SIMULATIONS OF A SINGLE-PASS THROUGH A COHERENT ELECTRON COOLER FOR 40 GeV/n Au^{+79}*

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Abstract

Increasing the luminosity of ion beams in particle accelerators is critical for the advancement of nuclear and particle physics. Coherent electron cooling promises to cool high-energy hadron beams significantly faster than electron cooling or stochastic cooling [1]. Here we show simulations of a single pass through a coherent electron cooler, which consists of a modulator, a free-electron laser, and a kicker. In the modulator the electron beam copropagates with the ion beam, which perturbs the electron beam density according to the ion positions. The FEL, which both amplifies and imparts wavelength-scale modulation on the electron beam. The strength of modulated electric fields determines how much they accelerate or decelerate the ions when electron beam recombines with the dispersion-shifted hadrons in the kicker region. From these field strengths we estimate the cooling time for a gold ion with a specific longitudinal velocity.

INTRODUCTION

Advances in particle and nuclear physics depend on increased luminosity of hadron accelerators. Coherent electron cooling (CeC) is one method of achieving this goal. The mechanism of standard electron cooling is dynamical friction on the ions[2]. Coherent electron cooling operates via density and velocity perturbations in the electron beam resulting from anisotropic Debye shielding, which we have explored previously[3, 4].

Through self-amplified spontaneous emission (SASE), a free election laser (FEL) amplifies this density modulation while imparting on it a sinusoidal modulation with a period equal to the FEL wavelength λ_{FEL}. The resulting longitudinal electric field is the kicker field. The ions are dispersion-shifted such that when encountering the kicker field, the slower ions are accelerated while the faster ions are decelerated, which results in cooling [5, 1].

In this paper we model a single pass through a CeC system and predict the kicker field strength and cooling time.

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MODULATOR

The proof-of-principal simulations begin by using a Vorpal δf particle-in-cell method [6] to model shielding from a single ion, as described in Ref.[3]. Here, a gold ion (Au^{+79}) is surrounded by an isotropic plasma, which are both described in Table 1. The simulation runs for half a plasma period, which corresponds to the maximum shielding of the ion charge by the plasma. Figure 1 shows the on-axis perturbation of the electron density from the background equilibrium distribution.

The perturbed ion density caused by the ion introduces bunching in the electron beam. Bunching is a measure of a specific spatial frequency component of the longitudinal electron density. In this case, the spatial frequency of interest corresponds to the free-electron laser wavelength, λ_{FEL}, and the spatial frequency is $k_{\text{FEL}} = 2\pi/\lambda_{\text{FEL}}$. The complex bunching factor for N particles in a volume is $b = \frac{1}{N}\sum_{j=1}^{N} w_j e^{i\theta_j}$. Here, $\theta = (k + k_{\text{u}})z - ckt$, the ponderomative phase of the electron, and $k_{\text{u}} = 2\pi/\Lambda \ll k$, where is the Λ is the period of the FEL undulator [7].

The bunching expression above also includes the weights of the macroparticles w, as the δf ion shielding simulation produces variably-weighted particles represent-

Table 1: Ion, Electron Beam and FEL Parameters

ion parameter	value
Lorentz factor, γ_{i}	43.66
v_z	3.06 $\times 10^5$ m/s
e-beam parameter	**value**
Lorentz factor, γ_{e}	43.66
rms energy spread, relative	0.001
rms velocity, v_{rms}	2.93 $\times 10^5$ m/s
peak current	100 A
normalized emittance	0.97 mm mrad
amplitude function, $\hat{\beta}$	4.9
electrons per bunch, N_{e}	1.54 $\times 10^9$
number density, n_{e}	5.5 $\times 10^{16}$ m^{-3}
FEL parameter	**value**
wiggler type	helical
wiggler period, Λ	4 cm
wiggler parameter, a_{w}	0.437
FEL wavelength, λ_{FEL}	12.5 μm
FEL bandwidth, $\Delta\nu$	90 GHz

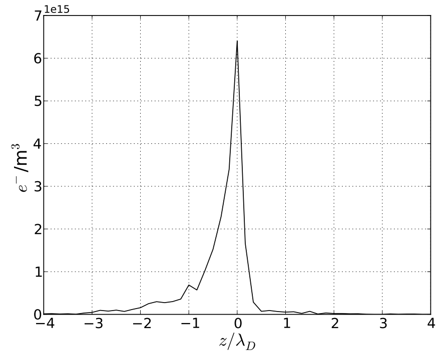

Figure 1: VORPAL δf computation of longitudinal on-axis electron density perturbation near a Au^{+79} ion with longitudinal velocity $v_z\hat{\mathbf{z}}$ in an isotropic plasma. The total number of shielded electrons is N_s=119 and λ_D=22.2 μm.

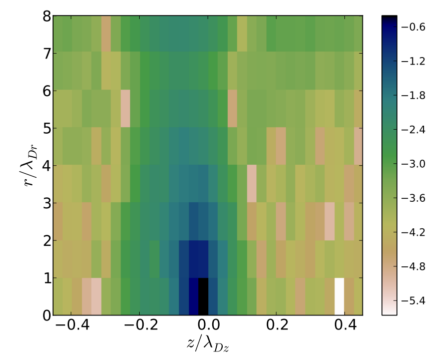

Figure 2: Magnitude of electron beam bunching coefficients b, plotted as $\log_{10}(|b|)$, at λ_0 = 12.5 μm in vicinity of a shielded ion located at z=0 with positive velocity $v_z\hat{\mathbf{z}}$.

ing the deviation from the equilibrium distribution f_0. Figure 2 shows the bunching coefficients resulting from the ion shielding shown in Fig. 1. Each box represents a volume of electrons with dimensions $L_r = \lambda_{\mathrm{D}}$ and L_z = 0.05λ_{FEL}. The factor N is the number of particles in an annular ring spanning the radial values of the box.

FEL RESPONSE TO BUNCHED ELECTRON BEAM

Table 1 shows the electron beam parameters entered into GENESIS 1.3. Since GENESIS 1.3 creates its own particles based on the input to the program. Features of the algorithm combined with the short spatial scale of the nontrivial bunching coefficients b (compared to λ_{FEL}) prohibit directly loading particle phase space coordinates into it. The bunching information would be lost. Hence, we used GENESIS 1.3 to create its own particles first, which represent the beam described in Table 1.

To distinguish the coherent kicker electric field caused by the ion from those from shot noise, we created particles in GENESIS 1.3 in an artificial case of no shot noise. Per the GENESIS 1.3 algorithm, they had linearly increasing ponderomotive phase θ_0 across each λ_{FEL}-wide slice of the electron beam (2^{18} macroparticles per slice). Using an SDDS-compliant version of GENESIS 1.3,[8] we added the bunching according to the expression used in the GENESIS 1.3 source code: $\theta_{\mathrm{bunched}} = \theta_0 - 2|b|\sin(\theta_0 - \arg(b))$ [9]. Since the electron beam is much longer than the region over which we computed the bunching, only particles in the leading few slices of the electron beam had non-zero bunching coefficients.

Table 1 shows the FEL parameters for the proof of principle CeC experiment. The bunching introduced by the single ion increases as the electron beam travels through the FEL. For the coherent case, the bunching from ion shielding increased from 2.0$\times 10^{-15}$ to 3.5$\times 10^{-3}$. For the incoherent case, the bunching from shot noise increased from 5.6$\times 10^{-5}$ to 2.4$\times 10^{-1}$. This results in an amplification and sinusoidal modulation of the original signal at the FEL wavelength, as shown in Fig. 3.

This charge density modulation represents the coherent signal of the CeC system. To compare the coherent field strength with the incoherent shot noise fields, we ran an identical GENESIS 1.3 simulation, but with shot noise providing the source for SASE instead of bunching factors.

FIELDS IN KICKER

A simple one-dimensional model of kicker fields assumes a sinusoidal kicker field $\vec{E} = E_z\hat{\mathbf{z}}$ with wavenumber $k = 2\pi/\lambda_{\mathrm{FEL}}$ and an FEL-amplified electron density perturbation $n_e = \delta n_e e^{ikz}$, the differential form of Gauss's law yields $|E_z| = \frac{e\delta n_e \lambda_{\mathrm{FEL}}}{2\pi\epsilon_0}$.

To compute the electric fields associated with the charge density modulation at the end of the FEL, the particle phase space data from the GENESIS 1.3 simulation was loaded into VORPAL and run for a single time step. Figure 3 shows the on-axis charge density. The maximum deviation of the number density is δn_e=5.3$\times 10^{16}$ m^{-3}. Using this value in the simple analytic expression above, $|E_z|_{\mathrm{max}}$=1910 V/m, which compares well to the maximum on-axis coherent kicker field E^{c} shown in Fig. 4.

Figure 4 shows the coherent electric fields in the kicker due to the bunching. The peak coherent field value is $E^{\mathrm{c}}_{\mathrm{max}}$ = 1940 V/m. The peak incoherent field from shot noise was $E^{\mathrm{i}}_{\mathrm{max}}$ = 16,600 V/m, yielding a noise-to-signal power ratio of $U = (E^{\mathrm{c}}_{\mathrm{max}}/E^{\mathrm{i}}_{\mathrm{max}})^2$=73.

To estimate the cooling time τ we assumed a kicker of length l_k= 3 m and an ion beam consisting of N_i = 1.54 $\times$ 10^9 gold ions (u=197) and relative energy spread $\Delta\mathcal{E}/\mathcal{E}^{\mathrm{ion}}_{\mathrm{k}}$=3.4$\times 10^{-4}$. The relative energy correction per turn is $g = eZl_k E^{\mathrm{c}}_{\mathrm{max}}/\Delta\mathcal{E}$ = 1.7 $\times 10^{-4}$. Here we assume that while in the kicker the ion does not move very much with respect to the kicker fields. This is reasonable, as given the ion's with the longitudinal velocity given in Table 1, it advances by only one-eighth of an FEL wavelength while in the l_k-long kicker.

Per Ref. [10], the expression for cooling time τ is $\tau^{-1} = \frac{\Delta\nu}{N_i}[2g(1-\tilde{M}^{-2}) - g^2(M + U/Z^2)]$ where U is the noise-to-signal power ratio. The mixing terms M had little effect, as $\tilde{M} \approx 300$, $M \approx 0.5$ and $g^2 \approx 10^{-8}$ with the RHIC

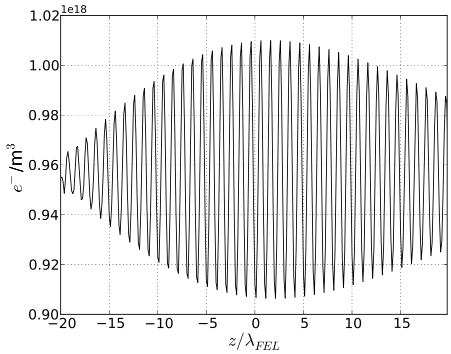

Figure 3: VORPAL prediction of electron density along the longitudinal (z) axis of the electron beam after single pass through the FEL. The peak electron density perturbation δn_e is 5.3 $\times 10^{16}$ m^{-3}.

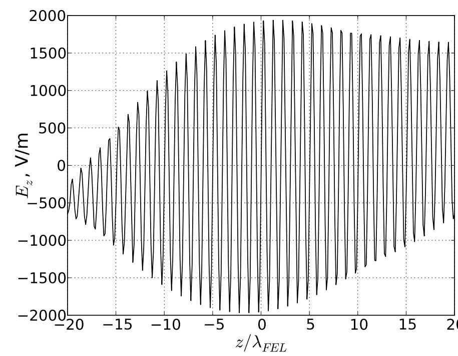

Figure 4: VORPAL prediction of coherent kicker electric fields E^{c} from the modulator after single pass through then FEL.

storage ring length and transition energy γ_t=23[11]. With these quantities, τ= 50 seconds, which both compares well with previous predictions and is significantly shorter than other cooling mechanisms [5].

CONCLUSION

In this work we modeled a single pass of a gold ion with longitudinal velocity through a coherent electron cooling system using 3D simulations of each component. The predicted cooling time validates previous predictions that CeC can cool high-energy hadron beams faster than conventional cooling methods.

Future work will test numerical convergence and account for effects that we have not yet included in our models, such as how kicker fields evolve [12], modulation of electron energy from ion shielding, and noise from coherent signals of nearby ions. It will also use or include parameters that better reflect the proof-of-principle experiments being developed at Brookhaven National Laboratory, such as plasma anisotropy, the transverse velocity of ions, and a longer electron beam.

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