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TRANSITION JUMP SYSTEM OF THE HADRON STORAGE RING OF THE ELECTRON ION COLLIDER*

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Abstract

Matched first order transition crossing in the Relativistic Heavy Ion Collider (RHIC) is performed by using two families of jump quadrupoles when ramping species through transition to storage energy. The jump quadrupole families control γ transition and the working point of the accelerator by compensating for the tune shift from the jump and minimizing optical distortions. After transition, amplitude and phase of the RF cavities need to be rematched to maintain constant acceleration. This configuration has proven to be effective in maintaining beam quality and reducing beam loss. The Hadron Storage Ring (HSR) retains the arcs and most of the insertion regions of RHIC. This paper discusses the gamma transition crossing of the HSR by the implementation of a matched first order transition jump.

INTRODUCTION

The Hadron Storage Ring (HSR) of the electron ion collider (EIC) [1, 2] will provide stored beam energies ranging from 41 GeV to 275 GeV protons without crossing transition energy. For heavy ions, the maximum energy for $^3He^{+2}$ and for Au^{+79} are 183 GeV and 110 GeV, respectively. These species require that transition is crossed. Transition occurs when less energetic particles and particles with energies higher than the synchronous particle have the same revolution period. When the slippage,

$$\eta_s = \alpha_0 - 1/\gamma^2 < 0$$

, where α_0 is the momentum compaction and γ is the Lorentz boost, the beam is said to be below transition [3]. The momentum compaction is defined as defined as

$$\alpha_0 = \oint ds(\eta_x/\rho_(x))$$

, where $\eta_{(x)}$ is the dispersion, ρ is the bending radius, and C is the lattice circumference. If $\eta_s > 0$ the beam is above transition. As the beam approaches transition the synchrotron tune slows and momentum spread increases. The adiabaticity condition,

$$\frac{1}{\omega_s^2}\left|\frac{d\omega_s}{dt}\right| \ll 1$$

, where ω_s is the angular frequency and t is time, ceases to be satisfied [4]. The nonadiabatic time, T_c, where the bunch length becomes shorter and can lead to the beam becoming unstable is

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

, 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 $\gamma' = d\gamma/dt$.

The nonlinear time, T_{NL} [5], describes the time duration that particles within a bunch of a given momentum spread start to experience transition crossing. First formulated by Johnsen [6], it is

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

where β_T is the velocity ratio of the beam centroid, δ_{max} is the maximum momentum spread of the bunch, and α_1 is the "nonlinear parameter". The α_1 is defined by [7]

$$\delta L/L_0 = \alpha_0\delta(1 + \alpha_1\delta + ...)$$

.

TRANSITION OPTICS

A transition lattice optics, trans-5m-03-15-23, has been designed to study the transition crossing of the HSR. Figure 1 shows the Twiss parameters and dispersion function, η of the lattice. The horizontal β^* of the 2 colliding interaction regions (IR) is 5 m and the vertical is 0.43 m. The β^* of these two IR was scaled from the 0.8 m and 0.72 m while maintaining the β_h^*/β_v^* ratio. The β^* of the 3 RHIC like straights sections is 5 m for both planes. The cooling section does not have a definitive β^*. The lattice working point at transition is 28.228, horizontal and 27.210 vertical.

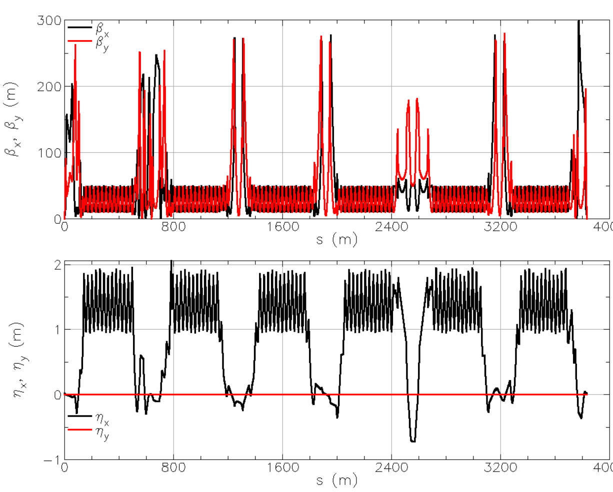

Figure 1: Transition β (top)- and η (bottom)-functions.

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Lattice Transition Parameters

The nonadiabatic and nonlinear times for this lattice are shown in Tab. 1. The RF voltage and stable phase angle parameters are taken from the RHIC Au21-100GeV-e0 Au^{+79} energy ramp. The T_{NL} is dominant, $T_c << T_{NL}$, due to the energy ramp rate.

Table 1: Nonadiabatic and nonlinear parameters of the HSR lattice trans-5m-03-15-23

Parameter	Value
Atomic Weight, A	196.97
Atomic Number, Z	79
Transition Energy, E_T [GeV]	20.734
RF Voltage, [kV]	200
Stable Phase, ϕ_s [rad]	0.065
Gamma Transition, γ_t	22.3
Harmonic Number, h	315
γ' [s^{-1}]	0.278
Circumference, C [m]	3833.888
Nonadiabatic Time, T_c [ms]	75
Velocity Ratio, β_T	0.9986
Maximum Momentum Spread, δ_{max}	0.00432
Nonlinear factor, α_1	-3.52×10^{-3}
Nonlinear Time, T_{NL} [ms]	516

γ TRANSITION JUMP

Manipulating transverse properties of the lattice generates a time dependent transition energy. The time dependent transition reduces the duration of time the beam experiences transition minimizing the space charge forces due to bunch length contraction. The Relativistic Heavy Ion Collider (RHIC) [8] uses a first order transition jump scheme [9, 10]. Which uses pairs of doublets in the straight section (Q family) and the arcs (G family) to control the β and η waves generated from the excitation of the jump quadrupoles Fig. 2.

The current layout of the HSR has 38 jump quadrupoles, 10 less than RHIC. While the arcs are preserved, the straight sections are modified to accommodate new experimental detectors, beam cooling systems, injection, and switchyards [11]. These changes to the layout break the symmetry of the first order jump scheme thus new schemes are explored for transition jump crossing.

First Order Scheme with Reduced Number of Jump Quadrupoles

In [12], we discuss sensitivities associated with the jump quadrupole families of the September release of the HSR 220921a that has the same layout as discussed in this paper. With the new transition optics, new sensitivities were calculated and summed to produce a T matrix

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

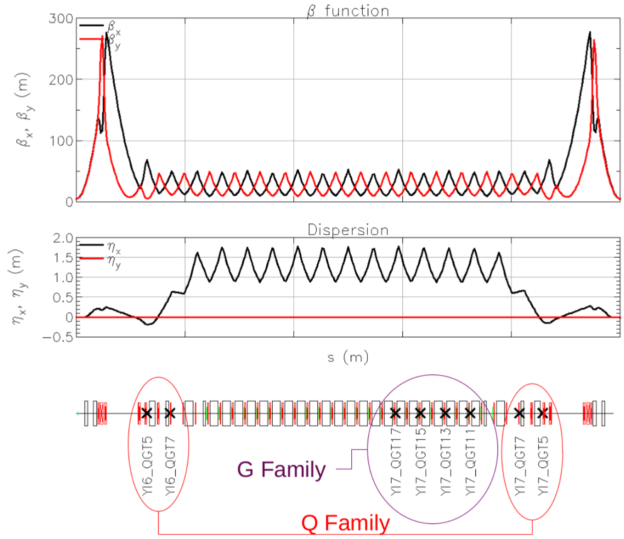

Figure 2: The first order scheme of RHIC. Top: β, middle: η, and bottom: layout. The two families in each sextant, G and Q, are used to control the γ_T and compensate for tune change, respectively.

A two-knob scheme is then derived from inverse of this T matrix. The ratio of the $(-T_{QG}/(T_{QQ}) = k$, where k is the proportionality constant that relates the strength, q_Q, of the Q family to the strength, q_G, of the G family,

$$q_G = kq_Q$$

. The two-knob scheme for the HSR transition lattice is further optimized to compensate for the larger β-functions at the jump quadrupoles, where the β-functions exceed the mode by more that 10 m. Those jump quadrupoles strengths are reduced by a factor of $\beta_{mode}/\beta_{quad}$, where β_{mode} is the most frequent β-function and β_{quad} is the β-function at the quadrupole. The k value for the transition lattice becomes -1.6639.

A "stay clear" area is needed to safely cross transition if T_{NL} is dominant defined through

$$\Delta\gamma_T \approx 4\dot{\gamma}T_{NL}$$

. The value of this area for the transition lattice is approximately ±0.57.

The β and η waves generated by the jump quadrupole excitation are

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

and

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

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where the phase, ϕ, is taken at the jump quadrupole and the difference of 90° between jump quadrupoles is the optimum. The phase advances between the jump quadrupoles of the HSR are 79° horizontal and 82° vertical. Figures 3 and 4 show the β and η waves generated by exciting the jump quadrupoles to an integrated normalized strength of ± 0.004 T/m. This strength corresponds to a $\Delta\gamma_T$ of 0.8 units which is less than the 1.14 units that determined by the T_{NL}. From the wave analysis, the peak β wave is twice the β wave generated by RHIC during transition. The η wave is 10 times greater. This increase can be attributed to the reduced number of jump quadrupoles and the phase advance between the jump quadrupole being 20° less that the optimal 90°.

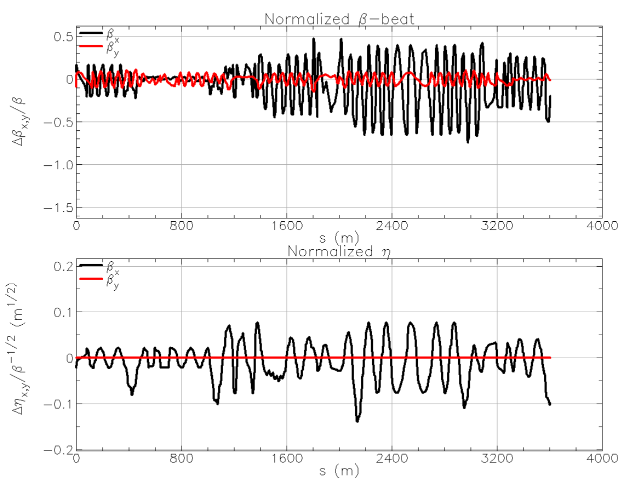

Figure 3: Wave analysis of the transition lattice at $\Delta\gamma_T = -0.45$. Top: β, bottom: η.

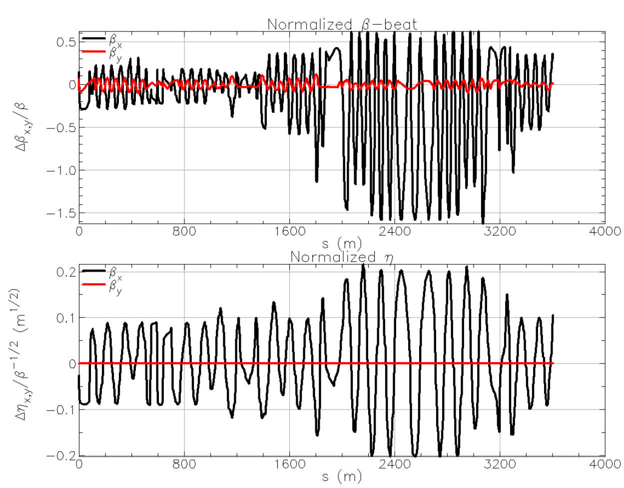

Figure 4: Wave analysis of the transition lattice at $\Delta\gamma_T = +0.34$. Top: β, bottom: η.

The tune evolution through the jump quadrupole excitation is shown in Fig. 5. The horizontal spread maximum is 0.05 units and the vertical maximum spread is less than 0.01.

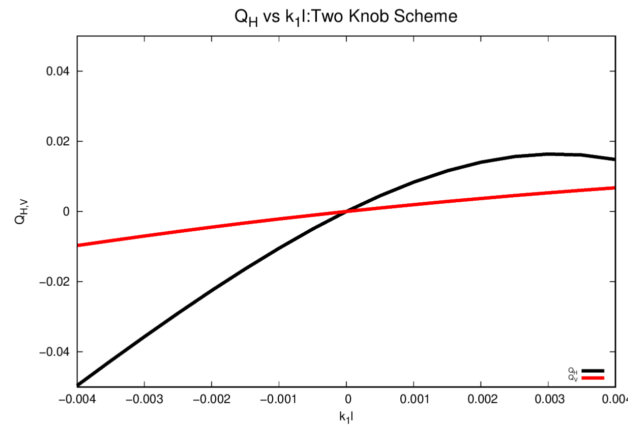

Figure 5: Tune evolution through the excitation of the jump quadrupoles. $Q_{H,V}$ is the difference in the working point of the lattice and the tune with jump quadrupole excitation

CONCLUSION

A transition jump scheme for the HSR is presented. The first order jump scheme that is currently used for RHIC may work in the HSR with 38 jump quadrupoles which is 10 less than RHIC. The consequences removing 10 jump quadrupoles, and having a phase advance 20° less than the optimal 90° reduces the range of the $\Delta\gamma_T$ available to cross transition comfortably, according to T_{NL}, and causes large β and η waves to generate that are not locally compensated. The tune evolution is well within reason.

FUTURE WORK

Further exploration into increasing the phase advance between jump quadrupoles, exploring higher vertical integer tunes, and increasing the number of jump quadrupoles in the HSR is underway. Alternative transition jump schemes using the resonance island jump scheme (RIJ) [13] are also being investigated.

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