COMMISSIONING SRF GUN FOR THE R&D ERL AT BNL*

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Abstract

The R&D ERL project at BNL aims to demonstrate a high charge, high current Energy Recovery Linac (ERL). One of the key ERL systems is the 704 MHz half-cell Superconducting RF (SRF) photoemission gun. The 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 in the ERL block house started in November of 2012. After high power RF conditioning, the cavity is now able to operate at 2 MV in CW mode. 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 with a 1 MW klystron has started in November of 2012. Since then, we conditioned the Fundamental Power Couplers (FPCs) *in situ*, measured *Q* values, amplitude and phase stability, microphonic noise and so on. The SRF gun is now able to operate at an accelerating voltage of 2 MV. The rms amplitude and the phase stability is 4.8×10^{-4} and 0.07 degrees, respectively. In this paper, we describe results of 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].

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SRF GUN COMMISSIONING

The SRF gun was first cool-down to 2 K on November 7, 2012. Since then, we carried out 19 high power tests, until in March the gun operation was interrupted to prepare the system for the photo-cathode insertion. During the commissioning, the most of the time was spent on fundamental power coupler conditioning and high power RF processing of the SRF cavity. Eventually, we reached 2.2 MV in CW mode, although accompanied by heavy field emission. Achieving this field level was possible only after pulsed processing with the RF power up to 490 kW with the pulse duration of 700 µs.

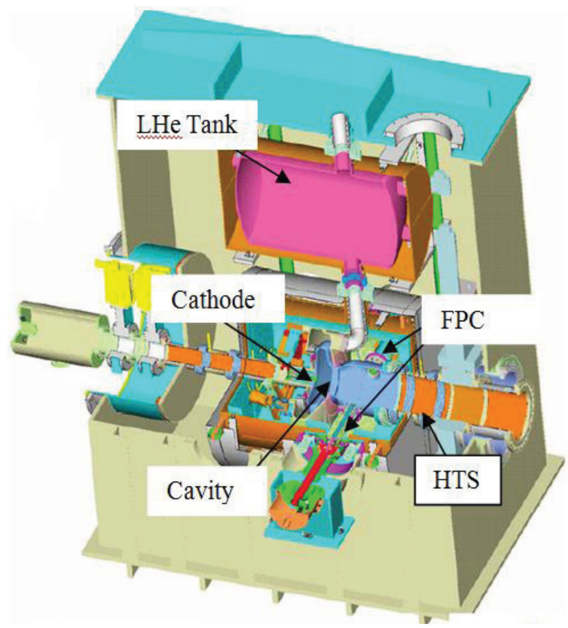

Figure 1: ERL SRF gun cryomodule.

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, which is much higher than the dynamics heat load at field levels below the field emission onset. This makes measurements of *Q* even more difficult.

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In the beginning, the onset of the field emission was at about 1 MV. High power pulse RF processing helped to condition the cavity. Eventually the cavity reached 1.8 MV with a radiation level of only 18 mrem/hr measured at ~1 meter from the cryomodule, and 2 MV with about 40 mrem/hr. We expect further reduction of field emission as we spend more time on high power RF processing in the future.

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 results. These measurements were 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 (~ 1Hz/ step).

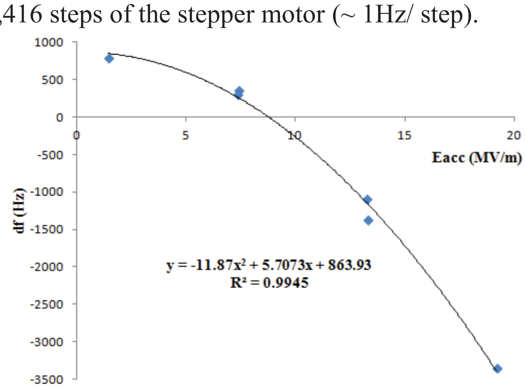

Figure 2: Lorentz detuning of the SRF gun cavity.

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 was showed 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.

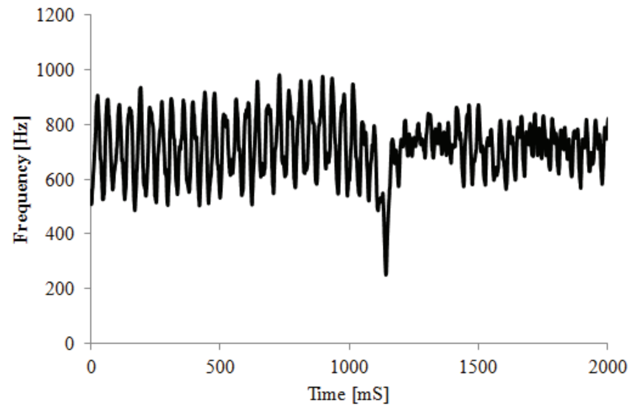

Figure 3: Baseline signal.

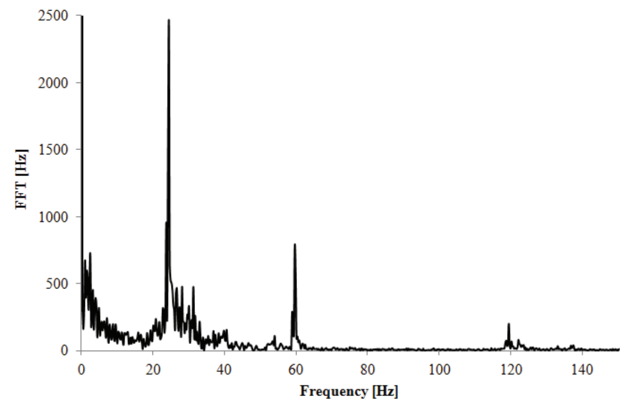

Figure 4: FFT microphonics spectrum.

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 0.42° peak-to-peak or 0.07° rms.

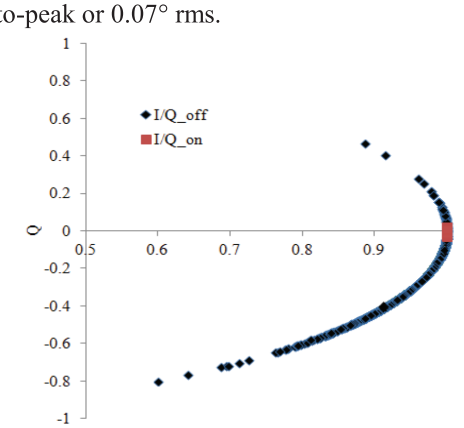

Figure 5: Field stability with I/Q loop.

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Qext Versus Phase Difference

RF power from the 1 MW klystron is transmitted via a WR1500 waveguide. A shunt tee is used to split RF into two waveguide arms, terminated by two fundamental power couplers [5]. The phase difference between these two arms will affect the external Q value. Different initial phase state of the two arms would influence how the external Q factor changes with phase difference ϕ between the arms [6]. In Figure 6, 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 external Q factor 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 external Q factor of the system is 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 7. Measurements were carried out at both high power (via LLRF) and low power with a network analyzer, producing the same results.

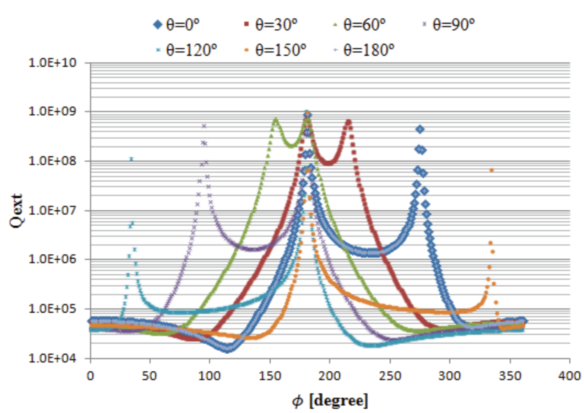

Figure 6: The external Q factor change with one phase shifter at different initial states.

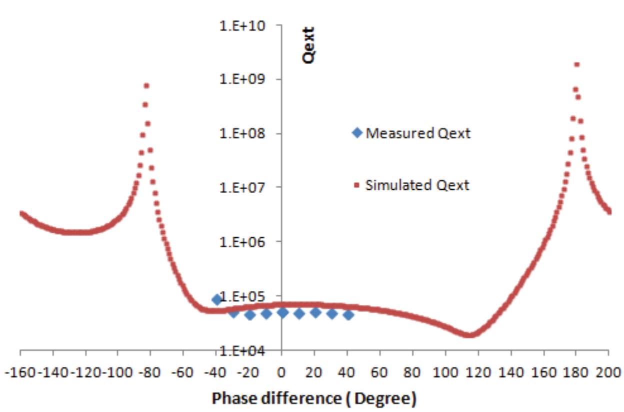

Figure 7: Comparison of measured external Q factor and simulation results.

HOM Damping by the Fundamental Power Coupler

The HOMs of the SRF gun cavity were studied along with the damping capabilities of the FPCs. 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 up to ~2 GHz. The Q measurement was taken up to 2.2 GHz, through S_{21} from 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 2 MV. The cavity's frequency sensitivity to helium pressure is high, so as the Lorentz force detuning. However, with digital LLRF control system developed by BNL, the amplitude and phase stability were measured 4.8×10^{-4} (rms) and 0.07 degree (rms), respectively. The cavity is ready for electron beams.

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