ADVANCES ON ELIC DESIGN STUDIES*

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Abstract

A conceptual design of a ring-ring electron-ion collider based on CEBAF with a center-of-mass energy up to 90 GeV at luminosity up to 10^{35} $cm^{-2}s^{-1}$ has been proposed at JLab to fulfil science requirements. Here, we summarize design progress including collider ring and interaction region optics with chromatic aberration compensation. Electron polarization in the Figure-8 ring, stacking of ion beams in an accumulator-cooler ring, beam-beam simulations and a faster kicker for the circulator electron cooler ring are also discussed.

INTRODUCTION

An electron-ion collider with luminosity at or above 10^{34} $cm^{-2}s^{-1}$ and both electron/positron and light ion beams highly polarized is essential for exploring the new QCD frontier of strong color fields in nuclei and precisely imaging the sea-quarks and gluons in the nucleon. A conceptual design of a ring-ring electron-ion collider (ELIC) based on CEBAF, as shown in a schematic drawing in Fig. 1, has been proposed at JLab to answer this science call and to serve as the next step for CEBAF after the planned 12 GeV energy upgrade of the fixed target program.[1]

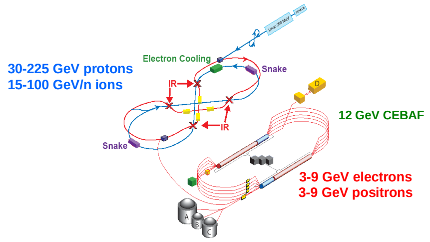

Figure 1. A schematic drawing of ELIC design.

The concept of ELIC ultra-high luminosity, up to 10^{35} $cm^{-2}s^{-1}$, is established on careful consideration of multi-beam physics effects including cooling, beam-beam interactions and intra-beam scattering. It calls for a green-field design of an ion complex and a new approach for its four interaction regions (IR). Selection of a storage ring over an energy recovery linac with or without a circulator-collider ring reduces the high-average-current requirement of the polarized electron source while still preserving ultra-high luminosity.[1] Beam cooling in cooperation with strong SRF bunching in the collider ring delivers very short ion bunches with small transverse emittences, enabling a strong final focusing (FF) at interaction points (IP) and crab crossing colliding beams, which allow a very high collision rate. The choice of a modest ion bunch charge at relatively high average currents reduces electron cloud effects and microwave instabilities. The main design parameters of the ring-ring ELIC can be found in Ref. 1.

FIGURE-8 RING OPTICS

ELIC is designed as two vertically stacked identical Figure-8 rings of 2.1 km total length, each with two 330-m long crossing straight sections to accommodate two pairs of interaction points (IP). The ring optics is built up on compact FODO structures of 60^0 or 120^0 betatron phase advance per cell for ions or electrons respectively. A high (over 60%) dipole packing factor guarantees small momentum compaction ($\sim 10^{-4}$) to alleviate bunch lengthening and limits RF needs (about 1 GV).

Special care must be exercised in the electron optics for minimizing emittance dilution due to quantum excitations as well as lowering synchrotron radiation power by using short strongly focusing cells. Dispersion is naturally suppressed at every third cell shown in Fig. 2, forming a pattern similar to that formed via the emittance-preserving double bend achromat, resulting in an equilibrated emittance just twice of emittence of that structure.

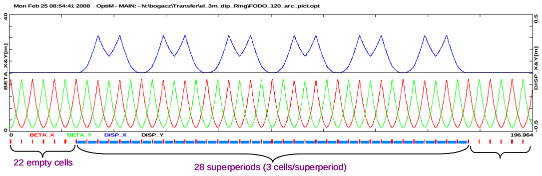

Figure 2. ELCI electron collider ring Lattice

In the ELIC ion ring, each half arc of the Figure-8 forms a (periodic) minimum dispersion achromat in which dispersion is suppressed by the 'missing dipole' technique as illustrated in Fig. 3. This suppression is purely geometric with no change to Twiss function periodicity, which has great impact on the chromatic properties of the lattice. [3]

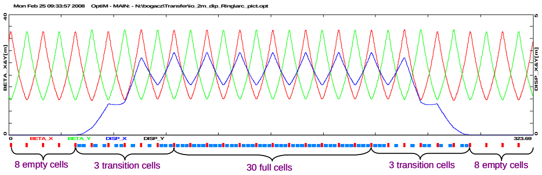

Figure 3. ELIC ion collider ring lattice

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IP OPTICS WITH CHROMATIC ABERRATION COMPENSATION

The strong beam focusing (β*~5 mm) in the IRs is achieved by two sets of FF quad doublets with maximum field gradient of 250 T/m (namely, 7.5 T peak field over 3 cm aperture radius). Due to small vertical crossing angles (~22 mrad), the FF quad doublets for electrons and ions must 'interleave' in order to avoid physical magnet overlap, as illustrated in Fig. 4. The quad design calls for a 'pass through' hole through a magnet yoke. [1,5]

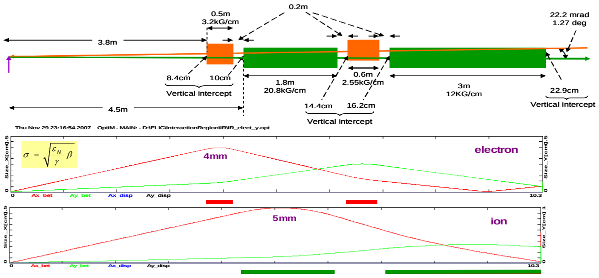

Figure 4. Layout and optics of an ELIC IR.

The ELIC lattice design with extremely low β* and large longitudinal acceptance (~0.005) makes chromatic corrections of paramount importance. As illustrated in Fig. 5, the chromatic effects of the FF quads are corrected by two families of sextupoles placed symmetrically around the IP in a dispersive region. A confined dispersion wave is launched by a four-bend-chicane used to create the vertical crossing. Undesired spherical aberrations introduced by the sextupoles are mitigated by design, via a dedicated optics, which features an inverse identity transformation between sextupoles in each pair. In addition the optics guarantees sextupole orthogonality in both planes, which in turns minimizes the required sextupole strength and eventually leads to larger dynamic aperture of the collider. The resulting phase space correction with two families of sextupoles is illustrated in Fig. 6.

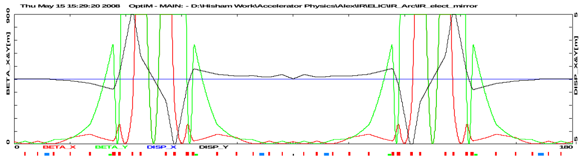

Figure 5. Electron optics around a pair of IRs -- Twiss functions with a confined vertical dispersion.

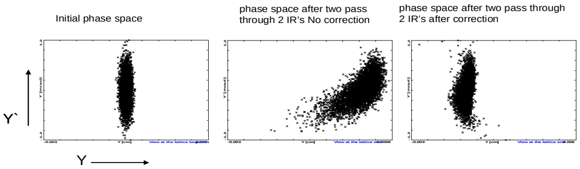

Figure 6. Electron horizontal phase space distribution after two passes of an IP without and with sextupole correction.

ELECTRON POLARIZATION

The polarized electron beam in ELIC is supplied by the CEBAF machine in which electrons from a (>70%) polarized photo-injector are accelerated to a 3-9 GeV energy in the recirculating linac and then injected into the Figure-8 collider ring with a vertical polarization. To achieve a longitudinal polarization at IPs required by physics experiments, the vertical crossing dipoles can be utilized for a portion of the required spin rotation, however, with unpleasant energy dependence. A scheme of "energy transparent" spin rotation has been proposed that utilizes horizontal arc dipoles and superconducting solenoid spin rotators to ensure longitudinal polarization at the IPs. One possible implementation of such scheme is illustrated in Fig. 7, in which the last two arc dipoles interleave with two solenoids to provide the other part of the required spin rotation. Further, with two solenoids, each rotating spin 90^0, placed between two IPs on a crossing straight, the longitudinal polarization will be achieved at the second IP of the same crossing straight section, and with the symmetric principle, vertical polarization is restored in the other half of the Figure-8 ring.

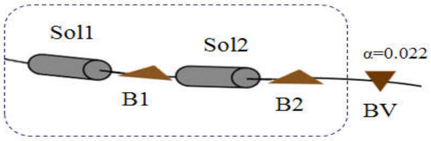

Figure 7. A prototype of arc-to-IR spin rotator for the ELIC electron ring.

An equilibrated electron polarization in a storage ring depends on a balance between the Sokolov-Ternov self-polarizing effect [4] and various depolarization factors including quantum depolarization induced by synchrotron radiation emission, vertical betatron oscillations, orbit distortions and beam-beam interactions. In the ELIC design, a great effort has been made to ensure "spin transparency" with minimum number of solenoids which could cause depolarization. Our calculations based on Derbenev-Kondratenko formula [6] have provided very promising estimates, about 90% polarization at a 7 GeV energy. In the meantime, spin dynamics simulations using SLICKTRACK package [7] are in progress, by which we hope the analytic estimates will be confirmed.

ION STACKING IN ACCUMULATOR-COOLER RING

Stacking fully stripped positive ions in ELIC can be realized in an accumulator-cooler ring (ACR) with low-energy DC electron cooling, Table 1 summarizs the ACR design parameters. A 200-400 MeV ion beam of pulse duration about a number of revolutions of the ACR is injected into the ACR from a SRF linac and experiences damping and cooling by a 100-200 keV DC electron beam in a characteristic time of 0.01 s. Then the next ion beam pulse will be injected and subsequently cooled. Accumulation of a 1 A ion beam could only take about 3 -

10 s. This method was used for accumulating polarized proton beam in the Proton Cooler Ring of IUCF.[8] To approach 1 A ion current, while diminishing the space charge impact on beam quality, a round mode beam optics technique for stripping injection can be implemented in the ring with electron cooling.[9] After stacking, the ion beam will be injected and accelerated in the pre-booster.

The ACR can be designed as a Figure-8 as well as a race-track or a "quadrant" with strong solenoids along straight sections that can be used to transport electron and ion beam. The solenoids also could be used to stabilize the horizontal spin for all polarized ion species. Implementation of the ACR in the beam injection system requires a profound simulation effort and experimental study.

Table 1. Parameters of the Accumulator-Cooler Ring

Circumference	m	50
Arc radius	m	3
Crossing straights length	m	2 x 15
Energy/u	GeV	0.2 -0.4
Electron current	A	1
Electron energy	keV	100-200
Cooling time for protons	ms	10
Stacked ion current	A	1
Norm. emit. After stacking	µm	16

BEAM-BEAM INTERACTIONS

Several important ELIC design features including strong FF, short bunches, large synchrotron tune and crab-crossing colliding beams make the beam-beam interaction an important R&D issue. The importance of longitudinal dynamics in collisions as well as near-limit vertical beam-beam design parameters demand a strong-strong simulation in a full 6D phase space. Our simulations based on BeamBeam3D package [10] track a half million macro-particles for each electron or proton bunch with beam-beam forces calculated over a 2D mash and 20 longitudinal slices using the Particle-in-Cell method. Bunches are transported between IPs with idealized linear maps determined by the synchro-betatron tunes, as well as radiation damping and quantum excitations for electrons. The present phase of studies assumes a head-on bunch collision for a 7 GeV 2.5 A electron beam and a 150 GeV 1 A proton beam with a 1.5 GHz collision frequency. Other design parameters could be can in Ref. 1. Simulations of a single IP with one bunch from each beam showed that the luminosity reaches an equilibrium value of $6.1 \cdot 10^{34}$ $cm^{-2}s^{-1}$ after one damping time, and the approximately 25% luminosity reduction from the peak value is mostly due to the hour-glass effect. Studies of parameter dependence of the ELIC luminosity further revealed coherent instabilities and emittance blow-up above 6.5 A of electron current, which is safely away from the ELIC design point. When all four IPs of ELIC open for collisions, two sets of 12 bunches, one for each colliding beam, were tracked in a full-scale simulation with a total of 48 bunch collisions per turn of the ELIC rings. The equilibrated luminosity per IP at $5.9 \cdot 10^{34}$ $cm^{-2}s^{-1}$ indicates the luminosity reduction due to the bunch-bunch or IP-IP couplings is small.

FAST KICKER

To date, much of the conceptual design for an ultra-fast, single-bunch kicker needed in a circulator electron cooler has focused on generation of 1 ns, multi-kW RF pulses at a 15 MHz repetition rate [11,12]. Beam interaction with these pulses poses several technical challenges due to the very short interaction time (~1 ns); thus use of elements possessing moderate to high Q values is not permissible since the RF fields excited by each pulse would continue long after the intended bunch has left the structure. Efforts are investigating TM11 propagating schemes since the magnetic field is transverse to the beam, and is strongest at boresight [13]. If the beam pipe serves as a circular waveguide at 1497 MHz, the propagating TM11 mode could interact with the specific bunch and provide the necessary deflection after several stages. Interaction time is most likely limited by the slower group velocity of the 1497 MHz pulse, and is expected to be on the order of 1 ns. To prevent subsequent bunches from exhibiting significant deflection, RF must be eliminated either by use of loads, directional couplers or perhaps tapering the beamline, thus implementing a waveguide below cutoff.

TM11 excitation is achieved by a mode-transition device installed between rectangular and circular beam pipe sections, or by loading the circular waveguide with E-field structures, so as to force the TM11 mode conditions. [14]

SUMMARY

Significant efforts have been made to complete the ELIC conceptual design and to address several key R&D issues. The nicely designed ring and IP optics and beam physics studies including beam-beam interactions not only closed the design gaps but also provided strong support for the design scheme and choices of parameters, and created a platform for more future simulation studies such as electron cooling and spin matching, on which the further design optimizations will be based.

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