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ADVANCES IN COHERENT ELECTRON COOLING*

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Abstract
Cooling techniques are required for improving the quality of hadron beams and increasing the luminosity in hadron- and electron-hadron-colliders. In this paper, we focus on the advances in, and challenges of Coherent Electron Cooling (CeC) that promises to be an effective method of cooling of high-energy hadron beams, and potentially even ultra-relativistic muon beams.

While we described physics principles in an earlier paper [1], our comprehensive studies revealed several other important factors affecting the CeC's performance [2-5]. In this paper, we summarize our main findings as well as presenting current advances and novel CeC schemes. Details can be found in our longer paper on this subject [6].

INTRODUCTION

Cooling hadron beams transversely and longitudinally at the energy of the collision may greatly increase the luminosity of high-energy hadron colliders and future electron-hadron colliders, such as the RHIC [7], eRHIC [8], ELIC [9], and even the LHC/LHeC [10]. Presently, two techniques are used for efficiently cooling hadron beams; electron cooling [11], and stochastic cooling [12,13]. Unfortunately, the efficiency of traditional electron cooling rapidly falls with the increase in the beam's energy. The efficiency of traditional stochastic cooling, while independent of the particles' energy, rapidly falls with the particles' number and their longitudinal density [12]. Accordingly, it is impossible to assure the cooling of protons with energies from about 100 GeV in RHIC/eRHIC with conventional techniques. However, two potential candidates might be up to the task; viz., optical stochastic cooling [14], and CeC [1].

Finally, there are CeC schemes that do not require the FEL as an amplifier, the so-called hybrid and bunching/ micro-bunching schemes [15-19]; however, they await a detailed evaluation of their performance.

COHERENT ELECTRON COOLING

The CeC scheme is based on the electrostatic interactions between electrons and hadrons that are amplified ether in a high-gain FEL or by other means. The CeC mechanism bears some similarities to stochastic cooling, but with the enormous bandwidth of the amplifier. Here, we briefly review the fundamental principles of physics involved in CeC. Fig.1 is a schematic of a classical coherent electron-cooler, comprising a modulator, a FEL-amplifier, and a kicker. Figs. 2-4 depict three other schematics of the CeC using approaches other than an FEL amplifier [15-19]. These schemes are developed conceptually, and detailed studies still are essential, similar to that of the classical CeC scheme, to support our evaluations of both their potential and their limitations. In contrast to the two schemes shown in Figs. 1 and 2, which have a limited bandwidth ~ 10^{14} Hz, the schemes shown in Figs. 3 and 4 essentially can generate a single wavelet of the bunch density and extend the CeC' bandwidth to ~ 10^{17} Hz.

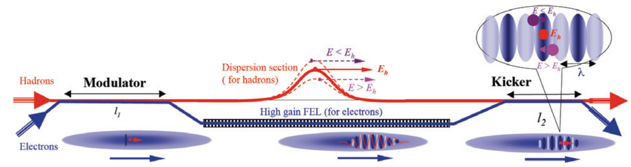

Figure 1: A general schematic of the classical Coherent Electron Cooler comprising three sections: A modulator, an FEL plus a dispersion section, and a kicker. For clarity, the size of the FEL wavelength, λ, is exaggerated grossly.

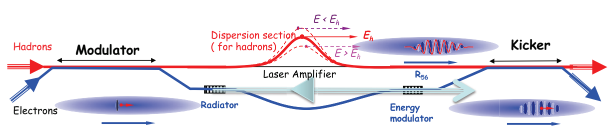

Figure 2: A hybrid CeC schematic uses a broad-band laser amplifying electron-beam's radiation from a short wiggler. The amplified laser power then, in a second wiggler, modulates the electrons energy. The latter is transferred into a density modulation using the R_{56} of an achromatic dog-leg.

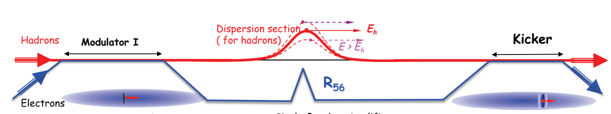

Figure 3: A CeC with an enhanced bunching by a single strong-field buncher. The scheme requires that the electron beam has special qualities [15-19].

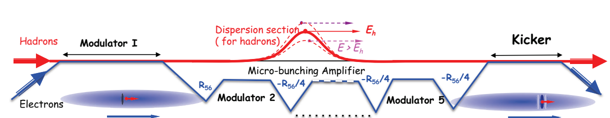

Figure 4: A layout of a CeC using a micro-bunching instability as an amplifier [17].

In the CeC, the electron- and hadron-beams have the same velocity, v:

$$\gamma_o = E_e / m_e c^2 = E_h / m_h c^2 = 1/\sqrt{1 - v^2/c^2} >> 1 \quad (1)$$

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and co-propagate, in a vacuum, along a straight line in the modulator and the kicker. The CeC works as follows: In the modulator, each hadron (with charge, Ze, and atomic number, A) induces density modulation in electron beam that is amplified in the high-gain FEL; in the kicker, the hadrons interact with the beam's self-induced electric field and experience energy kicks toward their central energy. The process reduces the hadrons' energy spread, i.e., it cools the hadron beam.

The co-moving frame (c.m.) of reference, where the electron- and hadron-beams are at rest, is the most natural one for describing the processes in the modulator and the kicker. We note that the velocity spreads of the electrons and hadrons are highly anisotropic with $\sigma_{v_{x,y}} >> \sigma_{v_z}$, where z is direction of beams' propagation. In the modulator, a positively charged hadron attracts electrons, creating a cloud of them around it with typical dimensions of this disk-shaped electron cloud (a pancake). [1, 20, 33-34]. We can show analytically (for an infinite plasma [20]) that the total charge induced by the hadron in the electron plasma is:

$$q = -Ze \cdot \left(1 - \cos\omega_p t\right), \qquad (2)$$

where Ze is the charge of the hadron, $\omega_p = \sqrt{4\pi n_e e^2 / \gamma_o m_e}$, n_e is the lab-frame electron density, and $-e$, m_e are the electron's charge and mass. The VORPAL code [21] currently can simulate modulators for an finite electron beam with arbitrary distributions [22]. However, for the LHC with TeV-scale hadron beams the phase-advance of the plasma oscillation is very small, $\omega_p t << 1$. One solution to resolving this problem is using a compensated chicane as a buncher [16] after the modulator. An exact analytical solution of the Vlasov equation in an impulse model [18] yields following expression for the density modulation:

$$\tilde{\rho}\left(z \cdot R_{56}\sigma_\varepsilon\right) = \pi c_o \cdot \int_0^\infty Y\, dY \cdot \left\{ \begin{array}{l} \dfrac{Erf\left(\dfrac{Y - \Omega Y^{-2} + z}{\sqrt{2}}\right) + Erf\left(\dfrac{Y - \Omega Y^{-2} - z}{\sqrt{2}}\right)}{1 - \Omega Y^{-3}} \\ -Erf\left(\dfrac{Y + z}{\sqrt{2}}\right) - Erf\left(\dfrac{Y - z}{\sqrt{2}}\right) \end{array} \right\};$$

where $\Omega = Z \cdot r_e L / R_{56}^2 \gamma_o^3 \sigma_\varepsilon^3$, r_e is the classical electron's radius, and R_{56} is the longitudinal dispersion of the buncher [18] and σ_ε is RMS energy spread. A typical distribution of induced charge is shown in Fig. 5. For a wide beam, the peak of such distribution contains

$$N_e \approx 4\pi Z n_o \frac{r_e L \left|R_{56}\right|}{\gamma_o} \qquad (4)$$

of electrons, which is proportional to the buncher's longitudinal dispersion [18,19], while its width is proportional to its product on the relative energy spread of electrons. Thus, the maximum induced-charge can be increased to the limits set by the space charge [23].

Hence, such bunching can be used to increase the induced charge in classical CeC, or to use this effect directly in enhanced bunching CeC, shown in Fig. 3. Fig. 4 shows the CeC scheme wherein this process is applied periodically to facilitate micro-bunch instability and to increase the induced bunch's density beyond that in eq. (4) while keeping a similar spiked induced- density profile and the same duration [17]. The bandwidth of the CeC based on the bunching is determined by the duration of the density spike,

$$\Delta f \cong c / \left(R_{56}\sigma_\varepsilon\right)$$

and could be in the 10^{17} Hz range [17,18]. While looking very promising and potentially cost-effective, these schemes require detailed studies. One potential complication is the need for a very high R_{56} value that might significantly delay the electrons. To assure that the hadrons interact with the self-induced spike in the e-beam, the delay of the hadrons should be equal to that of electrons. Achieving the latter may require a very strong and large magnetic system to delay the hadron beam and also to match its longitudinal dispersion to the value required for optimum cooling (discussed in [6]).

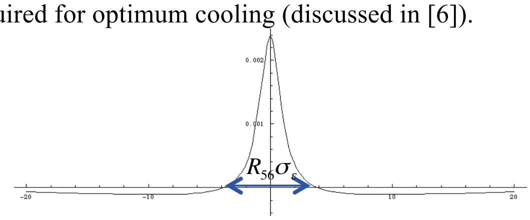

Figure 5: Profile of the induced density modulation in the modulator-buncher section.

In the classical CeC scheme the FEL serves as amplifier at the wavelength of

$$\lambda_o = \lambda_w \left(1 + \left\langle \vec{a}_w^2 \right\rangle\right) / 2\gamma_o^2;\ k_o = 2\pi / \lambda_o,$$

where λ_w is the wiggler's period and $\vec{a}_w = e\vec{A}_w / mc^2$ is the its dimensionless vector potential . If the longitudinal extent of an induced perturbation is considerably shorter than the FEL wavelength, it will be amplified similar to the shot noise (δ-functions in z-direction), a case well known in the theory of SASE FELs [24]. Since we are interested in a linear regime of FEL amplification, a response on a δ-function-like density perturbation can be described by a Green function:

$$\delta n = G_\tau(z - z_o),\ G_\tau(z) = \mathrm{Re}\, G_o(z) e^{ik_o z}, \qquad (5)$$

While analytically exploring the evolution of the density modulation wave-packet originating from a δ-function-like perturbation to the best possible extent, [25-27], we took full advantage of the well-tested 3D FEL code Genesis 1.3 [28] to detail its evolution [3,29]. Fig. 6 in ref [6] shows a typical simulated Green function for a FEL operating in the visible range [3,4].

We also explored the evolution of the wave packet as it propagates along the FEL [3,4,29]. In short, its evolution can be described as follows [6]: During four gain-lengths, the peak density remains in its original state, propagating with the longitudinal velocity of the electron beam, e.g., slipping behind the light for one FEL wavelength per wiggler period. Its amplitude falls slightly because of the

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de-phasing caused by energy spread and emittance. At the same time, a wave-packet of the optical wave, energy, and density modulation starts forming in front of the perturbation. After about 4 gain-lengths, the amplitude of the density modulation (bunching factor) in the wave-packet reaches the level of the initial perturbation; thereafter, growth is nearly exponential. We also found [3,4] that group velocity of the wave-packet was slightly lower than the predicted 1D FEL theory value of $\mathrm{v}_{gr1D} = (c + 2\langle \mathrm{v}_{ze} \rangle)/3$, and is closer to $\mathrm{v}_{gr3D} = (c + 3\langle \mathrm{v}_{ze} \rangle)/4$. There also is an additional delay of the wave-packet occurring during the formation period, as detailed in [3,4]. Since the delay in the formation of the wave-packet is about 4 gain-lengths, the maximum gain of the density modulation (i.e., the maximum value of the Green-function) is less than a simple exponential estimate for the amplification in a continuous wave in an FEL, $G_{1DCW} \cong \exp\left[L_w / L_g\right]/3$, where L_g is the amplitude e-fold gain length of the FEL.

The gain limitation can be treated in model-independent way for a case wherein the initial density perturbation comprise a random, uncorrelated shot-noise; details of the derivation appear in [30]. It is well known that e-beam instabilities, including that in FEL, are described by a set of self-consistent Maxwell and Vlasov equations. In its classical limit, Maxwell equations are completely linear. The latter is not true for the Vlasov equation; hence, it is responsible for the saturation, which occurs when the e-beam's density modulation becomes comparable with the initial beam's density: $|\delta n| \sim n_o$.

Using the randomness of the short noise in both the electron- and hadron- beams, we readily show [30] that amplification is limited by the following:

$$g_{\max} \le 144 \cdot \sqrt{\frac{I_{pe}[A] \cdot \lambda_o[\mu m]}{N_c}} \qquad (6)$$

where $g(z) = \int_{-z}^{\lambda_o - z} G_\tau(\zeta) e^{ik_o\zeta} d\zeta$ is the amplification of the e-beam bunching factor, and N_c is the Green-function correlation length in units of the wavelength:

$$N_c = \frac{\int |G(z)|^2 dz}{\lambda_0 |G(z)|^2_{\max}} \propto \frac{\omega}{\delta\omega}$$

that is inverse proportional to the amplifier's relative bandwidth [30]. For example, the Green function shown in Fig.6 [6] has $N_c \cong 38$ corresponding to FEL amplification bandwidth of 1.13x10^{13} Hz. Formula (6) was checked with direct simulations using Genesis 1.3 [29] for wavelength from tens of nm to tens of microns; it showed an excellent agreement within 10-20%. As a practical limit for Green-functions, we do not exceed 50% of the limit in eq. (6). It is important that eq. (6) applies to the other CeC schemes shown in Fig. 3-4. The advantage of the bunching schemes is that $N_c \sim 1$.

As indicated in Fig. 2, a broad-band laser amplifier can be used to amplify the density modulation in an electron beam. While looking simpler and likely less expensive than an FEL amplifier, the laser-amplifier-based CeC would be required to accommodate a few-cm delay for a hadron beam, which could be very complicated and very expensive.

CeC employs a longitudinal electric field self-induced by a hadron in form of density modulation in electron beam to correct the energy of the hadron. When in the c.m. frame the transverse size of the beam is significantly larger that the modulation period $\sigma_\perp >> \gamma_o \lambda_o$, the electric field is practically one-dimensional and can be easily calculated [1]. Otherwise, the field [6,31,32] and the CeC efficiency will be reduced. Fig. 6 below shows influence of the transverse beam size on the value of electric field on the beam axis. The dots indicate values for three CeC cases [6].

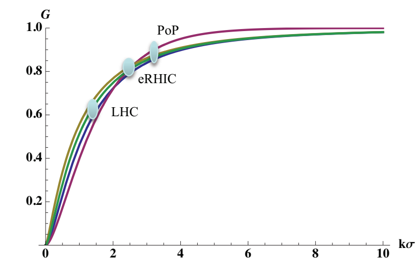

Figure 6: Normalized dependence of the electric field on the e-beam's axis as function of $k_o \sigma_\perp / \gamma_o$ for Gaussian, uniform, Lorentzian (κ-1) and κ-2 transverse distributions.

The bandwidth of the CeC also can limit the maximum cooling rate. As was shown in [1], the rate of CeC cooling rate could not exceed that rate set by the limit on stochastic cooling :

$$\xi_{CeC\max} \le \frac{2}{N_{eff}}; N_{eff} \cong N_h \frac{N_c \lambda_o}{\sqrt{4\pi}\sigma_{z,h}} + \frac{N_e}{Z^2}\frac{N_c \lambda_o}{\sqrt{4\pi}\sigma_{z,e}}$$

where N_{eff} is effective number of hadrons interacting in CeC process. This limit may become important either for a very high density of the hadron beam (e.g., in eRHIC, we plan to have ~ 10^{12}/nsec particle density in proton beam) or when a short cooling times in very large accelerators (e.g., the LHC) are required.

For a given charge of an electron bunch, our study showed that optimal cooling rates can be obtained by long electron bunches whose length is comparable to that of the hadron bunch. A table summarizing most important parameters and our estimates for three test cases for CeC can be found in ref. [6]

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