SIMULATION STUDIES OF BEAM-BEAM EFFECTS OF A RING-RING ELECTRON-ION COLLIDER BASED ON CEBAF

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Abstract

The beam-beam effect can potentially cause a rapid growth of transverse beam emittances and reduction of the luminosity of a collider to an unacceptably low level. The ELIC, a proposed ring-ring electron-ion collider based on CEBAF, stores high repetition CW beams with very short bunch lengths, and collides them at up to 4 interaction points with very strong final focusing and crab crossing. All of these features can make the beam-beam effect very challenging. In this paper, we present simulation studies of the beam-beam effect in ELIC using a self-consistent strong-strong code developed at LBNL. This simulation study is used for validating the ELIC design and for searching for an optimal parameter set.

INTRODUCTION

In recent years, Jefferson Lab has been actively engaged in a conceptual design of a ring-ring electron-ion collider (ELIC).[1] Design studies are driven to achieving ultra high luminosity, up to 10^{35} $cm^{-2}s^{-1}$ per detector, over all four interaction points (IP). The high luminosity of ELIC appears realizable using concepts of high bunch repetition rate, crab crossing colliding beams, very small transverse emittance and bunch length of both electron and ion beams, and very strong final focusing at IPs. Such cutting-edge design features are also aggressively pursued in several proposals of the next generation ultra high luminosity colliders including Super-B Factory and muon collider. In all cases, beam-beam parameters are pushed into a region that existing colliders have never achieved. To support such conceptual designs, computer simulations are routinely utilized to examine beam-beam instabilities, to explore limits of machine parameters and to reach design optimization.[2,3] Here we report the first phase of beam-beam simulation studies for ELIC.

SIMULATION MODEL AND CODE

At the highest level, simulating beam-beam effects in ELIC can be divided into two parts: tracking of particle collisions at IPs, and transporting beams through the storage-collider rings. These are modeled differently to address different physics mechanisms and characteristic timescales. At IPs, colliding beam bunches are modeled by groups of macro-particles (with the same mass-to-charge ratio) interacting with each other through nonlinear beam-beam kicks. The key of this part of simulation is calculation of the nonlinear particle-particle forces using standard particle-in-cell methods. On the other hand, transport of beams inside a storage-collider ring is, at the present time, simplified as a set of linear transfer maps to bring bunches from one IP to the next, or a one-turn linear map if there is only one IP in the ring. Such a highly idealized beam transport model, though usually including synchrotron radiation damping and associated quantum fluctuations for lepton particles, ignores other collective beam effects in the storage-collider rings which could also be important experimentally. Nevertheless, due to the large difference in characteristic timescales of collision and beam transport, we have to settle for such imperfect models given present computer capabilities, if we would like to focus on the details of the collision effect and the limits it imposes on the machine design parameters.

The simulation code utilized in the present study is BeamBeam3D,[4] developed at Lawrence Berkeley National Laboratory. It is a 3D self-consistent strong-strong beam-beam code which solves the Poisson equation for electromagnetic fields using the shifted integrated Green function method over a 3D mash of a beam bunch and applies the beam-beam kicks to the opposite beam. The term strong-strong refers to a feature of the simulation model whereby both colliding beams can be perturbed by the beam-beam interactions in collisions, as opposed to a weak-strong model in which only one colliding beam can be perturbed. Several attempts at code benchmarking against other beam-beam codes or experimental data had yielded reasonable agreements, [5] and since then, the code has been used for simulating beam-beam effects in several machines including RHIC and LHC. As a highly parallelized code, it was ported to parallel supercomputers at the DOE National Energy Research Computer Center (NERSC), on which our simulations were performed.

SIMULATION RESULTS: SINGLE IP

ELIC Nominal Design Parameters

The ELIC collider parameters used for this study are given in Table 1, and only proton beam was studied. The final focusing parameter, β^*, is 5 mm in both transverse directions; the chromatic effect is assumed being corrected through optical procedures. The radiation damp time of the electron beam is given in number of turns in a 1.5 km figure-8 shape ring.

It should be pointed out that this parameter set is one of several sets that had been evaluated in the ELIC design optimization process. Since the ELIC design and the science program it intends to serve are still evolving, naturally many parameters of the collider facility were still

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not finalized at the time of this study. Nevertheless, it is believed that simulation results for typical parameter sets should shed light on the general trend of beam-beam effects in ELIC.

Table 1: ELIC Design Parameters

		Proton	Electron
Energy	GeV	150	7
Current	A	1	2.5
Particles/bunch	10^{10}	1.04	0.42
Normalized emittance ε^n_x / ε^n_y	µm	1.06/0.042	90/3.6
β^*_x / β^*_y	mm	5 / 5	5 / 5
Bunch length σ_z	mm	5	5
Damping time	turn	---	800
Beam-beam parameter		0.002/0.01	0.017/0.086
Beatron tune (fractional part)		0.71/0.70	0.91/0.88
Synchrotron tune		0.06	0.25

Before production runs, a numerical convergence test was carried out to determine the code parameters. It was determined that a 64x128 2D transverse mash and 20 longitudinal slices are sufficient to produce reliable simulation results with minimum 200k macro-particles for each beam bunch. With these run parameters, a typical production run for tracking two colliding bunches over 10000 turns in the storage ring (corresponding to about 0.15 second beam storing time, and approximately 12 damp times) usually takes about 24 hours of wall clock time in a 64 CPU cluster of a NERSC supercomputer, as a consequence defining the scope of our simulations. Though our simulations should reveal short-time dynamics under repeated particle collisions, it could not be able to predict long term (minutes or longer) beam dynamical behavior.

ELIC Luminosity for Nominal Design Parameters

When only one IP is opened for collisions, any bunch of one beam always collides with a specific bunch of the opposite beam due to identical lengths of the two storage-collider rings in ELIC; thus only two collideing bunches, one from each beam, need to be tracked. The turn-by-turn evolution of ELIC luminosity, normalized by its peak design value $7.9 \cdot 10^{34}$ $cm^{-2}s^{-1}$, is shown in Figure 1a. It starts at an initial (normalized) value of 0.73 due to a hourglass effect (the bunch length is same as the beta-star), then quickly drops to a plateau value in about one damping time, with equilibrium luminosity $4.3 \cdot 10^{34}$ $cm^{-2}s^{-1}$. Reduction of luminosity is caused by nearly a factor of three increase of electron beam vertical emittance (and similarly vertical electron beam size increase at an IP), as shown in Figure 1(b), due to the beam-beam effect.

Beam Currents Dependence of ELIC

As a part of an ELIC parameter dependence study, a series of simulations were performed with various beam currents, i.e., bunch charges, as the bunch repetition rate is a constant. Figures 2a and 3a show the ELIC luminosity as a function of electron or proton beam current and Figures 2b and 3b display the transverse RMS sizes at an IP. It can be observed that in the region near the design currents (1 A and 2.5 A for the proton and electron beam respectively), ELIC luminosity increases almost linearly as beam currents. The vertical RMS size of the electron beam also increases proportionally to increase of the proton current while electron horizontal RMS size and both transverse RMS sizes of the proton beam remain the same. At a region far away from the nominal design point, however, nonlinear interactions become a dominating cause of beam-beam effects, hence inducing a clear trend of slowdown of luminosity increase in response to beam current increase.

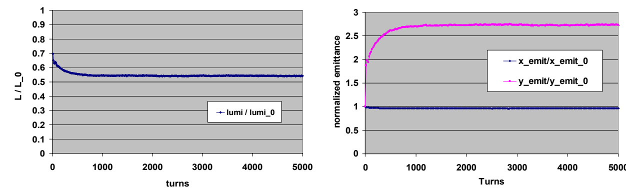

Figure 1: (a) ELIC luminosity (normalized by the peak design value) and (b) transverse emittance (normalized by their design values) for proton (blue line) and electron (red line) for ELIC nominal design parameters.

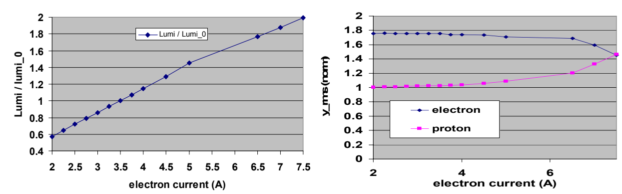

Figure 2: (a) ELIC luminosity (normalized by the peak design value) and (b) vertical emittance (normalized by their design values) as functions of electron beam current.

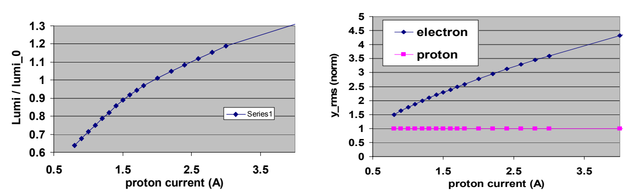

Figure 3: (a) ELIC luminosity (normalized by the peak design value) and (b) vertical emittance (normalized by their design values) as functions of proton beam current.

Coherent Beam-Beam Instability

The coherent beam-beam instability, namely, a coherent oscillation of particle distribution of colliding beams[6], was observed, as shown in Figure 4, when electron current reaches 7.5 A (three times nominal design value). It marks the point beyond which the colliding beams will blow up. Further studies of coherent beam-beam instability are in progress.

Betatron Tune Working Point

It is well known that collider luminosity are very sensitive to synchrotron and betatron tunes; thus a good tune working point should be chosen such that it not only is away from resonance lines, but also the tune spread caused by various beam physics effects including beam-

beam interactions should avoid crossing lower tune resonance lines. We had examined several betatron tune working points selected *empirically* with beam-beam simulations and found that one of them, namely (0.71, 0.7) and (0.63, 0.645) for proton beam and electron beam respectively, provides systematically better luminosity, as shown in Figure 5. However, the critical electron current at which the coherent beam-beam instability is incited remains the same.

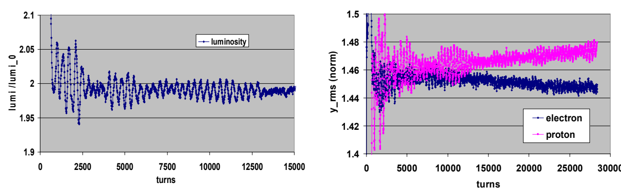

Figure 4: (a) ELIC luminosity and (b) vertical emittance of proton beam (red line) and electron beam (blue line) when a coherent beam-beam instability is incited.

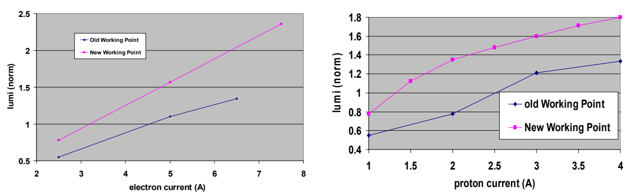

Figure 5: ELIC luminosity (normalized by the peak design value) as functions of (a) electron beam current and (b) proton beam current

SIMULATION RESULTS: MULTIPLE IPS

With a 1.5 GHz bunch repetition rate and a 20 cm bunch spacing, over 7500 bunches can be stored in each of two collider rings of ELIC. In principle these 15000 bunches are coupled together through collisions at 4 IPs and possible other corrective beam effects. Considering a special case that the distance between two IPs on the same straight section of figure-8 ring is one twenty-fourth of the ring circumference, then the system of 15000 bunches can be reduced to many *independent* subsets of 12 electron bunches and 12 proton bunches, as shown in Figure 6. Such subset of 24 bunches will produce 48 collisions at 4 IPs during each evolution time of the ring, and therefore requires 48 times more computing time or power that it needs in a single IP case for reaching the same level of details in simulation. Figure 7 shows collision-by-collision evolution of the ELIC luminosity per detector, using the same parameters as in Table 1 but at new betatron tune working point discussed above. It shows that ELIC luminosity in the case of multiple IP and multiple bunch behaves very much like the case of the single IP, with an equilibrium value of $5.5\cdot10^{34}$ $cm^{-2}s^{-1}$, nearly identical to the single IP luminosity of $5.8\cdot10^{34}$ $cm^{-2}s^{-1}$. We can conclude that multiple bunch and multiple IP couplings do not amplify the old beam-beam instability nor introduce any new coherent instability.

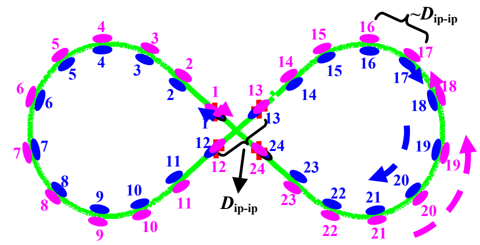

Figure 6: Two sets of 24 electron or proton bunches are distributed uniformly over a Figure-8 shape collider ring. Even or odd number electron bunches would only collide with even or odd number proton bunches at four IPs.

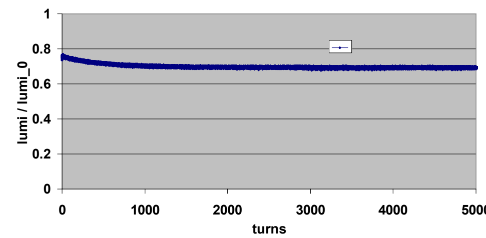

Figure 7: ELIC luminosity per detector (normalized by the design peak value) as a function of turns (and collisions) when all 4 IPs of ELIC are open for collisions.

CONCLUSIONS

Recently we have conducted a first phase beam-beam simulation study for ELIC. While we have utilized simple linear mapping model for beam transport in the storage-collider ring, we have tracked beam collisions with large number of macro-particles and detailed field calculations of the beam-beam interaction using particle-in-cell method; therefore these simulations provided us fairly reliable beam dynamics over a short time scale. It was found that for a design parameter set we used, the ELIC luminosity reaches $5.5\cdot10^{34}$ $cm^{-2}s^{-1}$ per detector, under both single IP and multiple IP operation conditions. The parameter scan studies showed that the nominal design values of electron and proton beam currents are away from the region dominated by the nonlinear beam-beam effect and coherent beam-beam instabilities. The initial betatron tune working point search points to a very good candidate at which luminosity reduction due to the beam-beam effect is quite minimized. Our future simulation work will focus on beam collisions with crab crossing and effects of coupling of the beam-beam interaction with other collective beam physics effects.

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