BEAM COMMISSIONING RESULTS FROM THE R&D ERL AT BNL*

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Abstract

BNL R&D ERL beam commissioning started in June 2014 [1]. The key components of R&D ERL are the highly damped 5-cell 704 MHz superconducting RF cavity and the high-current superconducting RF gun. The gun is equipped with a multi-alkaline photocathode insertion system. The first photocurrent from ERL SRF gun has been observed in November 2014. In June 2015 a high charge 0.5 nC and 20 uA average current were demonstrated [2]. In July 2015 gun to dump beam test started. The beam was successfully transported from the SRF gun through the injection system, then through the linac to the beam dump. All ERL components have been installed. In October 2015, SRF gun cavity has been found contaminated during severe cathode stalk RF conditioning. This cavity has been sent for repair and modification for later use in low-energy RHIC electron cooler (LEReC). LEReC scheduled to start commissioning in early of 2018 [3]. We present our results of BNL ERL beam commissioning, the measured beam properties, the operational status, and future prospects.

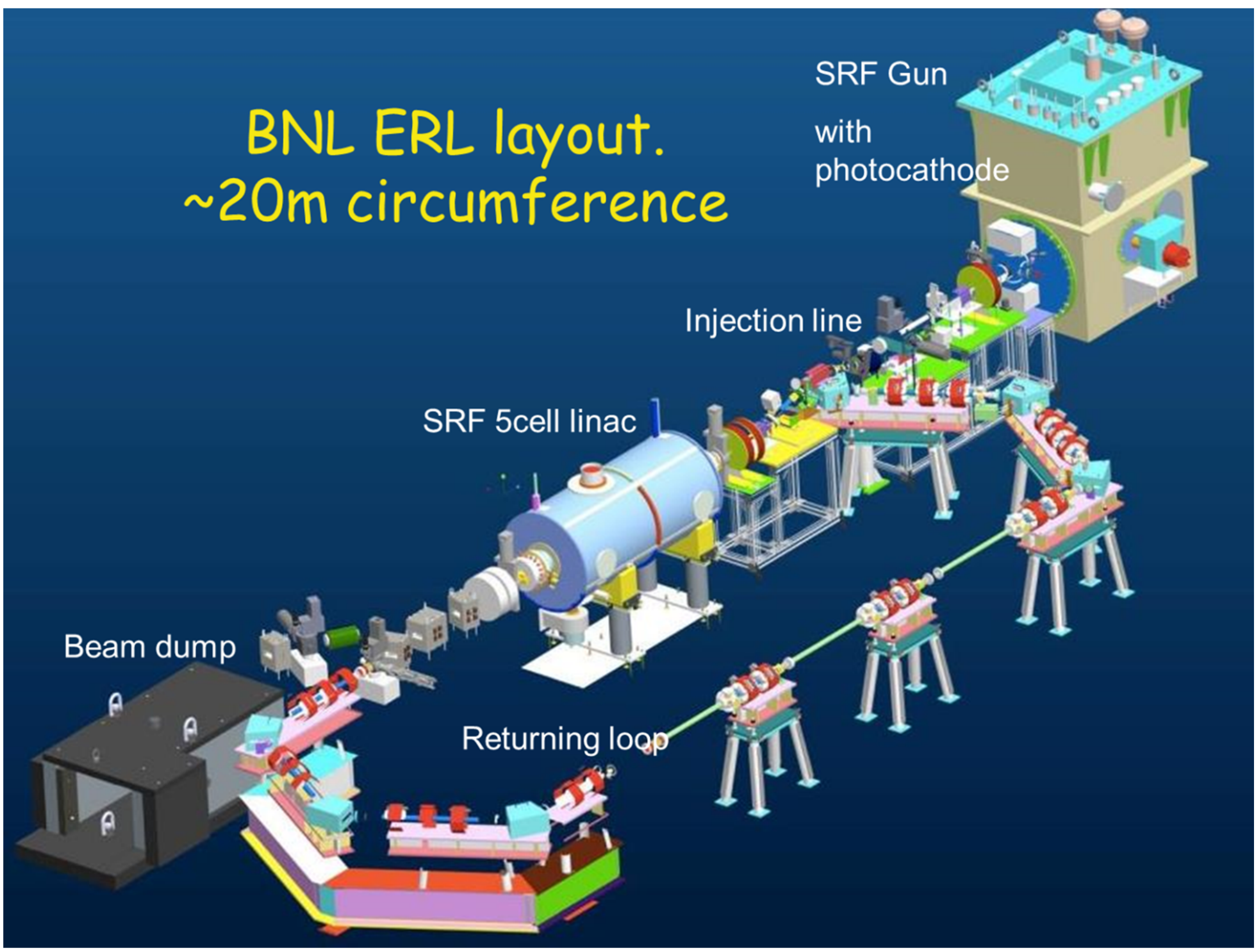

Figure 1: Schematic layout of the R&D ERL at BNL.

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INTRODUCTION

The ERL installation has been completed in one of the spacious bays in Bldg. 912 of the RHIC/AGS complex [4]. The R&D ERL designed to test many generic issues relevant with ultra-high current continuously operation ERLs: 1) SRF photo-injector (704 MHz SRF Gun, photocathode, laser) [5-6] 2) preservation of low emittance for high-charge, bunches in ERL merger [7]; 3) high current 5-cell SRF linac with efficient HOM absorbers [8]; 4) BBU studies using flexible optics; 5) stability criteria of amp class CW beams. BNL ERL design has one re-circulating loop with achromatic flexible optics [9].

ERL schematic layout is shown on Fig. 1. Electrons are generated and accelerated in superconducting half-cell gun to 1-2 MeV. Then electrons are injected into the ERL loop through the merging system, which incorporate emittance compensation scheme. The SRF linac accelerates electrons up to 20 MeV. Accelerated electron beam passes through two achromatic arcs and a straight section between them, and returns to the same linac. The path-length of the loop provides for 180 degrees change of the RF phase, causing electron deceleration in the linac (hence the energy recovery) down to injection energy. Decelerated beam is separated from the higher energy beam and is directed to the beam-dump.

BEAM COMMISIONING STAGING

We are commissioning system by system as it becomes available since 2009 [10].

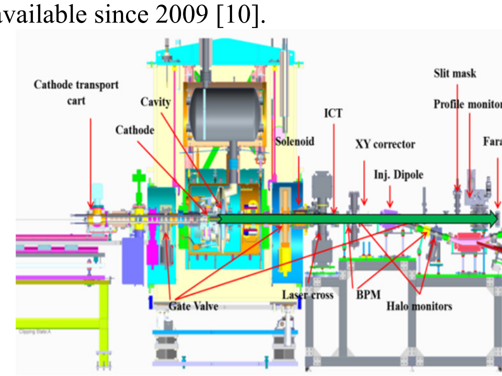

Figure 2: Schematic layout of the SRF gun beam test.

The first beam test setup is shown on Fig. 2. The ERL injection dipole is off during first beam test. The current coming from the gun goes straight to the faraday cup where current can be measured. Steering magnet is installed next to the laser cross. The beam profile monitor (YAG crystal) can be inserted before the faraday cup to measure beam size.

Beam commissioning has been started in June 2014. During the first beam test only dark has been observed. Initial dark current with cathode inserted at SRF gun gradient 16 MV/m measured 1.7 μA. Gun with cathode has been conditioned to reduce dark current level below 0.1 μA (See Fig. 3). The beam energy measurements have been performed. The measurements results are in good agreement with RF voltage pick up calibration of SRF gun. Photocurrent has not been observed during first attempt most likely due to QE degradation during cathode transportation and/or strong multipacting in choke join during intensive SRF gun with cathode conditioning.

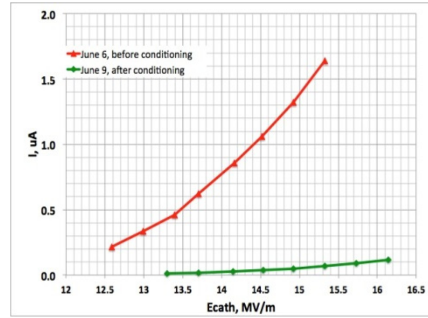

Figure 3: Dark current vs RF field gradient at the cathode. Measurements have been carryout before and after conditioning of SRF gun with cathode inserted in June 2014.

Next Cs_3Sb photocathode has been deposited with QE 0.25% measured in deposition chamber using laser wavelength 552 nm. During second beam test in November 2014 first photocurrent from ERL SRF gun has been generated and some beam parameters have been measured [11]. We were able to run SRF gun with 50% duty cycle (500msec every sec). With maximum available laser power 4W we were able to extract 7.7 pC measured by integrated current transformer (ICT) charge per bunch. We reached average current during RF pulse 1 μA measured by Faraday Cup (FC). Dark current measured at gun voltage 1.2 MV 28 nA (See Fig. 4).

Figure 4: Faraday cup (1 MOhm) signal during the first beam test SRF 704 MHz SRF Gun. (Top: laser shutter closed dark current 38 nA. Bottom: laser shutter open photocurrent during RF pulse 1.09 uA).

During cathode stalk transfer to the gun QE significantly degraded. Additional QE reduction has been observed when cathode has been used at liquid nitrogen temperature. In cold gun cathode QE is measured 2.7e-5.

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New cathode stalk with Ta tip has been fabricated [12]. We tested 3.8% QE K2CsSb cathode in the 704MHz SRF gun. The cathode survives well during the gun and stalk RF conditioning. The maximum cathode QE inside the gun (cold) measured 1%. We didn't see any QE degradation after two days of high bunch charge operation. The vacuum at the gun exit is at 10^{-9} scale during gun operation. After extracting the measured QE at room temperature is still 3.8% [13] (see Fig. 5).

During the beam tests bunch charge was measured by FC and ICT. Both measurements agreed (Fig. 6).

With initial laser spot size at the photocathode of 2 mm FWHM, we observed saturation of the extracted charge per bunch at 200 pC. Increasing spot size up to 4 mm allows us to extract more charge with the same gun voltage. With new photocathode 550 pC charge per pulse has been achieved (see Fig. 7).

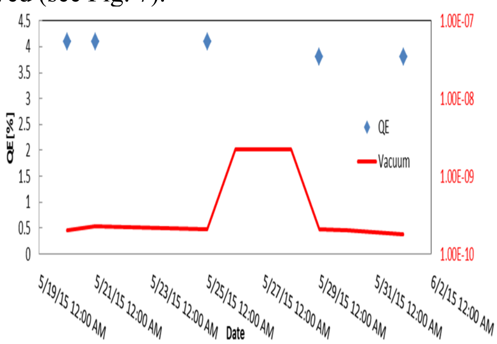

Figure 5: QE (blue diamonds) of K2CsSb cathode deposited to the new cathode stalk and vacuum (red trace) measured at room temperature before beam test 4% and after beam test 3.8%.

Figure 6: Straight beam line with beam diagnostics components (top). Dark current (slop) and photocurrent (spikes) measured one faraday cup (left bottom). Cross calibration charge measurements at ICT (right bottom).

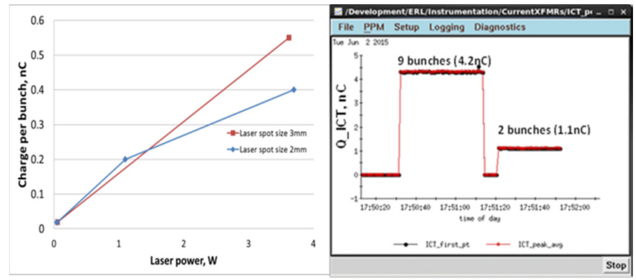

Figure 7: Charge per pulse measurements. At left: charge vs laser power. Due to space charge limitation some saturation has been observed at high average laser power (blue diamonds). Laser spot size has been increased to reach 550 pC per bunch (red square). At right: ICT signal during high charge operation of 704 MHz SRF gun. Maximum charge per one bunch Q=550 pC.

ASTIGMATISM AND EMITTANCE MEASUREMENTS

Instrumentation beam line equipped with beam profile monitors YAG crystal. Several attempts have been made in order to measure emittance. The straight line is axial symmetric system except RF fundamental power couplers (FPC). During solenoid scan very strong astigmatism has been observed (see Fig. 8).

Based on these measurements we suspect that there is strong quadruple focusing in the system. One of the suspects is FPC. This required further investigation. For rough emittance measurements we used solenoid scan (see Fig. 9).

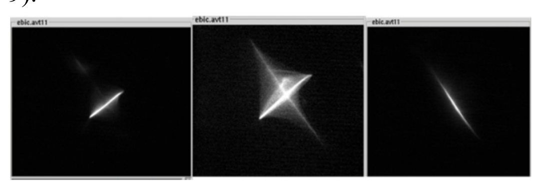

Figure 8: Beam image at beam profile monitor located before faraday cup for three different solenoid settings.

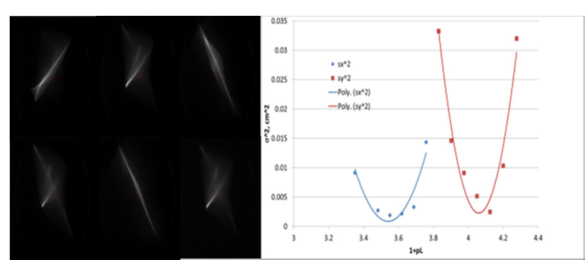

Figure 9: Solenoid scan for 130 pC charge per bunch. 1) Beam images during solenoid scan. 2) Beam profile parabola fits. Normalized emittance vert./horiz. 3.5/2.5 µm.

BEAM FOR RADIATION STUDIES

In order to continue the commissioning of the rest of the ERL systems we had to carry out set of fault studies to confirm that ERL block house shielding satisfies radiation safety committee requirement. Laser power has been reduced while macro-pulse length has been increase to

4 msec in order to match with maximum available RF pulse length 5 msec (see Fig. 10). The highest average current 22 uA from SRF gun has been achieved (see Fig. 12).

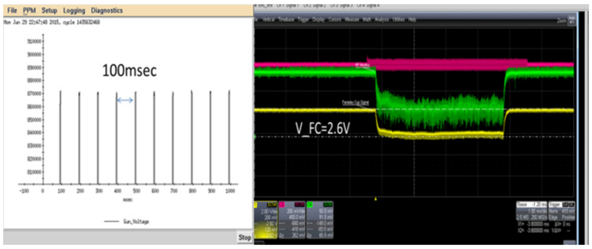

Figure 10: Beam time structure during fault studies.1) RF pulses structure 5 msec, 10 Hz (left). 2) Closed look at one single RF pulse (right): 5 msec (magenta), laser pulses 4 msec (green) and faraday cup signal 4 msec (yellow).

In order to measure current more than 5 uA 10 kOhm termination has been installed at scope. As a result 260 uA in pulse at FC has been measured. With duty cycle 4% corresponds to 10.4 uA average current at beam dump. Beam with average power in order to 10 Watts has been provided for radiation survey to FC. The flange has been warmed up to 3 ºC per 30 minutes.

Maximum average current and charge per 5 µsec from the gun during fault studies measured by ICT and pulse counter (see Fig. 11.).

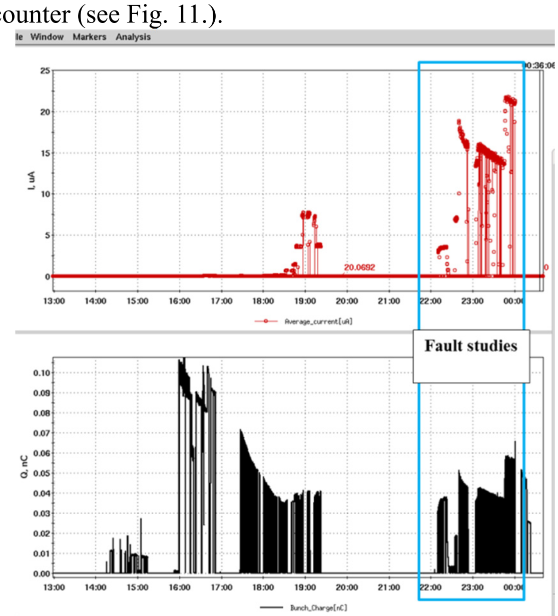

Figure 11: Average current (top) and charge per bunch (bottom) ICT measured after the gun during fault studies. Maximum average current from gun 22 uA.

The results of these studies allowed us to receive DOE approval for full power gun-to-dump test commissioning in July 2015.

CATHODE LIFE TIME

Due to limitation of liquid He supply the cathode stalk has to be retracted from the gun at the end of each beam test day and inserted before next beam test. After the first week of beam tests cathode QE drops from 1% to 0.4% (Fig. 12). Applying some heat to the cathode tip outside the gun helped to recover cathode quality July 5. However, this procedure leads to additional time spend for conditioning stalk inside the gun at liquid He temperature. We decided to stop heating up cathode tip and used cathode as is. After that cathode QE stayed relatively stable at level of 4e-4 (at LN2 temperature) after each cathode insertion to the gun.

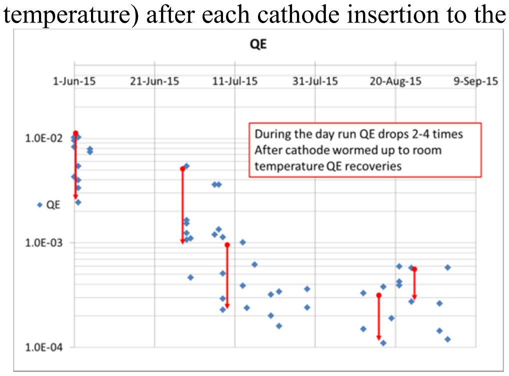

Figure 12: LN2 Photocathode QE measured inside the SRF gun at the beginning and at the end of each beam test day.

GUN TO DUMP BEAM COMMISSIONING

Next stage of ERL commissioning is to transport beam through ERL injection system, 5 cell cavity linac, extraction system then to the beam dump. Schematic of gun to dump commissioning stage is shown in Fig. 14.

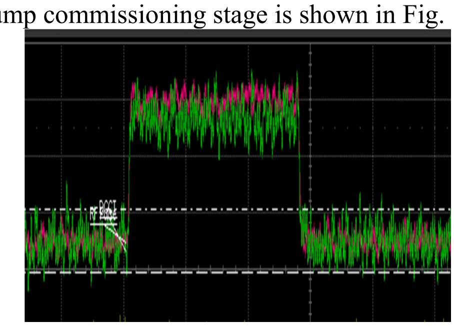

Figure 13: Beam current measured by injection line DCCT (magenta) and by extraction line DCCT (green). 90% transport efficiency has been achieved.

During the gun to dump stage of ERL commissioning 5cell cavity stays off. Two DCCTs (Fig. 13) and beam dump measure beam transport efficiency at three locations: injection line, extraction line, and the beam dump.

During gun to dump beam tests we continued commissioning and calibration of beam instrumentation: beam position monitors (BPM), DCCTs, and beam loss monitor (BLM) system. These systems are essential for successful MPS operation [14].

Measured beam parameters during ERL low energy beam commissioning are summarized in Table 1.

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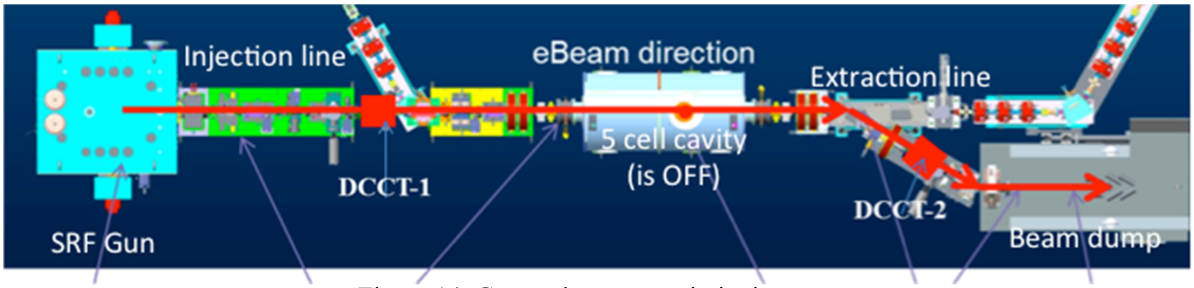

Figure 14: Gun to dump commissioning set up.

Table 1: Measured Beam Parameters

Parameter	Measured*
Max. Kinetic Energy	1.2 MeV
Charge per bunch	0.55 nC
Current	20 μA
Laser Rep. Rate	9.38 MHz
Laser Bunch Length	8.5, 22 ps
Norm. emittance	2.5/3.5 μm**
Beam dump Power	10 W (@FC)

*Listed parameters have been achieved in different modes of operation.

**Preliminary results.

ICT CERAMIC CHARGE DISCHARGE OBSERVATION

During commission significant jumps of trajectory (Fig. 15) and propagation transparency have been observed. We suspect that ICT, DCCTs ceramic breaks are slow charged by halo or dark current and then sudden discharge. These process leads to very unreliable operation. The shielding for each ceramic break location has been designed it will be implemented where these elements are used in LEReC.

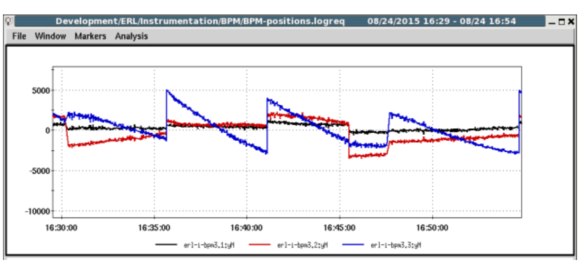

Figure 15: Trajectory drifts and jumps at BPM signals.

SUMMARY AND PLANS

All ERL components have been installed by May 2015.

The first test with “multipacting-free” Ta tip cathode took place in June, 2015. The highest charge from SRF gun .55 nC has been achieved. Max average current from this gun 22 uA has been demonstrated.

Beam has been propagated from the gun to beam dump with SRF linac off. 90% injection to extraction current transparency routinely has been achieved.

Cathode with QE 4e-4 level allowed to commissioning ERL systems with bunch charge 30-50 pC.

During first 3 month of beam commissioning we were able to test and cross calibrate most of the beam diagnostics which will be used for the next project LEReC.

LEReC will use SRF gun as a booster cavity without cathode inserted. The booster needs to operate CW at 2.2 MV of voltage. In 2013 this cavity has been commissioning for such operation. However after beam tests it was discovered that the cavity can run only at 1.6 MV of voltage. Cavity was opened and copper marks have been observed at niobium part of chock join. Presumably cavity has been contaminated during severe cathode stalk RF conditioning. This gun as a booster cavity needs to be install for LEReC commissioning in summer of 2017. In summer of 2016 cavity has been sent for cleaning and testing.

Future beam tests are planned to resume when LEReC components is installed and relocated to RHIC IP2 at the end of 2017.

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