# ELECTRON-ION COLLIDER AT CEBAF: NEW INSIGHTS AND CONCEPTUAL PROGRESS *

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*Abstract*

We report on progress in the conceptual development of the proposed high luminosity (up to $10^{35}$ cm$^{-2}$s$^{-1}$) and efficient spin manipulation (using “figure 8” boosters and collider rings) Electron-Ion Collider at the CEBAF. This facility would use a polarized 5-7 GeV electron beam from a superconducting energy recovering linac with a kicker-operated circulator ring, and a 30-150 GeV ion beam in a storage ring (for polarized p, d, $^3$He, Li and unpolarized totally stripped nuclei up to Ar). Ultra-high luminosity is envisioned to be achieved with very short crab-crossing bunches at 1.5 GHz repetition rate. Our recent studies were concentrated on understanding beam-beam interaction, ion beam instabilities, luminosity lifetime due to intrabeam scatterings, ERL-ring synchronization, and ion spin control. We also proposed a preliminary conceptual design of the interaction region. These studies have been incorporated into the development of the luminosity calculator and the formulation of minimum requirements for the polarized electron sources.

## INTRODUCTION

The nuclear physics community worldwide has envisioned a high luminosity polarized electron-ion collider (EIC) as a powerful microscope to probe the hadronic structure of matter. Luminosity of this collider should be $10^{33}$ cm$^{-2}$s$^{-1}$ as a minimum, and one to two order of magnitude higher for many critical experiments. Both electron and light ion beams should be at least 80% polarized longitudinally. The center-of-mass energy of colliding particles should be variable between 20 to 100 GeV. Spin-flip of both beams is extremely desirable for exclusive measurements. [1]

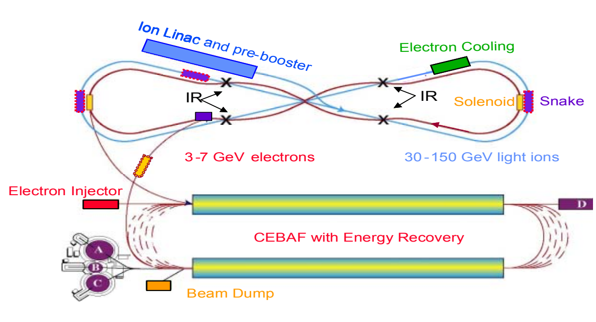


Figure 1: ELIC schematic layout

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The **E**lectron–**L**ight **I**on **C**ollider (**ELIC**) [2,3], shown schematically in Figure 1, is a high luminosity polarized electron–ion collider with center of mass energy range of 20-65 GeV. It would require an upgrade of the CEBAF to an energy recovering linac (ERL) and realization of an ion complex at JLab for accelerating and storing ions up to 150 GeV. Preliminary design studies indicated luminosity of the colliding electron and light ion beams can be as high as $10^{35}$ cm$^{-2}$s$^{-1}$ for up to four interaction regions with an arbitrary polarization direction of heavy particles. The CEBAF development for ELIC could be combined with upgrading the CEBAF to a 25 GeV fixed-target facility [2]. Table 1 shows the ELIC design parameters for three different center of mass energies.

Table 1. Basic parameters for ELIC

| Parameter | Unit | Value | Value | Value |
|---|---|---|---|---|
| Beam Energy | GeV | 150/7 | 100/5 | 30/3 |
| Cooling beam energy | MeV | 75 | 50 | 15 |
| Bunch collision rate | GHz | 1.5 | | |
| # of particles/bunch | $10^{10}$ | .4/1.0 | .4/1.1 | .12/1.7 |
| Beam current | A | ½.4 | 1/2.7 | .3/4.1 |
| Cooling beam current | A | 2 | 2 | 2 |
| Energy spread, rms | $10^{-4}$ | 3 | | |
| Bunch length, rms | mm | 5 | | |
| Beta-star | mm | 5 | | |
| Horizontal emit. norm. | µm | 1/100 | .7/70 | .2/43 |
| Vertical emit., norm. | µm | .04/4 | .06/6 | .2/43 |
| Number of IPs | | 4 | | |
| Beam-beam tune shift (vertical) per IP | | .01/.086 | .01/.073 | .01/.007 |
| Space charge tune shift in p-beam | | .015 | .03 | .06 |
| Lumi. per. IP*, $10^{34}$ | cm$^{-2}$s$^{-1}$ | 7.7 | 5.6 | .8 |
| Core & luminosity. IBS lifetime | H | 24 | 24 | >24 |
| Lifetime due to background scattering | H | 200 | >200 | >200 |

The ELIC should be operated in the following way. After stacking and accelerating ions to about 3 GeV/*c* in the pre-booster, the ion bunch train is injected into the large booster (the “Figure 8” ring in red color in Figure 1) for acceleration to 20-30 GeV/*c* and then injected into the ion collider ring (blue color) for cooling, final acceleration and storing. The large booster is then used as a circulator-collider ring (one or multi-turn) for 3-7 GeV electron beam accelerated in the ERL. With number $q_r$ of bunch revolutions in the circulator ring, the required average current from polarized electron source is reduced by a factor of $q_r$. It is anticipated, therefore, that the high luminosity of ELIC shown in Table 1 can be achieved at a moderate averaged current from the injector (2-30 mA).

There are a number of critical issues currently under investigation for high luminosity and operational efficiency of ELIC. The JLab injector group proceeds with study and design of 2.5 to 25 mA electron injector with state of art and prospective improvements of polarized source technology [4]. Other efforts are devoted to the theory and experiments on energy recovery in superconducting linac [5], optimum ERL-CR beam switch regime and simulations of the coherent synchrotron radiation effect on short electron bunches in circulator ring. Below we report on recent advances of other groups on basic topics of ELIC design.

## IBS, ELECTRON COOLING AND LUMINOSITY LIFETIME

Estimates of the proton bunch lifetime due to multiple intrabeam scatterings (IBS) in ELIC were based on models developed earlier for a round or flat ion bunch with small energy spread and a transverse temperature much larger than the longitudinal one [6,7]. When the model was applied to ELIC, formulas for the beam emittance growth rates were modified [8] due the non-negligible contribution of the energy spread to the beam horizontal size. The numerical results using the modified formulas for a bunch of $2x10^9$ protons with $\beta_x=\beta_y=10$ m, R=100 m and $\Delta p/p=3x10^{-4}$ are shown in Table 2.

Table 2: IBS calculations parameters

| E (GeV) | $\sigma_s$ (mm) | $\varepsilon_{x,norm}$ (μm) | K | Longitudinal Lifetime (min) | Horizontal Lifetime (min) |
|---|---|---|---|---|---|
| 20 | 80 | 4 | 1 | 120 | $1.7x10^5$ |
| 150 | 5 | 1 | 1/25 | 4.2 | 2.9 |

Electron cooling (EC) is introduced for suppressing ion beam blowup due to IBS and reduction of the transverse and longitudinal equilibrium emittances to a minimium. An EC design utilizing a circulator-cooler ring incorporated with an ERL will provide a high electron cooling current (up to 2-3 A) at a moderate average current in ERL to meet ELIC's ultra-high luminosity requirement. One important advantage of an ERL-based cooler is the possibility of *staged cooling* for reduction of the initial cooling time [7]. The conceptual development of an ERL based 75 MeV EC is being pursued at the JLab and parameters for the two-stage cooling for ELIC are shown in Table 3.

Table 3: Electron cooling parameters for ELIC

| Parameter | Unit | | |
|---|---|---|---|
| Beam energy | GeV/MeV | 20/10 | 150/75 |
| Length of cooling section | M | 30 | 30 |
| Particles per bunch | $10^{10}$ | .2/1 | .2/1 |
| $I_{ave}$ in ERL | MA | 2x25 | 2x25 |
| $I_{circulating}$ | A | 1/2.5 | 1/2.5 |
| Proton emit., norm (injected) | μm | 4x4 | |
| Proton emit., norm (equilibrium) | μm | 1x1 | 1x.04 |
| Initial cooling time | Min | 10 | 10 |
| Cooling time at equilibrium | Min | .2 | 1 |

In conventional EC designs, a superconducting solenoid is used in the cooling section for electron beam magnetization. We started to explore using a quadrupole or axial symmetric focusing along the entire electron track while using a non-magnetized electron gun. While the magnetization feature of EC is preserved, such a transport concept has an important advantage in effective beam diagnostics and alignment.

At equilibrium in collider mode, the cooling beam area frequently exceeds the ion beam area. The lifetime of the ion beam core and luminosity shown in Table 1 has been estimated by taking into account the Touscheck scattering of particles beyond the edge of the cooling beam [7].

## ERL-RING SYNCHRONIZATION

Synchronization between electron and ion bunches is a common constraint of EIC design. The synchronization condition can be expressed by a relationship, $f=q_e f_e=q_i f_i$, between RF frequency $f$ and the revolution frequencies $f_e=v_e/C_e$, $f_i=v_i/C_i$, where $v_e$, $v_i$ and $C_e$, $C_i$ are the beam velocities and orbit circumferences for electron and ion bunches respectively, and $q_e$, $q_i$ are integers. The constraint is due to the ion velocity change by a factor of $10^{-3}$ in the energy range of an EIC. The difficulty is due to compensate the related change of ion beam revolution frequency by changing of the ion orbit length with energy. In the ELIC design where the ion beams are driven by RF of very high $q_i$ (about 7500 at $f$=1.5 GHz), a possible solution consists of varying the integer $q_i$ yet accepting a "residual" change of ion path length in arcs up to one bunch spacing (about 20 cm, corresponding to ±12 mm orbit displacement in the arcs). Ion acceleration in the collider ring can be achieved using warm resonators of variable frequency; after that one can switch (via beam re-bunching) to high voltage superconducting resonators.

## SPIN IN ELIC

The use of figure-8 boosters and collider rings ensures zero spin tune, thus avoiding intrinsic spin resonances. No spin rotators are required. Longitudinal to transverse ion spin control, stabilization and fast flipping can be achieved for all polarized species at all energies by the weak steering dipole magnets distributed around the arcs in cooperation with solenoids in the straight sections. Spin stability issues are virtually eliminated. Solenoids in electron arcs and helical Siberian Snakes in the ion arcs can be used to obtain longitudinal spin for electrons and protons at 4 interaction points simultaneously [9].

## ION BEAM STABILITY

Instabilities have been examined for the ELIC parameters at the top luminosity. The threshold beam currents for longitudinal and transverse microwave instabilities are found safely above our ELIC design current. The longitudinal coupled bunch modes as well as the transverse ones would require feedback for stabilization. The electron cloud instability is also found insignificant for the highest ELIC bunch repetition rate of 1.5 GHz.

## ELIC INTERACTION REGION

To implement very tight focusing in the ELIC interaction region, it is beneficial to use a focusing triplet (DFD or FDF) which provides a net focal length of about 5 m at the collision energy of 150 GeV. This triplet uses two types of quadrupoles: 1.12 m long defocusing one and 1.96 m long focusing one, with transverse aperture radius of 3 cm and 7.5 T peak field. The quadrupole parameter defines a maximum field gradient of 250 T/m.

Our preliminary lattice design assumes $\beta^*$=1 cm and $\beta^{max}$=3800 m. The final focus lattice can be configured either symmetrically (DFDODFD) or anti-symmetrically (FDFODFD). The advantage of the anti-symmetric configuration is its lower sensitivity to ground motion and magnet power supply fluctuation etc. Assuming a final normalized ion beam horizontal emittance after cooling of $10^{-6}$ µm, this yields the beam width in the final triplet of about 5 mm. Further, a more aggressive lattice design would assume a peak field of 9 T at the same aperture and $\beta^{max}$ of about 6 km, which would allow us to reduce $\beta^*$ to about 5 mm. However, much shorter focal length of the triplet (less than 5 m) would significantly reduce free space around the interaction point available for the detector (to less than 4 m). The interaction region will consist of two final focus points for two detectors separated by about a 60 m section. The IR region will then be matched through another lattice with arcs where a β function equals 12 m or less.

## BEAM-BEAM SIMULATIONS

The beam-beam effect in a linac-ring collider has been studied using simulation techniques. The simulation model includes the following features: (1) Colliding beams are modeled by extended macroparticles with their aspect ratio chosen appropriately using the beam parameters. (2) The beam-beam interaction is calculated using a summation within each longitudinal slice of space charge of the two colliding beams. The force between two macroparticles follows the Bassetti-Erskine formula. (3) Outside of the interaction region, the ions are treated as a beam stored in a ring, using a linear update model for the transverse dynamics, and a non-linear model for the longitudinal dynamics, which includes the ring chromaticity and the non-linear RF bunching from an RF cavity. (4) The ions are collided each turn with new electron bunches at a single interaction region. It remains to study the effects of multi-turn interactions that will arise in a circulator ring.

Figure 2 illustrates the simulation results for a bunch of $2\times10^9$ protons with .04 µm vertical emittance and .06 synchrotron tune. The vertical beam-beam tune shift in proton beam is then 0.02. The values of the rest parameters are the same as in Table 1 at proton energy 150 GeV. The simulation was done with 1000x1000 marcoparticles in a single collision per turn, tracked through 20,000 collisions (turns). The results show that the luminosity stabilizes at a level of several times $10^{34}$ $cm^{-2}s^{-1}$. The reduction in luminosity observed is due to about 20% spot size growth in the vertical (small) direction. [10] One finding of the simulation work is that it is quite important to properly match the ions to the ring in order to eliminate luminosity fluctuations from breathing modes of the ion beam. Likewise, luminosity may be enhanced by properly matching the electron envelope to the ion space charge, but such a matching procedure was not used in the results reported here.

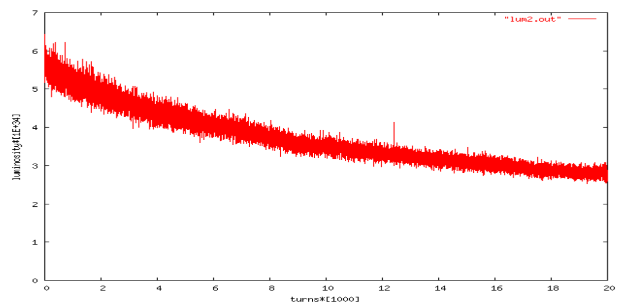


Figure 2. Luminosity/$10^{34}$ $cm^{-2}s^{-1}$ vs. number of turns/1000.

## CONCLUSIONS

An excellent scientific case started development of a high luminosity polarized electron-light ion collider to address fundamental questions in Hadron Physics. JLab design studies have led to an approach that promises luminosities from $10^{33}$ up to nearly $10^{35}$ $cm^{-2}c^{-1}$ for electron-light ion collisions at a center-of-mass energy between 20 and 65 GeV. This design can be realized using energy recovery on the JLab site and can be integrated with a 25 GeV fixed target program for physics. Planned R&D will address open readiness issues.

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