ISBN: 978-3-95450-198-4 doi:10.18429/JACoW-COOL2017-WEM12

# DEVELOPMENT OF A BUNCHED BEAM ELECTRON COOLER BASED ON ERL AND CIRCULATOR RING TECHNOLOGY FOR THE JEFFERSON LAB ELECTRON-ION COLLIDER*

Stephen Benson†, Yaroslav Derbenev, David Douglas, Fay Hannon, Andrew Hutton, Rui Li, Robert Rimmer, Yves Roblin, Chris Tennant, Haipeng Wang, He Zhang, Yuhong Zhang,
Jefferson Lab, Newport News VA, USA



*Abstract*

Jefferson Lab is in the process of designing an electron ion collider with unprecedented luminosity at a 45 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. There are two designs for such a cooler. The first uses a conventional Energy Recovery Linac (ERL) with a magnetized beam while the second uses a circulating ring to enhance both peak and average currents experienced by the ion beam. This presentation will describe the design of both the Circulator Cooling Ring (CCR) design and that of the backup option using the stand-alone ERL operated at lower charge but higher repetition rate than the ERL injector required by the CCR-based design.

## INTRODUCTION

The JLEIC electron-ion collider is designed to produce extremely high luminosity at 45 GeV center-of-mass (CM) energy in electron ion collisions [1]. To accomplish this, the proton or ion beams must be cooled during the operation of the collider. The ion and proton energy is as high as 100 GeV so an electron cooling beam must have an energy of 55 MeV to match the velocity of the protons. To produce a beam of such an energy requires an RF accelerator so the electron beam used to cool the protons/ions must be bunched rather than CW.

We have attempted to design an electron cooling system for JLEIC that strongly cools the ion or proton beams. The specifications for the cooler are shown in Table 1 for the electron and Table 2 for the proton beams for two different CM energies. The electron beam parameters are difficult to achieve due to both the very high charge and high average current. Space charge forces, coherent synchrotron radiation, and wakes tend to create large energy shifts in the electrons. The layout of the cooling complex is show in Fig. 1. The ion ring is cooled by a Circulating Cooler Ring (CCR) that circulates high-charge bunches 11 times through the ion or proton beam. The bunches are injected from an Energy Recovery Linac (ERL) via a harmonic kicker [2]. After 11 round trips, the electron bunches are extracted and decelerated in the ERL and diverted to the dump. The gun frequency is then one eleventh of the cooling ring frequency.

At full CM energy (63.5 GeV), the colliding beams are reduced to one third of their usual frequency while the proton bunch charge is tripled. This is the worst case for cooling so we will consider that case first.

Table 1: Electron Specifications for Strong Cooling

| 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.)* | $3\times10^{-4}$ |
| Energy spread (p-p corr.)* | $<6\times10^{-4}$ |
| Solenoid field | 1 T |
| Electron beta in cooler | 36 cm |
| Solenoid length | 4x15 m |

Table 2: Proton Specifications for Strong Cooling

| Parameter | 63.5 GeV CM | 45 GeV CM |
|---|---|---|
| Energy | 100 GeV | 100 GeV |
| Particles/bunch | $2.0\times10^{10}$ | $6.6\times10^{9}$ |
| Repetition rate | 158.77 MHz | 476.3 MHz |
| Bunch length (rms) | 2.5 cm | 1.0 cm |
| Normalized emittance (x/y) | 1.2/0.6 mm-mrad | 1.0/0.5 mm-mrad |
| Betatron function | 100 m | 100 m |

Note that we have chosen to use a magnetized beam in the cooler [3]. In a magnetized source, the cathode is immersed in a solenoid. The gun generates an almost parallel (laminar) electron beam. This beam state is then transplanted to the solenoid in the cooling section. The

*Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177, the Office of Naval Research and the High Energy Laser Joint Technology Office. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
†felman@jlab.org

ISBN: 978-3-95450-198-4 doi:10.18429/JACoW-COOL2017-WEM12

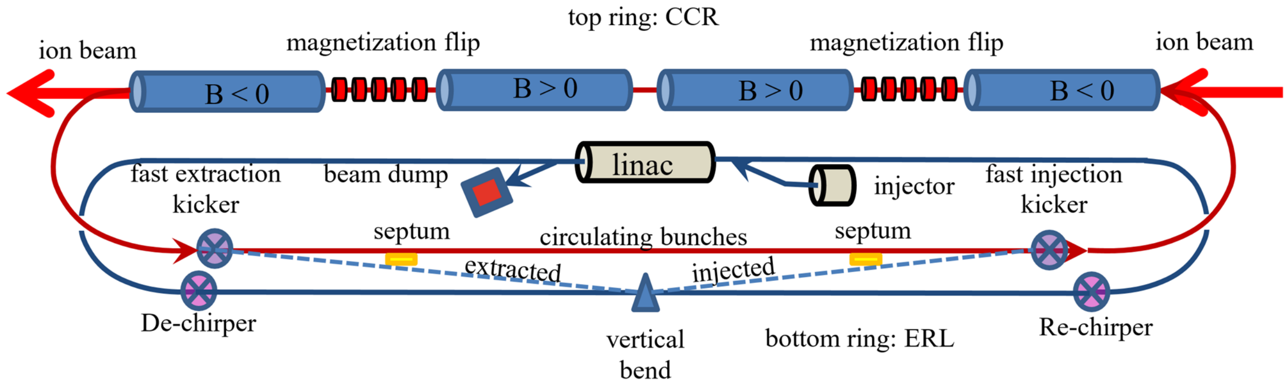


Figure 1: Layout of the Circulating Cooler Ring (CCR) concept. The ion ring is cooled by a magnetized beam circulating for 11 passes of the CCR and fed by an Energy Recovery Linac (ERL) producing and recovering high charge, magnetized bunches at a 43.3 MHz repetition rate.

ratio of the solenoid fields at the gun and cooler can be adjusted to match the e-beam size to the ion beam size. We do not, however, maintain the solenoid field from cathode to dump, so this Canonical Angular Momentum (CAM) beam must be transported in such a way that the magnetization is preserved between the gun and cooler. Derbenev has shown that this is possible if the transport if axisymmetric [4].

The helicity of the angular momentum is flipped in two transport sections between the cooler solenoids. This preserves the spin in the collider ring.

Magnetization has the following advantages over a non-magnetized gun/cooling solenoid):

- It has significantly stronger cooling than non-magnetic case [5].
- There is a large reduction (by a factor 20 – 30) of the deleterious impact of space charge on dynamics in the CCR (e.g, the tune shift).
- There is a strong suppression of the CSR micro-bunching/energy spread growth (though CSR can still increase the correlated energy spread) [6].
- It suppresses the deleterious impact of high electron transverse velocity spread and short-wave misalignments to cooling rates (thanks to ion collisions with “frozen” electrons at large impact parameters).

## COOLING SIMULATIONS

A simulation code JSpec, which uses algorithms similar to BETACOOL [7], was used to simulate cooling in the ring for the 65 GeV CM parameters [8]. The calculated cooling and Intra-Beam-Scattering (IBS) rates are shown in Table 3.

Table 3: Sample Cooling Rates and Intra-Beam Scattering Rates for a 63.5 GeV Center-of-Mass Energy

| | Units | x | y | z |
|---|---|---|---|---|
| Cooling rate | $10^{-3}$ 1/s | -0.431 | -1.434 | -1.605 |
| IBS rate | $10^{-3}$ 1/s | 3.192 | 0.102 | 0.618 |
| Total rate | $10^{-3}$ 1/s | 2.761 | -1.332 | -0.987 |

Note that the transverse heating in the x-direction is much larger than the cooling and the opposite is true for the vertical direction. The longitudinal cooling is also much stronger than the heating. If we cool with these cooling and heating strengths, the bunch becomes shorter and the IBS increases so that the horizontal emittance starts to increase very rapidly after about 20 minutes of operation.

Changing the partition of the cooling and heating might be accomplished by using skew quad coupling between vertical and horizontal axes for the proton beam. This must be done in such a way that the luminosity is not degraded. Transverse dispersion at the solenoid might also be able to couple the transverse and longitudinal cooling. The JSpec code must be modified to do this accurately.

## ERL SIMULATION RESULTS

### *Weak Focusing Results*

Historically, we first studied a weak cooling solution without the CCR. This had just an ERL with higher average current but lower charge than the ERL used with the CCR. The ERL design accelerates on the rising side of the acceleration phase and debunches the beam in an arc with non-zero $M_{56}$. An RF cavity operated at zero crossing is then used to remove the energy chirp on the beam. After going through a 30-meter solenoid the helicity is reversed in a magnetization reversing set of skew quads. The beam is then sent through a second 30-meter solenoid before going through a chirping cavity and a second arc, where the beam is bunch down to the proper length for the decelerating pass of the ERL. At the end of the second pass through the linac the beam is separated and sent to a 5 MeV dump.

This system was simulated from the cathode to the dump (Start-to-End) and from the exit of the injector booster to the dump (Injector-to-End). In the latter case, an ideal super-Gaussian distribution was used for the electron bunches.

11th Workshop on Beam Cooling and Related Topics COOL2017, Bonn, Germany JACoW Publishing
ISBN: 978-3-95450-198-4 doi:10.18429/JACoW-COOL2017-WEM12



In Fig. 2 we show the *rms* bunch size vs. position for the Injector-to-End simulations both with and without CSR. With the very long bunch it is not clear that the CSR will have such a large effect because CSR shielding may reduce the CSR forces [9], but the dominant effect so far is to cause some mismatches, which can be rematched to optimize the system. The beam is well behaved through the ERL. The transverse Larmor emittance grows from an initial value of 2 mm-mrad to 4.4 mm-mrad without CSR and 7.8 mm-mrad with CSR. Both are well within the specifications in Table 1. The emittance growth is dominated by the growth in the merger between the booster and the linac. The longitudinal behaviour is also acceptable. The addition of CSR leads to some tilt in the phase-energy phase space but this can easily be removed by changing the de-chirper phase a bit. The start-to-end simulations do not achieve a smooth super-Gaussian distribution at the booster exit but the resulting distribution is maintained well through the machine and the transverse emittances are similar to the ideal Injector-to-End case.

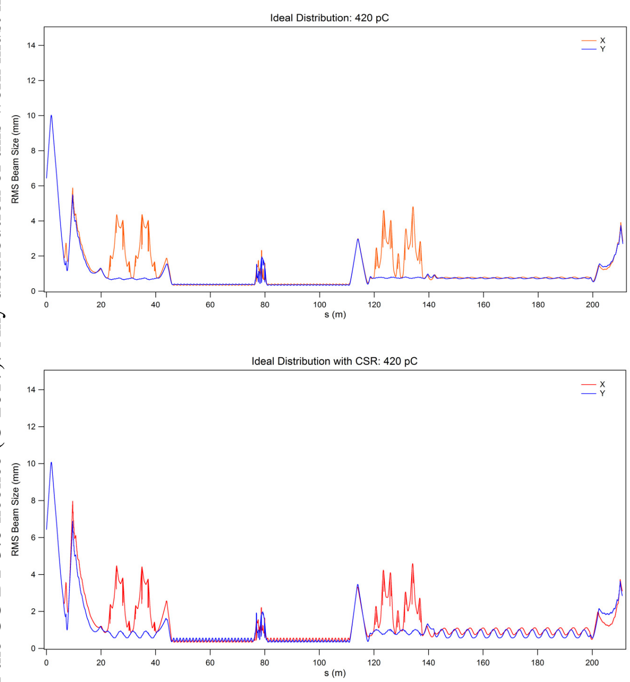


Figure 2: Simulation of the transport of the magnetized bunches from the exit of the injector booster to the dump both without (top) and with(bottom) CSR effects.

## *Strong Focussing Results*

In the CCR design, the charge per bunch is increased from 420 pC to 3.2 nC. This strongly enhances the effects of CSR and space charge. The arcs must also now be isochronous since the bunch length and shape have to be maintained for 11 turns.

Designing an isochronous arc with equal two-plane focussing is quite difficult due to the rather weak focussing in the double focusing dipoles. We have therefore explored the used of globally symmetric arcs. In such an arc, the transport matrix from the beginning to the end of the arc is a unit matrix. The design does use quadrupoles however, which are explicitly asymmetric. We have found that magnetization can be maintained even with a globally symmetric arc.

Though the transverse properties of the beam are maintained in the arc, the longitudinal properties are badly degraded by CSR. This is shown in Fig. 3 for 5, 10, and 20 passes through the CCR. The bunch develops a strong energy chirp due to the CSR wake.

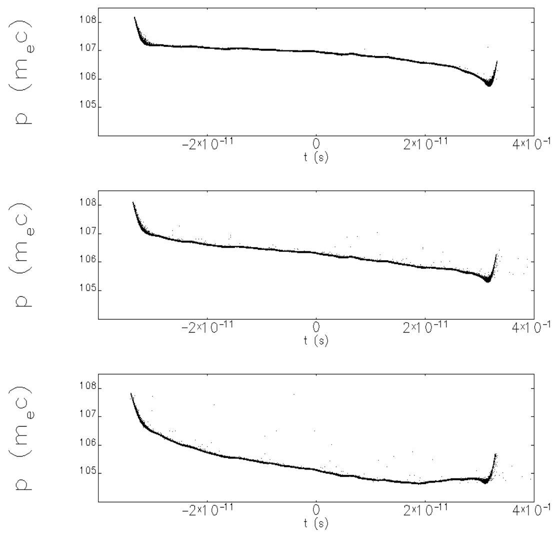


Figure 3: Longitudinal phase space for 5 (top), 10 (middle), and 20 (bottom) passes through the CCR. This assumes a super-Gaussian distribution in the ring.

Since the CSR effects appear to be fairly linear it is worth exploring whether an RF cavity can be used to compensate some of the energy loss and chirp. This was done with some success. The result is show in Fig. 4. Note that we expect that the CSR will be at least partially shielded so the longitudinal distortion in both Fig. 3 and Fig. 4 should be much less when shielding is added.

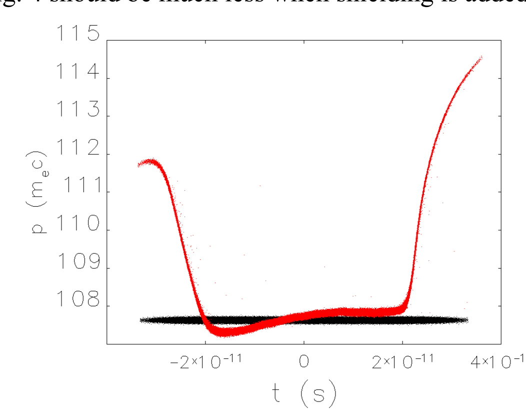


Figure 4: Longitudinal phase space after 20 passes with an RF cavity compensating the energy loss and chirp. The compensation is not perfect but it is possible to get close to the correlated energy variation specification in Table 1 of $6\text{x}10^{-4}$ peak-to-peak.

ISBN: 978-3-95450-198-4 doi:10.18429/JACoW-COOL2017-WEM12

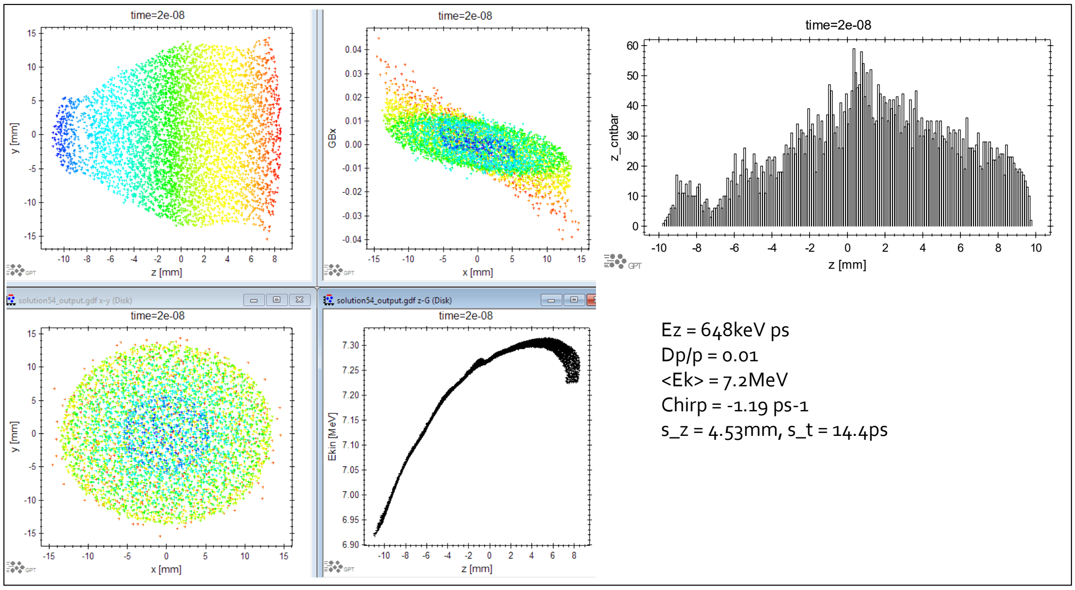


Figure 5: Particle distributions at the end of the booster for the injector. Each slice of the distribution has good magnetization but the slices do not have the same Twiss parameters so the projected emittance is larger than the specification.

### *Exchange Region*

The beam is kicked into the CCR and back out to the ERL using two harmonic kickers [2]. The kickers provide a 2.5 mrad kick to one of 11 bunches and no net kick on any of the others. There is some variation of the kick around zero for each of the bunches but the two kickers are separated by 180° of betatron phase shift so the slope and curvature of the kicker pulse cancels out.

It is possible that there may be some residual effects on the unkicked bunches after traversing the exchange region several times. We have modelled the effects of the kickers and the intervening transport on the beam over 11 passes through the CCR. There are some small effects due to chromaticity but the bunches maintain their *rms* properties.

### *Injector Simulations*

The current injector layout consists of a 433 MHz NCRF gun (ten times the bunch frequency) followed by a 433 MHz buncher, a 952.7 MHz buncher, and a booster module with 4 2-cell 952.7 MHz cavities. There are solenoids in the first part of the line to create a magnetized beam. The longitudinal magnetic field must go down to zero before the superconducting cavities of the booster. The results of optimized simulations are shown in Fig. 5. The optimization algorithm tried to produce a uniform distribution with a very linear longitudinal phase space. It was found that the two tend to be inversely related, i.e. a more uniform distribution has worse longitudinal phase space distribution and vice versa. Note the strong variation in bunch size vs. micropulse position. This variation leads to projected emittance growth.

One way to address the non-uniformity in the micro-bunches would be to go to a lower frequency. We will be doing this next to find a more optimum configuration.

## CONCLUSIONS

The Cooler ring design is not yet complete, though we have made progress in several areas. The following are items that must be pursued before a complete design can be established:

- We have to find the proper cooling partition that matches the cooling to the Intra-Beam Scattering.
- An injector design that preserves the beam quality of the beam from the cathode must be derived. It is our expectation that we must use lower frequency RF.
- The longitudinal match to the CCR must be derived. If the injector bunch is too long we might have problems with getting the energy spread to match the specifications.
- CSR and space charge shielding effects must be added to the simulations to show if CSR can be managed in the arcs.
- The mergers at several points in the machine must be designed. There are many possible designs that might be used, including some that do not bend the injected beam at all.

The weak cooling design is almost complete but the strong cooling design has priority for now.

## REFERENCES

[1] S. Abeyratne *et al.*, "MEIC Design Summary", ArXiV 1504.07961 (2015).

[2] Y. Huang, H. Wang, R. A. Rimmer, S. Wang, J. Guo, "Multiple Harmonic Frequencies Resonant Cavity Design and Half-Scale Prototype Measurements for the Fast Kicker in JLEIC", *Phys. Rev. ST Accel. Beams*, **19**, 122001 (2016).

[3] G. I. Budker and A. N. Skrinsky, *Sov. Phys. Usp.* **21**, 277 (1978).

[4] A. Burov, S. Nagaitsev, A. Shemyakin, and Ya. Derbenev, "Optical Principles of Beam Transport for Relativ-

ISBN: 978-3-95450-198-4 doi:10.18429/JACoW-COOL2017-WEM12



istic Electron Cooling", *Phys. Rev. ST Accel. Beams*, **3**, 094002 (2000).

[5] A. Burov, V. Danilov, Ya. Derbenev, and P. Colestock, *Nucl. Instrum. Methods Phys. Res.* **A441**, 271 (2000).

[6] C.-Y. Tsai, Ya. S. Derbenev, D. Douglas, R. Li, and C. Tennant, "Vlasov Analysis of Microbunching Instability for Magnetized Beams" *Phys. Rev. ST Accel. Beams*, **20**, 054401 (2017).

[7] I. Meshkov *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A558** 325 (2006).

[8] https://github.com/zhanghe9704/electroncooling

[9] G. Stupakov and D. Zhou, "Analytical Theory of Coherent Synchrotron Radiation Wakefield of Short Bunches Shielded by Conducting Parallel Plates", *Phys. Rev. ST Accel. Beams*, **19**, 044402 (2016).