ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-MOP041

COMMISSIONING OF FEL-BASED COHERENT ELECTRON COOLING SYSTEM*

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Abstract

An FEL-based Coherent electron Cooling (CeC) has a potential to significantly boosting 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 pursue a proof-of-principle experiment at Relativistic Heavy Ion Collider (RHIC) using an SRF accelerator and SRF photo-injector. In this paper, we present status of the CeC systems and our plans for next year.

INTRODUCTION

An effective cooling of ion and hadron beams at energy of collision is of critical importance for the productivity of present and future colliders. Coherent electron cooling (CeC) [1] promises to be a revolutionary cooling technique which would outperform competing techniques by orders of magnitude. It is possibly the only technique, which is capable of cooling intense proton beams at energy of 100 GeV and above.

The CeC concept is built upon already explored technology (such as high-gain FELs) and well-understood processes in plasma physics. Since 2007 we have developed a significant arsenal of analytical and numerical tools to predict performance of a CeC. 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.

A dedicated experimental set-up, shown in Fig. 1, has been under design, manufacturing, installation and finally commissioning during last few years [2-4]. The CeC system is comprised of the SRF accelerator and the CeC section followed by a beam-dump system. It is designed to cool a single bunch circulating in RHIC's yellow ring (indicated by yellow arrow in Fig. 1). A 1.5-MeV electron beam for the CeC accelerator is generated in a 113-MHz SRF quarter-wave photo-electron gun and first focussed by a gun solenoid. Its energy is chirped by two 500-MHz room-temperature RF cavities and ballistically compressed in 9-m long low energy beamline compromising five focusing solenoids. A 5-cell 704-MHz SRF linac accelerates the compressed beam to 15 MeV. The accelerated beam is transported through an achromatic dogleg to merge with ion bunch circulating in RHIC's yellow ring.

In the CeC beamline, interaction between ions and electron beam occurs in the common section, e.g. a proper coherent electron cooler. The CeC works as follows: In the modulator, each hadron 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. Fourteen quadru-

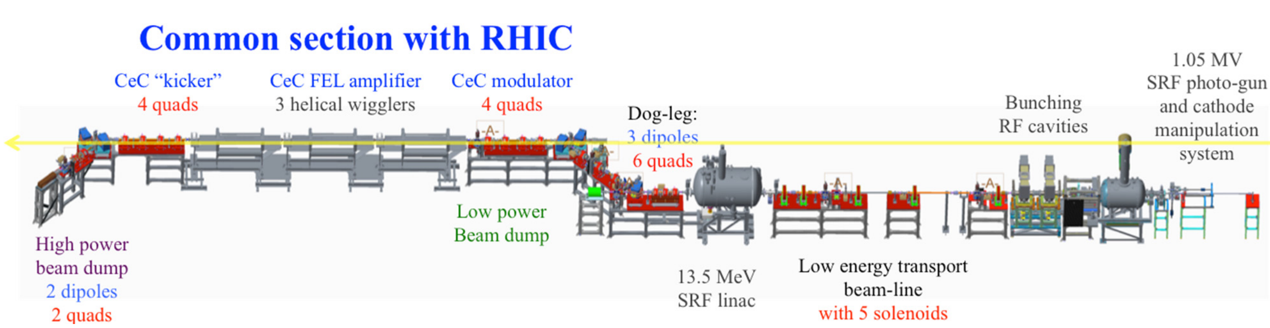

Figure 1: Layout of the CeC proof-of-principle system at IP2 of RHIC.

* Work is supported by Brookhaven Science Associates, LLC under Contract No. DEAC0298CH10886 with the U.S. Department of Energy, DOE NP office grant DE-FOA-0000632, and NSF grant PHY-1415252.
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ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-MOP041

poles are used to optimize the e-beam interaction with the ion beam and FEL performance. Finally, the used electron beam is bent towards an aluminium high-power beam dump equipped with two quadrupoles to over-focus the beam.

COMMISSIONING OF THE CEC SYSTEM

The CeC accelerator SRF system uses liquid helium from RHIC refrigerator system, which operates only during RHIC runs, typically from February till end of June every year. Hence, the commissioning and operation of CeC accelerator is synchronized with RHIC runs.

The commissioning of the CeC accelerator was accomplished during three RHIC runs: Runs 15, 16 and 17.

During the run 15, only SRF gun and a part of the low energy beam line had been installed and commissioned. The installation of the equipment was continued during the RHIC maintenance days. We went through a steep learning curve of how to condition and operate an SRF gun with CsK_2Sb photocathode and how to prevent its QE degradation. The run was very successful and the SRF gun generated electron bunches with 1.15-MeV kinetic energy and 3-nC charge per bunch.

The major installation of the CeC system, including all common section with FEL, occurred during RHIC shutdown in 2016. We had received 5-cell SRF linac cryostat from Niowave Inc, and three helical wigglers for our FEL amplifier from BINP, Novosibirsk, Russia. The latter were assembled, magnetically measured and tuned to design performance at BNL (see [5]).

Installation of 5-cell SRF linac system suffered from two major problems. First, after installing the cryostat into the CeC system we discovered that the integrity of the linac helium system and the cryostat cooling circuits was destroyed during truck transportation from Lansing, MI to BNL. Specifically, the cavity fell from its support inside the cryostat because of the major shocks during transportation and cracks appeared in the liquid helium and nitrogen systems. The cryostat was partially taken apart and leaks repaired in situ. The second even was even more damaging – an incompetent person opened the inside of the SRF cavity to a dirty air in the tunnel. The latter resulted in excessing field emission and limited the maximum operational voltage to about 6-7 MV, instead of design value of 20 MV. The 5-cell cavity, built by Advanced Energy Systems, demonstrated voltage close to 20 MV in prior vertical tests and we decided to take the SRF linac apart and re-clean it after the end of the Run 16.

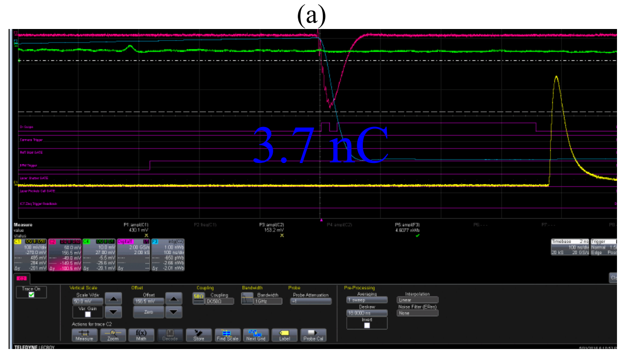
Nevertheless, the CeC team managed to make significant progress in CeC accelerator commissioning during RHIC run 16. Electron beam from the SRF gun was properly analysed, its emittance was measured and we had first clear indication that the SRF gun is generating electron beam of exceptionally high quality.

We also were discovering complexity of operating SRF quarter-wave gun with CsK_2Sb photocathode. We discovered that while in a normal (high 1 MV scale voltage) mode of operation the SRF gun naturally has excellent vacuum, at low voltage it has a number multipacting (MP) zones. One of these zones, in the range of 28 kV to 40 kV of the gun accelerating voltage, was very strong, frequently preventing us from passing to operational voltage using 2 kW power amplifier. In addition to the frustrating incapability of achieving the operational voltage, MP was spoiling the gun vacuum and was destroying photocathode's QE. Lastly, this process was also enhancing the strength of MP, presumably by depositing high second-emission-yield (SEY) material from the photocathode to the surrounding surfaces. More details about our findings can be found in Refs. [6-7].

As the result of our experiences we increased the power of our transmitter to 4 kW and also developed a dedicated LLRF procedure providing for a single-shot pass through the most dangerous 40-kV multipacting barrier. After the passing the barrier, the gun was kept at operation voltage all the time and was intentionally turned down only for access to the RHIC IP2, where the gun is located. Accidental turning off the gun voltage – either by operator errors or system failures – were infrequent. If, by a chance, the gun was caught at MP level (mostly because of operator mistakes) and the MP barrier went above 4 kW of available power, keeping the gun idle for about 30 minutes was solving the problem.

During CeC run 17 (February-June 2017) the CsK_2Sb photocathodes QE ~ 3-4% was stable for months of operation. We used only two cathodes for five month of continuous operation and the change was done simply to explore an additional cathode. Our SRF gun had generated electron beam with charge up to 4 nC per bunch and extremely high quality. The best measured normalised emittance of the 1.56-MeV, 0.5-nC bunch was 0.32 mm-mrad [8].

(a)



(b)

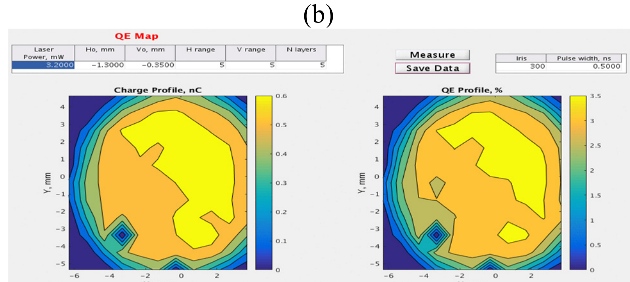


Figure 2: (a) A typical digital scope trace showing the electron bunch pulse (from integrated current transformer, red trace) and delayed trace of laser pulse (from a slow photo-diode sensor); (b) a measured QE map of CsK2Sb photocathode after two months of operating in the SRF gun.

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The main efforts during the shutdown period between Runs 16 and 17 were dedicated to complete disassembly of the SRF linac cryostat (done by the SRF group at BNL), re-cleaning of the 5-cell cavity system (which was perform at ANL SRF facility), to reassemble the cryostat (at BNL) and to install it back onto CeC accelerator system. Unfortunately, the SRF linac could operate only at voltage below 13.5 MV and exhibited typical hard-quench behaviour above this level. The quenching characteristics are typical for a cavity defect near its equator, which cannot be repaired. Hence, this setback with the SRF linac limited the energy of electron beam from CeC accelerator to about 15 MeV. This created a major obstacle in commissioning of the CeC FEL system by shifting its wavelength from 13 µm to 30 µm and rendering all our IR diagnostics practically useless: its vacuum out-coupling window had cut off above 16 µm.

Nevertheless, we had fully commissioned the CeC accelerator and propagated CW beam through the entire CeC system – including FEL system - to the high-power dump with very low losses. Table 1 summarizes the main parameters of the CeC system and it electron beam.

Table 1. Main Parameters of the CeC system

Parameter	Design	Status	Comment
Species in RHIC	Au^{+79}, 40 GeV/u	Au^{+79} 26.5 GeV/u	To match e-beam
Particles/bucket	10^8 - 10^9	10^8 - 10^9	✓
Electron energy	21.95 MeV	15 MeV	SRF linac quench
Charge per e-bunch	0.5-5 nC	0.1- 4 nC	✓
Peak current	100 A	50 A	Sufficient for this energy
Pulse duration, psec	10-50	12	✓
Beam emittance, norm	<5 mm mrad	3 - 4 mm mrad	✓
FEL wavelength	13 µm	30 µm	New IR diagnostics
Rep-rate	78 kHz	26 kHz**	Temporary**
e-beam current	Up to 400 µA	40 µA	Temporary**
Electron beam power	< 10 kW	600 W	Temporary**

The second consequence of the electron beam's low energy was a mismatch between the frequency of the SRF and revolution frequency of 26.5 GeV/u gold ions, f_{rev}. The nearest of the harmonics of the revolution frequency was outside of the available tuning range provided by movable gun's FPC [11,12].

In order to test the interaction of the electron beam with the ion beam circulating in RHIC, we had tuned the gun to the frequency (n+1/3) f_{rev}, resulting in the e-beam rep-rate of 26 kHz. This problem will be fixed before the next RHIC run by mechanically retuning the gun frequency. Using this set-up, we synchronised the electron beam with the ion bunch circulated in RHIC's yellow ring and scanned electron beam energy. In this case, the ion beam was overlapping with electron bunch at each third turn. Beams were overlapped both the temporarily and spatially. The recorded beam parameters during the scan are shown in Fig. 3. Without IR diagnostics we did not had chance to CeC cooling – it would require scan of 10 parameters, but we managed to detect weak energy-dependent interaction between the beams.

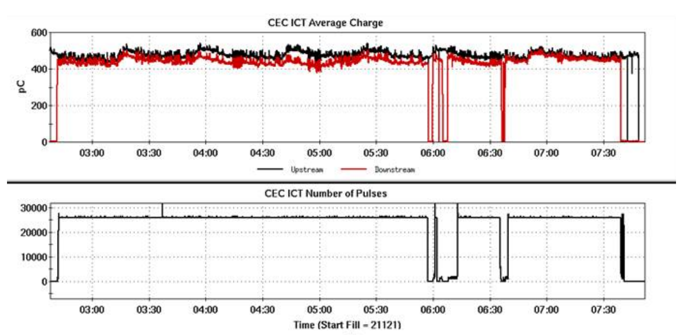

Figure 3: The charge per bunch and repetition rate during the interaction experiment.

PLANS FOR RUN 18

Currently, RHIC is in shutdown mode and we are pursuing a program of modifications and small repairs to the CeC system. The main advances to the CeC capabilities will come from new IR diagnostic system, which would be coupled, to FEL via an SVD diamond window transparent in the entire IR spectrum. Other modifications are aimed to improving accuracy of SRF controls and orbit correction in low-energy transport beamline.

We expect to start CeC operation in January 2018 and finish the run, which is determined by RHIC operation schedule, in mid-June 2018. First, we plan to establish a stable phase, amplitude and timing operation of RF and laser system to reliably deliver a stable electron beam. After that we plan to commission our new IR diagnostics and establish FEL operation/amplification. This will be followed by synching electron beam with 26.5 GeV/u gold ion beam, aligning them transversely and synchronizing the ion and

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electron beams energies using IR diagnostics. Specifically, we will observe energy-dependent increase in the intensity of FEL radiation. Finally, we plan to test and characterize Coherent electron Cooling.

CONCLUSION

We successfully commissioned SRF-based CeC electron accelerator with beam parameters sufficient for CeC demonstration experiment [11-12]. We plan to undertake the challenging task of experimentally demonstrating coherent electron cooling during next RHIC run.

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