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COMMISSIONING OF THE ELECTRON ACCELERATOR LEReC FOR BUNCHED BEAM COOLING*

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Abstract

The brand-new state of the art electron accelerator, LEReC, was built and commissioned at BNL. LEReC accelerator includes a photocathode DC gun, a laser system, a photocathode delivery system, magnets, beam diagnostics, a SRF booster cavity, and a set of Normal Conducting RF cavities to provide sufficient flexibility to tune the beam in the longitudinal phase space. Electron beam quality suitable for cooling in the Relativistic Heavy Ion Collider (RHIC) was achieved, which lead to the first demonstration of bunched beam electron cooling of hadron beams. This presentation will discuss commissioning results, achieved beam parameters and performance of the LEReC systems. The layout of LEReC is shown in Fig. 1.

INTRODUCTION

A new, state of the art, electron accelerator for cooling low energy RHIC hadron beams (LEReC) was built and commissioned at BNL [1]. 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) [2-3].

Unlike all electron coolers to date, LEReC uses bunched electron beams accelerated to the required energies using RF cavities [4]. 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 is designed to provide electron beam for cooling RHIC Ions at energy 3.85-5.75 GeV/nucleon.

LEReC uses a DC photocathode gun similar to the one used at Cornell University [5]. The gun itself was built by Cornell University. The gun tests with beam started in 2017 when the gun delivered up to 10 mA average current [6]. Electron beams are generated by illuminating a multi-alkali (CsK2Sb or NaK2Sb) photocathode [7] with green light (532 nm) from a high-power fiber laser [8] by utilizing sophisticated laser transport and stabilization [9-10].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 [11]). For initial gun tests in 2017-2018 we used large cathode active are 12 mm. Later, in order to reduce cathode QE degradation due to ion back bombarding during high current operation, we used small 6 mm diameter active area cathodes deposited 4 mm off the puck center (see Fig. 2).

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.

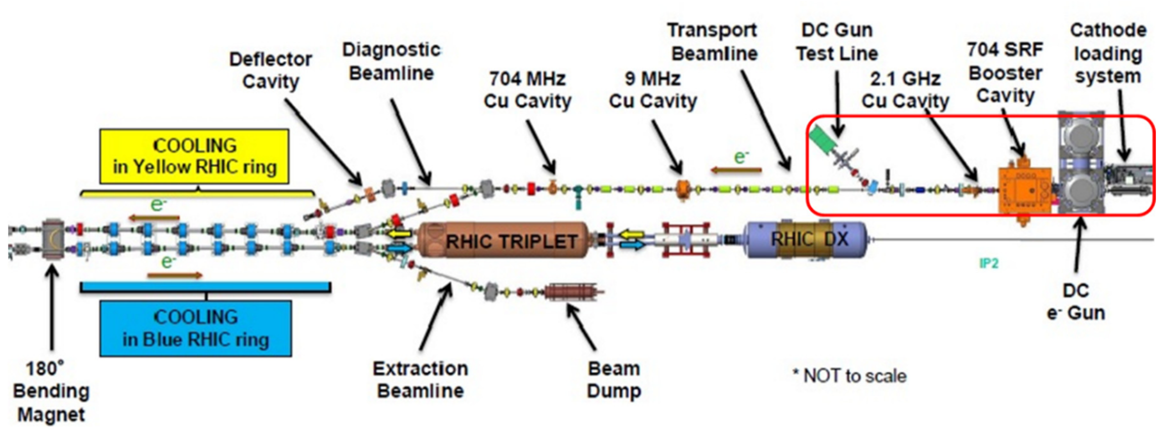

Figure 1: Layout of the LEReC accelerator. The red contour box indicates DC gun test area.

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Figure 2: LEReC insertable cathode pucks with deposited cathode material. At the left, cathode of 12 mm diameter on the puck center used during the DC gun commissioning in 2017. At the right, cathode of 6 mm diameter shifted by 4 mm off the puck center is used during LEReC high current operation in 2018 and 2019.

Electron beams can be accelerated to maximum kinetic energy of 2.6 MeV. Then the electron bunch is ballistically stretched to the required bunch length in the transport line. The accumulated energy 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. The electron beam is then merged to cool the hadron beam in the RHIC Yellow Ring and then turned 180 degrees for cooling in 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. [12-15]. The optics of the entire transport line has been designed and optimized to deliver electron bunches for different operational energies with an electron beam quality satisfactory for cooling [16]. 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. The LEReC operation required to chop the 704 MHz laser pulses into the macro-bunches 110 nsec apart, as illustrated in Fig 3. The bunch train repetition rate must be the same as the repetition rate of ion bunches in RHIC. All RF cavities and beam instrumentation were first commissioned with electron beam in the pulsed mode (several macro bunches at 1 Hz rate).

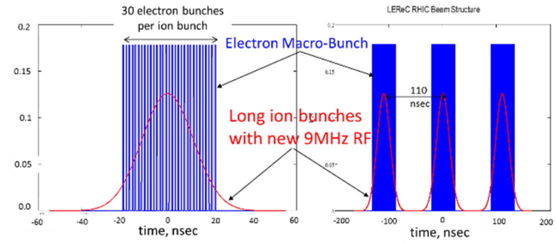

Figure 3: LEReC time structure. One macro-bunch consist of thirty electron bunches (blue) spaced by 1.4 ns placed on a single ion bunch (red).

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. [17] and [18], respectively.

RF Diagnostic Line

Based on the tolerance studies, keeping the rms energy spread of the electron beam <5e-4 in the cooling sections, requires 2.5e-4 voltage- and 0.25 degrees rms stability for the 704 MHz SRF cavity (stability requirements for the other cavities are 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. 4) 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-dependent kicks. If the first dogleg merger dipole is turned off the electron beam is transported to the RF diagnostic line to measure longitudinal phase space profiles.

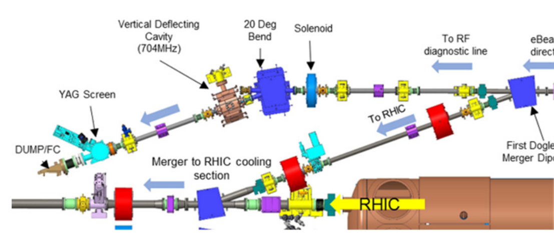

Figure 4: RF diagnostic line layout.

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. 5 and 6, for example. The horizontal rms size of the macro-bunch center part is 0.16 mm, which corresponds to an energy spread of better than $2x10^{-4}$ or an absolute energy spread of 400 eV. By proper adjusted voltage and phase of the 9MHz cavity the beam loading effect along a single macro-bunch was well compensated. The energy difference between macro-bunches during pulsed operation with

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several macro-bunches was measured to be 2 keV. Later, during cooling optimization, we used energy differences between macro-bunches for fine energy matching.

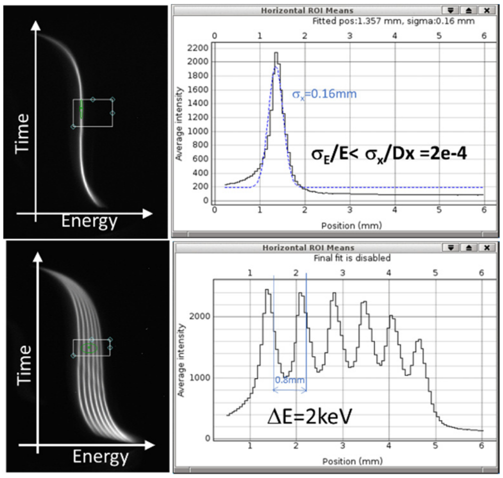

Figure 5: Longitudinal phase space measurements at RF diagnostic YAG profile monitor for a bunch charge of 75 pC, time is in vertical, energy is in horizontal axis: At the top: single macro-bunch full profile with zoom in to horizontal distribution of the center part. At the bottom: six macro-bunch train profile with zoom in to horizontal distribution of the center part for measure of macro-bunches energy differences along the six macro-bunch train.

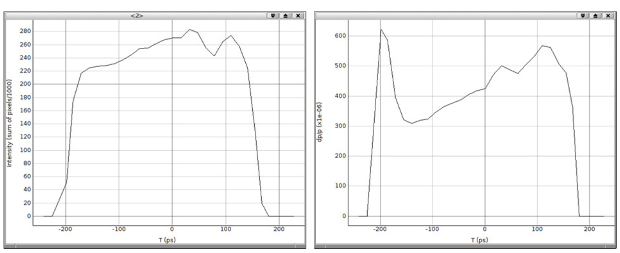

Figure 6: Longitudinal profile (left), and sliced energy spread (right) measurements at RF diagnostic YAG profile monitor for a bunch charge of 100 pC, FWHM of 400 psec.

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 (see Fig 7). In the RHIC cooling sections, emittance was measured using movable slits [19].

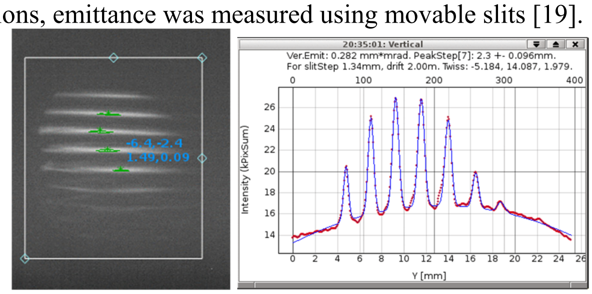

Figure 7: Transverse phase space measurements (geometrical emittance) in the injection line using a multi-slit mask for a bunch charge of 75 pC: 1) slits image at YAG profile monitor, 2) result of image analyzes.

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. Optimization results for a bunch charge of 75 pC in the cooling sections are shown at Fig 8. Normalized rms transverse emittances in both cooling sections are lower than 1.6 μm.

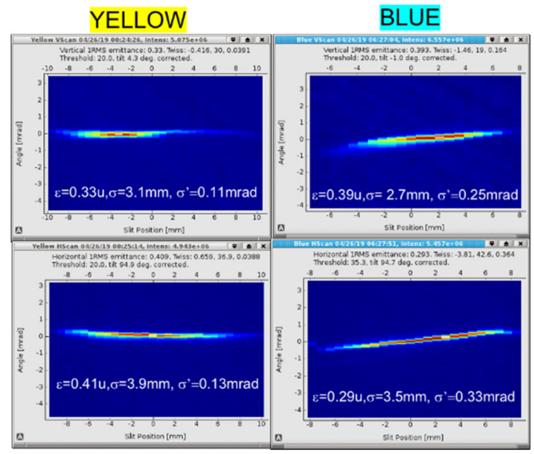

Figure 8: Transverse phase space measurements (geometrical emittance) in the two cooling sections.

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 deliver stable 30 mA beams to the injection beam dump using reduced SRF booster voltage. During 30 mA CW operation for several hours, instead of QE degradation we observed slightly cathode QE recovery as shown at Fig. 9. Such QE behavior has been repeatedly confirmed as well during the run in 2019.

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 due to worsening beamline vacuum resulting from beam-induced thermal cycling of the flange in front of the dump. After opening the high-power beam dump at the end of the run 2018 we observed overheating marks at the entrance flange and at the cone tip of the high-power beam dump (see Fig. 10).

The high-power beam dump and the extraction beam line were fully redesigned in the Fall of 2018. As a result of these modifications during run 2019 we were able to operate high-current CW beam to the final high-power dump with acceptable vacuum and temperature changes, see Fig 11, for example.

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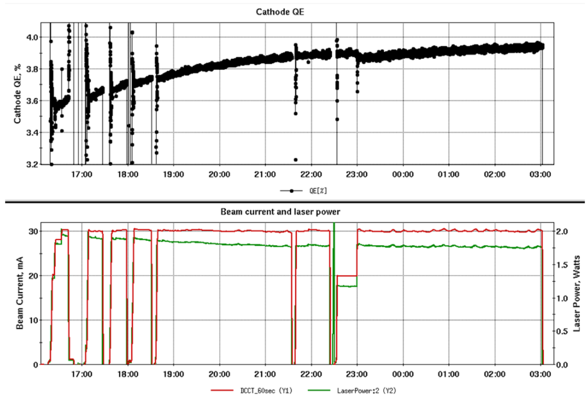

Figure 9: High current 9MHz CW operation with laser beam intensity feedback at the end of run 2018 with beam current up to 30 mA and kinetic energy of 500 keV in the injection line. At the bottom plot: laser average power delivered to the cathode (red) and beam current measured by DCCT (green), at the top plot: cathode QE in % (black).

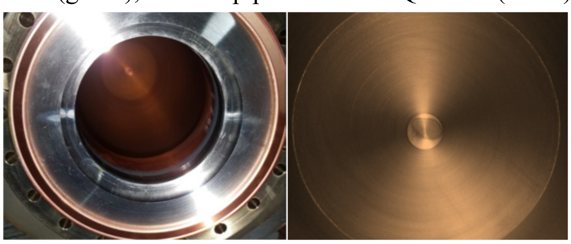

Figure 10: Beam dump marks as a result of a high power beam operation during the 2018 run. Beam current 20 mA, kinetic energy 1.6 MeV: 1) entrance flange; 2) end of the cone. No new marks have been developed after operation of 20-25 mA average current at energy 1.6-2 MeV during the 2019 run.

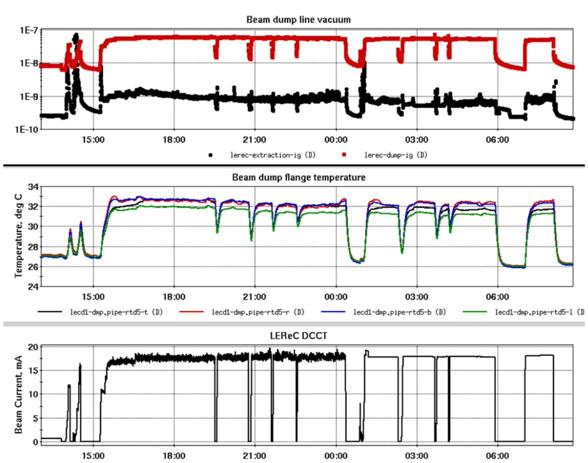

Figure 11: High current 9MHz CW operation to the final high-power beam dump at the end of run 2019 with average beam current up to 18 mA and kinetic energy 2 MeV. At the top plot, vacuum in the extraction line and near the beam dump, at the middle plot beam dump entrance flange different sides temperatures, at the bottom plot beam current measured by DCCT. Intensity feedback was turned on at 01:00 am then beam fast intensity fluctuation has been reduced from $5x10^{-2}$ to $5x10^{-4}$ peak-to-peak.

COOLING DEMONSTRATION

During Spring of 2019, a new RF timing system, including a 76 kHz mode of operation, was commissioned. The 76 kHz corresponds to the RHIC revolution frequency at gamma of 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 successful commissioning of cooling in the 76kHz mode, cooling was commissioned in the 9MHz 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. 12. At the end of the run, electron cooling at one more RHIC energy of 4.6 GeV/nucleon has been commissioned using electron beam energy of 2 MeV. For more details on cooling commissioning and challenges see [20].

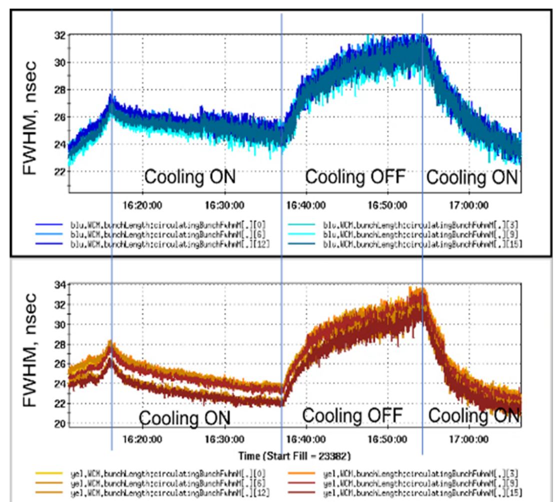

Figure 12: Bunch length reduction of all bunches in both RHIC rings as a result of longitudinal electron cooling running 9MHz CW.

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	1-6
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

*) transverse emittance and energy spread were measured in pulsed mode.

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 at two different energies (summarized in Table 2). World's first

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electron cooling using bunched electron beams based on RF acceleration was demonstrated. We were also able to cool ions in both RHIC rings simultaneously during colliding beam operation and provide increasing of collision rate [20].

Next, we plan to optimize of LEReC cooling efficiency and effects on ion beam lifetime to maximize collision rates during the next RHIC low-energy run in 2020.

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