NSF supported Project: Physics of Advanced Beam Cooling

Present and future high-energy hadron, lepton and hadron-lepton colliders [1-9] will continue to be the key scientific instruments for major advances in fundamental physics. Their discovery potential spans understanding of fundamental and universal aspects of QCD including the nature of mass and spin of hadrons, exploration and study of high-density phases of QCD matter and discovery of new elementary particles. The recent discovery of the Higgs boson at LHC was a clear demonstration of the special powers of circular colliders. It also encompasses physics beyond the standard model [10-15], understanding the origin of our universe [16-17], and addressing some questions in modern cosmology [18-21]. The high luminosity of these colliders, which cannot be realized without advanced cooling techniques, is vital for assuring that these discoveries are realized within a reasonable time. Hence, cooling intense high-energy hadron- and lepton-beams is required for advances in fundamental physics. Lepton colliders offer unique capabilities for precision study of new states such as the Higgs boson [9,49]. The techniques outlined in this proposal would be applicable to substantial cooling in muon (but not electron) colliders.

Cooling intense high-energy (i.e TeV range) hadron beams is a major challenge, appropriately named the "Maxwell Demon" problem of accelerator physics [22]. There are two successful well-tested cooling techniques: Stochastic cooling (SC) [22-26] and electron cooling (EC) [27-31]. The cooling speed of EC is independent of the beam's intensity, but its efficiency falls as a high power of the beam's energy [32]. At TeV energies, the EC is feeble and the cooling time is measured in thousands of hours. In principle, the SC technique, recognized by the 1994 Nobel Prize awarded to Simon van der Meer (CERN), can work at any energy. It recently was extended to cooling bunched 100 GeV/u heavy-ion beams [24] in RHIC at BNL, but cannot be used for effective cooling of proton beams in RHIC or the LHC. Comprehensive studies of SC confirmed the most important conclusion made by Van der Meer [22], i.e. that the cooling time for a beam of particles circulating in a storage ring with circumference C can be estimated as:

$$\tau_{SC} \approx T_o \frac{\dot{N}}{\Delta f}, \tag{1}$$

where $T_o = C / \mathrm{v}$ is the revolution time of particles in the ring, v is the beam's velocity, $\dot{N}$ is the longitudinal particle density (which can be estimated using the number of particles per bunch, N_b and the RMS bunch duration σ_τ as $\dot{N} \approx N_b / \sqrt{2\pi}\sigma_\tau$) and Δf is the SC system's frequency bandwidth. The existing state-of-the-art SC cooling systems are based on RF technology and have bandwidth of few GHz [23-26], e.g. $\Delta f \sim 10^9 \div 10^{10}$ Hz. However, the large circumferences of high-energy hadron accelerators (the 3.8 km RHIC/eRHIC and the 27 km LHC) and high proton densities ~ 10^{20} per second make this technique incapable of cooling proton or muon beams in present or future colliders. For example, a 5 GHz bandwidth a SC system installed at the LHC would have cooling time ~ 1,000 hours for a proton beam. Hence, there is pressing need to increase the bandwidth of SC systems. Two such advanced cooling techniques, Optical Stochastic Cooling (OSC) [33-39], and Coherent Electron Cooling (CeC) [37-40] were proposed in last two decades. They promise to extend the bandwidth to the IR-UV optical frequency range ~10^{13} -10^{14} Hz [34,36,37]. These techniques currently are planned to be tested at US National Laboratories: OSC is proposed as a part of a program for the ASTA test facility at Fermilab [41-42], and CeC will be tested at a proof-of-principle test facility at RHIC (supported by BNL and the DOE) [43-44]. If successful, both techniques could shorten the proton beam cooling time to a few minutes in RHIC and to about an hour in LHC. Still, they would fall short by many orders of magnitude from being able to cool beams in a $\mu^+\mu^-$ collider [9,35], one of the foremost current challenges in accelerator physics.

The muon beam's intensity (and luminosity) in a TeV-scale $\mu^+\mu^-$ collider is fundamentally limited by the radiation at the earth's surface generated by neutrinos from the beam muon decays [50-52] (muons have ~2 microsecond lifetime in the rest frame). One exciting possibility for increasing the luminosity is reducing the beam emittance, ε, and attaining desirable luminosity L with a reduced beam intensity, $I \sim f_c \cdot N$:

$$L = f_c \frac{N^2}{4\pi\beta^*\varepsilon} h, \tag{2}$$

where f_c is the collision frequency, N is the number of particles per bunch, β^* is the value of betatron function at the collision point, and $h \sim 1$ is the hourglass factor. The TeV-scale beams with $\sim 10^{12}$ muons in a 0.1 nsec bunch would require cooling time of 10 to 100 milliseconds. This would necessitate a cooling system with a bandwidth of $10^{17} - 10^{18}$ Hz.

A new proposed technique, which we call Enhanced electron Cooling (EeC), promises to be superior to other current or proposed cooling schemes. The EeC seeks to extend the frequency bandwidth by an additional three orders-of-magnitude into the X-ray frequency range, a bandwidth of $\sim 10^{17} - 10^{18}$ Hz [45]. Such a system could cool TeV-range muon beams. It also would offer the possibility of a significant boost in luminosity in the proposed polarized electron-hadron colliders, eRHIC and LHeC. The EeC concept emerged as a spin-off from our attempts to apply CeC to the LHC proton beam [45-47]. It was further studied and developed recently by D. Ratner at SLAC [48].

We propose to explore this frontier in cooling physics. During that research, we will undertake in-depth theoretical studies of the proposed phenomena and also will experimentally test the key component of the process, i.e. the enhanced bunching through the enhancement of the system's response to the external density perturbation. This enhanced bunching, which is at the core of the EeC, will potentially uncover novel types of intense sources of incoherent synchrotron radiation. We can conduct the experimental test of the enhanced bunching cost effectively by using the accelerator developed for the CeC proof-of-principle experiment, and the EeC-specific equipment we are requesting as part of this proposal.

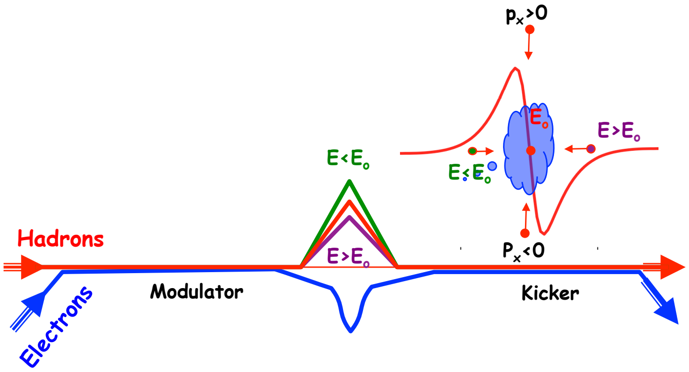

Fig.1. Schematic of Enhanced electron Cooling (EeC).

We briefly review the fundamental physics principles of the EeC, shown schematically in Fig. 3.b.3.1. The EeC is based on the electrostatic interactions between electrons and hadrons that are amplified in a buncher (dispersion section). Its mechanism bears some similarities to stochastic cooling, but with an enormous bandwidth. The EeC comprises a modulator, a buncher, and a kicker. The electron- and hadron-beams co-propagate at the same velocity in a vacuum along a straight line in the modulator and the kicker. In the former, each hadron induces energy (longitudinal momentum) modulation in the electron beam, that is subsequently transformed in the buncher into a density modulation (a clump); in the kicker, the hadrons interact with the self-induced electric field of the electron clump and receive energy and momentum kicks toward the beam's center. The process reduces the hadrons' energy spread, i.e., cools the hadrons. Similarly to the CeC scheme, the time-of-flight dependence on the hadron's energy provides natural longitudinal cooling.

In detail, within the modulator, each individual hadron attracts the surrounding electrons and generates an imprint of electron-velocity modulation. These individual velocity modulations are transformed in the buncher into a clump of electrons, generating a short spike of longitudinal electric field. We select the delay between the self-induced clump and the hadron such that a hadron with higher energy reaches the kicker ahead of the negatively charged clump, and is decelerated by its self-induced electric field. Similarly, a hadron with lower energy is pulled accelerated by the clump's electric field. The outcome of this process is a reduction in the hadrons' energy spread, and the consequent longitudinal cooling of the beam.

Transverse cooling in EeC could be achieved using a natural coupling between the longitudinal and transverse degrees of freedom (see for example [37,46]), or, as depicted in Fig. 3.b.3.1, by the transverse electric field induced by such electron cloud. The latter makes the EeC process similar to, but much more powerful than, the conventional electron cooling. Hence he name of Enhanced electron Cooling was derived.

The EeC theory is very new and its details are in flux, with many remaining challenges and unanswered questions. For example, the simple question remains unanswered of what determines the maximum achievable charge of the clump induced in an EeC? In short, the EeC concept is at the leading edge of our current understanding of accelerator physics.

Physics of the process. For compactness, here we focus on the describing the process from the first principles. Let us consider an electron and a hadron beams co-propagating in a vacuum with the same velocity, $\mathrm{v}_o = \beta_o c$:

$$\gamma_o \equiv E_e / m_e c^2 \equiv E_h / m_h c^2 \equiv 1/\sqrt{1-\beta_o^2} \tag{3}$$

along a straight line for a brief interval $\Delta t = L/\mathrm{v}_o$ (e.g. significantly shorter that 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 [46-48]:

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

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. Fig. 1 illustrates the velocity and the energy modulation map after such interaction [46].

As depicted in Fig. 3.b.3.2, 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 [53] in an electron beam with an initial Gaussian energy distribution $\sqrt{2\pi}\sigma_\gamma g\left(\delta\gamma = \gamma - \gamma_o\right) = e^{-\frac{\delta\gamma^2}{2\sigma_\gamma^2}}$:

$$\tilde{\rho}\left(z\cdot\frac{R_{56}\sigma_\gamma}{\gamma_o}\right) = 2\pi n_o \sigma_\gamma^2 R_{56}\left|R_{56}\right|\cdot\int_0^\infty Y\,dY\left\{\frac{H(z,Y_1)}{Y_1}-\frac{H(z,Y_2)}{Y_2}\right\};\ \Omega=\frac{Zr_eL}{R_{56}^2\sigma_\gamma^3\beta_o^2};\ \alpha=\frac{a}{D\sigma_\gamma};$$

$$Y_1 = Y\left(1-\frac{\Omega}{Y^3}\right);Y_2 = Y\left(1-\frac{\Omega}{\left(Y^2+\alpha^2\right)^{3/2}}\right);\ H(z,Z)=\frac{1}{2}\left(Erf\left(\frac{z+Z}{\sqrt{2}}\right)-Erf\left(\frac{z-Z}{\sqrt{2}}\right)\right). \qquad (4)$$

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 change could create a clump comprising hundreds of electrons. Longitudinally, this clump looks like a short density spike with lenght from a nanometer to a micron [54,48].

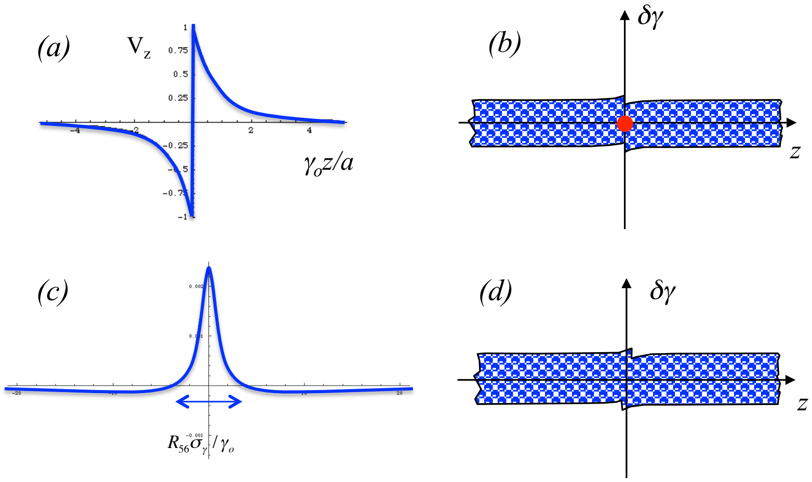

Fig. 3.b.3.2. (a) A normalized velocity variation resulting from the interaction (in the c.m. frame of reference) and (b) a sketch of the corresponding longitudinal phase-space (in the lab frame). (c) shows the simulated density modulation after the buncher (eq. (4)) and (d) is a the sketch of the corresponding longitudinal phase-space resulting from the enhanced bunching.

We call this process generating a charge significantly larger (by orders of magnitude) than the perturbing charge the enhanced bunching. It does not happen naturally. It is well known from plasma physics that process of Debye screening of a perturbing change, *q,* could not generate charge exceeding -*2q* [37,55]. 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. The effect enhancement is purely relativistic in nature 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. 3.b.3.3 [54].

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, $\Delta f \sim \gamma_o / R_{56}\sigma_\gamma$) and the amplitude of the perturbation (EeC cooling power $\Omega \sim 1/R_{56}^2\sigma_\gamma^3$). 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 [56-58]. 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.

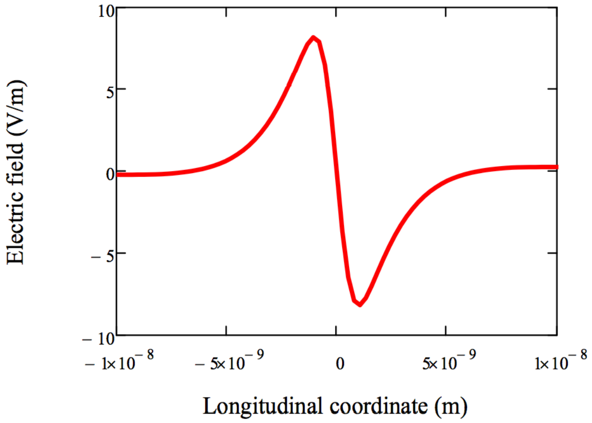

Fig.3.b.3.3. Electric field induced by the modulation of the electron beam density in EeC.

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.

As we discussed above, the focus of this activity will be on theoretical and experimental studies of this cooling technique. While exploring the theory and simulation of the EeC processes, we will install our buncher and IR diagnostic system onto the CeC accelerator. This will provide the necessary experimental set-up for evaluating enhanced bunching. The CeC system is designed to have a co-propagating heavy ion beam (fully stripped $^{79}Au^{197}$ at 40 GeV/u), which would induce the energy modulation – shot-noise like – inside the electron beam. After the e-beam passes the buncher, the energy modulation will turn into a density modulation. We will evaluate the latter by measuring the intensity of spontaneous radiation from the CeC PoP helical undulator.

This setup provides for a very clear way of detecting and evaluating enhanced bunching. First, we will establish three baselines: a) with the electron beam passing with the buncher off and without co-propagating ion beam; b) with the electron beam passing with the buncher on and without co-propagating ion beam; and c) with the electron beam interacting with the ion beam but with the buncher off. Then we will compare these baselines with the enhanced modulation induced by the ion beam and the buncher. Thus, by having a double control of the process, e.g., the buncher and ion beam, we can reduce systematic errors.

The CASE team has established leadership in studies of EeC, with three of its members involved in various aspects of the problem. This research will be lead by Prof. Litvinenko and will involve a new

Associate Professor, two graduate students, and one post-doctoral fellow. One of the PhD students who will focus on the EeC theory has already been identified.

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