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COHERENT ELECTRON COOLING EXPERIMENT AT RHIC: STATUS AND PLANS *

Vladimir N. Litvinenko[1,2†], Zeynep Altinbas[2], Jean Clifford Brutus[2], Anthony Di Lieto[2], David Gassner[2], Thomas Hayes[2], Patrick Inacker[2], James Jamilkowski[2], Yichao Jing[1,2], Robert Kellermann[2], Jun Ma[2], George Mahler[2], Michael Mapes[2], Robert Michnoff[2], Kentaro Mihara[1], Michiko Minty[2], Toby Allen Miller[2], Geetha Narayan[2], Matthew Paniccia[2], Irina Petrushina[1], David Phillips[2], Igor Pinayev[2], Thomas Roser[2], Scott Keith Seberg[2], Freddy Severino[2], Kai Shih[1], John Skaritka[2], Loralie Smart[2], Kevin S. Smith[2], Zachary Sorrell[2], Roberto Than[2], Joseph Tuozzolo[2], Erdong Wang[2], Gang Wang[1,2], Yuan Hui Wu[1], Binping Xiao[2], Tianmu Xin[2], Alex Zaltsman[2]

[1] Department of Physics and Astronomy, Stony Brook University, Stony Brook, USA

[2] Collider-Accelerator Department, Brookhaven National Laboratory, Upton, USA

Abstract

We present currents status of the CeC experiment at RHIC and plans for future. Special focus will be given to unexpected experimental results obtained during RHIC Run 18 and discovery of a previously unknown type of microwave instability. We called this new phenomenon micro-bunching Plasma Cascade Instability (PCI). During this year we demonstration control of this instability in our SRF CW accelerator. We present plan for future experiments using this instability as a broad-band amplifier in the CeC system – so called PCA-based 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 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 with FEL amplifier, 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 1.25 MeV electron beam for the CeC accelerator is generated in an 113 MHz SRF quarter-wave photo-electron gun and first focused by a gun solenoid. Its energy is chirped by two 500 MHz room-temperature RF cavities and ballistically compressed in 9-meter long low energy beamline compromising five focusing solenoids. A 5-cell 704 MHz SRF linac accelerates the compressed beam to 14.5 MeV. Accelerated beam is transported through an achromatic dogleg to merge with ion bunch circulating in RHIC's yellow ring. In CeC 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 CeC amplifier; 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.

Finally, the used electron beam is bent towards an aluminum high-power beam dump equipped with two quadrupoles to over-focus the beam.

STATUS

The CeC accelerator SRF system uses liquid helium from RHIC refrigerator system, which operates only during RHIC runs. The commissioning of the CeC accelerator was accomplished during RHIC 15-18 runs. Electron beam parameters at the design level or above, except the beam energy, had been successfully demonstrated – see Table 1 [5-16]. Accordingly, we had adjusted the ion beam energy to 26.5 GeV/u to match relativistic factors with that of electron beam.

Our attempt to demonstrate cooling during RHIC run 18 was not successful. While the attempt was hindered by a number of technical problems beyond control of the CeC group, the main reason for our inability to demonstrate cooling was excessive noise in the electron beam at frequencies ~ 10 THz (wavelength ~ 30 μm).

As soon as we achieved all necessary electron beam parameters, we demonstrated high gain operation of our FEL by observing very strong amplification of the IR radiation from the FEL with increase of the beam peak current. The power of generated radiation was measured by broad-band IR diagnostics [17] (including a spectrometer), which was upgraded to be sensitive in far-IR range before the 2018 run. After that we verifiably aligned electron and an ion bunches both transversely and temporarily well within the

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† vladimir.litvinenko@stonybrook.edu

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beam's sizes and duration. Next important steps in our plan was to match relativistic factors of electron and ion beam by observing increase in the spontaneous radiation of electron beam caused by the ion's imprint (induced density modulation). Specifically, each ion interacting with electron beam in the CeC modulator [1,16] creates a localized density modulation whose intensity depends on the mismatch between relativistic factors of the beams – Fig. 2.

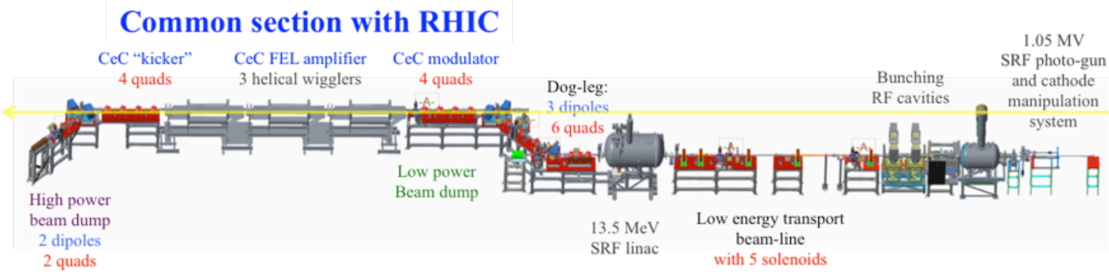

Figure 1: Layout of the CeC proof-of-principle system at IP2 of RHIC. Out CW SRF accelerator uses LiHe delivered by RHIC cryogenic system – it can operated only when RHIC is running.

Table 1: Main Parameters of the CeC System

Parameter	Design	Achieved	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	14.5 MeV	SRF linac quench
Charge per e-bunch	0.5-5 nC	0.1- 10.7 nC	✓
Peak current	100 A	50-100 A	Sufficient for this energy
Pulse duration, psec	10-50	10-20	✓
Beam emittance, norm	<5 mm mrad	3 - 5 mm mrad	✓
FEL wavelength	13 µm	30 µm	New IR diagnostics

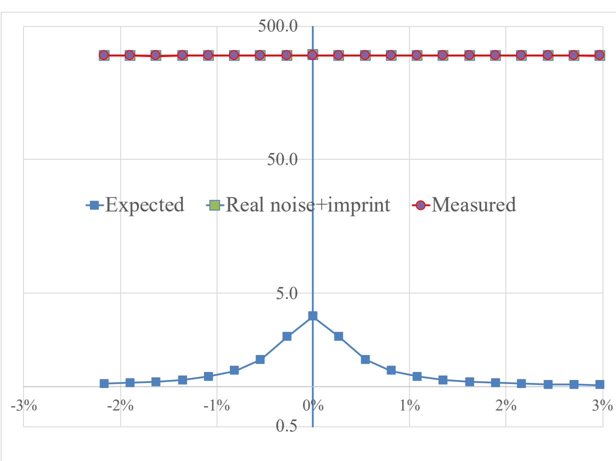

Figure 2: Predicted and measured dependence of radiation power from the electron beam resulting from ion beam imprint. Vertical scale is logarithmic and shows radiated power normalized to the natural synchrotron radiation (e.g. by shot noise with Poisson statistics) as a function of relative difference of relativistic factors in two beams.

Observing tripling of the radiation power predicted by the theory and simulation would not be a problem, but our attempts to observed it by scanning energy of the electron beam were unsuccessful. Surprized by experimental measurements showing no indication of the measurable "imprint" from the ion beams, we verified that beam indeed overlap, and that beam's relativistic factors were equal within ±1%. We also observed interactions between overlapping electron and ion bunches. By design of the CeC experiment, electron beam interacts only with one of ion bunches circulating in RHIC yellow ring. Hence, we compared bunch-lengthening rate of interacting ion bunch (effected only by IBS) with witness bunches and found growth rate is doubled, when the CeC FEL gain was high – see Fig. 3. Turning the FEL gain off (observed by the FEL power level) eliminated the heating of the interacting bunch.

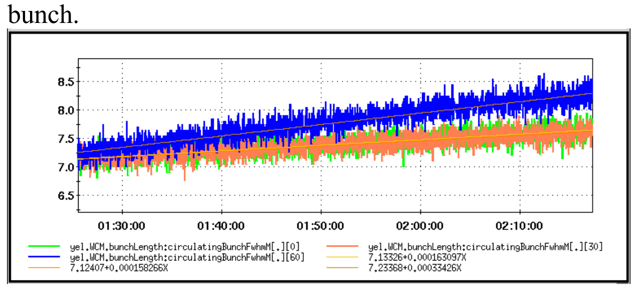

Figure 3: Evolution of the bunch lengths for interacting (blue trace, RF bucket #30) and witness bunches (orange and green traces, RF buckets #0 and #60) shows doubling of the growth rate.

We continued improving our measurement technique and clearly demonstrated (see Fig. 2) absence of measurable imprint within a statistical error of 2% Attempts to resolve the "imprint absence" puzzle did not allow us to investigate the cooling in FEL-based CeC.

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This was definitely unexpected result: all in-depth simulation using standard accelerator physics codes (PARMELA, ASTRA, GPT, Elegant, etc.) predicted that there will be no instabilities in the electron beam transport from the gun to the FEL amplifier. Our experiment proved this assumption to be wrong when we were unable to observe expected strong "imprint" from ion beam in the radiation power of the electron beam. This puzzle was not resolved till the end of regular RHIC run with ion beam in mid-June 2018. We took advantage of availability of LiHe during the summer for commissioning of Low Energy RHIC electron Cooler (LEReC) and found a new instability occurring in beams propagating in straight section, which we called Plasma-Cascade Instability [14-16].

Post-Run Studies. We completed CeC run 18 by investigating electron beam quality and resolving the "imprint" measurement puzzle, for which we considered a number of possible explanations (such as 3% error in beam energies, FEL saturation, poor beam overlap, etc.), all of which were eliminated (or proved highly unlikely), except excessive noise in the election beam at frequencies ~ 10 THz.

While there were a number of other indications, the most convincing measurement was when we fully opened FEL wiggler (e.g. effectively turned them off) and found that measured radiation power of electron beam from a bending magnet exceeded natural (spontaneous or Poison statistical random noise) level by ~300-fold. E.g. in the lattice used for the "imprint" studies the amplitude of the beam density modulation at frequency ~ 10 THz was ~17-fold above the shot-noise level. While this was sufficient to explain the results shown in Fig. 2, we wanted to find the origin of this broad-band noise. The possibility of instabilities caused by CSR and wakefield were eliminated in our simulations. We also eliminated possibility that this modulation originates at the laser pulse structure by measuring its spectrum. Finally, we discovered the real culprit of this noise – a Plasma-Cascade Instability (PCI) in the low energy beam transport used for ballistic bunch compression. We demonstrated both experimentally and later in simulations that PCI is driven by strong modulation of the beam radius [16]. We gain sufficient experience and understanding of PCI both to predict it and, when needed, to suppress it.

CONTROL OF NOISE IN ELECTRON BEAM

We learned how to use one of the most universal codes, Impact T, to simulate PCI in the CeC SRF accelerator. Two samples of successful simulations, using NERSC supercomputer, are shown in Fig. 4. It took us awhile to learn how to the code for simulating PCI at 10s of THz correctly: specifically, we adjusted the mesh size, the time steps and number of macroparticles to avoid massive superficial spikes in the spectrum. Some of the remaining spikes can be seen in red line near 15 THz and 20 THz. While Impact T allowed us to simulate PCI, it worth noting that the noise floor in these simulations exceeds that of the baseline (e.g. of shot noise with Poisson statistics) by about an order of magnitude.

The simulations for graphs showing in Fig. 4. were performed for 1.25 MV SRF gun voltage, standard bunching cavity voltages for 20-fold compression of electron bunches. They were done for a regular (strong focusing) lattice and a relaxed lattice in the low-energy beam transport of the CeC accelerator. We were able to show in these simulations that (1) indeed we had strong PCI with the lattice we used for the ion impact studies; (2) that we can reduce noise level in the electron beam using relaxed lattice with a smooth beam envelope.

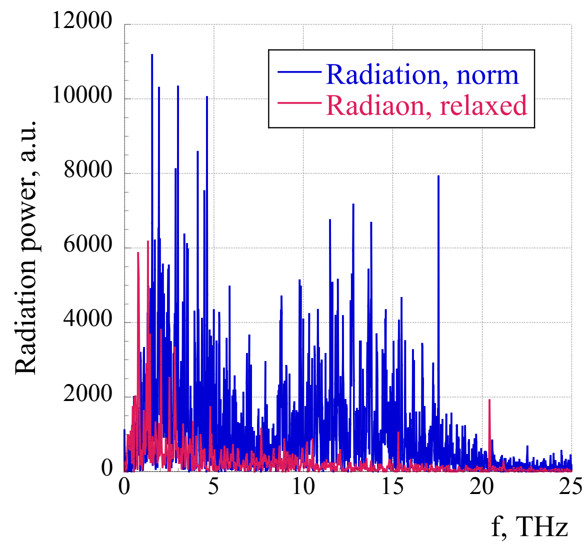

Figure 4: Radiation spectrum of the compressed 0.7 nC electron bunch profile at the exit of the SRF linac simulated by Impact-T. Blue colour line is for strong focusing lattice (used during RHIC Run 18) and Red colour lines are for a relaxed lattice of the CeC accelerator. Horizontal axis is the frequency measured in THz.

These simulations were indications of possibility to control noise level in electron beam and making it useful for CeC experiments. We just needed to demonstrate it using a real "quantum computer" – the beam itself.

During RHIC run 19, we had a short three-week-long experiment with CeC accelerator with main goal of reducing noise in electron beam to acceptable level. We installed new broad-band mid-IR diagnostic system down-stream of the first bending magnet located just downstream of our SRF linac. During this run, access to the RHIC vacuum system was terminated and the beam was dumped into the wall of the dipole magnet vacuum chamber. In this mode, the beam current was limited to 2.5 μA.

The layout of IR diagnostic system is shown in Fig. 5. Electron beam is bent by 45-degree dipole magnet and IR radiation is reflected by 45-degree Cu mirror though CVD diamond window in atmosphere. The window is covered by metal 1.4 mm x 1.4 mm mesh to prevent sub-THz radiation from reaching the IR detector. 2" off-axis parabola focuses radiation onto the entrance window of GentecTHZ5I-BL-BNC pyroelectric detector. This detector is sensitive to all sources of energy including X-ray, vibrations and audio noise, and has only a slow AC msec scale

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response time. We operated electron beam with 10 Hz trains of 78 kHz bunches and used lock-in amplifier to achieve necessary sensitivity.

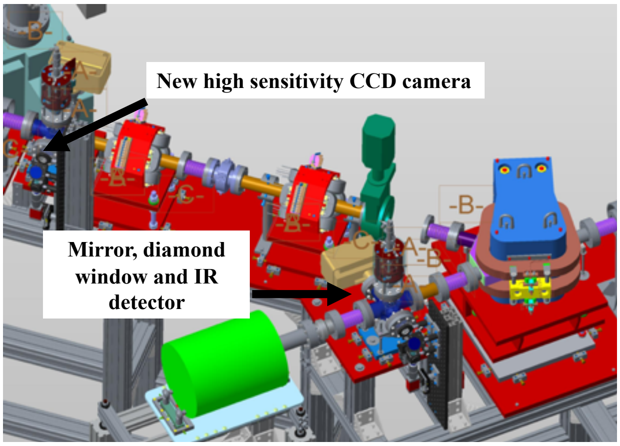

Figure 5: IR diagnostics set-up for the noise-control experiment. The reflecting mirror is located 0.73 meters downstream of the front edge of the bending magnet.

We used Igor-Pro code and measured map of magnetic field to calculate distribution of radiation power at the 1" reflecting mirror and the energy spectrum of the radiation reflected to the IR detector – see Fig. 6.

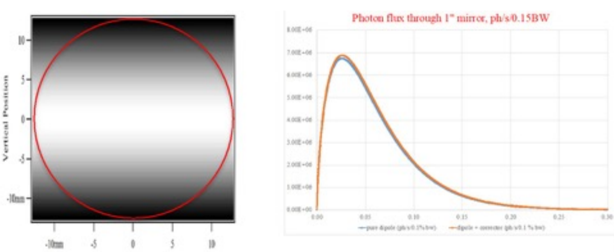

Figure 6: Left is the distribution of IR radiation power at 1" reflecting mirror (red circle) and right is simulated spectrum for normal and tilted by 2.5 mrad entrance into the bending magnet. Simulations done with Igor-Pro code.

The most important part of the experiment was to establish the baseline, e.g. the power originating from Poisson statistics shot noise. With typical beam current of 1.5 μA and ~50% transport efficiency (most of the losses originated from the metal mesh) total baseline radiation power reaching the IR detector was ~ 50 pW. The corresponding signal from lock-in amplifier would be ~ 20 μV*, e.g. the expected baseline ratio between measured voltage and beam current is ~15 V/A.

We measured the baseline level using a weakly compressed (only by 4-fold) electron beam and relaxed lattice of the accelerator. To demonstrate that shot noise in our beam was not amplified by instabilities, we measurements radiation power with the bunch charge varied by a factor of 5, e.g. with 0.3 nC and 1.5 nC bunches. Measured powers normalized to the average current agreed well within measurement errors.

The baseline measurements were non-trivial and required use of modulation-demodulation (MDM) technique in addition to the lock-in amplifier. Specifically, we were inserting and removing reflecting mirror and measured difference between two states. Measurements were performed for few (from 2 to 12) hours to achieve necessary accuracy. While all our measurements were performed by a dedicated MDM code, which was taking into account the state of the accelerator as well as pausing during transition between states, here we present in Fig. 7, a graph from RHIC control system illustrating the need for the MDM measurements. The base line was measured in 4 long MDM scans to be 14.5±1.5 V/A

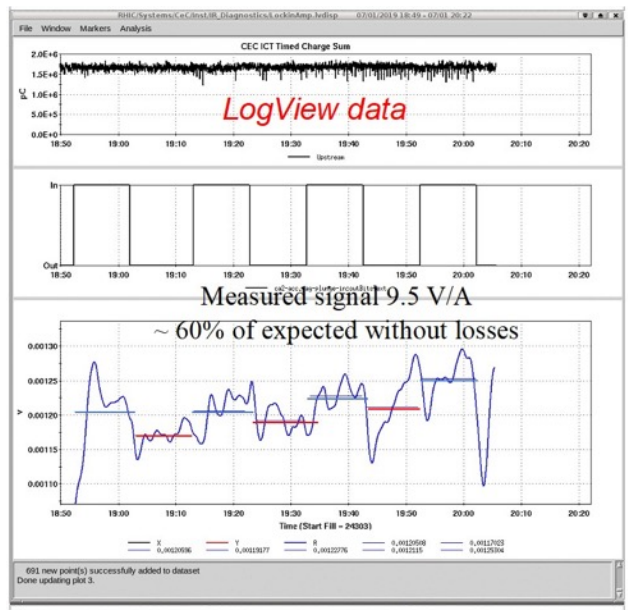

Figure 7: Illustration of the evolution of signal from lock-in amplifier and the need for the MDM method. Top graph shows the charge per bunch train. The middle graph shows location of the reflecting mirror (IN/OUT). The bottom graph shows evolution of the lock-in signal with time constant of 30 seconds. Significant drifts illustrate the need for averaging and the MDM method for accurate measuring the radiation power at this level.

The applied methods allowed us to achieve the required sensitivity and to reliably measure the baseline of radiation power and to compare it with that for the compressed beam. First, we confirmed that the noise level in the electron beam used for the Run 18 imprint studies (600 pC per bunch, 20X compression, strong focusing lattice) has noise power level ~ 250 above the baseline.

After that we investigated dependence of the noise level in electron beam with 1.5 nC per bunch compressed to 75 A beam current as function of solenoid focusing of the low energy transport line. We found that there is a rather large

* Main uncertainty comes from approximation in the transparency of the metal mesh.

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valley of setting with noise level at or below 10-fold the baseline. Figure 8 shows one of best results obtained during these studies when the noise level was reduced to about 6-times of the baseline.

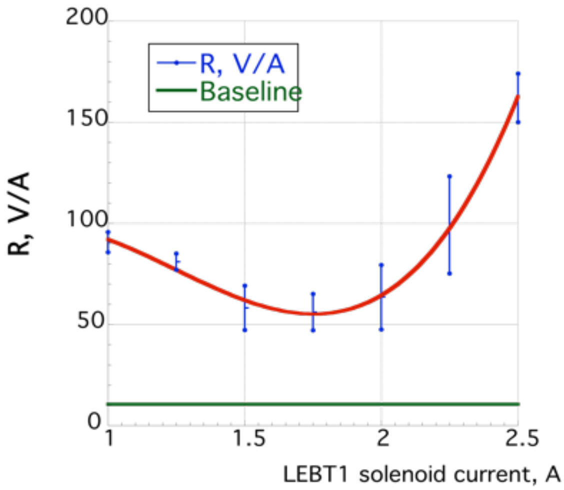

Figure 8: Redline is the measured ratio of the lock-in amplifier voltage to the average beam current, R, as function of the current in LEBT1 solenoid Green line shows the baseline for R value corresponding to the shot noise.

PLANS

Starting from Run 19 RHIC switched to low energy operation. This mode requires avery large aperture, which is incompatible with that of the CeC FEL wiggler. Hence, the FEL wigglers system had been removed and the system was replaced with large aperture chamber. We designed new CeC system compatible with this new requirement. Our next step in the CeC demonstration experiment with microbunching Plasma-Cascade Amplifier (PCA) is shown in Fig. 9.

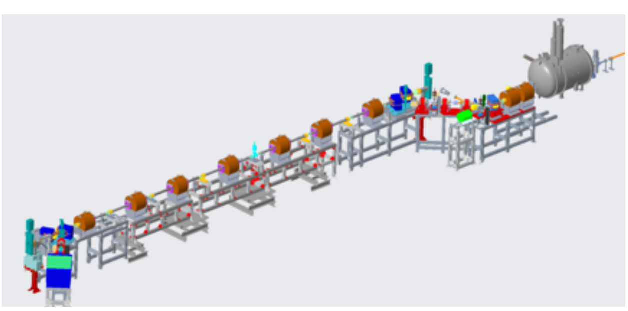

Figure 9: Layout of the CeC experiment with micro-bunching Plasma-Cascade Amplifier at IP2. It has seven solenoids: the modulator section IS between THE first and THE second solenoids, strong-focusing 4-cess PCA formed by 5 central solenoids, and the kicker section is upstream of the last solenoid.

Our broadband (~20 THz) PCA is the only micro-bunching amplifier which does not require separation and delay system for ion beam. In other words, this is the unique possibility to demonstrate CeC with micro-bunching amplifier without a millions-dollars investment in significant lattice modification of RHIC. The vacuum system for PCA_based CeC experiment is already installed. All solenoids had been produced, underwent magnetic measurements and are in the process of installation.

During last year we developed reliable self-consistent full-3D simulations of PCI and PCA capable of predicting CeC performance– see Fig. 5.

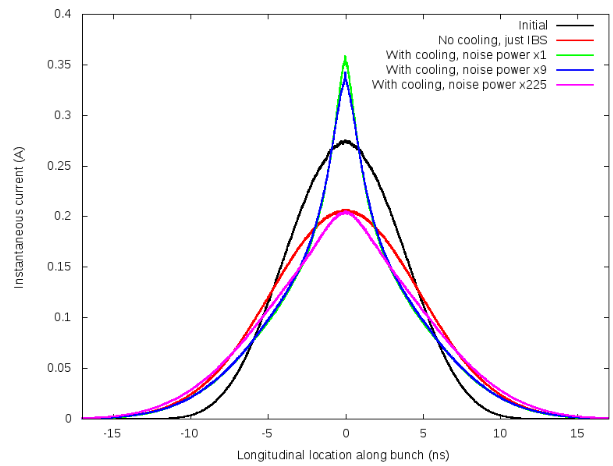

Figure 10: Evolution of the 26.5 GeV/u ion bunch profile in RHIC. Black - initial profiles at t=0. All other profiles are shown at t=40 minutes. Red– evolution of witness bunch without cooling; green – cooled with e-beam having natural shot noise; blue- cooled with e-beam with 9 time increase in the noise power; crimson - e-beam with 255 time increase in noise power.

Successful demonstration of electron beam with low noise gives us confidence that we should be able to demonstrate cooling of 26.5 GeV/u ion beam in RHIC – e.g. something resembling blue line in Fig. 10. Our three-year plan includes demonstration of ion imprint and PCA during RHIC run 20, followed by demonstration of longitudinal (energy) cooling during RHIC run 21, and simultaneous transverse and longitudinal cooling during RHIC run 22.

CONCLUSION

We successfully commissioned SRF-based CeC electron accelerator and achieved all design beam parameter, except the energy. Unfortunately, we stumble into a previously unknown microwave instability - occurring in beam propagating along straight line – which prevented demonstration of FEL-based CeC last year. We developed a new – more advanced - CeC system, which is fully compatible with RHIC low energy operation requirements, to continue our experimental program. The hardware necessary for the next step of our experiment is in the process of installation. Successful commissioning of this system will allow us to demonstrate CeC experimentally in near future.

REFERENCES

[1] V.N. Litvinenko, Y.S. Derbenev, *Physical Review Letters* **102**, 114801, 2009.

ISBN: 978-3-95450-218-9 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2019-TUZ01

[2] V. Litvinenko *et al.*, “Proof-of-principle Experiment for FEL-based Coherent Electron Cooling”, in *Proc. 33rd Int. Free Electron Laser Conf.* (FEL'11), Shanghai, China, Aug. 2011, paper WEOA3, pp. 322-325.

[3] I. Pinayev *et al.*, “Present Status of Coherent Electron Cooling Proof-of-principle Experiment”, in *Proc. 9th Workshop on Beam Cooling and Related Topics* (COOL'13), Mürren, Switzerland, Jun. 2013, paper WEPPO14, pp. 127-129.

[4] I. Pinayev *et al.*, “First Results of the SRF Gun Test for CeC PoP Experiment”, in *Proc. 37th Int. Free Electron Laser Conf.* (FEL'15), Daejeon, Korea, Aug. 2015, paper TUD03, pp. 564-566.

[5] I. Pinayev *et al.*, “Helical Undulators for Coherent Electron Cooling System”, in *Proc. 38th Int. Free Electron Laser Conf.* (FEL'17), Santa Fe, NM, USA, Aug. 2017, pp. 519-521. doi:10.18429/JACoW-FEL2017-WEP051

[6] I. Petrushina *et al.*, “Novel Aspects of Beam Dynamics in CeC SRF Gun and SRF Accelerator”, in *Proc. 38th Int. Free Electron Laser Conf.* (FEL'17), Santa Fe, NM, USA, Aug. 2017, pp. 313-316. doi:10.18429/JACoW-FEL2017-TUP034

[7] I. Petrushina *et al.*, “Mitigation of multipacting in 113 MHz superconducting RF photo-injector”, *Phys. Rev. Accel. Beams* 21, 082001, 2018.

[8] K. Mihara, Y. C. Jing, V. Litvinenko, I. Petrushina, I. Pinayev, and G. Wang, “Emittance Measurements from SRF Gun in CeC Accelerator”, in *Proc. 38th Int. Free Electron Laser Conf.* (FEL'17), Santa Fe, NM, USA, Aug. 2017, pp. 470-474. doi:10.18429/JACoW-FEL2017-WEP025

[9] G. Wang, Y. C. Jing, V. Litvinenko, and J. Ma, “Electron Beam Requirements for Coherent Electron Cooling FEL System”, in *Proc. 38th Int. Free Electron Laser Conf.* (FEL'17), Santa Fe, NM, USA, Aug. 2017, pp. 323-325. doi:10.18429/JACoW-FEL2017-TUP039

[10] Y. C. Jing, V. Litvinenko, and I. Pinayev, “Simulation of Phase Shifters Between FEL Amplifiers in Coherent Electron Cooling”, in *Proc. 38th Int. Free Electron Laser Conf.* (FEL'17), Santa Fe, NM, USA, Aug. 2017, pp. 386-388. doi:10.18429/JACoW-FEL2017-TUP072

[11] T. Xin, J. C. Brutus, S.A. Belomestnykh, I. Ben-Zvi, C. H. Boulware, T. L. Grimm, *et al.*, *Review of Scientific Instruments,* 87, 093303, 2016.

[12] I. Pinayev, V.N. Litvinenko, *et al.*, “High-gradient High-charge CW Superconducting RF gun with CsK2Sb photocathode”, arXiv:1511.05595, 17 Nov 2015.

[13] V. Litvinenko *et al.*, “Commissioning of FEL-Based Coherent Electron Cooling System”, in *Proc. 38th Int. Free Electron Laser Conf.* (FEL'17), Santa Fe, NM, USA, Aug. 2017, pp. 132-135. doi:10.18429/JACoW-FEL2017-MOP041

[14] V.N. Litvinenko, G. Wang, D. Kayran, Y. Jing, J. Ma, I. Pinayev, “Plasma-Cascade micro-bunching Amplifier and Coherent electron Cooling of a Hadron Beams”, arXiv preprint arXiv:1802.08677.

[15] Vladimir N. Litvinenko, Gang Wang, Yichao Jing, Dmitry Kayran, Jun Ma, Irina Petrushina, Igor Pinayev and Kai Shih, “Plasma-Cascade Instability- theory, simulations and experiment”, arXiv:1902.10846, 2019

[16] J. Ma, V. Litvinenko, and G. Wang, “Simulations of Modulator for Coherent Electron Cooling”, in *Proc. 9th Int. Particle Accelerator Conf.* (IPAC'18), Vancouver, Canada, Apr.-May 2018, pp. 2953-2956. doi:10.18429/JACoW-IPAC2018-THPAF005

[17] T. A. Miller, D. M. Gassner, V. Litvinenko, M. G. Minty, I. Pinayev, and B. Sheehy, “Infrared Diagnostics Instrumentation Design for the Coherent Electron Cooling Proof of Principle Experiment”, in *Proc. 36th Int. Free Electron Laser Conf.* (FEL'14), Basel, Switzerland, Aug. 2014, paper THP074, pp. 905-908.