DESIGN OF A HIGH CHARGE, LOW ENERGY, MAGNETIZED ELECTRON INJECTOR

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Abstract

Simulations of a magnetized injector for the bunched-beam electron cooler ring, as part of the Jefferson Lab Electron Ion Collider (JLEIC) are presented. A challenge of such an injector is in generating a magnetized, 3.2nC electron bunch at low energy and preserving the angular momentum so it can subsequently be merged into the cooler ring and transported to the cooling solenoid without degradation. The design of the proposed injector and the effect it has on the beam are discussed in detail.

INTRODUCTION

Jefferson Lab is currently in the process of designing an electron ion collider, JLEIC, to be built on site utilizing existing accelerator facilities. The proposal for this machine is to have unprecedented luminosity at a 45 GeV center-of-mass energy. The luminosity is heavily dependent on ion cooling in both the booster and the storage ring of the accelerator, shown in Figure 1 [1].

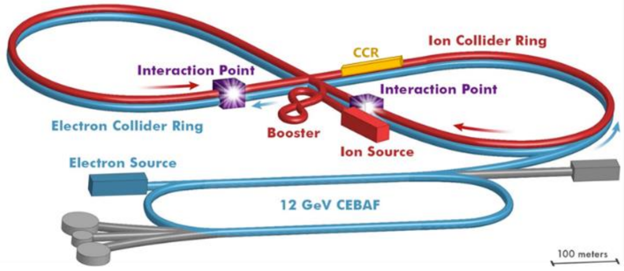

Figure 1: A schematic of the JLEIC accelerator complex.

To counter the effects of emittance growth from intra-beam scattering in the ion beam, electron cooling is employed. The cooling in the booster will be a conventional DC cooler of a similar design to COSY. The high-energy storage ring will require novel bunched beam cooling to achieve the required luminosity. The JLEIC design considered and investigated two concepts for the cooling. The first is based on a standard Energy Recovery Linac (ERL) [2], the second uses a Circulating Cooling Ring (CCR) [3], which also leverages energy recovery and a harmonic kicker cavity [4]. The advantage of the CCR is that both peak and average current can be increased in the cooling channel in comparison to that achievable in a traditional ERL. This is due to the electron bunch making several passes through the cooler loop before being energy recovered. This paper discusses the injector design for the CCR injector, shown in Figure 2.

To achieve the high luminosity for 45 GeV center-of-mass collisions, the ion beam must be continuously cooled [5]. The proton energy is up to a maximum of 100 GeV/u, which therefore requires the electron cooling bunches to have an energy up to 55 MeV such that they co-propagate in the cooling solenoid channel. To improve the cooling efficiency, a magnetized electron beam is used, The electron bunches are produced in the presence of a uniform longitudinal magnetic field. When the electrons exit this field they acquire angular momentum, which if preserved throughout the CCR, will be removed as the beam enters the fringe field of the cooling solenoid. Hence, the usual Larmor rotation inside the cooling solenoid is no longer present and electrons are forced to travel along magnetic field lines with small helical motion, supressing the electron-ion recombination, thus increasing cooling efficiency.

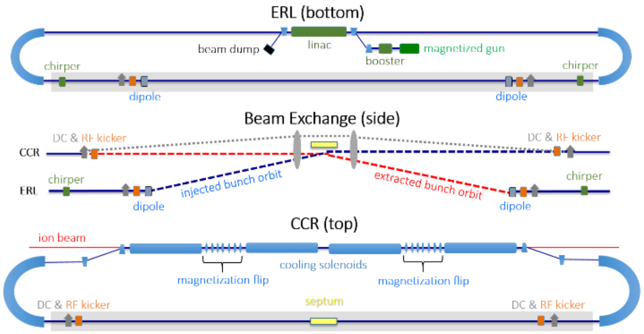

Figure 2: Circulating Cooling Ring (stacked vertically). Top: The ERL ring, Middle: The beam injection/extraction region into the CCR, shown Bottom.

INJECTOR DESIGN

The design of the CCR injector is demanding and is beyond what is currently state-of-the art. These simulations make assumptions that beam charge and current can be delivered from a multi-alkali photocathode inside a 400kV DC electron gun. Otherwise, components have been chosen conservatively. The complete beam parameters for the injector are listed in Table 1. Additionally, cooling simulations indicate that a bunch with uniformly filled cylinder shape produces slightly improved cooling over bunches that have Gaussian longitudinal and transverse characteristics. Therefore a 'beer-can' volume is preferred.

Table 1: CCR Operating Specification.

Parameter	
Energy at the cooler	20-55 MeV
Bunch charge	3.2 nC
CCR bunch frequency	476 MHz
Bunch length at cooler (full)	2 cm
Injector bunch frequency	43.3 MHz
Drift emittance	36 mm-mrad
Gun voltage (DC)	400 kV

A schematic layout of the injector is shown in Figure 3. A DC gun is immersed in the field of a Helmholtz coil

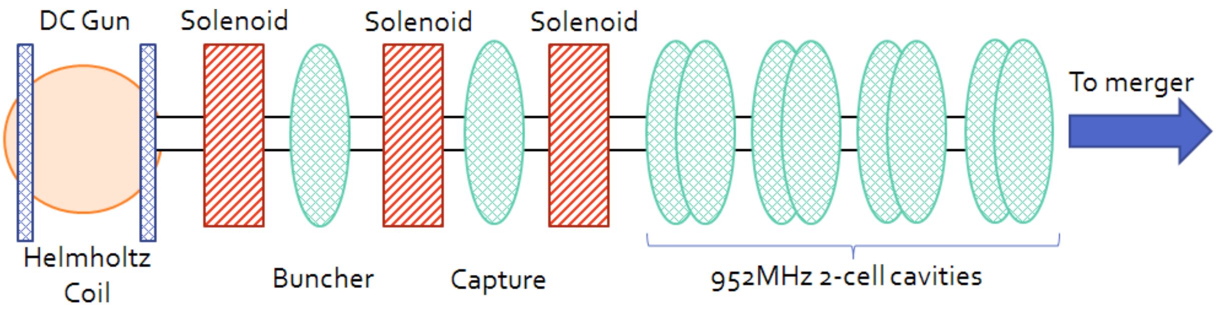

Figure 3: CCR injector schematic

(magnetizing solenoid), which is assumed to give a uniform longitudinal magnetic field over the diameter of the photocathode. The field from such a magnet has considerable longitudinal reach. This is followed by an additional traditional solenoid, buncher cavity, further focusing, a capture cavity, a final solenoid and a booster unit containing 4 double-cell cavities. The fundamental frequency of the RF is 952 MHz to be compatible with the ion collider ring frequency.

Multi-objective genetic algorithms are commonly used to optimize the performance of injectors, and indeed was employed here. Particle tracking tools are typically excellent predictors for beams that are both travelling close to the ideal axis and small transversely. In this situation, with beams dominated by the angular momentum imparted from the magnetizing solenoid, the beam is large transversely throughout the transport of the injector. Extra care is required that any field maps used are representative and valid at the extremes of the beam. The tracking code General Particle Tracer was used for the optimisation of this injector, and to avoid discrepancies in the off-axis field computation at large radius, 2D or 3D field maps were employed wherever possible in the simulation.

The magnetic field on the cathode is chosen specifically, in conjunction with the transverse emitting size to result in a drift emittance, ϵ_d, (that associated with the canonical angular momentum) of 36 μm, calculated using:

$$\epsilon_d = \frac{eB_{cath}a_0^2}{8m_e c} = 36\mu m \tag{1}$$

Where e is the electron charge, m_e is the electron mass, c is the speed of light , B_{cath} is the field at the cathode, and a_0 the beam transverse radius (assuming a radial, uniform distribution). The drift emittance is chosen so that when the beam arrives at the cooling channel that it is cancelled by the cooling solenoid field, such that:

$$B_{cath}a_0^2 = B_{cool}\sigma_e^2 \tag{2}$$

B_{cool} and σ_e are the field and beam radius at the cooler, fixed at 1 T and 0.7 mm respectively.

All other component settings are considered free variables within realistic limits. The objectives of the optimization were to minimize the 4D transverse emittance, minimize longitudinal emittance, and create a long bunch of 2 cm with a small uncorrelated energy spread.

Simulation Results

The results in Figure 4 show the bunch evolution through the injector beamline.

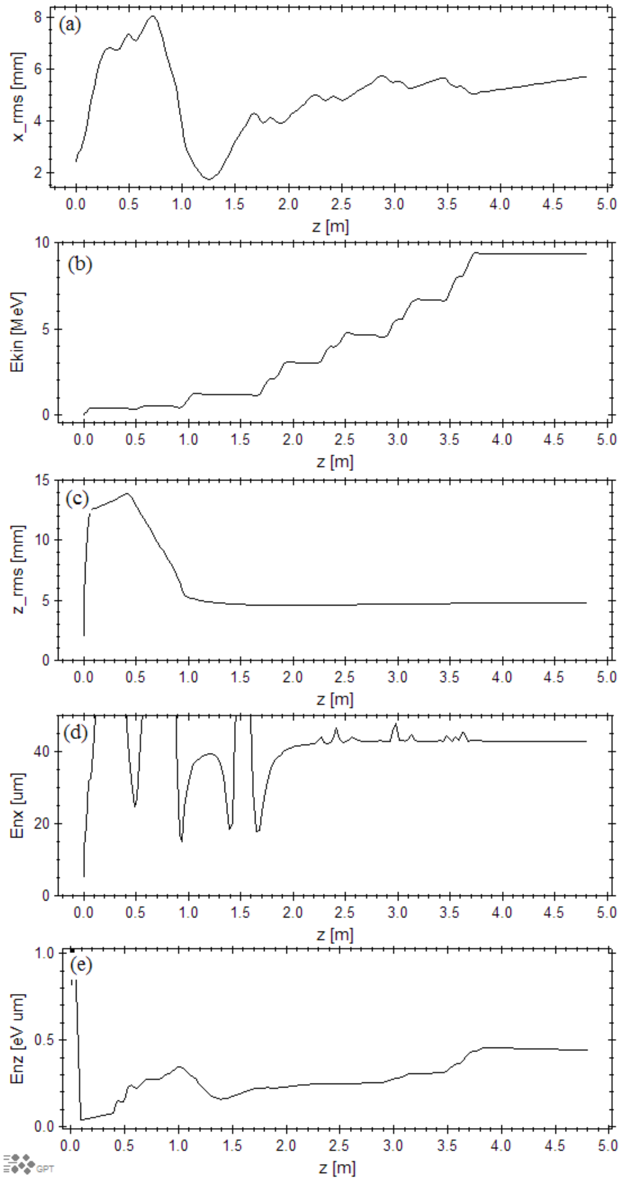

Figure 4: Bunch evolution through the injector beamline. (a) horizontal rms beam size, (b) average kinetic energy, (c) longitudinal rms beam size, (d) horizontal normalised rms emittance, (e) longitudinal normalised rms emittance.

In this configuration, the transverse emitting area is considerably large with a 1cm diameter and has an emission time of 143 ps. This is required to extract 3.2 nC bunches from the cathode with a surface electric field of 4.3 MV/m.

As the bunch progresses through the fringe of the Helmholtz coil, which is 1% of peak on-axis value at 50 cm, it acquires angular momentum due to Busch's principle of conservation. Transverse space charge forces, and solenoid focusing are also acting to determine beam properties in this region.

While the bunch is at low energy, below ~2 MeV in this scenario, space charge forces dominate both transversally and longitudinally. Beyond this energy the angular momentum of the beam dominates the transverse dimensions, whilst the longitudinal progression is still affected by space charge.

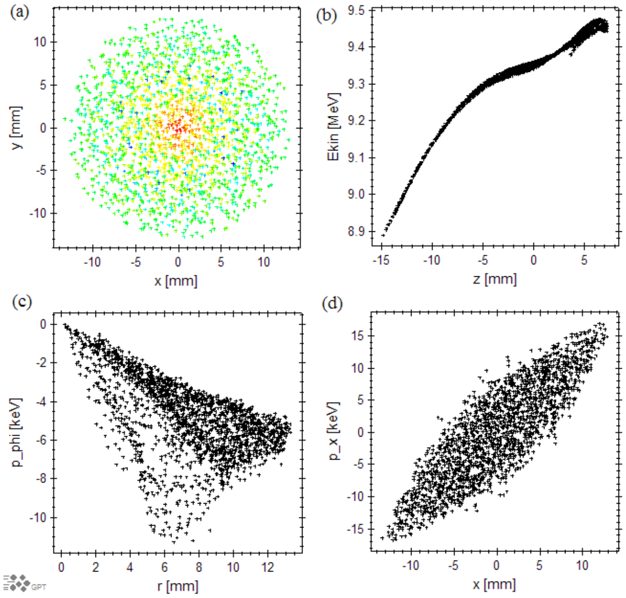

Figure 5: Phase space at the exit of the injector. (a) configuration space (colour scale p_φ), (b) longitudinal phase space, (c) radial phase space, (d) horizontal phase space.

Longitudinally, the bunch is compressed in both the buncher and capture cavities. The capture cavity is also phased to provide some energy gain that would facilitate better acceleration in the beta=1 cavities of the booster. Each booster cavity increases the kinetic energy by ~2 MeV resulting in an average of 9.3 MeV with a 0.55 MeV full energy spread. The longitudinal emittance remains small, as shown in Figure 5, owing to the small uncorrelated energy spread. The full bunch length, shown in Figure 6, is ~2 cm as required.

In the transverse plane, the beam size is determined by a balance between the angular momentum of the beam and solenoid and RF focusing. At the exit of the injector, the beam has a full ~2.5 cm diameter. The resulting transverse emittance is large at 43 μm, which is a combination of thermal, space charge and angular momentum contributions. If all the transverse correlations are removed, and the ultimate 4D emittance calculated, this yields the emittance as will be seen by the ion beam. This has been calculated as 18.3 μm. In an ideal magnetized beam, with no degradation rom the cathode, the $r - \rho_\varphi$ phase space would be a thin line with a small width indicative of a small thermal energy contribution from the photocathode. Here degradation from space charge at low energy and non-linear off axis field effects can be seen in Figure 5.

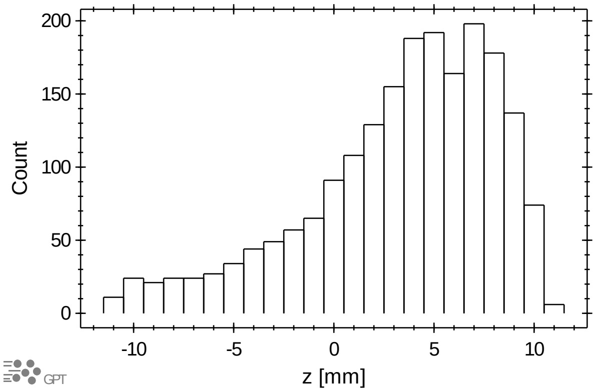

Figure 6: Histogram of the bunch, longitudinally.

DISCUSSION & CONCLUSION

This injector design demonstrates the complexities in transporting low energy, high charge, magnetized beams. Because of the low voltage gun and low electric field at the cathode, the bunch must have a large volume in that region to extract the charge. Most of the transverse emittance degradation happens before the beam reaches 2 MeV and this uses most of the emittance budget for the entire CCR. Future work should include a low frequency RF gun as a front end such that the bunches exit closer to the 2 MeV range where beam manipulation is more linear.

The 3D bunch shape does not meet the beer-can criterion particularly longitudinally, where it has a Gaussian profile at the extremities as it exits the gun. Again, a higher cathode gradient could be beneficial in achieving this goal.

ACKNOWLEDGEMENT

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