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3.14 Beam-Beam Issues in ELIC

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3.14.1 **Introduction**

Over the last decade, Jefferson Lab has been actively pursuing design studies of an electron-ion collider for future nuclear physics research articulated in the most recent Long Range Plan of the DOE/NSF Nuclear Science Advisory Committee [1]. This collider (ELIC), [2], which is based on the existing CEBAF facility, would provide collisions between polarized electrons and polarized light ions or unpolarized heavy ions over a wide CM energy range at multiple interaction points (IP). Recent evolution of science programs and accelerator design iterations guided us toward a staged path, making a low-to-medium energy collider (CM energy up to 51 GeV) an immediate project goal and a high-energy collider (CM energy 100 GeV or higher) a future upgrade option.

The present medium-energy ELIC design features a high luminosity, at the level of 10^{34} $cm^{-2}s^{-1}$ per detector, with the possibility of up to three IPs, by taking full advantage of a high bunch repetition CW electron beam from the upgraded 12 GeV CEBAF recirculated SRF linac, construction of a new ion complex and two new figure-8 shape collider rings. As a design concept, ELIC high luminosity is attained by utilizing high bunch repetition and high average current crab-crossing colliding electron and ion beams with small transverse emittance and short bunch length, and strong final focusing at collision points. Choice of this luminosity concept was motivated by the remarkable success of two electron-positron colliders – KEK-B and PEP II B-factories – which reached luminosities over 10^{34} $cm^{-2}s^{-1}$. In a way, Jefferson Lab is poised to replicate the same success in a collider involving *hadron* beams. The new concept requires the colliding ion beams of ELIC to be very different from all existing or previously operated hadron colliders in terms of bunch charge (very small), bunch length (very short), transverse emittances (very small) and repetition frequency (very high and CW), while, at the same time, it pushes the final focusing parameter β^* to be an order of magnitude smaller than what has been achieved in hadron colliders. To support such a conceptual design, extensive R&D programs have been established at Jefferson Lab, supplemented by several external collaborations.

Since several key parameters of the ELIC ion beam and IR design have been expanded into an unexplored region, in particular, ELIC employs very small (cm or less) β^* to squeeze transverse beam sizes to several μm at collision points, and requiring a moderate (50 to 100 mrad) crab crossing angle due to very high (0.5 to 1.5 GHz) bunch repetition, investigating the beam-beam effect becomes critically important as part of feasibility study of this conceptual design. The sheer complexity of the problem requires us to rely on computer simulations for evaluating this nonlinear collective effect. It is our R&D goal to examine the incoherent and coherent beam-beam effects under the nominal design parameters, to characterize luminosity and operational sensitivities of these parameters as well as to take into account coupling to single particle nonlinear dynamics in the collider rings. In a late phase of this study, we plan further to evaluate beam-beam instability coupled to several other collective beam effects of a similar time scale, such as electron cooling of the colliding ion beam, and, at low ion energy, the space charge. This work is partially supported by a DOE SciDAC grant and as a collaboration with the Accelerator Modeling and Advanced Computing Group of the Center for Beam Physics at LBNL.

3.14.2 **Simulation Model, Code and Scope**

From the simulation standpoint, a ring-ring beam-beam study can be divided into two naturally distinct parts: tracking of particle collisions at IPs, and transporting beams through collider rings. These two parts are usually modeled differently to address different physics mechanisms and characteristic timescales. At the present stage, our attention is focused on disruption of colliding beams by nonlinear beam-beam kicks and induced luminosity reduction. Tactically, we simplify beam transport in the rings by ideal linear mappings plus synchrotron radiation damping and associated quantum fluctuations of electrons, effectively omitting rich and important single and collective effects in the rings, in order to extract maximum information about the pure beam-beam effect through the most detailed tracking within the current computer capability. This idealized physics model is in a so-called strong-strong regime in which both colliding beams can be disrupted by the beam-beam kicks. On the computational level, colliding bunches are modeled by groups of macroparticles interacting with each other through nonlinear beam-beam kicks calculated using the standard particle-in-cell method.

The simulation code utilized in the present ELIC study is BeamBeam3D, a self-consistent code developed at LBNL which solves the Poisson equation for electromagnetic fields using the shifted integrated Green function method over a 2D mesh for a number of longitudinal slices [3]. The code has been benchmarked against other beam-beam codes and experimental data with reasonable success [4]. A numerical test indicated that a 64×128 transverse mesh and 20 slices are sufficient to produce converged results with minimum 200,000 macroparticles for each colliding bunch. With these run parameters, a typical production run for tracking two colliding bunches and a single IP over 10,000 turns in the ring (corresponding to roughly 0.1 seconds storing time, and approximately 10 to 12 electron damping times) usually takes about several hours of wall clock time on a 64 CPU cluster of a NERSC supercomputer or the JLab LQCD parallel computer, as a consequence defining the scope of the simulations. It should be acknowledged that while our ELIC simulations should reveal short-term (fractions of a second) dynamics under repeated particle collisions, they could not be used to predict long-term (minutes or longer) beam behaviour.

3.14.3 **Simulation Results**

We have completed two ELIC beam-beam simulation studies: one for an early ELIC design with a higher CM energy (7 GeV electron to 150 GeV proton), and the other for the present medium-energy (5 GeV electron to 60 GeV proton) version of ELIC. These two studies are very similar in scope, starting with simulations using nominal design parameters with a synch-betatron tune working point selected empirically, followed by a luminosity scan against the current of one of the two colliding beams in order to explore both limits of design parameters and threshold values for the onset of coherent beam-beam instabilities. Both studies also present very similar simulation results. An empirical search for a better working point in the two dimension betatron tune space was also commenced, assisted by examination of the footprints in the tune space. For the first study, in addition to the single IP case, simulations for a system of four collision points and two subsets of 12 bunches were also performed to examine the influence of coupling of multiple bunches through multiple IPs on the beam-beam effect. Details of these two studies were documented in two PAC and IPAC papers [5,6]. Here we only present a brief summary of some of the main results.

3.14.3.1 ***Luminosity Trends for Normal Design Parameters***

With a fair working point, ELIC luminosity settles on an equilibrium value of about 50% of the design value (including 25% loss due to the hourglass effect for the case of high energy ELIC) after an initially rapid decay usually within one electron damping time. The saturated luminosity is highly sensitive to choice of the betatron tune working point, as is readily seen from the relative position of the beam footprint in the tune map. The reduction of luminosity, apart from the hourglass effect, is primarily due to large degradation of the vertical emittance of the electron beam, indicating that the flat electron beam (with emittance aspect ratio 25 at 7 GeV) is a relatively weak beam. A troubling observation is that there is a very slow decay of luminosity, indicating an unknown underlying physical process with a time scale on the order of few seconds or longer, which is far beyond scope of this simulation study. It should be noted that planed electron cooling of ion beams in the ELIC design will indeed introduce a damping mechanism with a damping time in order of several seconds, and therefore will very likely, pending further simulation studies, suppress this slow drift of luminosity and deliver stable collider operation.

3.14.3.2 *Luminosity Dependence on Beam Current*

The simulations show that in the region near the ELIC nominal design, luminosity increases almost linearly as the current of each beam is increased, one at a time. For example, as the proton currents are increased, the vertical RMS size of the electron beam also increases, while the horizontal RMS size of the electron beam and both transverse RMS sizes of the proton beam remain the same. When a current is increased far beyond the design values of either proton or electron beams, nonlinear beam-beam interactions start to dominate, causing a notable slowdown of luminosity increase, and eventually breakup of the beams. The fact that the linear region of beam currents is very large, up to a factor of three over the design current (1 A and 2.5 A for proton and electron, respectively, for the high energy ELIC case), does not mean we can immediately take advantage of increasing design beam currents to harvest a much higher luminosity. It is not only that the stored beam currents are limited by other effects in the ring such as allowable total synchrotron radiation power for the electron beam, but also by the fact that our simulations are based on a simplified model which has already excluded nonlinear single particle dynamics in the ring and other coupled collective effects. The main result from these numerical simulations is that the limit of current in ELIC colliding beams due to the *pure* beam-beam effect alone is very large. Including in the simulation the coupling to nonlinear beam dynamics and other collective effects could change the situation significantly; this will be addressed in the next stage of the ELIC beam-beam studies.

3.14.3.3 *Coherent Beam-Beam Instability*

The coherent beam-beam instability – a coherent oscillation of particle distribution of colliding beams – was observed for the high-energy ELIC collider when the electron current is increased to three times its design value. Further increase of the beam current leads to beam blow-up. For the medium-energy ELIC, the coherent beam-beam instability was not observed, even when the electron and proton beam currents were increased four and six times their design value, respectively.

3.14.3.4 *Multiple Interaction Points*

The ELIC design supports collisions at multiple IPs. Attempts have been made to evaluate the additional bunch-to-bunch coupling brought by multiple IPs. Taking advantage of a symmetric layout of the figure-8 shape collider rings and assuming certain integer ratio of the IP-to-IP distance over the ring circumference, the simulated system can be reduced into two coupled sets of small number of bunches, one set from each beam, leading to significant computational savings. For the high-energy ELIC, simulations demonstrate that luminosity in the case of four IP operation behaves very much like the case of the single IP, with equilibrium luminosity per IP nearly identical to the single IP luminosity. We can conclude that multiple bunch and multiple IP couplings do not amplify the old beam-beam instability nor introduce any new coherent instability at least for this set of ELIC design parameters.

3.14.3.5 *Locating Optimal Working Point Using an Evolutionary Algorithm*

It is well known that the beam-beam effect and collider luminosity are sensitive to synchro-betatron resonances of the two colliding beams. Therefore, careful selection of a tune working point is essential for successful operation of a collider as well as for achieving high luminosity. A systemic method of searching a good working point is certainly preferable to empirical methods, which are traditionally used. A brute-force scan of the 4D (betatron tunes only for the two colliding beams) or 6D (also including synchrotron tunes) parameter space is computationally prohibitive, which is why we turned to other advanced searching algorithms. To that end, we implemented an evolutionary algorithm, similar to what was used in a photoinjector design [7]. The objective function here is the collider's luminosity, computed by the BeamBeam3D code, and subject to constraints of the independent variables – in this case the four betatron tunes. The algorithm traverses only relatively small regions of the parameter space devoid of resonance lines, and has located excellent working points which reach very close to (and sometimes even exceed) the design luminosity [8]. This automation of the search for the working point is a valuable tool for numerical optimization of the collider's performance.

3.14.4 **Discussion and Outlook**

There are several outstanding issues we would like to address in the future beam-beam simulation studies of ELIC. The first issue is improving the simulation model by including nonlinear dynamics in the collider ring and taking into account such complications as chromatic effect and imperfect magnets, which will require expansion of scope of simulation both in the complexity and execution time. The next issue is examining the effect of several unique features of ELIC IR design on the beam-beam problem, most important among which is a crab crossing of the colliding beams enabled by high integrated-voltage SRF crab cavities. The third issue is assessing the effect of coupling between beam-beam and other collective phenomena. Two of such coupling effects are of particular interest: a damping mechanism associated with electron cooling of ion colliding beams, and, at very low energy, the ion space charge effect. The former effect should help stabilize the ion beam and improve collider performance, while the latter should add coupling between different slices of colliding bunches at and near collision points, thereby presenting a tremendous challenge to the computational algorithm and capability.

On the methodology level, we will consider using both strong-strong and weak-strong simulation regimes to yield answers for questions associated with different time and particle scales. The strong-strong self-consistent code enables the study of the beam-beam physics alone to a high precision, but only limited complexity of the underlying model. At the price of sacrificing the self-consistency of the model, the much-faster strong-weak simulations can enable the study of the long-term beam-beam behavior of ELIC. Ultimately, our goal for beam-beam studies is to ensure the validity of the ELIC conceptual design as well as of the design optimization.

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3.15 Beam-Beam Issues in the ILC and in CLIC

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3.15.1 Introduction

In future linear colliders, beam-beam effects are of critical importance. They limit the achievable luminosity and strongly impact the choice of fundamental machine parameters, e.g. the crossing angle at the interaction point or in case of CLIC the design of the accelerating structure. During the beam collisions background particles are produced that impact the design and performance of the detectors.

In this paper we will remind the reader of the relevance of the beam-beam effects for the machine design and show how they impact the optimisation of the specific luminosity in ILC and the parameter choice in CLIC. We will discuss the difficulties in the beam delivery system to achieve and maintain small beam sizes and the importance of ATF2. The need to produce luminosity at lower than nominal energy is an important concern for ILC and CLIC, we will briefly discuss the consequences. Finally we will remind the reader of the beam-beam background and mention some new developments of the simulation codes.

3.15.2 ILC Optimization

The GDE [25] currently attempts to reduce the cost of the International Linear Collider (ILC) to make funding more likely. One of the cost reduction options that have been considered is to reduce the total charge per beam pulse, while the pulse length remains basically unchanged. In this case, the beam will extract only half the RF power from the klystrons. This allows one to reduce the number of klystrons. In order not to compromise the luminosity target, the specific luminosity has been increased. The trade-off between cost reduction and increase in risk is still being debated, we will not comment on this here. However, the increase of specific luminosity is of great interest and one can take advantage of it independent of the RF power chosen. In the following we will briefly discuss the consequences for the machine.