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FIRST RESULTS FROM COMMISSIONING OF LOW ENERGY RHIC ELECTRON COOLER (LEREC)*

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Abstract

The brand new non-magnetized bunched beam electron cooler (LEReC) has been built to provide luminosity improvement for the Beam Energy Scan II (BES-II) physics program at the Relativistic Heavy Ion Collider (RHIC). The LEReC accelerator includes a photocathode DC gun, a laser system, a photocathode delivery system, magnets, beam diagnostics, an SRF booster cavity, and a set of Normal Conducting RF cavities to provide sufficient flexibility to tune the beam in the longitudinal phase space. This high-current high-power accelerator was successfully commissioned in the period of March -September 2018. Beam quality suitable for cooling has been achieved which led to the first demonstration of bunched beam electron cooling of hadron beams in April 2019. In this paper we discuss achieved results and experience learned during commissioning.

INTRODUCTION

A new, state of the art, electron accelerator for cooling low energy RHIC hadron beams (LEReC) was built and is being commissioned at BNL. The purpose of LEReC is to provide luminosity improvement for the RHIC operation at low energies to search for the QCD critical point (Beam Energy Scan Phase-II physics program) [1-2].

Unlike all electron coolers to date, LEReC uses bunched electron beams accelerated to the required energies using RF cavities [3]. To achieve efficient cooling, the electron beam must not only be optimized for low transverse emittance but, more importantly, for low energy spread.

The LEReC accelerator includes a photocathode DC gun with a high power laser system, magnets, beam diagnostics, an SRF booster cavity, and a set of normal conducting RF cavities to provide sufficient flexibility to tune the beam in the longitudinal phase space.

LEReC uses a DC photocathode gun similar to the one used at the Cornell University [4]. The gun itself was built by the Cornell University. The gun tests with beam started in 2017 when it operated up to 10 mA average current [5]. Electron beams are generated by illuminating a multi-alkali (CsK2Sb or NaK2Sb) photocathode [6] with green light (532 nm) from a high-power fiber laser [7] by utilizing sophisticated laser transport and stabilization [8].

To optimize operational time and minimize the cathode exchange time three multi-cathode carriers were built. Each cathode carrier, which can hold up to 12 pucks of photocathodes, is attached to the gun in a 10-11 Torr-scale vacuum (for details of design see [9]).

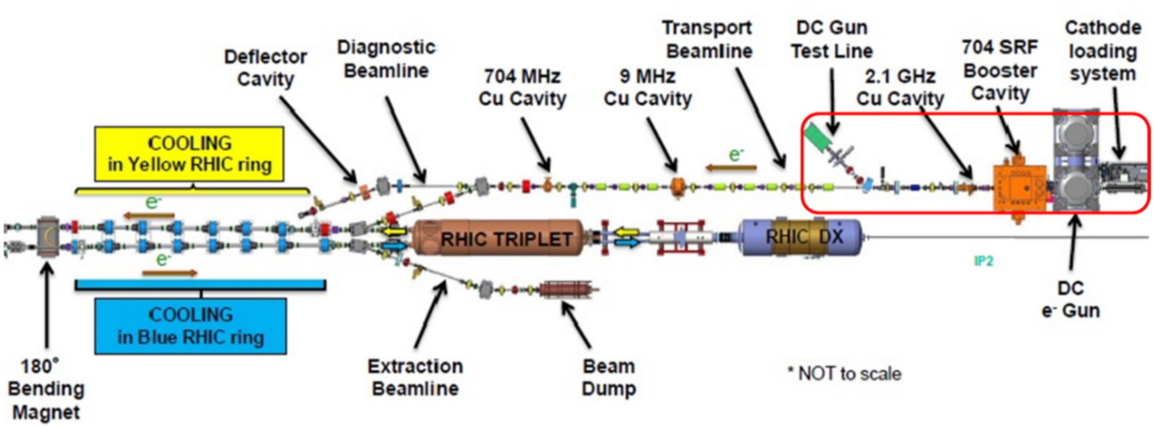

Figure 1: Layout of the LEReC accelerator. The red contour box indicates DC gun test area.

The layout of LEReC is shown in Fig. 1. The 350-400 keV electron beam from the gun is transported via a 704 MHz SRF booster cavity and a 2.1 GHz 3rd harmonic linearizer normal conductive cavity. Electron beams can be accelerated to maximum kinetic energy of 2.6 MeV. The electron bunch is ballistically stretched to the required bunch length in the transport line. The accumulated energy

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chirp is compensated by a normal conductive 704 MHz cavity before entering the first cooling section. The 9 MHz normal conductive RF cavity is used to remove bunch-by-bunch energy variation along one macro-bunch caused by beam loading in the upstream RF cavities. After finishing longitudinal gymnastics, the electron beam is merged to the hadron beam in the RHIC Yellow Ring for cooling and then turned 180 degrees for cooling the Blue RHIC Ring. The electrons are then extracted from the RHIC cooling loop and sent through beam diagnostic equipment to the high-power beam dump (HP beam dump).

Design and commissioning of the RF cavities are described in Refs. [10-13]. The optics of entire transport line has been designed and optimized to deliver electron bunches for different operational energies with an electron beam quality satisfactory for cooling [14]. The LEReC beam quality requirements are summarized in Table 1.

Table 1: LEReC Electron Beam Requirements

Kinetic energy, MeV	**1.6**	**2.0**	**2.6**
Bunch Charge, pC	130	160	200
Bunches per train	30	27	24
Macro bunch charge, nC	3.9	4.3	4.8
Macro bunch rep. f, MHz	9.3	9.3	9.3
Total beam Current, mA	36	40	45
Normalized Emittance, µm	< 2.5	< 2.5	< 2.5
Energy spread, 10^{-4}	< 5	< 5	< 5

PULSED BEAM OPERATION

The LEReC equipment installation was completed by the end of February 2018. Commissioning of the full LEReC accelerator started in March of 2018 All RF cavities and beam instrumentation were first commissioned with electron beam in the pulsed mode (several macro bunches at 1 Hz rate).

The LEReC operation required to chop the 704 MHz laser pulses into macro bunches 110 nsec apart, as illustrated in Fig. 2. The bunch train repetition rate must be the same as the repetition rate of ion bunches in RHIC.

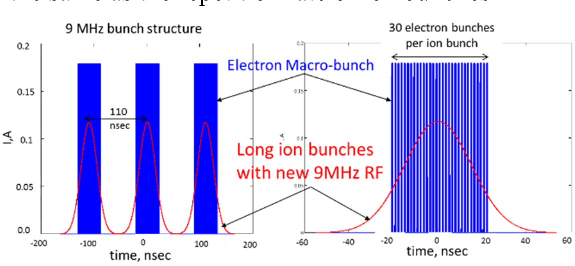

Figure 2: Thirty electron bunches (blue) spaced by 1.4 ns placed on a single ion bunch (red).

Bunch quality optimization and measurement were performed in the 1 Hz pulsed beam mode using beam instrumentation with the machine protection system (MPS) fully engaged. For the LEReC beam instrumentation and MPS details, see Refs. [15] and [16], respectively.

RF DIAGNOSTIC LINE

Based on the tolerance studies, keeping the rms energy spread of the electron beam <5E-04 in the cooling sections, it requires 2.5E-04 voltage- and 0.25 degrees rms stability for the 704 MHz SRF cavity (stability requirements for the other cavities is less stringent). To measure longitudinal beam quality with such accuracy, an RF diagnostic line was designed, built and commissioned.

The RF diagnostic line (see Fig. 3) includes a solenoid to provide small beta function at the YAG screen location, a 20 degrees dipole to generate a dispersion of 800 mm, and a 704 MHz deflecting cavity to provide vertical time dependant kick. If the first merger dipole is turned off the electron beam transports to the RF diagnostic line to measure longitudinal phase space profiles. Longitudinal phase space optimization is done by fine tuning of the RF cavities voltages and phases while observing the bunch profile on the YAG screen. A result of longitudinal phase space measurement after the RF cavities optimization for a bunch charge 75 pC is shown in Fig. 4, for example. The horizontal rms size of the macro-bunch centre part is 0.16 mm, which corresponds to energy spread better than 2 E-4 or an absolute energy spread of 400 eV.

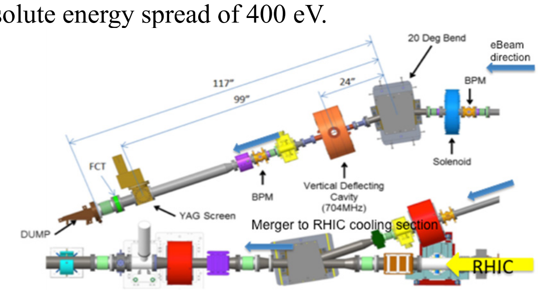

Figure 3: RF diagnostic line layout.

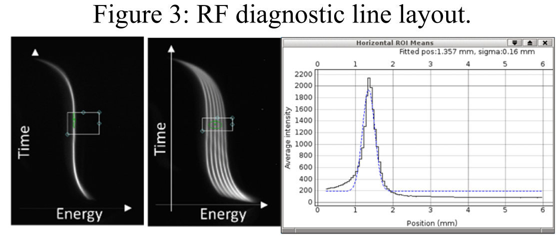

Figure 4: Longitudinal phase space measurements at RF diagnostic YAG profile monitor for a bunch charge of 75 pC, time is in vertical, energy is in horizontal axis: 1) single macro-bunch, 2) six macro-bunches train with good compensation of beam-loading effect by the 9MHz cavity, 3) horizontal profile of the center part of the single macro-bunch.

TRANSVERSE BEAM QUALITY

Due to low beam energy, beam dynamics in LEReC is dominated by space-charge effects. The transverse electron beam emittance in the injection line was characterized with a multi-slit system. In the RHIC cooling sections, emittance was measured by movable slits [17].

The electrons transverse phase space is matched with the RHIC beam phase space by adjusting the last transport line solenoid and the first solenoids in the cooling sections. Op-

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timization results for a bunch charge of 75 pC in the cooling sections are shown at Fig. 5. Normalized rms emittance in both cooling sections is lower than 1.6 μm.

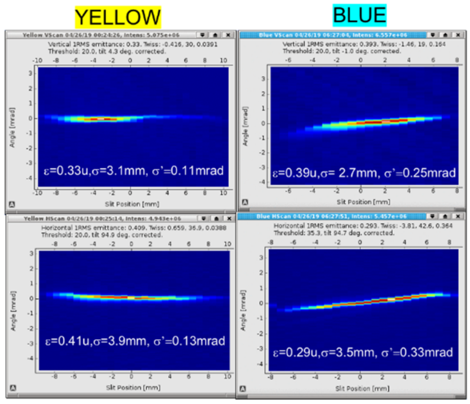

Figure 5: Transverse phase space measurements (geometrical emittance) in the two cooling sections.

9 MHz CW OPERATION

DC Gun Tests in CW Operation

Initial studies of high current DC gun operation were carried out using the DC gun test beam line. In April 2018, a CW electron beam was first run through the RF cavities. An average current of 1.3 mA was delivered to the injection beam dump. The injection beam dump is designed to accept average beam power up to 14 kW at lower energies of about 0.5MeV. In order to proceed with high current testing in the DC gun test-line, the SRF booster voltage was reduced. By September of 2018 we were able to delivery stable 30 mA beams to the injection beam dump using reduced SRF booster voltage. During 30 mA CW operation for several hours, no cathode QE degradations were observed (see Fig. 6).

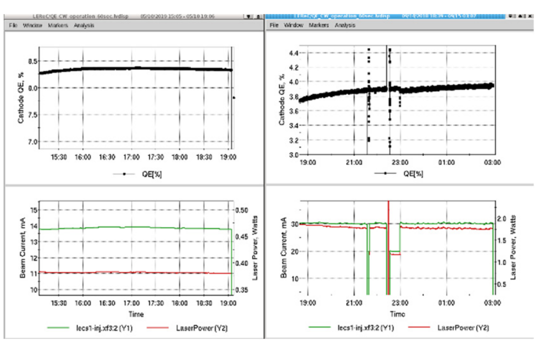

Figure 6: High current 9MHz CW operation with laser beam intensity feedback on. 1) 2018 run of 30 mA in injection line 2) 2019 run of 14 mA to the final high-power beam dump. At the bottom plot: laser average power delivered to the cathode (red) and beam current measured by DCCT (green), at the top cathode QE in % (black).

Full LEReC CW Operation

During the summer of 2018, we experienced some difficulties to operate at high current in the final high power beam dump: worsening beamline vacuum due to overheating and then cooldown process of the flange in front of the dump. As a result, the high power beam dump and the extraction beam line were fully redesigned in the Fall of 2018. As a result of these modifications this year we were able to operate CW to the final high-power dump without problems, see Fig. 6, for example.

Table 2: LEReC Measured Parameters

Parameter	Required	Achieved*
Bunch charge, pC	130-200	10-200
Laser pulse duration, psec	40	40
Laser average power, Watts	10	10
Macro-bunch charge, nC	4-6	6
Macro-bunch rep. rate, MHz	9.3	9.3
Average Current, mA	36-55	14-30
Kinetic Energy, MeV	1.6 -2.6	1.6-2.0
Normalized emittance, μm	<2.5	1.6
RMS energy spread, $x10^{-4}$	<5	<2

*) not at the same time.

COOLING DEMONSTRATION

During Spring of 2019 new RF timing system, including a 76 kHz mode of operation, was commissioned. The 76 kHz corresponds to the RHIC revolution frequency at gamma 4.1. Cooling commissioning started with the 76 kHz mode of operation, which reduces average beam current requirement and average power by a factor of 120, while providing beam quality and interaction frequency sufficient to cool one ion bunch in each of the RHIC rings. In April 2019 first cooling of a single ion bunch using bunched electron beam was demonstrated. After successfull commissioning of cooling in the 76kHz mode, cooling was commissioned in the 9 MHz CW mode, which allows to cool all ion bunches in RHIC. For example, cooling of six ion bunches in both RHIC rings simultaneously is shown Fig. 7. Details on cooling commissioning will be provided elsewhere [18].

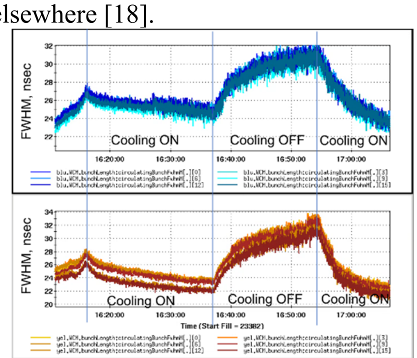

Figure 7: Bunch length reduction in both RHIC rings as a result of longitudinal electron cooling.

STATUS AND PLANS

We designed, built and commissioned a state-of-the-art electron accelerator which provides beam quality suitable for electron cooling using bunched electron beams (summarized in Table 2). The first electron cooling using bunched electron beams based on the RF acceleration was demonstrated. An optimization of cooling and effects on ion beam lifetime is in progress.

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Next, we plan to commission the LEReC accelerator at the higher energies of 2 and 2.6 MeV.

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