NUMERICAL SIMULATION OF BEAM-BEAM EFFECTS IN THE PROPOSED ELECTRO-ION COLLIDER AT JEFFERSON LAB*

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Abstract

One key limiting factor to a collider luminosity is bean-beam interactions which usually can cause serious emittance growth of colliding beams and fast reduction of luminosity. Such nonlinear collective beam effect can be a very serious design challenge when the machine parameters are pushed into a new regime. In this paper, we present simulation studies of the beam-beam effect for a medium energy ring-ring electron-ion collider based on CEBAF.

INTRODUCTION

For nearly a decade now, Jefferson Lab has been engaged in conceptual design studies of a ring-ring polarized electron-ion collider based on CEBAF recirculated SRF linac [1]. Recent evolution of science programs and design iterations guided us to make a low-to-medium energy collider (MEIC) our immediate project goal and a high energy collider as a future upgrade option. The design is geared toward realizing high luminosity, nearing 10^{34} cm^{-2}s^{-1} per detector, with the possibility of up to three interaction points (IP). The high luminosity of the MEIC is achievable using concepts of high bunch repetition rate, crab crossing colliding beams, small transverse emittance and bunch length of both electron and ion beams, and strong final focusing at IPs. To lend credibility to the conceptual design, we use computer simulations to examine beam-beam instabilities, to optimize and explore limits of machine parameters.

In an earlier study [3], beam-beam simulations were carried out for an earlier, high-energy, electron-ion design. Here we report the beam-beam simulation studies for MEIC.

Table 1: Design Parameters for the ELIC

Quantity	**Unit**	e^- **beam**	p **beam**
Energy	GeV	5	60
Collision frequency	MHz	1497	
Particles per bunch	10^{10}	1.25	0.416
Beam current	A	3.00	1.00
Energy spread	10^{-3}	0.71	
rms bunch length	mm	7.5	10
Horiz. bunch size at IP	μm	23.4	
Vertical bunch size IP	μm	4.7	
Horiz.l emit. (norm.)	μm	53.5	0.35
Vertical emit. (norm.)	μm	10.7	0.07
Horizontal β^*	cm	10	
Vertical β^*	cm	2	
Vertical beam-beam tune shift		0.03	0.007
Damping time	turns ms	1516 5	- -
Synchrotron tune		0.045	0.045
Ring length	m	995	995
Peak luminosity	cm^{-2}s^{-1}	0.564×10^{34}	
Reduction (hourglass)		0.957	
Peak luminosity with hourglass effect	cm^{-2}s^{-1}	0.54×10^{34}	

SIMULATION CODE

In general, simulation of beam-beam effects in MEIC can have two main components: tracking of particle collisions at IPs, and transporting beams through the storage-collider rings. Colliding beam bunches are modeled by groups of macro-particles with the same mass-to-charge ratio. At IPs, the bunches of colliding interact by nonlinear beam-beam kicks. The resulting nonlinear particle-particle forces are computed on a grid using standard particle-in-cell methods. In the current implementation, transport of beams throughout a storage-collider ring is modeled by a simplified set of linear transfer maps to transport bunches from one IP to the next, or a one-turn linear map if there is only one IP in the ring. Even though this idealized beam transport model includes synchrotron radiation damping and associated quantum fluctuations for lepton particles, it ignores other collective beam effects in the storage-rings which could also be important experimentally. Physically more faithful model, which will be employed in the future MEIC beam-beam simulations, will replace the simple linear maps with the maps of a complete ring lattice.

In the present study, we use BeamBeam3D [2] simulation code, developed at Lawrence Berkeley National Laboratory. BeamBeam3D is a 3D, self-consistent, strong-strong beam-beam code which uses shifted integrated Green's function method to solve the Poisson equation for electromagnetic fields on a 3D mesh of a beam bunch and impart the beam-beam kicks to the opposite beam. The

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
† Supported in part by SciDAC collaboration.

term strong-strong denotes a feature of the computational algorithm in which both colliding beams suffer perturbation by the beam-beam interactions in collisions, as opposed to a weak-strong feature in which only one colliding beam (weak) can be perturbed. The code has been benchmarked against other beam-beam codes or experimental data with reasonable success [4], and has been used since for simulating beam-beam effects in several machines including RHIC and LHC. BeamBeam3D code is parallelized so as to utilize computational prowess of supercomputers. The simulations in the present study have been carried out on Jefferson Lab's cluster, consisting of over 1500 cores, using a parallel MPI paradigm.

NUMERICAL SIMULATIONS

The nominal parameters for the MEIC used in this study are given in Table 1. For this study, proton beam is used in place of the ion beam, and only 1 IP is considered. The simulation also assumes that the chromatic effects have been already corrected through optics. The main goal of this study is to provide a first look at the general trend of beam-beam effects in the MEIC, and map out the requirements for a comprehensive and physically more faithful analysis, which is soon to follow.

We first carried out a convergence study so as to ascertain the optimal set of computational simulation parameters. We arrived at optimal resolution of the 2D transverse grid of 64×128, with 20 longitudinal slices, and 200000 particles per bunch. Simulations model collisions between an electron and proton beams at a single IP. Each of the simulations is carried out for 5000 turns, which amounts to more than 3 damping times, or 0.015s. Studying the long-term behavior (minutes or longer) of the beam is computationally prohibitive at this time.

In the present study, we carefully study the following issues: (i) systematic search for a (near-)optimal working point; (ii) dependence of beam luminosity on electron and ion beam current; (iii) the onset of beam-beam instability.

Searching For Optimal Working Point

Collider luminosity is sensitive to betatron and synchrotron tunes, which necessitates a careful search for an optimal working point. Such a working point has to be away from resonance lines, so that its tune spread (due to various beam physics effects, such as beam-beam interactions) avoids crossing lower tune resonance lines.

The newest feature of BeamBeam3D code allows for a scan of the tune space in one, massively-parallel simulation. This feature will be explored in the future beam-beam studies. Another possible way to search for a optimal working point is through the use of a "genetic algorithm", similar to what has been used in injector design [5]. We are currently investigating efficiency of this approach.

For the present study, we use a quasi-heuristic alternative to finding optimal working point: since the resonances cause instability and loss of luminosity, and one is best served staying away from rational numbers as the tune ratio ν_x/ν_y, use as the ratio of tunes the "most irrational number" — the golden ratio: $g = (1 + \sqrt{5})/2$. After a cursory search along $\nu_y = g\nu_x$ or $\nu_x = g\nu_y$, an excellent working point was found: $\nu_x = 0.1$, $\nu_y = 0.1618$ for electron beam and $\nu_x = 0.083$, $\nu_y = 0.1343$ for proton beam.

MEIC Luminosity For Nominal Design Parameters

The working point yields luminosity which is even slightly above the design luminosity, by about 2% (Figure 1). We verified that this high luminosity is maintained over at least 10 damping times (more than 15000 turns).

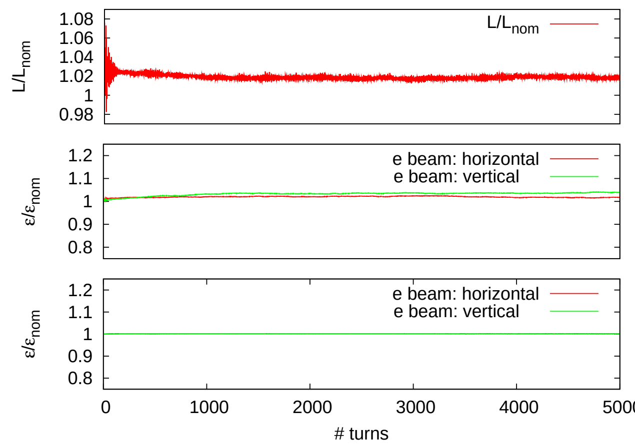

Figure 1: Top: MEIC luminosity, normalized to the peak design value. Middle: electron beam emittance normalized to the design value. Bottom: proton beam emittance normalized to the design value.

MEIC Luminosity Dependence on Beam Current

We study the dependence of the MEIC luminosity on the electron and proton beam current: the bunch charge for each beam is increased as the other is kept fixed. Figure 2 shows the luminosity and the emittances, normalized to the nominal design values, of the two beams as the electron current was increased. It is evident that the MEIC luminosity increases linearly with the current of the electron beam, while the emittance growth is on the order of few percent. Figure 3 shows the normalized luminosity and emittances of the two beams as proton current was increased. At about 2.5A, the linear increase in luminosity tapers off until it reaches a maximum at 4A. Increasing proton beam current beyond 4A leads to a steep emittance growth in the electron beam, which, in turn, decreases luminosity.

Coherent Beam-Beam Instability

The coherent beam-beam instability, manifested through a coherent oscillation of particle distribution of colliding beams, was not observed in this study, even as the electron

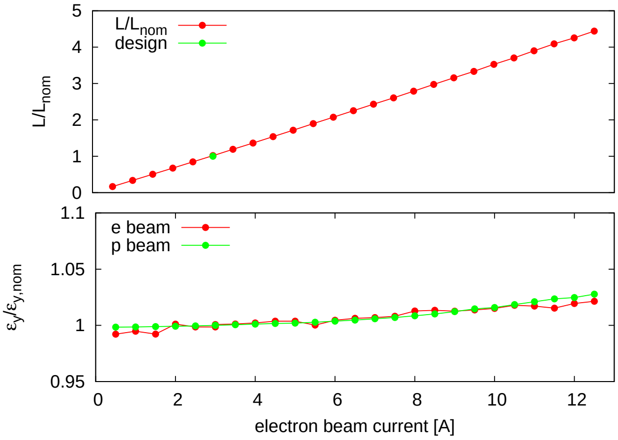

Figure 2: MEIC luminosity (top) and electron and proton beam emittances (bottom), normalized to the design value, as the electron beam current is increased.

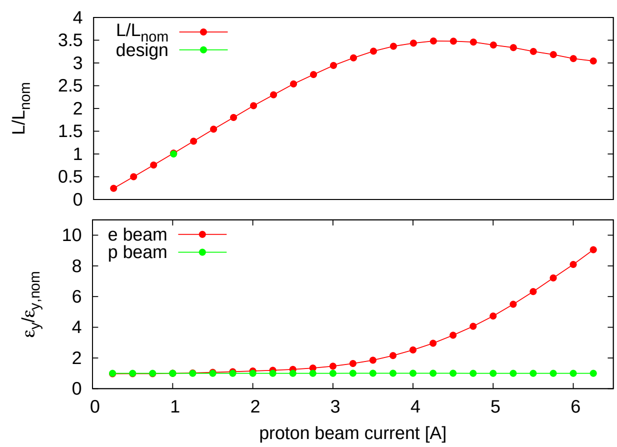

Figure 3: MEIC luminosity (top) and electron and proton beam emittances (bottom), normalized to the design value, as the proton beam current is increased.

and proton beam currents were increased by four and six times their design value, respectively.

Tune Footprint

Figure 4 shows the tune footprint of 400 random orbits from each of the beams. The tune spread of the proton beam is smaller than the spread of the electron beam, as is expected from their tune shifts (0.007 and 0.03; see Table 1). The tune footprint of each beam is safely away from lower-order resonances, which allows beams to maintain high luminosity for a very long time. A detailed, in-depth study of the nonlinear effects induced by the resonances is currently underway.

DISCUSSION AND FUTURE WORK

We reported on the preliminary simulations of beam-beam effects for the new parameters of the MEIC design. Excellent working point, which performs at the designed

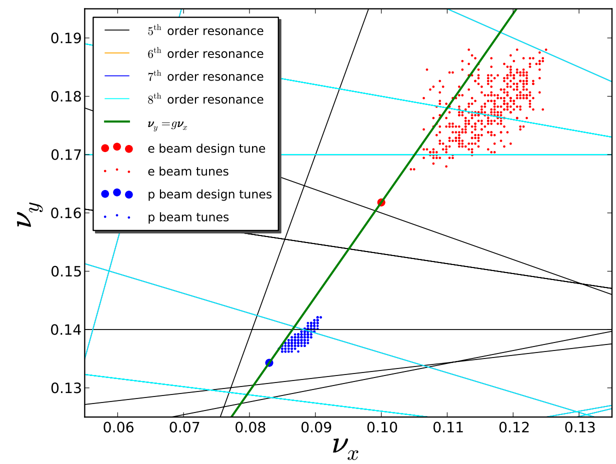

Figure 4: Tune space for the electron beam. High order resonant lines are shown in various colors. The line for which the ratio is equal to the golden mean is shown in green. Small red and blue dots represent the tunes of the 400 random orbits from electron and proton beams, respectively. Large red and blue dots represent design tunes for electron and proton beams.

luminosity, is found by marching along the lines in tune space for which the slope is equal to the golden mean. The simulations are carried out using a state-of-the art code BeamBeam3D [2], running on the Jefferson Lab's cluster. They demonstrate that the proposed parameter set is comfortably away from beam-beam instabilities and preserves the yields the design luminosity.

Even though these simulations use a simple linear transfer map, head-on collisions, and 1 IP, they do, however, provide a fairly reliable overall picture of the beam dynamics over short timescales. The more in-depth MEIC beam-beam studies which we are currently involved in will account for the following important issues: i) multiple IPs; (ii) crab crossing: MEIC design includes a crab crossing, which should be included in beam-beam simulations; (iii) chromaticity correction: because of strong focusing (small β^*), chromaticity is a serious issue; (iv) tolerance of imperfect ring optics: how sensitive is the beam stability to imperfections in the optics? (v) importance of space charge: is the low energy MEIC design sensitive to space charge?

Authors would like to thank R. Li and J. Qiang for helpful discussions.

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