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FIRST RESULTS OF COMMISSIONING DC PHOTO-GUN FOR RHIC LOW ENERGY ELECTRON COOLER (LEReC)*

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Abstract

Non-magnetized bunched electron cooling of ion beams during low energy RHIC operation requires electron beam energy in the range of 1.6-2.6 MeV, with an average current up to 45 mA, very small energy spread, and low emittance [1]. A 400 kV DC gun equipped with a photocathode and laser system will provide a source of high-quality electron beams. During DC gun test critical elements of LEReC such as laser beam system, cathode exchange system, cathode QE lifetime, DC gun stability, beam instrumentation, the high-power beam dump system, machine protection system and controls has been tested under near- operational conditions [2]. We present the status, experimental results and experience learned during the LEReC DC gun beam testing.

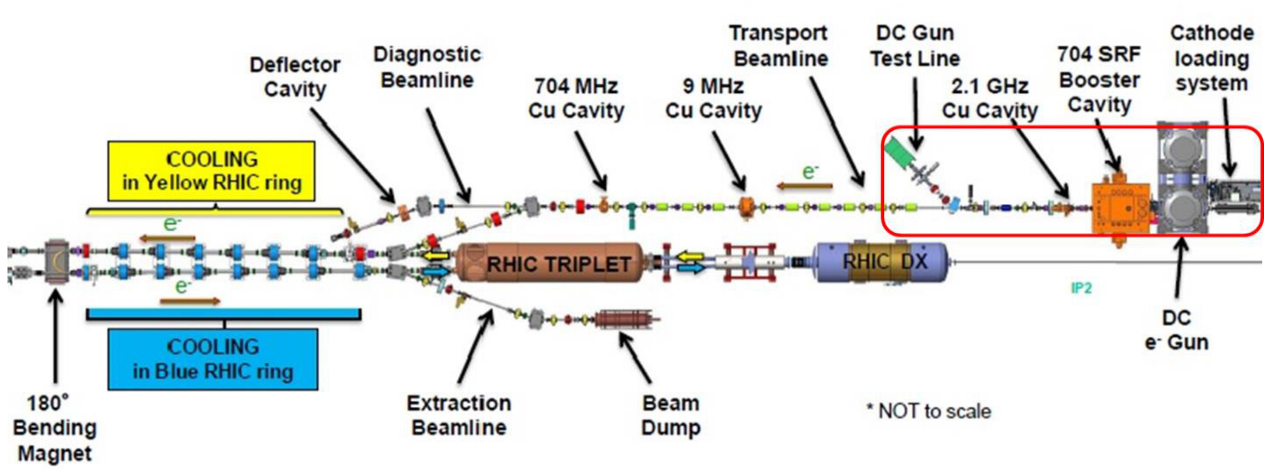
INTRODUCTION

The LEReC uses a replica of the DC photocathode gun used in the Cornell University prototype injector, which has already been producing record high-brightness, high average current electron beams [3]. The gun has been built by Cornell University. DC Gun is required to operate with more than 30 mA 24/7. Gun will use multi-alkali NaK2Sb (or CsK2Sb) photocathode, which will be illuminated with green (532 nm) laser light with an oscillator frequency of 704 MHz. We expect that lifetime of such cathodes should be 10s hours. In order to optimized operation time and minimized the cathode exchange time multi cathodes carrier has been built. It's designed to hold up to 12 pucks of photocathodes attached to the gun in 11 scale vacuum [4]. The 400 keV electron beam from the gun is transported via a 704 MHz SRF booster cavity and 2.1 GHz 3rd harmonic linearizer normal conductive cavity. Electron beam is accelerated to maximum kinetic energy of 2.6 MeV. In drift space electron bunch is stretched to required bunch length. Before entering the cooling section accumulated energy chirp is compensated by normal conductive 704 MHz cavity. Two dogleg-like mergers and mirror dipole are used to combine and to separate electron cooler electron beam with/from RHIC ion beams. The layout of LEReC is shown in Fig. 1. The optics of entire transport line has been designed and optimized to delivery electron bunches for different operation energies with quality satisfied electron cooling requirement summarized in Table 1 [5].

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

Figure 1: Layout of LEReC accelerator. Red contour box indicates DC gun test area.



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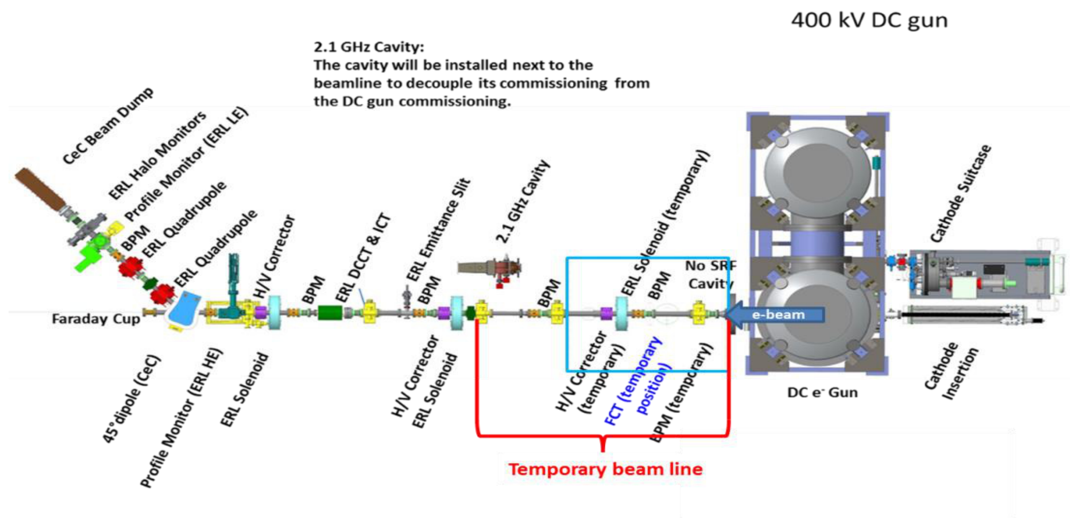

Figure 2: LEReC DC gun beam test layout. 2.1 GHz 3rd harmonic cavity (testing aside of DC gun test beam line) and 704MHz SRF cavities (shown as a blue box contour) will be installed in replacement of temporary beam line after gun test is finished in fall of 2017.

Many beam line components are transferred from R&D ERL test facility [6] SRF cavity, solenoids, quadrupoles, magnets power supplies, beam profile monitors, beam position monitors, DCCTs, ICT and from CEC POP test [7] 45 degrees dipole, 10 kW beam dump.

PURPOSE OF LEReC GUN TEST

The gun beam test (see Fig. 2) is the first stage of LEReC commissioning. Our aim is to test critical LEReC equipment in close to operation condition. This will demonstrate that the DC gun with photocathode meets its performance specifications and can work reliably.

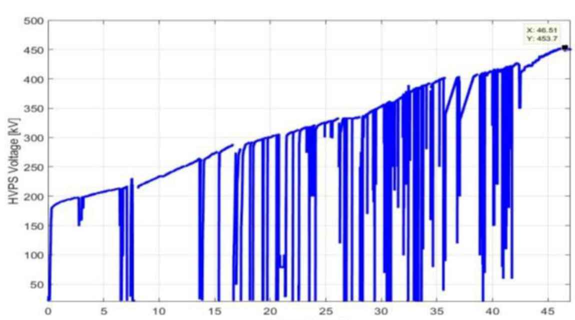

Figure 3: Voltage change during LEReC DC gun conditioning process at BNL.

Components to be tested during gun commissioning: a) laser beam delivery system (laser, laser shaping, laser transport, laser pulse stability); b) vacuum components; c) cathode manipulation system; d) DC gun characterization (stability, maximum operation voltage, electron beam quality); e) magnets (power supply); f) beam instrumentation; g) Control system (timing system, machine protection system, control of laser, gun power supply etc.); h) high average power beam extraction and dump system. Gun test is designed to measure: a) beam energy and energy spread; b) emittance (ε) and Twiss parameters (α, β) using solenoid scan and/or slits; c) Longitudinal and transverse halo. During later runs with booster cavity installed we should be able to measure: bunch length and slice emittance.

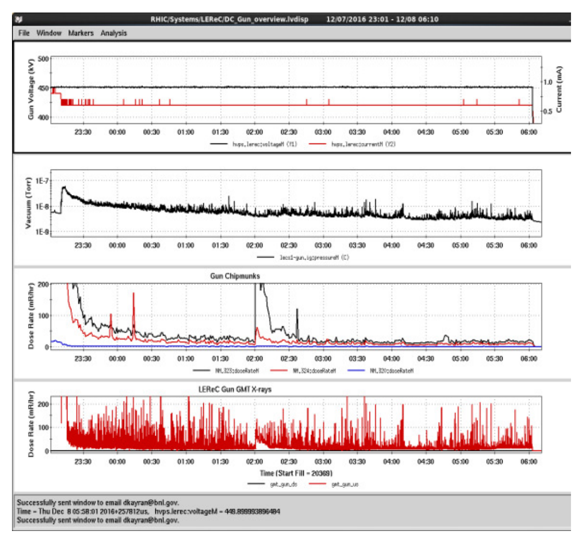

Figure 4: DC Gun stable operation during 7 hours at 450 kV after HV conditioning. (Top plot HV PS voltage and current. Second plot SHOWS in gun vacuum improvement from initial 1E-8 to 3E-9.

HV DC GUN CONDITIONING

First time gun has been conditioned at Cornell University in October 2016 gun reached 440 kV. After that gun has been dissembled and sent to Brookhaven National Lab (BNL). Where it was assembled and installed in final location. In November 2016 after 46 hours of conditioning the gun successfully reached 450 kV (see Fig. 3). Gun demonstrated stable operation at 450

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kV during 7 hours with very little radiation (see Fig 4.) The two bottom plots show radiation measured by different instruments, radiation level stays at 10-20 mR/hr).

FIRST PHOTOCURRENT FROM DC GUN

The gun to booster beam line includes two solenoids, H/V correctors, laser insertion and extraction ports, beam profile monitor (PM), and two beam position monitors (BPM) (see Fig. 5).

Temporary line presented at Fig. 2, consists of: ERL type solenoid, H/V corrector, beam position monitors (BPMs), fast current transformer (FCT).

Rest of the DC gun test transport line consists of: two ERL solenoids, two H/V correctors, three BPMs, integrated current transformer (ICT), direct current transformer (DCCT), multi-slits, and PM. Straight ahead line is terminated by Faraday cup (FC) at the end. This line is used for current control and transverse emittance measurements (for LEReC beam instrumentation details see [8, 9]).

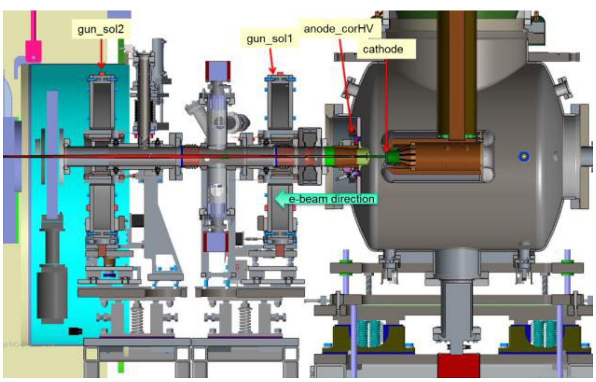

Figure 5: LEReC gun area side view.

1st cathode surface has been scratched during transportation from cathode deposition system to the gun (see Fig. 6). Initial without high power pulsed laser these clear straight lines helped to check first two solenoids calibration using photoelectrons generated by cathode illumination LED lamp. Lines rotation angle: $\varphi = \int Bz(z)dz/2B\rho$, where *Bz(z)*-longitudinal solenoid field, $B\rho$ – beam rigidity (see Fig. 7). As a result for different current we confirmed gun energy and solenoid field integral calibration.

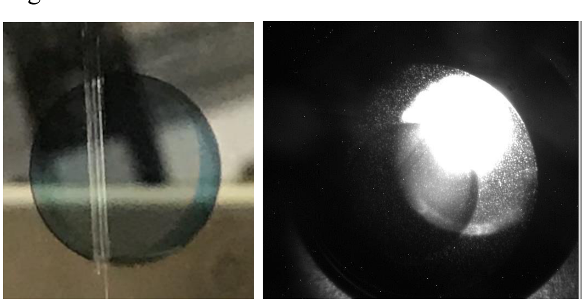

Figure 6: First cathode with scratch marks used in the DC gun test: (left) before installation, (right) cathode installed in the gun.

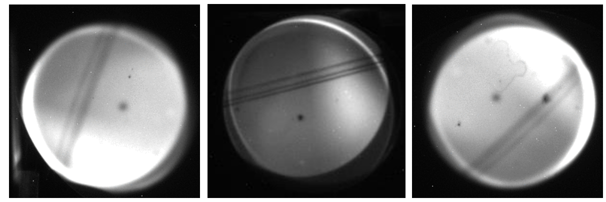

Figure 7: Beam images (DC "lamp current") are taken at YaG beam profile monitor for three different solenoid current settings.

Results of all three cathodes tested during DC gun test are summarized in Table 2 (for more details about LEReC cathodes see [10]).

Table 2: LEReC cathodes operations summary

	Cath #1	Cath #2b	Cath #3
Operation dates	Apr 17-June 2	June 2 – June 14	June 16-current
Lamp DC	40 nA	40 nA	150 nA
Max. charge	25 pC	33 pC	130 pC
In Lab QE	1.7%	7%	4%
In Gun QE	0.1%	0.3%	1.2%

Lamp DC beam produced by illumination of LED flash light has been used for initial commissioning and beam based calibration of faraday cups, halo scrapers and profile monitors. Rest of the beam instrumentation required bunched beam.

BEAM DUMP LINE

Beam dump extraction line consists of 45-degrees chevron dipole, two ERL quadrupoles with trims (one horizontal, one vertical correction), BPM, PM, 2D halo monitor, and fast current transformer (FCT). Inclined beam line is terminated by 10 kW beam dump that also serves as a Faraday cup. The inclined line will be used for beam energy and energy spread measurements, transverse and longitudinal halo studies.

The beam dump is cooled from top and bottom by water circulation. The sides are cooled only by copper thermo-conductivity. For optimum cooling, the electron beam will be spread more in the vertical direction. The beam profile monitor is used to match the electron beam with the aperture of the beam dump. At high beam current BPMs provide an interlock if the beam trajectory is out of a predefined range of offsets (for LEReC machine protection system details see [11]). A second protection method uses four sets of slightly inserted halo monitors. These monitors measure very small current deposition on any of the four beam dump jaws in order to detect any beam profile changes.

BUNCHED BEAM OPERATION

LEReC operation required to chop 704 MHz laser pulses into macro bunches with 106 nsec apart. Operation with macro bunches from single to few hundreds has been tested (see Fig. 8 and Fig. 9).

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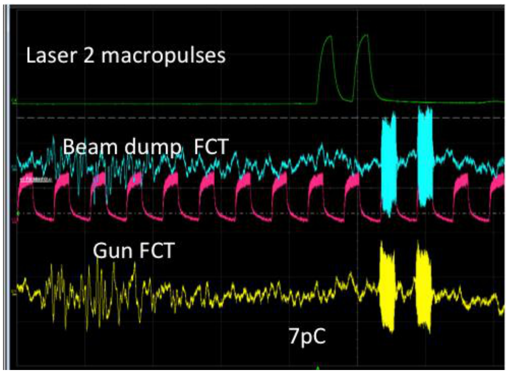

Figure 8: First pulsed beam observed during 2 macro bunch operations. Charged per bunch measured 7 pC by gun FCT (cyan) and beam dump FCT (yellow).

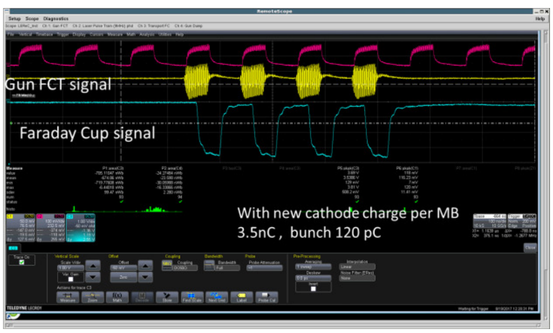

Figure 9: Charge per bunch reached minimum LEReC design requirement 120 pC. Cyan trace is beam dump faraday signal 4 macro bunches 30 bunches each.

As expected for train of several hundreds of macro bunches gun voltage dropped due to beam loading which has been clearly observed at beam dump line BPM and FCT signals. This is a result of large time constant of currently installed 100 MOhm processing resistor and estimated cathode capacitance of 75 pF (time constant 7.5 msec). 1 nC charge per macro bunch leads to gun voltage dropped by 13 V.

For 500 macro bunches train DC gun voltage and as result energy of the last macro bunch drops by 6.7 keV. On Fig. 10 it's shown how average bunch position moved in dispersive section when numbers of macro bunches increase.

Beam loss increases in beam dump line (see Fig. 11). Currently gun beam loading prevents us to run more total charge per second.

After replacing processing resistor to regular one with resistance of 400 Ohm and corresponding time constant of 30 nsec we expect that the effect of accumulated beam loading will be diminished.

BEAM LINE MAGNETIC SHIELDING

The energy of the electrons leaving the gun is ~400 keV. In tunnel measured residual field is in order of 0.5 Gauss (Earth's magnetic field) in 1 m will bend the beam to 20 mrad. The beam shift could be on the order of 1 cm. After 2 m of drift space, the beam would be lost on the minimum aperture of the vacuum chamber. On the bench test confirmed that 3 layers of 9 mils of μ-metal foil wrapped around the vacuum chamber diameter of 7.5 cm sufficient to reduce field more than 50 times (see Fig. 12). The same magnetic shielding has been installed everywhere at any open areas along DC gun beam line.

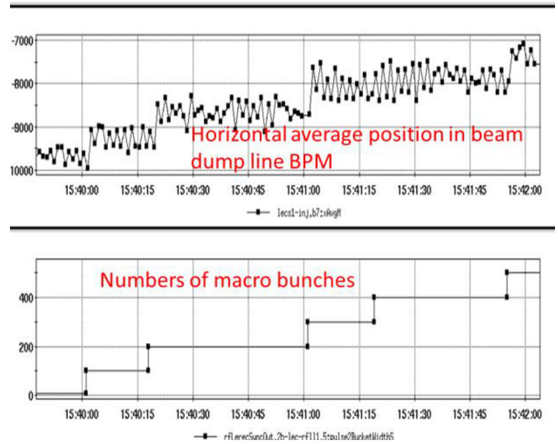

Figure 10: 100-500 macro bunches operation with 1 nC per macro bunch: (top) horizontal beam position in dispersive beam dump line, (bottom) numbers of macro bunches.

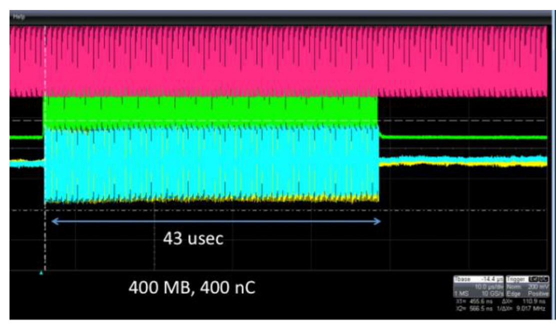

Figure 11: Gun FCT signal (yellow) and beam dump FCT signal (cyan) during 400 Macro bunches operation.

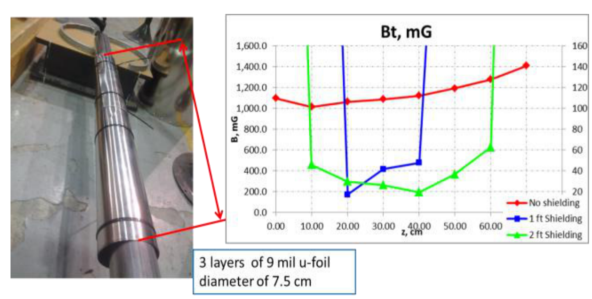

Figure 12: Transport line magnetic shielding test on the bench (left). Measured magnetic field (right). Without shielding 1.2-1.4 Gauss (left scale) with shielding 20-40 mGauss (right scale).

BEAM CURRENT RAMP UP

Space charge effect plays significant role to beam dynamics at low energy. In order to increase average current preferable scenario is to keep charge per bunch constant while increasing numbers of macro-bunches. Currently our laser bunch structure control system is

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capable to provide continuous increase numbers of macro-bunches up to 50 msec train duration. Work has been started to develop and test system which is capable to increase numbers of macro bunches from 1 to CW. Such system is required for LEReC commissioning which scheduled to start in spring of 2018.

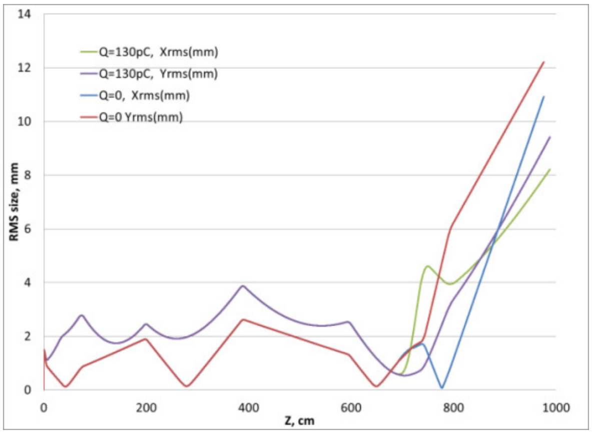

Figure 13: RMS beam envelope in the gun test beam line for nominal charge of 130 pC and very small charge of 0.13 pC.

Alternative could be increasing charge per bunch while keep pulse pattern untouched. As a results beam envelope will vary with space charge. For example on Fig. 13 we show RMS envelopes from gun to dump as a result of PARMELA [12] simulation with nominal charge per bunch and with significant low charge per bunch. Due to simplicity of the beam line and relatively weak optics in both cases beam reaches the beam dump while RMS transvers size stays below 4 mm in transport line. The slow increasing laser power seems to be good alternative to ramp up current during DC gun test.

Table 3: LEReC DC Gun beam test parameters

Parameter	Required	Achieved
Gun voltage , kV	400	400
Bunch charge, pC	130-200	0-130
Laser max frequency, MHz	704	704
Laser pulse duration, psec	80	80
Macro-bunch charge, nC	3-5	3.9
Macro-bunch rep. rate, MHz	9.3	9.3
Macro bunches per sec	CW	1400
Normalized emittance, µm	1-1.5	0.2-4*
Maximum average power, kW	10	0.0004

*) Preliminary results.

SUMMARY AND PLANS

To reduce risk and time required for LEReC systems commissioning we start testing the DC gun photo injector during RHIC Run 17.

Gun test is designed to provide initial studies of DC gun performance and test key concepts for LEReC commissioning: MPS operation, cathode delivery system, laser system, high average current capability etc.

The beam line optics is flexible enough to accommodate running gun with different charges required for final stage of LEReC operation.

Bunch with designed beam kinetic energy of 400keV and charges of 0-130 pC has been successfully delivered to the 10 kW beam dump. Measured beam parameters during gun test are summarized in Table 3.

Beam instrumentation has been tested and cross calibrated.

Maximum numbers of pulses has been limited by beam loaded voltage drop due to very long current replenishment constant. After replacing processing resistor in July 2017 we will continue increasing numbers of macro bunches and study CW operation of the HV DC gun photo injector.

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