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PERFORMANCE OF 112 MHz SRF GUN AT BNL*

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Abstract

There are many new uses of superconducting RF (SRF) technology and the high brightness continuous wave (CW) photoinjector is one that is attracting more and more interest for its unique advantages in providing high bunch charge, high brightness and high average current. At Brookhaven National Lab, we proposed a quarter wave resonator (QWR) SRF cavity driven gun for the electron cooling of hadron beams in the Relativistic Heavy Ion Collider (RHIC) [1, 2], and it is serving as the injector for the Coherent Electron Cooling (CeC) proof of principle project now. The QWR structure allows us to take the advantage of low frequency RF to generate long bunch beam which suffer less severe space charge effect, see reference [3] for more details.The Coherent electron Cooling Proof-of-Principle (CeC PoP) experiment [4-5]needs high-charge electron bunches, from 1 to 5 nC per bunch, with a repetition rate of 78 kHz. A 112 MHz superconducting quarter-wave resonator electrongun cryomodule was designed and built in a collaboration between BNL and Niowave, Inc. as part of testing the concept of coherent electron cooling [6]. The cryomodule, with its associated cathode preparation and insertion and other subsystems, serves as the CeC PoP injector. The gun is designed to deliver electrons with a kinetic energy of up to 2 MeV. Electrons are generated by illuminating a high quantum efficiency (QE) K_2CsSb photoemission layer with a green laser operating at a wavelength of 532 nm. Fig. 1 shows the layout of the 112 MHz gun, installed in the RHIC tunnel and commissioned with a beam, generating up to 10 nC bunches at 1.5 MeV. More details about the installation and commissioning information can be found in reference [3, 7–9].

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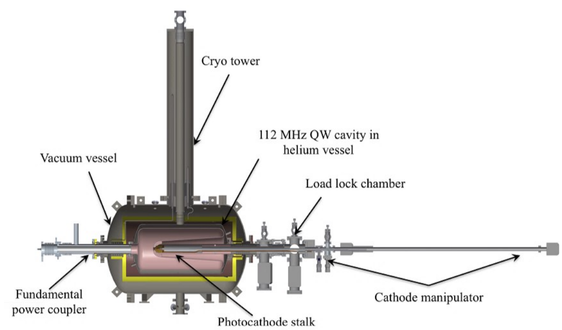

Figure 1: Cross section of the 112 MHz SRF gun (elevation view). The laser light is entering the gun through a hollow fundamental power coupler, which also provides an exit path for the electron beam.

DESIGN CONSIDERATION

The cavity frequency of the gun was chosen to be low enough to support long bunch length aiming to mitigate the space charge effect. And because the frequency is so low, the QWR shape was selected so that the cavity can be made com-pact enough to fit in RHIC tunnel. The designed parameters of the cavity are summarized in Table 1. As for the cathode, it is well known that the QE of photocathode drops signifi-cantly with temperature, as reported in Refs. [10-12] and the literature cited therein. Therefore, we needed a way of holding the cathode at room temperature while electri-cally shorting it to the cavity. For that we designed a cathode stalk to serve as a choke structure. The cathode stalk is permanently installed inside the gun and the only direct ther-mal contact between the room temperature stalk and the cold cavity are several point contact support made of Rexo-lite®. The K_2CsSb photoemission layer is deposited on the front surface of a small, 20-mm diameter, molybdenum puck and this puck is inserted with a specially designed cathode-manipulation system through the hollowed stalk, see Fig. 2 and Fig. 3.

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Table 1: Parameters of the 112 MHz SRF Gun

Parameter	Value
Frequency	112 MHz
R/Q	(linac definition) 126 Ω
Quality factor Q0,	w/o cath. insert >3.5 × 10^9
Operating temperature	4.5 K
Accelerating voltage Vacc	1.5–2.0 MV
Epk/Vacc	19.1 m-1
Epk/Ecath	2.63
Bpk/Vacc	36.4 mT/MV
Bunch charge	1–5 nC
Normalized emittance	<5 mm·mrad
Bunch repetition frequency	78 kHz
Available RF power	2 kW

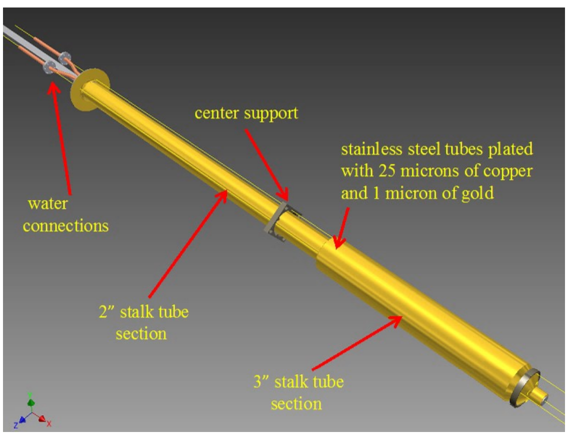

Figure 2: Cathode stalk assembly.

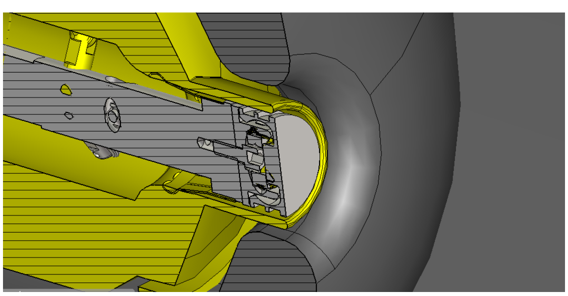

Figure 3: Sectional view of the puck inside the stalk.

Last but not the least, the fundamental power coupler(FPC) is a coaxial-type coupler similar to one used in the Naval Postgraduate School (NPS) gun [13]. The FPC is attached to the beam exit port of the SRF gun. Its hollow center conductor, or coupling tube, allows the passage of the laser and electron beams. By adjusting the penetration of the coupling tube, we can tune the cavity's resonant frequency as well as adjust the coupling strength [14]. Fig. 4 illustrates the FPC attached to the SRF gun port. Detailed information for the fabrication of cavity, FPC, cathode stalk and cathode launching system can be found in reference [15].

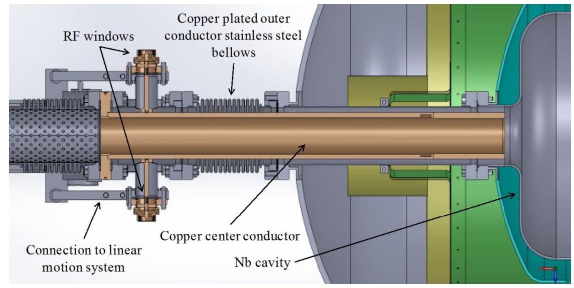

Figure 4: Cross section of the FPC attached to the beam-exit port.

CATHODE FABRICATION

A high QE cathode is needed for generating high-charge bunches. For the required high repetition frequency, it is difficult to obtain high laser pulse energy. Thus having a high QE cathode makes it practical to generate bunch charges in the nC range [16]. The cathodes are deposited at a deposition chamber described in Ref. [17] and shown in Fig. 5.

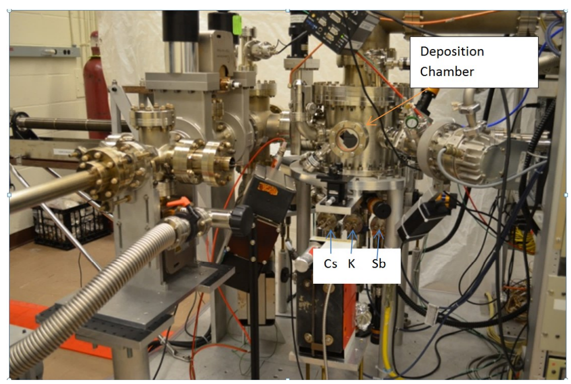

Figure 5: Multi-alkali deposition system for the 112 MHz gun.

The deposition chamber is equipped with a residual gas analyzer (RGA), a quartz-crystal monitor, and multiple view-ports for observation and laser irradiation of the cathode. Alkali-metal dispenser sources (6 mg potassium and 10.8 mg cesium from SAES Getter) and antimony (99.999% purity pellets from Goodfellow) are used for the deposition and the procedure was standard:

- Heat the substrate at 350°C for 6 hours;
- hold it at 90°C;
- 10 nm Sb approximately 1 Å/s;
- raised the substrate's temperature to 130°C;
- 20 nm of potassium at 0.6 Å/s;
- Turned down the heater in order for the substrate to be cooled at around 1°C/min;
- Evaporated Cs and watch QE increased steadily;
- When the photocurrent reached a plateau, turn off heater, turn on cold N2, reduce Cs until 80°C;

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- Cool down to room temperature quickly by cold N2.

This recipe can routinely provide us with high QE (>8% fresh) cathode and the QE can hold for months of CW operation as long as the vacuum level in side the gun stays below 1×10^{-10} torr.

MULTIPACTING SIMULATIONS

Since the cavity is loaded with coaxial structures, we were quite concerned about the multipacting (MP) in the gun that could potentially render the gun useless. Initial MP analysis of the cavity, the FPC, and cathode stalk was done using Track3P [18] and our own Graphics processing unit (GPU)-based particle tracking code [19]. Both simulations found several MP barriers, as shown in Fig. 6, where the enhanced counter function indicates the total number of secondary electrons generated by a single initial electron after a given number of impacts. The first barrier, located inside the cavity, appears when the gun voltage gets into the range of 40–50 kV. The second barrier emerges at approximately 200 kV gun voltage and continues to exist until about 650 kV is located inside the FPC. Finally, the third barrier is inside the cathode stalk, and the corresponding gun voltage is from 600 kV to 1 MV. The MP locations are shown in Fig. 7. As we can see, the barriers are rather persistent both in terms of width and height. Fortunately, our FPC was designed to be adjustable so that we had the ability to lower the coupler external quality factor for stronger coupling as needed and that was exactly what we needed. All MP barriers were observed during the gun's commissioning and haunted us throughout the experiment. In reference [20] a more thorough study was performed and found more barriers that match with our observation. Moreover, the analytically study from above reference drew the same conclusion as before, that stronger coupling is helpful when fighting the low level MPs. More discussion in following section.

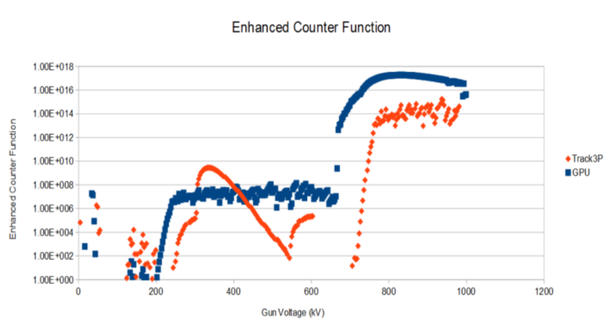
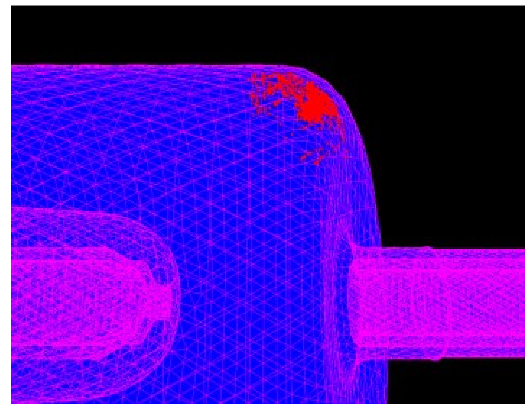
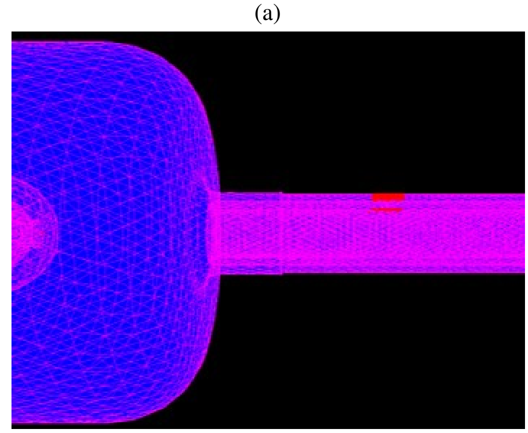


Figure 6: Enhanced counter function given by GPU code and Track3P.



(a)



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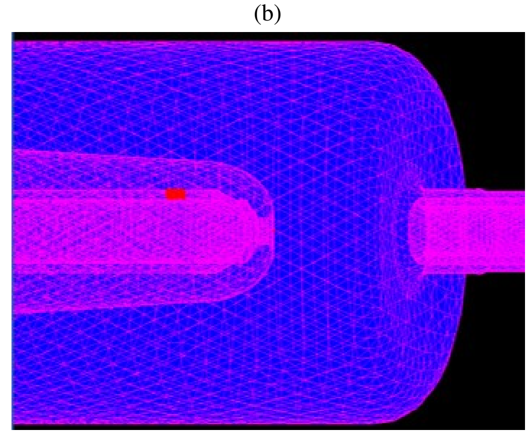

(c)

Figure 7: Location of MP in the 112 MHz injector given by GPU code, resonant particles shown as red dots. From top to bottom show the MP at gun voltage equal to 40 kV, 200 kV, and 600 kV, respectively.

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GUN PERFORMANCE AND DISCUSSION

Our SRF gun is part of the RHIC accelerator complex. It uses the RHIC cryogenic system for operation. This synchronizes its operation with RHIC runs. The gun has been providing beam for four consecutive RHIC runs and the beam quality, with improved instruments and experience, is exceptionally good. The best emittance measured was 0.32 mm mrad at 0.5 nC bunch charege [21], the highest bunch charge we can generate so far is 10 nC per bunch and the highest average current was 150 µA [8]. The QE of the cathode suffered no significant degradation during CW operation at 1.23 MV for months.

There are two major enemies of the gun operation: multipactor and field emission. The occurrence of multipactors in the gun, if unchecked, kills the cathode instantaneously every time. Years of studying and struggling with the phenomenon gave us better confidence in dealing with it. Our low level RF group was able to develop numbers of scripts that can provide tremendous amount of help when we are trying to turn on the voltage with a live cathode. It can automatically detect the status of the gun, whether it's trapped in the MP or not, in a time span that is short enough so that it can decide whether to turn off the power to avoid deadly vacuum excursion or keep ramping up the voltage to working condition. There are theory trying to link "hardening" of the MP barrier to migration of the photocathode material. But we still need to conduct more dedicated and systematic study in order to confirm or deny it.

As for the field emission of the cavity, we did see degradation of the performance over the years. But the cause of that has multiple factors behind it. Considering the starting condition of the cavity, it is still difficult to quantify the contribution from the cathode insertion mechanism. Fortunately we were able to perform several rounds of He processing and bring the gun to its current normal working voltage.

SUMMARY

We have designed a high-charge superconducting RF photoemission electron source, based on a 112 MHz quarter-wave resonator. The gun employs high QE multi-alkali photocathodes deposited on small molybdenum pucks. The cathodes are prepared in a deposition chamber and transported between the chamber and the gun in a "garage" under ultra-high vacuum. A half-wavelength cathode stalk allows the cathode to operate at room temperature. The gun's fundamental RF power coupler is adjustable and serves also as a fine-frequency tuner. The SRF gun was fabricated and installed in the RHIC tunnel as part of the CeC PoP experiment. So far the gun can provide up to 10 nC bunch charge, the best emittance measured was 0.32 mm mrad at 0.5 nC/bunch, and highest average current the gun can provide is 150 µA.

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