Design Studies of High-Luminosity Ring-Ring Electron-Ion Collider at CEBAF*

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Abstract Experimental studies of fundamental structure of nucleons require an electron-ion collider of a center-of-mass energy up to 90 GeV at luminosity up to 10^{35} $cm^{-2}s^{-1}$ with both beams polarized. A CEBAF-based collider of 9 GeV electrons/positrons and 225 GeV ions is envisioned to meet this science need and as a next step for CEBAF after the planned 12 GeV energy upgrade of the fixed target program. A ring-ring scheme of this collider developed recently takes advantage of the existing polarized electron CW beam from the CEBAF and a green-field design of an ion complex with electron cooling. We present a conceptual design and report design studies of this high-luminosity collider.

INTRODUCTION

A polarized high-luminosity electron-ion collider (EIC) as a future facility for advanced nuclear physics research has been receiving wide-range support due to a continually emerging science case and advances of accelerator technology. There are a few conceptual design studies currently underway worldwide [1]. A ring-ring polarized EIC design with luminosity $5{\cdot}10^{32}$ has been developed, and an energy-recovery linac (ERL)-ring scheme is under study at the Brookhaven National Laboratory, both based on use of the RHIC complex for ion beams. At the Jefferson Laboratory, a high-luminosity polarized electron-ion collider (ELIC) based on the Continuous Electron Beam Accelerator Facility (CEBAF) was proposed to meet the nuclear science quests at luminosity levels up to 10^{35} [2,3].

ELIC RING-RING DESIGN

The very high luminosity of the ELIC conceptual design calls for the green-field design of an ion complex and a new approach to organization of the interaction region. For the electron complex, selection of a storage ring over an ERL with or without a circulator-collider ring [2] relaxes the high-average-current requirement of the polarized electron source while still preserving ultra- high luminosity of the collider [3].

Figure 1 shows a schematic drawing of the ELIC ring-ring design. The CEBAF accelerator after the 12 GeV upgrade with the existing polarized source and injector, capable of delivering a beam of up to 9 GeV energy, up to 1 mA CW current and over 70% polarization, will be utilized as a full-energy injector of electron bunches into a storage ring of a 2.5 A stored current. It is expected for the duration of storing the beam polarization will be maintained at the 90% level due to the electron storage ring self-polarization effect. Addition of a positron source to the CEBAF injector will allow positron beams to be accelerated in CEBAF, accumulated and self-polarized in the storage ring, and used for collisions with ions at luminosity similar as for electron-ion collisions [3].

The ELIC ion complex will generate, accelerate and store up to 1 A polarized (p, d, ^{3}He and Li) or non-polarized (up to A=208) ion beam with energy up to 225 GeV for protons or 100 GeV/n for completely stripped lead. An ion beam from a 285 MV SRF linac will be stacked in a 3 GeV pre-booster with stochastic cooling [4]. The 30 GeV large booster has common arcs with the electron ring. Beam optics of boosters and collider ring are carefully designed to avoid crossing the transition energy at acceleration. Stochastic cooling will be called for again in the collider ring for initial ion transverse cooling at injection energy. After that, electron cooling (EC) [5] will be used for initial longitudinal cooling and a continuous 6D cooling of the ion beam in collisions mode.

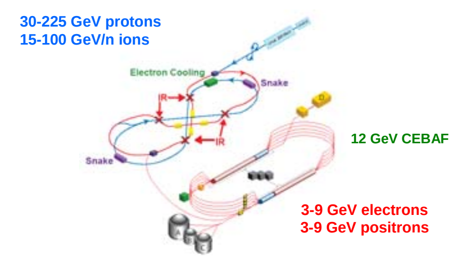

Figure 1: A schematic drawing of ELIC ring-ring design.

One unique ELIC design feature is the figure-8 shape for the boosters and collider rings. Such ring topology conveniently eliminates spin sensitivity to beam energy for all species, i.e., provides ion spin preservation during acceleration, and ensures easy spin manipulation. There are four interaction points (IP) arranged symmetrically on the two crossing straights of the figure-8 for high science productivity. Two solenoid snakes for the polarized electron beam and snakes on dipole fields for the polarized proton and ^{3}He beam are installed in the arcs to provide longitudinal polarization at four IPs simultaneously.

The luminosity concept of ELIC has been established on careful consideration of multi beam physics effects including cooling, beam-beam interactions, space charge and intra-beam scattering. Beam cooling in cooperation with a strong bunching SRF field of high frequency in the collider ring delivers very short (5 mm or less) ion bunches with desired small emittances. The advantages of small longitudinal and transverse sizes of ion bunches are enabling a *super-strong final focusing* at the collision points and *crab crossing colliding beams* which allow a very high bunch collision rate (1.5 GHz). Choice of a modest bunch charge at relatively high

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average currents reduces electron cloud effects and microwave instabilities of intense ion beams. Large synchrotron tunes that exceed the beam-beam tune shifts allow one to avoid dangerous synchro-betatron non-linear beam-beam resonances, thus allowing a large beam-beam tune shift. Equidistant phase advance between four IPs effectively reduces the combined beam-beam tune shift to a value of a single IP. Flat beams, by lowering x-y coupling at a fixed beam area, bring a significant reduction of the intra-beam scattering impact on luminosity. Table 1 displays the main parameters of the ring-ring design.

Table 1: Basic parameters for ELIC

Beam energy	GeV	225/9	150/7	100/5	30/3
Collision rate	GHz	1.5			
Particles/bunch	10^{10}	.42/.77	.42/1	.42/1.1	.125/1.7
Beam current	A	1/1.85	1/2.5	1/2.7	.3/4.1
Ener. spread, rms	10^{-4}	3			
Bunch length, rms	mm	5			
Beta-star	mm	5			
Hori. Emit. norm.	µm	1.2/90	1.06/90	.65/60	.21/37.5
Vert. emit., norm.	µm	.05/3.6	.04/3.6	.06/6	.21/37.5
Beam-beam tune shift (vert.) per IP		.006/ .086	.01/ .086	.01/ .075	.01/ .007
Space charge tune shift in p-beam			.015	.03	.06
Lumi. per IP, 10^{34}	$cm^{-2}s^{-1}$	5.7	6	4.4	0.6
Lumi. lifetime	Hrs	24	24	24	>24

* Note the peak luminosity values include the hourglass effect.

RECENT DEVELOPMENTS

Forming of ion beam with stochastic cooling

Space charge effect is a challenge in the process of forming ELIC intense ion beams at the low-energy region. Transverse stochastic cooling [4] of a coasted beam will be utilized in the pre-booster where stacking of ion beams takes place. Our estimates showed accumulation of a 1 A ion beam with space charge limited emittances of 10-15 µm within several minutes. Accumulated beam in the pre-booster, after bunching and accelerating to 3 GeV, will be injected into the large booster. About 10 to 15 injections are needed to fill the whole orbit of the large booster ring. The beam then be accelerated to 30 GeV for protons or up to 15 GeV/n for ions and injected into the ion collider ring. Here stochastic cooling will be put to work again for reduction of normalized emittance to a level below 1 µm in about 30 min. At this stage, electron cooling starts to work effectively for further reduction of energy spread and for reaching and maintaining ion beam quality required for the ELIC high luminosity. Table 2 summarizes design parameters for stochastic cooling in the pre-booster and collider ring.

Table 2: Stochastic cooling in pre-booster/collider ring

Parameter	Unit	Value
Beam energy	GeV	0.2/30
Momentum spread	%	1/0.5
Pulse current from linac	mA	2
Cooling time	s	4/1200
Accumulated current	A	0.7/1
Stacking cycle duration (pre-booster)	min	2
Equilibrium emittance, norm.	µm	12/0.1
Laslett tune shift		0.03

Circulator electron cooler

To achieve and maintain a high luminosity for ELIC, an electron cooling facility capable of delivering a 3 A beam up to 125 MeV energy must be realized. Currently, an R&D program is in progress at BNL for design and test of a 54 MeV 100 mA ERL-based facility for cooling heavy ion beams in RHIC [6]. The ELIC electron cooling facility design is based on a multi-turn ERL scheme with a circulator-cooler ring (CCR) as shown in Figure 2 [3]. Electron bunches circulate one hundred turns inside the CCR while cooling ion bunches before being ejected and sent to the ERL for energy recovery. Our estimates showed that the quality of the electron beam survives at least a few hundred revolutions in the CCR before the cooling rate decays noticeably due to degradation of beam energy spread and emittance caused by the inter-beam and intra-beam scattering. By employing a CCR, the required average current from the injector and ERL is reduced to a modest value of 20-30 mA. Such a CW electron beam with about 2 nC bunch charge and small emittance is already within the range that current ERL-based light-source programs are actively pursuing [7]. Several recent injector simulations that employed sophisticated optimization algorithms indicate that the beam property design goal should be readily met [8].

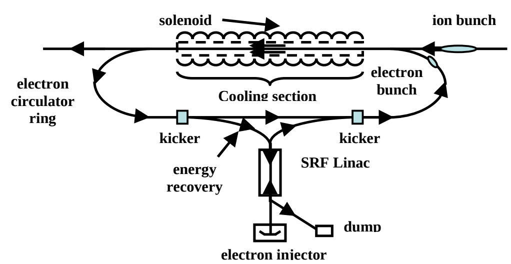

Figure 2: Layout of electron cooler for ELIC

Fast kicker for a circulator cooler ring

In the CCR scheme, a 10-20 kW, 500 ps pulse is responsible for kicking out every 100th bunch in the CCR and another similar pulse kicks in a fresh bunch from the ERL to fill the empty bucket, while leaving neighbouring bunches unaffected. At the present time, a few options exist for producing short, medium-power pulses with 15 MHz repetition rates. Pulse compression techniques employ a dispersive element to pile up many wave fronts of a broad-band, frequency-modulated input pulse [9]. The result is a very short pulse with high peak power. Recent experiments using a helically corrugated waveguide as the dispersive element have achieved compression and power enhancement ratios of 12 or better, creating 2 ns pulses with a 12 MHz repetition rate and a peak power of 10 kW [10]. Our kicker development plan includes bench testing of a low-power system using a 1 W amplifier, a surface-acoustic wave dispersive filter and 10 ns pulse generator. After an optimum frequency sweep range is identified, it is hoped that a corrugated waveguide could be built and tested with higher powers.

Crab crossing and high bunch collision rate

A 20 cm bunch spacing due to a 1.5 GHz repetition rate of colliding beams dictates a crab crossing for the ELIC IP design to avoid undesired parasitic beam-beam interactions. Crab cavities must be used to restore head-on collision mode; otherwise, the drop of the peak luminosity due to crossing angle can be too severe. The initial ELIC IP design assumed a 100 mrad crossing angle with a ±2 m detector region [11]. To minimize the required crab crossing angle, iterations of the IP design were performed. The first optimization was done in IP configuration. With an observation that the final focusing quads for the electron beam are significantly smaller and have lower fields, they should be located nearest the IP while the ion quads should be placed farther away. This new configuration permits the electron beam to pass the ion quads with less stray field interaction. The order of focusing/defocusing quad doublets was also switched to take advantage of much smaller vertical emitances. The new IP configuration is able to enlarge the detector region to ±3 m. The second optimization was achieved by employing Lambertson magnets for final focusing such that the electron beam can pass through ion quads as close (15 cm) as possible to the ion beam center. Consequently, the required ELIC crab crossing angle after optimization is down to 30 mrad, more than a three-fold reduction.

Magnetic design for the final focusing magnets has been carried out at the JLab. The electron quad is a single-sector two-layer design with a magnetic iron collar operating below saturation. The ion quad is a four-layer single-sector design with a non-magnetic stainless steel collar and magnetic iron immediately outside the collar. Both magnets feature a beam pass-through in a shielded path in the cold iron. Table 3 provides the basic design parameters. The ion quads are candidates for operation at 2 K due to the high 8 T fields in the superconducting windings and the compact design.

Table 3: Final focusing element design parameters

Parameter		Electron quad	Ion quad
Gradient	T/m	64	220
Integral gradient	T	73.7	248
EFL	M	1.15	1.13
Diameter	Cm	5	6
Length	Cm	130	130
Integral BdL along shield	kG cm	0.241	7.336
Current density	A/cm^2	15,000	37,000
Amp turns	A	$2.07 \cdot 10^5$	$2 \cdot 10^6$
Current	A	3500	6000
Max field in coil	T	2	8

It has been estimated that a KEK-type single-cell SRF cavity [12] of 1.2 MV integrated voltage would be enough for the ELIC electron beam. For a 225 GeV proton beam, a kicker of 24 MV integrated voltage (180 G integrated magnetic field on axis over 4 m) [13] is required. Currently, a prototype design of a multi-cell SRF crab cavity of 24 MV or above is underway [14].

To accommodate the very high bunch collision rate available with crab crossing, a solenoid field of the detector should be introduced to the IR area, which is very likely a choice of detector concept. This field will also help operation of the start counters at high luminosity in close proximity to the IP. Such counters provide a time stamp for detector electronics and allow one to use an arbitrary high bunch collision rate. Calibration of the detector could be performed at a reduced luminosity and lower bunch rate.

Achromatic interaction point design

Due to a very short (5 mm) beta-star parameter of ELIC, special care for chromatic aberration of an IP must be taken for the stored electron beam of 0.1% energy spread. An achromatic IP design based on a preventive compensation concept provides a necessary mitigation. In this concept, all additional dipoles, sextupoles and quadrupoles required for compensation are placed before the final focusing block (FFB), thus composing a special *compensating block* (CB) which does not affect the FFB linear strength and compactness. The linear CB optics is designed to leave the beam parallel. Based on symmetry of the magnets configuration the sextupoles of the CB result only in creation of chromatic terms needed to compensate those of the FFB, while the quadratic terms associated with emittances and energy spread are self-compensated along the CB. Thus, compensation for chromatic spread of the star point is achieved without impact on both the FF efficiency and ring dynamical aperture. A similar IP chromatic aberration compensation design can be used for the ion beam, if needed.

CONCLUSIONS AND OUTLOOK

The conceptual design of a CEBAF-based ELIC has been through quite significant evolution from a linac-ring schema to a ring-ring schema since it was first introduced. By increasingly using existing and proved technologies, the design evolves toward bringing more robust and reliable, with less required R&D efforts. There are a few areas critical for reaching the 10^{35} luminosity level. First, the above-described ERL-based electron cooling facility must be designed, and a prototype device or its critical components should be built and tested. Second, a multi-cell crab cavity should be developed and tested. A comprehensive program for beam physics study with computer simulation tools and prototype designs of key components of the collider is currently underway at JLab.

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