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LEReC PHOTOCATHODE DC GUN BEAM TEST RESULTS *

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Abstract

Low Energy RHIC Electron cooler (LEReC) project is presently under commissioning at Brookhaven National Laboratory (BNL). LEReC requires high average current up to 85mA and high-quality electron beam [1]. A 400 kV DC gun equipped with a photocathode and laser system has been chosen to provide a source of high-quality electron beams. We started testing the DC gun during the RHIC run 2017. First electron beam from LEReC DC gun was delivered in April 2017 [2]. During the 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 have been tested. Average current of 10 mA for few hours of operation was reached in August 2017. In this paper we present experimental results and experience learned during the LEReC DC gun beam testing.

PURPOSE OF LEReC GUN TEST

The gun beam test (see Fig. 1) is the first stage of LEReC commissioning. Our aim is to test critical LEReC equipment in close to operation condition. DC gun test will demonstrate that the DC gun with photocathode meets its performance specifications and can work reliably.

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 can 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]. 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 beam dump system.

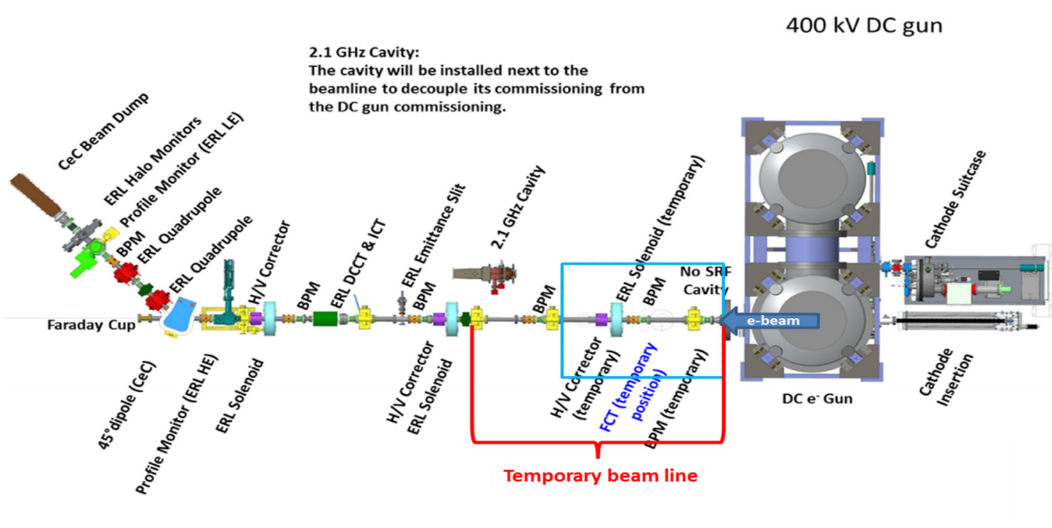

Figure 1: LEReC DC gun beam test layout. 2.1 GHz 3rd harmonic cavity (testing aside of DC gun test beam line) and 704MHz SRF cavities (shown as a blue box contour) will be installed in replacement of temporary beam line after gun test is finished in fall of 2017.

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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). In November 2016 after 46 hours of conditioning the gun successfully reached 450 kV [5]. Gun demonstrated stable operation at 450 kV during 7 hours with very little radiation 10-20 mR/hr.

FIRST PHOTOCURRENT FROM DC GUN

For details about DC gun test optics and beam line components please see [2, 5]. For LEReC beam instrumentation details see [6] and for MPS see [7].

The first cathode surface has been scratched during transportation from cathode deposition system to the gun (see Fig. 2). 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. 3).

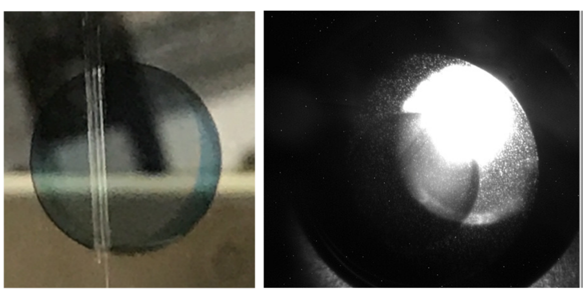

Figure 2: First cathode with scratch marks used in the DC gun test: (left) before installation, (right) cathode installed in the gun.

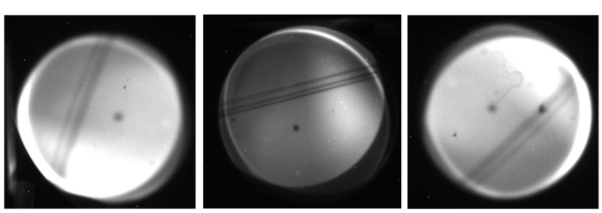

Figure 3: Beam images (DC "lamp current") are taken at YaG beam profile monitor for three different solenoid current settings.

Table 1: LEReC Cathodes Operations Summary

Cath#	1	#2b	#3	#4
Material	Na_2KSb	Na_2KSb	Na_2KSb	Cs_2KSb
Operation dates	Apr 17-Jun 2	Jun 2 – Jun 14	Jun 16-Jun 30	Jul 20-Aug 11
Lamp DC	40 nA	40 nA	150 nA	72 nA
Max. charge	25 pC	33 pC	130 pC	50 pC
In Lab QE	1.7%	7%	4%	5%
In Gun QE	0.1%	0.3%	1.2%	0.7%

Results of all four cathodes tested during DC gun test are summarized in Table 1 (for more details about LEReC cathodes see [8]). The last cathode #4 was used during CW operation generating 10 mA average beam current.

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.

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 (see Fig. 4) to few hundreds has been tested

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 initially used 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.

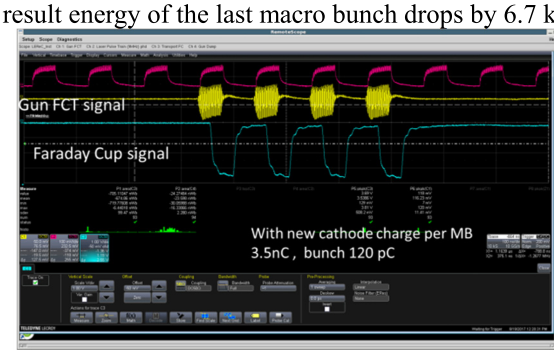

Figure 4: Charge per bunch reached minimum LEReC design requirement 120 pC. Cyan trace is beam dump faraday signal 4 macro bunches 30 of 704 MHz bunches each.

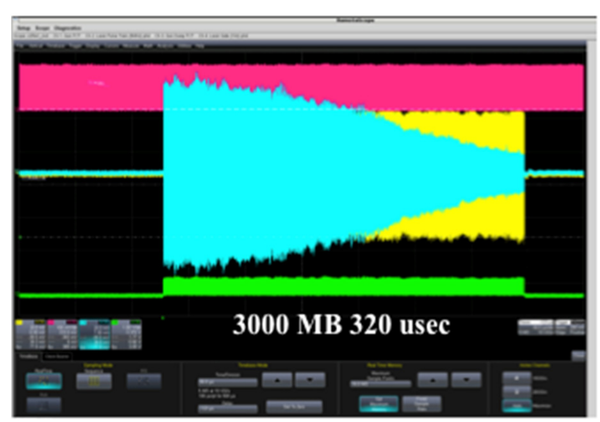

Figure 5: Gun FCT signal (yellow) and beam dump FCT signal (cyan) during 3000 Macro bunches operation.

With increasing numbers of macro-bunches the beam loss increases in beam dump line and can be clearly observed by beam dump FCT signal declining along the macro-bunch train (see Fig. 5). To avoid voltage drop from long trains we replaced 100 MOhm processing resistor to running resistor of 400 Ohm.

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LONG TRAINS AND CW OPERATION

With running resistor we increased length of macro bunches train to 15 msec using 150 thousand macro-bunches. We observed the gun voltage drop due to initial transient is still significant (see Fig. 6). The measured present power supply voltage regulation bandwidth is too low. For commissioning of RF cavities which have their own transients we want to go up to 0.5 ms long bunch trains with fast voltage regulation (>3kHz). For CW operation it requires to ramp up current with small steps.

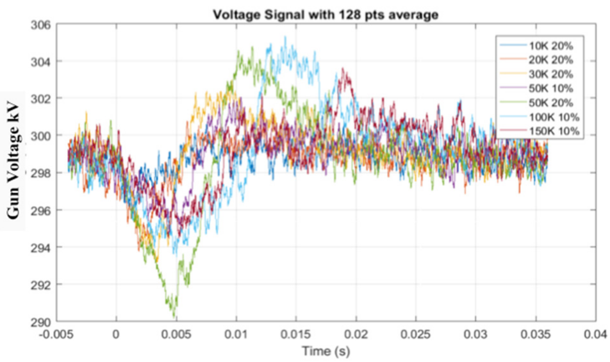

Figure 6: High voltage responses to trains of macro-bunches (MB) of different durations.

Laser system and MPS have been switched in to CW mode of operation. In August 1, 2017 we first time run CW. At the end of the Gun test on August 10, 2017 beam current of 10 mA has been delivered to gun beam dump using 704 MHz CW mode of laser operation (see Fig. 7).

SUMMARY

To reduce risk and time required for LEReC systems commissioning we tested the DC gun with photocathodes during RHIC Run 17.

All major goals of DC Gun test were achieved. CW operation was tested both at 9 MHz macro-bunch structure and at 704 MHz. CW beam current of 10 mA and kinetic energy 300 kV has been delivered to the gun test beam dump. Beam instrumentation and MPS are commissioned and calibrated both for pulsed and CW mode of operation. Cathode delivery-exchange system has been tested.

Sseveral issues, which limited of maximum average current, have been found and it has been addressed

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

Measured beam parameters during gun test are summarized in Table 2.

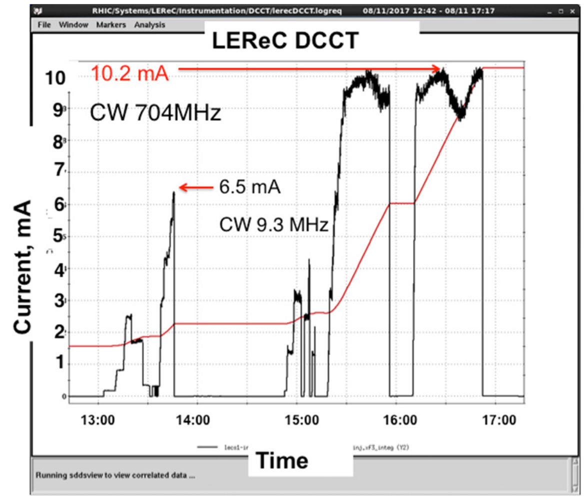

Figure 7: Beam current (black) measured by DCCT during CW operation with 9.4 MHz modulation up to 6.5 mA then ramp up to 10 mA 704MHz CW.

Table 2: LEReC and DC Gun Beam Test Parameters

Parameter	LEReC	Test Designed	Measured
Max. Kinetic Energy, MeV	2.6	0.4	0.4
Gun voltage, kV	400	400	400
Max. Bunch charge, pC	200	200	130
Laser max frequency, MHz	704	704	704
Laser pulse duration, psec	80	80	80
Macro-bunch charge, nC	3-5	3-5	3.9
Macrobunch rep. rate, MHz	9.3	9.3	9.3
Max. Average current, mA	45	25	10
Normalized emittance, µm	<2.5	<2.5	0.2-4
Max. average power, kW	150	10	3

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