ELECTRON COOLING FOR A HIGH LUMINOSITY ELECTRON–ION COLLIDER*

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Abstract

A conceptual design of a polarized ring-ring electron-ion collider (ELIC) based on CEBAF with luminosity up to 10^{35} cm^{-2}s^{-1} has been developed at Jefferson Lab. A vital component of this collider is high energy electron cooling (EC) of ion beams. This cooling facility consists of a 30 mA, 125 MeV energy recovery linac (ERL) and a 3 A circulator-cooler ring (CCR) operating at 15 and 1500 MHz bunch repetition rate respectively. Fast kickers of frequency bandwidth above 2 GHz have been designed for switching bunches between the ERL and CCR. Design parameters of this cooling facility, preliminary studies of electron beam transport, stability and emittance maintenance in the ERL and CCR, and the scenario of forming and cooling of ion beams will be presented.

INTRODUCTION

At Jefferson Lab, a polarized high luminosity electron-ion collider (ELIC) based on the CEBAF facility, as shown in Figure 1, was proposed as a future facility for nuclear science quest [1,2]. The ultra high luminosity of ELIC calls for a green-field design of its ion complex and a new approach to organization of the interaction region. For the ELIC electron complex, selection of a storage ring over an energy recovery linac (ERL) relaxes the high average current requirement on the polarized source while still preserving high luminosity. The 12 GeV CEBAF accelerator will be utilized as a full-energy injector of electron bunches into a ring of a 2.5 A stored current [3]. The ELIC ion complex, consisting of a SRF linac, a pre-booster, a large booster and a collider ring, will generate and store up to a 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 ions [1]. The figure 8 topology of the ELIC booster and collider rings provides preservation and easy manipulation of spins for all species. There are four interaction points arranged symmetrically on the two crossing straights for high science productivity. Table 1 summarizes ELIC's main design parameters.

The luminosity concept of ELIC has been established on careful consideration of multi beam physics effects including beam cooling, space charge, beam-beam interactions and intra-beam scattering (IBS) [3,4]. In this paper we present a scheme of forming of high intensity ion beams and cooling of these beams to meet requirements of ultra high luminosity. To assist ion beam stacking and accumulation, stochastic cooling will be utilized in the pre-booster and the collider ring [1]. Electron cooling (EC) will provide initial longitudinal cooling and a continuous 6D cooling of the ion beam in collisions mode. In cooperation with a strong bunching SRF field of high frequency in the collider ring, EC delivers very short (5 mm or less) ion bunches with desired small emittances, thus enables *super-strong focusing* at collision points and *crab crossing colliding beams* required for a high bunch collision rate (1.5 GHz) [5].

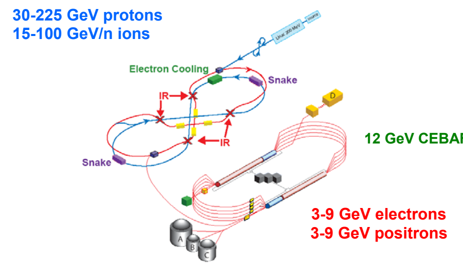

Figure 1: A schematic drawing of ELIC ring-ring design.

Table 1: Basic parameters for ELIC.

Beam energy	GeV	225/9	150/7	30/3
Collision rate	GHz	1.5		
Particles/bunch	10^{10}	.42/.77	.42/1	.13/1.7
Beam current	A	1/1.85	1/2.5	.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	.21/37.5
Vert. emit., norm.	µm	.05/3.6	.04/3.6	.21/37.5
Beam-beam tune shift (vert.) per IP		.006/ .086	.01/ .086	.01/ .007
Space charge tune shift in p-beam			.015	.06
Lumi. per IP, 10^{34}	cm^{-2}s^{-1}	5.7	6	0.6
Lumi. lifetime	hours	24	24	>24

ION STACKING AND COOLING SCENARIO

Forming and Pre-cooling of Ion Beams by Stochastic Cooling

An ion beam from a 285 MV SRF linac will be stacked in a 3 GeV pre-booster with stochastic cooling. Our estimates show accumulation of a 1 A ion beam of space charge limited emittances of 10-15 µm within several minutes. Accumulated beam, after bunching and accelerating to 3 GeV, will be injected into the large booster which has common arcs with the electron ring. About 10 to 15 injections are needed to fill the whole orbit of the large booster ring. The beam will then be accelerated to 30 GeV for protons or up to 15 GeV/n for ions and injected into the ion collider ring. Here

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stochastic cooling will be put to work again for reduction of normalized emittance to a level below 1 μm in about 30 min. Table 2 summarizes design parameters for stochastic cooling in the pre-booster and collider ring.

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

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.	mm	12/0.1
Laslett tune shift		0.03

ERL-based Electron Cooling with Circulator Ring

At this stage, electron cooling starts to work effectively for further reduction of energy spread and for reaching and then maintaining ion beam quality required for the ELIC high luminosity. To achieve the goal, the ELIC electron cooling facility should be capable of delivering a 3 A beam up to 125 MeV energy. 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 with a circulator-cooler ring as shown in Figure 2 [1]. Electron bunches from the ERL circulate one hundred turns inside the CCR while cooling ion bunches before being ejected and sent back to the ERL for energy recovery. Therefore, by employing a CCR, the required average current from the ERL is reduced to a modest value of 20-30 mA. Our estimates showed that high 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 [4].

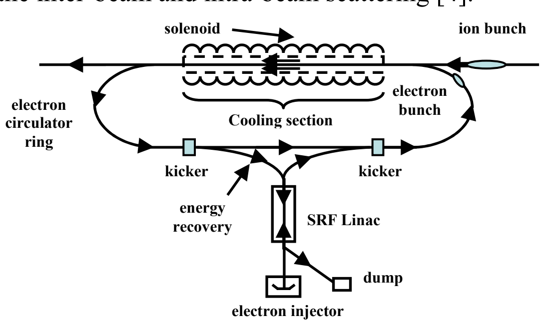


Figure 2: Layout of electron cooler for ELIC.

CONDITIONED ELECTRON COOLING

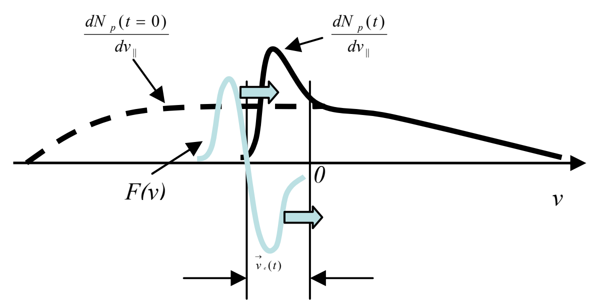
Several schemes/techniques may be implemented in the ELIC electron cooling design in order to minimize cooling time and equilibrium emittances.

Staged Cooling

Since electron cooling time drops when ion beam energy and emittance decrease, it is advantageous to start electron cooling as early as possible, which is at injector energy of the collider ring, then to continue cooling after acceleration of the ion beam to high energy with already reduced emittance [5].

Sweep Cooling

After transverse stochastic cooling at injection energy in the collider ring, ion beams will have quite a small transverse temperature but a large longitudinal one. In order to reduce the time required for initial longitudinal electron cooling, one can use *sweep cooling* [7,8] illustrated in Figure 3, in this way gaining a factor of $(\Delta\gamma_i/\Delta\gamma_e)^2$ in cooling time.



.Figure 3: The longitudinal sweep cooling method.

Dispersive Electron Cooling [8]

This method can be used to compensate low transverse cooling rate at high energies due to large transverse velocity spread compared to the longitudinal one (in rest frame) caused by IBS. The transverse temperature of relativistic beams is usually large with respect to the longitudinal one ($\gamma\theta >> \Delta\gamma/\gamma$, where θ is the angular spread, γ is the Lorentz factor and $\Delta\gamma$ is spread of γ). This results in a correspondent ratio between cooling times: $(\tau_\perp / \tau_{\|}) \approx (\gamma^2 \theta / \Delta\gamma)$. The transverse extension of beams is usually considered as a method to raise the transverse cooling rate; however, this requires a very large beam defocusing in the cooling section, which makes beam alignment difficult. Instead, one can redistribute the cooling decrements according to the *dispersive cooling* method. The arrangement may consist of introducing dispersion for both the hadron and electron beam in the cooling section.

Flat Beam Cooling [4]

This method is based on flattening ion beam by reduction of coupling around the ring, while maintaining beam area. Here, the IBS impact on the 6D emittance becomes reduced compared to the cooling rate. The minimum coupling leads to a flat equilibrium, minimum ε_6 and maximum cooling rate. Since the luminosity is determined by the product of two transverse emittances, reduction of transverse coupling to a minimum while conserving the beam area would benefit one with a decrease of energy scattering, and hence, a decrease of the whole IBS impact on luminosity. Electron cooling then leads to a flat equilibrium with a large aspect ratio. In order to achieve an optimum cooling effect at equilibrium, the electron beam area in the solenoid should also be transformed to an elliptical one of a similar aspect ratio, applying adapting optics [16].

BEAM TRANSPORT AND CCR DESIGN

Use of an electron circulator ring as a complement to the accelerator line was suggested earlier as an option for beam transport for medium energy relativistic electron cooling [7]. The optical scheme of a circulator ring matched with a magnetized electron gun through an RF accelerator line has been developed in conceptual studies of electron cooling of a proton beam in PETRA for HERA [9]. A circulator-cooler ring can work in conjunction with ERL as well; the only considerable addition to a CW single loop scheme would be fast kickers for switching the electron bunches between the ERL and the circulator [1].

EC AND BEAM PARAMETERS

Tables 3 and 4 illustrate design parameters of the electron cooler for the ELIC [5].

Table 3: Initial electron cooling (p/e).

Energy	GeV/MeV	20/10
Cooling length/ circumference	%	1
Particles/bunch	10^{10}	0.2/1
Energy spread*	10^{-4}	3/1
Bunch length*	cm	20/3
Proton emittance, norm*	µm	4
Cooling time	min	10
Equilibrium emittance, **	µm	1
Equilibrium bunch length**	cm	2
Laslett tune shift		0.1

* max.amplitude

** norm.,rms

Table 4: ERL-based EC with circulator ring.

Max/min energy of e-beam	MeV	75/10
Electrons/bunch	10^{10}	1
Number of bunch revolutions in CR	100	1
Current in CR/current in ERL	A	2.5/0.025
Bunch rep. rate in CR	GHz	1.5
CR circumference	M	60
Cooling section length	M	15
Circulation duration	µs	20
Bunch length	Cm	1
Energy spread	10^{-4}	3-5
Solenoid field in cooling section	T	2
Beam radius in solenoid	Mm	1
Cyclotron beta-function	M	0.6
Thermal cyclotron radius	µm	2
Beam radius at cathode	Mm	3
Solenoid field at cathode	kG	2
Laslett tune shift in CR at 10 MeV		0.03
Time of longitudinal inter/intra beam heating	µs	200

ELECTRON INJECTOR

An electron injector capable of delivering 30 mA average current up to 125 MeV energy, with appropriate bunch length, transverse emittance and energy spread for an optimal cooling effectiveness, is required to fill electron bunches in the CCR. This injector operates at a 15 MHz bunch repetition rate, taking into account 100 circulations of a bunch in the CCR, which leads to 1 nC charge per bunch. In designing such an injector, two challenging requirements must be met first. The first one is the source life time. The electron photo-injector of the ELIC cooling facility draws about 2.6 kC charge per day from the source, a considerably challenging R&D requirement from the current 0.2 kC/day state-of-art [10]. More beam studies, especially computer simulations, will help to exploit the higher number of circulations of electron bunches in the CCR, thus further reducing the average current from the injector. The second one is 3.75 MW average beam power from the RF cavities. This challenge can be solved readily through energy recovery.

The high average current electron beam is one of the key R&D issues for many ERL based light sources; therefore high current injectors for these light source applications are under active R&D worldwide. Two outstanding programs, among others, are the JLab 10 kW and 100 kW FEL facility [11] and the Cornell ERL based light source [12], both employing DC photo-injectors. Though there may be different requirements for beam properties, much R&D done for injectors of light source applications can be readily applied to the ELIC cooling application. As an initial conceptual design of the driving injector for the ELIC circulator cooler, we will adopt the existing baseline of the JLab FEL photo-injector. Future design iteration and optimization will be carried out as the ELIC design continually evolves.

The injector design for the ELIC cooling facility consists of the following key elements: a 350 to 500 keV photo-cathode DC gun, a single cell normal or superconducting RF bunching cavity, two high gradient SRF modules for energy boost, and several solenoids and quadrupoles for beam focusing and emittance compensation. Magnetization of electron bunches is realized by adding a solenoid at the photo-cathode. In addition, a fast kicker will be attached to the injector for kicking bunches into the CCR. One previous study showed that, after optimization, the injector beam with 0.8 to 0.9 nC bunch charge up to 15 MeV can reach a 1 mm or shorter bunch length while the longitudinal emittance is less than 50 mm-keV, and transverse emittence is less than 0.8 mm-mrad [12].

DEVELOPMENT OF AN ULTRA-FAST KICKER

Requirements to the ERL-CCR Kicker

Operation of the multi-turn CCR requires that a single electron bunch be extracted after 100 turns and replaced by a fresh bunch from the injector. To achieve such extraction, a kicker must be able to interact temporally with a single bunch while leaving neighboring bunches unaffected. Therefore, a pulse having an envelope of 0.5 ns in duration and a peak power of 10-20 kW is required to achieve the necessary integrated transverse field to kick the electron bunch.

Since the ultra fast kicker (UFK) is one of the key components in the electron cooling system, it is imperative to realize electronics which can produce the required pulses. Estimated parameters for a UFK system and electronics appear in Table 5.

Table 5: Estimated parameters for the 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

Pulse-compression Technique

Present research involving *pulse compression techniques* is providing several potential options for producing short, medium-power RF pulses with the required 10 to 15 MHz repetition rate. Pulse compression employs a swept RF source in conjunction with a dispersive element, resulting in multiple wave-fronts piling up at the output to produce a very short, high peak power pulse [14]. 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 at a 12 MHz repetition rate, and having a peak power of 11 kW [15]. In these tests, a swept RF source provides a gated “chirp” signal, which is then amplified by a gated traveling-wave tube amplifier (TWTA), which is coupled to the load via the dispersive helically corrugated waveguide. Figure 4 illustrates the technique, along with associated frequency spectra.

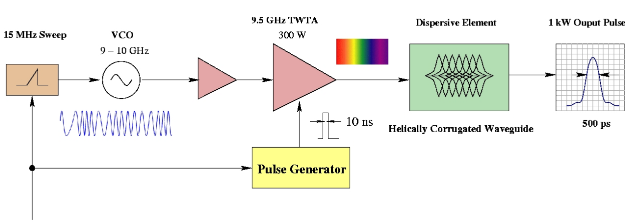


Figure 4: Schematic of pulse compression technique using helically corrugated waveguide. Output pulse envelope is the result of “chirping” the RF input, and letting all wave-fronts pile up at the output.

Although experiments have shown that it is possible to nearly realize the required pulse parameters with a single stage, it is likely that more stages (10-20) having reduced power, will provide the required BdL (1.25 G m), and also possibly satisfy space limitations. This is especially attractive, since the required output power from each individual amplifier decreases quadratically with the total number of stages. Also, since the primary goal of the experimenters was high peak power, specifically for plasma physics and radar applications, it can be expected that a reduction in peak power will further reduce pulse width. Conceptually, the power electronics would reside above-ground to facilitate accessibility and repair. Due to its manageable size, the dispersive element can be located either with the electronics, or at the beamline.

An optimum frequency range will have to be selected, based on pulse-beam interaction requirements, and also on availability and cost of components. Given some freedom, it would be possible to benefit from previous research efforts, RADAR, satellite transponder or ISM band component availability.

Pulse compression appears to possess many of the virtues required by the kicker electronics. Therefore, it is expected that this is the clearest path to achieving the required pulse requirements. A test stand is proposed which would verify the operational parameters of pulse compression techniques, as well as the ability to optimize pulse widths vs. peak output power and repetition rates. In addition to pulse compression, other options and techniques will continue to be explored, in an effort to find the most efficient conceptual and technical solution.

CONCLUSIONS

The ERL-based high energy electron cooling seems quite promising in approaching a very high luminosity in colliders with hadron beams. The low longitudinal emittance of the electron beam and possibility of staged cooling are the important advantages of the ERL approach. To operate at a modest average beam current, the ERL accelerator should be complemented with an electron circulator-cooler ring. Also, certain improvements in forming and transporting the hadron beams before injecting to collider ring might be required in order to reduce time of initial electron cooling in the ring [9]. A comprehensive analysis, simulation and experimental studies should precede development of recommendations for practical design of electron cooling and high luminosity colliding beams.

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