INJECTING AND RAMPING TRAPPED BEAM IN HADRON ACCELERATOR*

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Abstract

In developing an alternative method of jumping transition in the Electron Ion Collider Hadron Storage Ring, simulations have been performed to show feasibility. Many challenges occur while ramping trapped beam. The effect of snapback on the superconducting magnets, longitudinal oscillations, and evolution of the island tune will be presented.

INTRODUCTION

The Electron Ion Collider (EIC) Hadron Storage Ring (HSR) will collide 110 GeV Au^{+79} with ~10 GeV electrons to provide asymmetric collisions within the electron/Proton Ion Collider (ePIC) detector [1]. The HSR accelerates all species, except protons, through the lattice transition. The higher momentum particles traverse a longer path in the dipoles, but at transition energy, their increased velocity exactly compensates for this path length, causing the revolution period to become momentum-independent. During this time, the beam may suffer from a number of instabilities [2]. The HSR reuses the Relativistic Heavy Ion Collider (RHIC) arc magnets with modified straight sections. A new state of the art interaction region with a 25 mrad crossing angle is where the ePIC detector resides surrounded by crabbing cavities [3,4]. The method of crossing transition in RHIC is based on the First Order Matched (FOM) scheme discussed in Ref. [5] and commissioned [6] in the early years of RHIC. Ideally, with the reuse of the RHIC arcs and the minimum redesign of all but one straight section, the interaction region where the detector is located, the FOM will continue to be effective in crossing transition [7].

The current HSR contains 24 jump quadrupoles in the arcs that directly effect γ-transition, γ_T, by distorting the lattice dispersion, and 20 jump quadrupoles in the straight sections to mitigate the dispersion and betatron wave that is generated by the excitation of the jump quadrupoles. With cooling, the number of jump quadrupoles is reduced by 4 from the modifications needed in the electron cooling straight section. The FOM becomes less effective with inclusion of a second detector in the HSR due to the need for increased quadrupole strength outside the current power supply limits for sufficient change in the γ_T of the lattice. With this concern, alternative methods of crossing transition must be explored to provide stable operations through future HSR upgrades. The method of crossing transition through the usage of resonance islands was first proposed by M. Giovannozzi [8] and further explored by S. Peggs [9]. The principal premise of the Resonance Island Jump (RIJ) scheme is to inject the beam on-axis or into the island [10] where the γ_T of the island differs from the on-axis γ_T, ramp the beam to transition, and nonadiabatically kick the beam over a single turn to a lower γ_T whether the beam is displaced onto the central axis or into the island. Figure 1 is a schematic of the placement of the beam for the HSR where γ_T of the island is higher than the on-axis γ_T.

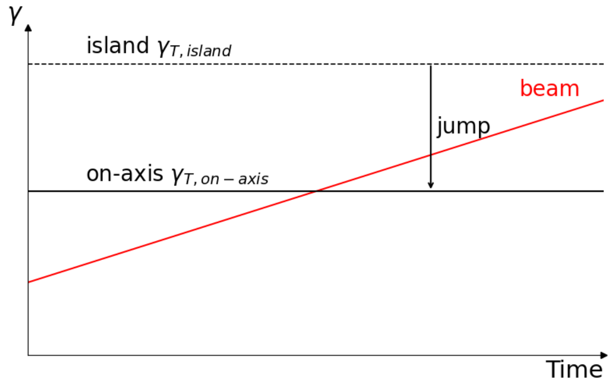

Figure 1: The γ_T of the island is higher than the on-axis γ_T for the HSR. The jump in the HSR case will be from the resonance island to the on-axis with a single turn kick.

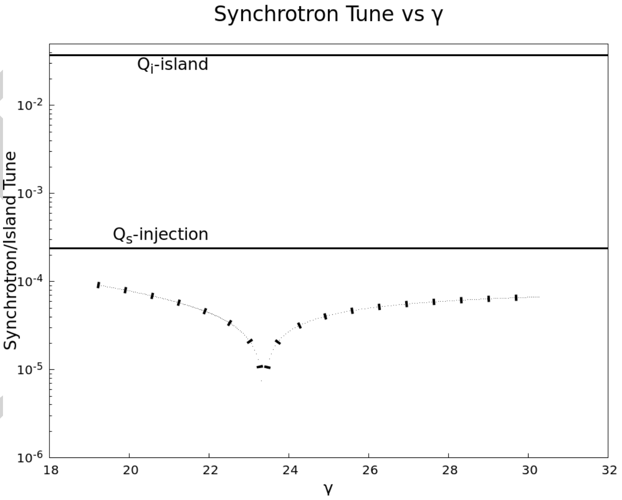

Figure 2: Shown is island tune , Q_I, synchrotron tune, Q_s, and the change in the synchrotron tune during the ramp. The injection Q_s does not cross the Q_I. The dashed marks show the decrease in the Q_s transition is crossed.

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RESONANCE ISLAND JUMP PROCEDURE

The beam may be injected directly into the islands. The injection process is relatively simple in the sense that the lattice into which the beam is transferred must have an established nonlinear optics in which the island is aligned with kicker magnet and kicked with the correct angle into the island. The size of the island must be large enough to accommodate the beam size [11] and stable through transition energy. An Accelerator Physics EXperiment (APEX) was conducted in 2024 that demonstrated that beam from RHIC can be injected into resonance islands [10]. The next step is to show that trapped beams can be ramped to higher energy.

Transverse Island Tune Shift Program

Using the Bmad accelerator toolkit [12], a program was designed to calculate the detuning coefficients,

$$\begin{aligned}\alpha_{xx} &= \frac{1}{16\pi}\sum_{octupoles} b_3\beta_x^2,\\ \alpha_{xy} &= -\frac{1}{8\pi}\sum_{octupoles} b_3\beta_x\beta_y,\\ \alpha_{yy} &= \frac{1}{16\pi}\sum_{octupoles} b_3\beta_y^2,\end{aligned}\tag{1}$$

where β is the Twiss function in the plane indicated by the subscript, b_3 is the integrated octupole strength. The program also calculates the detuning $\vec{V}_{40}$ and the resonance driving terms V_{44}.

$$\begin{aligned}V_{40} &= \frac{1}{16}\sum_{octupoles} b_3\beta_x^2\\ \vec{V}_{44} &= \sum_{octupoles}\frac{-b_3\beta_x^2}{48}\begin{pmatrix}\sin(4\phi-\pi/2)\\ \cos(4\phi-\pi/2)\end{pmatrix}\end{aligned}\tag{2}$$

, where ϕ is the phase advance at the octupole with respect to some common point say the beginning of the lattice directly from the lattice file. The action at the fixed point J_{fp} and island tune Q_I are evaluated using

$$\begin{aligned}J_{fp} &= \left(-\frac{2\pi}{V_{40}}\Delta Q\right)^{1/2},\\ Q_I &= \left|\frac{8\vec{V}_{44}}{V_{40}}\right|^{1/2}.\end{aligned}\tag{3}$$

The fixed point calculation uses the algorithm established in chapter 4.5 of [13].

TRACKING RESULTS

Ramping

In preparation for an APEX session ramping trapped Au^{+79} ions, simulations were performed on the known RHIC Au25-18GeV lattice which is a shortened ramp to 18 GeV. The ramp has all the components of a typical RHIC ramp except that it falls short of transition. Using the configurations mentioned in Ref. [10], an 08-08-00 configuration was generated with the parameters that are found in Table 1. The base horizontal tune $Q_x = 0.228$. Care was taken to verify that any tune modulation [14] from the synchrotron tune Q_s crossing the island tune during the ramp, shown in Fig. 2, was avoided.

Table 1: Ramping and Transition Jump Lattice Parameters

Parameter	Au25-18GeV	Au25-100GeV
α_{xx} [m^1]	11383	4181
V_{40} [m^1]	23249	13137
V_{44} [m^1]	2917	1351
J_{fp} [µm]	2.98	9.56
Q_I (Theory,Sim.)	0.022, 0.025	0.036, 0.037

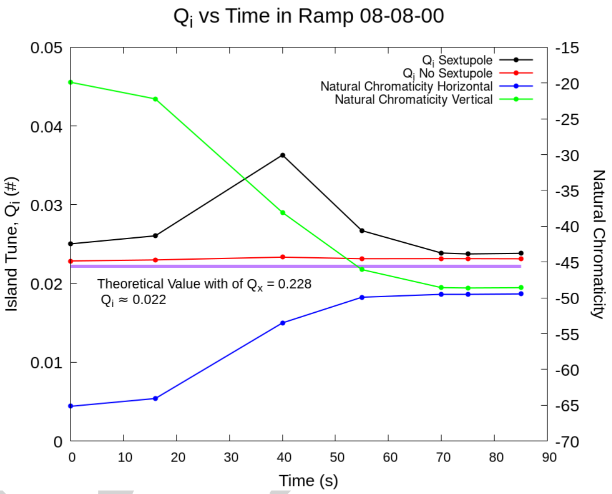

Figure 3: Shown is the Q_I and the natural chromaticity vs the time in the ramp. The purple horizontal line is the theoretical value of the Q_I.

A ramp was designed to accelerate the beam to 18 GeV and observe the effects of the natural chromaticities on the island tune, Fig. 3. Near snapback at 16 s, where the field harmonics change in the superconducting magnets, the natural chromaticity starts increasing horizontally changing the Q_I until the higher order fields decay. A tracked beam of 100 particles, shown in Fig. 4 was simulated with an accelerated ramp to reduce the simulation time. During the ramp 9 particles, out of the 100 particles ramped, were lost during ramp. The initial normalized emittance was 1.6 µm and synchrotron oscillations were not included. The ramping of the trapped beam shows feasibility due to only 10 % beam loss from a 3σ beam. With further tuning of the island size through the octupole or sextupole strengths the losses generated might be eliminated. Continued study is needed to confirm.

Transition Crossing

The lattice parameters used for ramping through transition are shown in Table 1. The horizontal fractional based tune used was 0.210. The Twiss parameters of each resonance island are shown in Table 2. The Twiss parameters are calculated using the 2-dimensional phase space coordinates

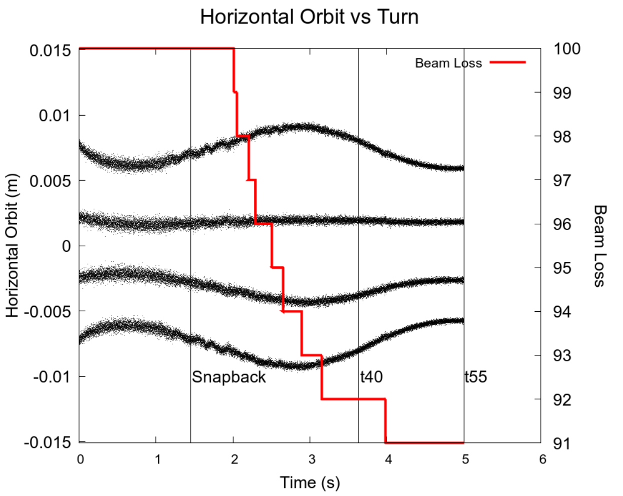

Figure 4: Shown are 100 particles initially trapped at injection and ramped to 18 GeV. The centroid is placed onto the fixed point. All focusing magnets except the octupoles have dynamic normalized strength through the ramp.

Table 2: Twiss Parameters for Each Island

Fixed Point	$\bar{x}$ [mm]	$\bar{p}_x$ [mrad]	[m]	[#]
0	0	0	45.51	-2.16
1	-0.30	0.68	371.50	-19.79
2	33.47	1.51	16.21	1.06
3*	-1.01	-0.72	331.07	-9.98
4	-35.57	-1.60	47.48	-1.19

over many turns observing, $\bar{x}$, $\bar{p}_x$, every 4^{th} turn at the fixed points. The phase space plot is shown in Fig. 5. The β and α-functions at the kicker are 45.51 m and -2.16, respectively. The island in which the non-adiabatic angular kick is applied for transition crossing is marked with an asterisk in Table 2. The deflection angle is calculated using:

$$\Delta p_x = -(\alpha_x/\beta_x)\cdot x - p_x, \qquad (4)$$

where the Twiss are the Twiss of the island and not the on-axis beam. The deflection angle used in the simulation was 0.6951 mrad. Figure 6 is the single particle tracking results with a synchrotron oscillations of transition crossing with the single turn kick, without the single turn kick, and on-axis without kick. In all tracking the phase jump, 180°-ϕ_s where ϕ_s is synchronous phase, is applied. The difference in $\gamma_T = 0.1$ and is calculated using the one-turn-map M

$$\Delta\gamma_T = (\tilde{M}_{56}/C)^{-1/2} - (M_{56}/C)^{-1/2}, \qquad (5)$$

where the $\tilde{M}$ is the one-turn-map with the particle at the fixed point.

CONCLUSION

The feasibility of injecting and ramping a trapped beam within a hadron accelerator have been presented. Implementing the RIJ scheme may prove essential if an additional experimental detector is integrated into the HSR due to the reduction of transition jump quadrupoles. More studies, including a comparison of simulation results with experimental measurements, are required to fully evaluate the risks associated with implementing the RIJ scheme as a cost-effective transition crossing alternative to the FOM scheme.

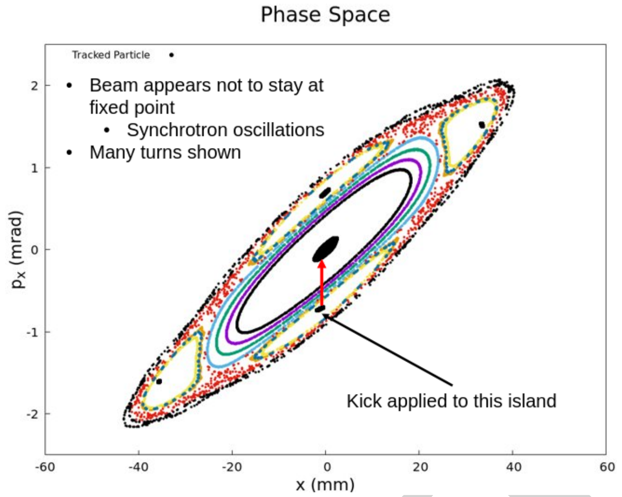

Figure 5: The phase space plot of the Poincaré curves, multicolored, and the single particle tracked through transition. The particle suffers little filamentation when kicked onto the central axis.

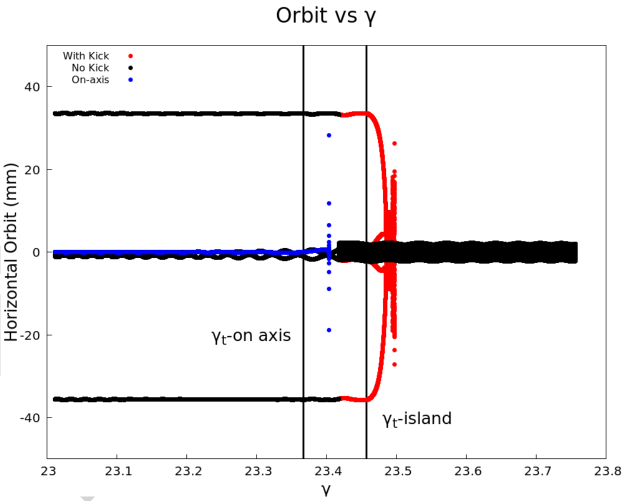

Figure 6: Single particle tracking with synchrotron oscillations through transition. The blue data points describe the tracking on-axis, red data points indicates the particle trapped in the island, and black data points indicate the trapped particle with the non-adiabatic kick before transition.

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