BNL SRF GUN COMMISSIONING*

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Abstract

The R&D ERL project at BNL serves as a test bed for future RHIC projects, i.e., e-cooling and eRHIC, so this prototype ERL aims to demonstrate the main parameters for electron beam in these projects. The 704 MHz half-cell SRF gun is designed to deliver up to 0.5 ampere beam at 2 MeV with 1 MW of CW RF power. The gun commissioning without a cathode stalk insertion in the ERL block house started in November of 2012. After high power RF conditioning, the cavity was able to operate at 2 MV (23.5 MV/m) in CW mode. The commissioning with the cathode stalk insertion is still in progress, and so far, the gun reached 1.8 MV with 40% duty cycle. This paper briefly addresses the SRF gun system design, then describes the cold emission tests and discusses the results.

INTRODUCTION

The Collider-Accelerator Department at Brookhaven National Laboratory is building a high-brightness 500 mA capable ERL [1] as one of its main R&D thrusts towards eRHIC, the electron-hadron collider upgrade of the operating RHIC facility [2]. The ERL 5-cell SRF linac cavity [3] has been extensively tested already [4], and commissioning of the SRF gun without a cathode stalk insertion was completed in early 2013. The half-cell SRF cavity reached the design requirement for the ERL operations [5]. The commissioning with the cathode stalk is ongoing now. So far, the cathode stalk went through the multipacting zones that were found during vertical testing of the gun cavity. To date, the gun reached 1.8 MV with 40% duty cycle. In this paper, we describe main results of the SRF gun commissioning.

SRF GUN SYSTEM

The SRF gun is a half-cell cavity that is designed to deliver 0.5 A at 2 MeV with 1 MW of CW RF power. It incorporates a double quarter-wave (QW) choke joint cathode insert, a pair of opposing fundamental power couplers, a high-temperature superconducting (HTS) emittance compensation solenoid and a beam-pipe damper of Higher Order Modes (HOMs). The layout of the ERL SRF gun cryomodule is shown in Figure 1. For the details of the SRF gun system, please refer to reference [1].

SRF GUN COMMISSIONING

The strategy of the SRF gun commissioning is following: 1. Commissioning without a cathode stalk insertion; 2. Commissioning with the cathode stalk insertion; 3. Electron beam commissioning. The first step was completed earlier this year. The gun went through FPC conditioning *in situ,* which took most of the time for rising the forward RF power and the cavity accelerating voltage. Eventually, after pulsed processing with the RF power up to 490 kW with the pulse duration of 700 µs, we reached 2.2 MV in CW mode, although accompanied by heavy field emission. The cavity was able to operate at 2 MV with little radiation. The commissioning (step2) with the cathode stalk insertion started in Aug. 2013. The main purpose of this test was to condition the multipacting in the quarter wavelength RF choke-joint for cathode insertion, where multipacting happened in vertical tests. The simulation results showed that multipacting occured at 3.5 MV/m, 6 MV/m and 11 MV/m. During the commissioning, we confirmed this multipacting zones and also went through them quickly with high power conditioning. After less than 20 hours of the 2 K test, the accelerating voltage in the gun reached 1.8 MV with 40 % duty cycles.

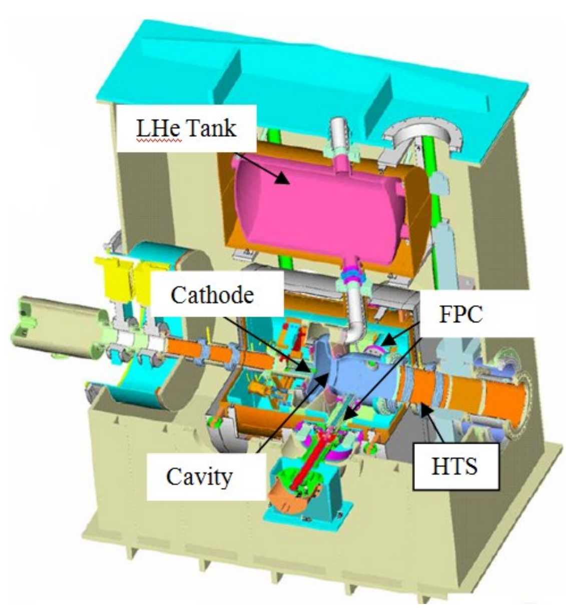

Figure 1: ERL SRF gun cryomodule.

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Cavity Performance

RF losses in the cavity walls can be measured either via the helium boil-off flow rate or the liquid helium level change. However, the boil-off data is too noisy to resolve heat loads of the order of 1 W, and the liquid helium level measurement is unreliable at present. In addition, the static heat load is about 14 W (without cathode stalk insertion) and 21 W (with cathode stalk insertion), which is much higher than the dynamics heat load at field levels below the field emission onset. This makes measurements of Q_0 even more difficult. Rough estimation, the Q_0*-value* should be about 10^9 at 1.8 MV and will be better with reduction of field emission if we spend more time on the RF processing.

Helium Pressure Sensitivity and Lorentz Force Detuning

Due to the half-cell geometry, the cavity is very sensitive to the helium bath pressure, the frequency changes from 704.535 MHz at 4 K to 704.158 MHz at 2 K only because of pumping down. The simulated helium pressure sensitivity of the SRF gun is 651 Hz/Torr, which is in good agreement with the tested result, i.e., 703 Hz/Torr. This measurement was done by closing the helium pumping valve to allow the helium pressure to drift up to 30 Torr.

The cavity's Lorentz detuning factor was measured to be -11.9 Hz/(MV/m)^2. This high value is due to the cavity shape with almost vertical back wall. The Lorentz force detuning data are shown in Figure 2.

The tuner range was measured at 2 K. We were able to tune the cavity from 703.6945 MHz to 704.604 MHz with 911,416 steps of the stepper motor (~ 1 Hz/ step).

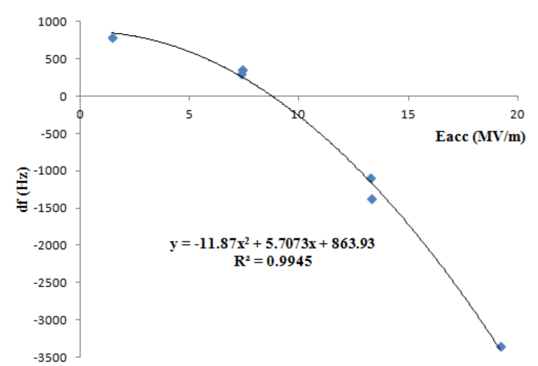

Figure 2: Lorentz detuning of the SRF gun cavity.

Microphonics

Figure 3 shows the typical frequency error signal of the phase-lock loop (PLL), measured at low field with the helium bath pressure regulated at 20 Torr. The data set here was sampled at a 1 kHz rate. The standard deviation of the frequency error is 77.8 Hz. The microphonics spectrum is shown in Figure 4. There is a dominant 24 Hz line in the spectrum. It is a mechanical resonance of the cryomodule, which can be excited by any background vibrational source. Occasionally, we observe bursts at this frequency. The bursts can be correlated with different actions such as closing/opening the liquid helium ballast valve, increasing the forward power and so on.

We tried to close the valve in the liquid helium pumping line and measured the frequency deviation versus pressure rising, however, this did not help to calm down the spectrum at all because the helium pressure was not regulated any more.

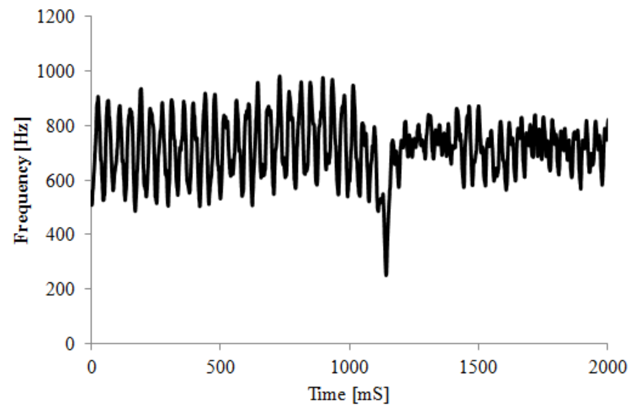

Figure 3: Baseline signal.

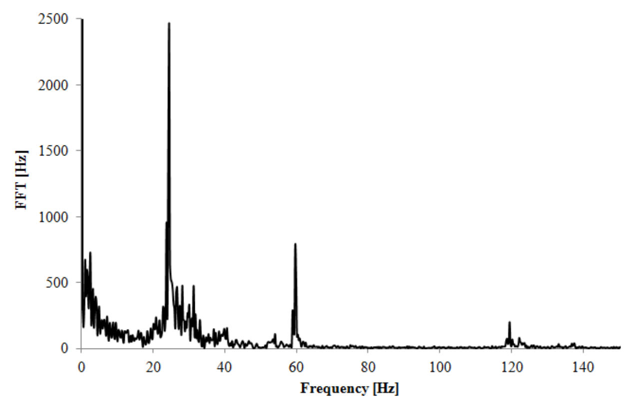

Figure 4: FFT microphonics spectrum.

Field Stability

The field in the ERL SRF cavity can be controlled through the I/Q feedback loop and/or the phase-lock loop (PLL). However, during operation with beam, the gun frequency will have to be locked with the laser and the 5-cell cavity, so only the I/Q control loop will be implemented. Figure 5 shows the field stability with I/Q feedback loop on and off. The field amplitude stability (measured at 1.5 MV gun voltage) is 2.8×10^{-3} peak-to-peak or 4.8×10^{-4} rms. And the phase stability is 1.4° peak-to-peak or 0.2° rms. The phase stability will be able to improve through suppressing noise in LLRF and klystron power supply.

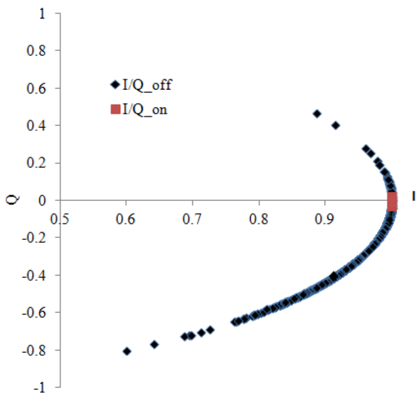

Figure 5: Field stability with I/Q loop.

Commissioning with the Photocathode Insertion

Insertion of K_2CsSb photo-cathode in the ERL SRF gun presents special challenges. The photocathode is deposited in a clean room outside the ERL blockhouse and transported to the gun cryomodule for insertion using a specially designed transport cart. Figure 6 shows the load-lock photocathode preparation system, which comprises a preparation chamber and transport cart. The deposition system and cathode are baked and pumped with sputter ion pumps and titanium sublimation pumps to achieve the required vacuum of 10^{-10} Torr. Figure 7 shows the cathode transport cart connection with SRF gun. The cathode stalk is cooled by LN_2, which is supposed to take away 188 Watt heat load.

During the vertical test in 2009, multipacting in the quarter wavelength choke-joint was found when a Nb photocathode stalk was inserted. A series of studies revealed that mulitpacting was caused by distortion of the anti-multipacting grooves by BCP. There are three multipacting zones found in the simulations, which are at gradient of 3.5 MV/m, 6 MV/m and 11 MV/m [6]. The commissioning with the cathode stalk insertion confirmed these multipacting zones and went through quickly as it is shown in Figure 8. So far, the field level reached in the SRF gun with the cathode stalk insertion is 1.8 MV with 40% duty factor.

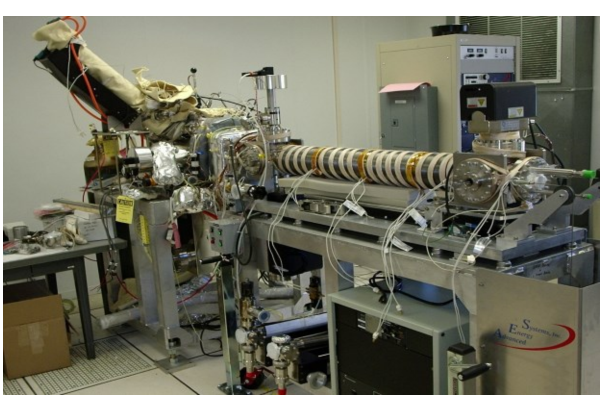

Figure 6: The load-lock photocathode preparation system.

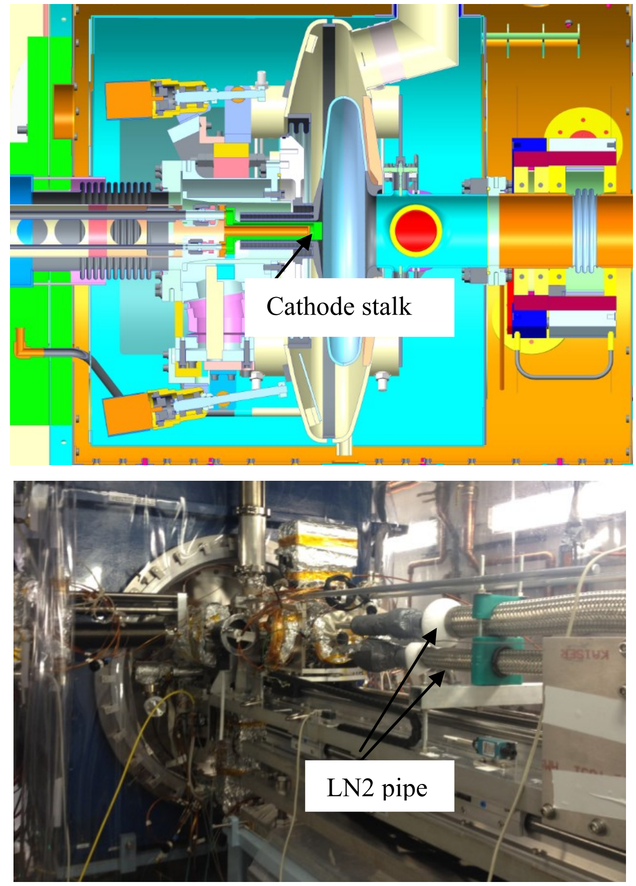

Figure 7: Photocathode stalk insertion cross-sectional view (top) and photo (bottom).

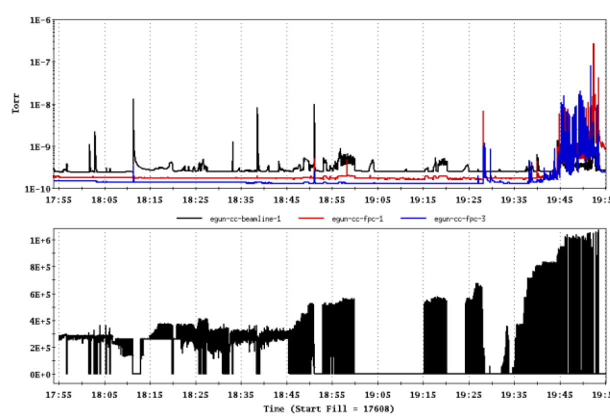

Figure 8: Conditioning through multipacting zones in the QW choke-joint. Top: two FPCs' vacuum and cavity's vacuum; Bottom: Gun voltage.

Tuning Q_{ext} by Adjusting Phase Difference

RF power from the 1 MW klystron is transmitted via a WR1500 waveguide. A shunt tee is used to split the power into two waveguide arms, terminated by two fundamental power couplers. The phase difference between these two arms will affect the Q_{ext} value [7]. Different initial phase state of the two arms would influence how the Q_{ext} changes with phase difference ϕ between the arms. In

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Figure 9, θ represents the initial phase of phase shifters in the arm 1 and 2, then one phase shifter is fixed at phase θ and the phase of the other is adjusted from θ to $\theta+\phi$. Simulation results show that there are always two Q_{ext} peaks within one period (360°). One peak is fixed at 180° for all conditions and the other one would move with the different initial phase θ periodically with a period of 180°. When there is no phase shift for both phase shifters (both set at 0°), the Q_{ext} of the system was measured as 5.75×10^4. The phase shifter in each arm is only able to shift the phase by 40°. Measured Q_{ext} versus phase shift in the actual ERL SRF gun setup is compared with simulations in Figure 10. Measurements were carried out at both high power (via LLRF) and low power with a network analyzer, producing the same results.

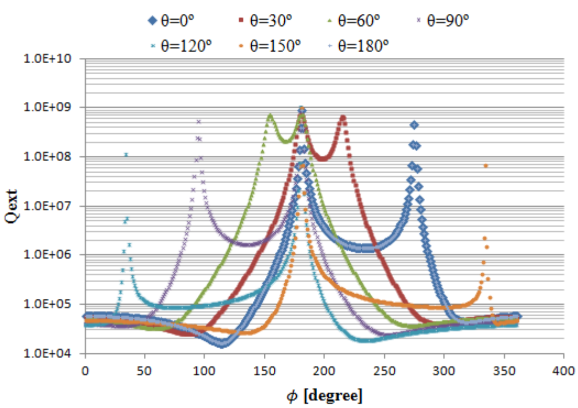

Figure 9: The Q_{ext} changes with one phase shifter at different initial states.

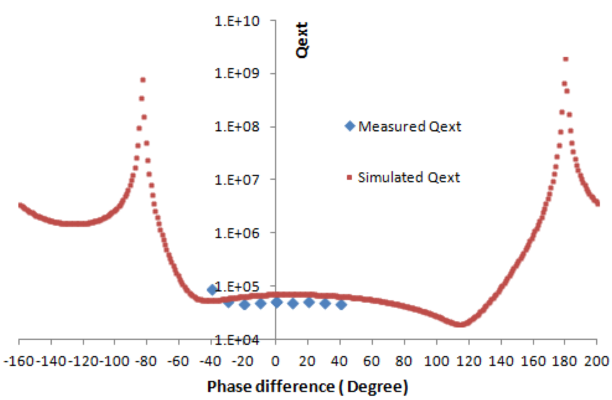

Figure 10: Comparison of measured Q_{ext} and simulation results.

Fundamental Power Coupler for HOM Damping

The HOMs damping for the SRF gun is achieved by enlarging beam pipe enough to allow propagation of all HOMs to the ferrite HOM load, which is at room temperature downstream of the cavity. Additionally, in simulation and measurements, we found that the HOMs of the SRF gun cavity are damped by FPCs [8]. Simulation results showed that the FPCs couple strongly to many of the HOMs. However, the damping capability of the FPCs is limited by the narrow-band doorknob, which has a reasonable transmission only up to ~2 GHz. The Q measurement was taken up to 2.2 GHz, through S_{21} from the waveguide to pickup. Currently, the ferrite HOM damper is not installed yet. The measurement results for the first three HOMs are shown in Table 1. One can see that the two lowest dipole modes are damped pretty well by the FPCs.

Table 1: HOM measurements

Mode	Frequency (GHz)	Q_load	Mode type
1	1.00827	47,600	Dipole
2	1.47795	800,000	Monopole
3	2.1459	76,000	Dipole

SUMMARY AND PLAN

The BNL R&D ERL project reached a milestone with commissioning of the SRF gun. After conditioning, the cavity voltage reached the goal of CW, 2 MV without a cathode stalk insertion. The commissioning with the cathode stalk insertion is ongoing and reached 1.8 MV with 40% duty cycle.

REFERENCES

[1] I. Ben-Zvi, et al., The Status of the BNL R&D ERL final, Beam Dynamicas Newletter , No. 58, August 2012.
[2] V. N. Litvinenko, et al, High-energy high-luminosity electron-ion collider eRHIC, Beam Dynamicas Newletter, No. 58, August 2012.
[3] R. Calaga, et al., High current superconducting gun at 703.75 MHz, *Physica C: Superconductivity* **441**, 159, (2006).
[4] B. Sheehy, et al., BNL 703 MHz Superconducting RF cavity testing, PAC’11, 2011.
[5] Wencan Xu, et al., Commissioning SRF gun for the R&D ERL at BNL, IPAC’13, 2013.
[6] Wencan Xu, et al., Multipacting simulation and test results of BNL 704MHz SRF gun, PAC’ 11, 2011.
[7] J. Dai, et al., these proceedings.
[8] H. Hahn, et al., these proceedings.