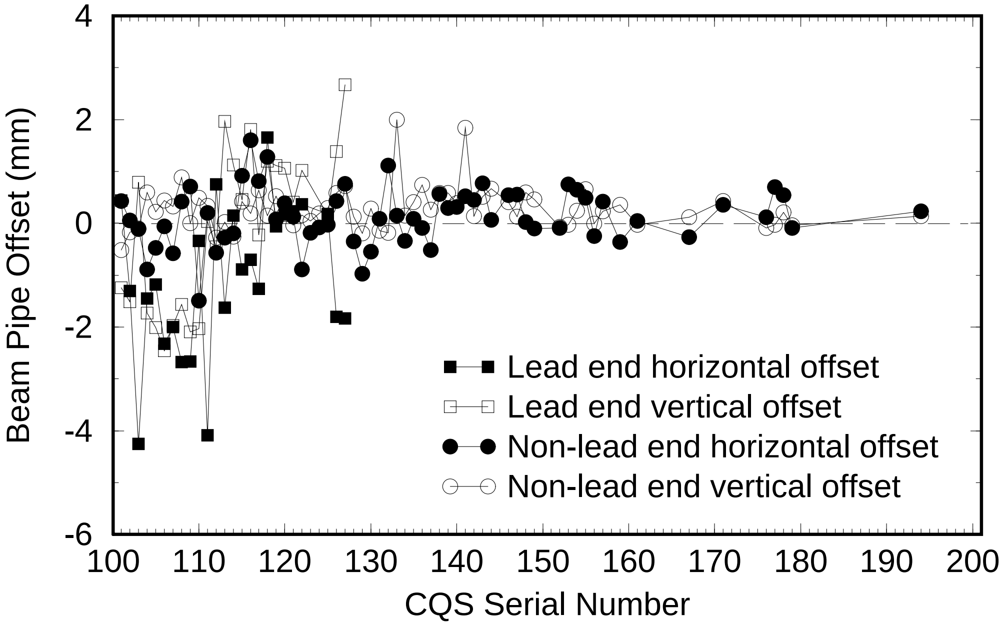

Figure 1: Beam-pipe position measurement data from the survey of 65 CQS assemblies performed before October 1995.

is determined using the warm colloidal-cell measurement, quadrupole fiducials, while the sextupole center is determined by the cold-mass mechanical fiducials. Because the ideal beam orbit is defined as the particle trajectory passing through the center of the quadrupole (measured by warm colloidal cell) and sextupole (mechanically measured), each CQS has been aligned to zero the center offsets of the quadrupole and sextupole. Consequently, the beam pipe offset at the non-lead end is significantly smaller than that at the lead end (Table 1).

Among the early production of the CQS assemblies, CQS103 and CQS111 have the largest horizontal beam-pipe offsets at their lead ends (corrector end). CQS103 was previously installed in the RHIC tunnel at a focusing location (YO5-CQS18) and electrically connected to the neighboring dipoles, while CQS111 was installed at a de-focusing location (BO2-CQS11) and not connected. These two assemblies were later removed from the tunnel due to the large offsets of their components.

Starting with CQS112, the systematic vertical offset of the CQS assembly was corrected during the assembly process when the cold-mass fiducials are mechanically measured. The subsequent over-shooting of the vertical offset might result from over-correction. Both

Offset	Magnet counts	Mean (mm)	Standard deviation (mm)
Beam pipe corrector end (horizontal)	25	-1.1	1.5
Beam pipe corrector end (vertical)	25	-0.1	1.5
Beam pipe sextupole end (horizontal)	63	0.1	0.6
Beam pipe sextupole end (vertical)	63	0.3	0.4
Corrector center (horizontal)	65	-0.4	0.8
Corrector center (vertical)	65	0.2	0.6

Table 1: Mean and standard deviation of the CQS beam-pipe position offsets shown in Fig. 1. The values for the corrector offsets are evaluated based on warm colloidal quadrupole center measurement only.

mechanical and the optical measurements were performed and compared on the CQS assemblies from CQS101 to CQS122. Starting with CQS123, optical measurement was eliminated, and only mechanical measurement was performed to record the cold-mass fiducial positions. The relatively large offset is thought to be mostly caused by the asymmetric welding pattern of the cover plates performed after the mechanical measurement.[1] Starting with CQS133, the welding process was modified to be more symmetric, and the offset was greatly reduced.

In an early stage of production, it was found that the range of transverse play of the CQS cold-mass relative to the cryostat was close to ± 1 mm. After subsequent tests, measurements, and discussions, it was decided by the Alignment Task Force that all the CQS assemblies were to be fitted with "springs".[2] It is expected that the transverse play will be effectively eliminated during the normal operation of the machine.

Before connecting with the neighboring dipoles, the CQS can be installed in various ways by centering any two of the three elements, or by a minimization scheme. Since the quadrupoles and the sextupoles are always powered during normal operation, while the octupole and the decapole layers of the correctors are not yet planned to be powered, all the CQS assemblies are aligned by centering on the quadrupoles and the sextupoles. Fig. 2 shows the offset of the corrector center when the CQS is aligned in such a way. In the

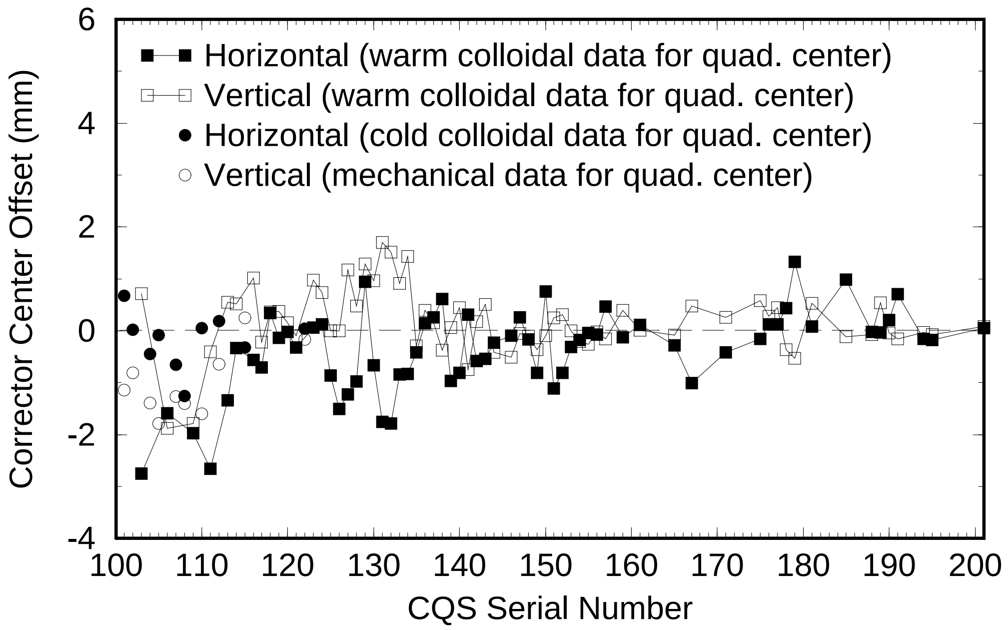

Figure 2: Corrector center offset from the ideal beam orbit determined by averaging the warm-measured positions of the four corrector mechanical fiducials.

subsequent sections, we investigate the effects on RHIC operations when any one of the three elements is misaligned.

2.1 Effects of Arc Quadrupole Misalignment

In this section, we study the effects of the transverse center offset, longitudinal play, and roll of the arc quadrupoles in the CQS assembly.

2.1.1 Quadrupole center transverse offset

Misalignment of the quadrupole center results in a feed-down[3] of dipole field which requires correction from the normal and skew dipole correctors. Because of the high beam rigidity at top energy, the required corrector current reaches its maximum value during the beam storage. Table 2 shows the integral transfer function (I.T.F.) of the various magnets[4], defined as the magnetic field component integrated through the length of the magnet generated at the reference radius of R_0 =25 mm by 1 Ampere of current.

If the CQS assemblies are aligned by centering the sextupoles and the correctors, the

	Dipole (DRG)	Quadrupole (QRG)	Sextupole (SRE)	Corrector (dipole layer)
Maximum operating current (kA)	5	5	0.05^a	0.05^b
I.T.F. (Mean) (T·m/kA)	6.42	0.42	5.2	5.6
I.T.F. (SD) (T·m/kA)	0.0024	0.00029	0.011	0.008
I.F.A. (Mean) (mrad)	-0.7	-1.8	0.0	-3.3
I.F.A. (SD) (mrad)	0.7	0.6	0.3	3.0

Table 2: Integral transfer functions (I.T.F.) measured at maximum operating current and integral field angles (I.F.A.) measured at room temperature test current of the arc dipole, quadrupole, sextupole, and dipole corrector at the reference radius of R_0 =25 mm.

a) For storage operation with 2 IRs at $\beta^* = 1$ m and the rest at $\beta^* = 10$ m (see Table 3).

b) The design current is 50 Amperes, while the day-one power supplies are 25 Amperes.

offset of the quadrupole center can be as large as 1.5 mm from the ideal beam orbit. With such an offset, the quadrupole produces an equivalent relative change of dipole I.T.F. of 4.0×10^{-3}, which requires a corrector current of about 7 Amperes at the top energy (Table 2). Since there is a normal (or skew) corrector for every other dipole and CQS, the maximum corrector current required can be as large as 14 Amperes, comparing with the day-one designed corrector power supply limit of 25 Amperes. Therefore, the CQS assembly must be aligned to minimize the quadrupole center offset.

2.1.2 Quadrupole longitudinal play

In addition to the thermal contraction in the longitudinal direction during the cool down of the superconducting magnet assembly, the measurement shows a longitudinal play of the cold-mass of about $\Delta_l = 2$ mm relative to the CQS cryostat. This longitudinal play causes an uncertainty in the focal point of the quadrupoles and generates a β-function variation (β-wave),

$$\left|\frac{\Delta\beta}{\beta}\right|_{max} \approx \frac{\Delta_l}{f}, \qquad (1)$$

where the focal length f of an arc quadrupole is

$$f = \frac{B\rho}{B'l} = \frac{3.45(\mathrm{T}) \times 240(\mathrm{m}) \times 0.025(\mathrm{m})}{0.42(\mathrm{Tm/kA}) \times 5(\mathrm{kA})} = 9.9\ (\mathrm{m}). \tag{2}$$

The 2 mm play corresponds to an effective change in the quadrupole I.T.F. of about 2×10^{-4}. This value is smaller than the standard deviation in quadrupole integral transfer function of 5×10^{-4}. The effect of the longitudinal play is therefore tolerable.

2.1.3 Quadrupole roll

When measured as individual elements, the arc quadrupoles display an integral field angle of -1.8 ± 0.6 mrad, as shown in Table 2. Independent measurements in the CQS assembly show similar behaviour.[5] In order to minimize the induced skew quadrupole (a_1) component, the CQS assembly will be rolled individually along the longitudinal axis according to its measured I.F.A. in the CQS during installation.

2.2 Effects of Sextupole Misalignment

In this section, we study the effects of the transverse center offset, longitudinal play, and roll of the arc sextupoles in the CQS assembly.

2.2.1 Sextupole center transverse offset

Misalignment of the sextupole center produces the most significant effects during the low-β^* storage operation when the required sextupole current I_S is high. Due to the relatively low β_x and dispersion, the required sextupole current at the de-focusing locations is about 3 times as high as that at the focusing location, as shown in Table 3.[6]

If the CQS assemblies are aligned by centering the quadrupoles and correctors, the offset of the sextupole center can again be as large as 3 mm. With such an offset, a sextupole at a de-focusing location produces an equivalent change of quadrupole I.T.F. of 3×10^{-3} (Table 2), which causes a significant amount of β-function variation (β-wave), tune shift, and skew quadrupole component a_1.

The amplitude of the β-wave can be estimated for the storage lattice. The maximum β-wave is produced in the vertical direction from the de-focusing sextupole with[7]

$$\left|\frac{\Delta\beta}{\beta}\right|_{max} \approx \beta_y \Delta(f^{-1}) \approx 15\%, \tag{3}$$

Sextupole location	β_x (m)	β_y (m)	I_S (max.) (A)	I.T.F. (T·m/kA)
Focusing	48	10	14	5.6
De-focusing	11	48	48	5.2

Table 3: Design lattice functions, sextupole maximum required currents, and measured sextupole integral transfer functions at the reference radius of 25 mm for the storage operation with 2 IRs at $\beta^* = 1$ m and the rest at $\beta^* = 10$ m.

where $\Delta(f^{-1}) = \Delta B'l/B\rho$ is the change in quadrupole focal length from the sextupole feed-down. Such a large $\left|\frac{\Delta\beta}{\beta}\right|$ produced by a single sextupole offset is certainly not tolerable.

The tune shift produced by an offset of 3 mm of a single sextupole at a de-focusing location is approximately

$$|\Delta\nu|_{max} \approx \frac{\beta_y}{4\pi}\Delta(f^{-1}) \approx 10^{-2}, \tag{4}$$

which is large compared with any contribution from other magnetic multipoles.

A vertical offset of a sextupole produces a skew quadrupole component a_1. With a vertical offset of 2 mm, a single sextupole at a de-focusing location produces an $a_1 \approx 10$ in the prime dipole units,[3] which is much larger than the measured $a_1 = 0.6 \pm 1.4$ (mean $\pm$ standard deviation) in the current distribution of about 160 dipole (DRG) magnets.

The estimates in Sections 2.1.1 and 2.2.1 show that the CQS assemblies must be aligned to minimize both the quadrupole and sextupole center offsets. If the rms value of the sextupole center offset can be limited to 0.25 mm after alignment, the total β variation produced by the feed-down of all the sextupoles will be limit to be

$$\left|\frac{\Delta\beta}{\beta}\right|_{max} \approx \sqrt{N}\beta_y\Delta(f^{-1})|_{rms} < 10\% \tag{5}$$

which is tolerable during normal operation. Here, $N \approx 76$ is the number of sextupoles at de-focusing locations.

2.2.2 Sextupole longitudinal play

At the reference radius of R_0 =25 mm, a sextupole operating at 50 Amp has a focal length f of

$$f = \frac{B\rho}{B''lR_0} = \frac{3.45(\mathrm{T}) \times 240(\mathrm{m}) \times 0.025(\mathrm{m})}{5.6(\mathrm{Tm/kA}) \times 0.05(\mathrm{kA})} = 74\ (\mathrm{m}), \tag{6}$$

which corresponds to a focusing strength much weaker than those of the quadrupoles. A longitudinal play of 2 mm gives an effective change in sextupole I.T.F. of about 2×10^{-4}, which is small compared with the standard deviation (2×10^{-3}) in the sextupole I.T.F. (Table 2).

2.2.3 Sextupole roll

Since the CQS assemblies are rolled around their longitudinal axis by an angle of -1.8 ± 0.6 mrad to compensate for the arc quadrupole field angle misalignment, the roll in sextupole is about -1.8 ± 0.7 mrad (see Table 2). This roll produces an a_2 multipole component which, in terms of the arc dipole units, is

$$a_2 = -0.2 \pm 0.1. \tag{7}$$

Since this value is much smaller than the a_2 ($a_2 = -1.1 \pm 0.2$) measured in the arc dipoles, the effect is tolerable.

2.3 Effects of Arc Corrector Misalignment

In this section, we study the effects of the transverse center offset, longitudinal play, and roll of the arc correctors in the CQS assembly.

2.3.1 Corrector center transverse offset

When the CQS is aligned to minimize the quadrupole and sextupole offsets, the corrector center will inevitably be misaligned from the ideal beam orbit, as shown in Fig. 2. Such a misalignment will produce a significant undesired effect on the octupole and decapole correction. Table 4 shows the various types of arc correctors and their mean and standard deviation of the integral transfer function measured at 50 Amperes.

With a horizontal or vertical offset of 2 mm from the ideal orbit, Table 5 shows the amount of feed-down toward the lower normal and skew harmonics. Note that for CQS103 and CQS111 (Fig. 2) where the horizontal offset was about 3 mm, an operating current of 50 Amperes on the decapole corrector layer will produce a feed-down that corresponds to the octupole layer operating at about 20 Amperes. Based on this analysis, these two assemblies (CQS103 and CQS111) have been removed from the RHIC tunnel to be reworked to ensure satisfactory decapole and octupole corrections in the future.

Corrector type (b_n/a_n)	Coil name	I.T.F. (Mean ± SD) (T·m/kA)	I.F.A. (Mean ± SD) (mrad)
Normal dipole (b_0)	CB1	5.622 ± 0.012	−3.9 ± 3.7
	CD1	5.622 ± 0.009	−2.6 ± 3.0
	CF1	5.615 ± 0.001	−3.3 ± 3.0
Skew dipole (a_0)	CC1	5.610 ± 0.006	−3.8 ± 2.8
	CE1	5.609 ± 0.010	−3.1 ± 2.5
Normal quadrupole (b_1)	CB2	0.765 ± 0.002	−4.7 ± 4.3
Skew quadrupole (a_1)	CC2	0.760 ± 0.001	−2.9 ± 5.4
	CF2	0.760 ± 0.001	−1.1 ± 4.7
Normal octupole (b_3)	CB4	0.193 ± 0.002	−4.2 ± 4.5
	CC4	0.192 ± 0.002	−6.1 ± 4.0
	CF4	0.191 ± 0.000	−3.7 ± 4.9
Normal decapole (b_4)	CB5	0.152 ± 0.002	−3.9 ± 4.8
	CC5	0.150 ± 0.001	−5.1 ± 4.1
	CF5	0.151 ± 0.000	−4.2 ± 3.6

Table 4: Mean and standard deviation of the integral transfer function (I.T.F.) and integral field angle (I.F.A.) of the arc correctors measured at 50 Amperes at the reference radius of 25 mm.

Corrector type (b_n/a_n)	Nominal b_n/a_n (dipole units)	Feed-down b_{n-1}/a_{n-1} (dipole units)
Normal/skew dipole (b_0/a_0)	86	—
Normal/skew quadrupole (b_1/a_1)	12	0.9
Normal octupole (b_3)	3.0	0.71
Normal decapole (b_4)	2.3	0.75

Table 5: In terms of the arc dipole prime units, the nominal magnetic multipole produced by 50 Amperes of arc corrector current and the feed-down produced by a 2 mm offset of the corrector center operating at 50 Amperes.

For a particular type of corrector (CRB) which includes a normal quadrupole layer to be pulsed for the transition jump, a separate AP Note[8] has been written to discuss the misalignment issue. The currently proposed transition jump scheme can tolerate a corrector offset of standard deviation less than 1 mm.

2.3.2 Corrector longitudinal play

Since the effective change in I.T.F. of the correctors is also about 2×10^{-4}, a longitudinal play of 2 mm in the corrector position is not significant.

2.3.3 Corrector roll

Table 4 shows the mean and standard deviation of the integral field angles of each layer of correctors measured as an individual element. The measurements in the CQS assembly show the similar behaviour.[5] Here we estimate the effects of this roll misalignment.

A roll of -3.3 ± 3.0 mrad in the normal (or skew) dipole layer produces a skew (or normal) dipole component of -33 ± 30 in the corrector dipole units, or a_0(or b_0) $= -0.3 \pm 0.2$ in the arc dipole units when the corrector is operating at 50 A. The effect is insignificant.

A roll of -4.7 ± 4.3 mrad in the normal quadrupole layer produces a skew quadrupole component of -94 ± 86 in the corrector quadrupole units, or $a_1 = -0.1 \pm 0.1$ in the arc dipole units when the corrector is operating at 50 A. This is again insignificant.

A roll of -2.9 ± 5.4 mrad in the skew quadrupole layer produces a normal quadrupole component of -58 ± 108 in the corrector quadrupole units, which corresponds to a relative variation in arc quadrupole integral transfer function of $(-1 \pm 2) \times 10^{-4}$ when the corrector is operating at 50 A. This is tolerable when compared with the measured arc quadrupole I.T.F. standard deviation of 5×10^{-4}.

For the octupole and decapole corrector layers, an individual roll of 20 mrad will produce a skew component of about 10% strength, which is marginally acceptable. Fortunately, the rolls in all the octupole and decapole layers so far measured are below this value.

3. DIPOLE MISALIGNMENT

In this section, we study the effects of the transverse center offset, longitudinal play, and roll of the arc dipoles.

3.1 Dipole Center Transverse Offset

Fig. 3 shows the warm measurement data of the horizontal and vertical beam-pipe offsets at both the lead and non-lead ends for the first 31 arc dipole (DRG) magnets. The analysis in Ref. 9 concludes that the dipole magnet should be installed with a deliberate offset of 0.05 inches, radially outwards, at the dipole ends. With such a measure, the effect of the systematic offsets of the magnet is minimized, and we therefore only estimate the effect of the random offsets.

As shown in Table 6, the standard deviations of the dipole offsets are expected to be

Beam pipe offset	Mean (mm)	Standard deviation (mm)
Horizontal lead end	2.6	1.1
Vertical lead end	0.4	0.7
Horizontal non-lead end	1.6	0.8
Vertical non-lead end	0.0	0.7

Table 6: Mean and standard deviation of the dipole (DRG) beam-pipe position offsets shown in Fig. 3.

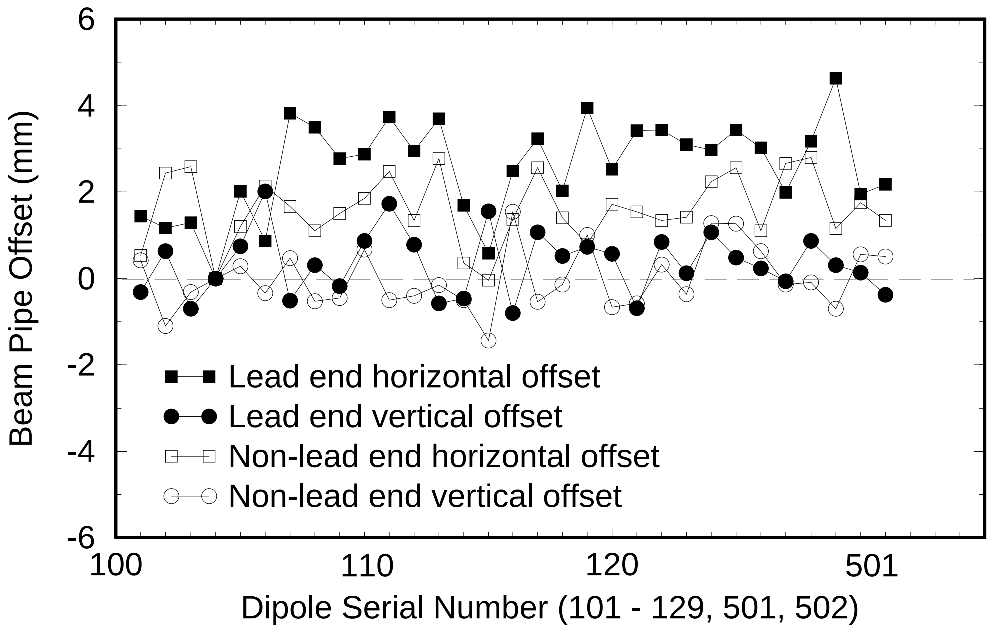

Figure 3: Beam-pipe position measurement data from the survey of 31 dipole (DRG) magnets performed before July 1995.

about 1 mm. During injection when the beam size is the largest in the arc dipoles, the rms beam size (σ) of the gold beam at the nominal emittance of 15 mm·mr is about 3 mm. The slight reduction of the linear and dynamic apertures of a fraction of σ caused by the dipole misalignment is tolerable. Furthermore, the feed-down of the relatively large harmonics of normal (b_2=0.7$\pm$1.7) and skew (a_2=$-$1.0$\pm$0.2) sextupole component (mean $\pm$ standard deviation) produces a skew quadrupole of $a_1 \approx 0.1$ units and a relative quadrupole I.T.F. variation of about 2×10^{-4}. The effects are again insignificant.

3.2 Dipole Longitudinal Play

A longitudinal play of 2 mm in the arc dipole position (with a bending angle of 39 mrad) produces a closed orbit deviation of about 0.04 mm. This value is well within the correction range.

3.3 Dipole Roll

Each arc dipole will be aligned individually to compensate for the field angle deviation (Table 2).

4. CONCLUSIONS AND DISCUSSION

The misalignment of the individual elements in the CQS assemblies can cause significant undesired effects on the nominal RHIC operation. Based on the survey measurements of the CQS beam pipe positions and the centers of the individual elements, two previously installed CQS assemblies (CQS103 and CQS111) with largest horizontal offsets have been removed from the RHIC tunnel to be re-worked. The remaining CQS assemblies should continue to be installed such that the centers of the quadrupole and the sextupole are on the design trajectory of the beam, and that the integral field angle of the quadrupole is zero. The transverse offset and roll of the corrector center should be limited below 2 mm and 20 mrad, respectively, to provide satisfactory decapole and octupole corrections in the future.

The dipole magnet[9] should be installed with a deliberate offset of 0.05 inches, radially outwards at the dipole ends, to minimize the systematic misalignment effects. The effect of the random misalignment is insignificant.

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