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PROOF-OF-PRINCIPLE EXPERIMENT FOR FEL-BASED COHERENT ELECTRON COOLING *

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Abstract

Coherent electron cooling (CEC) has a potential to significantly boost luminosity of high-energy, high-intensity hadron-hadron and electron-hadron colliders. In a CEC system, a hadron beam interacts with a cooling electron beam. A perturbation of the electron density caused by ions is amplified and fed back to the ions to reduce the energy spread and the emittance of the ion beam. To demonstrate the feasibility of CEC we propose a proof-of-principle experiment at RHIC using SRF linac. In this paper, we describe the setup for CeC installed into one of RHIC's interaction regions. We present results of analytical estimates and results of initial simulations of cooling a gold-ion beam at 40 GeV/u energy via CeC.

INTRODUCTION

An effective cooling of ion and hadron beams at energy of collision is of critical importance for the productivity of present and future Nuclear Physics Colliders, such as RHIC, eRHIC and ELIC. Such cooling would allow to cool beam beyond their natural emittances and also to either overcome or to significantly mitigate limitations caused by the hour-glass effect and the intra-beam scattering. It also would provide for longer and more efficient stores, which would result in significantly higher integrated luminosity.

Coherent electron cooling (CeC) [1] promises to be revolutionary cooling technique which would outperforms competing techniques by orders of magnitude and possible the only technique which is capable of cooling both intense proton at energy of 100 GeV and above. The use of CeC at RHIC promises up to 6-fold increase in useful polarized proton luminosity and 10-fold increase in future polarized electron-ion collider eRHIC. It would be of similar importance for cooling hadron beam in ELIC, where very strong cooling with sub-second cooling time is required to achieve its luminosity goals.

The CeC concept is build upon already explored technology (such as high-gain FELs) and well-understood processes in plasma physics. In last three years we had developed a significant arsenal of analytical and numerical tools to predict performance of an CeC (see examples in [2] and [3]). Nevertheless, being a novel concept, the CeC should be first demonstrated experimentally before it can be relied upon in the up-grades of present and in the designs of future colliders for Nuclear Physics.

This experiment is the joint response by Brookhaven National Laboratory and Thomas Jefferson National Accelerator Facility on recommendation by Electron Ion Collider Advisory Committee that "the R&D on the proof of principle CeC experiment that is proposed to be done in RHIC should be included on the list" of a joint highest priority accelerator R&D. This is a cost-effective proof-of-principle experiment where we plan to demonstrate cooling of ion beam in RHIC using the CeC principle. The experiment will be located in IP2 of RHIC (see Fig.1) and utilize the 19-m long straight section between DX-magnets. The BNL, BINP and Daresbury lab will provide the equipment, while Tech X will provide the simulations.

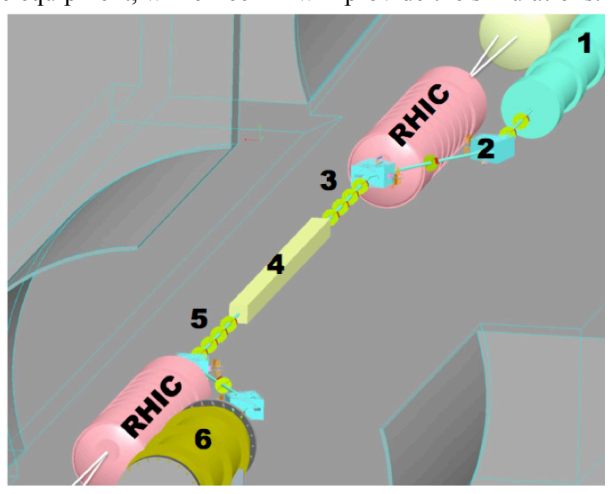

Figure 1: 3-D rendering of the CeC set-up in the RHIC's IP2: 1. 21.8 MeV CW linear accelerator; 2. e-beam transport; 3. CeC modulator section , 4. helical wiggler-FEL amplifier, 5. CeC kicker section , 6. beam dump.

All collaborators will combine the available expertise and the intellectual resources to address of one of the key accelerator R&D challenges required for future electron-

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ion colliders. If successful, the project will open new horizons for high-energy high-luminosity colliders for Nuclear Physics.

DESCRIPTION OF EXPERIMENT

The CeC scheme is based on the electrostatic interactions between electrons and hadrons that are amplified in a high-gain FEL. The proposed CeC mechanism bears some similarities to stochastic cooling, but with the enormous bandwidth of the FEL-amplifier. Here, we briefly review the fundamental physics principles of the coherent electron cooling (CeC). Fig.2 is a schematic of a coherent electron cooler, comprised of a modulator, a FEL-amplifier, and a kicker. It also depicts some aspects of coherent electron cooling. In the CeC, the electron- and hadron-beams have the same velocity, v:

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

and co-propagate in a vacuum along a straight line in the modulator and the kicker, which is achieved by selecting the energy of electrons such that the relativistic factors of the two beams are identical.

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 self-induced electric field of the electron beam and receive energy kicks toward their central energy. The process reduces the hadron's energy spread, i.e. cools the hadron beam.

In contrast with the CeC shown in Fig. 3, its economic version, which we plan to use for the experiment, does not require separating the electrons and the hadrons. The straight section between the modulator and the kicker acts as the dispersive section for the hadron, i.e. we are exploiting the weak dependence of the ultra-relativistic hadrons on their energy:

$$\frac{d\ln(\mathrm{v})}{d\ln(\mathrm{E})} = \frac{1}{2\gamma^2}.$$

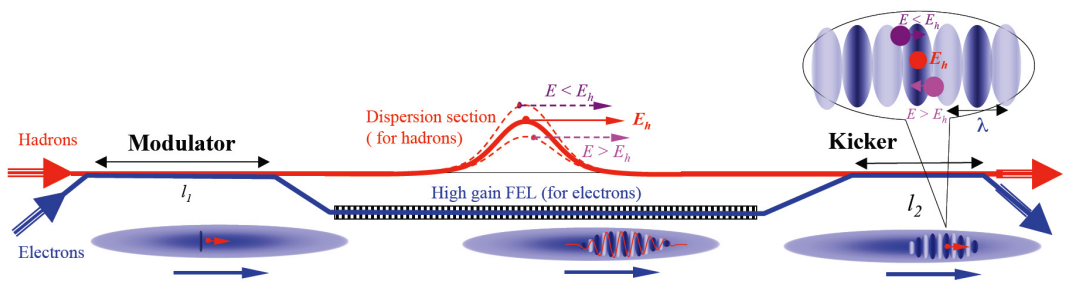

Figure 2: A general schematic of the Coherent Electron Cooler comprising three sections: A modulator, an FEL plus a dispersion section, and a kicker. The size of the FEL wavelength, λ, is exaggerated grossly for visibility.

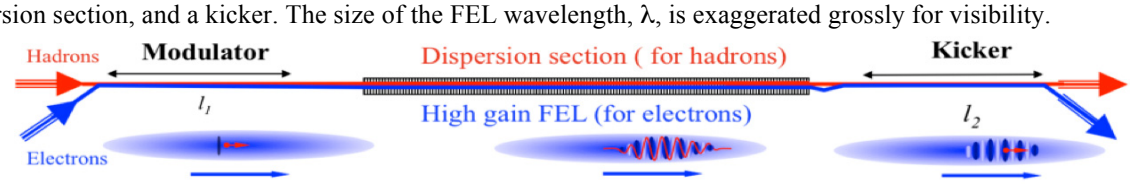

Figure 3: Economic version of coherent electron cooler, wherein electrons and hadrons are not separated transversely.

Because hadrons are much heavier than electrons, the optics and magnets for electrons have very little effect on hadron's dynamics. Hence, nearly optimal FEL and other e-beam-line elements can be used in this layout. For example, a small, weak three-pole wiggler at the end of the FEL will serve for fine path-length adjustment at the scale of one FEL wavelength.

Another, more important, limitation is imposed by this scheme on the value of the wiggler parameter in FEL. It arises from requirement that hadron's position in the kicker should be near the center of its self-induced wave-packet. Because any common delay system, for example, a compensated three-pole bump, will delay electrons but practically would not affect hadrons, the group velocity of the density wave-packet in the FEL should not be lower than the velocity of the hadron.

The group velocity of the density wave-packet in an FEL depends on several parameters. Because the information is carried by the electron beam (both its density and the energy modulation) and the light, group velocity can be expressed as

$$\mathrm{v}_{gr} = \mathrm{v}_{ze} \cdot (1-\alpha) + \alpha \cdot c; \quad 0 < \alpha < 1.$$

For a case of 1D FEL (i.e., the absence of diffraction), α=1/3; for a realistic 3D FELs α typically is between 1/4 and 1/5. Hence, $\mathrm{v}_{ze}/c \cong 1 - \left(1 + a_w^2\right)/2\gamma_0^2$ the dimensionless strength of the wiggler $a_w = eB_w\lambda_w / 2\pi m_e c$ should be limited by $a_w \le \sqrt{\alpha/(1-\alpha)}$. For a typical 3D case under consideration, α spans from 0.2 to 0.25, i.e $a_w \in \left\{0.5, 1/\sqrt{3}\right\}$. Table 1 shows a set of parameters, which satisfy the requirements for the economic version of the CeC system.

Figs. 4 and 5 show results of Genesis-3, 3D FEL simulations for the beam's peak current of 100 A. The initial conditions at the entrance of the FEL comprise a very short spike (a very thin pancake) in the density

modulation of electrons that is amplified as the e-beam propagates through the FEL.

Table 1: Main parameters for the CeC experiment with $^{197}Au^{79}$ ions

Parameter	Units	
Ion's energy	GeV/u	40
RMS norm. emittance, x,y	mm mrad	2
Ion per bunch		$1x10^9$
Longitudinal emittance	eV sec	0.5
RMS bunch-length	nsec	1.5
RMS momentum spread		$3.5x10^{-4}$
β*	m	5.5
Rep-rate	kHz	78.3
Electron beam energy	MeV	21.8
Charge per bunch	nC	0.5-1
RMS normalized emittance	mm mrad	5
Peak current in FEL	A	60-100
RMS energy spread		$1x10^{-3}$
Electrons per bunch	$x10^9$	3.1-6.2
Electrons beam current	μA	78
e-beam power	kW	1.7
Length of the CeC	m	14
Length of FEL wiggler	m	7
Type of wiggler		Helical
Wiggler period	cm	4
Wiggler parameter, a_w		0.437
FEL wavelength	μm	10

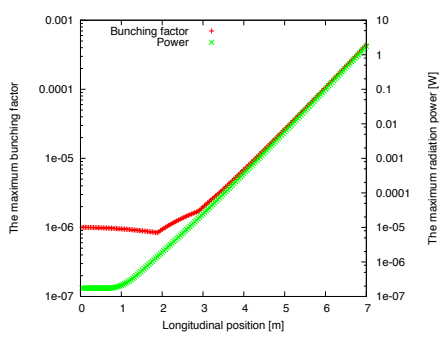

Figure 4: The evolution of optical power (green +) and the bunching factor (red +).

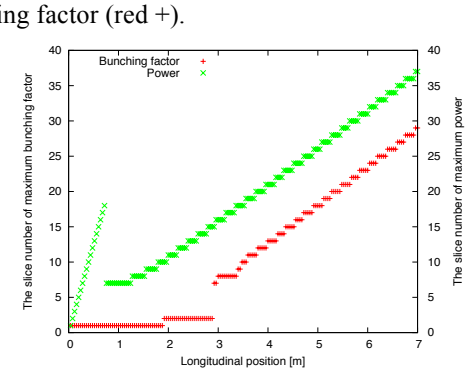

Figure 5: The position of the maxima of optical power (green +) and the bunching factor (red +) with respect to the initial spike, expressed in units of the FEL's wavelength (i.e. 10 μm).

The initial spike is amplified about 500-fold in a 7-m long FEL, which is five times higher than our design requirements for the CeC. This signifies that we either can reduce length of the wiggler to 6 meters, lower e-beam's peak current to 60 A, or relax the requirements for energy spread and emittance of the electron beam. What is also of critical importance that the group velocity in this FEL is perfectly matched with the velocity of the ions. Our analytical estimation predict that ion beam will be cooled (locally) within few minutes.

We are developing all necessary computational tools to predict the cooling dynamics in the proposed experiment prior to the beginning of the experiment.

HARWARE FOR THE EXPERIMENT

We identified all necessary hardware for the proposed experiment and started procurement of first items. We have very aggressive schedule to finish the accelerator in two years and to start experiments in 2014. One of the largest items under construction for the experiment is $2M cryogenic facility which will provide 4K and 2K liquid helium for the SRF accelerator and the gun.

Fig. 6 shows designed beam optics in the CeC section, while Fig. 7 shows present layout for the 21.8 MeV accelerator.

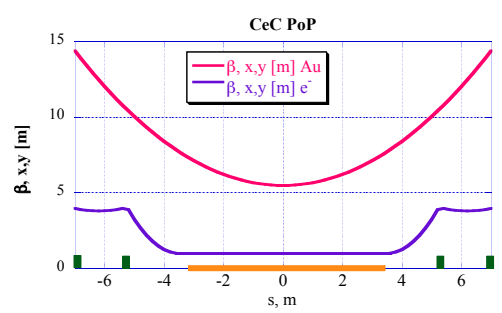

Figure 6: Beta-functions for the ion- (red) and electron-beam (cyan) in the IP2 for our CeC experiment

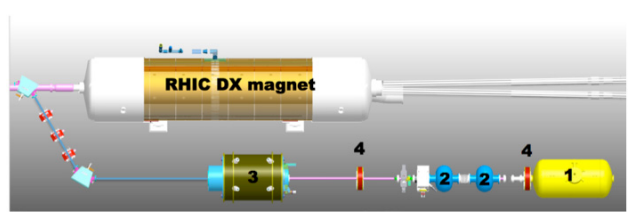

Figure 7: Layout of CeC linear accelerator: (1) 112 MHz SRF gun; (2) 500 MHz bunching cavities; (3) 5-cell BNL3 704 MHz 20 MeV SRF linac; (4) focusing solenoids.

The beam dynamics studies and design of the gun and the accelerator aew in progress. The 2 MeV 112 MHz SRF gun will be a modification of existing 112 MHz cavity built by Niowave [4]. Two 500 MHz room-temperature cavities from former synchrotron radiation facility at Daresbury will serves for ballistic bunching the e-beam to 50-100 A level of peak current. The BNL3 5-cell 707 MHz SRF linac [5] will be used as the main 20

MeV accelerator. Since we plan to cool a single ion bunch in RHIC, all RF systems will operate on harmonic of RHIC revolution frequency of 78 kHz.

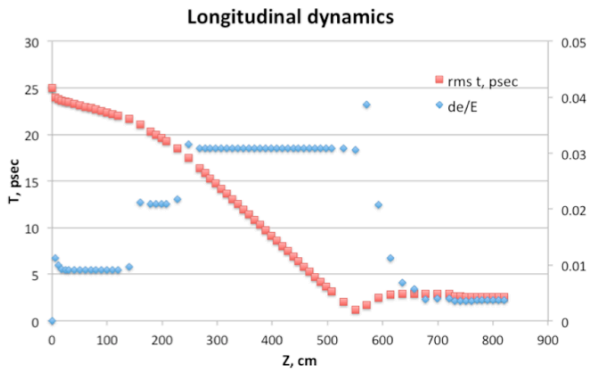

Figure 8: Longitudinal beam dynamics in the CeC accelerator: red dots – e-bunch length in psec, blue – relative energy.y spread (RMS, scale on the right)

Figure 8 shows longitudinal beam dynamics of preliminary CeC accelerator simulations. Further optimization is in progress to obtain desirable transverse emittance.

Since both accelerator cavities are experimental, we are considering possible back-up options – one based on existing equipment DC gun from JLab and the other is based on using existing BNL1 cavity from BNL's R&D ERL.

We designed a novel helical permanent-magnet wiggler with 4 cm period and variable gap [6], shown in the figure below. A 32 mm aperture will be used for the CeC demonstration experiment. A 50-cm long prototype is under production at BINP.

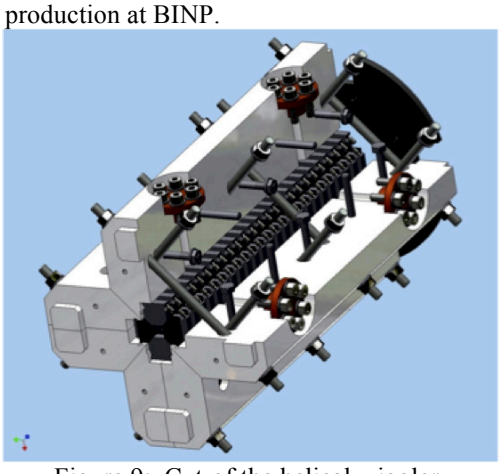

Figure 9: Cut-of the helical wiggler.

ION BEAM FOR THE EXPERIMENT

We plan using six to twelve of heavy ion bunches in RHIC for the experiment. One of them will be used for cooling, the others will be used for comparison with the cooled bunch and for other ion beam diagnostics. If necessary, we also could switch cooling to another bunch.

During this RHIC run, we had developed RHIC lattice a ramp and a store suitable for CeC experiments. We injected twelve Au ion bunches at 10 GeV/u and accelerated them to 40 GeV/u using new lattice and new ramp. We had directly measured all relevant parameters of ion beam necessary for our simulations.

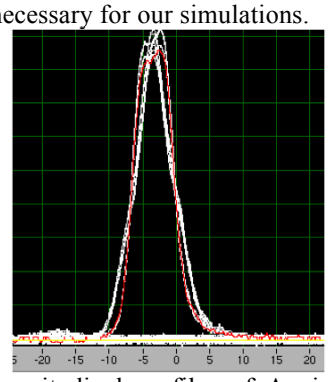

Figure 10: Longitudinal profiles of Au ion bunches in RHIC at 40 GeV/u store.

CONCLUSIONS

We plan to complete the program in five years. During first two years we will build coherent electron cooler in IP2 of RHIC. In parallel we will develop complete package of computer simulation tools for the start-to-end simulation predicting exact performance of a CeC. The later activity will be the core of Tech X involvement into the project. We will use these tools to predict the performance of our CeC device.

The experimental demonstration of the CeC will be undertaken in years three to five of the project. The goal of this experiment is to demonstrate the cooling of ion beam and to compare its measured performance with predictions made by us prior to the experiments.

Stony Brook and Old Dominion University as well as CASE (Center for Accelerator Science and Education) and CASA (Center for Advanced Studies of Accelerator) will be active participant of this project.

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