

STATUS AND COMMISSIONING RESULTS OF THE R&D ERL AT BNL*

D. Kayran^{#,1,2}, Z. Altinbas¹, D. Beavis¹, S. Belomestnykh^{1,2}, I. Ben-Zvi^{1,2}, S. Deonarine¹,
 D. M. Gassner¹, R. C. Gupta¹, H. Hahn¹, L. R. Hammons^{1,2}, Chung Ho¹, J. Jamilkowski¹,
 P. Kankiya¹, N. Laloudakis¹, R. Lambiase¹, V.N. Litvinenko^{1,2}, G. Mahler¹, L. Masi¹, G. McIntyre¹,
 T. A. Miller¹, J. Morris¹, D. Phillips¹, V. Ptitsyn^{1,2}, T. Seda¹, B. Sheehy¹, L. Smart¹, K. Smith¹,
 T. Srinivasan-Rao¹, A.N.Steszyn¹, T. R. Than¹, E. Wang¹, D. Weiss¹, Huamu Xie¹, Wencan Xu¹,
 A.Zaltsman¹

1) Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973, USA

2) Physics & Astronomy Department, Stony Brook University, Stony Brook, NY 11794, USA

Abstract

An ampere class 20 MeV superconducting Energy Recovery Linac (ERL) is presently under commissioning at Brookhaven National Laboratory (BNL) for testing of concepts relevant for high-energy coherent electron cooling and electron-ion colliders [1]. The injector subsystems tests and installation were finished in fall 2013. The injector includes: SRF photoelectron gun with 1 MW amplifier, 10W green drive-laser system, multi-alkaline cathode deposition system, cathode transport system, beam instrumentation and control. First beam test conducted in June 2014 only dark current observed during first beam test [2]. The first photo current from ERL SRF gun has been observed in fall 2014 after second attempt [3]. The ERL returning loop components installed. New cathode with Ta tip conditioned. QE 4% observed. Bunch charge 0.55 nC achieved with new cathode. After ERL commissioning in BLDG 912 the ERL will be relocated to RHIC IP2 to be used for LEReC.

INTRODUCTION

The R&D ERL facility at BNL aims to demonstrate CW operation of ERL with average beam current up to 0.3 ampere, combined with very high efficiency of energy recovery. The ERL is being installed in one of the spacious bays in Bldg. 912 of the RHIC/AGS complex. The intensive R&D program geared towards the construction of the prototype ERL is under way [4]: from development of high efficiency photo-cathodes [5], design, construction and commissioning SRF gun [6], to the development of new merging system compatible with emittance compensation technic [7]. The R&D ERL will test many generic issues relevant with ultra-high current continuously operation ERLs: 1) SRF photo-injector (704 MHz SRF Gun, photocathode, laser) capable of 300 mA; 2) preservation of low emittance for high-charge, bunches in ERL merger; 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]. 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.

Two operating modes will be investigated, namely the high current mode and the high charge mode. Beam parameters for each mode and recent tests results summarized at Table 1.

Table 1: ERL Beam Parameters

| Parameter | High Charge | High Current | Measured |
|--------------------|-------------|--------------|--------------------|
| Gun energy | 3 MeV | 2.5 MeV | 1.4 MeV |
| Max. Energy | 20 MeV | 20 MeV | 1.4 MeV |
| Charge per bunch | 5 nC | 0.5 nC | 0.55 nC |
| Current | 50 mA | 350 mA | 6 μ A |
| Laser Rep. Rate | 9.38 MHz | 350 MHz | 9.38 MHz* |
| Laser Bunch Length | 30 ps | 8-20 ps | 8.5, 22 ps |
| Norm. emittance | 5 μ m | 1.4 μ m | 12 / .25 μ m** |
| Energy spread | 1% | 0.35% | |
| Beam dump Power | 150 kW | 875 kW | 8 W (@FC) |

*) 5 μ sec train every 500 μ sec.

**) Full beam rms /20% core, preliminary results.

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 #dkayran@bnl.gov

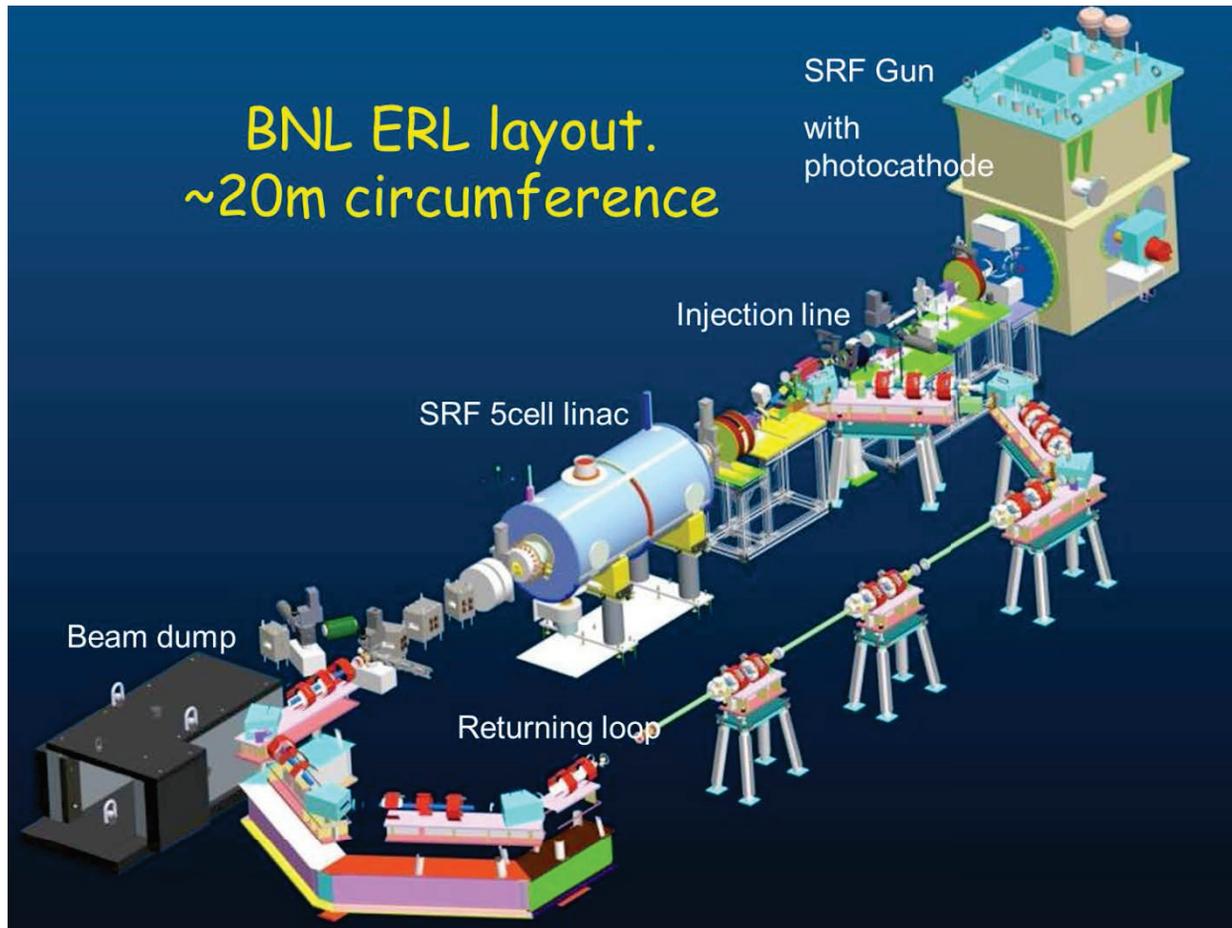


Figure 1: Schematic layout of the R&D ERL at BNL.

In the high current (0.3 A) mode ERL will accelerate electron 0.5 nC per bunch with 703 MHz rep-rate. In this case the energy gain of electrons at gun exit is limited to 2.0 MeV by the available RF CW klystron power of 1 MW. In the high charge mode, ERL will have electron beam with 5 nC per bunch and 10 MHz repetition rate, i.e. it will produce 50 mA average current. In this mode, the electrons energy at the gun exit could be pushed higher. The maximum voltage at the gun is 2.5 MV limited by power coupling design and available RF power.

SRF COMPONENTS

The most important element of BNL ERL is SRF photo-injector. BNL 704 MHz SRF gun has been designed with a short 8.5 cm cell. The short length was chosen to provide high electric field at the cathode at low accelerating voltage. In order to provide effective damping of high order mode (HOM) this gun has rather large iris radius of 5 cm. Ferrite dumpers are installed around ceramic break at the exit of the gun. Gun has been installed at ERL in 2012. SRF gun now routinely operates CW without the cathode at 2 MV accelerating voltage.

With new cathode stalk installed the gun operated at 1.25 MV [10] with good vacuum and no radiation. (See Fig. 2)

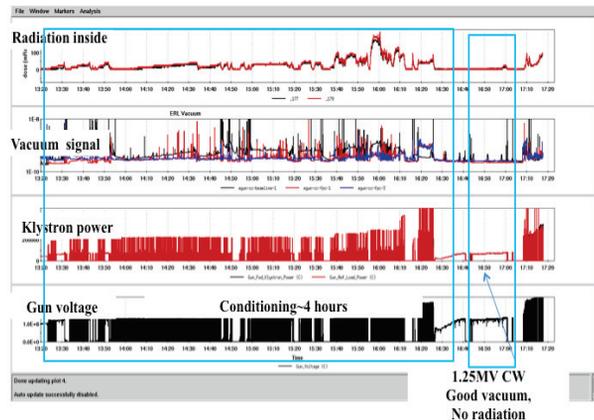


Figure 2: ERL 704MHz SRF gun performance during conditioning and CW operation with new cathode stalk. From top to bottom: radiation, beam-line vacuum, klystron power and gun voltage signals.

The heart of the ERL facility is 5-cell 704MHz SRF linac, which is designed for operating with ampere-class CW beam current [8]. The cavity was designed as a “single-mode” cavity, in which all Higher Order Modes (HOMs) propagate to HOM ferrite absorbers through the large beam pipe. This design provides for very low Q’s for HOMs and hence very high ERL stability.

Measurements of the damped Q and R/Q of the HOMs and simulations show that in nominal operation regime the cavity is stable to over 20 amperes in a one pass ERL and over 2 amperes for two passes ERL. The 5cell cavity has been commissioned in 2010. In cold emission tests high gradients are achieved for short period of time (as shown in Fig. 3).

A thermal problem has been discovered during commissioning SRF 5-cell cavity, which prevents CW operation at gradients above 12 MV/m. However, the prototype program can still be pursued if the cavity can be operated in a pulsed “quasi-cw” mode up to 20 MV/m, in which the cavity is on, with stable gradient, for a time long compared with the transit time through the ERL loop (10 nsec).

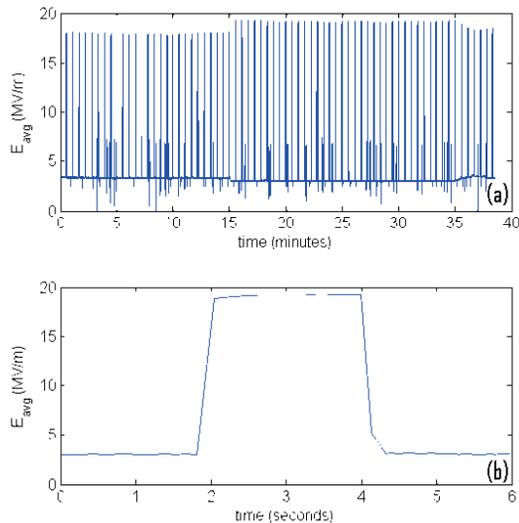


Figure 3: Five cell cavity performances during horizontal test. Pulses are 2 seconds long with a 30 second interval .

SRF PHOTOINJECTOR BEAM TEST SETUP

The beam commissioning has been started on June 2014. The first beam test schematic setup shown in Fig. 4. 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 [11] (see Fig. 4).

For the first beam test, a Cs3Sb cathode was fabricated using copper substrate and QE has been measured at value of $2E-3$ in deposition chamber. 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. Final QE measured was very low of $2.7e-5$.

With maximum available laser power 4W we were able to extract only 7.7 pC charge per bunch. This first photocurrent was measured during the first ERL gun beam test [3] (see Fig. 5).

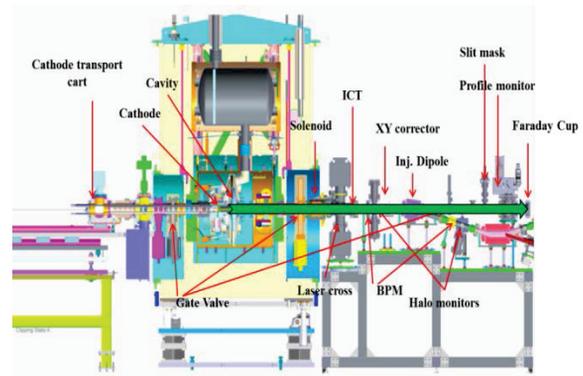


Figure 4: Schematic layout of the SRF injector at BNL R&D ERL.

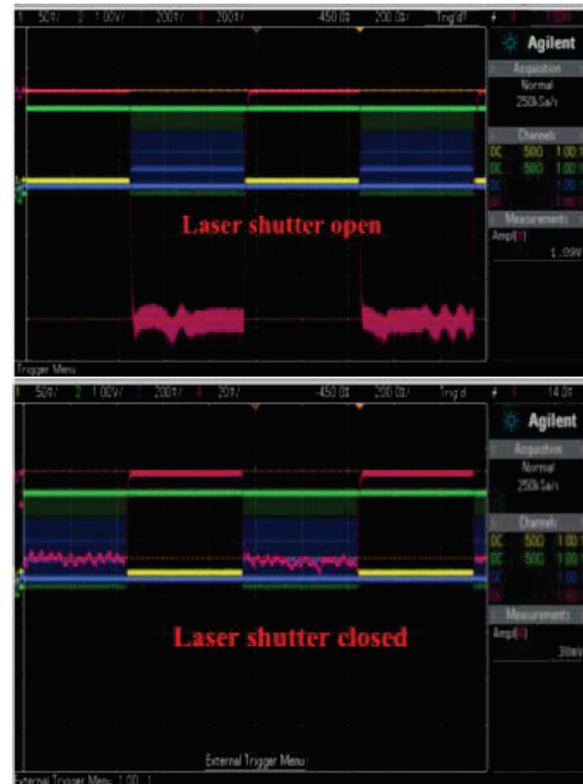


Figure 5: Faraday cup (1M Ω termination) signal during first beam test of ERL 704 MHz SRF Gun. Top: laser shutter open 1.09V; bottom: laser shutter closed 38mV. It corresponds to dark current 38nA, photocurrent 1.09 mA.

RESULTS WITH NEW CATHODE STALK

New cathode stalk with Ta tip has been fabricated. 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% [12] (see Fig. 6).

During the beam tests bunch charge was measured by FC and ICT (Fig. 7). Both measurements agreed.

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 (see Fig. 8). With new photocathode 550pC charge per pulse has been achieved (see Fig. 9).

location is equal to 65cm. This required further investigation.

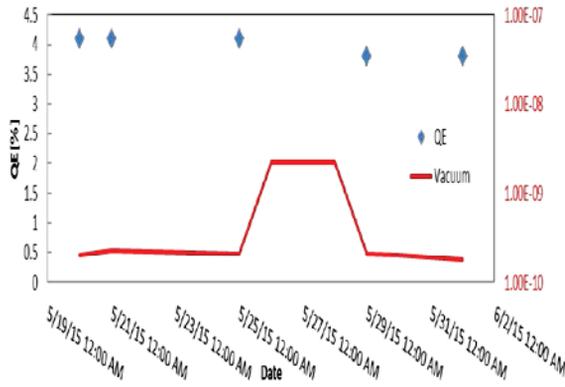


Figure 6: QE (blue diamonds) of K2CsSb cathode deposited to the new cathode stalk and vacuum (red trace) measured at room temperature before beam test 4% and after beam test 3.8%.

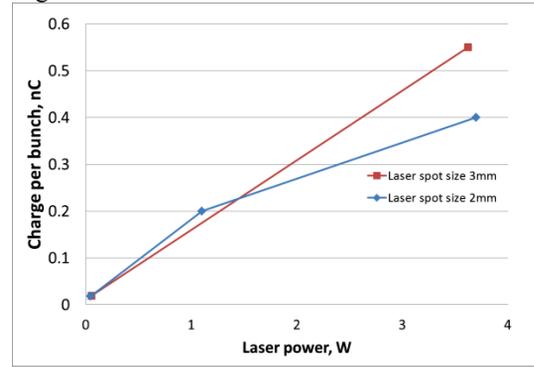


Figure 8: Charge per pulse vs laser average power. Due to space charge limitation some saturation has been observed at high average laser power (blue diamonds). Laser spot size has been increased to reach 550pC per bunch (red square).



Figure 7: 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).

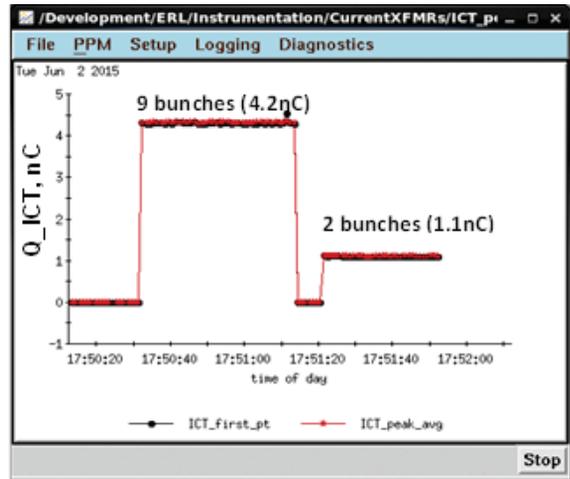


Figure 9: ICT signal during high charge operation of 704MHz SRF gun. Maximum charge per one bunch Q=550 pC.

UNEXPECTED ASTIGMATISM

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 10.).

Based on these measurements we suspect that there is strong quadruple focusing in the system. One of the suspects is FPC. We estimate that focusing strength of quadrupole responsible for the same kick placed at FPC

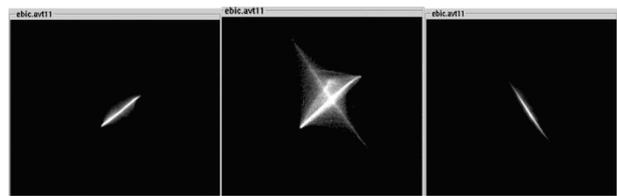


Figure 10: Beam image at beam profile monitor located before faraday cup for three different solenoid settings.

STATUS AND PLANS

An ampere class 20 MeV superconducting Energy Recovery Linac (ERL) is presently under commissioning at Brookhaven National Laboratory (BNL) for testing of concepts relevant for high-energy electron cooling and electron-ion colliders. Commissioning with beam started on July, 2014.

- Gun to dump commissioning has been approved. Full ERL loop commissioning approval is under its way.
- The first photo current from ERL SRF gun has been observed in November 2014 (1 mA per 500msec RF pulse). New “multipactor free” Ta tip cathode stalks conditioned for CW operation in March, 2015. ERL returning loop components installation is completed in May, 2015. QE with Ta cathode tip: room temperature measured 4%, cold in gun 1%. May, 2015.
- Beam commissioning with new cathode started in June 2015. Some beam parameters measured: energy, emittance. The highest charge per bunch from SRF gun .55 nC has been demonstrated, max average current per 3 msec RF pulse 3.5uA. We started commissioning beam instrumentation with beam.
- After ERL commissioning in BLDG912 the ERL components will be relocated to RHIC IP2 to be used as low energy RHIC electron cooler [13].

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