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COHERENT ELECTRON COOLING EXPERIMENT AT RHIC: STATUS AND PLANS *

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Abstract

We present currents status of the CeC experiment at RHIC and discuss 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). Our plan for future experiments includes suppressing this instability in the CeC accelerator and using it as a broad-band amplifier in the CeC system.

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 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.

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 except – see Table 1 [5-13,20]. 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). This was definitely unexpected result: all simulation 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

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(LEReC) and found a new instability occurring in beams propagating in straight section, which we called Plasma-Cascade Instability [14-16]. 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 radiation [17,19] 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 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.

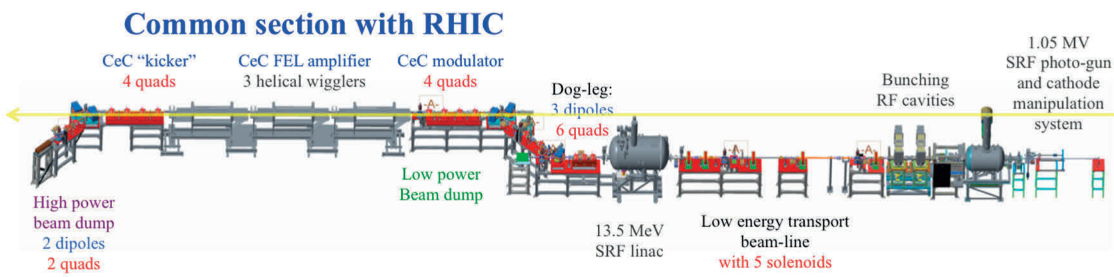

Figure 1: Layout of the CeC proof-of-principle system at IP2 of RHIC.

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

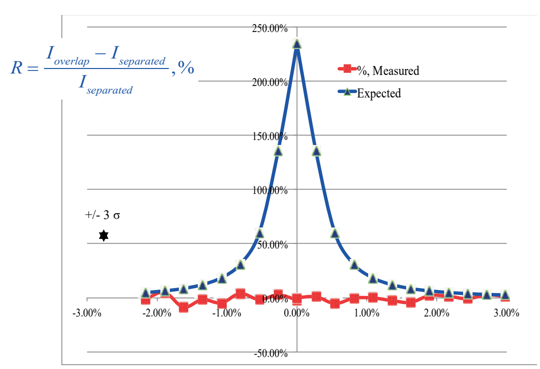

Figure 2: Predicted and measured relative increase in the radiation of electron beam by overlapping ion beam as a function of relative error in relativistic factors.

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.

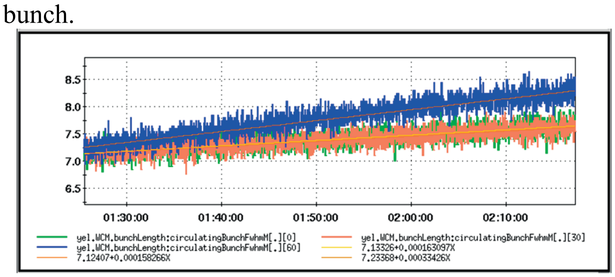

Figure 3: Evolution of the bunch lengths for interacting (blue trace, RF bucket #30) and witness bunches (orange and green traces, RF buckets #0 and #60) shows doubling of the growth rate.

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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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 (for the lattice used for the "imprint" studies), e.g. an increase in the amplitude of the beam density modulation ~17-fold above shot-noise level. While this sufficient to explain the results shown in Fig. 2, we wanted to find the origin of this broad-band noise at 10 THz and around. The possibility of instabilities caused by CSR and wakefield were eliminated in our simulations, we 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 in simulations that PCI is driven by stung modulation of the beam radius [16,18]. We gain sufficient experience and understanding of PCI to predict it and to find ways of suppressing it [18].

FUTURE PLANS

RHIC switching to low energy operation the IP2 requires a very large aperture, which is incompatible with that of the CeC FEL wiggler – hence, the wigglers had been removed in Fall of 2018. The system was replaced with large aperture system, which is compatible with the next proposed step in the CeC demonstration experiment – the CeC with microbunching Plasma-Cascade Amplifier (PCA) – see Fig. 4. In addition to a very broad-band (~20 THz) the PCA is the only micro-bunching amplifier which does not require a monstrous separation and delay system for ion beam. In other words, this is the unique and the only possibility to demonstrate CeC with micro-bunching amplifier without investing tens of millions of dollars and very significant lattice modification of hadron rings.

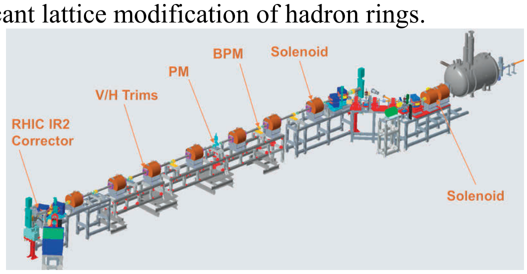

Figure 4: Layout of the CeC experiment with micro-bunching Plasma-Cascade Amplifier at IP2. It has seven solenoids – it has the modulator section between first and second solenoids, strong-focusing 4-cess PCA formed by central 5 solenoids, and the kicker section upstream of the last solenoid.

The vacuum system for this experiment is already installed and all solenoids (plus spared) had been produced and undergoing magnetic measurements. They can be installed onto the IP2 section during RHIC shutdown this year.

During last year we developed reliable self-consistent full-3D simulations of PCI and PCA [21] capable of predicting CeC performance. Having experience with the excessive noise in electron beam, we performed detailed simulation of the PCA-based CeC cooling of 26.5 GeV ion bunch for various levels of noise amplitude (note that the radiation power scales as square of the amplitude) – see Fig. 5 [20].

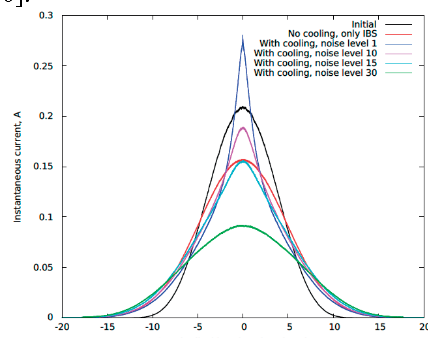

Figure 5: Evolution of the 26.5 GeV/u ion bunch profile in RHIC. Black - initial profiles at t=0. All other profiles are shown at t=40 minutes. Red– evolution of witness bunch without cooling; blue – cooled with e-beam having natural shot noise; crimson - cooled, e-beam with 10 time increase in amplitude of shot noise; cyan - cooled, e-beam with 15 time increase in amplitude of shot noise; and green - , e-beam with 30 time increase in amplitude of shot noise.

We had found – in simulations – lattice which would suppress PCI in the CeC accelerator while providing necessary quality beam for the PCA-based CeC experimental demonstration. We started CeC accelerator operation in May 2019 with goal to demonstrate that high frequency (e.g. tenths of THz) noise in the electron beam can be brought close to the statistical level. This experiment will continue till mid-July 2019. If successful, we plan to continue the CeC demonstration experiment, but this time with a very broad-band microbunching plasma-cascade amplifier.

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. Most of the hardware necessary for the next step is either installed or is in hands, which would allow us to undertake the challenging task of experimental. CeC demonstration during next RHIC run in 2020.

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