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LARGE RADIAL SHIFTS IN THE EIC HADRON STORAGE RING

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Abstract

The Electron Ion Collider will collide hadrons in the Hadron Storage Ring (HSR) with ultra-relativistic electrons in the Electron Storage Ring (ESR). The HSR design trajectory includes a large radial shift over a large fraction of its circumference, in order to adjust the hadron path length to synchronize collisions over a broad range of hadron energies. The design trajectory goes on-axis through the magnets, crab cavities and other components in the six HSR Insertion Regions. This paper discusses the issues involved and reports on past and future beam experiments in the Relativistic Heavy Ion Collider (RHIC), which will be upgraded to become the HSR.

COLLISION SYNCHRONIZATION

Electrons and hadrons in the ESR and HSR must circulate with the same revolution period $\tau \approx 12.8\,\mu\mathrm{s}$ to maximize luminosity and to avoid deleterious beam-beam effects [1]. The electron beam is highly relativistic over its entire energy range from 5 to 18 GeV, so the electron revolution period is practically constant, except for the modest circumference *shortening* (by as much as about 8 mm) that occurs when super-bends are used to enhance synchrotron radiation at 5 GeV. In contrast, the hadron relativistic speed β varies significantly over the proton energy range 41 GeV$< E_{\mathrm{tot}} <$ 275 GeV. The hadron design orbit circumference must be

$$C \;=\; \beta C_1 \;=\; C_0 + \Delta C, \qquad (1)$$

where C_1 is the ultra-relativistic circumference and C_0 = 3833.824 m is the (current) on-axis reference circumference at a mid-range energy of about 133 GeV. Between proton energies of 100 GeV and 275 GeV the circumference is adjusted by introducing a radial shift in all 6 HSR arcs, modified from 3 inner and 3 outer RHIC arcs. In operation at 41 GeV the protons (or ions with the same speed) pass on-axis through 4 inner and 2 outer arcs, and so do not need a significant radial shift.

The total additional circumference is

$$\Delta C \;=\; \int_0^C \frac{\Delta R(s)}{\rho}\, ds \;=\; \int_0^{2\pi} \Delta R \, d\theta, \qquad (2)$$

where the bending strength $1/\rho$ is zero except in dipoles. The average radial offset,

$$\langle \Delta R \rangle \;=\; \Delta C / 2\pi, \qquad (3)$$

Table 1: Circumference Offsets and Average Radial Shifts

E_{tot} GeV /	γ GeV/u	$1-\beta$ 10^{-3}	C m	ΔC mm	$\langle\Delta R\rangle$ mm
PROTONS					
41.0	43.70	0.2619	3832.92	-908.7	–
100	106.58	0.0440	3833.75	-73.4	-11.7
133	141.75	0.0249	3833.82	0.0	0.0
275	293.09	0.0058	3833.90	73.1	11.6
GOLD IONS					
40.7	43.70	0.2619	3832.92	-908.7	–
110	118.09	0.0359	3833.78	-42.1	-6.7

Protons pass through 3 inner and 3 outer arcs except at 41 GeV, when they pass through 4 inner and 2 outer arcs.

must therefore span the range listed in Table 1. The maximum displacement $|\Delta R_{\mathrm{max}}|$ depends on the implementation of the radial shift, but in all cases it is significantly larger than the maximum average value $|\langle \Delta R \rangle|$ = 11.7 mm.

ON-AXIS INSERTION REGIONS

In HSR the design orbit is on-axis in the 6 Insertion Regions (IRs) that contain experiments, hadron cooling, crab cavities, Siberian snakes, and various utilities [2–4]. Dipole angles in the non-straight IRs are held constant while the main arc dipoles are perturbed to deliver the required ΔC. Beam is accelerated with no radial shift, so the most challenging scenario (with the largest beams) is with 100 GeV protons. Figure 1 illustrates how RHIC beam studies in 2021 tested “short” (Q4-to-Q4) and “long” (Q10-to-Q10) on-axis

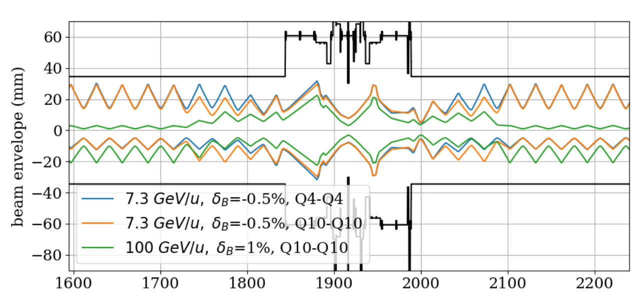

Figure 1: RHIC gold beam study envelopes. Orange and blue (5σ plus separatrix) indicate the “long” and “short” configurations tested in 2021 with $\Delta B/B = \pm 0.005$. The green envelope (10σ plus separatrix) is planned for future studies with 100 GeV/u gold beam and $\Delta B/B = \pm 0.01$.

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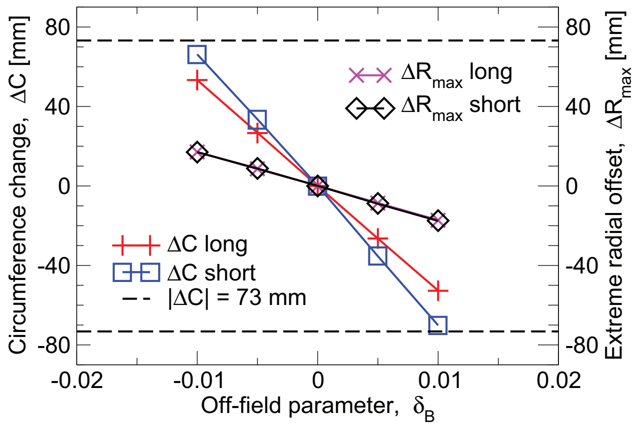

Figure 2: Configurations with shorter on-axis regions are more efficient at generating ΔC, so larger $|\delta_B|$ values are necessary when the on axis regions are longer. Closed orbits have the same $\Delta R_{\max}$ values for a given δ_B, independent of the on-axis region length. Dashed lines show the most challenging ΔC requirements, at 100 and 275 GeV.

configurations with 7.3 GeV/u gold beam. Also shown is the 100 GeV/u configuration planned for future studies.

Off-axis beams in the arcs come closer to the vacuum beampipe and increase the cryogenic heat load due to resistive wall and electron cloud effects. Simulations find that sextupoles suffer the worst electron cloud heat load, but if the Secondary Emission Yield (SEY) is less than 1.0, then the heat load is dominated by resistive-wall heating. The cooling of quadrupoles and sextupoles then becomes less critical than for the arc dipoles, which are much longer, occupy a significant fraction of the circumference, and have narrower cooling channels around the beam pipe. A local radial shift of 20 mm enhances the arc dipole resistive wall mid-plane heat load by a factor of about 13.4 [5,6]. Average heat loads are reduced below the 0.5 W/m limit by fitting the vacuum beampipe with a copper beam screen liner coated with a thin film of amorphous carbon [5].

The extreme and average radial shifts are related to the minimum and maximum dispersions in the arcs through

$$|\Delta R_{\max}| \,/\, \langle \Delta R \rangle \;\approx\; \sqrt{D_{\max}/D_{\min}}, \tag{4}$$

and so one way to reduce the maximum displacement is to reduce $\Delta\phi$, the phase advance per arc FODO cell. The extreme displacement is reduced by about 3 mm when $\Delta\phi = 40$ degrees [1]. However, Intra-Beam Scattering times decrease significantly at such values, so $\Delta\phi$ reductions are held in reserve as a potential mitigation strategy.

DIPOLE CORRECTOR SUBSETS

The design trajectory in the arcs needs to avoid peak displacements of more than about 20 mm in superconducting magnets with a coil ID of 80 mm. This is primarily achieved by adjusting the arc dipole *off-field parameter*

$$\delta_B \;\equiv\; \Delta B/B \tag{5}$$

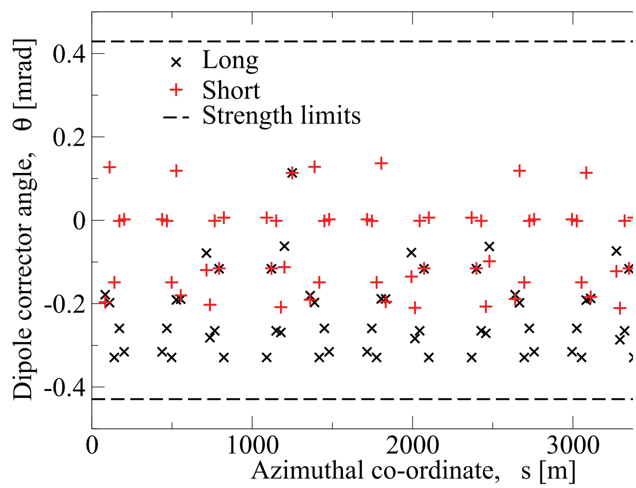

Figure 3: Dipole corrector angles used in the 2021 RHIC beam studies, with $\delta_B = -0.01$ and before correction of random closed orbit errors. The long and short configurations have angles of $\theta = -0.228 \pm 0.096$ mrad and -0.062 ± 0.102 mrad, respectively, well within the angular strength limits at 275 GeV indicated by the dashed lines.

to deliver the desired ΔC. Secondarily, $|\Delta R_{\max}|$ is minimized by adjusting dipole correctors to achieve the ideal arc design trajectory, which is

$$\Delta R(s) \;=\; -D_{\text{matched}}(s)\cdot\delta_B, \tag{6}$$

where D_{matched} is the dispersion of a matched series of arc FODO cells – even if the actual dispersion is *not* perfectly matched. A subset of dipole correctors at the end of an arc matches the ideal arc trajectory into a trajectory with $\Delta R = 0$ in the IR. Figure 2 shows how shorter on-axis regions generate larger $|\Delta C|$ values for a given δ_B in the RHIC tests. Extreme radial shifts of about ± 23.7 mm and ± 18.5 mm would be required if unmodified RHIC long and short configurations were used in HSR.

The subsets of dipole correctors that are selected on each side of every IR (depending on local needs) must also remain capable of correcting random closed orbit errors. Figure 3 shows that the subsets of RHIC dipole correctors used in 2021 beam studies are within the quench-test acceptance threshold of ± 70 A. However, most RHIC dipole corrector power supplies are rated at ± 50 A, generating the angular strengths listed in Table 2. Ten have been upgraded to 55 A,

Table 2: Maximum Dipole Corrector Bend Angles at the Nominal Maximum Power Supply Current of 50 A, and at the Quench-test Maximum Current of 70 A

Current	**Integrated field**	**Maximum bend angle [mrad] (Proton energy [GeV])**			
[A]	[Tm]	(41)	(100)	(133)	(275)
50	0.281	2.055	0.842	0.633	0.306
70	0.393	3.877	1.179	0.887	0.429

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Table 3: Parameters During 2021 Injection Beam Studies with Gold Beam in the RHIC Yellow Ring at 7.3 GeV/u

Parameter	Unit	Horz.	Vert.
RMS emittances, ϵ_N	μm	2.0	2.0
Separatrix offset, $\Delta p/p$	±	0.00171	–
Betatron tunes		28.234	29.224
Chromaticities		-5	-5
Insertion Regions β^*	m	10.0	10.0

and two to ±60 A [7]. Warm leads enter cryostats to power individual dipole correctors. Thermal runaway is absent up to 60 A, but needs further testing at 70 A [7].

Main arc quadrupoles and sextupoles are adjusted to hold tunes and chromaticities at goal values. Individual quadrupoles in the insertion regions are tuned to maintain Twiss functions everywhere [2–4]. Table 3 lists typical primary optical parameters in RHIC beam tests.

BEAM STUDIES

In 2018 beam studies a large emittance gold beam was stored at an injection energy of 10 GeV/u with an RMS beam size of about $\sigma = 2.8$ mm [8]. The ramp to radial shift operations maintained clean off-momentum optics and minimized the $\Delta R_{\max} / \langle \Delta R \rangle$ ratio by careful closed orbit correction. Performance with $\langle \Delta R \rangle = -8.6$ mm was mostly satisfactory, but significant beam losses were seen with $\langle \Delta R \rangle = -11.0$ mm. An extreme displacement of -25.4 mm was observed, maintaining a 4.5 mm clearance with an assumed inner beampipe radius of 34.5 mm, including a 6σ envelope. Extrapolations to 100 GeV/u suggested that $\langle \Delta R \rangle$ could be reduced to about -15 mm, significantly better than the required range of $\langle \Delta R \rangle = \pm 11.7$ mm.

In 2020 a brief study at 26.5 GeV/u held constant the RF frequency f while varying δ_B. Tune feedback was on, and closed orbit feedback was used as needed. Data showed spikes in Yellow ring losses, first on the outside when $R_{\max} \approx 12$ mm, and later on when $R_{\min} \approx -14$ mm.

In 2021 beam studies demonstrated – for the first time – large radial shifts in the arcs with on-axis closed orbits in the IRs. Summary results are shown in Figure 4. Red curves and blue data show good agreement in both long and short configurations when the RF frequency was shifted by

$$\Delta f / f = -\Delta C / C. \tag{7}$$

Arc displacements as large as +23 mm were achieved when the RF frequency was not well-matched.

Future beam studies will:

1. Test a mix of on-axis configurations, some with $|\delta_B| > 0.010$
2. Analyze data taken during RF frequency scans at constant δ_B
3. Maintain tunes and chromaticities with high accuracy

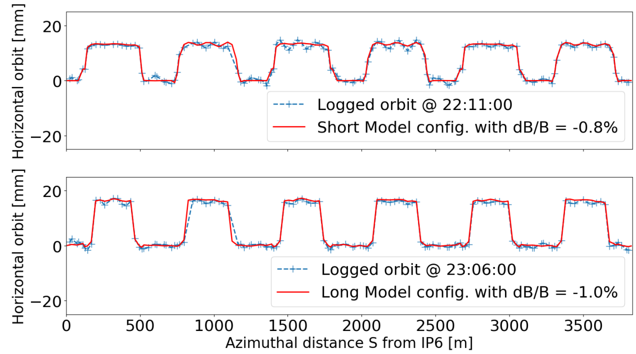

Figure 4: Closed orbits (on-axis in the IRs) measured in 2021 with 7.3 GeV/u gold beam. Top: short configuration with $\delta_B = -0.008$. Bottom: long configuration with $\delta_B = -0.010$. Model and observation are in excellent agreement when the RF frequency f is well-matched. Arc displacements as large as +23 mm have been achieved.

4. Minimize and collimate beam losses while exploring apertures
5. Expose and resolve logistical issues

CONCLUSIONS

HSR operations require circumference changes as large as $\Delta C = \pm 73.2$ mm with extreme radial shifts of about ±20 mm. The design trajectory is on-axis in all 6 insertion regions, over lengths that are currently under discussion and study. Longer on-axis regions necessitate larger extreme displacements in the arcs.

2021 beam studies in RHIC demonstrated, for the first time, large radial shifts in the arcs with on-axis closed orbits in the (non-zero dispersion) Insertion Regions. “Long” and “short” configurations were tested with off-field parameters as large as $\delta_B = \pm 0.010$, broadly confirming the feasibility of large radial shifts in the HSR.

Shorter configurations more efficiently generate circumference changes without exceeding the dipole corrector strength limits and while minimizing aperture demands, at the cost of decreasing the on-axis range necessary for experiments, Siberian snakes, crab cavities, et cetera.

Future beam studies at higher energies will investigate: 1) optimum on-axis lengths and configurations, 2) ramp and optics design techniques, 3) aperture limits and beam losses, and 4) logistical issues.

Future simulation studies will help to prepare a customized design in each IR and neighboring arcs, and will explore the need for main dipole shunts in the IRs.

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