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FIXED-ENERGY COOLING AND STACKING FOR AN ELECTRON ION COLLIDER*

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Abstract

The proposed designs for polarized-beam electron-ion colliders require cooling of the ion beam to achieve and sustain high luminosity. One attractive approach is to make a fixed-energy storage ring in which ions are continuously cooled and stacked during a collider store, then transferred to the collider and accelerated for a new store when the luminosity decreases. An example design is reported for a 6 GeV/u superferric storage ring for this purpose, and for a d.c. electron cooling system in which electron space charge is fully neutralized so that high-current magnetized e-cooling can be used to best advantage.

EIC DESIGNS

High-energy collisions of polarized beams of electrons and ions provide the possibility of extending the study of the spin structure and dynamics in nuclear matter to clarify the spin dynamics of quarks and gluons in nuclei [1]. Those studies require highly polarized beams of electrons and ions, colliding in an asymmetric pair of storage rings.

Several designs have been proposed for the purpose: eRHIC [2], in which polarized electrons from a recirculating electron linac (ERL) are collided with polarized ions in one ring of RHIC; MEIC [3], in which highly polarized beams of electrons and ions are collided in a pair of rings configured as a figure 8 lattice to naturally preserve high polarization; ENC [4], in which polarized beams are colliding in a pair of circular rings.

All such colliders share a common challenge: to accumulate a filling of intense ion bunches with high polarization so that they are ready for injection to the ion ring of the collider whenever the present store loses either luminosity or polarization.

Accumulation of intense beams of polarized ions requires a matching of particle flow between the low-energy stage and the high-energy stage of acceleration. The line current density in a bunch is limited at low energy by the space charge tune shift [5]

$$\Delta\nu_{SC} = \frac{NBIr_i\beta_y}{\pi\nu\beta^2\gamma^3\sigma_y(\sigma_x+\sigma_y)}$$

and by intrabeam scattering (IBS) [6]

$$\Gamma_{IBS} = \frac{N_b r_i^2 c}{64\pi^2\beta^3\gamma^2\epsilon_x\epsilon_y\sigma_p\sigma_s} L_C I$$

where N = total number of particles in a bunch, R = ring radius, B = ratio of peak to average current in bunches, $L_C \sim 20$ = Coulomb logarithm, I = amplification factor from image currents on the beam tube, $r_i = Z^2e^2/Am_pc^2$, a = r.m.s. beam radius, $\mathcal{E}_x, \mathcal{E}_y$ = invariant emittances, σ_p = fractional energy spread, and σ_s = bunch length.

Particle flow through the acceleration sequence must accommodate the strong energy dependence of Γ_{IBS} and $\Delta\nu_{SC}$. It would not be possible to accelerate at low energy the line charge density that could be sustained in collision at high energy. Maximum bunch charge and minimum emittance are attained if ion bunches are accelerated to an intermediate (relativistic) energy and cooled using d.c. electron cooling. The same e-cooling can be used to accumulate repeated cycles of ion production to build bunch intensity to the limits imposed by Γ_{IBS} and $\Delta\nu_{SC}$ at that energy. The cold stack is then available whenever the luminosity or polarization declines in a store.

This approach was used with great success in the Fermilab Recycler [7]. The choice of optimum energy for cooling and stacking is a balance: as energy increases the sustainable bunch line intensity increases, but also the maximal longitudinal drag force $F_\parallel$ and transverse damping rate $\Gamma_\perp$ from electron cooling decreases. These quantities in the co-moving frame come directly from the plasma physics of non-equilibrium relaxation between plasmas of electrons and ions [8]:

$$\Gamma_\perp^* = \frac{8\sqrt{2\pi}Z^2r_er_ic\mathcal{L}}{3}n_e^*\left(\frac{kT_e}{m_ec^2}+\frac{kT_i}{m_ic^2}\right)^{-3/2}$$

$$F_\parallel^* = 2\pi Z^2r_e^2m_ec^2n_e^*\mathcal{L}\left(\frac{c}{\Delta_\parallel^*}\right)^2,$$

where $\mathcal{L}$ is the Coulomb logarithm over the accessible range of impact parameters, and n_e^* is the electron density and T_e and T_i are the electron and ion temperatures in the co-moving frame.

The lab-frame quantities are γ-boosted appropriately:

$$\Gamma_\perp = \eta\Gamma_\perp^*/\gamma^2 \qquad F_\parallel = \eta F_\parallel^*/\gamma$$

where η is the fraction of the cooling ring circumference in which electron cooling is happening.

For the example of the MEIC design for ion acceleration, the approximate optimum choice of ion kinetic energy for cooling is ~6 GeV/u. The cooling ring design and the electron cooling discussion below pertain to that MEIC Ion Ring.

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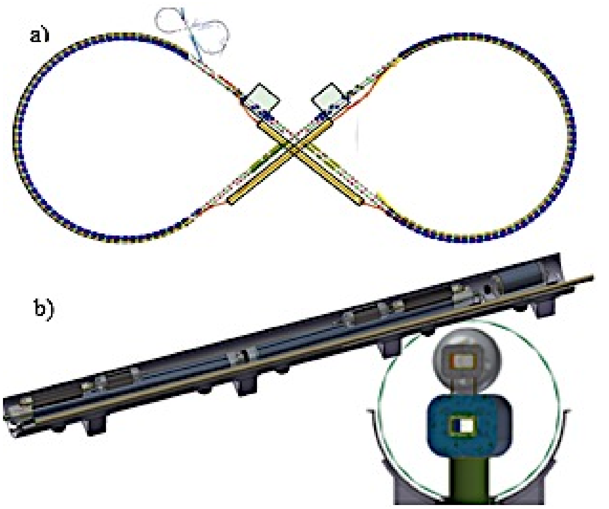

Figure 1: a) MEIC Ion Ring configuration, showing an overlay of an ECR with its cooling straight sections displaced; b) half-cell cryostat of the Ion Ring lattice, showing a full-cell of the ECR mounted piggy-back.

ELECTRON COOLING RING

The MEIC Ion Ring is designed with a figure-8 lattice to naturally preserve ion polarization through acceleration and collision. The ring has a 2.2 km circumference and is designed to accelerate and collide ions at an energy of ~100 GeV for protons, ~50 GeV/u for ions. The arc lattice utilizes superferric dipoles and quadrupoles. The magnets comprising each half-cell are housed in a common cryostat shown in Figure 1b. This configuration offers a particularly cost-effective way to provide a 6 GeV/u Electron Cooling Ring (ECR). A full cell of superferric dipoles and quadrupoles for the ECR is mounted piggy-back on the dipoles of the Ion Ring, sharing the same cryostat. This arrangement is illustrated in Figure 1b. The ECR dipoles in this full-cell would operate at ~1 T for the lengths shown and for 6 GeV/u ion energy.

The short magnet length keeps sagitta to a minimum, and the low field makes for simple, cost-effective magnetics for the dipoles and quadrupoles. By making the ECR lattice with twice the betatron tune of the Ion Ring, its transition energy will also be twice as large, γ_t~25, so the cooled stack could in fact be accelerated in the ECR to ~15 GeV and then transferred to the Ion Ring to avoid any need to cross transition.

Table 1 summarizes the parameters of *non-magnetized electron cooling* in two regimes. The first entry refers to the beam parameters for e-cooling $\bar{p}$s in the Fermilab Recycler [9]: $E_{\bar{p}}$ = 8.9 GeV, $\varepsilon_{95\%}$ = 0.3 μm, $\Delta p/p$ = 0.05%. The entries for protons and ions are typical of the EIC designs: E_i = 6 GeV/u, $\varepsilon_{95\%}$ = 1 μm, $\Delta p/p$ =0.5%. The electron beam parameters are assumed the same in all cases: I_e = 0.5 A, $T_{e\perp} = 900eV, T_{e\parallel} = 1eV$. The cooling fraction is η = .006 for Recycler, .05 for ECR.

The cooling force that is available for cooling and stacking ions in ECR must be averaged over the rest-frame ion velocity distribution. The rest-frame velocity distributions are very different for the Recycler $\bar{p}$s (which were pre-cooled using stochastic cooling and scraped) and for the EIC ions (which are freshly accelerated and ready to be cooled and stacked). Figure 2 shows the rest-frame velocity profiles for the electron and ion distributions for the two cases. The velocity dependence of e-cooling force between velocity distributions is precisely analogous to the spatial dependence of the Coulomb force between charge distributions. In the $\bar{p}$ case, all $\bar{p}$s are near the flat electron disk, and so the cooling force on all $\bar{p}$s is nearly equal to the maximum drag force $F_{\parallel}$. In the EIC case, the proton velocity distribution is oblate, and most protons see a ~1/v^2 force from the electron disk. Correspondingly the minimum drag force available to cool the proton distribution is reduced:

$$F_{min} \approx \left(v_{p\perp}^2/4v_{p\parallel}^2\right)F_{\parallel max} = 0.05F_{\parallel max}.$$

The time for one cycle of cooling and stacking in the ECR is that required to drag ions through the spread of a fresh bunch into the stack: $\tau_{cycle} = 2\Delta p/F_{min}$.

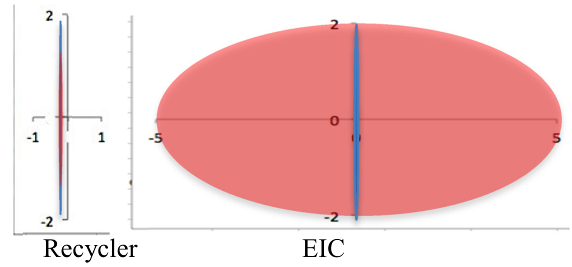

Figure 2: Rest-frame velocity distributions (units of 10^{-3} c) of the electrons (blue) and ions (red) for the Recycler antiprotons and for the EIC protons.

Table 1: Non-magnetized Cooling in Recycler and EIC

	η	$T^*_{i\parallel}$	$T^*_{i\perp}$	$F_{\parallel max}$	F_{min}	τ_{cycle}
		keV		MeV/c/hr		hr
$\bar{p}$	.006	0.1	0.8	70	~70	0.1
p	.05	11	2.7	1250	~62	1.0
d	.05	23	5	1250	~62	1.9
$^3He^{++}$	.05	35	8	5000	~250	0.7

ELECTRON BEAM FOR COOLING

The electron beam for cooling in the ECR is similar to that used in the Fermilab Recycler, shown schematically in Figure 3. The acceleration of a multi-MeV d.c. electron beam requires an electrostatic column. Commercial electrostatic columns can accelerate a few mA of d.c. beam using multiple chains, but cooling requires ~A current. This is achieved by energy recovery, in which the electron beam is returned to the column after it passes through the cooling straight section, decelerated to low energy, and collected on a collector at a potential that is ~kV from gun potential. The electron beam is re-supplied to the cathode through a booster power supply, and d.c. currents on the order of 1 A can be sustained.

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The electron beam must be guided magnetically throughout its trajectory to prevent blow-up from space charge. For low-energy beams this is done by maintaining immersed flow from gun through the cooling straight to the collector. For MeV beams, however, a magnetic guide field cannot be integrated within an electrostatic column. Derbenev [10] devised a resonant optics in which the angular momentum that is transferred to the electrons when they leave the magnetic field in the gun region is resonantly cancelled when they re-enter the magnetic guide field as they approach the cooling straight, and the reverse on their return trip. The Fermilab group made this method work very well, and it provides a quiescent Brillouin flow in the cooling straight.

Brillouin flow comes at a price, however. The repulsion due to the electron beam space charge is exactly transformed by the magnetic field into an azimuthal drift velocity $\vec{v}_d = \vec{E}_{sc} \times \vec{B}_s$. $\vec{v}_d$ acts as a shear velocity between ions and electrons and slows cooling. The product $I_e B_s$ has a maximum value beyond which cooling is limited. Although non-magnetized cooling was adequate for the requirements for accumulation of pre-cooled $\bar{p}$s in the Recycler, it is problematic to optimize ion cooling and accumulation of the hotter ion beams of EIC.

SPACE CHARGE NEUTRALIZATION, MAGNETIZED COOLING

McIntyre *et al.* demonstrated a better solution to the space charge limitations in the first Fermilab Electron Cooling Experiment (ECE) in 1979 [11]. A 100 keV d.c. electron beam was operated with I_e = 2-7 A of current, and was instrumented with depressed collection for which the collection losses were ~10^{-4} when the beam was decelerated to just ~1 kV. The virtual cathode in an unneutralized beam creates a potential depression at the beam axis of $U_{sc} = 30\ \Omega$, $I_e/\beta = 3.3$ kV when a $I_e = 7$ A beam is decelerated to 1 keV. Without neutralization that depressed collection would have been impossible, yet it worked with great stability and 10^{-4} loss.

A d.c. electron beam continually ionizes residual gas atoms to form ions. The ions are born at locations throughout the beam. If the configuration of electric and magnetic fields in the beam are compatible with stable trapping, then ions trap sufficiently to rapidly neutralize space charge (neutralized in ~50 s at 10^{-10} Torr vacuum).

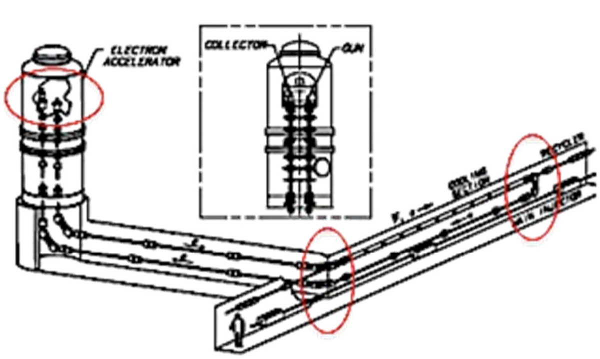

Figure 3: Schematic view of electron beam for ECR (from [7]). Red regions highlight the transitions between immersed Brillouin flow and periodically lensed flow of the electron beam.

A model of the trapping dynamics and conditions for trapping stability was developed [12]. Stable ion trapping for neutralization requires that the combination of electric and magnetic fields at the end of each segment where neutralization is needed must confine the ion plasma longitudinally but not provide mechanisms for diffusion to the side walls. That requires that a set of annular electrodes be configured at those locations and set to produce trapping stability. The trapped ions are also subject to an 'electron wind' instability [12,13] in which the electron beam exerts a net drag force on the trapped ions.

The original Fermilab ECE succeeded spectacularly with stable neutralization, for which the electron flow was magnetized throughout. We are working to design a similar strategy for stable trapping in the resonant transitions from magnetized to field-free electron flow for a relativistic beam. It will require a much higher magnetic guide field than was provided for the Recycler beam - ~1 T contrasted to .02 T. All of the above criteria are consistent with the possibility to produce and sustain a fully neutralized d.c. electron beam for cooling ions at 6 GeV/u, with I_e ~5A.

In fully *magnetized cooling*, an electron is not free to recoil in scattering from an ion, but instead spirals with a Larmor radius ρ about a magnetic field line. Cooling is thereby enhanced by the number N_s of spiral orbits for which the longitudinal distance between ion and electron is less than ρ: $N_s = 1 + \frac{1}{2\pi}\sqrt{T_{e\perp}/T_{e\parallel}}$. The transverse electron temperature is governed by the alignment of the guide fields in the cooling straight; the ECE beam achieved $T_{e\perp} \sim 0.25$ eV. The longitudinal electron temperature would be comparable without neutralization; with neutralization it should be possible to obtain $T_{e\parallel} \sim 10^{-4}$ eV, corresponding to an enhancement $N_s \sim 8$. That enhancement was observed in the classic magnetized cooling experiments of Budker [14].

The non-magnetized cooling performance of Table 1 is barely adequate for the reduction of emittance required in both EIC designs, and inadequate to support stacking. Magnetized cooling enhances emittance cooling and drag force by a factor $N_s \sim 8$, and it also permits a beam current of 3 A with stable neutralization, so that the overall magnetized cooling is enhanced by a factor of ~50 compared to Table 1. The cooling time for protons is reduced from an hour to a minute, so successive cycles can be cooled and stacked and ready when needed to replace a store with minimum interruption to physics utilization.

The next step is to experimentally develop methods for space charge neutralization consistent with Derbenev's resonant transform optics for a relativistic electron beam.

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