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DEVELOPMENT OF A BUNCHED BEAM ELECTRON COOLER FOR THE JEFFERSON LAB ELECTRON-ION COLLIDER *

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Abstract

Jefferson Lab is in the process of designing an electron ion collider with unprecedented luminosity at a 65 GeV center-of-mass energy. This luminosity relies on ion cooling in both the booster and the storage ring of the accelerator complex. The cooling in the booster will use a conventional DC cooler similar to the one at COSY. The high-energy storage ring, operating at a momentum of up to 100 GeV/nucleon, requires novel use of bunched-beam cooling. We will present a new design for a Circulator Cooler Ring for bunched-beam electron cooling. This requires the generation and transport of very high-charge magnetized bunches, acceleration of the bunches in an energy recovery linac, and transfer of these bunches to a circulating ring that passes the bunches 11 times through the proton or ion beam inside cooling solenoids. This design requires the suppression of the effects of space charge and coherent synchrotron radiation using shielding and RF compensation.

INTRODUCTION

As described in more detail in reference [1], Jefferson Lab is designing an electron-ion collider with unprecedented luminosity. The baseline design features a low emittance proton or ion beam with high frequency, low charge bunches at an energy of 40 to 100 GeV. To maintain the low emittance, it is necessary to aggressively cool the beam. We have chosen conventional (incoherent), magnetized electron beam cooling as the most cost effective and low risk approach to cooling the full-energy beam [2]. This paper describes the initial design of such a cooler and describes some of the design challenges that must be met in the cooler ring.

Electron cooling effectiveness is reduced at high energy so a magnetized beam is necessary to enhance the cooling efficiency [3]. Only an RF accelerator (linac or storage ring) can provide continuous high-current, beams at this energy. The cooling inherent in a storage ring at low energy is extremely low and intra-beam scattering is strong. We have therefore chosen an energy recovery linac (ERL) to reduce the emittance and energy spread of the electrons in the cooler.

We have found that the required electron bunch charge is a rather high 3.2 nC. These bunches must be supplied at the 476.3 MHz repetition rate of the ion bunches, resulting in a 1.5 Ampere beam current, far higher than has ever been demonstrated in an ERL. To reduce the current required from the linac we use a Circulating Cooler Ring (CCR) that circulates the high charge bunches 11 times through the cooler before returning them to the ERL. This hybrid of an ERL and a storage ring combines the best feature of the ERL (high brightness) with that of the storage ring (high current). We summarize the specifications in Table 1.

Table 1: Electron specifications for cooling ring

Parameter	Value
Energy	20–55 MeV
Charge	3.2 nC
CCR pulse frequency	476.3 MHz
Gun frequency	43.3 MHz
Bunch length (tophat)	2 cm (23°)
Thermal emittance	<19 mm-mrad
Cathode spot radius	2.2 mm
Cathode field	0.1 T
Gun voltage	>400 kV
Norm. hor. drift emittance	36 mm-mrad
rms Eng. spread (uncorr.)	3×10^{-4}
Energy spread (p-p corr.)	$<6\times10^{-4}$
Solenoid field	1 T
Electron beta in cooler	36 cm
Solenoid length	4x15 m

OVERALL LAYOUT

The baseline layout is show in Fig. 1. A high charge electron beam source provides magnetized beam to a booster that accelerates this beam to over 5 MeV. The electrons are then matched through a merger to the linac. The superconducting linac accelerates the beam off-crest to anywhere between 20 and 55 MeV. The first arc then transports the beam to the exchange region, where the beam is kicked up into the CCR via a septum and harmonic kicker. After circulating through the cooler and two recirculation arcs 11 times, the beam then exits the CCR via another harmonic cavity and septum. At this point the beam is bent back into the linac to be decelerated to the dump energy, where it is ejected into a water-cooled beam dump.

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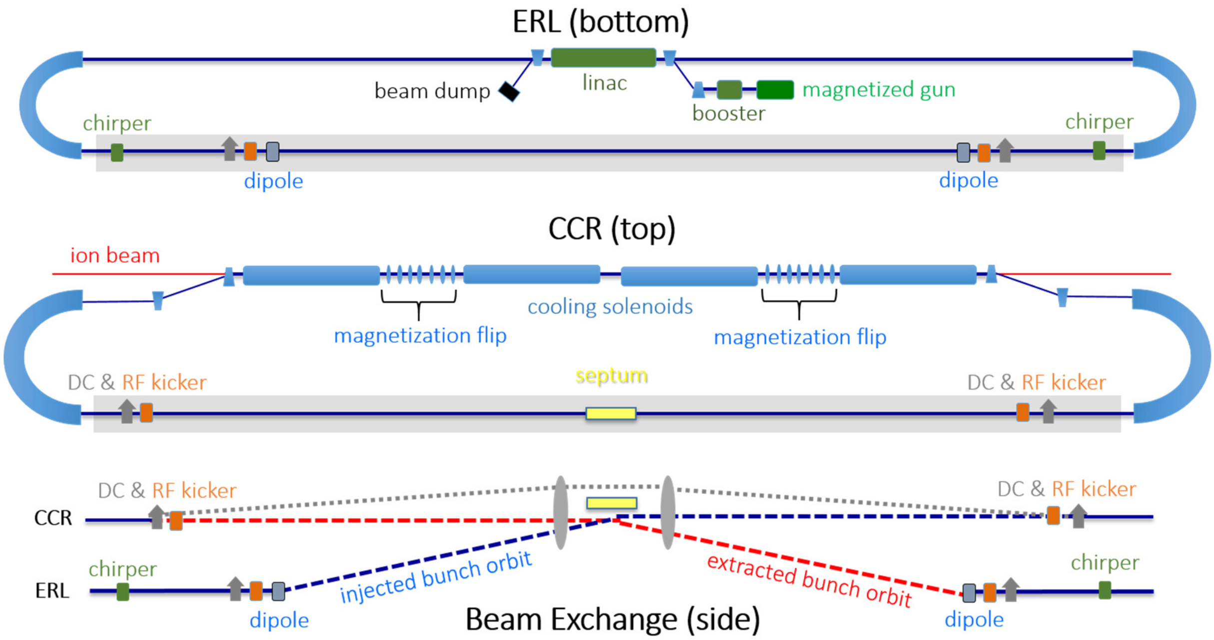

Figure 1: Layout of the Circulating Cooler Ring (CCR) concept. The ion ring is cooled by a magnetized beam circulating for 11 passes of the CCR laying atop and fed by an Energy Recovery Linac (ERL) producing and recovering high charge, magnetized bunches at a 43.3 MHz repetition rate.

INJECTOR

The injector must not only provide bright, high charge bunches but must preserve the magnetization of the beam. Though the beam is created in a magnetic field, it is allowed to exit this field after the gun. At this point the beam "spins up" and develops an angular momentum equal to the canonical momentum at the cathode. Both the small Larmor emittance and the magnetization must be preserved throughout the injector [4].

The beam must then be merged with the decelerating beam in the ERL. We are looking at several different designs:

- A toroidal field merger similar to those used in DC coolers [5].
- A magnetic merger using indexed dipoles.
- An RF merger that kicks the energy recovered beam but not the injected beam.
- An RF merger that uses the RF focussing in the linac module to merge the two beams.

Both DC photocathode guns and low frequency normal conducting photocathode guns are being considered. The RF guns provide higher gradients at the cathode and can provide higher energy from the gun but may introduce RF focussing effects.

LINAC AND ERL ARCS

The linac can use 952.6 MHz cavities similar to those of the ion ring but with more cells. Due to the long bunch length in the linac, second order corrections in the arc delivering the beam to the exchange region will be necessary to linearize the bunch. This has previously been demonstrated in the IR Upgrade FEL at Jefferson Lab [6].

After the arc, an SRF de-chirper cavity will be used to remove this energy slew in the bunch and prepare the beam for the CCR.

After the beam is ejected from the CCR it must be chirped and shortened as necessary to match to the linac for deceleration.

EXCHANGE REGION

To bring in the 43.3 MHz bunches to the CCR and then eject them after 11 passes a combination of a harmonic kicker and a septum will be used. The beam will be bent upwards to the level of the CCR and then brought almost parallel to the CCR using a septum magnet [7]. The harmonic kicker will then kick the beam on axis into the CCR [8].

There is a second harmonic kicker upstream of the injection kicker. It kicks every 11th bunch out of the CCR and down into a septum, which bends the beam back down to the level of the ERL. The upstream and downstream harmonic kickers are 180° of betatron phase apart so that their time dependent effects are cancelled for all other circulating bunches. Each harmonic kicker has an overlapping magnetic field that bends the beam up so that it misses the septum during the 11 passes through the CCR.

CIRCULATING COOLING RING

The challenge of the CCR is to bend the beam through 22 arcs while preserving the beam quality and magnetization. We have looked at several different arc

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designs. In general, the arc should have the following properties:

- Isochronous and Achromatic.
- High periodicity with rational tune
- Moderate size
- Local axial symmetry
- Local isochronicity⇔small compaction oscillations (for µBI)
- Local dispersion suppression

In addition, the CCR as a whole must have no tune resonances beyond the coupling resonance.

One arc that seems to have good properties, especially low microbunching gain, is a simple four bend arc shown in Fig. 2. Note that the microbunching instability (µBI) gain must be no greater than unity or the net gain after 22 arcs will be quite large.

Though this arc does possess excellent microbunching properties, it does not eliminate CSR wakes altogether. Only transverse wakes can be compensated. Beam chamber shielding may be used to reduce the strength of the longitudinal CSR wake, especially the lower frequencies, but the higher frequencies, especially the ends, are strongly accelerated relative to the core. The core beam will also lose energy and develop an energy chirp but this could be compensated via an RF cavity in the CCR. Space charge forces are comparable to the longitudinal CSR wakes. The longitudinal distribution after 10 passes is shown in Fig. 3. Even though the microbunching gain is small, the correlated energy spread is much larger than the specification in Table 1. We are therefore exploring other architectures that might also have low microbunching gain but also have small CSR wakes.

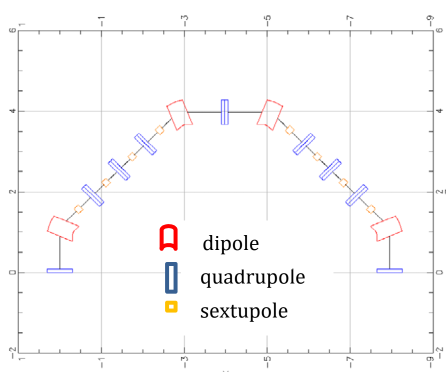

Figure 2: Layout of a simple arc. This design has global but not local symmetry.

COOLING SECTION

In the interest of minimizing the impact of the cooler on the spin rotation in the collider ring, we are using four separate 15 meter solenoids in the cooling section. The outer two have the opposite polarity from the inner two, thus cancelling any spin effects. We then have to flip the angular momentum of the electron beam between the 1st and 2nd and the 3rd and 4th segments. This is done with several quadrupoles and is essentially a parity reversal for the electron beam [9].

In addition to the bunched beam cooling we also plan to include DC cooling into the first 15 meters of the cooler to cool the beam during the initial fill [10].

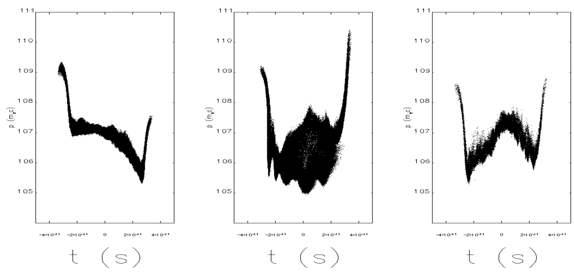

Figure 3: Longitudinal phase space after 10 turns through the CCR with the simple arc. (L) no shielding or csr drift. (C) no shielding. (R) no csr drift.

DESIGN CHALLENGES

This design has many challenges.

- The injector must provide a high current beam with a reasonable cathode lifetime. It must also preserve the magnetization in the presence of strong space charge forces.
- The CCR must preserve both a very small energy spread and magnetization despite strong CSR and space charge forces.
- The CCR vacuum system must be able to handle extremely high currents without overheating due to wakes and resistive wall heating.
- The beamlines must stay as symmetric as possible despite the need for bends and quadrupoles.

Since many of these parameters are outside of any demonstrated regime of operation, simulation codes have not been benchmarked for this system. We therefore have an added challenge of being able to simulate the system accurately [11].

CONCLUSION

We have developed a design for a bunched beam cooler for an electron ion collider. Though conservative in its choice of technologies and designs, the operating parameters are significantly beyond the state-of-the-art for ERLs. We will be testing out some aspects of the design in experimental tests in the coming years.

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