A COOLING STORAGE RING FOR AN ELECTRON-ION COLLIDER

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Abstract

Electron cooling offers performance advantages to the design of an electron-ion collider. A first design of a 6 GeV/u storage ring for the cooling of ions in MEIC is presented, along with some remarks on the particulars of electron cooling in this ring.

INTRODUCTION

Previously, we have proposed the design of a fixed-energy storage ring [1] for electron cooling as an improvement to the MEIC baseline [2], which plans for DC electron cooling at 0.1 GeV/u and 2 GeV/u in the Booster, and bunched beam cooling using an energy recovery linac (ERL) at 7.9 GeV/u and at collision energy, 100 GeV/u. Most of this cooling is aimed at suppression of IBS and maintenance of emittance during the beam lifecycle. To supplement this approach, our design aims to reduce emittance with DC cooling at the fixed energy of 6 GeV/u. The primary design criteria for the ring are: 1) accumulation of ions by momentum stacking, 2) electron cooling and stacking times commensurate with the existing MEIC structure, so as not to bottleneck the acceleration process, 3) minimization of additional cost to accommodate the ring, compared with the benefits offered.

CURRENT DESIGN

Regarding criterion (1), lab-frame longitudinal cooling force $F_{\parallel}$ scales with $1/\gamma$, lab-frame cooling rate τ^{-1} scales with $1/\gamma^2$ [3]. This motivates DC cooling at lower energies, and a lower limit is established by space charge dominance. An operating point near the top energy of the MEIC booster (~7-8 GeV/u) is a good compromise between these opposing constraints, as well as the operational flow of the machine. With this energy and electron current of hundreds of mA, the characteristic cooling time (due to Spitzer) for protons in MEIC is

$$\tau_{\text{lab}} = \frac{3}{8\sqrt{2\pi}\, n_e Z^2 r_e r_i c\Lambda}\left[\frac{T_e}{m_e c^2}+\frac{T_i}{m_i c^2}\right] \le 5\ \text{min},$$

meeting the needs of criterion (2) assuming a physics time of ~1 hr in the collision ring and ~10 cycles of the Booster. With a dedicated cooling ring, once a beam has been transferred to the collision ring for final acceleration and collision operation, preparation and storage of a new beam can begin immediately, bringing down the time needed between dumping old beam and resumption of physics operations. The integration of the arcs (Figure 2) in the same cryostat as the ion collision ring (in currently unallocated space) goes a long way to meeting criterion (3), as no addition provisions need be taken for the cryogenic systems. The magnet strengths given in Table 1 do not represent large demands on top of the existing cryogenic design.

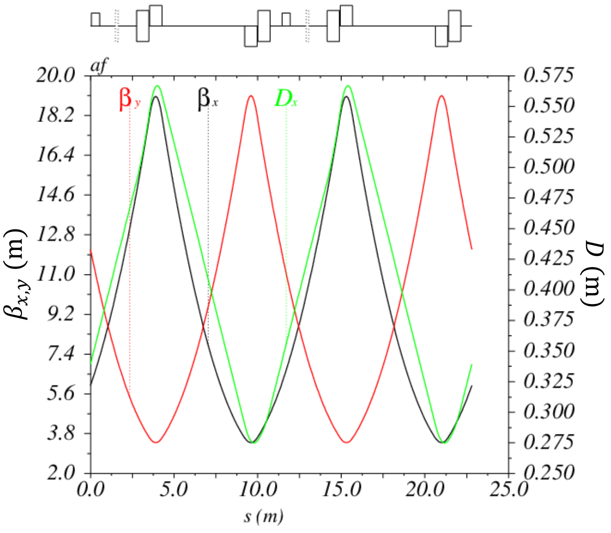

Figure 1: Arc cell optics, shown over the length of one collision ring period.

Figure 2: Schematic layout of placeholder cooling ring integrated above the collider ring in the same cryostat.

Table 1: Cooling Ring Parameters

Arc dipole	0.245 T
Focusing gradient	9.363 T/m
Defocusing gradient	9.424 T/m
Cooling solenoid field	>1.0 T
Electron energy	3-4 MeV
Electron beam current	>250 mA

In the electron cooling section (see Figure 3), the dispersion is matched to zero to maximize the effectiveness of electron cooling. If the dispersion is non-zero, there will be some ions whose velocity is less than that of the electron beam on many turns, resulting in heating and eventual loss of these particles. Note that although the betatron function is shown in the figure, the cooling solenoids occupying the drift spaces will couple the transverse motions and provide

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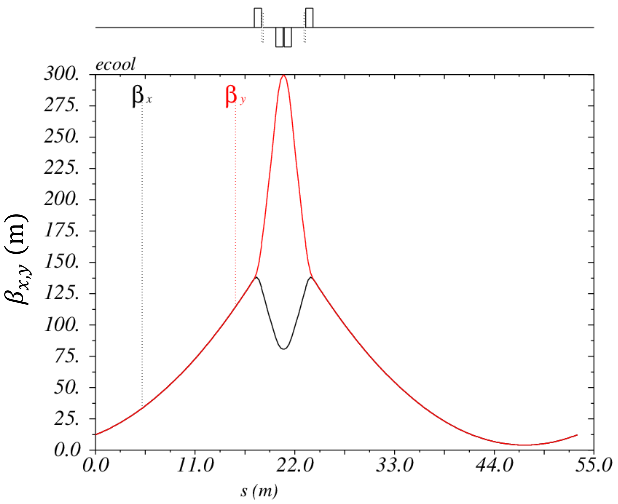

Figure 3: Electron cooling period optics.

focusing. The Courant-Snyder formalism (and thus the betatron amplitude function) are therefore not valid in this region, but an analogous description of the true motion is possible [4]. Quadrupoles between the solenoids will be used for additional control of the beam, and it may be necessary to operate with a skew component for compensation of the transverse coupling introduced by the solenoids.

Injection is performed in the opposing straight, with an insertion (Figure 4) that has a large constant dispersion, to allow side-by-side injection (at an appropriate offset velocity) of new beam which will then be merged with the circulating beam and cooled, making room for more injected beam, and so on. The design of the injection insertion is based on the conceptual design [5] of a beta-beam facility, which has similar requirements for stacking.

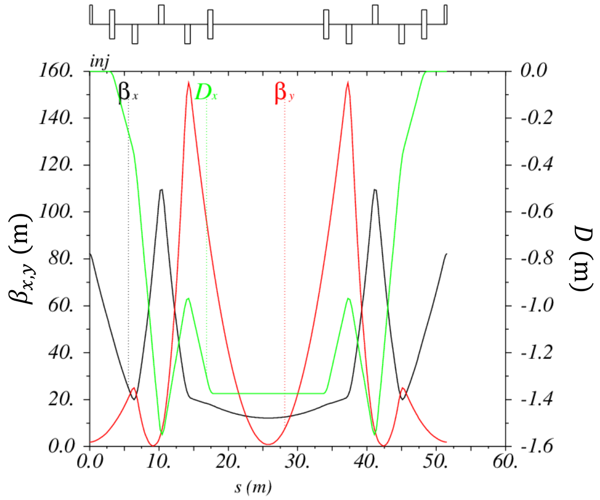

Figure 4: Fixed-dispersion injection insert optics.

ELECTRON COOLING

Our approach to the design of the electron cooling ring is inspired in large part by the success of DC cooling of antiprotons at the Fermilab Recycler. Storage ring cooling of a similar form would augment the MEIC baseline's provisions for bunched beam electron cooling, enabling greater performance without straying prohibitively far from 'traditional' electron cooling. In the Recycler, a magnetic field of ≤600 G was used in the cooling region. [6] Stronger magnetization results in confinement of the charged particles to a smaller gyroradius, and this improves cooling, as the electrons will traverse many periods during a single collision, so that the contribution from their transverse motion is cancelled.

With higher electron density, collisions will occur more frequently, such that the cooling rate scales with the density. The effect of space charge in the cooling section is an $\vec{E} \times \vec{B}$ 'drift' term, creating a radially-varying azimuthal velocity in the electron beam. For steady-state operation this can be approximated as:

$$\frac{\Delta E(r)}{E_0} \approx \frac{I_e r_e}{ec} \frac{\gamma + 1}{\beta_0^3 \gamma^2} \left(\frac{r}{r_0}\right)^2.$$

This drift term places a limit on the useful perveance that can be used for magnetized cooling. To overcome this limit requires neutralization of the space charge, which was successfully implemented at Fermilab and LEAR in a series of experiments focused on trapping residual gas ions. [7,8] We propose to extend the 'conventional' approach to cooling used in the Recycler by utilizing both strong magnetization and neutralization of space charge by the same ion trapping techniques used in those experiments.

In MEIC, the longitudinal temperature of the ion beam at the top of the booster is likely to be much higher than the 'natural' distribution of the electrons. To some extent, cooling scales with $\Delta v_{\parallel}$, but eventually the difference in velocity distributions results in a slower cooling rate because of the rarity of favourable Coulomb collisions. Therefore, we wish to investigate a variable energy scheme relying on sweeping the mean electron energy through a range of values, creating an inertial force term that 'drags' the extremes of the ion beam velocity distribution to a central value, and reduces the cooling time. This cooling strategy has been investigated experimentally at LEAR and TSR [9,10], and may prove to be extremely advantageous for the cooling ring envisioned here.

CONCLUSION

With this first design of a 6 GeV/u in place, we will proceed toward simulations of the cooling process in this ring, beginning with transport of electrons born in a strong field into the cooling region, and working towards additional quantitative metrics for measuring the benefits of this ring to the MEIC layout. We also plan to investigate the dynamics of the magnetized and neutralized cooling with simulation in the code WARP. In particular, we intend to first focus on simulation of electrons born immersed in a strong magnetic field, transported in a non-immersed section, and matched to a strongly magnetized cooling section using the method proposed by Derbenev [11]. From there, the combination of neutralization and magnetization can be studied, and finally a full study of cooling of ions under these conditions may be undertaken to characterize the improved luminosity and other metrics relevant to MEIC.

Additionally, some cooling hardware from the Fermilab Recycler is available for repurposed use, including parts of the Pelletron. We would like to acquire this hardware and assemble a testbed for the key technologies involved in the cooling process we propose, allowing for feedback between simulation and experimental processes. Once complete, this testbed could be transported to the site of MEIC construction and integrated as a piece of production hardware.

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