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high-energy hadron colliders***

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Presented at the 11th Biennial European Particle Accelerator Conference (EPAC 2008)
Genoa, Italy
June 23-27, 2008

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FEL-BASED COHERENT ELECTRON COOLING FOR HIGH-ENERGY HADRON COLLIDERS *

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Abstract

Cooling intense high-energy hadron beams is a major challenge in modern accelerator physics. Synchrotron radiation is too feeble and two common methods – stochastic and electron cooling – are not efficient in providing significant cooling for high energy, high intensity proton colliders.

In this paper we discuss a practical scheme of Coherent Electron Cooling (CeC), which promises short cooling times (below one hour) for intense proton beams in RHIC at 250 GeV or in LHC at 7 TeV [1].

A possibility of CeC using various microwave instabilities was discussed since 1980s [2]. In this paper, we present first evaluation of specific CeC scheme based on capabilities of present-day accelerator technology, ERLs, and high-gain Free-Electron Lasers (FELs). We discuss the principles, the main limitations of this scheme and present some predictions for Coherent Electron Cooling in RHIC and the LHC operating with ions or protons, summarized in Table 1.

INTRODUCTION

There are several reasons why cooling high-energy hadron beams in a collider is strongly desirable.

First, any increases in the longitudinal- and transverse-emittances of a hadron beam accumulated during multi-

stage acceleration from a source to the store energy (collision) remain in the beam.

Any instability causing the growth of emittance may entail the need to discard accelerated beams and start the process again. Thus, present-day high-energy hadron colliders do not have control of beam emittances at the collision energy, and are forced to use beams as they are; this is not always the optimum approach.

The main figure of merit of any collider is its average luminosity and cooling of hadron beams at top energy may further the luminosity. For a round beam, typical for hadron colliders, the luminosity is given by:

$$\mathcal{L} = f_c \frac{N_1 N_2}{4\pi\beta^* \varepsilon} \cdot h \left(\frac{\sigma_s}{\beta^*} \right), \quad h(x) = \frac{\sqrt{\pi}}{x} e^{1/x^2} \operatorname{erfc}(1/x). \quad (1)$$

where N_1, N_2 are the number of particles per bunch, f_c is their collision frequency, β^* is the transverse β -function at the collision point, ε is the transverse emittance of the beam, σ_s is the bunch length, and $h \leq 1$ is a coefficient accounting for the so-called hourglass effect. For $h > 0.75$, β^* should be limited to values $\beta^* \geq \sigma_s$. Hence, longitudinal cooling of hadron beam may allow reduction of β^* and increase the colliders' luminosity. LHC plans to use a non-zero crossing angle. In this case, reducing the bunch's length would directly contribute to increasing the luminosity.

Table 1. Comparison of estimations for various cooling mechanisms in RHIC and LHC colliders.

The sign ∞ is used to indicate helplessly long damping times.

Collider	Species	Energy, GeV/n	Synchrotron radiation	Electron cooling	Coherent electron cooling
RHIC	Au ions	100	$\sim 2 \cdot 10^4$	~ 1	0.015
RHIC	proton	2,750	$\sim 4 \cdot 10^4$	> 30	0.3
LHC	Pb ions	450	10	$> 4 \cdot 10^4$	0.15
LHC	protons	7,000	13	∞	~ 1

The effect of transverse emittance cooling on the collider's luminosity is less straightforward, but is also important. For beams with limited intensities, like LHC, the luminosity (1) grows as the transverse emittance decreases. Reduction of the beam emittance and bunch shortening provide favorite conditions for lowering β^* using final aperture focusing quadrupoles. In colliders limited by beam-beam effects possible luminosity improvements are collider-specific.

In eRHIC – BNL's version of electron-hadron collider (EIC) – polarized electrons accelerated in an ERL will collide with hadrons stored in the RHIC's storage ring. In

this case, a reduction of the transverse emittance of the hadron beam engenders a proportional reduction of the electron beam's intensity while maintaining its ultimate luminosity constant [3]. Reduction of the electron beam's current has multiple advantages: reducing the strain on the polarized electron source, proportionally lowering synchrotron radiation (the main source of the detector's background); and, offering the possibility of increasing the electron beam's energy.

ELIC – Jlab's version of EIC – plans to take full advantage of transverse cooling of hadron beam [4].

In this paper, we focus on complete evaluation of a specific case of using a high gain FEL for CEC. The

* Work performed under the auspices of the U.S. Department of Energy.

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proposed CeC combines the advantages of electrostatic interaction with the broad band of FEL-amplifiers. The CeC has some similarity with stochastic cooling - both conventional and optical [5] -, but as discussed in [1] has significant advantages compared with the techniques. In the CEC scheme, the FEL frequency can be chosen appropriately to match the energy of the electron beam. Consequently, for LHC energies the FEL wavelength naturally extends into the soft-X-ray range (nm), where frequencies are measured in ExaHertz (10¹⁸ Hz). Even a tiny fraction of this frequency extends far beyond the bandwidth of any other useful amplifier.

PRINCIPLES OF HIGH ENERGY COLLECTIVE ELECTRON COOLING

Figure 1 shows a couple of possible layouts of a longitudinal coherent electron cooler. In CeC electrons and hadrons should have the same relativistic factor: $\gamma_o = E_e / m_e c^2 = E_h / m_h c^2$. The simplest version of the CEC allows electrons and hadrons to co-propagate along the same straight section. It has a weak chicane at the end of the FEL section for adjusting the timing between the electron-beam's modulation and that of the hadron. This scheme imposes limitations on the value of the wiggler parameter, a_w (see discussion in [1]). A more generic scheme separates the hadron- and electron- beam to be individually manipulated.

In this short paper we discuss only longitudinal (energy) cooling of the hadron beam. Decrement of CEC can be re-distribution to transverse degrees of freedom-see [1] for details.

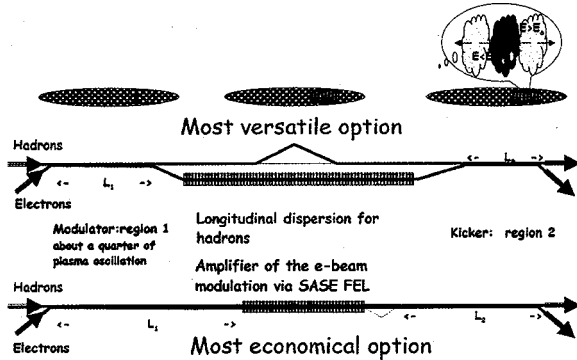


Fig. 1. Schematic layout of the Coherent Electron Cooler with three sections: a) A modulator, where the electron beam is polarized (density modulated) by presence of hadrons; b) an FEL, where density modulation in the electron beam is amplified / longitudinal dispersion for hadrons; c) a kicker, where the longitudinal electrostatic field in the electron beam accelerates or decelerates hadrons. The cooling mechanism is based upon longitudinal dispersion in the hadron beam, i.e., dependence of the time-of-flight on their energy.

The CeC shown in Fig.1 has three parts: The Modulator, the FEL Amplifier/ Dispersion, and the Kicker. Many processes are easier to describe in a co-moving (CMS) frame propagating with beam velocity.

For high-quality ultra-relativistic ($\gamma_o \gg 1$) hadron- and electron-beams of interest for this paper, the motion of the particles in the CMS frame usually is non-relativistic ($v \ll c$). In addition, the velocity distribution function is highly anisotropic with RMS) velocity spread in the longitudinal direction, $\sigma_{v_{||,CMS}}$, much smaller compared with that in the transverse direction, $\sigma_{v_{\perp,CMS}}$. In short, the CeC principles of operation are as follows (see [1] for more details):

In the modulator, individual hadrons attract electrons and create local density (and velocity) modulation centers at the position of individual hadrons. The process is a linear one, and density modulation on the ensemble of the hadrons is the direct superposition of density modulations induced by individual hadrons. Because of the flat velocity-distribution, the shape of the charge-density modulation resembles that of a flat pancake, with longitudinal extent significantly smaller than the transverse size. When translated into the lab-frame, the longitudinal extent of the pancake shrinks by a factor of γ_o into the nanometer range. If the length of modulator is chosen to allow for about a quarter to a half of the plasma oscillation to occur within the electron beam, then, at the end of this section, the electron beam density has a pancake-like distortion with a total excess charge of $-Ze$ centered at the location of the hadron.

In a FEL-amplifier this modulation of charge density in the electron beam is amplified with exponential FEL growth. Maximum optical power gain in an FEL amplifier is limited [6,7] to about few millions by saturation. Thus, a linear amplitude gain $\sim G_{FEL} \leq 10^3$ is practical. In this case, at the exit of the FEL, the individual charge pancake will become a wave-packet (stack) of such pancakes separated by the FEL's resonant wavelength $\lambda_o = \lambda_w (1 + a_w^2) / 2\gamma_o^2$, (where λ_w and a_w , respectively, are the wiggler period and wiggler parameter). Most importantly, the pancake contains G_{FEL} - times larger charge. The duration of such a wave-packet (i.e., the thickness of the individual pancake stack) is equal to the coherence length of SASE FEL radiation [6,7], and can be as short as a few or a few tens of FEL wavelengths. This pancake stack of charge-density modulation will generate a periodic longitudinal electrostatic field with period of the FEL wavelength: $k_o = 2\pi / \lambda_o$,

$$E_z \approx E_o \cdot \sin(k_o(z - v_o t) / \beta_o); \quad E_o = \frac{2G_{FEL} \cdot Ze}{\beta_{\perp} \epsilon_n} \gamma_o \quad (2)$$

Hadrons' time of flight *through the dispersion section* depends on the hadrons' energy:

$$(t - t_o)v_o = -D \cdot \delta, \quad (3)$$

where t_o is time of flight of a hadron with ideal energy and δ is relative energy deviation of the hadron. The pass-time of hadron with ideal energy should be equal to that of the space-charge wave-packet. The wave-packet of charge-modulation propagates with the group velocity of the FEL's optical wave-packet [8]:

$$v_g \cong c \left(1 - \left(1 + a_w^2 \right) / 3\gamma_o^2 \right). \quad (4)$$

Fine tuning the chicane provides for synchronization between the space-charge wave-packet induced by a hadron in such away that the hadron with central energy, E_o , arrives at *the kicker section* just on the top of the pancake of increased electron density (induced by the hadron), wherein the longitudinal electric field is zero. Hadrons with higher energy will arrive at the kicker ahead of their respective pancake in the electron beam, and will be pulled back (decelerated) by the coherent field of the electron beam; we note that positively charged hadrons are attracted to high-density pancakes of electrons. Similarly, a hadron with lower energy falls behind and, as a result will be dragged forward (accelerated) by the clump of electron density. While propagating in a kicker section of length, L_2 , the hadrons will experience an energy kick of

$$\Delta E = -eZ \cdot E_o \cdot L_2 \cdot \sin(kD\delta), \quad (5)$$

where Ze is the hadron's charge ($Z=1$ for protons and $Z=79$ for Au ions). Thus, hadrons with energy deviation within the $|\delta| < \pi/kD$ range will experience a coherent cooling, strength of which is proportional to FEL gain. Simple calculations [1] yield following estimate for decrement of CeC:

$$J_{CEC} = \frac{1}{\sigma_{\delta,h}} \frac{d\sigma_{\delta,h}}{dn} \sim G \cdot \frac{r_p}{\varepsilon_{n,h}} \cdot \frac{\sigma_{s,e}}{\sigma_{\delta,h}\sigma_{s,h}} \cdot \frac{Z^2}{A}, \quad (6)$$

where $r_p = e^2/m_p c^2$ is the classical radius of proton, and A is atomic number of hadron, $\varepsilon_{n,h}$ is normalized emittance, $\sigma_{\delta,h}$ is RMS relative energy spread and $\sigma_{s,h}$ is RMS bunch length of hadron beam, $\sigma_{s,e}$ is electron bunch length.

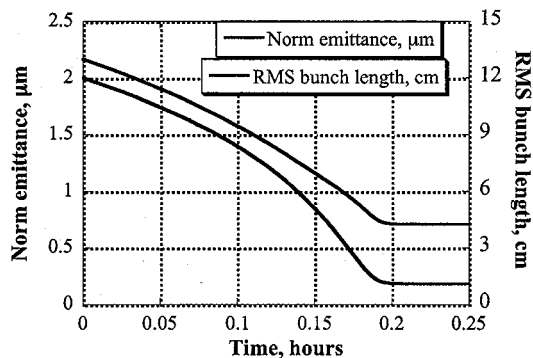


Fig. 2. Simulated evolution of proton beam parameters in RHIC

The most remarkable that the CeC decrement (6) does not depend on hadron energy, which make it attractive for high energy hadron colliders like RHIC, Tevatron and LHC (see [1] for details of the LHC case). Second feature is that the CeC decrement is inverse proportional to product of transverse and longitudinal emittances of hadron beam. Thus, the cooling of the hadron beam increases the efficiency of the CeC cooling. Fig.2 shows

evolution of normalized transverse emittance and bunch-length of 250 GeV bunch with $2 \cdot 10^{11}$ protons, which reaches stationary state when CeC and IBS rates equalize.

CONCLUSIONS

As discussed in [1], there are collective effects, which can limit the CeC process. Analogous to stochastic cooling calculations we get equation for RMS spread [1]:

$$\frac{d\sigma_E^2}{dn} = -2\Delta \frac{kD}{E_o} \sigma_E^2 + \frac{1}{2} \Delta^2 \tilde{N}; \quad \Delta = eZ^2 \cdot L_2 \cdot E_o,$$

where \tilde{N} in the number of particles in the sample. Thus, the maximum cooling rate can not be larger that $1/\tilde{N}$ per turn. This limitation is taken into account by properly selecting the FEL gain for cooling rates shown in Table 1. We used electron beam parameters typical of ERL design developed for electron cooling at BNL [9].

Proof-of-principle (PoP) experiment to cool Au ions in RHIC at ~ 40 GeV/n is feasible using the existing R&D ERL, which is under construction in BNL's Collider-Accelerator Department (C-AD). Commissioning this ERL is planned for early 2009. PoP CeC experiment using this ERL at RHIC could be possible in 2012.

ACKNOWLEDGEMENTS

We want to thank Ilan Ben Zvi and Thomas Roser (BNL) for encouraging discussions and well-pointed questions and suggestions, which lead to some of the technical solutions presented in this paper. The first author also would like to thank C-AD's electron cooling and R&D ERL groups for being a test-bed for our initial discussion of ideas used for the FEL-based CEC, and for generating several valuable suggestions.

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