IMPACT OF ARC PHASE ADVANCE ON CHROMATIC OPTICS IN RHIC *

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Abstract

The phase advance between the two interaction points in RHIC is optimized for dynamic aperture for a initial design beta-star. This may not hold true as RHIC presently operates with a considerably reduced beta-star. Additionally the reduction of the available beam aperture due to an enlarged chromatic beta-beating is evident. Measurements of the chromatic optics in the RHIC are presented along with the proposal to optimize the arc phase advance between the two IPs to adjust the chromatic beta-beating. Measurements of chromatic optics from the LHC at injection and top energy are presented.

INTRODUCTION

Knowledge of chromatic optics and deviations from the model is useful with decreasing β^* as the interaction regions (IRs) could pose an aperture limitation. The initial motivation to measure the chromatic optics were triggered from the systematic discrepancy seen at the Super Proton Synchrotron (SPS) between the model and measured off-momentum β-beating [1].

Colliders such as Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) are aiming at smaller collision point optics as means to increase the luminosity. In the LHC, the chromatic limit for correction with existing sextupole families is reached for β^* well below the final goal. Additionally, the hierarchy of the collimation system may not preserved for off-momentum particles. To overcome these limits, a new scheme under the name of "ATS" is proposed [2]. This scheme implements a new phase advance conditions at all eight interaction regions with increased β-functions in the arcs to efficiently use the sextupole families.

In RHIC with heavy ions, re-bucketing at top energy increases the momentum spread by a factor of 3. For operation with protons, the tune space is limited for the present working point between the $3^{\rm rd}$ and the $7^{\rm th}$ order resonances. To further reduce β^* below the present level, improved chromatic optics is needed to gain physical aperture and potentially improve dynamic aperture and lifetime. Schematics of the LHC and RHIC rings with the corresponding interaction points are depicted in figure 1.

CHROMATIC OPTICS

In the absence of coupling, the linear chromatic β-functions can be defined as,

$$W_{x,y} = \sqrt{a_{x,y}^2 + b_{x,y}^2} \tag{1}$$

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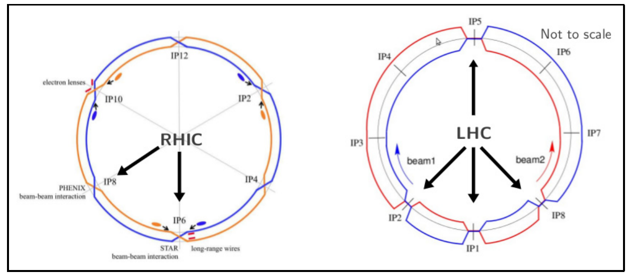

Figure 1: Schematic of RHIC and LHC rings with interaction points.

where $a_{x,y} = \frac{1}{\beta}\frac{d\beta}{d\delta}$ and $b_{x,y} = \frac{d\alpha}{d\delta} - \alpha.a_{x,y}$[3]. A momentum offset scan with simultaneous turn-by-turn BPM trajectories synchronized with transverse kicks to measure chromatic optics in both LHC and RHIC were carried out. In the LHC an ac dipole was used to impart an continuous excitation while in RHIC a single impulse kick is used for simplicity. The chromatic optics can be computed from a linear fit of β-functions with respect to energy. The normalization with on-momentum β-function provides a BPM calibration independent observable.

LHC Measurements

During the commissioning period of the LHC in 2010 and 2011, off momentum optics were performed with frequency offsets of 50-100 Hz. Table 1 show some relevant parameters of the LHC during these measurements.

Table 1: LHC parameters for injection and top energy.

Quantity	Blue Ring	
	0.45 TeV	3.5 TeV
# of bunches	1	1
Bunch Intensity [10^{10}]	1.0	1.0
Emittance, $\epsilon_{x,y}$ [μrad]	2-2.5	
Tunes, $Q_{x,y}$	64.28, 59.31	64.31, 59.32
Chromaticity, (ξ_x, ξ_y)	2.0	2.0
$\text{IP}_{1,5,2,8}$ β^* [m]	10	1.5,1,5,10,3.5
σ_z (rms) [cm]	7.55	7.55

The measured chromatic β-beating at injection is about $\pm 3\%$ at $\delta = 1 \times 10^{-3}$ with only a partial agreement to the model. At collision energy and $\beta^* = 3.5$m, the measured chromatic β-beat is less than $\pm 10\%$ at $\delta = 1 \times 10^{-3}$. Agreement in the vertical plane is better than that in the horizontal plane. Since, the measured β-functions are model dependent, the exact model at each $\delta p/p$ is used to recompute the β-functions and consequently the chromatic W-functions. Figure 2 shows the W-functions at 3.5 TeV and $\beta^* = 3.5$m. Agreement to the model improves quiet signififcantly by using exact model at each momentum offset except for certain regions which are under investigation. A measurement was attempted after a β-squeeze to 1.5 m, but the beams were lost during the radial modulation.

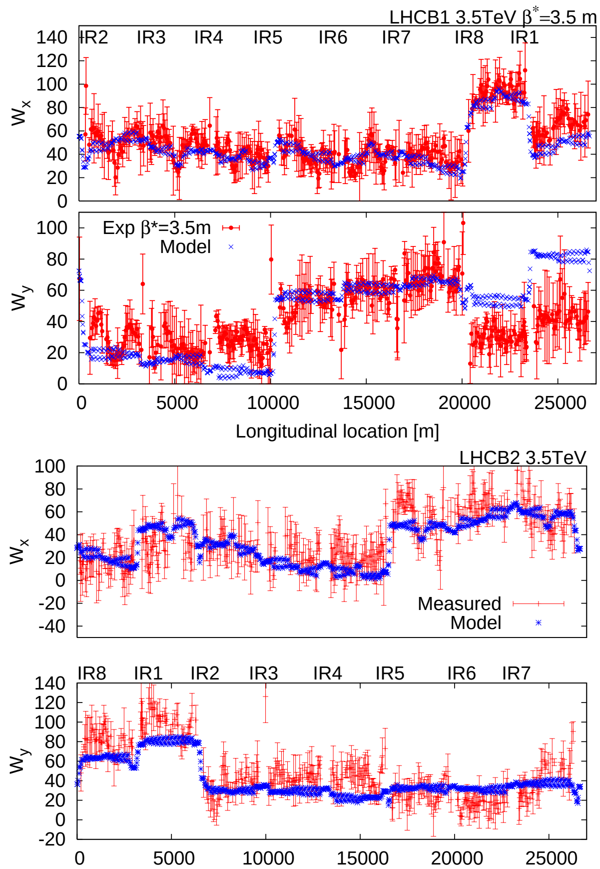

Figure 2: Chromatic W-functions for beam 1 and beam 2 in the LHC for 3.5 TeV at $\beta^* = 3.5$ m

RHIC Measurements

In RHIC two measurement campaigns were held to measure the chromatic optics at both injection and collision energy. In 2009, these measurements were performed with protons and more recently in 2011 with gold ions. Some relevant parameters for the Blue and the Yellow rings are listed in Table 2. For both measurement periods, the Yellow ring suffered higher losses than that of the Blue ring. In addition, the Yellow ring suffered significantly larger losses with a positive momentum offset compared to a negative offset. This mismatch is under investigation. It should be noted that an impulse kick was used to acquire turn-by-turn data for the sake of simplicity as the ac dipoles are common for both beams.

The agreement of chromatic β-functions at injection in the Blue ring are very good with the model. The maximum chromatic beta-beat is measured to be ~5% for a momentum deviation of $\delta = 1 \times 10^{-3}$ [4]. Recent measurements

Table 2: RHIC beam parameters for injection and top energy. Note that measurement with gold ions and protons is at 100 GeV and 250 GeV respectively.

Quantity	Blue Ring	
	Injection	100/250 GeV
# of bunches	6×6	12×12
Bunch Intensity [10^{11}]	Au-0.01, p-1.0	
Max Beam loss [%/h]	100-150	
Emittance, $\epsilon_{x,y}$ [μrad]	12/21	10/25
Proton Tunes, $Q_{x,y}$	28.74, 29.72	28.69, 29.70
Au Tunes, $Q_{x,y}$	31.232, 32.23	
Chromaticity, (ξ_x, ξ_y)	2.0	~2.0
Quantity	**Yellow Ring**	
	Injection	250 GeV
# of bunches	6×6	12×12
Bunch Intensity [10^{11}]	1.0	1.0
Max Beam loss [%/h]	100-3000	
Emittances, $\epsilon_{x,y}$ [μrad]	12/20	12/-
Proton Tunes, $Q_{x,y}$	28.72,29.74	28.69, 29.70
Au Tunes, $Q_{x,y}$	31.23, 32.22	
Chromaticity, (ξ_x, ξ_y)	2.0	2.0
IP$_{1,5}$ β^* [m]	7.5	0.7

from with gold ions at 100 GeV at β^* =0.7m is shown in figure 3 for the Blue ring and figure 4. At collision optics, the measured chromatic β-beat is in good agreement with the model with some deviation between the two low-beta IRs. The maximum chromatic beta-beat at collision optics is approximately ±50% which is consistent with the measurements performed in 2009. Due to several BPM failures, data in the Blue beam is not measured at most BPM locations in the ring.

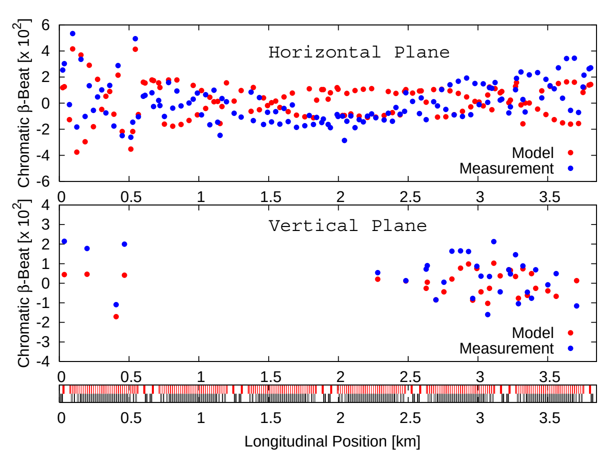

Figure 3: Chromatic β-beating in the Blue ring with gold ions at 100 GeV and 0.7m β^*.

As the average orbits as a function of momentum offsets are also available, dispersion functions can be computed. Measurements show about 15% dispersion beating which should also be corrected simultaneously with optics corrections.

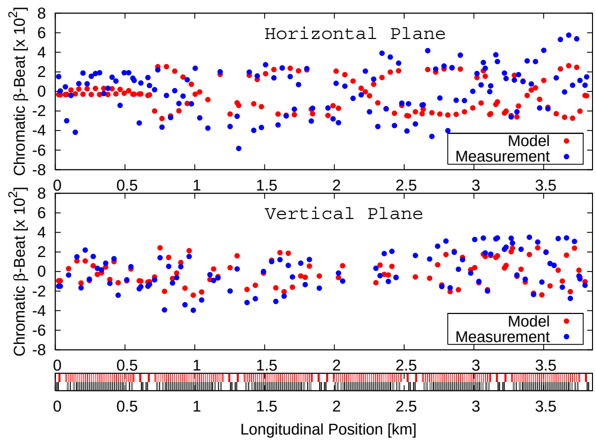

Figure 4: Chromatic β-beating in the Yellow ring with gold ions at 100 GeV and 0.7m β^*.

CHROMATIC CORRECTION ATTEMPT

As the chromatic β-beating is approximately 50% already at 0.7m, improvement in the model is needed to squeeze further. A first attempt towards a correction is proposed using the γ-T quadrupoles. The RHIC lattice already consists of two families of γ-T quadrupoles primarily used for γ-T transition during the ramp with heavy ions. The γ-T families are placed next to focusing quadrupoles with phase advance of approximately 90°. A schematic of the γ-T quadrupoles in the arc section are depicted in figure 6.

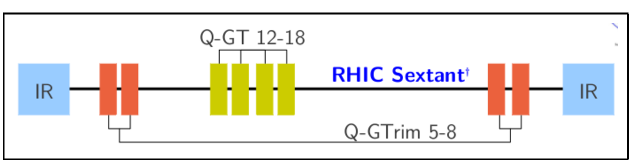

Figure 5: Schematic of the γ-T quadrupoles in one of the RHIC arc sections.

Therefore, 4 quadrupoles in the arc are used to locally perturb both the β-functions and dispersion functions and the exterior 4 quadrupoles are used to compensate the corresponding tune shift. These quadrupoles in each arc section can be used to independently change the arc phase advance to consequently act on the chromatic functions to minimize them in the regions with aperture bottle-necks. It is sufficient to use the γ-T quadrupoles in the arc section between the IR_6 and IR_8 low beta insertion regions, but additional quadrupoles in the other arcs can also be used to reduce the chromatic beating in the insertion regions (see figure 6) at the expense of increasing them in the arc sections where the available aperture is larger.

An more detailed scheme with the γ-T quadrupoles and simultaneous re-matching of the collision point β^* is required as the optics perturbations from the γ-T quadrupoles are not truly local. In addition, they are all placed close to focusing quadrupoles and thus less efficient to compensate the vertical chromatic functions as visible in figure 6.

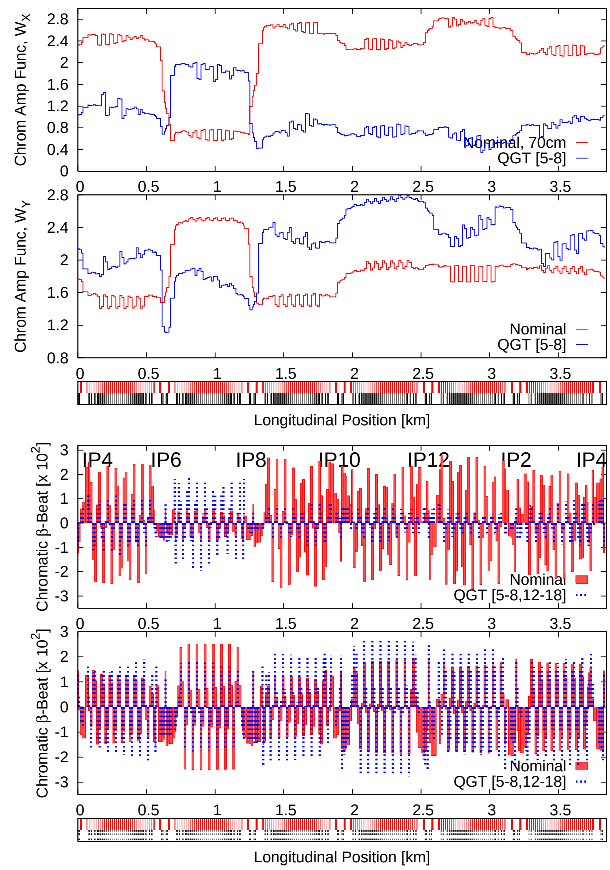

Figure 6: Chromatic W-functions for the nominal lattice at $\beta^* = 0.7$m and lattice with γ-T quadrupoles used to minimize them in the IR6 and IR8 regions.

CONCLUSIONS

Chromatic optics were measured successfully at both the LHC and the RHIC colliders at injection and collision energy optics. These were compared to the model and the agreement is fairly good in both cases. An elaborate scheme for chromatic β-beating is already in place for the LHC under the new ATS scheme. In RHIC, an attempt to change the chromatic functions with γ-T quadrupoles is proposed and preliminary simulations indicate that they can be used to improve the chromatic β-beating. A detailed correction scheme for the appropriate optics for future operation is underway.

ACKNOWLEDGMENTS

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