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PLASMA SIMULATIONS FOR AN MBEC COOLER FOR THE EIC*

W. F. Bergan†, Brookhaven National Laboratory, Upton, NY, USA

Abstract

In order to reach its maximum luminosity, the electron-ion collider (EIC) is being designed to use microbunched electron cooling (MBEC) to cool the hadron beam. This involves having the hadron beam imprint on a beam of electrons, enhancing the perturbations in the electron beam using the microbunching instability, and feeding back on the original hadron beam to correct deviations in hadron energy, and, through the use of dispersion, the transverse emittances. This process has been modelled analytically in the linear regime. However, in order to maximize the cooling rate, we wish to know how much saturation in the electron beam is acceptable before the effects of nonlinearity cause significant deviations from the analytic results. To understand this, we have developed a code to do fast one-dimensional plasma simulations of hadrons and electrons as they move through the MBEC section of the EIC. In addition to permitting us to understand the effects of saturation, other effects are included which do not fit easily in the analytic formalism.

INTRODUCTION

Microbunched electron cooling (MBEC) is a promising technique for reducing the emittance of dense hadron beams, and is planned for use in the Electron-Ion Collider (EIC) for that purpose [1]. The principle of the cooling is to copropogate the hadron beam which you want to cool with an electron beam in a "modulator" section. The hadrons apply energy kicks to the electrons, thereby imprinting information about their noise on the electron beam. The two beams travel through separate bypasses to reach a kicker section, where they again copropogate and the electrons provide energy kicks to the hadrons. The electron bypass includes some number of chicanes and drifts to translate their energy modulation into a density modulation and amplify it, while the hadron bypass is tuned to give the hadrons path length delays dependent on their energy and transverse coordinate errors. By proper choice of the hadron transfer elements and of their dispersion and Courant-Snyder parameters in the kicker, we may arrange for the energy kicks the hadrons receive from the electrons in the kicker to reduce their longitudinal and transverse actions, providing cooling. The linear theory of this process is well-studied [2–6]. However, attaining cooling rates sufficient to counteract the intrabeam scattering (IBS) expected at the EIC forces us to use large density modulations in the electron beam, as shown in Fig. 1. In this case, saturation is expected to become important, so that accurate predictions of cooling performance require that we accurately model these nonlinear effects.

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† wbergan@bnl.gov

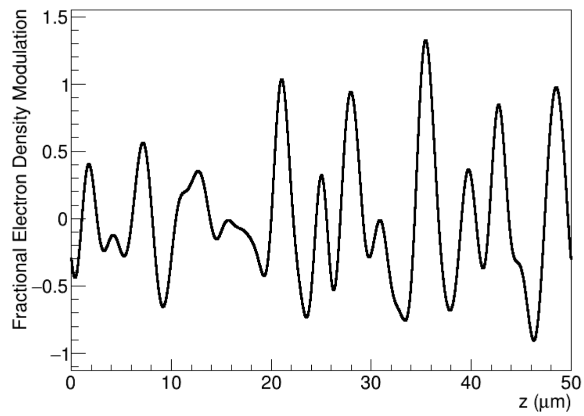

Figure 1: Plot of fractional density deviations in the electron beam at the start of the kicker for the 275 GeV cooling parameters described in [7]. RMS saturation is 47%.

To do so, we have developed a one-dimensional cloud-in-cell code to simulate the interparticle interactions in the modulator, amplifier drifts, and kicker, translate electron energy deviations into spatial deviations in the chicanes, and obtain the energy kick which a test charge would receive at an arbitrary point in the kicker. Repeating this process with an additional hadron charge at the origin, we can measure the effective wake function and provide corrections to the theoretical results.

CLOUD IN CELL CODE

Seeding

As is usual in cloud-in-cell codes, it is useful to simulate some number of charge macroparticles rather than individual particles in order to make the simulation more tractable. However, we must be careful in doing this, since the Poisson noise will be dependent on this number-rescaling. For this reason, we distribute the hadron macroparticles over the simulation length (significantly less than the hadron or electron bunch lengths so that we may take the longitudinal particle densities as constant), with each hadron charge rescaled by the square root of the ratio of the number of hadrons to the number of macroparticles, since their noise will add in quadrature. We are unable to use the same trick with the electrons, since their coherent behavior is useful for the cooling process. We therefore use electron macroparticles, each with 100 times the electron charge, and with 100 times fewer macroparticles than electrons. We partition the position-energy phase space into discrete bins and place the number of electron macroparticles into each bin as would be expected from a uniform longitudinal and Gaussian energy distribution, with Poisson noise.

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Interaction Function

To model interactions between the macroparticles, we use the interaction paradigm of [3], where the individual hadron and electron macroparticles are represented as elliptical sheets of charge. Appendix C of [5] allows the generalization of this to cases where the electron and hadron beams have different cross-sections. In this case, the force between particles of species 1 and 2 is given by

$$F = \frac{4Q_1Q_2\gamma z}{4\pi\epsilon_0\sqrt{\pi}}\int_0^\infty d\lambda\lambda^2 \times \frac{\exp(-\lambda^2\gamma^2z^2)}{\sqrt{1+2\lambda^2(\Sigma_{x,1}^2+\Sigma_{x,2}^2)}\sqrt{1+2\lambda^2(\Sigma_{y,1}^2+\Sigma_{y,2}^2)}}, \quad (1)$$

where z is the distance between the macroparticles, Q_i is the charge of a macroparticle of species i, and $\Sigma_{x,i}$ and $\Sigma_{y,i}$ are the horizontal and vertical beam sizes of species i.

Particle Tracking

Efficient particle tracking is performed using the cloud-in-cell formalism. An overview of this process is readily available in the literature, eg [8], and only a short summary is provided here. We divide space into discrete grid points[1], and assign the charge of each particle to be split linearly between the two adjacent grid points. The force which a particle would feel at an arbitrary grid point is the convolution of the force function described above with the charge density function. Making use of the convolution theorem, we may easily obtain the force felt at each grid point by taking the Fourier transforms of the above force and density functions, multiplying them together, and then transforming back to real space. Finally, the force on a given particle is the linear interpolation of the forces on the grid points adjacent to it. Periodic boundary conditions are used.

We employ a kick-drift scheme in the drift elements (modulator, kicker, and the two amplifier drifts). Each particle receives an energy kick equal to the force found above times the step distance and then moves longitudinally by an amount $\Delta z = \frac{dL}{\gamma^2}\delta$, where dL is the step length, γ is the relativistic gamma factor of the beam, and δ is the fractional energy deviation of the particle. Chicanes are modelled as discrete elements characterized by a strength R_{56} which translates a macroparticle from coordinates $(z,\delta) \to (z + R_{56}\delta, \delta)$. In the kicker, we integrate the total energy kick which a test charge would receive at each grid point, as shown in Fig. 2.

Subtraction Scheme

To understand the effect of saturation on the wake, we make use of a subtraction scheme. We run the simulation twice with the same random noise, but include an extra proton macroparticle at the origin in one run. Subtracting the resulting energy-vs-z curves gives an effective wake.

[1] These grid points measure position relative to the bunch center, and move with the bunch. However, all calculations are done in the lab frame.

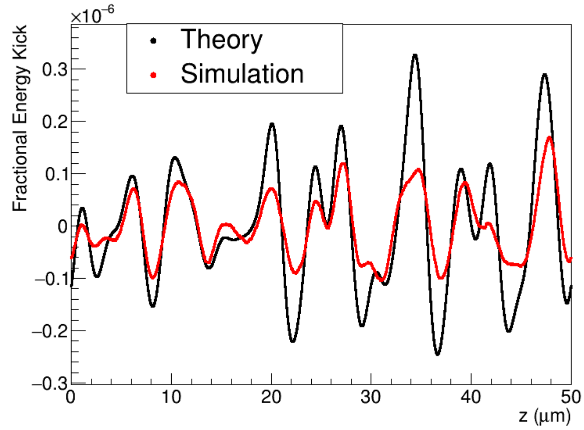

Figure 2: Plot of the fractional energy kick a test proton would receive at various locations within the bunch, in both theory and simulation. We use the 275 GeV parameters described in [7].

This procedure may be repeated for several seeds and the results averaged to obtain an effective wake.

VERIFICATION AT LOW SATURATION

In order to test our code in the linear, low-saturation regime, we run the simulation code with only one amplifier included, rather than the two amplifiers used in the current design, using the same procedure as above. We find good agreement with the theoretical predictions using the methods of [4], as shown in Fig. 3. Better agreement is obtained when we also remove the effects of plasma oscillations in the modulator and kicker by tracking the protons and electrons through those elements in a single time step. The wake obtained in this case is shown in Fig. 4, nearly exactly matching the theoretical expectation. This provides some verification of both the theory and simulation.

RESULTS FOR CURRENT DESIGN

We apply the above procedure to the current MBEC designs for cooling protons at 275 GeV and 100 GeV, with parameters described in [7]. Plots of the wakes are shown in Fig. 5. We compute the reduction in the coherent kick to the protons by making a linear fit the slope of the wakes near $z = 0$ and comparing the fit slopes of theory and simulation. Based on this analysis, we find that the coherent kick to the protons is reduced to 63% of the theoretical value at 275 GeV and to 59% of the theoretical value at 100 GeV. We also make an estimate for the reduction in the rate of diffusion by taking the ratio of the mean squared amplitude of all the individual simulated wakes to the mean squared amplitude of the theoretical wake. The diffusion rate is reduced to 64% of its theoretical value at 275 GeV and to 43% of its theoretical value at 100 GeV. These adjustments are included in the turn-by-turn simulation described in [7].

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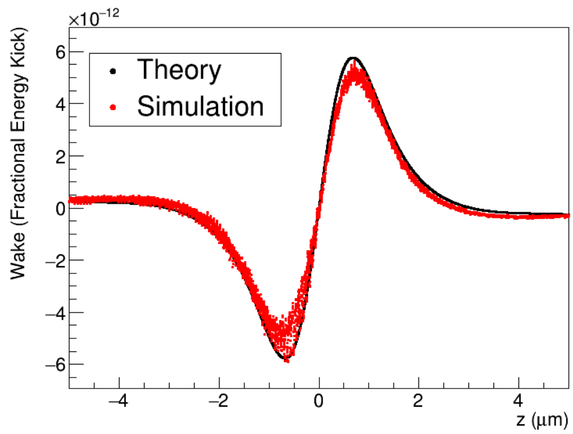

Figure 3: Wake for the case of one amplifier for 275 GeV protons, both from the linear theory and the average of 10 runs of the simulation. Good agreement is observed. Lingering errors are due to plasma oscillations in the modulator and kicker.

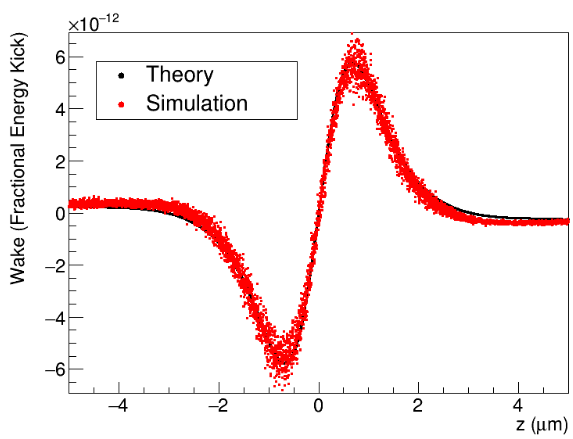

Figure 4: Wake for the case of one amplifier for 275 GeV protons without plasma oscillations in the modulator and kicker, calculated from the linear theory and the average of 10 runs of the simulation. Excellent agreement is observed.

CONCLUSIONS

We have detailed a procedure which allows us to easily simulate the full 1-dimensional physics of the hadron and electron beams moving through the MBEC cooler. This allows us to understand the degree to which saturation impacts the cooling performance, and to thereby correct for this in the cooling codes. It also enables us to verify that the plasma amplifiers work as we expect them to.

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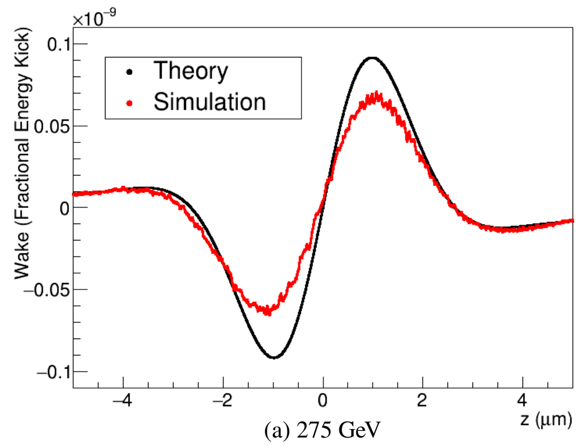
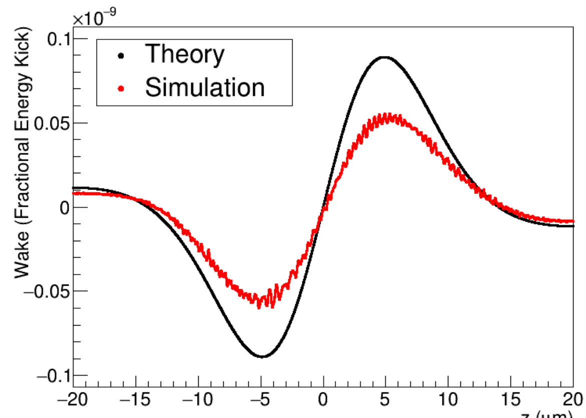


(a) 275 GeV



(b) 100 GeV

Figure 5: Wakes for the 275 GeV and 100 GeV parameters described in [7]. We find that, due to saturation and other nonlinear effects, the coherent kick to protons is 63% of the theoretical kick in the 275 GeV case and 59% of the theoretical kick in the 100 GeV case.

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