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MODELING LOCAL CRABBING DYNAMICS IN THE JLEIC ION COLLIDER RING *

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Abstract

The Jefferson Lab Electron-Ion Collider (JLEIC) design considers a 50 mrad crossing angle at the Interaction Point. Without appropriate compensation, this could geometrically reduce the luminosity by an order of magnitude. A local crabbing scheme is implemented to avoid the luminosity loss: crab cavities are placed at both sides of the interaction region to restore a head-on collision scenario. In this contribution, we report on the implementation of a local crabbing scheme in the JLEIC ion ring. The effects of this correction scheme on the stability of proton bunches are analyzed using the particle tracking software *elegant*.

INTRODUCTION

The need for a physics program with an Electron Ion Collider (EIC) is thoroughly described in [1]. As part of this effort, two EIC designs have been put upfront for consideration, e-RHIC at Brookhaven National Lab [2] and JLEIC at Jefferson Lab [3]. Two notable characteristics of the JLEIC design are the high luminosity requirement, in the order of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, and the integration of a full acceptance detector in the Interaction Region (IR). For this detector, a relatively large crossing angle $\phi_{cross} = 50 \text{ mrad}$ ensures a rapid beam separation, making space for IR magnets and reducing parasitic collisions. However, because of the crossing angle, without compensation, luminosity could get reduced by a factor [4]

$$R_{\Theta} = \frac{1}{\sqrt{1 + \Theta^2}}. \quad (1)$$

Here, Θ is the Piwinski angle $\Theta \equiv \phi_{cross}\sigma_z/2\sigma_x^*$ and characterizes the aspect ratio of the collision. For JLEIC design parameters, $R_{\Theta} = 0.11$, an order of magnitude reduction. The JLEIC high luminosity approach is based on a high bunch repetition rate, low β^* at the Interaction Point (IP), ion beam cooling and the use of crab cavities to compensate for the geometric luminosity loss [3]. Originally proposed for linacs [5] and soon afterward for storage rings [6], a crabbing scheme for luminosity compensation uses an rf dipole field to impart a transverse kick to the bunch relative to its center. A kick is first given to the head of the bunch and then in the opposite direction to the tail. With an appropriate deflecting voltage and phase advance, a tilt in the bunch is produced,

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see Fig. 1, such that a head-on collision is effectively restored at the IP. In the following sections, we report on the

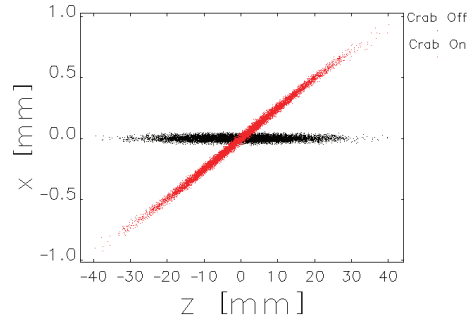


Figure 1: Crabbed (red) and normal (black) bunch at the IP for the last 10 turns of the 100 GeV simulation shown in Fig. 6.

implementation of a local crabbing scheme in the JLEIC ion ring. Particles are tracked using the software *elegant* [7], developed at Argonne National Lab.

JLEIC CRAB COMPENSATION SCHEME

This work is a continuation of the previous work on the crabbing design for JLEIC, see [8, 9]. A local crabbing scheme involves the use of crab cavities at both sides of the IR. The upstream cavity imparts the required kick on the beam to recover head-on collisions at the IP. The downstream cavity cancels the initial kick on the beam, effectively constraining the crabbed beam to a region around IP; thus limiting beam effects induced by the transverse kick along the ring. A relative phase advance $\Delta\phi = n\pi$ between the two cavities is required for a full kick cancellation. The design of the IR includes horizontal and vertical Chromaticity Compensation Sextupoles (CCS) [10], that cancel the chromatic kick from the final focusing quadrupoles. These sextupole locations have high β function values and the necessary phase advances suitable for crabbing. Figure 2 shows the ion ring baseline collision optics, where the high β_x peaks are ideal locations for crab cavities to be placed. In a local crabbing scheme, the voltage required to tilt the bunch by an angle ϕ_{crab} at the IP is [11]

$$V = \frac{cE_b \tan \phi_{crab}}{e2\pi f \sqrt{\beta_{crab}\beta^*}} \quad (2)$$

where E_b is the beam energy, ϕ_{crab} is half the crossing angle, β_{crab} is the horizontal beta function at the crab cavity

location and β^* is the horizontal beta function at the IP. Crabbing parameters for the baseline lattice are stated in Table 1.

Table 1: Crabbing Parameters for Proton Bunches

Parameter	Ion ring	Units
Energy	100	GeV
Frequency	952.6	MHz
Crossing Angle	50	mrad
β_x^*	0.1	m
β_x^{crab}	400	m
Deflecting Voltage	19.81	MV

Non-Zero Dispersion at Crab Cavity Locations

The local crabbing scheme relies on the full cancellation of the transverse kick effects. This involves the cancellation of the energy change due to beam beam interaction. However, if there is dispersion at the crab cavity locations, this energy change may not be completely cancelled. A stability criterion on the tolerable values of η and η' at the crab cavity location is [12]

$$\eta\eta' \leq \frac{\sigma_x^*}{2\sigma_s} \frac{\alpha C}{\phi_{crab}}, \quad (3)$$

with η , η' are the dispersion and its derivative at the crab cavity locations, σ_x^* is the horizontal transverse bunch size at IP, σ_s is the r.m.s length of the bunch, α is the momentum compaction factor, C is the circumference of the ring and ϕ_{crab} is the crabbing angle. For the JLEIC crabbing parameters, this criterion is well satisfied: $|\eta\eta'| = 0.4565 \text{ m} < 5.0763 \text{ m}$.

SIMULATION

For these studies, the particle tracking software *elegant* is used. Bunches of 1000 particles are tracked turn by turn using a complete Ion Ring lattice. Particles follow a 3- σ Gaussian distribution with normalized emittance $\epsilon_{x/y} = 0.35/0.07 \mu\text{m}\cdot\text{rad}$. The bunches are generated at $s = 0 \text{ m}$, in a zero dispersion location outside the crabbing region. Crab cavities are modeled in *elegant* via RF DeFlector (RFDF) thin elements. In the following, for ‘‘Crab On’’ situations, the crab cavity voltage is ramped over a period of 2000 turns, unless otherwise stated. Similarly, for ‘‘Crab Off’’ scenarios, the RFDF element is present in the lattice, but its voltage is kept at 0 V.

Ion Ring Baseline Lattice

Figure 2 shows the collision optics of the ion ring baseline lattice. A local crabbing scheme is implemented in this lattice using the parameters in Table 1. Figure 3 shows the evolution of the crabbed bunch angle at the IP as a function of the number of turns. ϕ_{crab} is determined by the average of the transverse and longitudinal correlations through $\phi_{crab} = \langle xz \rangle / \langle z^2 \rangle$. In this lattice, the vertical CCS are

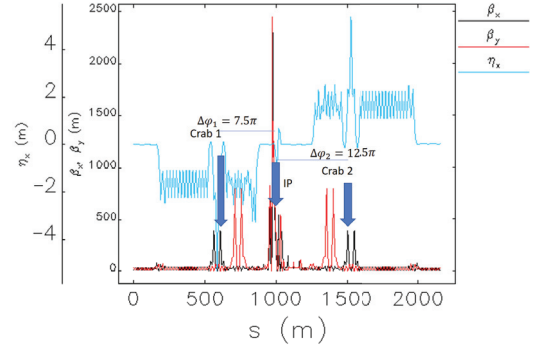


Figure 2: JLEIC Ion Ring baseline collision optics.

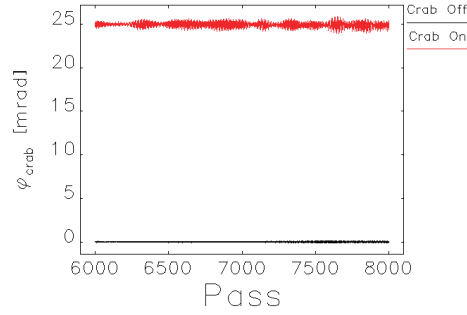


Figure 3: Crab angle evolution in the baseline Ion ring lattice.

located within the crabbed bunch region. Simulation suggests a strong effect of the vertical CCS non-linear fields on the bunch that dramatically increases the emittance and eventually blows up the beam, see Fig. 4.

Ion Ring Lattice with Switched x/y Chromatic Compensation Sextupoles

Figure 5 shows a modified collision optics of the ion ring, where the vertical and horizontal Chromaticity Compensation Blocks (CCB) locations have been switched, leaving the vertical CCS outside of the crabbed beam region. In this new lattice, the crab cavity locations have $\beta_x = 363.44 \text{ m}$, which

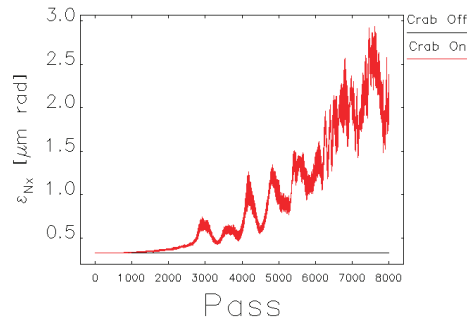


Figure 4: Emittance growth due to crab cavities in the baseline Ion Ring lattice.

increases the crab voltage requirement, see Table 2. Crab cavity phase advances with respect to the IP are 4.5π and 9.5π for the upstream and downstream cavity, respectively.

Table 2: Crab Cavity Voltage Requirement

Energy [GeV]	Crab Voltage [MV]
20	4.18
60	12.50
100	20.82

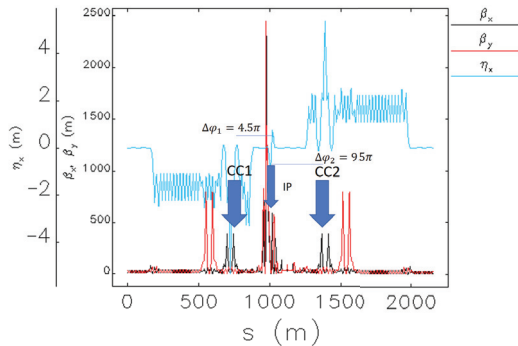


Figure 5: Collision optics of the JLEIC lattice with switched horizontal/vertical CCB.

Similarly, Fig. 6 shows the evolution of the crabbed bunch angle at the IP as a function of the number of turns, note that the angle is stable at a lower turn number than for the baseline lattice. We also looked at the emittance increase

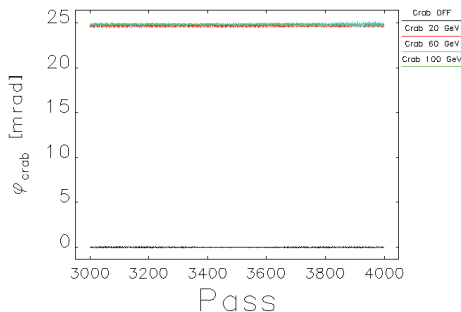


Figure 6: Crab angle evolution at the IP in the lattice with switched CCB. Angle is shown for low, medium and high energy proton beam.

due to the crab cavities, Fig. 7 shows the emittance evolution for the lattice with different crab cavity turn-on rates. This emittance increase seems to be a correlated effect [11, 13]. The crabbing kick may not be exactly compensated, causing non-zero correlations between the horizontal and longitudinal degrees of freedom. This establishes a new matched 6D phase-space ellipsoid around the ring. The non-correlated phase-space emittance is recovered as long as the crab cavity voltage turn-on is done adiabatically.

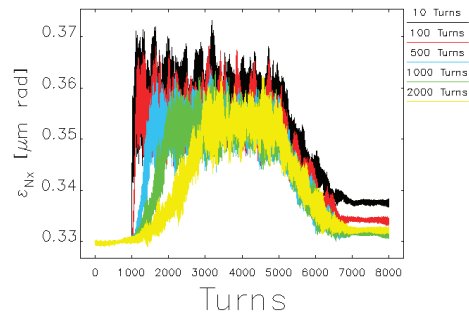


Figure 7: Projected normalized horizontal beam emittance in the modified lattice. The growth is due to the establishment of a new matched ellipse. The voltage on the crab cavities is ramped over 10, 100, 500, 1000 and 2000 turns for comparison. Emittance can be preserved as long as the turn-on rate is longer than 500 turns.

CONCLUSION

A local crabbing scheme is implemented on the baseline lattice of JLEIC ion ring. It is observed a large emittance growth, simulation results suggest that this effect is due to a coupling of the vertical CCS with the crabbed bunch. Switching the vertical and horizontal CCB, a smaller, correlated emittance growth is observed. Local crabbing is achieved for low, medium and high energy proton beams.

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