

Transition Crossing with Reduced Number of Jump Quadrupoles

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Transition Crossing with Reduced Number of Jump Quadrupoles

H. Lovelace III

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Abstract

The Electron Ion Collider (EIC) Hadron Storage Ring (HSR) is the reconstructed Relativistic Heavy Ion Collider (RHIC) where arcs of the accelerator will not change and all but one insertion region (IR) will be slightly modified during commissioning. The experimental insertion region, IR6, will break the symmetry of the γ -transition crossing scheme that was used in RHIC by reducing the number of effective compensation jump quadrupoles by four, eight, and with an additional experiment twelve. The reduction of jump quadrupoles during transition may cause unwanted emittance growth, additional beam loss, or prevention of crossing transition in the HSR. This tech note shows the results of the Accelerator Physics Experiment 2310 (APEX2310) using the $^{197}\text{Au}^{+79}$ ramp where four then eight, Q family, compensation γ -transition quadrupoles located in the straight sections from a total 24 were turned off.

The results show that transition was crossed with 6% beam loss and minimal emittance growth for the G24Q20 and G24Q16 configurations with 111 bunches. The metric for success is to show beam loss less than 10% and the minimal emittance growth shown in the experiment. These results add to the feasibility of efficient transition crossing with unequal arc, G-family, and Q-family jump quadrupoles in the HSR. With the loss of additional Q-family jump quadrupoles due to the addition of a second detector, alternative methods of crossing transition will need to be explored.

1 Introduction

The Electron Ion Collider (EIC) is currently under design and construction on the campus of Brookhaven National Laboratory [1]. The EIC is composed of the new Electron Storage Ring, with its new injectors and the modified Relativistic Heavy Ion Collider (RHIC) [2] ring serving as the new Hadron Storage Ring (HSR) with its series of injectors. Figure 1 is of the EIC with the electron Proton Ion Collider (ePIC) detector hosted in the 6 o'clock region of the EIC and a future detector to be designed and built in the 12 o'clock region.

The new HSR is similar to the RHIC yellow ring with modifications to the interaction regions where the low/medium energy electron cooling and the experimental detector will be located. These modifications reduce the number of Q-family jump quadrupoles which compensate for the tune shift and β -Twiss/ η -dispersion waves generated during the transition jump [3, 4]. The latest commissioning lattice design has 4 fewer jump quadrupoles than RHIC, where the ultimate design will have 8 fewer. Including a second detector will mean that alternative methods of crossing transition will be needed [5, 6, 7]. If the number of compensation jump quadrupoles falls below 16 the compensation quadrupoles will not have enough strength to match the tunes before and after the transition jump.

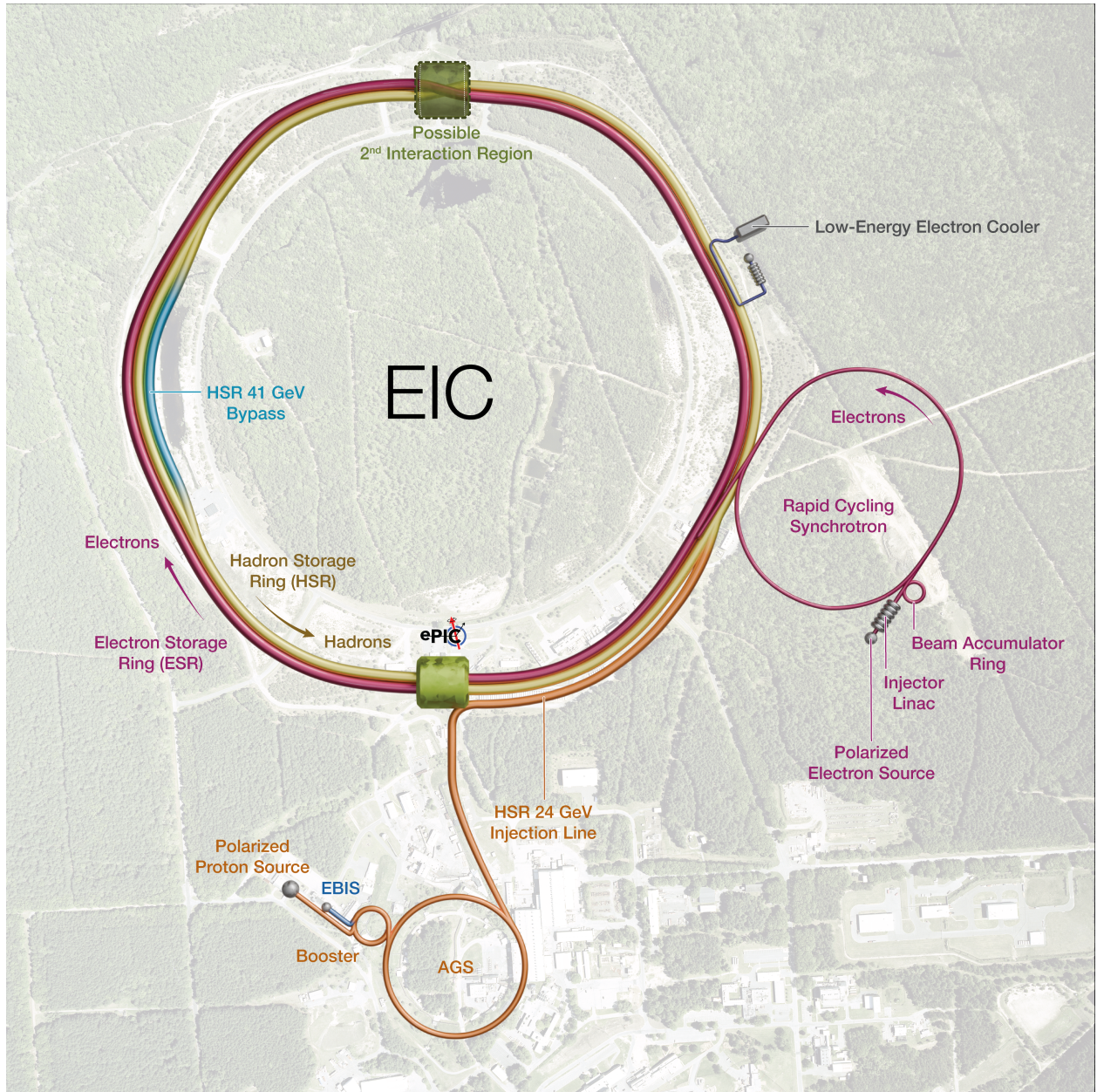


Figure 1: The EIC areal schematic including the HSR and ESR injectors.

2 Theory

Besides the longitudinal phase jump that is needed at transition [8], the dispersion of the lattice is distorted to change the value of the lattice γ -transition, γ_T to allow a transverse adiabatic jump of the γ_T . The First Order Matched (FOM) scheme is a two “knob” method which uses a pair of jump quadrupole families, G and Q , that becomes excited to perturb the dispersion of the lattice while simultaneously mitigating the tune shift and distorted optics. Figure 2 shows the Twiss β , dispersion η , and layout of a RHIC sextant. The G -family jump quadrupoles are located in the dispersive arcs while the Q -family jump quadrupoles are hosted within the straight sections where dispersion is at a minimum. For RHIC, each sextant has 8 jump quadrupoles, 4 in the arcs and 2 pairs of doublets in the straight sections. There is a total of 48 jump quadrupoles in the ring, evenly matched into the G and Q families (G24Q24).

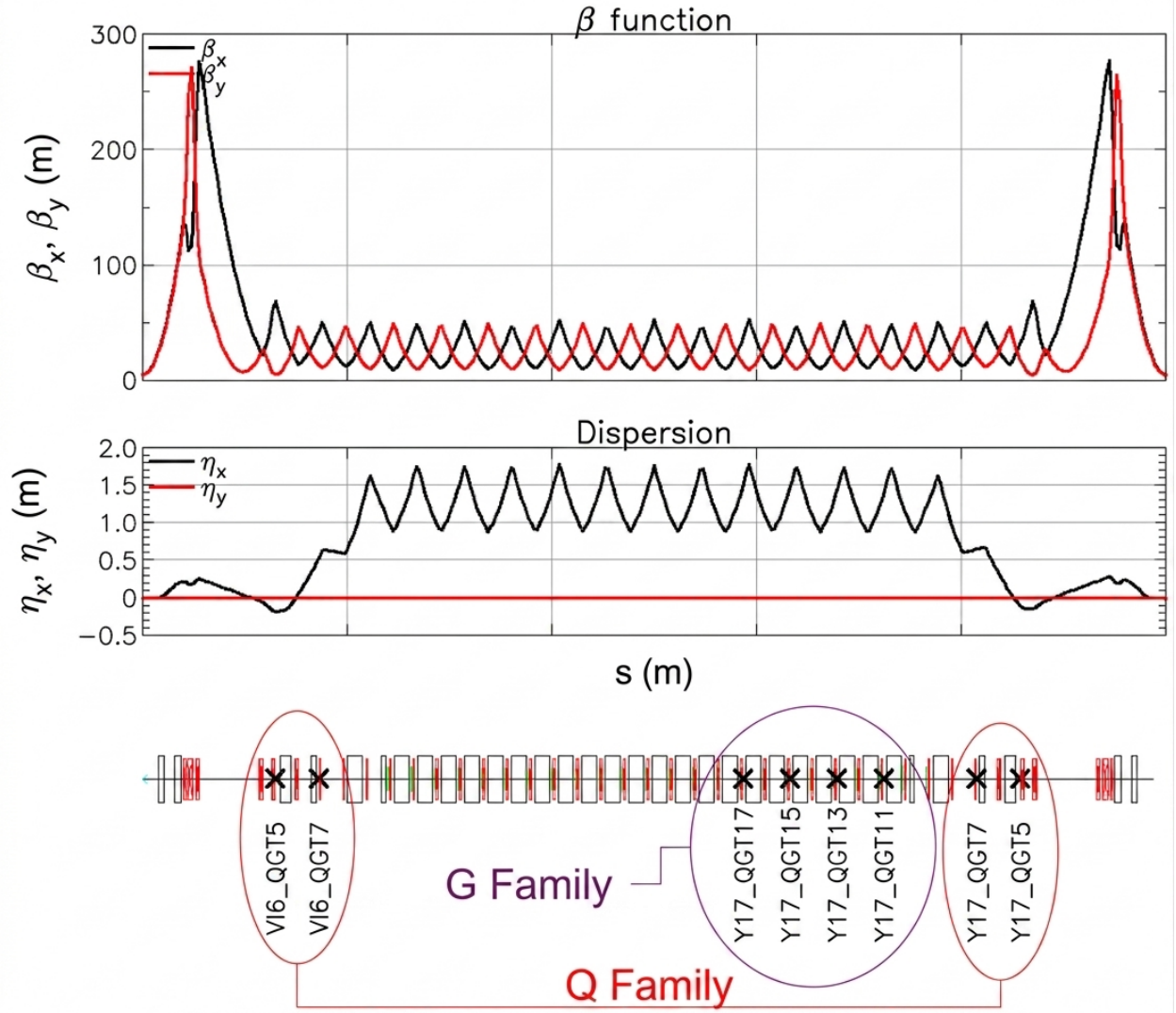


Figure 2: The first order scheme of RHIC. Top: β , middle: η , and bottom: layout. The two families in each sextant, G and Q , are used to control the γ_T and compensate for tune shift, respectively.

The β -beat and η -wave at the peak absolute excitation of the jump quadrupoles is [9]

$$\frac{\Delta\beta_H}{\beta_H} = \frac{1}{2\sin(2\pi Q_H)} \sum_i (k_1 l)_i \beta_{Hi} \cos(2|\phi - \phi_i| - 2\pi Q_H) \quad (1)$$

and

$$\frac{\Delta\eta}{\sqrt{\beta}} = \frac{1}{2 \sin(\pi Q_H)} \sum_i (k_1 l)_i \eta_i \sqrt{\beta_{Hi}} \cos(|\phi - \phi_i| - \pi Q_H) \quad (2)$$

where the difference in phase advance $\Delta\phi = |\phi - \phi_i|$ is taken at the jump quadrupole from a phase advance upstream of the doublet or quadruplet. The horizontal tune, Q_H , is the baseline tune and the β_H -function is taken at each active jump quadrupole. Here, we see that if the phase advance between the jump quadrupoles is 90° and the β -functions are uniform, the β -beat and η -wave are fully suppressed. The integrated normalized quadrupole strength $k_1 l$ for the jump quadrupoles are taken at their maximum and minimum strengths for each active jump quadrupole. Ideally, the dispersion, η_H is only present at the locations of the arc jump quadrupoles. The relationship between the strengths of the two jump quadrupole types, G and Q, is [10]

$$q_G = \hat{k} q_Q \quad (3)$$

where $\hat{k}$ is the proportionality constant that relates the integrated normalized strength, q_Q , of the Q family to the integrated normalized strength, q_G , of the G family. The value of $\hat{k}$ is determined by sensitivities associated with the jump quadrupole families. A response matrix, T , that is used to obtain the G-family to Q-family ratio, is obtained from these sensitivities [10]

$$T = \begin{pmatrix} T_{GG} & T_{GQ} \\ T_{QG} & T_{QQ} \end{pmatrix} = \begin{pmatrix} \sum S_{G,p} & \sum S_{G,p} \\ \sum S_{Q,p} & \sum S_{Q,p} \end{pmatrix} \quad (4)$$

The ratio of the

$$(-T_{QG}/T_{QQ}) = \hat{k}. \quad (5)$$

A “stay clear” area is needed to safely cross transition if

$$T_{NL} \gg T_C. \quad (6)$$

The nonlinear time T_{NL} is

$$T_{NL} = \left(\alpha_1 + \frac{3}{2} \beta_T^2 \right) \frac{\gamma_T}{\dot{\gamma}} \delta_{max} \quad (7)$$

where β_T is the velocity ratio of the beam centroid,

$$\delta_{max} = \Delta p_{max}/p \quad (8)$$

is the maximum momentum spread of the bunch, and α_1 is the “nonlinear momentum compaction factor” defined in [3]. The characteristic time (non-adiabatic time) T_C is

$$T_C = \left(\frac{AE_T}{ZeV |\cos(\phi_s)|} \times \frac{\gamma_T^3}{h\dot{\gamma}} \times \frac{C^2}{4\pi c^2} \right)^{1/3} \quad (9)$$

where A is the atomic weight, Z is the atomic number, E_T is the transition energy, e is the charge of the electron, V is the RF cavity voltage, γ_T is the transition γ , h is the harmonic number, and $\dot{\gamma} = d\gamma/dt$. The change in γ_T for the pre- and post-jump, is defined as

$$\Delta\gamma_T \approx 4\dot{\gamma} T_{NL}. \quad (10)$$

For RHIC,

$$\begin{aligned} T_{NL} &= 432.7 \text{ ms}, \\ T_C &= 71.3 \text{ ms}, \\ \Delta\gamma_T &= 1 \end{aligned} \quad (11)$$

where the given values to calculate the values in Eq. 11 are summarized in Tab. 1. RHIC magnet and electrical systems have strong reproducibility [11, 12, 13] which keeps the values in Eqs. 11 and Tab. 1 near constant from one ramp to the next.

Table 1: Machine and beam parameters for transition crossing.

Parameter	Symbol	Value	Unit
Circumference	C	3833.85	m
Acceleration rate	$\dot{\gamma}$	0.35	γ^{-1}
Momentum spread	$\Delta p/p$	4.32×10^{-3}	–
Atomic number (Au)	Z	79	–
Mass number	A	196.97	–
RF voltage	V	200	kV
Harmonic number	h	360	–
Transition energy	E_t	21.83	GeV/u
Revolution frequency f_{rev}	78123.6	Hz	
Synchronous phase	ϕ_s	6.11×10^{-2}	rad
Momentum compaction	α_0	1.89×10^{-3}	–
Nonlinear momentum compaction	α_1	-9.33×10^{-4}	–

Figure 3 is a schematic of a change in γ_T with respect to time with a jump and without a jump. The jump duration is 33 ms which in RHIC is approximately 2800 turns. During the jump the γ_T value of γ_T changes by 1 unit. For RHIC we adopted a “4 knob” scheme based on the marginal difference in the inner and outer cell lengths that introduces deviations in the phase and β -functions at the jump quadrupoles. The tables in App. A show the calculation of the sensitivities and the theoretical value of the k proportionality constants. The Twiss parameters, phase advance, ϕ , and the dispersion, η are taken from the **beta5** stone of the design lattice. The β^* of each IR is 5 m. The sensitivity of the power supply is the summed value of the individual quadrupoles on energized by that supply. As a note, Table 9’s theoretical value $\hat{k}$ is **not** 1 due to the 60 m β -functions at the inner jump quadrupoles in slot 5 of the straight sections.

Non-adiabatic the tune changes cause unwanted detrimental effects to the beam such as beam loss. The tune change remains adiabatic within n turns if

$$\Delta Q_n = \frac{1}{f_{rev}} \left| \frac{dQ}{dn} \right| \ll 1. \quad (12)$$

The revolution frequency, f_{rev} , is given in Tab. 1. Appendix B contains tables that show a brief study on the adiabaticity of the transverse tune shifts during transition.

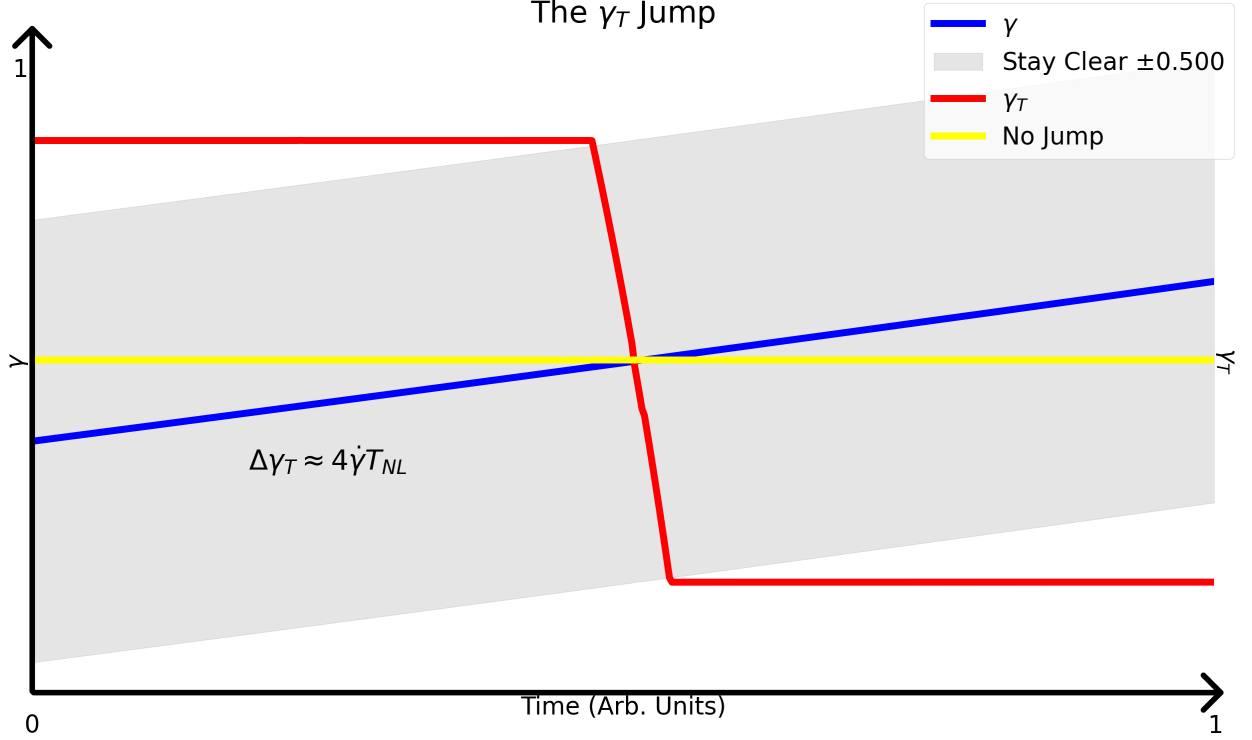


Figure 3: Transition with and without jump. The shaded gray region is the “stay clear” area defined by $4\dot{\gamma}T_{NL}$. The $\dot{\gamma} = 0.35 \text{ s}^{-1}$ ramp rate is the typical $^{197}\text{Au}^{+79}$ ramp rate of RHIC. For RHIC, $\Delta\gamma_T = 1$

3 Model

The design lattice, **Au25-100GeV-e0**, was used as a baseline for modeling simulations. The same base optics was used for the configurations where 4 (G24Q20) and 8 (G24Q16) jump quadrupoles were turned off. The crucial differences in the optics and dispersion are generated when the jump quadrupoles are energized and when they are at their full excitation. The unperturbed lattice is shown in Fig. 4. The jump quadrupoles start to ramp at the **beta5** stone, where a stone is a snapshot of the energy ramp. The base fractional tunes are 0.238, horizontal and 0.232, vertical. The horizontal and vertical design phase advances in the outer arcs are approximately 85.4° and 87.5° , while the inner arcs have phase advances of 85.1° and 87.2° .

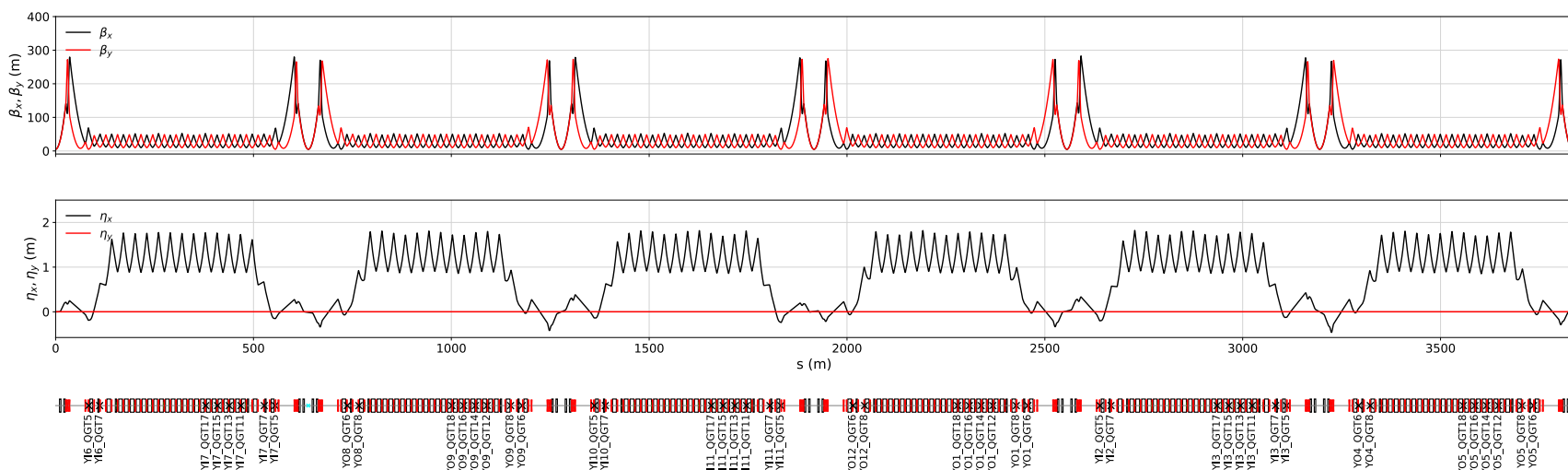


Figure 4: RHIC lattice optics at the **beta5** stone. The lattice start at IP6 detector and increases in s clockwise. The top plot shows the β -functions, the middle plot η -function. The bottom is the lattice layout, black box: dipoles, red xbox: quadrupoles, and green box: sextupoles. The black x:jump quadrupoles are labeled.

The design chromaticity is -2 in both planes below transition where **ideally** after the transition quadrupole jump, the chromaticity also jumps to +2 units in both planes solely due to the polarity flip of the jump quadrupoles changing the natural chromaticity of the lattice. Table 2 shows the change in the tune and chromaticities from the jump quadrupole polarity flip. The Q24Q16 configuration exhibits the greatest deviation in tune and chromaticity pre- and post-jump.

Table 2: Total Tune Shift and Chromaticity Jump by Configuration

Configuration	$\Delta Q_x \times 10^{-5}$	$\Delta Q_y \times 10^{-5}$	$\Delta \xi_x$	$\Delta \xi_y$
G24Q24	0.00	0.00	-6.668	-2.366
G24Q20	0.00	0.00	-6.334	-2.310
G24Q16	-1.45	-31.1839	-5.946	-2.220

The linear octupole detuning is

$$\begin{aligned}
\alpha_{xx} &= \frac{1}{16\pi} \sum_{octupoles} k_3 \beta_x^2 \\
\alpha_{xy} &= -\frac{1}{8\pi} \sum_{octupoles} k_3 \beta_x \beta_y \\
\alpha_{yy} &= \frac{1}{16\pi} \sum_{octupoles} k_3 \beta_y^2
\end{aligned} \tag{13}$$

where β is the Twiss function in the plane indicated by the subscript, k_3 is the integrated octupole strength. The octupole detuning during transition is shown in Tab. 3. The octupole detuning provides Landau damping through transition which aids in stabilizing the beam by providing additional frequency spread.

Table 3: Octupole Detuning Coefficients

Coefficient	Strength (m^{-1})
a_{xx}	-20806.2333
a_{xy}	18144.1352
a_{yy}	-19996.9186

The $\hat{k}$ proportionality constants from the simulation were obtained through a custom Bmad [14] script written to optimize the jump quadrupole “knob” strengths post-jump to match the tunes post-jump by using a separate identical lattice. The constraints on the lattice are the difference in the lattice γ_T for pre- and post-jump must be 1 and the tunes, both horizontal and vertical, must be equal. The variables differ depending on the configuration where the 4-knob scheme was used for G24Q24 and G24Q20. The G24Q16 Q-family jump quadrupoles were allowed to vary freely as individual power supplies, 4 in total, to optimize to the given constraints. A comparison between the theoretical and simulation $\hat{k}$ values are shown in Tab. 4. The $\hat{k}$ theoretical and simulated values differ due to the simulation placing a constraint on the working point

Table 4: Theoretical and Simulated $\hat{k}$ Values

Configuration	Theory		Simulation	
	$\hat{k}_{\text{inner}}$	$\hat{k}_{\text{outer}}$	$\hat{k}_{\text{inner}}$	$\hat{k}_{\text{outer}}$
G24Q24	-0.8300	-1.0354	-0.9325	-0.9264
G24Q20	-1.2441	-1.0354	-1.3843	-0.9245
G24Q16	-1.2441	-1.5316	-1.6178	-1.5532

to remain the same pre- and post jump. The theory is constructed for the ideal lattice where the working point will remain the same pre- and post-jump. For the experiment, the simulated $\hat{k}$ values were used where additional care was taken to implement the G24Q16 configuration due to RHIC’s assumed 4-knob scheme.

The RMS calculation of the waves generated by perturbed optics from the base lattice pre- and post-jump generated for each configuration is shown in Tab. 5. The RMS values of the waves generated are taken over each tracked lattice element. The β -waves are generated from the varying β functions at the location of the jump quadrupoles and the phase advance between the jump quadrupoles not equalling 90° . The dispersion wave RMS increases as the number of jump quadrupoles decreases due to the ineffectiveness of the energized Q-family jump quadrupoles to locally close the dispersion wave for the post-jump optics.

Table 5: Pre-Jump and Post-Jump RMS Normalized Waves

Configuration	State	$\Delta\beta_x/\beta_x$	$\Delta\beta_y/\beta_y$	$\Delta\eta_x/\beta_x$	$\Delta\eta_y/\beta_y$
G24Q24	Pre-Jump	0.3817	0.0282	0.0226	0.0000
	Post-Jump	0.3739	0.0339	0.0351	0.0000
G24Q20	Pre-Jump	0.4163	0.0342	0.0309	0.0000
	Post-Jump	0.4131	0.0388	0.0409	0.0000
G24Q16	Pre-Jump	0.4359	0.0447	0.0043	0.0000
	Post-Jump	0.4120	0.0466	0.0605	0.0000

4 Accelerator Physics Experiment

The Accelerator Physics Experiment (APEX) sessions were conducted on 3 separate days, August 6 (14 Ramps), October 15 (16 Ramps), and November 5 (8 Ramps) in 2025. For the experiments, marginal changes were made to the strengths of the jump quadrupoles, amplitude of the voltages and timing [15] of the jump quadrupoles polarity flip to force, at transition, all jump quadrupoles strengths to cross zero at the same time. For the G24Q20 configuration, the yi2-qgt-ps power supply was turned off and for the G24Q16 configuration the yi2-qgt-ps and the yo4-qgt-ps power supplies were turned off. Each power supply energizes 4 Q-family jump quadrupoles. Figure 5 shows the integrated strengths of the jump quadrupoles from their maximum (minimum) to the minimum (maximum) strengths. The maximum absolute strength of the jump quadrupoles is 0.0078 m^{-1} . The crossing point is the moment of transition in the lattice of the energy ramping accelerator where the longitudinal phase jump occurs. There are no ramp chromaticity measurements for any ramp due to time constraints and slight modifications to the quadrupole and sextupole strengths based on beam stability occurred during the sessions.

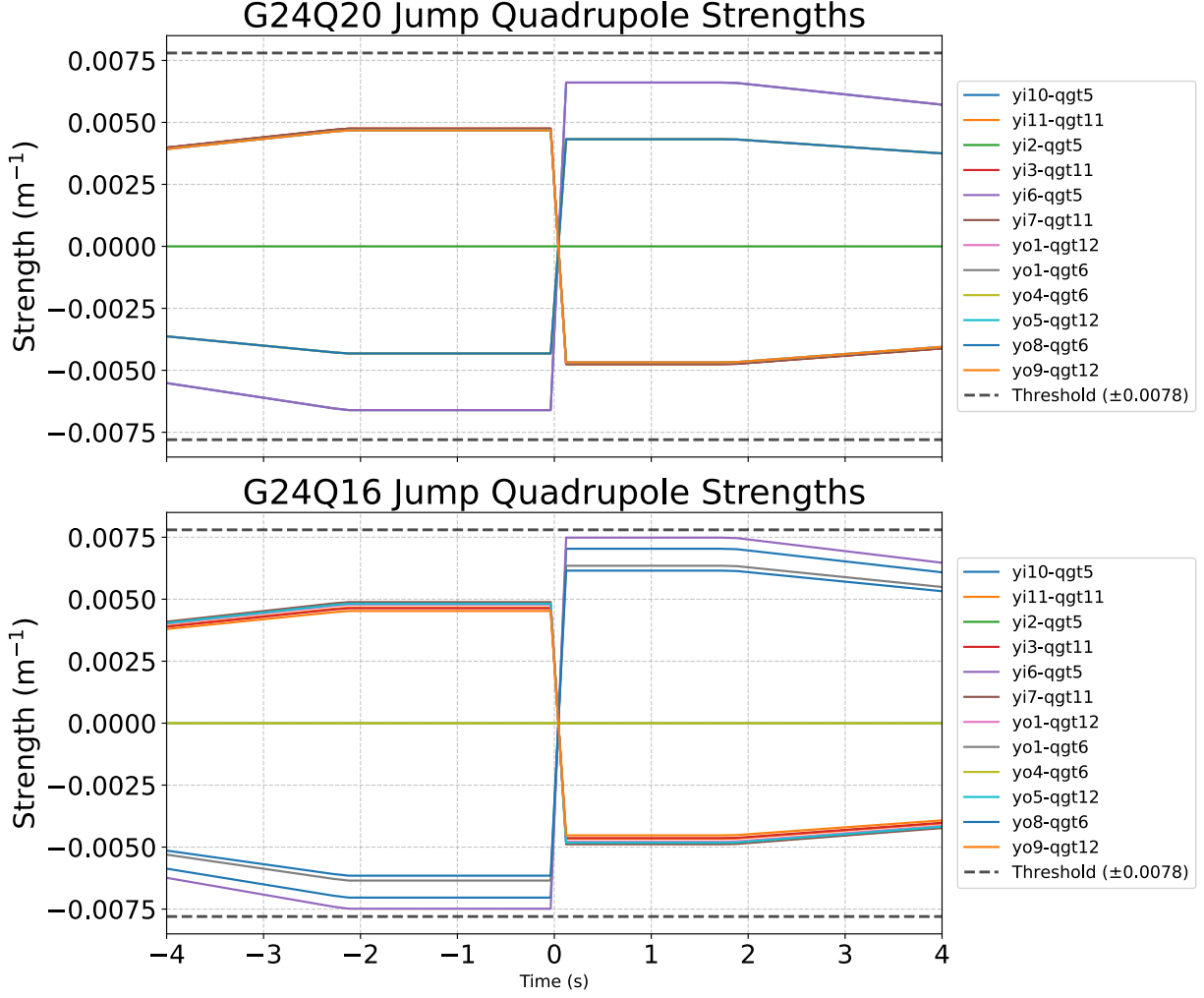


Figure 5: The integrated strengths of the jump quadrupoles for the G24Q20 and G24Q16 configurations. For the G24Q20 configuration, the yi2-qgt-ps power supply is off and for the G24Q16 configuration the yi2-qgt-ps and the yo4-qgt-ps power supplies were off. The strength thresholds for the jump quadrupoles are $\pm 0.0078 \text{ m}^{-1}$

4.1 G24Q20

For the August 6th session, the experiment first encountered challenges with the overshoot of the jump quadrupole yi2-qgt-ps current with polarity flips at 2 A which was resolved by turning off the jump quadrupole power supply. The 28 bunch ramp afterwards with 1×10^9 per bunch intensity successfully crossed transition with 1% beam loss and minimal 3D emittance growth. The jump quadrupole 600 V DC high voltage power supply which charges the capacitor bank was used to control the di/dt effecting the polarity flip duration. The 56 bunch ramp was successful with 1.5×10^9 per bunch with minimal beam loss and emittance growth shown in Fig. 6 and Fig. 7. The beam loss measured by the direct current current transformer (DCCT) was 2% with 7% horizontal emittance growth measured by ionization profile monitor. The high resolution tune evolution for the 56 bunch ramp is shown in Fig. 8 measured by the baseband tune monitor (BBQ). With the attempt at 111 bunches at 1.5×10^9 , coherence and vertical emittance growth were observed.

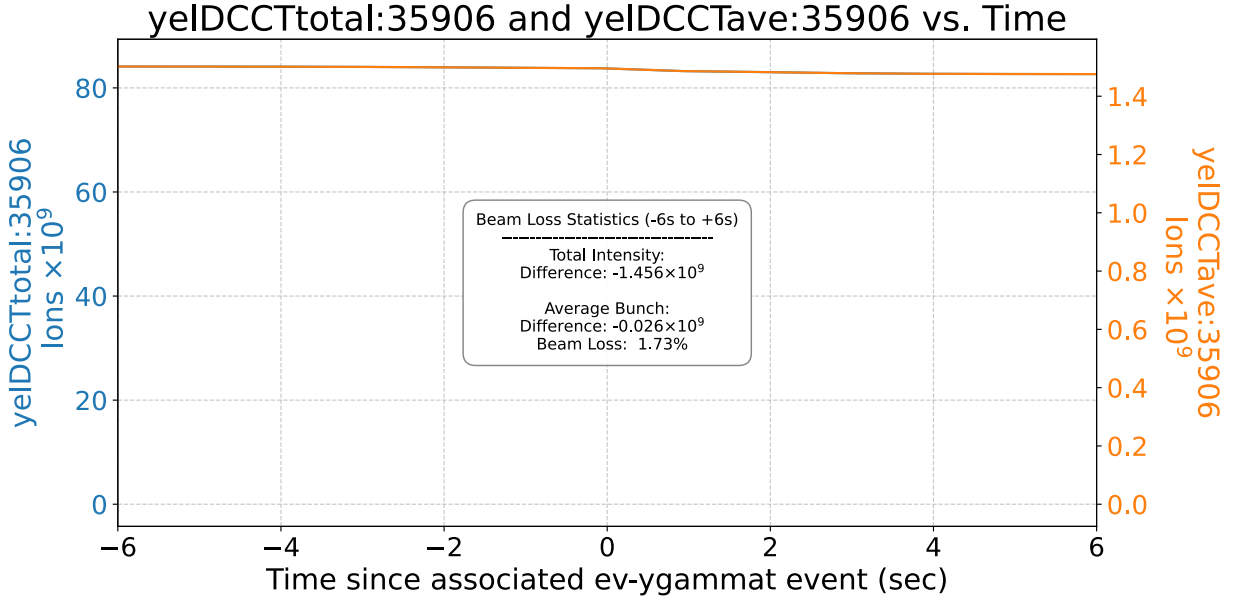


Figure 6: G24Q20 configuration for 56 bunches. The left (Y1) axis is the total intensity of the beam and the right (Y2) axis is intensity per bunch.

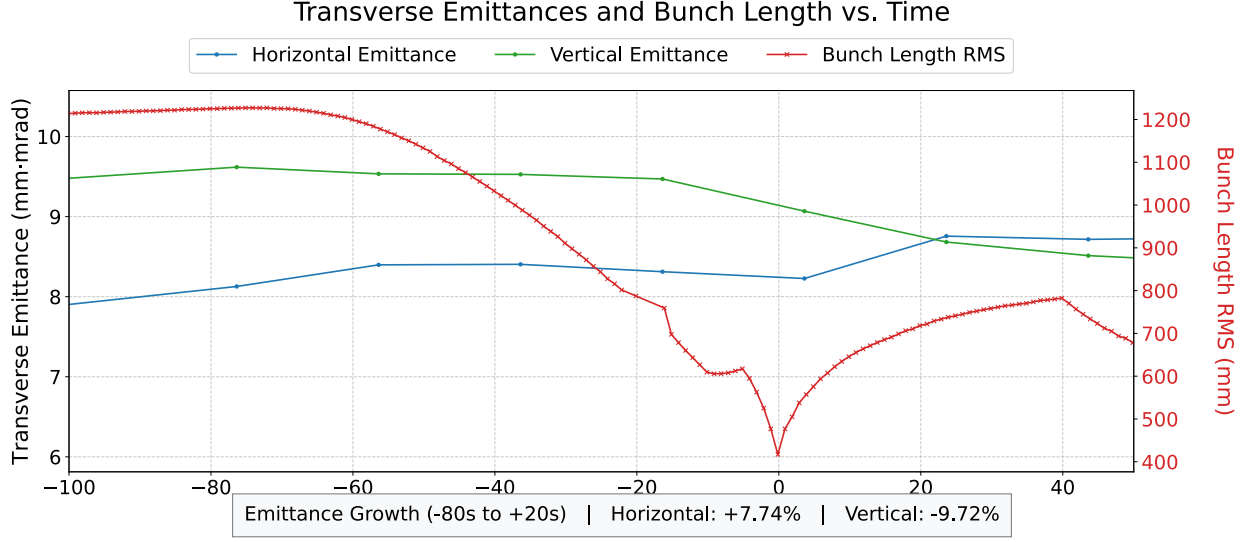


Figure 7: Transverse emittance, left (Y1) and bunch length, right (Y2).

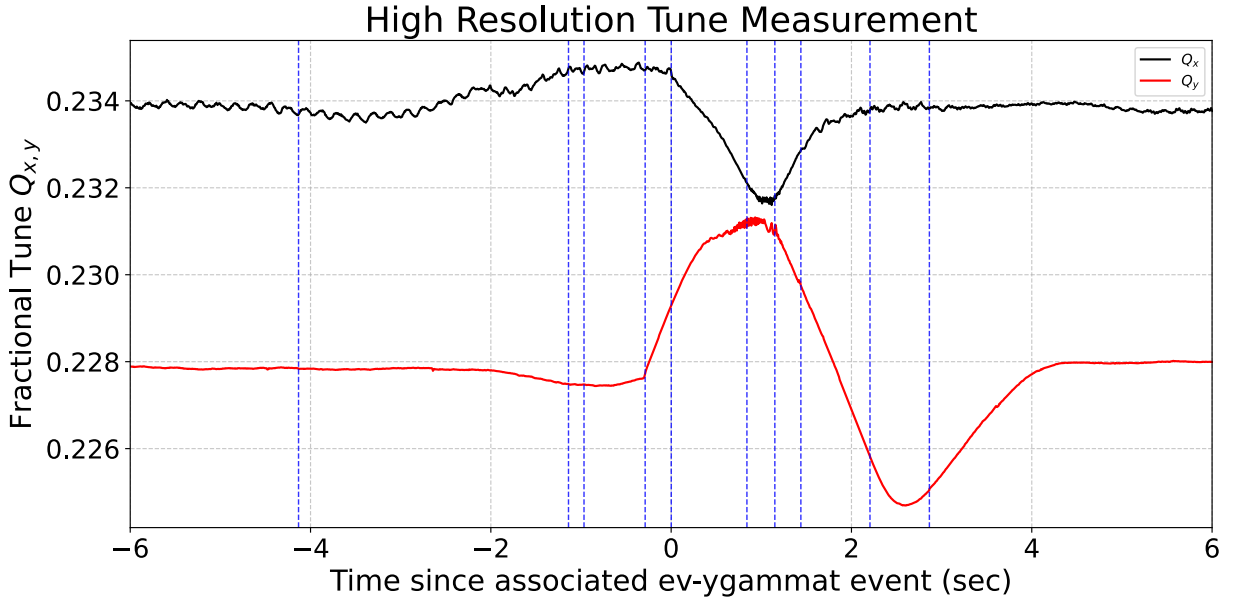


Figure 8: High resolution tune measurement for 56 bunch ramped without feedback with transition occurring at 0 s. The blue vertical lines indicate top 10 tune derivative magnitudes. Table 10 shows the values of each derivative as well as the adiabaticity check.

On October 15th the second APEX session was held. It was found that to ramp the 111 bunches successfully through transition with 1.5×10^9 per bunch without substantial beam loss or emittance growth shown in Fig. 9 and Fig. 10 the tune feedback must be off. The beam loss during transition was 2% and the emittance growth was 10% horizontally. The tune measurements are shown in Fig. 11.

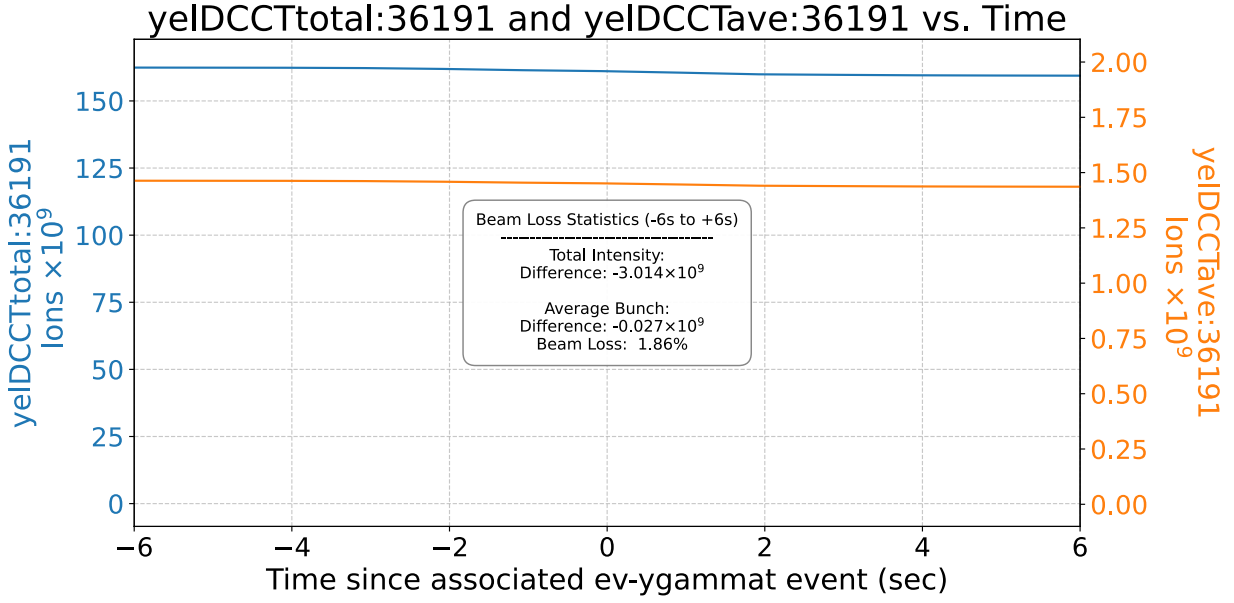


Figure 9: G24Q20 configuration for 111 bunches. The left (Y1) axis is the total intensity of the beam and the right (Y2) axis is intensity per bunch.

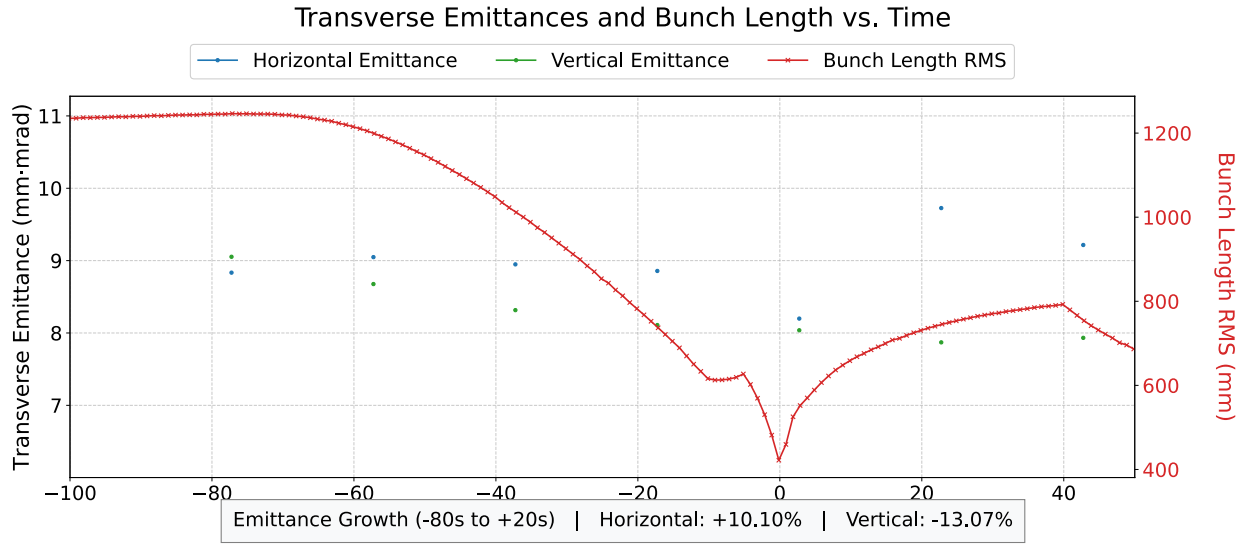


Figure 10: Transverse emittance, left (Y1) and bunch length, right (Y2).

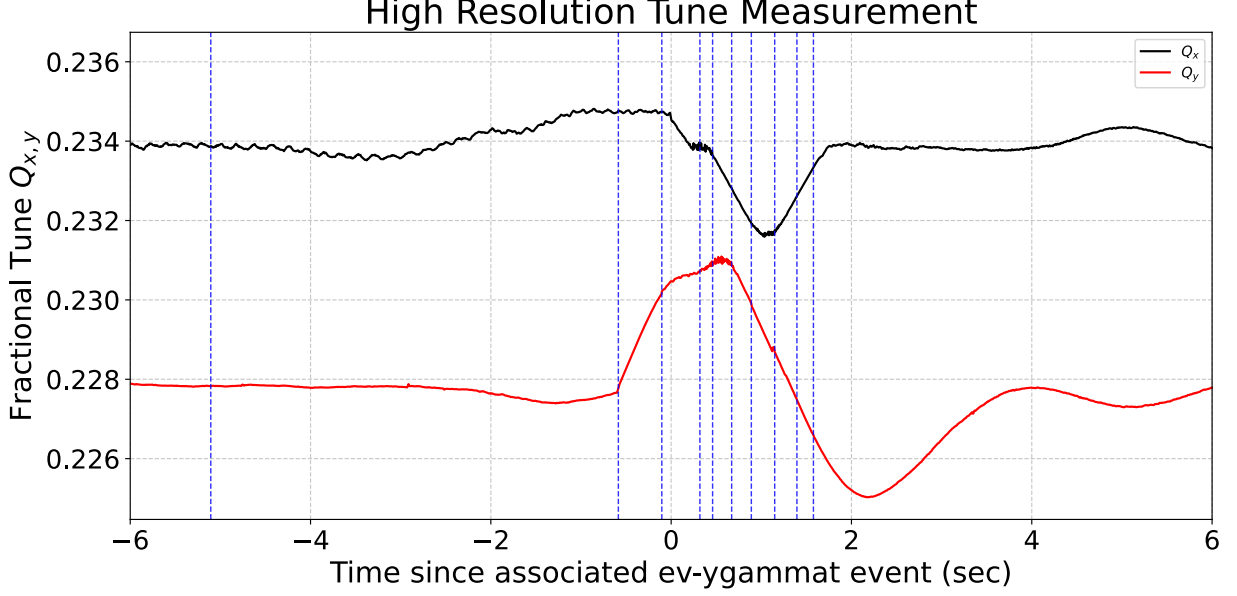


Figure 11: High resolution tune measurement for 111 bunch ramped without feedback with transition occurring at 0 s. The blue vertical lines indicate top 10 tune derivative magnitudes. Table 11 shows the values of each derivative as well as the adiabaticity check.

4.2 G24Q16

During the November 5th of 2025 session, a ramp of 111 bunches with 2.2×10^9 bunch intensity with 6% beam loss, Fig. 12 and no appreciable emittance growth, Fig. 13 was made without tune feedback. The effect of tune feedback on the ramp still remains a mystery as well as the chromaticity during the transition period. The reduction of the number of jump quadrupoles used changes the natural chromaticity of the lattice during the jump. Speculation on the tune feedback mystery starts with the tune mismatch pre- and post-jump of the operational (real accelerator) lattice. The high resolution tune measurement during transition is shown in Fig. 14. The beam loss and horizontal emittance growth for the successful ramp were 6% and -11.54%, respectively. The negative emittance growth is an artifact of the measurement accuracy of the IPM which is based on the β -function at the location of the IPM. Table 6 is a summary of the transition crossing performance for the different configurations.

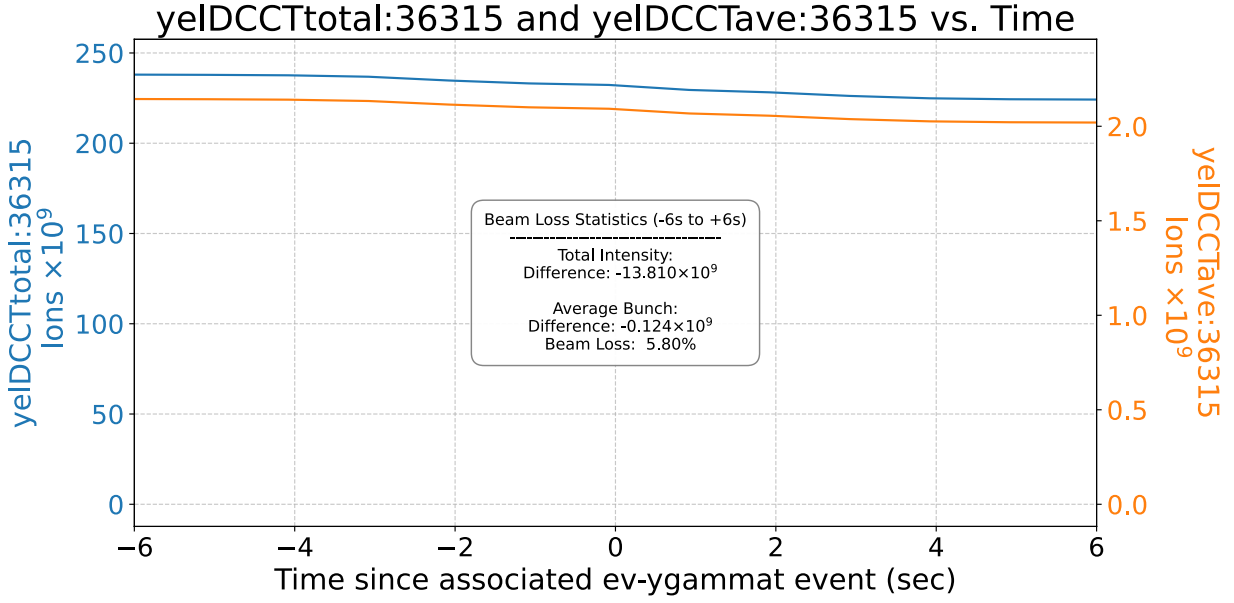


Figure 12: G24Q16 configuration for 111 bunches. The left (Y1) axis is the total intensity of the beam and the right (Y2) axis is intensity per bunch.

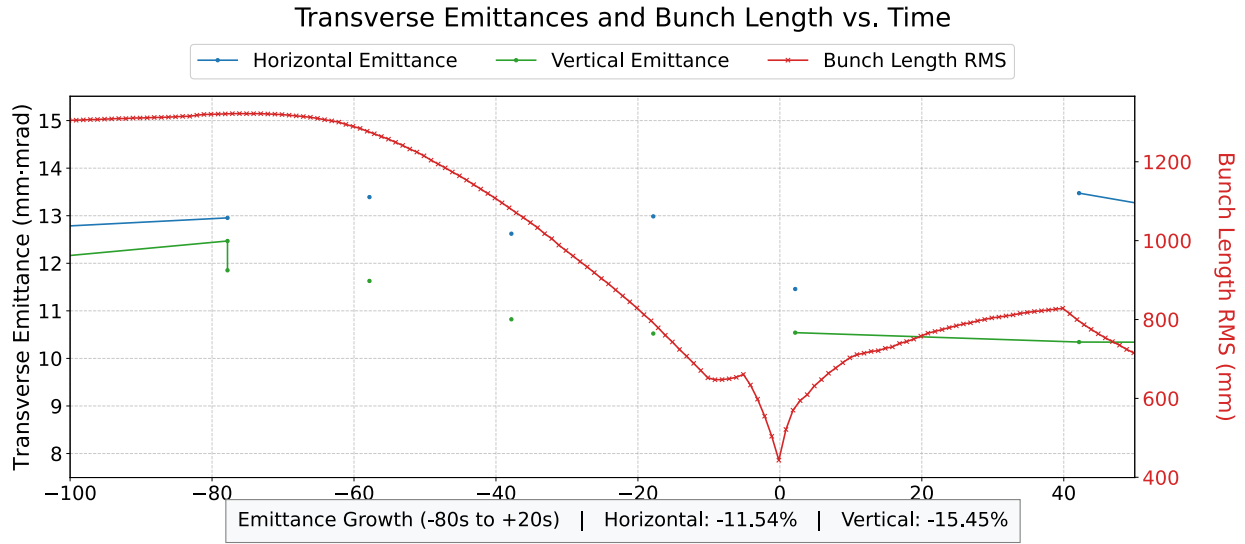


Figure 13: Transverse emittance, left (Y1) and bunch length, right (Y2).

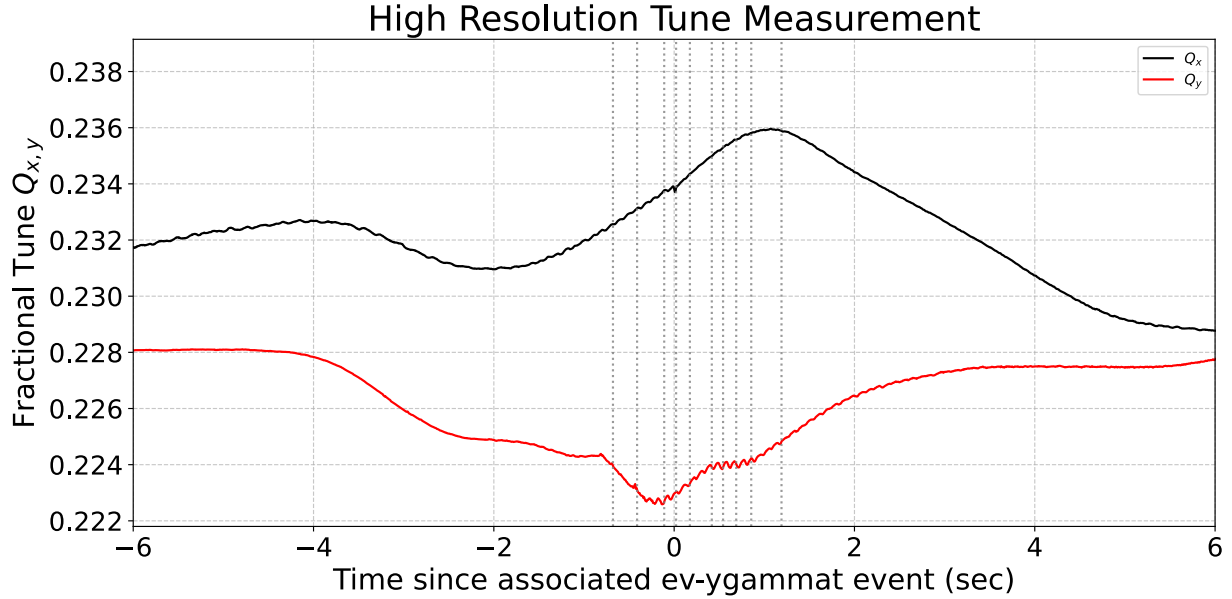


Figure 14: High resolution tune measurement for 111 bunch ramped without feedback with transition occurring at 0 s. The blue vertical lines indicate top 10 tune derivative magnitudes. Table 12 shows the values of each derivative as well as the adiabaticity check.

Table 6: Summary of Transition Crossing Performance

Configuration	Bunches	Intensity [ions/bunch]	Beam Loss	Horiz. Emittance Growth
G24Q20	56	1.42×10^9	2%	8%
G24Q20	111	1.50×10^9	2%	10%
G24Q16	111	2.20×10^9	6%	-12%

4.3 Beam Loss and Emittance Growth Mechanisms

During transition in all configuration beam loss occurs. A possible reason for the beam loss is that the beam capture during the longitudinal phase jump [16] is not as efficient for the different configurations. Transition is a lattice parameter that is subject to change based on the optics and dispersion of the lattice. As the jump quadrupoles are excited the optics deviate which during the jump causes transition to change value and the time of transition on the order of milliseconds from one configuration to the next. Another mechanism for beam loss and emittance growth is the chromaticity control through transition [17]. RHIC has no normal operational method to measure the chromaticity [17] so that the value pre- and post-transition remained unknown. The ramp efficiency of RHIC through transition after years of operation is near 98% to 99% with minimum emittance growth [18].

5 Conclusion

The APEX2310 session took place over three days with results that show that transition with a reduced number of jump quadrupoles is feasible for the operation of the EIC hadron storage ring. The inclusion of a second detector within the EIC will make the current scheme for transition crossing infeasible without additional upgrades to the jump quadrupole system. If the upgrade to the jump quadrupole system is not possible, alternative methods of crossing transition such as the use of resonance islands will need to be further explored.

During the sessions, it was observed that the tune feedback had an adverse effect on transition crossing with no clear reason as to the cause. Further investigation led by the possibility tune mismatch theory, may provide a reason to update the feedback systems to accommodate the asymmetric transition jump scheme. From the experiments, the G24Q20 configuration beam loss during transition was 2% with 7.74% horizontal emittance growth at a bunch intensity of 1.42×10^9 ions per bunch with 56 bunches. With 111 bunches the beam loss was 2% and horizontal emittance growth was 10.10% for 1.5×10^9 ions per bunch. The G24Q16 configuration beam loss and horizontal emittance growth for 111 bunches at 2.2×10^9 were 6% and -11.54%.

6 Acknowledgments

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A Sensitivity Tables

The tables below are of the Au25-100GeV-e0 which is identical to the design lattice used in the APEX sessions. There are marginal differences in actual optics of the accelerator due to magnet errors and misalignment [19] that generate coupling within the lattice. Marginal differences in the computational online model also generated slight differences in the online design optics used in the varying configurations.

Table 7: Hadron Storage Ring ($\beta^* = 5$, Au25-100GeV-e0) γ_T -Quadrupole Sensitivities and Optics Parameters (G24Q16)

Parameter	Unit	This Calc.	RHIC		HSR	Inner Ring Summary			Outer Ring Summary		
Circumference	m	3833.8452	3833.8450		3833.8880	SUM $T_{QG} = 44.2286$			SUM $T_{QG} = 43.9637$		
γ_T	—	23.4485	23.2620		22.1937	SUM $T_{GG} = 57.1807$			SUM $T_{GG} = 57.2006$		
						SUM $T_{QQ} = 35.5513$			SUM $T_{QQ} = 28.3047$		
						SUM $T_{GQ} = 2.5511$			SUM $T_{GQ} = 5.8619$		
$k(\text{inner}) = -1.2441$					$k(\text{outer}) = -1.5532$						
PS Index	Power Supply	Quadrupole	β_H [m]	β_V [m]	η_H [m]	$\phi_H/2\pi$	$\phi_V/2\pi$	S_Q (Quad)	S_G (Quad)	S_Q (PS)	S_G (PS)
Inner Arc											
3	yi3.qgt.ps	yi3.qgt11	45.32	10.69	1.688	138.68	147.02	3.61	4.79		
		yi3.qgt13	47.21	10.18	1.718	137.28	145.51	3.76	4.96		
		yi3.qgt15	44.43	10.64	1.679	135.79	144.01	3.54	4.74	14.72	19.01
		yi3.qgt17	47.95	10.22	1.639	134.37	142.50	3.82	4.52		
6	yi6.qgt.ps	yi6.qgt5	64.40	5.22	−0.189	2.15	74.64	5.13	0.06		
		yi6.qgt7	47.50	11.81	0.589	63.20	36.31	3.78	0.58	17.78	1.33
		yi7.qgt5	63.81	5.09	−0.151	324.27	29.16	5.08	0.04		
		yi7.qgt7	47.70	12.15	0.623	23.22	27.50	3.80	0.65		
7	yi7.qgt.ps	yi7.qgt11	45.05	10.63	1.667	20.43	24.55	3.58	4.67		
		yi7.qgt13	47.67	10.17	1.670	19.03	23.04	3.79	4.69		
		yi7.qgt15	44.11	10.58	1.699	17.54	21.53	3.51	4.85	14.75	19.11
		yi7.qgt17	48.48	10.20	1.707	16.12	20.03	3.86	4.90		
10	yi10.qgt.ps	yi10.qgt5	63.76	5.20	−0.138	61.29	65.87	5.07	0.03		
		yi10.qgt7	47.98	11.94	0.582	62.33	67.55	3.82	0.57	17.77	1.22
		yi11.qgt5	63.57	5.24	−0.236	83.37	90.41	5.06	0.09		
		yi11.qgt7	48.03	11.80	0.558	82.32	88.76	3.82	0.52		
11	yi11.qgt.ps	yi11.qgt11	45.28	10.37	1.742	79.53	85.82	3.60	5.10		
		yi11.qgt13	47.72	10.34	1.669	78.14	84.30	3.80	4.69	14.77	19.06
		yi11.qgt15	44.03	10.45	1.631	76.64	82.80	3.50	4.47		
		yi11.qgt17	48.53	10.39	1.690	75.23	81.28	3.86	4.80		
Outer Arc											
1	yo1.qgt.ps	yo1.qgt12	44.14	10.39	1.663	108.37	115.48	3.51	4.65		
		yo1.qgt14	48.18	10.28	1.699	106.90	113.96	3.83	4.85	14.67	19.29
		yo1.qgt16	44.85	10.38	1.722	105.48	112.45	3.57	4.99		
		yo1.qgt18	47.23	10.31	1.691	103.99	110.93	3.76	4.81		
5	yo5.qgt.ps	yo5.qgt12	44.55	10.30	1.701	167.56	176.66	3.54	4.86		
		yo5.qgt14	47.46	10.53	1.636	166.09	175.16	3.78	4.50	14.64	18.79
		yo5.qgt16	45.05	10.26	1.640	164.66	173.64	3.58	4.52		
		yo5.qgt18	46.96	10.48	1.707	163.17	172.13	3.74	4.90		
8	yo8.qgt.ps	yo8.qgt6	46.28	15.61	0.005	32.06	36.55	3.68	0.00		
		yo8.qgt8	42.63	12.01	0.896	33.39	37.82	3.39	1.35	14.15	2.72
		yo9.qgt6	46.15	15.56	0.060	53.50	58.50	3.67	0.01		
		yo9.qgt8	42.78	11.84	0.902	52.17	57.19	3.40	1.37		
9	yo9.qgt.ps	yo9.qgt12	44.61	10.09	1.733	49.28	54.22	3.55	5.05		
		yo9.qgt14	47.45	10.65	1.706	47.80	52.71	3.78	4.90	14.65	19.12
		yo9.qgt16	45.58	10.03	1.647	46.39	51.19	3.63	4.56		
		yo9.qgt18	46.40	10.68	1.657	44.89	49.67	3.69	4.62		
12	yo12.qgt.ps	yo12.qgt6	46.39	15.22	0.030	91.16	97.80	3.69	0.00		
		yo12.qgt8	42.74	12.12	0.970	92.48	99.10	3.40	1.58	14.15	3.14
		yo1.qgt6	46.07	15.37	0.085	112.60	119.75	3.67	0.01		
		yo1.qgt8	42.64	12.08	0.959	111.27	118.45	3.39	1.55		

Table 8: Hadron Storage Ring ($\beta^* = 5$, Au25-100GeV-e0) γ_T -Quadrupole Sensitivities and Optics Parameters (G24Q20)

Parameter	Unit	This Calc.	RHIC		HSR	Inner Ring Summary				Outer Ring Summary		
Circumference	m	3833.8452	3833.8450		3833.8880	SUM $T_{QG} = 44.2286$				SUM $T_{QG} = 43.9637$		
γ_T	—	23.4485	23.2620		22.1937	SUM $T_{GG} = 57.1807$				SUM $T_{GG} = 57.2006$		
						SUM $T_{QQ} = 35.5513$				SUM $T_{QQ} = 42.4599$		
						SUM $T_{GQ} = 2.5511$				SUM $T_{GQ} = 8.6742$		
$k(\text{inner}) = -1.2441$					$k(\text{outer}) = -1.0354$							
PS Index	Power Supply	Quadrupole	β_H [m]	β_V [m]	η_H [m]	$\phi_H/2\pi$	$\phi_V/2\pi$	S_Q (Quad)	S_G (Quad)	S_Q (PS)	S_G (PS)	
Inner Arc												
3	yi3.qgt.ps	yi3.qgt11	45.32	10.69	1.688	138.68	147.02	3.61	4.79			
		yi3.qgt13	47.21	10.18	1.718	137.28	145.51	3.76	4.96			
		yi3.qgt15	44.43	10.64	1.679	135.79	144.01	3.54	4.74	14.72	19.01	
		yi3.qgt17	47.95	10.22	1.639	134.37	142.50	3.82	4.52			
6	yi6.qgt.ps	yi6.qgt5	64.40	5.22	−0.189	2.15	74.64	5.13	0.06			
		yi6.qgt7	47.50	11.81	0.589	63.20	36.31	3.78	0.58			
		yi7.qgt5	63.81	5.09	−0.151	324.27	29.16	5.08	0.04	17.78	1.33	
		yi7.qgt7	47.70	12.15	0.623	23.22	27.50	3.80	0.65			
7	yi7.qgt.ps	yi7.qgt11	45.05	10.63	1.667	20.43	24.55	3.58	4.67			
		yi7.qgt13	47.67	10.17	1.670	19.03	23.04	3.79	4.69			
		yi7.qgt15	44.11	10.58	1.699	17.54	21.53	3.51	4.85	14.75	19.11	
		yi7.qgt17	48.48	10.20	1.707	16.12	20.03	3.86	4.90			
10	yi10.qgt.ps	yi10.qgt5	63.76	5.20	−0.138	61.29	65.87	5.07	0.03			
		yi10.qgt7	47.98	11.94	0.582	62.33	67.55	3.82	0.57			
		yi11.qgt5	63.57	5.24	−0.236	83.37	90.41	5.06	0.09	17.77	1.22	
		yi11.qgt7	48.03	11.80	0.558	82.32	88.76	3.82	0.52			
11	yi11.qgt.ps	yi11.qgt11	45.28	10.37	1.742	79.53	85.82	3.60	5.10			
		yi11.qgt13	47.72	10.34	1.669	78.14	84.30	3.80	4.69			
		yi11.qgt15	44.03	10.45	1.631	76.64	82.80	3.50	4.47	14.77	19.06	
		yi11.qgt17	48.53	10.39	1.690	75.23	81.28	3.86	4.80			
Outer Arc												
1	yo1.qgt.ps	yo1.qgt12	44.14	10.39	1.663	108.37	115.48	3.51	4.65			
		yo1.qgt14	48.18	10.28	1.699	106.90	113.96	3.83	4.85			
		yo1.qgt16	44.85	10.38	1.722	105.48	112.45	3.57	4.99	14.67	19.29	
		yo1.qgt18	47.23	10.31	1.691	103.99	110.93	3.76	4.81			
4	yo4.qgt.ps	yo4.qgt6	46.29	15.38	0.074	150.32	159.01	3.68	0.01			
		yo4.qgt8	42.80	12.15	0.893	151.64	160.29	3.41	1.34			
		yo5.qgt6	45.65	15.34	0.024	171.79	180.93	3.63	0.00	14.16	2.81	
		yo5.qgt8	43.13	12.02	0.932	170.46	179.63	3.43	1.46			
5	yo5.qgt.ps	yo5.qgt12	44.55	10.30	1.701	167.56	176.66	3.54	4.86			
		yo5.qgt14	47.46	10.53	1.636	166.09	175.16	3.78	4.50			
		yo5.qgt16	45.05	10.26	1.640	164.66	173.64	3.58	4.52	14.64	18.79	
		yo5.qgt18	46.96	10.48	1.707	163.17	172.13	3.74	4.90			
8	yo8.qgt.ps	yo8.qgt6	46.28	15.61	0.005	32.06	36.55	3.68	0.00			
		yo8.qgt8	42.63	12.01	0.896	33.39	37.82	3.39	1.35			
		yo9.qgt6	46.15	15.56	0.060	53.50	58.50	3.67	0.01	14.15	2.72	
		yo9.qgt8	42.78	11.84	0.902	52.17	57.19	3.40	1.37			
9	yo9.qgt.ps	yo9.qgt12	44.61	10.09	1.733	49.28	54.22	3.55	5.05			
		yo9.qgt14	47.45	10.65	1.706	47.80	52.71	3.78	4.90			
		yo9.qgt16	45.58	10.03	1.647	46.39	51.19	3.63	4.56	14.65	19.12	
		yo9.qgt18	46.40	10.68	1.657	44.89	49.67	3.69	4.62			
12	yo12.qgt.ps	yo12.qgt6	46.39	15.22	0.030	91.16	97.80	3.69	0.00			
		yo12.qgt8	42.74	12.12	0.970	92.48	99.10	3.40	1.58			
		yo1.qgt6	46.07	15.37	0.085	112.60	119.75	3.67	0.01	14.15	3.14	
		yo1.qgt8	42.64	12.08	0.959	111.27	118.45	3.39	1.55			

Table 9: Hadron Storage Ring ($\beta^* = 5$, Au25-100GeV-e0) γ_T -Quadrupole Sensitivities and Optics Parameters (G24Q24)

Parameter	Unit	This Calc.	RHIC		HSR	Inner Ring Summary			Outer Ring Summary			
Circumference	m	3833.8452	3833.8450	3833.8880		SUM $T_{QG} = 44.2286$			SUM $T_{QG} = 43.9637$			
γ_T	—	23.4485	23.2620	22.1937		SUM $T_{GG} = 57.1807$			SUM $T_{GG} = 57.2006$			
						SUM $T_{QQ} = 53.2844$			SUM $T_{QQ} = 42.4599$			
						SUM $T_{GQ} = 3.6725$			SUM $T_{GQ} = 8.6742$			
$k(\text{inner}) = -0.8300$					$k(\text{outer}) = -1.0354$							
PS Index	Power Supply	Quadrupole	β_H [m]	β_V [m]	η_H [m]	$\phi_H/2\pi$	$\phi_V/2\pi$	S_Q (Quad)	S_G (Quad)	S_Q (PS)	S_G (PS)	
Inner Arc												
2	yi2.qgt.ps	yi2.qgt5	63.88	5.18	−0.201	120.38	127.13	5.08	0.07	17.73	1.12	
		yi2.qgt7	47.25	11.95	0.528	121.44	128.79	3.76	0.47			
		yi3.qgt5	63.39	5.11	−0.123	142.52	151.61	5.04	0.03			
		yi3.qgt7	48.32	12.07	0.577	141.48	149.96	3.85	0.56			
3	yi3.qgt.ps	yi3.qgt11	45.32	10.69	1.688	138.68	147.02	3.61	4.79	14.72	19.01	
		yi3.qgt13	47.21	10.18	1.718	137.28	145.51	3.76	4.96			
		yi3.qgt15	44.43	10.64	1.679	135.79	144.01	3.54	4.74			
		yi3.qgt17	47.95	10.22	1.639	134.37	142.50	3.82	4.52			
6	yi6.qgt.ps	yi6.qgt5	64.40	5.22	−0.189	2.15	74.64	5.13	0.06	17.78	1.33	
		yi6.qgt7	47.50	11.81	0.589	63.20	36.31	3.78	0.58			
		yi7.qgt5	63.81	5.09	−0.151	324.27	29.16	5.08	0.04			
		yi7.qgt7	47.70	12.15	0.623	23.22	27.50	3.80	0.65			
7	yi7.qgt.ps	yi7.qgt11	45.05	10.63	1.667	20.43	24.55	3.58	4.67	14.75	19.11	
		yi7.qgt13	47.67	10.17	1.670	19.03	23.04	3.79	4.69			
		yi7.qgt15	44.11	10.58	1.699	17.54	21.53	3.51	4.85			
		yi7.qgt17	48.48	10.20	1.707	16.12	20.03	3.86	4.90			
10	yi10.qgt.ps	yi10.qgt5	63.76	5.20	−0.138	61.29	65.87	5.07	0.03	17.77	1.22	
		yi10.qgt7	47.98	11.94	0.582	62.33	67.55	3.82	0.57			
		yi11.qgt5	63.57	5.24	−0.236	83.37	90.41	5.06	0.09			
		yi11.qgt7	48.03	11.80	0.558	82.32	88.76	3.82	0.52			
11	yi11.qgt.ps	yi11.qgt11	45.28	10.37	1.742	79.53	85.82	3.60	5.10	14.77	19.06	
		yi11.qgt13	47.72	10.34	1.669	78.14	84.30	3.80	4.69			
		yi11.qgt15	44.03	10.45	1.631	76.64	82.80	3.50	4.47			
		yi11.qgt17	48.53	10.39	1.690	75.23	81.28	3.86	4.80			
Outer Arc												
1	yo1.qgt.ps	yo1.qgt12	44.14	10.39	1.663	108.37	115.48	3.51	4.65	14.67	19.29	
		yo1.qgt14	48.18	10.28	1.699	106.90	113.96	3.83	4.85			
		yo1.qgt16	44.85	10.38	1.722	105.48	112.45	3.57	4.99			
		yo1.qgt18	47.23	10.31	1.691	103.99	110.93	3.76	4.81			
4	yo4.qgt.ps	yo4.qgt6	46.29	15.38	0.074	150.32	159.01	3.68	0.01	14.16	2.81	
		yo4.qgt8	42.80	12.15	0.893	151.64	160.29	3.41	1.34			
		yo5.qgt6	45.65	15.34	0.024	171.79	180.93	3.63	0.00			
		yo5.qgt8	43.13	12.02	0.932	170.46	179.63	3.43	1.46			
5	yo5.qgt.ps	yo5.qgt12	44.55	10.30	1.701	167.56	176.66	3.54	4.86	14.64	18.79	
		yo5.qgt14	47.46	10.53	1.636	166.09	175.16	3.78	4.50			
		yo5.qgt16	45.05	10.26	1.640	164.66	173.64	3.58	4.52			
		yo5.qgt18	46.96	10.48	1.707	163.17	172.13	3.74	4.90			
8	yo8.qgt.ps	yo8.qgt6	46.28	15.61	0.005	32.06	36.55	3.68	0.00	14.15	2.72	
		yo8.qgt8	42.63	12.01	0.896	33.39	37.82	3.39	1.35			
		yo9.qgt6	46.15	15.56	0.060	53.50	58.50	3.67	0.01			
		yo9.qgt8	42.78	11.84	0.902	52.17	57.19	3.40	1.37			
9	yo9.qgt.ps	yo9.qgt12	44.61	10.09	1.733	49.28	54.22	3.55	5.05	14.65	19.12	
		yo9.qgt14	47.45	10.65	1.706	47.80	52.71	3.78	4.90			
		yo9.qgt16	45.58	10.03	1.647	46.39	51.19	3.63	4.56			
		yo9.qgt18	46.40	10.68	1.657	44.89	49.67	3.69	4.62			
12	yo12.qgt.ps	yo12.qgt6	46.39	15.22	0.030	91.16	97.80	3.69	0.00	14.15	3.14	
		yo12.qgt8	42.74	12.12	0.970	92.48	99.10	3.40	1.58			
		yo1.qgt6	46.07	15.37	0.085	112.60	119.75	3.67	0.01			
		yo1.qgt8	42.64	12.08	0.959	111.27	118.45	3.39	1.55			

B Adiabaticity Tables

The adiabaticity of the transition crossing is determined using Eq. 12. In the evaluation of adiabaticity below, the threshold for resonance crossing is defined by the square of the resonance width [20]:

$$C_{width} = (\Delta Q)^2 \quad (14)$$

The width of the half-integer resonance is given by [21]

$$\Delta Q = \frac{1}{2\pi} \left| \sum_j \beta_j (\Delta k_1 L)_j e^{-i p \phi_j} \right| \quad (15)$$

where p is the integer harmonic closest to $2Q$, $\Delta k_1 L$ is the quadrupole perturbation, and the summation is over the active jump quadrupoles. A resonance crossing is considered non-adiabatic (fast enough to prevent beam degradation) if the tune change per turn exceeds this threshold:

$$C_{width} \ll \left| \frac{dQ_{x,y}}{dn} \right| \quad (16)$$

The resonance widths for the

Time (s)	$dQ_x/dt \times 10^{-3} [\text{s}^{-1}]$	$dQ_y/dt \times 10^{-3} [\text{s}^{-1}]$	$dQ_x/dn \times 10^{-7}$	$dQ_y/dn \times 10^{-7}$	Non-Adiabatic
-4.1330	8.22	-2.93	1.05	-0.38	No
-1.1387	7.52	-1.33	0.96	-0.17	No
-0.9666	8.24	-0.54	1.06	-0.01	No
-0.2883	1.52	8.33	0.194	1.07	No
0.0012	-11.6	4.95	-1.49	0.63	No
0.8404	-2.85	15.4	-0.37	1.97	No
1.1501	-0.90	16.1	-0.12	2.07	No
1.4388	3.72	-8.66	0.48	-1.11	No
2.2054	7.89	-5.43	1.01	-0.70	No
2.8642	14.00	17.2	1.79	2.20	No

Table 10: Top 10 tune derivative magnitudes and adiabaticity check for G24Q20 configuration with 56 bunches ($f_{rev} = 78123.6$ Hz).

Time (s)	$dQ_x/dt \times 10^{-3} [\text{s}^{-1}]$	$dQ_y/dt \times 10^{-3} [\text{s}^{-1}]$	$dQ_x/dn \times 10^{-7}$	$dQ_y/dn \times 10^{-7}$	Non-Adiabatic
-5.1065	7.75	3.05	0.99	0.39	No
-0.5857	1.88	8.61e	0.24	1.10	No
-0.1036	-0.80	15.50	-0.10	1.99	No
0.3189	-12.50	2.11	-1.60	0.27	No
0.4598	-10.30	-0.10	-1.32	-0.12	No
0.6710	-3.87	-8.55	-0.50	-1.09	No
0.8893	-5.45	-10.1	-0.70	-1.29	No
1.1485	5.41	-11.3	0.70	-1.45	No
1.3950	4.00	-6.19	0.51	-0.792	No
1.5781	3.82	-6.32	0.49	-0.81	No

Table 11: Top 10 tune derivative magnitudes and adiabaticity check for G24Q20 configuration with 111 bunches ($f_{rev} = 78123.6$ Hz).

A further study of the half-integer and higher-order resonance widths is needed to fully grasp if the tune oscillations during transition are non-adiabatic. The true mechanism that generates the beam loss is still unknown.

Time (s)	$dQ_x/dt \times 10^{-3} [\text{s}^{-1}]$	$dQ_y/dt \times 10^{-3} [\text{s}^{-1}]$	$dQ_x/dn \times 10^{-7}$	$dQ_y/dn \times 10^{-7}$	Non-Adiabatic
-0.6787	-0.13	-7.95	-0.01	-1.02	No
-0.4111	2.94	-9.55	0.376	-1.22	No
-0.1103	2.49	9.90	0.32	1.27	No
0.0217	13.90	1.90	1.78	0.24	No
0.1745	2.32	8.07	0.30	1.03	No
0.4175	2.85	-6.87	0.37	-0.880	No
0.5425	3.44	9.99	0.44	1.28	No
0.6883	0.59	-8.10	0.07	-1.04	No
0.8550	97.40	231.00	12.5	29.60	No
1.1907	-1.47	6.96	-0.19	0.89	No

Table 12: Top 10 tune derivative magnitudes and adiabaticity check for G24Q16 configuration with 111 bunches ($f_{rev} = 78123.6$ Hz).

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