ADVANCE IN MEIC COOLING STUDIES*

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Abstract

Cooling of ion beams is essential for achieving a high luminosity for MEIC at Jefferson Lab. In this paper, we present the design concept of the electron cooling system for MEIC. In the design, two facilities are required for supporting a multi-staged cooling scheme; one is a 2 MeV DC cooler in the ion pre-booster; the other is a high electron energy (up to 55 MeV) ERL-circulator cooler in the collider ring. The simulation studies of beam dynamics in an ERL-circulator cooler are summarized and followed by a report on technology development for this cooler. We also discuss two proposed experiments for demonstrating high energy cooling with a bunched electron beam and the ERL-circulator cooler.

INTRODUCTION

An electron-ion collider with both highly polarized electron and ion beams is considered a perfect probe for the study of QCD. At Jefferson Lab, a polarized medium energy electron-ion collider, MEIC, was proposed to answer this science call. Over the last twelve years, the MEIC design has been actively pursued; as a result of this effort, a comprehensive report summarizing the design concept and accelerator R&D was released [1].

The electron-ion collider science program demands high luminosities over a broad CM energy range with a peak value above 10^{33} /cm^2/s. This is a very challenging goal since it is 100 times above the highest luminosity ever archived in HERA, the only electron-proton collider ever built and operated. It is evident that, to achieve this goal, a form of efficient cooling of ions must be realized, given the fact there is no radiation damping in this medium energy range.

The MEIC proposal is based on the conventional electron cooling [2,3,4]. It is designed for achieving a significant reduction of beam emittance and maintaining the high phase space density during the store of the ion beam. While it is a fully developed technology at low energies, the MEIC proposal extends electron cooling to much higher energies for the cooling beam. In addition, the design demands a high brightness electron beam with a high repetition rate and average current. An advanced cooler design [1] based on an energy recovery linac and a circulator ring has been developed to meet several technical challenges. In the following, we first outline the MEIC cooling scheme and the cooler design concept [1,5,6,7], next present progress of an R&D program, both in simulations and in technology developments. We further discuss the proof-of-concept experiment utilizing facilities at Jefferson Lab or our collaborating institutes.

MULTI-STAGED COOLING SCHEME

Presently, MEIC is designed as a ring-ring collider [1]. The proposal requires the construction of two storage-collider rings and an ion complex at the Jefferson Lab site. The ion collider ring can accommodate protons with energy up to 100 GeV and light to heavy ions with energy up to 40 GeV per nucleon. The ion complex consists of sources, a linac and two booster rings, and is responsible for the formation and acceleration of ion beams. The top kinetic energies of protons in the pre- and large booster are 3 and 25 GeV respectively, while energies of ions vary, subject to the same magnetic rigidity, according to their masses and charges. The injection energies of the pre-booster are 285 MeV for protons and 100 MeV/u for lead ions. The pre-booster also serves as an accumulation ring for ion beams.

The MEIC proposal aims to deliver high luminosities up to above 10^{34} /cm^2/s. Its accelerator design has adopted a luminosity concept which has already been proven in lepton-lepton colliders. It has three equally important tiers, namely, (1) two colliding beams with ultra short bunch lengths and high repetition rates; (2) interaction regions with an unusually small beta-star for strong final focusing and also crab crossing of colliding beams, and (3) a fast damping mechanism for achieving very low 6D beam emittances. An expanded discussion of this luminosity concept and its application to MEIC--the first time to a collider involving a hadron beam--can be found in [7]. Regarding the last tier of the concept, for the lepton beams in electron-positron or electron-ion colliders, it is the synchrotron radiation that provides a rapid damping. For medium energy ions, there is no synchrotron radiation. Thus, a cooling of ion beams must be introduced in the MEIC to provide damping.

Conventional electron cooling is adopted for the MEIC design. We believe such a technology would most likely meet the MEIC requirement, and carry the least amount of technical uncertainty in the project time frame. Further, in order to achieve an adequate cooling efficiency, a multi-staged cooling scheme [1,5,6] has been adopted:

- *Stage 1*: A DC electron cooling (up to 100 keV electron energy) in the pre-booster for assisting accumulation of positive ions after being injected from the ion linac;
- *Stage 2*: Pre-cooling at the top energies of the ion pre-booster utilizing a 2 MeV DC electron cooler for the initial stage of ion emittance reduction;
- *Stage 3*: A final electron cooling in the collider ring and at the ion collision energies for achieving the designed low 6D emittance and short bunch length;

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- *Stage 4*: Continuous electron cooling during collisions for suppressing IBS induced beam degradation.

Pre-cooling at far below the ion collision energies is clearly advantageous. It would provide a superior cooling efficiency both from being at a lower energy for this stage of cooling itself, as well as due to a reduction of the starting beam emittance at the final cooling stage, thus dramatically reducing the total cooling time for meeting the design requirement. Cooling during collision is extremely critical for preserving MEIC's luminosities since the IBS induced emittance growth time is very short (less than a minute for the design case) [1].

Recently, this cooling scheme of MEIC has been optimized by moving the pre-cooling phase from the ion collider ring (at its injection energy) to the pre-booster (at its top energy) for gaining a significant improvement of the cooling efficiency. This change of the design also achieves a reduction of technical uncertainty since more cooling tasks are shifted to a relatively lower energy (a factor of 8.3 lower) and to the developed technology--low energy DC cooling. Table 1 below shows the present parameters and design cooling times [1]. As a matter of fact, the ion beam emittance after cooling in the pre-booster is limited by the acceptable space charge tune-shift in the large booster instead of the cooler capability.

Table 1: Electron Cooling of Proton Beam in MEIC

Ion ring		Prebooster	Collider
Energy (p/e)	GeV/MeV	3/2	100/55
Cooling length	m	5	60
Bunch frequency	MHz	~ 1	748.5
Energy spread	10^{-4}	10 / 3	5 / 3
Ion bunch length	cm	coasted	1
Electron bunch length	cm	DC	3
Proton emittance (x/y)	µm	1.6	0.35/0.07
Cooling time	min	~5	~ 0.4

It should be further pointed out that the formation of the ion beams in MEIC is both slow and complicated. These ion beams are accumulated in the pre-booster and stacked in the large booster before being transferred to the collider ring [1,7]. Their time structure also undergoes a process of de-bunching to a coasting beam in the pre-booster and re-bunching in the collider ring [1,7]. Cooling is integrated with this process and plays critical role.

ERL CIRCULATOR COOLER

The first two stages of cooling in MEIC take place in the pre-booster utilizing DC cooling technology; the design parameters are within the present state-of-art. In fact, a 2 MeV DC cooler has been built recently for the COSY facility [8,9] and is scheduled for commissioning soon. A DC cooler similar to that should meet the need in the MEIC pre-booster.

The other two stages of cooling are in the collider ring and at the collision energy up to 100 GeV per nucleon. Since the cooling electron energy is up to 55 MeV, it rules out any electrostatic apparatus which are used in all low energy coolers for acceleration of electrons. Therefore, the MEIC high energy cooler must rely on the SRF linac technology. Further, by the design, this cooler must deliver an electron beam with a 2 nC bunch charge at a 748.5 MHz repetition rate, resulting in an unprecedented 1.5 A averaged current. Such a beam could not be provided by an SRF linac presently or in the MEIC project time frame without utilizing additional advanced technologies and schemes.

Figure 1 illustrates a design concept of a high energy electron cooler based on a photo-cathode gun, an SRF linac with energy recovery (ERL) and a circulator cooler ring (CR). These technologies are adopted for the purpose of overcoming the two most critical technical challenges, namely, delivering and disposing an ultra high beam power (up to 80 MW) and achieving a long lifetime of the photo-cathode.

As a matter of the fact, both ERL and circulator ring ideas had been considered separately in the previous high energy electron cooler proposals for luminosity upgrades of HERA [10] and RHIC [11]. Some interesting earlier works including design of a circulator ring or a high current SRF ERL can be found in references cited above.

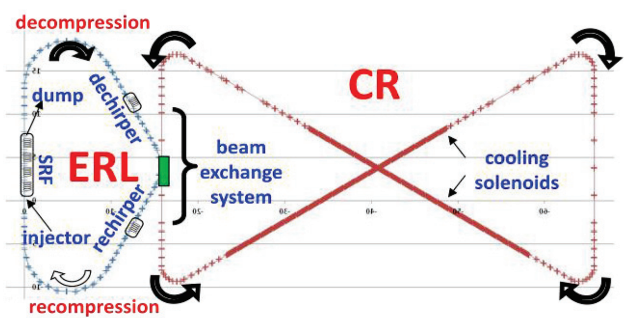

Figure 1: A schematic drawing of an ERL-circulator ring based electron cooling facility.

The working principle of this ERL-circulator cooler is as follows. A high charge electron bunch from a photo-cathode gun is accelerated in the SRF linac to the required energy and sent to the circulator ring with an optically matched channel for cooling ion bunches. The photo-cathode gun ensures a high quality (small emittance and energy spread) of the beam. The electron bunch circulates a large number (10 to 30) turns inside the circulator ring while continuously cooling ion bunches, thus leading to a reduction of the current from the photo-cathode gun and ERL by a factor equal to the number of circulations. The bunch then returns to the SRF linac for energy recovery and finally is sent to a dump while the recovered energy is used to accelerate a new bunch from the injector.

The ERL ring of this electron cooler includes a pair of de-chirper and re-chirper SRF cavities as shown in Figure 1 for a longitudinal matching of the electron beam [12]. The electron bunches must be very short in the SRF linac in order to maintain a low energy spread required for cooling and for a good energy recovery; however, they must be modestly long (a few cm in RMS size) for wrapping around the relatively long ion bunches in order to achieve a satisfactory cooling efficiency. In the design, the bunches are accelerated in an off-the-crest phase in the linac, thus gaining a large energy deviation from head

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to tail, which will be used for bunch decompression in the arc with a specially design optics. The de-chirper cavity then cancels the head-to-tail energy deviation before bunches enter the circulator ring. After cooling, bunches are kicked out of the circulator ring, the above process of longitudinal phase manipulation is reversed such that bunches become very short again when they enter the linac for an efficient energy recovery. It should be noted that such a longitudinal phase matching may be possibly avoided when a specially designed SRF cavity is used instead, thus the ERL ring can be significantly simplified. Such a scheme is currently under development.

An additional key element of this cooler is a beam exchange device which kicks bunches into and out of the circulator cooler ring. This kicker must act in a very high repetition frequency and have a very short rise/full time (shorter than the bunch spacing). It is one of several critical R&D programs for the MEIC high energy electron cooler, as is further discussed below.

Figure 1 also shows an optimization of the location of this cooler: placing the circulator cooler ring at the crossing point of the figure-8 shaped ion collider ring so two cooling channels could be arranged. Therefore, the cooling rate can be doubled by taking advantage of this unique ring geometry. Table 2 below shows the MEIC cooler design parameters, assuming the number of circulations is 30 [1].

Table 2: The MEIC ERL-Circulator Cooler Parameters

Min/max energy of electron beam	MeV	5.5/55
Electrons/bunch	10^{10}	1.25
bunch revolutions in CR		~30
Current in CR/ERL	A	1.5/0.05
Bunch repetition in CR/ERL	MHz	750/25
CR circumference	m	~100
Cooling section length	m	30x2
RMS Bunch length	cm	1-3
Energy spread	10^{-4}	1-3
Solenoid field in cooling section	T	2
Beam radius in solenoid	mm	~1
Beta-function	m	0.5
Thermal cyclotron radius	µm	2
Beam radius at cathode	mm	3
Solenoid field at cathode	T	0.2
Laslett's tune shift @60 MeV		0.07
Longitudinal inter/intra beam heating	µs	200

BEAM DYNAMICS IN THE CIRCULATOR COOLER RING

Success of the ERL-circulator cooler design concept is largely measured by how many circulations of the electron beam allowed in the cooler ring as well as whether good energy recovery can be achieved after these circulations. The allowable number of circulations is defined as the number where, after that many turns the electron beam is still able to maintain a sufficiently good quality required for delivering a satisfactory cooling efficiency. It is expected that the cooler performance should be largely limited by various collective beam effects in the circulator ring. To explore them, beam dynamics simulation studies have been initiated [13]; the methods and preliminary results are summarized below.

For simplicity, a Gaussian electron bunch with the MEIC cooling beam design parameters (emittance, bunch length and charge) is tracked turn-by-turn in the circulator cooler ring with a nominal optics design [12]. The code Elegant [14] is flexible such that the multi beam effects can be included individually in simulation.

The first investigated collective beam effect is coherent synchrotron radiation (CSR) [15]. The study [13,16] has shown that, in the MEIC parameter regime, the beam quality could be affected by the CSR, causing a noticeable deterioration as the number of circulations progress. In worst cases, the undesired micro-bunching instabilities [17,18] could be quickly excited. The study [16] has further shown that severity of the CSR induced beam degradation strongly depends on the bunch length as anticipated. Figure 2 shows the longitudinal phase space as a function of circulations for 1 and 3 cm RMS bunch lengths respectively while the bunch charge is a constant. The study [16] has also shown a strong correlation of the emittance aspect ratio to preservation of the energy spread, suggesting that a flat beam can hold itself much longer than a round beam, thus supporting a long standing assertion that a magnetized electron beam with a round-to-flat conversion would improve the beam circulation in the cooler ring [19]. It is clear that schemes for mitigating the CSR effect should be explored in the future. More studies including additional collective effect such as longitudinal space charge are in progress.

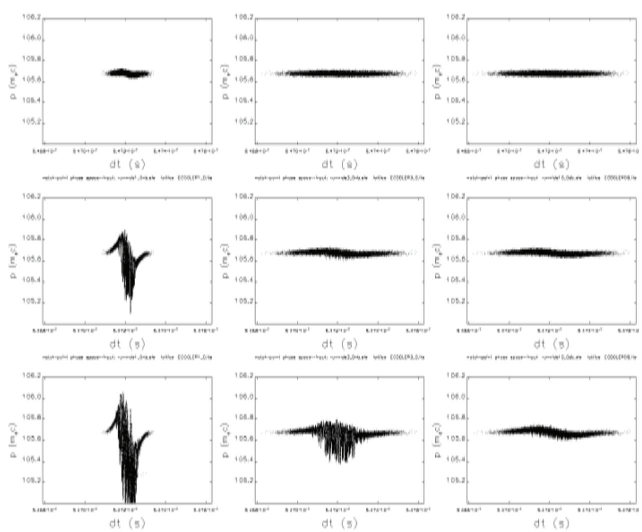

Figure 2: The longitudinal phase space of an electron bunch after 1, 10 and 20 circulations in the MEIC circulator cooler ring. The first two columns are for a 1 and 3 cm RMS bunch length. The last column is also for a 3 cm RMS bunch length, however, with an emittance aspect ratio of 10. A micro-bunching instability was excited before 20 circulations in the first two columns.

ACCELERATOR TECNHOLOGY R&D

Operation of an ERL-circulator electron cooler depends on a number of accelerator technologies, among them, a

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high brightness electron source and a fast kicker are the two most challenging ones. An R&D program has already been initiated to pursue these technologies and progress has been made since then. In this section, we report the development of an RF kicker design concept [20]. On the other hand, an alternate approach based on a beam-based kicker [21] was also considered for the MEIC cooler [6].

According to the operation scheme of a circulator cooler, an electron bunch is first kicked into a circulator ring, and later kicked out from it after a pre-determined number of circulations. The repetition rate of this kicker is on the order of 25 MHz if the number of circulations is 30. To avoid affecting the neighbouring electron bunches, the rise and full time of this kicker must be shorter than the bunch spacing, about 1.25 ns when the beam bunch repetition rate is 750 MHz. These specifications, high repetition rate and fast rise/full time combined together, represent orders of magnitude beyond the state-of-art. To provide a technical solution, we have been exploring a concept of an RF based faster kicker.

In principle, an RF kicker acts like an RF separator used in CEBAF for diverting one linac beam alternately to three experimental halls. In this case, an RF signal with a special wave form is required to drive a physical kicker (stripeline kicker for example) that kicks only every n-th bunches in a bunch train. Such an RF wave form can be constructed straightforwardly by superposition of a set of harmonic wave forms of different frequencies. An example of such an RF wave form is shown in Figure 3 for delivering a kick to every eleventh bunch [20]. Such a wave form needs to be amplified by a digital apparatus for gaining a required power. The simplest solution is a broadband amplifier, however, it is usually inefficient. Alternately, an electronic system that can achieve a high gain at each of all the individual frequencies is under development and a proto-type will be tested soon [20].

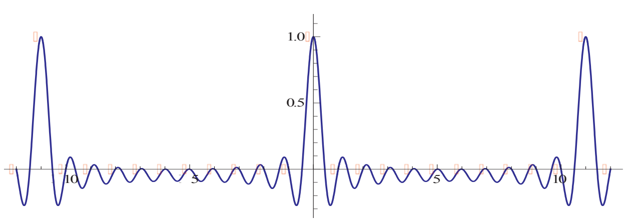

Figure 3. The RF waveform that results in a kick to every eleventh bunch with the other bunches receiving no kick.

PROOF-OF-CONCEPT EXPERIMENTS

Ideas of machine study experiments for proof of the MEIC cooling concept are being actively explored. Two ideas are particularly attractive and promising, therefore, they have been proposed for further study.

The first proposed experiment is a demonstration of cooling of ion beams by a highly bunched electron beam. In general, a bunched electron cooling beam is expected to work with a cooling rate similar to that of DC cooling with its beam current equal to the average current of the bunched beam; nevertheless, it has never been demonstrated experimentally, nor has its dependence on the bunch profile and other parameters been studied.

We propose this experiment to be carried out at a DC cooler at a collaborating institution, utilizing the existing facilities including an ion storage ring. A DC cooler is equipped with a thermionic gun and an electrostatic accelerating device. We propose replacing the thermionic gun by a laser driven photo-cathode gun for this experiment. By controlling the driver laser (its repetition rate and pulse time structure), a bunched electron beam can be drawn from the cathode. It is believed that, from the first principle, a bunched beam can be accelerated equally well by an electrostatic acceleration structure. This bunched electron beam will cool either a coasting or a bunched ion beam if there are RF cavities in the ring.

Alternately, by pulsing the grid voltage, a thermionic gun can also generate a bunched electron beam [22]. The latter method has an advantage of low invasiveness to an existing facility; however, it usually could not make the bunch as short as that in the MEIC design, nor deliver a very high repetition rate.

The second proposed experiment is focused on a proof of the concept of an ERL-circulator cooler and study of the beam dynamics in the circulator ring [23]. The Jefferson Lab FEL driver ERL has been selected as a test facility for this study, as discussed in the next section. The facility will also be used as a test bed for technology development and testing. Specifically, we summarize the goals [23] of the first phase studies as follows:

- Demonstrate fast exchange of high repetition rate bunches between the ERL and the circulator ring;
- Develop and test supporting technologies such as high current ERLs and faster kickers;
- Study beam dynamics and collective effects in the circulator ring, and determine the maximum number of allowable circulations;
- Test bunch length change and longitudinal phase matching between the ERL and the circulator ring.

COOLER TEST FACILITY

The FEL at Jefferson Lab is an ERL based light source presently delivering the highest average power laser in the infrared (IR) region. It also generated an ultra violet (UV) laser [24]. The facility consists of a 350 kV photo-cathode DC gun, a 9 MeV boosting injector, a 130 MeV three-module SRF linac, and two recirculators for IR and UV beams respectively. This facility has been chosen for the cooler demonstration because it provides a high quality electron beam with an energy range and bunch repetition rates similar to the MEIC cooler design. This allows maximum reuse of the existing hardware, thus reducing the capital costs of this experiment.

Both FEL driver ERL performance [25] and the MEIC cooler design parameters [1] are listed in Table 3. They are either overlapping or close to each other, except the bunch charge in the FEL ERL is about 15 times smaller than the 2 nC design value of the cooler. Higher bunch charge in this test facility will not be possible unless there is an upgrade of the injector/ERL merge beamline and several other parts of the FEL driver ERL. Such an upgrade has not yet been planned presently. Therefore,

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the cooler technology demonstration will use a set of reduced machine/beam parameters (mainly the bunch charge). Nevertheless, if the bunch length is kept appropriately short, the bunch intensity (linear charge density) could be made the same as the case of the cooler design; thus a class of collective beam effects could still be studied in this test facility.

Table 3: MEIC Cooler and JLab FEL Driver Performance

		FEL ERL	ERL-CR
Energy	MeV	80-210	10-54
Bunch charge	nC	0.135 (0.25)	2
Turns in CR			10 – 30
Bunch frequency	MHz	75	75 – 25
Gun current	mA	10	150 – 50
Trans. emit., norm.	µm	10	1-3
Long. emittance	keV-ps	25-75	150
Energy spread	%	0.4	0.01
RMS bunch length	ps	2	100

The layout of the cooler test facility is shown in Figure 4. The presence of the parallel IR and UV beam lines provides an opportunity for a most straight-forward implementation of a compact circulator ring by adding two 180° bends. The photo-cathode DC injector, SRF linac and ERL beam line will have no change while providing the electron bunches to the circulator ring. One fast kicker and two septum magnets will be installed in the UV beam line and are responsible for the bunch switching in and out of the circulator ring.

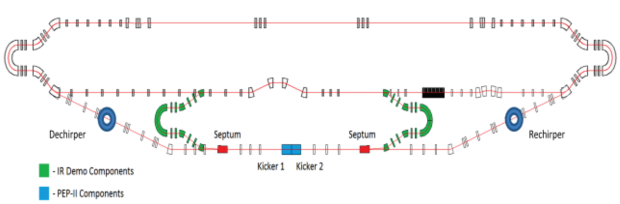

Figure 4: Layout of an ERL-circulator cooler test facility.

DISCUSSIONS AND SUMMARY

Electron cooling of proton and ion beams holds a great promise of very high luminosity for the MEIC proposal. Presently, a cooling design concept based on a multi-stage cooling scheme has been developed. It is centered on an ERL circulator cooler on the high energy end and is continuously being optimized.

The high energy electron cooling of MEIC depends on a number of critical technologies and advanced schemes to achieve its luminosity goal. They can be grouped in two directions: cooling at a high energy and with a bunched beam; and providing a high brightness, high current cooling electron beam. They are considered challenging and require a rigorous R&D program. In addition to theoretical and simulation studies currently underway, we have recently proposed two proof-of-concept experiments to demonstrate the cooling design concept and to develop and test accelerator technologies.

In the larger picture, other cooling technologies and schemes are under careful evaluation for alternate options or as a supplement to the present baseline design. Among them, the stochastic cooling of bunched heavy ion beams is of particular interest since the initial conceptual investigations suggested that the technology is applicable to the MEIC project. An integration of it to the present MEIC cooling baseline design is currently underway [26].

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