

TESTING ASPECTS OF ADVANCED COHERENT ELECTRON COOLING TECHNIQUE

Vladimir N. Litvinenko^{1,2}, Yichao Jing^{2,1}, Igor Pinayev², Gang Wang^{2,1}, Roman Samulyak³ and Daniel Ratner⁴

¹ Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA

² Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973, USA

³ Department of Applied Mathematics, Stony Brook University, Stony Brook, NY 11794, USA

⁴ SLAC Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

An advanced version of the Coherent-electron Cooling (CeC) based on the micro-bunching instability was proposed in [1]. This approach promises significant increase in the bandwidth of the CeC system and, therefore, significant shortening of cooling time in high-energy hadron colliders. In this paper we present our plans of simulating and testing the key aspects of this proposed technique using the set-up of the coherent-electron-cooling proof-of-principle experiment at BNL [2].

INTRODUCTION

In contrast to electron and positron beams, hadron beams in all present-day colliders do not have a strong natural damping mechanism to reduce their energy spreads and emittances. Cooling hadron beams transversely and longitudinally at the energy of collision may significantly increase the luminosity of high-energy hadron colliders and future electron-hadron colliders, such as RHIC, eRHIC [3] and even the LHC/LHeC. Coherent electron Cooling (CeC) [4] promises to deliver cooling of hadron beam with damping rates exceeding that of the existing cooling techniques by many orders of magnitude. The original CeC scheme is based on the amplified electrostatic interactions between electrons and hadrons using FEL as a broadband amplifier [4]. Bandwidth of FEL-based CeC is measured in THz compared with GHz for a traditional microwave stochastic cooling. It is well known that bandwidth of the amplifier determines the maximum cooling rate of the system. The bandwidth of the FEL-based CeC is determined by the duration of the FEL response – so called Green's function [5]. Typical bandwidth of FEL amplifier is a small portion (~ 0.1% to few %) of the FEL frequency. Using micro-bunching as an amplification mechanism [1] promises to extend the CeC bandwidth by additional one to two orders of magnitude. This makes this approach very interesting to explore.

Since the CeC is a novel concept, it first must be demonstrated experimentally before we rely upon it for upgrading present colliders. We are building at BNL a dedicated device, called CeC Proof-of-Principle experiment, supported by DoE Nuclear Physics office grant [2]. It is designed to demonstrate FEL-based CeC using 22 MeV electron beam.

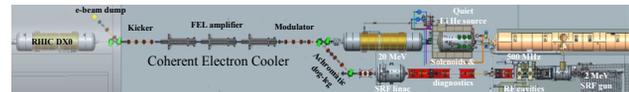


Figure 1: 3D rendering of the CeC demonstration set-up in the RHIC's IP2. It includes the following equipment: 112 MHz SRF gun; 500 MHz RF buncher/pre-accelerator; 20 MeV 704 MHz SRF module; electron beam transport magnets (dipoles, quadrupoles, solenoids, trims); helical FEL wigglers; beam dump; and RHIC DX-, D0-, and triplet-magnets. The electron beam is merged with the ion beam using an achromatic dog-leg, cools the ions in the CeC, and then is discarded into a beam dump.

We are extending this test, using NSF support, to demonstration of the key component of the micro-bunching-based CeC: specifically, demonstrating the amplification of the imprint of the hadron beam density modulation.

COHERENT ELECTRON COOLING

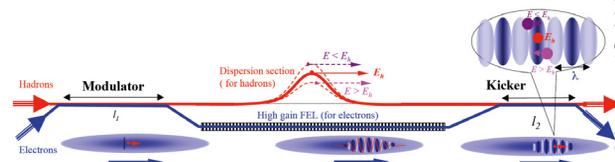


Figure 2: A general schematic of the classical Coherent Electron Cooler comprising three sections: A modulator, an FEL amplifier plus a dispersion section, and a kicker. For clarity, the size of the FEL wavelength, λ , is exaggerated grossly.

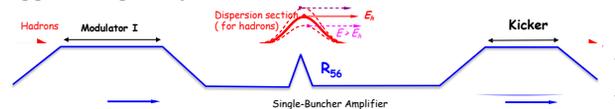


Figure 3: A CeC with an enhanced bunching by a single strong-field buncher. The scheme requires that the electron beam has special qualities [6-7,1].

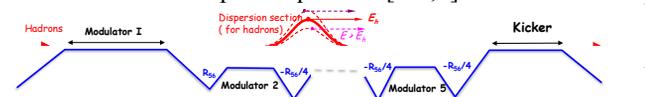


Figure 4: A layout of a CeC using a micro-bunching instability as an amplifier [1].

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The CeC scheme [is based on the amplified electrostatic interactions between electrons and hadrons. The proposed mechanism bears some similarities to stochastic cooling, but incorporates the enormous bandwidth of the amplifier. Figures 2 to 4 show schematics of coherent electron coolers based on various broadband amplifiers: an FEL, a single or a multi-stage buncher for micro-bunching amplification [1,6]. They also depict some aspects of CeC, but each of these schemes comprised of a modulator, an amplifier, and a kicker.

PHYSICS OF THE PROCESS

Let us consider an electron and a hadron beams co-propagating in a vacuum with the same velocity, $v_o = \beta_o c$:

$$\gamma_o \equiv E_e / m_e c^2 \equiv E_h / m_h c^2 \equiv 1 / \sqrt{1 - \beta_o^2} \quad (1)$$

along a straight line for a brief interval $\Delta t = L / v_o$ (e.g. significantly shorter than a period of plasma oscillation). As the result of the attraction by the positively charged hadron, the momentum of the electron's would change and the energy of electrons will change correspondingly [6-8,1]:

$$\frac{\delta\gamma}{\gamma_o}(z, r) = -Zr_e \frac{\gamma z}{(\gamma_o^2 z^2 + r^2)^{3/2}} \cdot c\Delta t$$

with radius-averaged value of

$$\left\langle \frac{\delta\gamma}{\gamma_o} \right\rangle \cong -2Z \frac{r_e}{a^2} \cdot \frac{c\Delta t}{\gamma_o} \cdot \left(\frac{z}{|z|} - \frac{z}{\sqrt{a^2 / \gamma_o^2 + z^2}} \right)$$

where a is the electron beam's radius. Figure 5 illustrates the velocity and the energy modulation map after such interaction [6].

$$\begin{aligned} \tilde{\rho} \left(z \cdot \frac{R_{56} \sigma_\gamma}{\gamma_o} \right) &= 2\pi n_o \sigma_\gamma^2 R_{56} |R_{56}| \cdot \int_0^\infty Y dY \left\{ \frac{H(z, Y_1)}{Y_1} - \frac{H(z, Y_2)}{Y_2} \right\}; \quad \Omega = \frac{Zr_e L}{R_{56}^2 \sigma_\gamma^3 \beta_o^2}; \quad \alpha = \frac{a}{D\sigma_\gamma}; \\ Y_1 &= Y \left(1 - \frac{\Omega}{Y^3} \right); \quad Y_2 = Y \left(1 - \frac{\Omega}{(Y^2 + \alpha^2)^{3/2}} \right); \quad H(z, Z) = \frac{1}{2} \left(\text{Erf} \left(\frac{z+Z}{\sqrt{2}} \right) - \text{Erf} \left(\frac{z-Z}{\sqrt{2}} \right) \right). \end{aligned} \quad (2)$$

where r_e is the classical radius of electron, n_o is the unperturbed density of electron beam. Our preliminary study showed that in the EeC operating with modest electron beam parameters (e.g. an e-beam peak current of 10-100 A), a hadron with a unit charge could create a clump comprising hundreds of electrons. Longitudinally, this clump looks like a short density spike with length from a nanometer to a micron [9-10,1]

We call this process generating a charge significantly larger (by orders of magnitude) than the perturbing charge

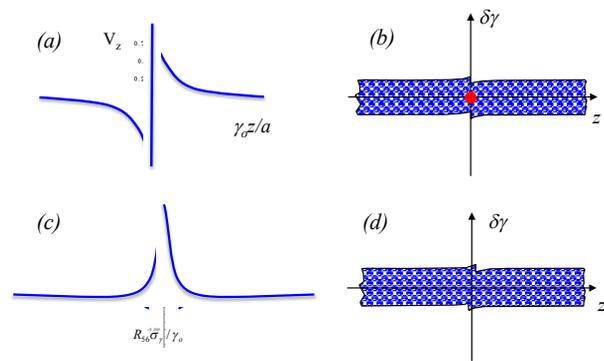


Figure 5: (a) A normalized velocity variation resulting from the interaction (in the c.m. frame of reference) and (b) a sketch of the corresponding longitudinal phase-space (in the lab frame). (c) shows the simulated density modulation after the buncher (eq. (4)) and (d) is a sketch of the corresponding longitudinal phase-space resulting from the enhanced bunching.

As depicted in Fig. 5, when the electron beam passes through a buncher (a compensated magnetic chicane) with longitudinal dispersion R_{56} :

$$\delta z = R_{56} \frac{\delta\gamma}{\gamma_o}$$

a density modulation with typical duration of $\sigma_z = R_{56} \sigma_\gamma / \gamma_o$ will appear. A detailed derivation (using the Vlasov/Maxwell set of self-consistent equations) yields the following expression for longitudinal density modulation [9] in an electron beam with an initial Gaussian energy distribution

$$\sqrt{2\pi} \sigma_\gamma g(\delta\gamma = \gamma - \gamma_o) = e^{-\frac{\delta\gamma^2}{2\sigma_\gamma^2}};$$

the enhanced bunching. It does not happen naturally. It is well known from plasma physics that process of Debye screening of a perturbing charge, q , could not generate charge exceeding $-2q$ [4,11]. The reason is that during the plasma oscillations, the kinetic energy generated by attraction from the perturbing charge is transferred into the potential energy of the electron cloud screening the charge. We discovered a mechanism that will allow us to overcome this limitation [12]. The effect enhancement is purely relativistic in nature [12] and allows us to boost the available kinetic energy by many orders of magnitude.

Thus, by applying this technique, clumps with charge exceeding the perturbation by 100 – 1000 could be generated. An example of longitudinal electric field generated by such a clump is shown in Fig. 6 [10].

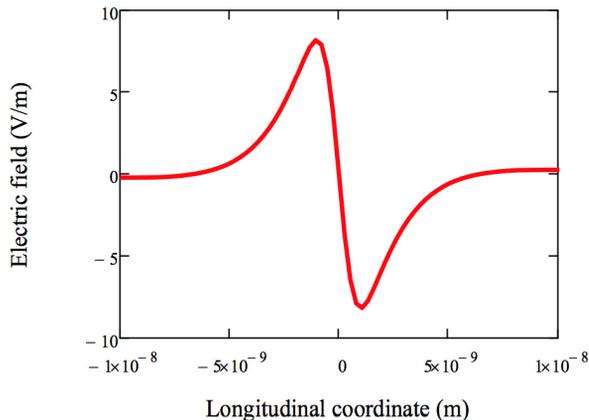


Figure 6: Electric field induced by the modulation of the electron beam density in EeC [10].

As is evident from eq. (4), the energy spread of electrons plays a major role both in the scale of the perturbation (e.g., the bandwidth of EeC, $\Delta f \sim \gamma_o / R_{s6} \sigma_\gamma$) and the amplitude of the perturbation (EeC cooling power $\Omega \sim 1 / R_{s6}^2 \sigma_\gamma^3$). Hence, the proposed research includes both theoretical and experimental studies of the attainable slice (local) energy spread in electron beams from a high brightness linac. Presently, the slice energy spread in high brightness guns and linacs is dominated by the spread induced by non-zero beam size in accelerating structures. For example, the energy spread of the high-brightness photocathodes is measured in eV; after acceleration in an RF linac slice (instantaneous) energy spread grows to few KeV, an increase of about three orders of magnitude [12-14]. It is well known (as a consequence of Maxwell equations) that energy gain in an RF accelerator depends on the radial position of the particle. Hence, a non-zero beam size in the RF gun and in the linac leads to accumulation of the local energy spread. For a given beam size, the energy gain variation is proportional to the square of the RF frequency.

We propose to cancel this energy spread using a high harmonic decelerating RF system in combination with the main RF of the gun and the linac. The required voltage scales as the inverse square of the harmonic number. Using a high harmonic ~ 5 -10 would result in a modest decelerating voltage.

First, we plan to demonstrate the cancelation using the available 2 MeV 112 MHz SRF gun and a 500 MHz room-temperature RF cavity in the CeC facility. We will run the 500 MHz cavity with 100 kV voltage in decelerating mode. We will use the solenoid between the gun and the cavity to equalize the beam sizes and to cancel the RF induced growth of the slice energy spread. We will model the process using PARMELA and ASTRA

simulations and compare results with the measurements.

As the second step in the process, we will build and install a dedicated high frequency RF system for eliminating such spreads in the 22 MeV beam. We plan to use a modest decelerating RF voltage of ~ 100 kV and to reach the desirable cancelation by increasing the transverse beam size in the compensating cavity. Our goal is to demonstrate the reduction of the slice energy spread from KeVs to eVs.

We plan to simulate all the processes involved and then to demonstrate the amplification experimentally.

While micro-bunching amplification was demonstrated experimentally (see for example [16-17]), our experimental demonstration would have two main advantages. First, it would allow us to demonstrate direct amplification of the signal without bunch compression, which significantly complicated interpretation of data [16]. Second, it allows us to conduct “a null” experiment:

1. We will measure the radiation of the electron beam with the buncher off but in the absence of the ion beam;
2. Measure the radiation with the buncher on in the absence of the ion beam;
3. Measure the radiation with the buncher off and with density modulation induced by the ion beam;
4. Finally, Measure the radiation with the buncher on and with density modulation induced by the ion beam;

This procedure will allow us to clearly separate the amplification of the induced density modulation from amplification of the perturbations in the electron beam originated from all its history.

Plans for conducting the proposed test are aligned with the commissioning schedule of the CeC system. We expect to perform them during RHIC runs 16 and 17.

ACKNOWLEDGMENT

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