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DESIGN OF AN MBEC COOLER FOR THE EIC*

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Abstract

Reaching maximal luminosity for the planned electron-ion collider (EIC) calls for some form of strong hadron cooling to counteract beam emittance increase from IBS. We discuss plans to use microbunched electron cooling (MBEC) to achieve this. The principle of this method is that the hadron beam will copropogate with a beam of electrons, imprinting its own density modulation on the electron beam. These electron phase space perturbations are amplified before copropogating with the hadrons again in a kicker section. By making the hadron transit time between modulator and kicker dependent on hadron energy and transverse offset, the energy kicks which they receive from the electrons will tend to reduce their longitudinal and transverse emittances. We discuss details of the analytic theory and searches for optimal realistic parameter settings to achieve a maximal cooling rate while limiting the effects of diffusion and electron beam saturation. We also place limits on the necessary electron beam quality. These results are corroborated by simulations.

INTRODUCTION

The electron-ion collider (EIC) which will be constructed at Brookhaven National Laboratory (BNL) will require some means of counteracting intrabeam scattering (IBS) in the hadron beam in order to maintain high luminosity [1]. The current proposed method to achieve this is to make use of microbunched electron cooling (MBEC). This method was first introduced in [2] and expanded upon in [3–6]. The principle of the method is to copropogate an electron bunch with the hadron bunch in some "modulator," during which time each hadron will provide energy kicks to nearby electrons. The two species are then separated, with the electrons travelling through a series of chicanes and drifts which alternately transform these initial energy perturbations into longitudinal density perturbations and back again, resulting in an amplified, density modulated electron beam at the end. The hadrons traverse an accelerator section which provides them with path-length delays dependent on their initial energy offsets and transverse positions and angles. The electrons and hadrons then copropogate again in a "kicker" section, where the electrons provide an energy kick to each hadron. Proper choice of the transfer elements of the hadron bypass and the dispersion and Courant-Snyder parameters in the kicker ensure that this energy kick serves to correct the hadron's transverse and longitudinal offsets, lowering its emittance.

A schematic of the layout of the MBEC section is shown in Fig. 1.

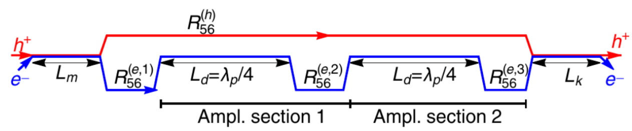

Figure 1: Layout of the MBEC section. The lengths of the modulator and kicker and given by L_m and L_k, respectively. The electron beam passes through an amplification section consisting of 3 chicanes of strengths $R_{56}^{e,1}$, etc, and 2 drifts, with lengths L_d, optimally set at 1/4 of the electron plasma wavelength. The hadron passes through a chicane of strength $R_{56}^{(h)}$. Figure from [4].

It is most important for the EIC to achieve strong hadron cooling for protons at its top two energies (100 GeV and 275 GeV), and so these are the cases which we focus on. For ease of transition, we will maintain the same physical layout for the two cases and optimize the linear optics parameters of the two species in order to achieve optimal cooling. We verify that the cooling is acceptable using turn-by-turn simulations of the proton beam. This analysis includes the effects of saturation, diffusion due to noise in the proton and electron beam, and plasma oscillations of the electron beam in the modulator and kicker. We also ensure that the provided MBEC designs will be insensitive to energy errors in the electron beam [7].

LINEAR MODEL

We describe the MBEC process using the 1-dimensional electron-proton interaction model and linearized theory introduced in [3], with expansions made to include amplifiers and non-circular, non-symmetric electron and proton beam profiles [4, 5]. The impedance in such a formalism is given by

$$Z(k) = \tag{1}$$
$$G_1(k)G_2(k)\frac{4iI_eL_mL_k}{c\Sigma^2\gamma^3I_A\sigma_e}q_1\varkappa e^{-\varkappa^2q_1^2/2}H_{ep,m}(\varkappa)H_{ep,k}(\varkappa)$$

with a corresponding wake, defined as the fractional energy kick received by a proton after a delay of z between modulator and kicker, given by

$$w(z) = -\frac{cr_h}{2\pi\gamma}\int_{-\infty}^{\infty}Z(k)e^{ikz}dk, \tag{2}$$

where $G_1(k)$ and $G_2(k)$ are the gain factors of the two amplifiers (see Eq. (26) of [4]), $H_{ep,m}(\varkappa)$ and $H_{ep,k}(\varkappa)$ define the electron-proton interactions in the modulator and kicker,

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respectively, using the Φ function from equation C9 of [5], and the other parameters are defined as in [4].

SIMULATION

We run a simulation of the beam, tracking 1,000 proton macroparticles through a simplified lattice incorporating betatron and synchrotron oscillations. Each turn, each macroparticle receives a coherent kick in the kicker whose amplitude is set by the particle's path length delay in travelling between the modulator and kicker. The diffusive term is simulated by also giving each macroparticle a Gaussian random fractional energy kick, of mean 0 and RMS $\sqrt{n\int_{-\infty}^{\infty} w^2(z)dz}$, where n is the proton density at the location of our macroparticle and $w(z)$ is the wake function. This is similar to the method of [8]. A similar term is added for the electrons, discussed below. For a macroparticle a distance z from the bunch center, the amplitudes of coherent and incoherent kicks are reduced by a factor of $e^{-z^2/\sigma_{z,e}^2}$, where $\sigma_{z,e}$ is the electron bunch length, since the wake amplitude is proportional to the square of the local electron density. We make the conservative estimate that no energy kicks are experienced by macroparticles more than $\sigma_{z,e}$ from the bunch center, since the lower electron densities decrease the number of plasma oscillations in the amplifier drifts, reducing amplification. To achieve cooling in a reasonable simulation time, we scale the coherent kick by the ratio of the number of real turns to the number of simulated turns, and scale the diffusive kick by the square root of this ratio. Effective cooling times may be extracted by taking an exponential fit to plots of horizontal and longitudinal emittance as functions of time.

Noise from the Electron Beam

The noise from the electron beam contributes to diffusion through two distinct effects. The first is that an initial electron density perturbation at some location will induce energy deviations in nearby electrons, resulting in a density modulation at the start of the first amplifier drift[1], in a process identical to the energy kicks which a proton provides, except with a different interaction model in the modulator. The corresponding impedance is

$$Z_{e,1}(k) = G_1(k)G_2(k)\frac{4iI_eL_mL_k}{c\Sigma^2\gamma^3I_A\sigma_e}q_1\varkappa e^{-\varkappa^2q_1^2/2}H_{ee,m}(\varkappa)H_{ep,k}(\varkappa) \quad (3)$$

where the variables are defined as in [4], $G_1(k)$ and $G_2(k)$ are the gains of the two amplifiers, and $H_{ee,m}(\varkappa)$ and $H_{ep,k}(\varkappa)$ characterize the electron-electron force in the modulator and the electron-proton force in the kicker, respectively.

The second effect is that an initial density modulation in the electron beam will itself result in a similar density perturbation at the start of the first amplifier, even in the absence of any interaction. In the simplest model, we assume that the density modulation at the first amplifier is equal to the initial density modulation, so that

$$Z_{e,2}(k) = G_1(k)G_2(k)\frac{-2ieL_k}{r_e\Sigma\gamma I_A}H_{ep,k}(\varkappa). \quad (4)$$

In reality, the chicane will shift the electron positions due to their energy deviations, so that the wake will be a function of $z + R_{56}^{(e,1)}\delta$, where the electron phase-space coordinates are evaluated at the start of the modulator.

Assuming constant electron density over the scale of the wake wavelength and Poisson shot noise, the diffusion rate is given by

$$\frac{d\sigma_h^2}{dt} = \frac{n}{T}\int_{-\infty}^{\infty} w^2(z)dz, \quad (5)$$

where σ_h is the RMS proton fractional energy spread, n is the linear number density of the electrons, T is the proton revolution time, and $w(z) = w_{e,1}(z) + w_{e,2}(z + R_{56}^{(e,1)}\delta)$ is the sum of the wakes from the two above effects. If we assume that the electron energy deviation is distributed as a longitudinally-independent Gaussian, we find that

$$\frac{d\sigma_h^2}{dt} = \frac{n}{T}\int_{-\infty}^{\infty}\left[w_{e,1}^2(z) + w_{e,2}^2(z)\right]dz + \quad (6)$$
$$\frac{2n}{T}\int_{-\infty}^{\infty}dz\int_{-\infty}^{\infty}d\delta\frac{1}{\sqrt{2\pi}\sigma_e}e^{-\delta^2/2\sigma_e^2}w_{e,1}(z)w_{e,2}(z + R_{56}^{(e,1)}\delta)$$

where the energy dependence of $w_{e,2}$ is integrated out in the first integral as long as the electron beam is homogeneous over longitudinal length scales of interest.

Saturation and Plasma Oscillations

Optimal cooling requires us to maximize perturbations in the electron beam, so that we must consider the nonlinear effects of saturation on the cooling process. Moreover, the electron beam will undergo plasma oscillations in the modulator and kicker, altering the forms of the kicks received. To that end, we have developed a one-dimensional plasma simulation code, described in detail in [9]. This allows a simulation of the interactions between the electrons and protons within the modulator and kicker and in the amplification sections without linearity assumptions. By introducing an additional test proton at the origin in the modulator, computing the electric fields in the kicker, and comparing with the case where no test proton is present, we obtain an effective single-particle wake. This may be compared to the wake obtained analytically from the linear theory, and a correction factor inserted to rescale the kicks.

DESIGN PARAMETERS

Table 1 summarizes the parameters considered for the design of the MBEC section. These were obtained using a combination of gradient descent and genetic algorithms, specifically SPEA2 [10] as implemented by PISA [11], to minimize the cooling times from the above simulation. Salient features

[1] Once we know the electron density modulation at the start of the first amplifier drift, the means of getting the eventual wake in the kicker are identical, no matter the origin of said perturbation.

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Table 1: Parameters for MBEC Cooling

Proton Energy (GeV)	**100**	**275**
Protons per Bunch	6.9e10	6.9e10
Proton Bunch Length (cm)	7	6
Proton Emittance (x/y) (nm)	30 / 2.7	11.3 / 1
Proton Fractional Energy Spread	9.7e-4	6.8e-4
Electron Normalized Emittance (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Electron Bunch Charge (nC)	1	1
Electron Bunch Length (mm)	14	7
Electron Peak Current (A)	8.5	17
Electron Fractional Energy Spread	7e-5	5e-5
Electron/Proton Betas in Modulator (m)	30 / 39	100 / 39
Electron/Proton Betas in Kicker (m)	10 / 39	8 / 39
Modulator Length (m)	39	39
Number of Amplifier Drifts	2	2
Amplifier Drift Lengths (m)	48.5	48.5
Kicker Length (m)	39	39
R56 in First Two Electron Chicanes (cm)	2.0	0.68
R56 in Third Electron Chicane (cm)	-5.20	-1.52
R56 in Proton Chicane (cm)	-0.52	-0.22
Proton Horizontal Phase Advance (rad)	4.46	4.79
Proton Horizontal Dispersion in Modulator & Kicker (m)	0.76	1
Proton Horizontal Dispersion Derivative in Modulator/Kicker	-0.023 / 0.023	-0.023 / 0.023
Electron Betas in Amplifiers (m)	11.2	2.5
Horizontal / Longitudinal IBS Times (hours)	2.0 / 2.5	2.0 / 2.9
Horizontal / Longitudinal Cooling Times (hours)	1.7 / 1.9	1.3 / 1.8

of the optimized parameters are the larger electron beta functions in the modulator relative to the kicker, which serves to reduce the electron beam density modulations and thus electron noise and saturation, the negative electron R_{56} in the third chicane, so that the total electron R_{56} (including drifts) is zero between the modulator and kicker centers, and the longer electron bunch length at 100 GeV, to increase the plasma wavelength in the amplifier drifts. These parameters are incorporated into the accelerator design [12].

ELECTRON BEAM QUALITY

We wish to understand the effect of electron beam quality on the cooling process. By keeping the summed electron R_{56} between modulator and kicker approximately equal to zero, we make the MBEC process insensitive to reasonable deviations in the electron beam energy, as shown in Fig. 2. We also seek to understand how much noise is acceptable in the electron beam. Running simulations with various noise levels shows that, at 275 GeV, increasing the Poisson noise by a factor of 5 increases the cooling times to 1.9 hours horizontally and 2.8 hours longitudinally, close to the IBS limit. At 100 GeV, the noise in the electron beam is limited to 2 times the Poisson random noise, at which point both the horizontal and longitudinal cooling times are 2 hours, at the limit of horizontal IBS.

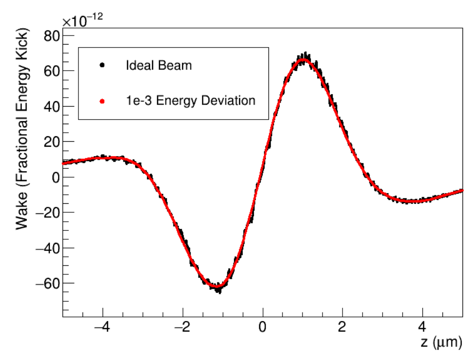

Figure 2: Comparison of the simulated wake at 275 GeV when we assume an on-energy electron beam and when the electron beam energy is offset by one part in 1000. No significant difference is present.

CONCLUSION

We have presented here a design of an MBEC cooler for use in the EIC. We have verified that it provides cooling rates in both the horizontal and longitudinal planes sufficient to counteract the effects of IBS. This analysis includes the effects of diffusion, plasma oscillations in the modulator and kicker, and saturation. Work is ongoing to translate this to a realistic lattice design and to verify its performance with a fully 3D simulation.

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REFERENCES

[1] Electron-ion collider at Brookhaven National Laboratory, conceptual design report 2021, https://www.bnl.gov/EC/files/EIC_CDR_Final.pdf

[2] D. Ratner, "Microbunched electron cooling for high-energy hadron beams", *Phys. Rev. Lett.*, vol. 111, p. 084802, Aug. 2013. doi:10.1103/PhysRevLett.111.084802

[3] G. Stupakov, "Cooling rate for microbunched electron cooling without amplification", *Phys. Rev. Accel. Beams*, vol. 21, p. 114402, Nov. 2018. doi:10.1103/PhysRevAccelBeams.21.114402

[4] G. Stupakov and P. Baxevanis, "Microbunched electron cooling with amplification cascades", *Phys. Rev. Accel. Beams*, vol. 22, p. 034401, Mar. 2019. doi:10.1103/PhysRevAccelBeams.22.034401

[5] P. Baxevanis and G. Stupakov, "Transverse dynamics considerations for microbunched electron cooling", *Phys. Rev. Accel. Beams*, vol. 22, p. 081003, Aug. 2019. doi:10.1103/PhysRevAccelBeams.22.081003

[6] P. Baxevanis and G. Stupakov, "Hadron beam evolution in microbunched electron cooling", *Phys. Rev. Accel. Beams*, vol. 23, p. 111001, Nov. 2020. doi:10.1103/PhysRevAccelBeams.23.111001

[7] P. Baxevanis and G. Stupakov, "Tolerances on energy deviation in microbunched electron cooling", in *Proc. NAPAC'19*, Lansing, MI, USA, Sept. 2019, paper WEPLH16, pp. 837-840. doi:10.18429/JACoW-NAPAC2019-WEPLH16

[8] G. Wang, "Evolution of ion bunch profile in the presence of longitudinal coherent electron cooling", *Phys. Rev. Accel. Beams*, vol. 22, p. 111002, Nov. 2019. doi:10.1103/PhysRevAccelBeams.22.111002

[9] W. F. Bergan, "Plasma simulations for an MBEC cooler for the EIC", presented at IPAC'21, Campinas, Brazil, May 2021, paper TUPAB180, this conference.

[10] E. Zitzler, M. Laumanns, and L. Thiele, "SPEA2: improving the Strength Pareto Evolutionary Algorithm for multiobjective optimization", in *Proc. EUROGEN2001*, Athens, Greece, Sep. 2001, pp. 95-100. doi:10.3929/ethz-a-004284029

[11] S. Bleuler, M. Laumanns, L. Thiele, and E. Zitzler, "PISA — A platform and programming language independent interface for search algorithms", in *Proc. 2nd Int. Conf. on Evolutionary Multi-Criterion Optimization (EMO'03)*, Faro, Portugal, Apr. 2003, pp. 494-508. doi:10.1007/3-540-36970-8_35

[12] E. Wang *et al.*, "The accelerator design progress for EIC strong hadron cooling", presented at IPAC'21, Campinas, Brazil, May 2021, paper TUPAB036, this conference.