ELECTRON COOLING FOR ELECTRON-ION COLLIDER AT JLAB*

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Abstract

A critical component of a conceptual design of a high luminosity electron-ion collider at JLab is an electron cooling facility which consists of a 10 mA, 33 MeV energy recovery linac and a circulator ring. A fast kicker has been conceptually designed for switching electron bunches between the linac and the circulator ring. To alleviate space charge impact on cooling, we developed a concept of *helical* electron cooling in which the cooled ion beam has a large round size but a low 4D emittance by matching the *circular eigenmodes* of the ion ring with solenoid in the cooling section. The collider luminosity could be restored by transforming the round ion beam to a flat one in the collision area. In this paper, design parameters of this cooling facility and a scenario of forming and cooling of the ion beam will be presented.

INTRODUCTION

The CEBAF recirculating SRF linac, currently under an energy doubling upgrade, will provide up to 12 GeV polarized CW electron beam with 3x499 MHz bunch repetition rates and excellent beam quality for fixed target nuclear science programs at JLab. The upgraded CEBAF will also open a great opportunity for a high luminosity electron-ion collider (ELIC) which can be achieved by adding an ion complex. [1] Such a collider could provide collisions between polarized electrons and polarized light ions or non-polarized heavy ions in a wide center-of-mass (CM) energy range, delivering a luminosity up to 10^{35} $cm^{-2}s^{-1}$. Electron cooling (EC) is essential both during the process of forming high intensity ion beams as well as at a collision mode for maintaining good beam quality. A conceptual design of the ELIC electron cooler was first reported in a previous paper of the same workshop series. [2] Here we will present an update of the design and also discuss several key technology R&D issues required for realizing this design.

ELECTRON-ION COLLIDER AT JLAB

JLab has been engaged in conceptual design of ELIC for nearly a decade. After several major design iterations, the latest ELIC design, as shown in Figure 1, focuses on a low-to-medium energy collider with CM energy up to 52 GeV. [3] There are three vertically stacked figure-8 shape storage rings, namely, the electron ring and two ion rings for low (up to 12 GeV/c) or medium (up to 60 GeV/c) momentum per proton respectively, in a small tunnel (red line in Fig.1a) of approximately 640 m, and crossed at four collision points as shown in Fig. 1b. Two large figure-8 rings (the grey line in Fig.1a) are for future upgrade to a high energy collider. Table 1 summarizes the design parameters for the low to medium energy ELIC.

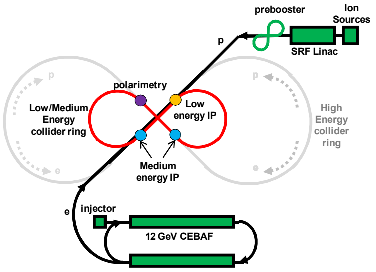

Figure 1a. Schematic drawing of a ring-ring electron collider based on CEBAF at JLab.

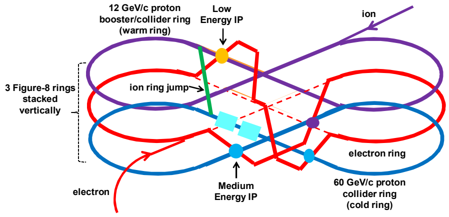

Figure 1b. Three figure-8 shape storage rings for electron, low and medium energy ions are stacked vertically and crossed at four collision points.

Table 1. ELIC main parameters

Beam energy	GeV	60/5	60/3	12/3
Collision frequency	MHz	499		
Beam current	A	0.6/2.3	1.1/6	0.5/2.3
Particles/bunch	10^{10}	0.7/2.9	0.86/4.8	0.47/2.3
Energy spread	10^{-4}	~3		
RMS bunch length	mm	5	5	50
Hori. emit., norm.	mm	0.56/85	0.8/75	0.2/80
Verti. emitt, norm	mm	0.11/17	0.16/15	0.18/80
Hori. beta-star	mm	25	25	5
Verti. beta-star	mm	5		
Verti. b-b tune shift		.01/.03	.015/.08	.015/.013
Laslett tune shift		0.1	0.054	0.1
Peak lumi./IP, 10^{34}	$cm^{-2}s^{-1}$	1.9	4	0.6

The ELIC high luminosity concept is based on the following design features: very high bunch collision rate (0.5 GHz), large beam-beam parameters, and very small bunch spot sizes at collision points. The very small β_y^* value (~5 mm) requires a very short ion bunch (~5 mm RMS) which is achievable due to not only electron cooling but also a relatively small bunch charge, a fraction of 10^{10} protons per bunch, compared to typical super bunches (of 10^{12} protons or more) with much longer bunch lengths (10 cm RMS or larger) in all existing hadron colliders.

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FORMING AND COOLING OF ION BEAM

One important task for the ELIC ion complex is forming a high intensity beam with high bunch repetition rate and short bunch length. The present design utilizes ion sources, an SRF linac (0.2 to 0.3 GeV/c) and a pre-3 GeV/c booster ring as shown in Figure 2 for achieving this goal. The ion beam is stacked at the pre-booster which also acts as an accumulator ring with multi-turn injections from the SRF linac and phase space damping through a cooling procedure. Negative ion beams such as H^- or D^- can be accumulated directly in the pre-booster without cooling due to their relatively small phase space footprints. The accumulated beam then fills the low energy collider ring for acceleration up to 12 GeV/c for proton or appropriate momentum per nucleon of ions. The beam can be either RF bunched and cooled for low CM energy collisions in this ring or injected into the medium energy ring for further energy boost in order to enable collisions at medium CM energies. Table 2 lists accelerating procedures of ion beams and appropriate cooling schemes at various stages.

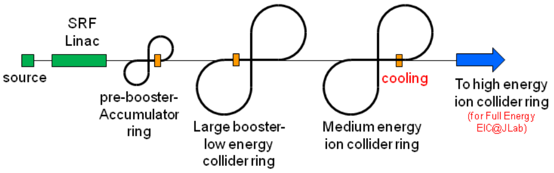

Figure 2. A flow chart for ELIC ion beam formation.

Table 2. Ion beam formation and acceleration scheme

	Length	Max. Energy	Cooling Scheme	Processes
	M	GeV/c		
Source/Linac		0.2		
Prebooster/ accumulator ring	~100	3	DC electron	Stacking Energy boost
Low energy collider ring (large booster)	~630	12	ERL electron	Fill ring Energy boost RF bunching
Medium energy collider ring	~630	60	ERL electron	Energy boost RF bunching
High energy collider ring	~630	250	ERL electron	Energy boost RF bunching

Electron Cooling at the Pre-booster

For stacking positive ions in the ELIC pre-booster, an efficient cooling mechanism must be introduced during the accumulating process. This reduces the phase space area the accumulated beam occupies in order to allow injection of new ions from the linac. Both stochastic and electron cooling were considered for this task and are still under evaluation. While the stochastic cooling option was reported earlier [2], table 3 shows the parameters for a DC electron cooling option.

Staged Electron Cooling in the Collider Ring

Immediately after an ion beam is injected into a collider ring, either low energy or medium energy, electron cooling is called to provide an initial cooling for phase space footprint reduction before the ion beam is accelerated to the final colliding energy and bunched by SRF cavities. Then electron is called again for minimizing 6D emittance of the ion beam to the design values. After the machine is switched on for collisions, electron cooling must be continued all the time in order to suppress heating of ion beams by intra-beam scatterings and to maintain beam quality. The three columns in Table 4 are design parameters for EC in the medium energy collider ring at initial and final stages of ion beam formation as well as at collision mode. In making this table, we have assumed the electron cooler is able to deliver up to 3 A CW electron beam with energy up to 33 MeV. The cooling rates are obtained using analytic formulas based on a simplified EC model. [4]

Table 3. Parameters for EC in the pre-booster

Circumference	m	~80
Arc radius	m	~3
Crossing straight length	m	2 x 15
Energy/u	GeV	0.2 -0.4
Electron current	A	1
Electron energy	MeV	0.1 - 0.2
Cooling time for protons	ms	10
Stacked ion current	A	1
Norm. emit. after stacking	µm	16

Table 4. Parameters for staged EC at ELIC medium energy collider ring.

		Initial cooling	After bunching	Colliding mode
Momentum	GeV/MeV	12/6.6	60/33	60/33
Beam current	A	0.6/3	0.6/3	0.6/3
Particle/bunch	10^{10}	0.7/3.8	0.7/3.8	0.7/3.8
Bunch length	mm	200/200	10/30	5/15
Energy spread	10^{-4}	5/1	5/1	3/1
Hori. Emit. norm.	mm	4	1	0.56
Vert. emtt. norm.	mm	4	1	0.11
Laslett tune shift		0.002	0.006	0.1
Cooling length	m	15	15	15
Cooling time	s	92	162	0.2
IBS growth time (longitudinal)	s			0.9

ERL BASED CIRCULATOR COOLER

The present ELIC electron cooler design, first described in a previous paper [2] and shown in Figure 3, is based on ERL and circulator ring (CR) technologies. Electron bunches from an injector and an SRF linac are arranged to circulate a number of times in a small (~ 50 m) ring while cooling ion bunches in each evolution in a 15 m long channel immersed inside a superconducting solenoid before being ejected and sent to the same SRF linac for energy recovery. The recovered energy will be used to accelerate new cooling electron bunches from the injector. The choice of ERL technology is aimed at overcoming the challenge of very high average RF power, up to 100 MW, drawn from klystrons in order to deliver a 3 A CW 33 MeV electron beam. With state-of-the-art ERL technology, the required power from wall plugs could be reduced to one MW or less (roughly beam power from an injector). The choice of CR solves the other challenge of the ELIC cooler design, namely, the photocathode lifetime due to demand of unprecedented high average current from a photocathode injector. With a 3 A CW operation, the cooler would draw about 260 kC electrons from the cathode each day. By recirculating electron bunches 100 to 300 times in a CR and assuming the cooling efficiency is still satisfactory, the amount of charge from a photocathode could be reduced by a factor of 100 to 300, to a level very much manageable with the present state-of-the-art photocathode injectors.

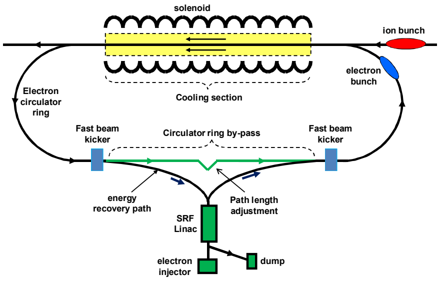

Figure 3. ERL based circulator electron cooler for ELIC.

Alternatively, one can use a grid-operated thermionic gun for producing a high average current electron beam with large bunch charge and long bunch length. Such guns normally have a much longer cathode lifetime, and are able to deliver thousands of kC charge before requiring a service of their cathode surfaces, therefore a circulator ring may only be needed for either avoiding high average current ERL or for reducing the bunch repetition rate of the injector.

A classical scheme with a magnetized electron beam can also be used for high energy electron cooling for ELIC. [5-7] After the gun which is immersed inside a solenoid, an electron beam can be transported for acceleration in RF or SRF cavities in the injector and in the ERL with axial-symmetric and quadrupole focusing lenses. The solenoids in the cooling section should be matched with the rest of the circulator ring optics to provide a magnetized parallel beam required for efficient cooling. [6]

MATCHED ELECTRON COOLING

In principle, equilibrium emittances of a high intensity low energy ion beam under cooling could be limited by Coulomb repulsion. A circulator ring whose optics is matched with solenoids in a cooling section prompts a possible way to reduce the space charge effect on ion transverse emittance.

Assuming such an optically matched ring is used for a low energy hadron collider, one principal feature of such optics design is that two components of a hadron particle's motion in solenoids, namely drift and cyclotron, are not mixed by optics outside of the solenoids. In other words, the radial fringe field of the solenoids transforms the cyclotron and drift motion into two circular modes of opposite helicities, and such modes can be transported around the ring by an axial-symmetric optics as well as quadrupoles. Tunes of two modes can also be split in order to prevent resonance exchange between them.

Further, if there is no organized redistribution of cooling decrements of emittances, only the cyclotron mode will experience the cooling. Thus, space charge cannot stop cooling of the cyclotron mode since the beam size will not shrink, being related to the drift mode. As a consequence, one of the two emittances can be cooled to a very low equilibrium, especially taking into account the magnetization effect on the cooling process [5,8]. The emittance associated to drift can be cooled to the space charge limit using the dispersive mechanism [5,9]. Since the cyclotron motion and momentum spread will already be cooled, the beam will shrink quickly.

A minimum spot of a cooled ion beam with an appropriate aspect ratio for matching with a flat electron beam at collision points can be obtained using round to flat beam transformers [9]. Other benefit of such optics concept is drastic reduction of the space charge impact on particle dynamics in low energy hadron beams for avoiding decrease of luminosity of the collider.

FAST KICKER FOR ERL-CCR

One key element in the ERL based circulator cooler for ELIC is an ultra fast kicker that will be used to switch electron bunches in and out of the circulator ring. Table 5 shows the basic parameters for the required kicker. A conceptual design of a RF kicker was developed and presented in a previous paper. [2]

Table 5: Estimated parameters for a RF kicker

Beam energy	MeV	125
Kick angle	10^{-4}	3
Integrated BdL	GM	1.25
Frequency BW	GHz	2
Kicker Aperture	cm	2
Peak kicker field	G	3
Kicker Repetition Rate	MHz	15
Peak power/cell	kW	10
Average power/cell	W	15
Number of cells		20

Beam-beam Kicker

An innovative idea recently under active investigation utilizes a non-relativistic sheet beam for providing transverse kicking to a flat electron bunch. [10] This idea of a beam-beam kicker was first proposed by Shiltsev [11] for two round Gaussian beams. Here we consider a case of two flat beams as shown in Figure 4, though analytical treatments for these two cases are quite similar. We present here final results plus considerations of cooling electron bunch requirement in order to have an effective kicker scheme. Two technical issues will be also briefly discussed.

Since the target flat (cooling) beam is moving at the speed of light, it passes through the non-relativistic kicking flat beam in a period of time determined by the length of the kicker beam l_k under condition $l_k<(\lambda-l)v_k/c$ where v_k, λ and l are speed, bunch spacing and bunch length of the target beam, respectively. At a close distance to the kicking beam, an electron in the target beam receives an instant angle kick determined by integration of the transverse force over that passing time

$$\delta\theta_y = \frac{2\pi N_k r_e}{\gamma\sigma_{xk}}$$

under conditions $\delta\theta_y >> \sigma_{\theta y}$ and $\sigma_{xk} >> \sigma_{yk}$, where N_k, σ_{xk} and σ_{yk} are number of electrons, horizontal and vertical RMS size of the kicker bunch, $\sigma_{\theta y}$ is the RMS angle spread of the cooling bunch, r_e is the electron classical radius.

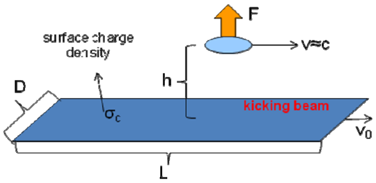

Figure 4. A schematic drawing of beam-beam fast kicker

In order to reducing the required kick, the cooling beam should have large vertical beta function at the kicker section. Combining this with the flatness condition, we find the following requirements to the cooling beam

$$1 << \frac{\beta_y}{\beta_x} << \frac{\varepsilon_x}{\varepsilon_y}$$

Table 6 summarizes the design parameters for a beam-beam kicker for the ELIC CR cooler design. It should be noted that, with 100 to 300 revolutions of cooling electron bunches in the CR, the repetition frequency of the kicking beam can be a factor of 100 to 300 smaller than the repetition rate of the CW cooling beam.

Table 6. Design parameters for beam-beam kicker

Circulating beam energy	MeV	33
Kicking beam energy	MeV	~0.3
Kicking Repetition frequency	MHz	5 – 15
Kicking angle	mrad	0.2
Kicking bunch length	cm	15 – 50
Kicking bunch width	cm	0.5
Kicking bunch charge	nC	2

Making of a Flat Kicker Beam

A flat kicker beam can be produced utilizing a grid-operated DC (thermionic) electron gun with a round magnetized cathode. While maintaining the beam in solenoid, one can impose a constant quadrupole field that causes beam shrinking in one plane while enlarging in the other plane due to the drift motion of particles. The process should be adiabatic relative to the particles' cyclotron motion in the solenoid [6]. The beam current density could be specifically profiled at the cathode to create uniform distribution in a homogenous field in a direction transverse to in the "plane" of flattened beam.

Obtaining a Flat Cooling Beam

While the magnetized state of a cooling beam is transplanted from the gun to the solenoids in the cooling section, the beam can be made flat at a kicker section of the circulator ring applying round-to-flat beam transformation proposed for an angular momentum dominated beam. [12] Such transformation can be performed by a special group of skew-quadrupoles matched with optics of the circulator ring. This will create flat beam with two very different emittances [7]:

$$\frac{\varepsilon_y}{\varepsilon_x} = \frac{r_c^2}{r_0^2}, \quad \varepsilon_x\varepsilon_y = \varepsilon_0^2$$

where r_0, r_c and ε_0 are the space and thermal cyclotron radii respectively and the normalized emittance of round beam at the cathode.

CONCLUSIONS

ELIC relies on staged cooling for making and maintaining small transverse emittance and short bunch colliding ion beams. Its cooler design is based on ERL and CR technologies for delivering high average current electron beam. This design can be easily scaled to higher electron energy to serve the cooling needs of a high energy electron-ion collider based on CEBAF. All key technology elements, namely a 10 to 30 mA average current injector, ERL and fast beam kicker, are either already existing and mature, or with promising conceptual designs. Our future R&D effort will be concentrated on the proto-typing of fast kickers, studies of high average current circulating electron beam dynamics, stability and precision control of coupled ion and cooling electron systems required for efficient electron cooling.

ACKNOWLEDGEMENT

We would like to thank P. Evtushenko for suggestion of a beam based kicker.

A note from the authors

The ELIC conceptual design is done by the JLab ELIC study group, of which both authors of this paper are members. It is presented here in unusual detail mainly for the purpose of self sufficiency of the paper since the latest design of a low-to-medium ELIC has never been documented anywhere else.

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