

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 $10^{35} \text{ cm}^{-2}\text{s}^{-1}$) 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, ^3He , 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 an electron-ion collider (EIC) of variable center mass energy between 20 to 100 GeV as a powerful microscope to probe the hadronic structure of matter. Luminosity of this collider should be $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ as a minimum, and one to two orders of magnitude higher for many critical experiments. Both electron and light ion beams should be at least 80% polarized longitudinally. Spin-flip of both beams is extremely desirable for exclusive measurements [1].

The Electron–Light Ion Collider (ELIC) [2,3], shown

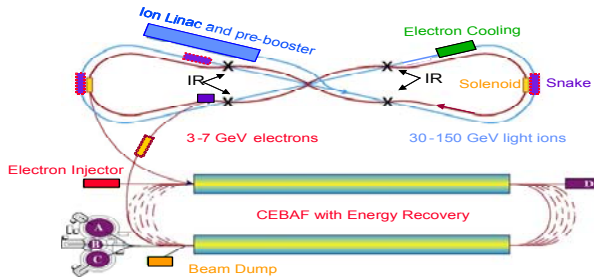


Figure 1: ELIC schematic layout

schematically in Figure 1, is a high luminosity polarized electron–ion collider with center of mass energy 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 $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ 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	1/2.4	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}	$\text{cm}^{-2}\text{s}^{-1}$	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 the 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 average current from the injector (2-30 mA).

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There are a number of critical issues currently under investigation for high luminosity and operational efficiency of ELIC. The JLab injector group is proceeding with study and design of a 2.5 to 25 mA polarized electron injector with state of art and prospective improvements of the polarized source technology [4]. Other efforts are devoted to theory and experiments on energy recovery in a superconducting linac [5], optimum ERL-circulator ring beam switch regime and simulations of the coherent synchrotron radiation effect on short electron bunches in the circulator ring. Below we report on recent advances of other 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 2×10^9 protons with $\beta_x = \beta_y = 10$ m, $R = 100$ m and $\Delta p/p = 3 \times 10^{-4}$ are shown in Table 2.

Table 2: IBS calculations parameters

E (GeV)	σ_z (mm)	$\epsilon_{x,norm}$ (μm)	K	Longitudinal Lifetime (min)	Horizontal Lifetime (min)
20	80	4	1	120	1.7×10^{-3}
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 minimum. 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 averaged current in the 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
Averaged current in ERL	MA	2×25	2×25
Averaged current in cooling ring	A	1/2.5	1/2.5
Proton emit., norm (injected)	μm	4×4	
Proton emit., norm (equilibrium)	μm	1×1	$1 \times .04$
Initial cooling time	Min	10	10
Cooling time at equilibrium	Min	.2	1

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

At equilibrium in the collider mode, the cooling beam area is a number of times larger than the ion beam area. The lifetime of the ion beam core and luminosity shown in Table 1 have been estimated by taking into account the Touschek scatterings 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 condition of synchronization 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. It would be difficult to compensate the related change of ion beam revolution frequency by changing the ion orbit length with energy. In the ELIC design where the beams are driven by RF fields of very high q_e and 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 orbit length in arcs in the interval of 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 value, 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 focal length of about 5 m at the collision energy of 150 GeV. This triplet uses two types of quadrupoles: 1.12 m long and 1.96 m long, with aperture radius of 3 cm and 7.5 T peak field, which yields a quadrupole field gradient of 250 T/m. Our preliminary lattice design assumes $\beta^*=1$ cm and $\beta^{\max}=3.8$ km. 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 fluctuation of magnet power supply. Assuming a normalized horizontal emittance of the ion beam after cooling of 1 μm , this yields a 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 β^{\max} of about 5 km, which would allow us to reduce β^* to about 5 mm. Further reduction of the final focal parameters to less than 5 m, however, would significantly reduce free space around the interaction point for the detector (to less than 4 m). The interaction region of each of two crossing straight sections 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 including the ring chromaticity and the RF bunching. (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 2×10^9 protons with .01 μm vertical emittance and .06 synchrotron tune. The values of the rest beam parameters are the same as in Table 1 at proton energy 150 GeV. The vertical tune shift in proton beam is then .02. The

simulation was done with 1000x1000 macroparticles 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 $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The reduction in luminosity observed is due to about 20% vertical size growth [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.

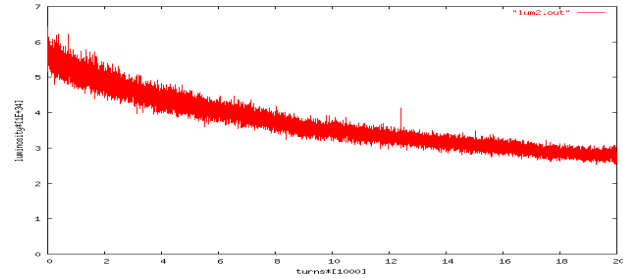


Figure 2. Luminosity/ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ vs. number of turns/1000.

CONCLUSIONS

An excellent scientific case started development of an ERL based 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 $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ for a center-of-mass energy between 20 and 65 GeV. This design can be realized using electron 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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