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ELECTRON-ION COLLIDER PERFORMANCE STUDIES WITH BEAM SYNCHONIZATION VIA GEAR-CHANGE *

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Abstract

Beam synchronization of the future electron-ion collider (EIC) is studied with introducing different bunch numbers in the two colliding beams. This allows non-pairwise collisions between the bunches of the two beams and is known as 'gear-change', whereby one bunch of the first beam collides with all other bunches of the second beam, one at a time. Here we report on the study of how the beam dynamics of the Jefferson Lab Electron Ion collider concept is affected by the gear change. For this study, we use the new GPU-based code (GHOST). It features symplectic one-turn maps for particle tracking and Bassetti-Erskine approach for beam-beam interactions.

INTRODUCTION

The Proposed Jefferson Lab Electron – Ion Collider (JLEIC) [1] is designed to accommodate a wide range of center of mass energies, from 21.9 GeV to 98 GeV. The ion beam energy varies in a range of 40-200 GeV and for electron beam it is 3-12 GeV. The figure-8 shaped electron and ion storage rings have nearly identical circumferences and intersect at two interaction points along two long straights, as shown in Fig. 1 [2].

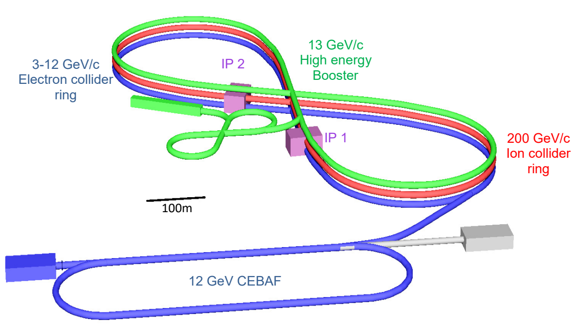

Figure 1: JLEIC layout for 200 GeV ion ring.

The electron beam is ultra-relativistic even for 3 GeV with a velocity of 0.99999971c, where c is the speed of light. But ion beam is not fully relativistic for low energy. This velocity difference in two beams causes a large difference of path lengths in the rings.

Both electron and ion rings are designed to match the revolution times of both beams at a specific center of mass energy (63.3 GeV). Then a particular ion bunch in ion-beam will collide with a same electron bunch at the interaction point (IP) for every turn.

This matching condition maintenance is impossible for the proposed large energy range due to non-relativistic ion velocities. Therefore, for lower energy values, bunches could miss each other at the IP due to different path lengths. This issue is known as beam synchronization and becomes more complicated if there is more than one IP in the machine as JLEIC [3].

Changing ring circumference is cumbersome and expensive. Other implementations to resolve this issue involve variation of bunch numbers, variation of ion path length, variation of electron path length and rf frequency. As the difference of revolution time is equal to ion-bunch spacing, synchronization between beams can be achieved when ion ring accommodates additional bunches. This implementation allows non-pairwise collisions between bunches of two beams at the IR and is known as 'gear-changing' of bunches. In order to avoid parasitic collisions, bunch numbers should satisfy the following relation.

$$N_0\beta_0 = N\beta \tag{1}$$

where, N_0 is bunch number at the matched energy, N bunch number at the new energy, β_0 relativistic beta at matched energy and β relativistic beta at new energy.

For JLEIC, reference beam path lengths are defined for medium energy (E_{CM} = 63.3 GeV) where, $E_{\text{e-beam}}$ = 5 GeV and $E_{\text{p-beam}}$ = 100 GeV. The electron ring circumference is 2336.00336 m [3]. Relation between path lengths is,

$$L_{0-ions} = L_{0-elec}\,\beta_{0-ions} \tag{2}$$

SIMULATION TOOLS

For this study GPU accelerated Higher Order Symplectic Tracking (GHOST) code was used [4]. In this code, particle tracking through a storage ring in six-dimensional phase space is carried out with arbitrary order symplectic Taylor maps. These maps were generated as in COSY Infinity [4] with omitting zero-coefficient terms to speed up calculations and coeffients are found by

$$x = \sum_{\alpha\beta\gamma\eta\lambda\mu} M(x|\alpha\beta\gamma\eta\lambda\mu)x^{\alpha}x'^{\beta}y^{\gamma}y'^{\eta}z^{\lambda}\left(\frac{dE}{E_0}\right)^{\mu}. \tag{3}$$

For initial and final coordinates (q_i, p_i) and (q_f, p_f) the second kind of generating function satisfies the following relations : $(q_f, p_i) = J\,\nabla F_2\,(q_i, p_f)$. Beam-beam kick calculation for both 'strong-strong' and 'strong-weak' modes is based on Bassetti–Erskine approximation [6]. It enables solving Poisson equation, assuming collision of infinitely short bunches. This thin-bunch model is used by dividing

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the realistic bunch length into thin slices, thereby requiring slice-to-slice collisions. In the code, both bunches have same number of slices (M), and the slice size is $\Delta = L/M$, where, L is the bunch length.

The collision of two opposing bunches at the interaction point (IP) is simulated as sum of the collisions of individual slices. Beam kicks experienced by two beams are calculated using the Basseti-Erskine [5,7].

BEAM PARAMETERS

Beam-beam interactions for JLEIC is studied for three essential kinematic ranges: (1) Low energy range (E_{CM} = 21.9 GeV) with E_p = 40 GeV and E_e = 3 GeV, where space-charge dominates; (2) Medium energy range (E_{CM} = 44.7 GeV) with E_p = 100 GeV and E_e = 5 GeV, where beam-beam interactions limit the luminosity; and (3) High energy range E_{CM} = 63.3 GeV and E_{CM} = 98 GeV, where luminosity is affected mostly by synchrotron radiation of high energy electron beam. For this study, beam parameters optimized for this medium energy are used to study how beam-beam interaction affects the collider performance in general.

Optimal working point for the preferred energy was found by performing tune-scans over a linear lattice model. From the tune diagrams, working points are found to be $\nu_x = 0.54$, $\nu_y = 0.567$, $\nu_s = 0.02$ for the electron beam and $\nu_x = 0.081$, $\nu_y = 0.132$, $\nu_s = 0.054$ for the proton beam [8]. Generation of tune maps was done using BeamBeam3D; a massively parallel beam-beam code based on shifted Green's function to solve Poisson's equation [9].

To achieve the desired high luminosity, JLEIC design relies on high repetition rate along with short bunch lengths. Luminosity of two colliding beams is calculated by:

$$L = \frac{n_b N_e N_p f_{rev}}{2\pi \sqrt{\sigma_{x-e}^2+\sigma_{x-p}^2}\sqrt{\sigma_{y-e}^2+\sigma_{y-p}^2}} \tag{4}$$

where, n_b is number of bunches, N_e number of particles in e-beam, N_p number of particles in p-beam and $\sigma_{x,y}$ rms beam sizes in transverse directions.

Also, smaller beam sizes are required for higher luminosity. Matching beam spot sizes at the IP is essential to minimize non-linear beam-beam forces and it is achieved by adjusting beta-function value at the IP (β*).

RESULTS

For this study beam parameters listed in Table 1 were used.

Table 1: Beam Parameters Used for the Study

Parameter	e-beam	p-beam
Energy	5.0 (GeV)	100.0 (GeV)
No. of part,	3.7 x 10^{10}	1.38 x 10^{10}
β^*_x	0.051 (m)	0.06 (m)
β^*_y	0.01 (m)	0.012 (m)
σ_x	21.77 x 10^{-6} (m)	21.77 x 10^{-6} (m)
σ_y	4.33 x 10^{-6} (m)	4.33 x 10^{-6} (m)
Bunch leng.	0.008 (m)	0.012 (m)

First 1-to-1 bunch collision was studied, and it was verified that GHOST results are acceptable. Comparison was done using BeamBeam3D and the luminosity output from both are shown in Fig. 2 below.

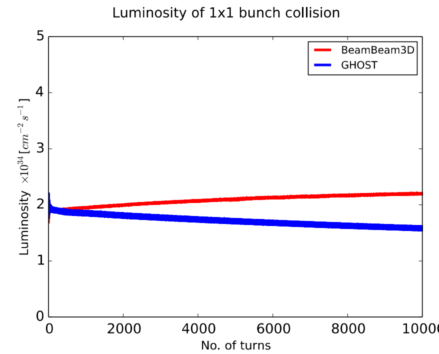

Figure 2: Luminosity output for 1-on-1 collision from BeamBeam3D and GHOST.

The expected peak luminosity value is 1.948 x 10^{34} cm^{-2} s^{-1} with hourglass reduction of 0.906. Hence the average luminosity is 1.76 x 10^{34} cm^{-2} s^{-1}, and from GHOST the average value is 1.86 x 10^{34} cm^{-2} s^{-1} and BeamBeam3D value is: 2.19 x 10^{34} cm^{-2} s^{-1}. BeamBeam3D gives higher value than expected, as it takes into account the dynamic beta effect and this proves the working points used are optimized for the symmetric design.

For this simulation 1024K microparticles were used and each bunch is slices into 10 slices to facilitate slice-by-slice collision.

BEAM DYNAMICS WITH GEAR CHANGE

Let N_1 be the number of bunches in the proton beam and N_2 be the number of bunches in electron beam ($N_1 > N_2$). If they are relatively prime, there will be N_1 x N_2 collisions for one iteration.

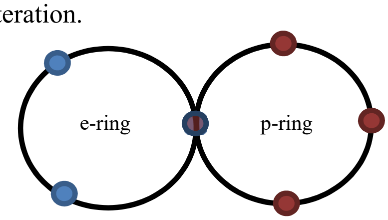

Figure 3: Schematic for 4 × 3 bunch collision.

Since 3 and 4 are relatively prime, there will be 3x4 = 12 different pairs of bunch collisions for the simple model illustrated in Fig. 3. For JLEIC actual number of bunches required is over 3000. Simulating that much larger number takes a large computational time and memory. Therefore, this paper is focused on basic cases of bunch number variations. Currently, GHOST enables only 1 x 1 and N x (N-1) bunch collisions. Hence the cases studied are 4 x 3, 7 x 6 and 11 x 10. For each case, 5000 tuns were simulated with collision frequency of 1 and revolution frequency of 476 MHz. Luminosity output from GHOST is shown in Fig. 4 below.

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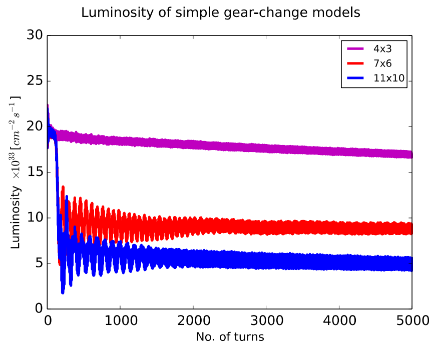

Figure 4: Luminosity vs turn number for simple *N*x(*N*-1) gear-change.

Above figure shows luminosity variation with respect to turn number for the cases mentioned above. According to these curves there is a large fluctuation of luminosity with a sudden drop in the beginning, but then they tend to stabilize after few thousands turns. Even though the system self-stabilizes, there is a small loss in luminosity. Luminosity loss increases with the increase of bunch number. Also, higher the bunch number, higher the initial luminosity fluctuation.

The blue curve which corresponds to 11x10 has the lowest stable luminosity after around 2000 turns and the loss of luminosity is almost 4 times compared with the 1 x 1. To benchmark these, simplest gear-changing simulation was done using BeamBeam3D and the comparison of luminosity results are given in Fig. 5.

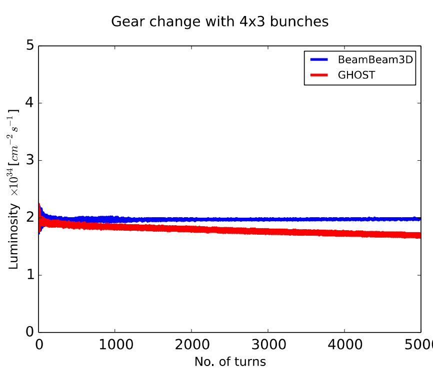

Figure 5: Simplest gear-changing (4x3) luminosity output comparison of BeamBeam3D and GHOST.

Unlike 1-to-1 collision, with different bunch numbers the collisions are not symmetric as they collide with multiple bunches. These asymmetric collisions introduce complications to the beam dynamics in the collider ring. They can be categorized in to two types [10]:

1. Multi-bunch offset or dipole instabilities
2. Multi-bunch beam size or quadrupole instabilities

These effects create linear and non-linear effects on beam stabilities, affecting transverse and longitudinal beam sizes and beam centroid offsets.

Working points were optimized for symmetric collisions, but with different bunch numbers (*N*) working points change. More resonances occur when the system operates at a point near to its theoretical working point, destabilizing two beams.

Various amount of oscillations at the beginning of luminosity curves reflect that the fixed working point used for the 1-to-1 collision is not optimized for different *N* values. Resonance strengths also vary as *N* value changes as there are different working points for different *N* values. These unwanted resonances can be minimized by optimizing tune for a range of 1/*N*.

Dipole errors can be suppressed with the use of a feedback system and recover a portion of luminosity loss. But correcting quadrupole instabilities need further study. To restore luminosity loss due to quadrupole and higher order instabilities, transverse damping methods are needed. These will be a focus of a future study.

SUMMARY

With this version of GHOST, 1 x 1 and N x (N-1) cases can be studied. This is helpful to understand the beam dynamics for collisions with different bunch numbers. Luminosity values fluctuate highly and drop quickly within first few thousand turns due to non-linear beam interactions and become stable with slight luminosity loss. The self-stabilized system has lower luminosity value than expected. Adding N x (N-n) collision functionality to GHOST is in progress and will provide additional tool to understand beam-beam effects in more detail.

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