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AN UPDATE ON THE TRANSITION CROSSING SCHEMES FOR THE EIC HADRON STORAGE RING*

H. Lovelace III†, J.S. Berg, K. Drees, G. Robert-Demolaize, S. Peggs, V. Ptitsyn, S. Verdu-Andres, B. Xiao, Brookhaven National Laboratory, Upton, NY, USA
R. Seviour, University of Huddersfield, Huddersfield, UK

Abstract

The Electron Ion Collider (EIC) Hadron Storage RIng (HSR) requires the crossing of transition for all species except for protons. The current scheme for the Relativistic Heavy Ion Collider (RHIC) utilizes the gamma transition quadrupoles will be adopted for the scheme of the HSR. With rebuilt straight sections, the jump quadrupoles responsible for tune compensation will need to be placed at the proper phase advance to mitigate the beta and dispersion waves generated. As an alternative method, the beam may be nonadiabatically kicked into a stable resonance island to place beam above transition. This paper discusses transition crossing using the matched first order method and resonance island jump schemes applied to the latest HSR lattice.

INTRODUCTION

The Electron Ion Collider (EIC) project [1] consists of two accelerator chains, a chain for electrons and the other for hadrons. The electron accelerator chain begins with the polarized electron gun of the 200 MeV LINAC that delivers polarized electron beam to the Rapid Cycling Synchrotron (RCS) booster that accelerates to 3 GeV extraction energy. The RCS, with extraction energy ranges from 5 GeV to 18 GeV, is the injector for the Electron Storage Ring (ESR) and contains the experimental detector, eletron Proton/Ion Collider (ePIC) [2].

The hadronic analogue to the electron accelerator chain starts with the Optically Pumped Polarized Ion Source (OPPIS) [3] of the 200 MeV polarized proton LINAC. The Electron Beam Ion Source, EBIS, supplies not only the heavier species but also the polarized deuterium and $^{+3}$He. The protons are accelerated through the 200 MeV LINear ACcelerator (LINAC) and injected into the Alternating Gradient Synchrotron (AGS) booster. The heavier ions are injected directly into the booster. From the booster the beam is accelerated to a rigidity, $B\rho$ where B is the magnetic field and ρ is the bending radius of the dipole, of 17 Tm [4]. The beam is then injected into the AGS and accelerated to a rigidity of 82 Tm then injected into the Hadron Storage Ring (HSR). The HSR preserves the arcs of yellow ring of the Relativistic Heavy Ion Collider (RHIC) [5] with modifications to the insertion regions.

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† hlovelace3@bnl.gov

TRANSITION CROSSING

All species except protons will cross transition in the HSR. The lattice parameter γ-transition, γ_T, is defined as,

$$\gamma_T = \sqrt{\frac{\delta_p}{\Delta C/C}} \tag{1}$$

where $\delta_p = \Delta p/p$ is the energy spread and C is the circumference. For the HSR, $\gamma_T = 23.08$, and the expected ramp rate $\gamma\grave{} = 0.4\,s^{-1}$. Table 1 shows the parameters of the HSR that are key to transition crossing. The nonadiabatic

Table 1: Transition Parameter Table

Parameter	Value
Species	Au^{79}
γ_T	23.08
Ramp rate, γ' (s^{-1})	0.4
Voltage, V (kV)	200
Harmonic (#)	315
Synchronous Phase, ϕ_s (rad)	0.06
Characteristic Time, T_c (ms)	69.85
Nonlinearity parameter, α_1 ($\times 10^{-4}$)	-4.21
Nonlinear Time, (ms)	371

or characteristic time, T_c,during which the beam loses its adiabaticity,

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

is

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

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 Johnsen time [6] in which the particles within a bunch with a given momentum spread experience transition is,

$$T_{NL} = \left(\alpha_1 + \frac{3}{2}\beta_T^2\right)\frac{\gamma_T}{\gamma'}\delta_{max} \tag{4}$$

where β_T is the velocity ratio of the beam centroid, $\delta_{max} = \Delta p_{max}/p$ is the maximum momentum spread of the bunch, and α_1 is the "nonlinear momentum compaction factor" defined by [7],

$$\delta L/L_0 = \alpha_0\delta(1 + \alpha_1\delta + ...) \tag{5}$$

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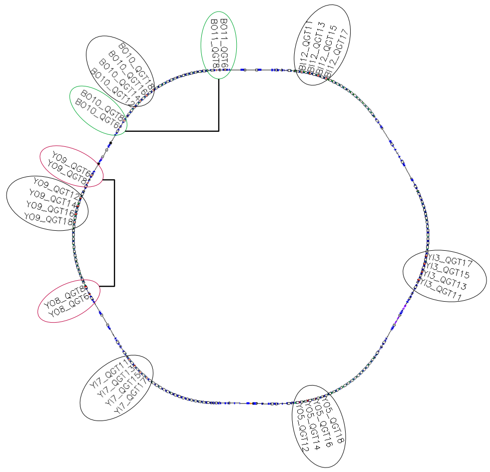

Figure 1: Jump quadrupole configuration with the Q-families in red and green. The G-families are in grouped with black circles. The circles indicate power supplies with the Q-families having a connection across the arc to the jump quadrupoles on the other side of the sextant.

where L_0 is the circumference of the lattice. If $\alpha_1/\alpha_0 = -1/2$, all particles within the bunch have the same γ_T. For all particles to cross transition at the same time, $\alpha_1/\alpha_0 = -3/2$.

FIRST ORDER MATCHED SCHEME

The First Order Matched (FOM) scheme was first design to be the method of crossing transition for the Fermi Main Injector [8]. The FOM is intuitive, have two families for the transition jump (as shown in Fig. 1). One family, G (as shown in Fig. 2), controls the change in transition of the lattice by perturbing the dispersion function. The other family, Q (as shown in Fig. 3), controls the betatron, β, and dispersion, η, waves generated by exciting the G-family. In RHIC, the families are paired in doublets. From Eqs. (6) and (7) that having a phase advance of 90^o fully cancels the wave generated by exciting the jump quadrupoles.

$$\frac{\Delta\beta_H}{\beta_H} = \frac{1}{2\sin(2\pi Q_H)} \sum_i (k_1 l)_i \beta_{Hi} \cos(2|\phi - \phi_i| - 2\pi Q_H) \tag{6}$$

and

$$\frac{\Delta\eta}{\sqrt{\beta}} = \frac{1}{2\sin(\pi Q_H)} \sum_i (k_1 l)_i \eta_i \sqrt{\beta_{Hi}} \cos(2|\phi - \phi_i| - \pi Q_H) \tag{7}$$

The FOM is design to be a local compensation scheme. For the HSR, this local scheme is expanded to compensate globally. Figure 1 shows the jump quadrupole positions where there are two Q-families preserved from the RHIC scheme. The quadrupole strengths are determined in the methods described in [9, 10]. As the number Q-families quadrupoles

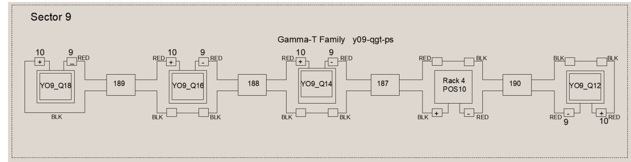

Figure 2: G-family, located in the arcs.

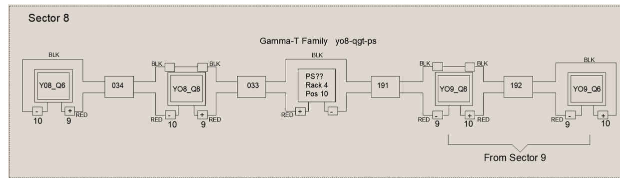

Figure 3: Q-family, the two doublets are in the low dispersion region of the insertion region.

is reduced, the strength of the remaining Q-family must increase. Figure 4 illustrates the strength needed to maintain a RHIC standard $\Delta\gamma = 1$. With 8 and 12 Q-family quadrupoles it is clear that the power supply limits will be exceeded. The maximum and minimum beam sizes during

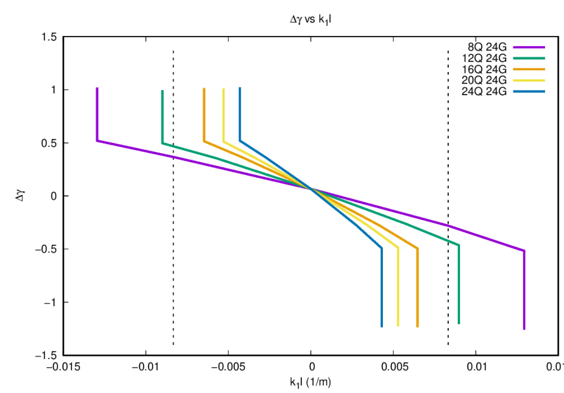

Figure 4: The amount of jump available within the constraints of the jump quadrupole power supply. The vertical dashed lines indicates the limits of the supply. The #Q#G, gives the number of Q-family quadrupoles and the number of G-family quadrupoles.

the jump are shown in Fig. 5. Both Fig. 4 and Fig. 5 are from the maximum excitation of the jump quadrupole through the polarity flip to the minimum excitation.

RESONANCE ISLAND JUMP SCHEME

The Resonance Island Jump (RIJ) scheme utilizes the nonlinear fields of the lattice to produce resonance islands that are purposely populated for transition crossing. First discussed as a novel method [11] to cross transition, and further expanded by Peggs [12], the RIJ scheme provides an alternative to using jump quadrupoles and only requires a single turn dipole kicker or injection directly into the islands.

From Peggs [12], the 3"knobs" control the resonance island width are ΔQ, the distance in tune space from the resonance, V_{44} and V_{40}, which are gauges of the octupole

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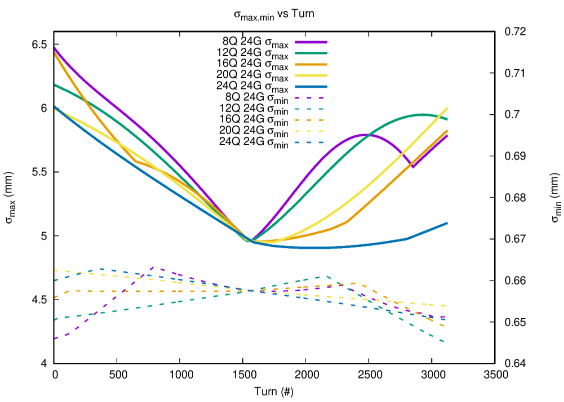

Figure 5: The beam sizes through transition which occurs at approximately 1500 turns. Transition occurs.The #Q#G, gives the number of Q-family quadrupoles and the number of G-family quadrupoles.

Table 2: Knob Parameters for Three Families

Family	V_44	V_40	ΔQ
yA	7349.66	22048.99	0.012
yB	7290.02	21870.07	0.012
yC	7318.87	21956.62	0.012

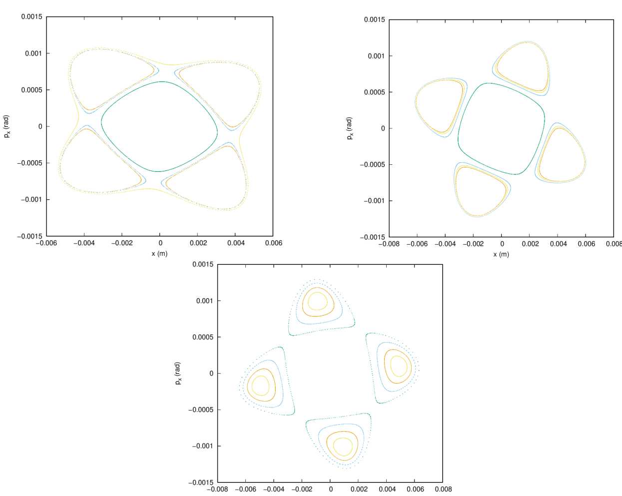

Figure 6: Phase space 120^o rotation of the resonance islands about the center of the beam axis. The particle initial amplitude is 3 mm and increasing to 4.5 mm by increments of 0.5 mm.

strength. Table 2 The island rotation is given by the sensitivity vectors defined as

$$\vec{S}_f = S_{PS}\begin{pmatrix}\sin\Psi_f\\ \cos\Psi_f\end{pmatrix} = \sum_{all\,octupoles}\frac{\beta^2}{48}\begin{pmatrix}\sin(4\theta-\pi/2)\\ \cos(4\theta-\pi/2)\end{pmatrix} \quad (8)$$

Effective power supply families can be generated from these sensitivities that are 120^o apart in phase. Figure 6 shows the rotation of the islands. The strength total integrated normalized strength of the octupoles is 110 m^{-1} in all cases. Placement of the bunch in the islands is provided by a 1 mrad

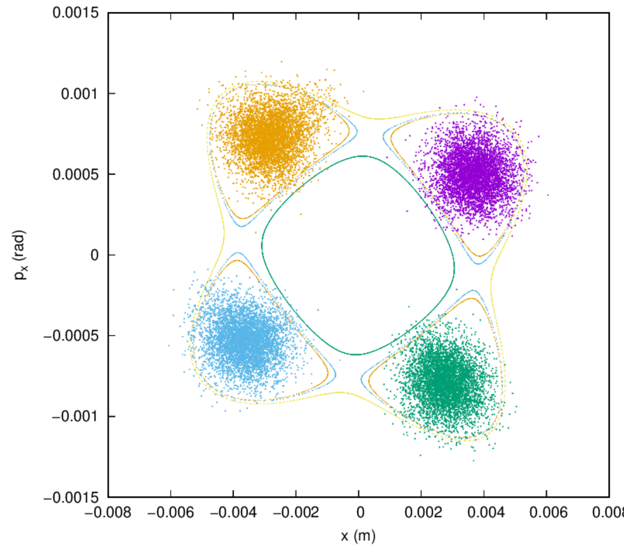

Figure 7: Resonance island generation in the RHIC ring using octupoles shown in (x, p_x) space. The purple, green, blue, and yellow bunches indicate turn numbers 1, 2, 3, and 4, respectively.

kicker at a location where the β-function is is 5 m. For the RIJ scheme to work, the beam must be kick prior to entering the nonadiabatic regime [13]. Figure 7 shows the first four turn of a bunch centroid placed at the center of the island. The round beam has an unnormalized emittance of the beam is 90 nm. The beam populates only one island with a periodicity that is equivalent to the resonance order. Inside the islands stable orbits may form and at the center of the island, the tune is at the 4^{th} order resonance. The γ_T of the beam within the island can be compared to on-axis value through,

$$\Delta\gamma_T = \sqrt{\left(\frac{C_{island} - C_{on-axis}}{C}\right)/\delta_p} \quad (9)$$

where the circumference is after 4 turns. The $\Delta\gamma_T$ at transition for RHIC is approximately 0.02524.

SUMMARY

An update to transition crossing for the HSR has been presented. The projected wiring scheme and the effects of the reduced number of Q-family tune compensation quads used for the FOM scheme was shown. The reduction of the Q-family quadrupoles will require stronger fields to compensate for the missing jump quadrupoles. If the number of Q-family quadrupoles is reduced to 8 or 12 quadrupoles, the power supply current limits of the RHIC jump quadrupole will be reached. The RIJ scheme is an attractive alternative to the FOM, however a greater $\Delta\gamma_T$ will be needed.

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