Simulation of Coherent Electron Cooling for High-Intensity Hadron Colliders

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Novel electron-hadron collider concepts are a long-term priority for the international nuclear physics community. Effective beam cooling for intense, relativistic hadron beams will be necessary to obtain the orders-of-magnitude higher luminosities being proposed. Coherent electron cooling (CEC) [1] combines the best features of electron cooling and stochastic cooling, via free-electron laser technology [2], to offer the possibility of cooling high-energy hadron beams much faster. Many technical difficulties must be resolved via full-scale 3D simulations, before the CEC concept can be validated experimentally. The parallel VORPAL framework [3] is the ideal code for simulating the modulator and kicker regions, where the electron and hadron beams will co-propagate as in a conventional electron cooling section. We present initial VORPAL simulations of the electron density wake driven by single ions in the modulator section. Also, we present a plan for simulating the full modulator-amplifier-kicker dynamics, by through use of a loosely-coupled code suite including VORPAL, an FEL code and a beam dynamics code.


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Electron cooling of relativistic ion beams is required for high luminosities of electron-ion collider (EIC) concepts

- in the mid-term, RHIC luminosity could be increased ~10x

- conventional wiggler could replace expensive solenoid

- e- “wiggle” motion suppresses recombination with ~10 Gauss

- provides focusing; reduces risk

- friction force should be reduced only by $\rho_{\text{min}} \rightarrow \rho_w$ in Coulomb log

$$\rho_w = \frac{\Omega_{\text{gyro}}}{k_w v_{\text{beam}}} \sim 1.4 \times 10^{-3} \lambda_w^2 [m] B_w [G]/\gamma$$

- suggested independently by V. Litvinenko and Ya. Derbenev

- confirmed via VORPAL simulations

• **Coherent Electron Cooling concept**
  – uses FEL to combine electron & stochastic cooling concepts
  – a CEC system has three major subsystems
    • **modulator**: the ions imprint a “density bump” on e- distribution
    • **amplifier**: FEL interaction amplifies density bump by orders of magnitude
    • **kicker**: the amplified & phase-shifted e- charge distribution is used to correct the velocity offset of the ions
  – standard electron cooling could work well for RHIC II…
  – but CEC could be orders of magnitude better:
    • stronger interaction implies shorter cooling times
    • effectiveness does not scale strongly with ion beam energy
      – could even be relevant to the LHC
  – modulator is now being simulated with VORPAL
Schematic of the CEC concept

Coherent electron cooling: ultra-relativistic case ($\gamma \gg 1$), longitudinal cooling

Most versatile option

Modulator: region 1 about a quarter of plasma oscillation

Longitudinal dispersion for hadrons

Amplifier of the e-beam modulation via SASE FEL

Most economical option


Simulation Overview

- Using standard electrostatic PIC with VORPAL
  - single, fully-ionized gold ion at rest
  - 3D domain with constant density thermal electron
    - bulk drift velocity corresponds to relative ion drift
- Computational noise must be suppressed
  - each e- represented by ~100 macro-particles
  - correlated e-/e+ pairs yield a perfectly quiet start
- We assume a semi-infinite e- beam
  - boundary conditions are difficult
  - Poisson solve is periodic
  - particles are destroyed at the boundaries
  - thermal particle distribution is injected from edges
Dimensionless & Dimensional parameters

- **Infinite e-beam size**
  - only 4 dimensionless parameters
  - finite beam size will be simulated in the future

- **VORPAL uses MKS**
  - use parameters relevant to Au$^{+79}$ at RHIC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>$R = \sigma_{v_x}/\sigma_{v_z} = 3$</td>
<td>Ratio of transverse to longitudinal RMS velocity spread.</td>
</tr>
<tr>
<td>$T$</td>
<td>$T = v_{ix}/\sigma_{v_z}$</td>
<td>Ratio of transverse ion velocity to RMS velocity spread.</td>
</tr>
<tr>
<td>$Z$</td>
<td>$Z = v_{iz}/\sigma_{v_z}$</td>
<td>Ratio of longitudinal ion velocity to RMS velocity spread.</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>$\zeta = Z_{ion}/(4\pi n_e R^2 \lambda_D^3)$</td>
<td>Plasma nonlinearity parameter. $\zeta = 0.1$ in the following simulations</td>
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$n_e$</td>
<td>$1.60 \times 10^{16}$ e-/m$^3$</td>
<td>Electron Density</td>
</tr>
<tr>
<td>$\omega_p = (2\pi)8.98 n_e^{1/2}$</td>
<td>$7.14 \times 10^9$ radians/second</td>
<td>Plasma frequency in radians per second</td>
</tr>
<tr>
<td>$f_p = 8.98 n_e^{1/2}$</td>
<td>$1.14 \times 10^9$ cycles/second</td>
<td>Plasma frequency in cycles per second</td>
</tr>
<tr>
<td>$1/f_p$</td>
<td>0.88 nanoseconds</td>
<td>Plasma frequency time scale</td>
</tr>
<tr>
<td>$\lambda_D = \sigma_{v_z}/\omega_p$</td>
<td>1.26 microns</td>
<td>Nominal longitudinal Debye radius</td>
</tr>
<tr>
<td>$(\sigma_{v_x}, \sigma_{v_y}, \sigma_{v_z})$</td>
<td>$(27, 27, 9) \times 10^3$ m/sec</td>
<td>RMS electron velocity spread</td>
</tr>
</tbody>
</table>
**Effects of Boundary Conditions**

- **Isotropic, Gaussian e- velocities**
  - steady-state, linear theory predicts e- charge distrib.
  - VORPAL simulations show reasonable agreement
  - cannot use periodic BCs for the electrons
  - time required to reach steady-state is seen

![Graphs showing periodic BCs for particles and thermal emission at boundaries.](image)
Effects of temperature anisotropy

Stationary ion
R = 3 (non-isotropic); T = 0 ; Z = 0
Z (along beam) vs. X (transverse)

X (transverse) vs. Y (transverse)
Effects of ion motion

Ion moving transversely

\[ R = 3; \ T = 5.6 \ ; \ Z = 0 \]

Z (along beam) vs. X (transverse)

\[ X (\text{transverse}) \ vs. \ Y (\text{transverse}) \]
Comparison with theory

• **Dynamical friction vs. details of e- density wake**
  – conventional electron cooling
    • key metric is dynamical friction force on ions
    • interaction time small compared to plasma period
  – Coherent Electron Cooling (CEC); modulator & kicker
    • dynamical friction is irrelevant
    • key metric is size/shape of e- density wake
    • very little theory available until recently

• **New analytical results for e- density wake**
  – many details for “kappa” or Lorentzian velocity distrib.
    • “kappa=1” distribution now implemented in VORPAL
    • for slow ions, results are very similar for Gaussian
Shielding charge within $4 \lambda_D$ of the ion

- Analysis of W&B provides more detail
  - anisotropic e- temperatures
  - time dependence

- VORPAL simulations do not agree closely
  - BCs are suspect; limited particle influx
  - larger domains, and kappa velocity distributions will be explored
Theory & numerics differ at early times

- **W&B assume infinite domain**
  - this e- reservoir moves inward at early times
  - VORPAL assumes external fields are zero

$$F(z) = \int f_e (\rho - \hat{z} \cdot Z \tau, \vec{v}, \tau) d\vec{v}^3 dx dy$$
Theory & numerics agree at later times

• after $t \sim 1/\omega_{pe}$, BCs become less important
  – sufficiently close to ion, dynamics remains nonlinear
• possibly exaggerated by cell size in simulations
Future work

• **Modulator / Amplifier / Kicker**
  – simulate modulator with VORPAL
    • 1D integrals of e- wake provide input to FEL theory
    • particle files converted for input to other codes
  – simulate FEL amplifier with GENESIS
  – simulate particle transport with MaryLie/IMPACT
    • phase shift of ions wrt electrons is critical
  – simulate kicker with VORPAL

• **Modulator simulations**
  – consider effects of finite e- beam size
    • wakes will be asymmetric
  – consider effects of multiple ions
    • dynamics is nonlinear in immediate vicinity of ion