ELIC AT CEBAF*

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Abstract

We report on the progress of the conceptual development of the energy recovering linac (ERL)-based electron-light ion collider (ELIC) at CEBAF that is envisioned to reach luminosity level of 10^{33}-10^{35} /cm^{2}s with both beams polarized to perform a new class of experiments in fundamental nuclear physics. Four interaction points with all light ion species longitudinally or transversally polarized and fast flipping of the spin for all beams are planned. The unusually high luminosity concept is based on the use of the electron cooling and crab crossing colliding beams. Our recent studies focused on the design of low beta interaction points, exploration on raising the polarized electron injector current to the level of 3-30 mA with the use of electron circulator-collider ring, forming a concept of stacking and cooling of the ion beams, and specifications of the electron cooling facility.

1. INTRODUCTION

Thirty years after the establishment of QCD as the theory of the strong nuclear interaction, and despite significant progress towards understanding of the structure of hadronic matter, some crucial questions involving the role and behavior of quarks and gluons in atomic nuclei remain open. In particular, one would like to: 1) develop a quantitative understanding of the contribution of gluons to the binding and the spin of the nucleon; 2) learn how the dynamics of confinement leads to the formation of hadrons as a perturbation of the QCD vacuum. This will require measurements of the spin dependence of hadronization – a key aspect of the transition from the deconfined state of free quarks and gluons in the Big Bang to stable hadron matter; and 3) determine how the nuclear medium affects quarks and gluons [1].

An electron – light ion collider of c.m. energy up to 60-65 GeV and luminosity from 10^{33} to 10^{35} cm^{-2}s^{-1} would be a powerful tool to answer these questions. Such high luminosity collider is envisioned as a future upgrade to CEBAF. The ELIC facility would produce a variety of polarized light ion species: p, d, ^{3}He and Li, and unpolarized light to medium ion species. The highest bunch repetition rate (up to CEBAF's RF frequency of 1.5 GHz) is envisioned for maximum attainable luminosity. Longitudinally and transversally spin-polarized light ion beams in the ring at all energies, with the flexibility of switching from longitudinal to transverse spin in the detectors, as well as fast flipping of the spin are of critical importance to the science [1].

To realize the required electron beam for ELIC, it is proposed to develop CEBAF to a single recirculation 7 GeV ERL with 3 to 30 mA polarized electron current from a photoinjector. This upgrade is deemed compatible with the CEBAF upgrade for a 24 GeV fixed target program [2].

To attain the required ion beams, we propose to build an ion facility, a major component of which is a 150 GeV, 1 Amp collider ring with 4 interaction regions. The booster rings, electron circulator-collider ring, and the ion collider ring are designed as a Figure 8. Such configuration eliminates the issue of spin maintenance at acceleration and allows one to easily arrange desired spin orientation and flipping for all ion species at all energies. Another critical component of the ion complex is a 75 MeV, 100 mA ERL-based *continuous electron cooling*, which is anticipated to provide low emittance and simultaneously very short ion bunches. The short bunches have two important advantages: 1) a *super-strong beam focusing* at the collision points and 2) *crab-crossing colliding beams*.

Table 1. Basic parameters for ELIC [3].

Parameter	Unit	Value	Value	Value
Beam Energy	GeV	150/7	100/5	30/3
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	½.7	.3/4.1
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
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
Luminosity lifetime	hours	24	24	>24

The concept of specific luminosity of ELIC has been established based on considerations of the beam-beam, space charge, intrabeam scattering and electron cooling effects [3,4]. In this paper, we report results of our recent studies on the realization of the necessary beam parameters and related constituents of the collider facility.

2. DEVELOPMENT OF POLARIZED ELECTRON INJECTOR

To meet the high current demands of ELIC, a number of advances must be made in the field of electron gun technology. These include developing new photocathode material that is immune to surface charge limit problems and also provides high quantum efficiency (QE) and

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polarization > 80%, gun vacuum improvement, better appreciation of the mechanisms that limit photocathode lifetime, and construction of new higher power lasers. Recently, new strained superlattice GaAs photocathodes have been used at CEBAF to provide experimenters with beam polarization ~ 85%, the highest value ever measured at JLab. Initial activation of these photocathodes consistently provides high QE but superlattice photocathodes have not yet demonstrated lifetime comparable to that of conventional strained layer GaAs material at CEBAF. More tests are necessary to determine if superlattice material suffers inherent lifetime limitations at high current [5].

3 INJECTION INTO THE CIRCULATOR RING

2.4 Amps polarized electron beam colliding with ion beams is required to reach the full luminosity of ELIC. It is generally anticipated that next generation electron guns will be able to produce up to 100 mA of polarized electrons, which is approximately two orders of magnitude higher than the demonstrated performance to date. To get around this constraint, it was proposed to use a circulator-collider ring in ELIC design. The electrons would go 100 turns in the circulator ring before being energy recovered [3]. Recently, a scheme of harmonic injection/extraction has been proposed to switch electron bunches between the ERL and the circulator ring. This scheme is based on existing CEBAF hardware and could be implemented right away. This proposal is similar to the one proposed for the International Linear Collider Damping Ring [6] but requires much higher frequencies.

The proposed harmonic scheme assumes that individual electron bunches are accelerated at a low repetition rate of 1497/*h* MHz (*h* is an integer). A 31.2 MHz (=1497/48 MHz) beam has been produced recently at CEBAF for a parity violation experiment. Several RF separator cavities at different frequencies are used to simultaneously extract one bunch every *h* bunches and re-inject a replacement bunch. If the harmonic number of circulator ring has no common factor with *h*, all bunches in the ring will be replaced after *h* turns. The scheme produces no kick on adjacent bunches, but the kick is not required to be zero between bunches. For *h*=16, the RF separator cavities together produce a kick of 320 μrad. Harmonic scheme using discrete cavities seems to be a reasonable option up to about h = 16.

4. OVERCOMING SPACE CHARGE AT ION INJECTION

Stripping injection can be used to stack polarized proton and deuteron beams in the pre-booster after 200 - 400 MeV linac. State of art polarized ion sources and RF linac can deliver 2 mA or higher polarized beam current with 0.3 μm normalized transverse emittance. To minimize the space charge impact on transverse emittance, the *circular painting* technique can be used at stacking. Such technique was originally proposed for stacking proton beam in the SNS [7]. In this concept, the optics of the booster ring is designed strong coupled in order to realize circular (rotating) betatron eigen modes of the two opposite helicities. During injection, only one of the two circular modes is filled with the injected beam. This mode grows in size (emittance) while the other mode is not changed. The beam sizes after stacking, therefore the tune shifts for both modes are then determined by the radius of the filled mode. Thus, reduction of tune shift by a factor of *k* (at a given accumulated current) will be paid by increase of the 4D emittance by the same factor, but not k^2. The circulating beam should be strongly focused to the stripping foil in order to diminish the Coulomb scattering impact on the beam emittance. An RF beam raster is introduced in order to prevent the overheating of the foil by the focused beam.

The low temperature rotating beam can be preserved at succeeding beam acceleration and injection into the large booster and the collider ring. This reduction of the 4D emittance growth at stacking 1-3 Amps of light ions is of a critical importance for effective use of electron cooling in collider ring, since the initial electron cooling time is determined by the 6D emittance value of the injected ion beam.

5 DESIGN OF INTERACTION REGION

To implement the ultra tight focusing of ions in the ELIC interaction region (IR), it is beneficial to use a focusing triplet (DFD or FDF), which provides a net focal length of about 4.5 m at the collision energy of 150 GeV. This triplet uses two types of quadrupoles: 1 m long defocusing one and 2 m long focusing one, with 3 cm transverse aperture radius and 7.5 T peak field. The quadrupole parameter defines a maximum field gradient of 250 T/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, magnet power supply fluctuations, etc. To optimize the luminosity for asymmetric emittance, our design assumes β_x*=2.5 cm and β_y*=0.5 cm with β_{max}=5200 m. Optics of the interaction region is illustrated in Figure 1.

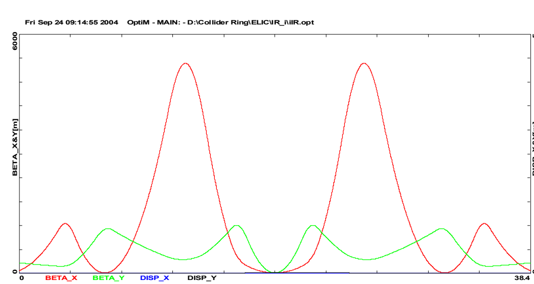

Figure 1. Beta functions in the interaction region

The ELIC IR will consist of two final focusing points for two detectors separated by about 60 m distance. The IR region will then be matched through another lattice with arcs where a β function equals 12 m or less.

The IR for 7 GeV electrons with 0.1 rad vertical crossing angle is designed to interleave transversely with the focusing system for ions. Here the optics is based on two doublets separated by a 9 m long drift to accommodate quads of the ion part. Similarly to the IR for ions, the IR for electrons assumes β_x^*=2.5 cm and β_y^*=0.5 cm with β^{max}=2600 m [8].

6 PROGRESS ON OTHER DESIGN ITEMS

ELECTRON COOLING ERL-based high energy electron cooling (EC) for heavy ion colliding beams in RHIC is currently under R&D at Brookhaven National Laboratory [9]. ERL-based EC for ELIC has been described in [4]. A possible advance of the cooling scheme for ELIC is the use of a circulator-cooler ring as a way to reduce the necessary electron current in the 75 MeV ERL. Other challenge of high energy EC is the design of the electron beam transport system compatible with efficient acceleration and beam alignment. Earlier, the classical scheme of low energy cooling with beam transport by solenoid was modified to a concept of *discontinuous solenoid* [10]. This solution has been recently implemented in the cooling facility for the 8 GeV antiproton beam in Fermilab's Recycler [11] and in the EC design for RHIC [9].

As an alternative to a solenoid transport based EC, we also explore cooling with electron beam focused along the cooling section by quadrupoles but delivered from a non-magnetized electron gun. The principal feature of such scheme is that the electrons oscillating in the focusing field do interact with ions of a beam under cooling in a way similar to that of high temperature electrons experiencing cyclotron motion in a solenoid. Cooling efficiency can be improved and optimized by *scanning* the electron beam around the ion beam area. Advantages of this concept are: 1) the absence of long, heavy superconducting solenoid in the cooling section; 2) superconducting RF gun can be employed; 3) the beams become easily accessible for diagnostics and alignment in the cooling section; 4) heavy ion recombination is practically gone.

SRF FOR BUNCHING OF THE ION BEAM
The proton ring will require the installation of a bunching system capable of providing 100 MV of voltage at 1.5 GHz, 90º out of phase with respect to a circulating beam current of 1 Amp. This voltage could be provided by 5 m of superconducting cavities operating at 20 MV/m. The power dissipation at 2 K in those cavities would be about 200 W, assuming an R/Q per unit length of 1000 Ω/m and a Q_0 of 10^{10}. These assumptions are consistent with the design parameters of the JLab 12 GeV upgrade. Ideal optimization of the RF parameters (detuning $\tan\psi$ and coupling coefficient β) would occur at $\tan\psi = 2.5\ 10^5$ and β=1, at which point only 200 W would need to be provided by the RF source. Larger amount of RF power would be needed to provide stabilization with respect to fluctuations in the time of arrival of the beam. For example, for the system to be stable with respect to fluctuations of the order of 10^{-2} rad, the RF source for the bunching cavities must be able to provide 1 MW.

CRAB CROSSING To eliminate the parasitic beam-beam interaction, the colliding beams should intersect at some angle. To avoid luminosity loss, bunches then should be turned by half of the angle thus becoming parallel to each other [12]. Bunch tilt is produced by *crab resonators*. In our design, the crab resonators are installed *before and after* the outer final focus magnets, namely, they are centered at the outer focus points of an experimental area with two interaction points. Then, the colliding bunches do not rotate, while the crab tilt becomes compensated after the second resonator. In our estimates, dipole magnetic field resonator with effective 1.5 GHz SRF voltage about 80 MV is sufficient to create 50 mrad bunch tilt for 150 GeV proton beam yet fit the free space near final focus magnets.

7 CONCLUSIONS

ELIC conceptual design has been continued and major R&D progress is reported in this paper. There have been specified technical solutions and design schemes for most of the critical issues. At present, there are still remaining issues that need further exploration: raising the polarized electron source current; advancing the schemes of electron beam injection into the circulator ring; reducing the electron beam halo in the ERL; and detectors' design adequate for the high collision rate electron-ion colliding beams.

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