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OFF-MOMENTUM OPTICS CORRECTION IN RHIC*

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Abstract

Future operations of the electron-hadron collider eRHIC [1] call for beams circulating off of the magnetic center of all arc elements. In order to ensure that both stable beam conditions and the desired circumference changes can be achieved, dedicated experiments were conducted during the 2018 RHIC Run, which included the first off-momentum linear optics correction. This article reviews the experimental setup and the offline modeling predictions, then presents the measured radial excursions and corresponding residual off-momentum β-beat.

INTRODUCTION

The eRHIC electron-hadron collider project is currently being designed with the goal of repurposing one of the two existing RHIC beamlines for circulating hadron bunches and aiming them at electron bunches inside of the interaction region (IR6) currently hosting the STAR detector. Collisions are planned for a range of center of mass energies $\sqrt{s_{e-h}}$ = 29-140 GeV, with the corresponding energies for each species as listed in Table 1.

The top energies listed for the hadrons are different enough that not all species will be able to travel through the magnetic center of the RHIC arc dipole magnets [2]: the central orbit reference is therefore taken as the one for 133 GeV protons with the requirement to be synchronous with the electron beam at IP6 to achieve collisions, giving a revolution time of $\tau_p = 12.78865$ μsec for a standard RHIC circumference $C_0 = 3833.845$ m. For proton energies 100 GeV and above, all RHIC Yellow arcs are used: the required revolution time is achieved by manipulating the circumference C via a closed orbit shift in the arcs (radial shift ΔR), within a range of ±14 mm for all energies between 100-275 GeV. As for proton energies below 100 GeV, C needs a large change, forcing the design to switch to a shorter, inner (Blue) arc between two of the non-colliding RHIC straight sections, IR12 and IR2 in this particular case. This shrinks the circumference by $\Delta C = 942$ mm ($C = 3832.903$ m) without requiring any radial shift. Table 1 reviews the circumference and arc radius changes for all eRHIC species, including heavy ions.

Having the beams circulating off-center in the arcs must be taken into account when designing the linear optics. This is particularly critical when considering the ramp in energy from injection to flattop, during which the beams will shift from one radius to the next as they get accelerated. To that end, the lattice design process must account for the momentum offset $\delta p/p$ that generates the required radial shit ΔR for each energy, which can be handled using programs like MAD-X [3] or Bmad [4].

Table 1: Design beam energies and circulating radii for the electrons and hadron species planned for eRHIC operations at $\sqrt{s_{e-h}}$ = 29-140 GeV [2].

Species	**Energy** [GeV/u]	C [m]	ΔR [mm]
Polarized electrons	5-18	3833.867	0.0
Polarized protons	41	3832.903	0.0
	100	3833.772	−14.0
	133	3833.845	0.0
	275	3833.981	14.0
Heavy ions *Au*	41	3832.903	0.0
	100	3833.803	−8.0

EXPERIMENTAL SETUP

Dedicated beam time was allocated during the 2018 RHIC Run to determine the largest achievable radial shift in the Yellow arc dipole magnets for Au ions at injection energy E = 10 GeV/u. The goal is to try and push the circulating beam as far as possible while maintaining the linear optics "constant", i.e. correct the off-momentum optics to match the on-momentum settings.

The experiment is performed at injection energy for practical reasons, mainly the convenience of repeatability in the face of limited machine time rather than going through the lengthier process of injection/acceleration/down ramp. There is no limitation from operating with larger transverse beam sizes: the mechanical aperture in the RHIC arcs is assumed circular with a radius r_{arc} = 34.5 mm (taking an arc quadrupole magnet as reference) while the maximum beam size at injection energy $\hat{\sigma}_{x,y}$ is calculated as:

$$\hat{\sigma}_{x,y} = \sqrt{\frac{\hat{\beta}_{x,y}\epsilon_{x,y}}{\gamma_{inj}}} = \sqrt{\frac{55.96\ \mathrm{m}\cdot 1.50\ \mu\mathrm{m}}{10.52}} = 2.83\ \mathrm{mm}, \tag{1}$$

where $\hat{\beta}_{x,y}$ is the peak betatron function in the arcs, $\epsilon_{x,y}$ is the transverse *rms* emittance in each plane and γ_{inj} the relativistic gamma at injection energy. Assuming a circulating round beam with $\pm 6\hat{\sigma}_{x,y}$ transverse size, the remaining space for radial shifts A_{inj} is therefore:

$$A_{inj} = r_{\mathrm{arc}} - 6.0\cdot\hat{\sigma}_{x,y} = 17.55\ \mathrm{mm}. \tag{2}$$

Since the off-momentum closed orbit actually oscillates based on the value of the dispersion function D_x, one has to make sure that the peak orbit excursion still fits within A_{inj}.

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Predictions from Models

The off-momentum closed orbit can be easily determined via the RHIC offline model in MAD-X: a preliminary estimate for ΔR = -8 mm gives a momentum offset calculated as $\delta p/p_{(8\text{ mm})} = -7.75 \cdot 10^{-3}$ based on preliminary eRHIC lattice design [2]. To ensure that this radius shift is achieved, one needs to correct the off-momentum linear optics by rematching to the on-momentum values as well as keeping the transverse tunes constant, which will avoid closed orbit distortion from $\beta_{x,y}$-beat and D_x-beat. Utilizing each IP along with the first and last beam position monitor (BPM) of every arc as anchor points for linear optics in MAD-X, one can turn the quadrupole magnets in each straight section into knobs for the rematching algorithm. An additional parameter for the momentum offset is also being used straight into MAD-X's `twiss` command.

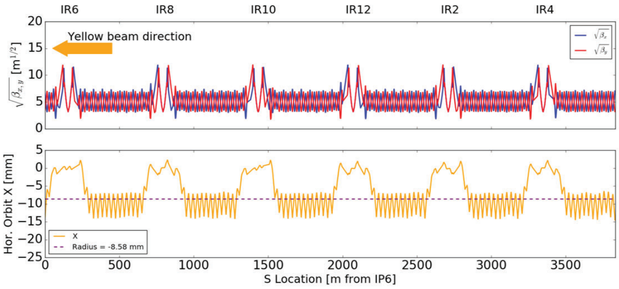

Figure 1: Linear optics (top) and horizontal closed orbit (bottom) for Au ion beam in the RHIC Yellow lattice at 10 GeV/u with $\delta p/p = -7.75 \cdot 10^{-3}$. The off-momentum optics were rematched to the on-momentum settings. The resulting radius shift is calculated at -8.58 mm.

Figure 1 shows the linear optics rematched to the design values for E = 10 GeV/u with $\delta p/p = -7.75 \cdot 10^{-3}$, as well as the resulting horizontal closed orbit for which the calculated radial shift is $\Delta R_1 = -8.58$ mm. The slight difference from the expected value of -8 mm is due to $\delta p/p_{(8\text{ mm})}$ being derived from a preliminary lattice design for eRHIC while the experiment reviewed in this article is based on the standard 2018 RHIC Au lattice parameters at injection energy.

Another takeaway from Fig. 1 is the amplitude of the orbit oscillations around the shifted radius in the arcs, with a peak excursion of -14.56 mm: with the aperture restriction A_{inj} from Eq. 2, and with concerns for the amount of beam losses the experiment could generate, the second radius shift to be tested experimentally is scaled back to a more conservative $\Delta R_2 = -11.0$ mm (via $\delta p/p = -9.94 \cdot 10^{-3}$) rather than the expected -14.0 mm for the eRHIC configuration. According to MAD-X, the beam oscillations should then extend to an amplitude of -19.09 mm at its largest point; at this location, β_x = 50.37 m which translates to A_{inj}(-11 mm) = 18.42 mm (assuming all other parameters from Eq. 2 are constant): even though this means that the 6 σ_x edge of the circulating beam will scrape the mechanical aperture at some locations in the arc, the expected level of beam loss is considered acceptable given the stated goal of testing the maximum radial shift for future eRHIC commissioning. Figure 2 presents the linear optics and horizontal orbit for this configuration.

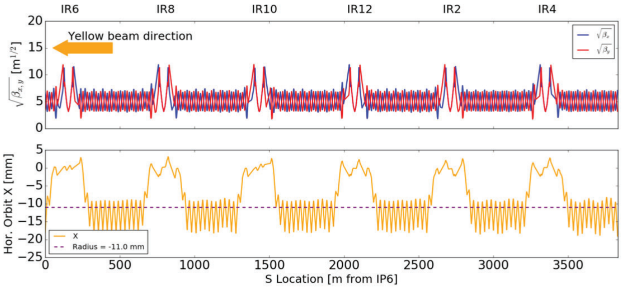

Figure 2: Linear optics (top) and horizontal closed orbit (bottom) for Au ion beam in the RHIC Yellow lattice at 10 GeV/u with $\delta p/p = -9.94 \cdot 10^{-3}$. The off-momentum optics were rematched to the on-momentum settings. The resulting radius shift is calculated at -11.0 mm.

Radius Control

To apply a radius change to RHIC, rather than sending a calculated momentum offset from offline models, it is the value of ΔR that is sent to the RF system which in turn converts it into a new circumference and modifies the circulating beam energy. This change is ramped into linearly over 30 seconds, which allows implementing the new, updated magnet settings while keeping the on-momentum linear optics matched to the off-momentum beam, as shown in Figs. 1 and 2.

MEASUREMENTS AND ANALYSIS

As described in the previous section, two radius changes were tested in the RHIC Yellow lattice at injection energy E = 10 GeV/u: 12 circulating Au ion bunches were pushed to $\Delta R_1 = -8.58$ mm, and $\Delta R_2 = -11.0$ mm. The lattice is ramped linearly into its new settings, the closed orbit is continuously logged and the linear optics are measured [5] upon reaching $\Delta R_{1,2}$. When comparing the predicted closed orbit to the measured one, it is important to remember that the BPM signal is only reported at the location of the horizontal BPM's, which gives fewer data points than what is shown in Figs. 1 and 2.

Figure 3 shows the comparison between predicted orbits and the measured ones for both ΔR_1 and ΔR_2, as well as the changes in beam intensity while the new settings for radius change and off-momentum optics are being ramped into. The ramping time is the same for both radial excursion attempts at 30 seconds (red line to blue line) and any post-ramping changes to the beam intensity are caused by machine tuning, mainly chromaticiy measurement and correction.

While beam loss rates for ΔR_1 are tolerable (7.5%/h), the implementation of ΔR_2 is causing about 29.5%/h of Au ions to be lost; despite multiple attempts at machine tuning (indicated by the slope changes in the beam intensity signal) there was no clear improvement to the beam lifetime.

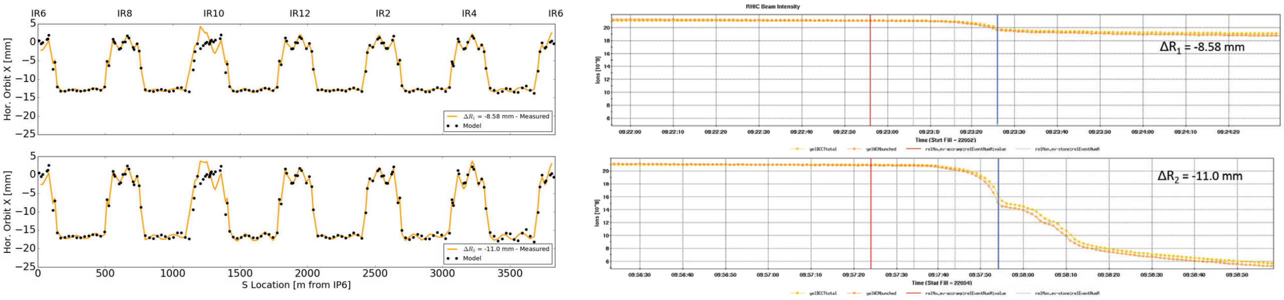

Figure 3: Left: comparison between the measured and predicted horizontal closed orbits of Au beams for $\Delta R_1 = -8.58$ mm (top) and $\Delta R_2 = -11.0$ mm (bottom) - Right: beam intensity changes during the experiment for each $\Delta R_{1,2}$ applied to the Au beam in the Yellow lattice. There is very good agreement between model orbit and measurements, a clear sign that in each case both the requested radius changes and the off-momentum linear optics corrections have been achieved.

Combined with the estimates for A_{inj} done in the previous section, this could be an indication that ΔR_2 represents a hard dynamic aperture limitation for Au ions at $E = 10$ GeV/u in RHIC.

Overall there is very good agreement between the predicted horizontal closed orbit in all arcs and most straight sections, thus ensuring that:

- the expected radius shift and energy change is achieved;
- the off-momentum linear optics are rematched to the on-momentum settings within tolerances.

That last point can be confirmed by performing linear optics measurements and looking at the β-beat offset from on-momentum optics. Following drastic improvement in machine modeling and correction techniques, the typical β-beat during regular RHIC operations is in the 10-15% range, accounting for offline/online model discrepancies and systematics [6]. Figure 4 shows the measured β-beat derived from the analysis of the linear optics measurement for ΔR_1: most of the off-momentum beating is contained within a ±15-20% range, within an acceptable range of typical on-momentum linear optics beating which is further demonstration that the RHIC off-momentum optics were corrected. Similar results were obtained for ΔR_2, not shown here for brevity.

The distortion in the horizontal plane is actually on the higher side of that range which can be explained by the contribution of dipole field errors at large orbit excursions: in particular, the third order component leads to feed-down effects that, in the case of RHIC, are larger for lower beam energies. Future experiments can address this by attempting radial shifts of similar amplitudes at $E = 100$ GeV/u.

CONCLUSION

To test some of the future electron-ion collider configurations at RHIC, there were two radial excursion attempts for Au ions at $E = 10$ GeV/u during the 2018 RHIC Run. Preliminary work was performed using the RHIC offline models to ensure that the requested radius changes would not send large fractions of the circulating bunches onto the mechanical aperture of the machine. These models were also able to determine new quadrupole magnet strengths in the straight sections to correct the off-momentum linear optics. This allowed reaching for the first time the targeted values $\Delta R_1 = -8.58$ mm and $\Delta R_2 = -11.0$ mm with reasonable control of the beam lifetime.

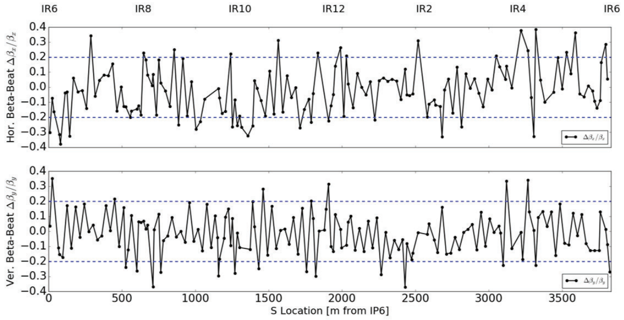

Figure 4: Horizontal (top) and vertical (bottom) β-beat measured for a radial shift ΔR_1 = -8.58 mm in the RHIC Yellow lattice. Most of the distortion is contained within the ±20% range (dashed lines), comparable to the typical RHIC on-momentum optics beating.

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[3] MAD - Methodical Accelerator Design, `http://mad.web.cern.ch/mad/`

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