K_2CsSb PHOTOCATHODE PERFORMANCE IN QWR SRF GUN*

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Abstract

In 2016 run of Coherent Electron Cooling (CeC), we have successfully tested the performance of a number of K_2CsSb cathodes. These cathodes with QE of 6%-10% were fabricated in Instrumentation Division, a few miles away, transported to RHIC tunnel under UHV conditions, attached to the CeC gun, kept in storage and inserted in the gun as needed. A maximum bunch charge of 4.6 nC was generated in the gun when the QE was 1.8%. With careful conditioning at increasing accelerating fields, it was possible to maintain the QE of several cathodes for more than a week. For the cathodes that experienced degradation, the primary cause was multipacting when the power into the gun reached certain level. For subsequent measurement, the substrate was masked to coat only the central 9 mm of substrate. By optimizing the procedure for boosting the power to the gun and covering all view-ports to minimize dark current, we were able to over come multipacting. In this paper, we discuss the cathode preparation, transfer to the gun and operational experience with the cathode in 112 MHz gun.

INTRODUCTION

In order to achieve high luminosity, eRHIC will need an electron cooling to reduce the ion beam emittance which is increased by intra-beam scattering. Currently, BNL is carrying on a Proof of Principle experiment to demonstrate an advance cooling scheme called coherence electron cooling (CeC) which needs high charge bunch 5 nC with a repetition frequency of 78 kHz. A 112 MHz superconducting quarter-wave resonator (QWR) with high quantum efficiency photocathode will generate this beam to cool one of the ion bunches in RHIC. Figure 1 shows the 112 MHz gun layout.

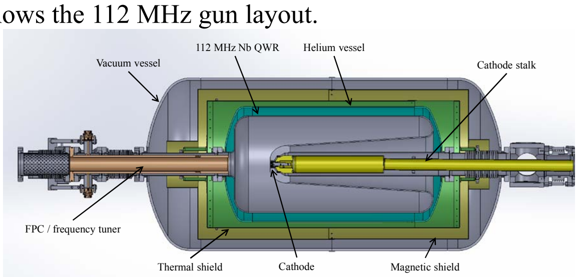

Figure 1: Plane view layout of the 112 MHz QWR gun.

In 112 MHz gun, we chose K_2CsSb as the photocathode material because of its high QE at green light and relatively long lifetime at 10^{-10} torr vacuum. With QE above 1%, the cathode can deliver more than 3 nC bunch charge. Typically, the fresh K_2CsSb cathode QE is in range of 8% ~12%.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
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The most challenging step in this experiment is compatibility of cathode and superconducting RF gun. Very strong multipacting was observed in 112 MHz gun after the insertion of cathodes. It was also observed in other SRF gun. By optimizing the power boost procedure, we were able to run the gun in CW mode in gun voltage around 1.2 MV.

CATHODE PREPARATION AND TRANSFER

Cathode Preparation

The cathodes are deposited at a deposition chamber described in [1] and shown in Fig. 2. The procedure of the cathode preparation is presented in [1].

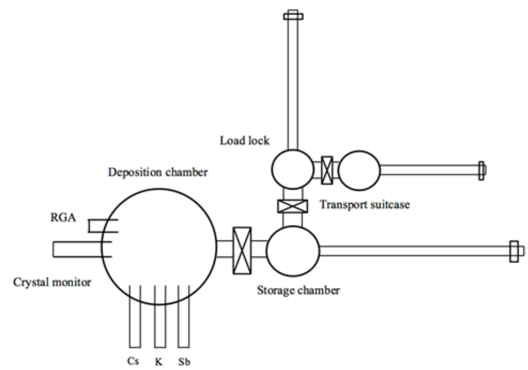


Figure 2: A schematic of the Instrumentation Division's K_2CsSb photocathode deposition system.

In 2015 run, the entire Molybdenum substrate pucks were exposed to alkali vapor. The alkali-coated cathode surface has relatively low work function and has very high secondary emission yield. This created favorable conditions for strong multipacting around cathode. The hard multipacting barrier only existed when the multi-alkali cathode was inserted into the gun. We developed a technique using excimer laser to remove the active cathode material from the puck's edge. However, the initial QE of 4.2% significantly degraded, to less than 0.0001%, due to outgassing during the laser ablation process. The pressure during cleaning process was in the 10^{-8} to 10^{-7} torr range, typically. We heated up the cathode to 80°C for two hours and rejuvenated it to a stable QE of 0.8%. This cathode maintained almost same QE in the gun and generated high charge beam in 112 MHz gun with CW operation.

The laser ablation takes time and also damages cathode. The rejuvenation process did work, but did not recover to the original QE. Simulations indicated that there are two multipacting sensitive zones, one in a narrow gap between the side surface of the puck and the inside surface of cathode stalk, another one between cathode edge and gun chamber. A mask to cover these areas from exposure to cathode material was designed and used in cathode preparation for gun run 2016. The mask covered both cathode side and cathode edge. Figure 3 shows the cathode with mask in preparation. The coated cathode size is 0.9 cm diameter. Under the mask, the QE is below the measurement limit of 10^{-9}. Without the mask, it was difficult to overcome multipacting without removing the cathode material from the edges of puck. Hence impact of operation in the gun on the QE could not be determined.

Figure 3: The coated cathode after the mask was removed from the puck.

Cathode Transfer

The photograph of load-lock chamber, garage, with the magazine supporting up to 3 cathode pucks is shown in Fig. 4. The vacuum in this chamber is maintained by a Saes Nextorr pump, which includes 10 l/s ion pump and a 100 l/s NEG pump. The magazine can store up to 3 cathodes reducing the down time for cathode exchange, once the load-lock is in place. The garage also has a QE diagnostic system that allows us to measure the QE evolution during transfer and before insertion into the gun.

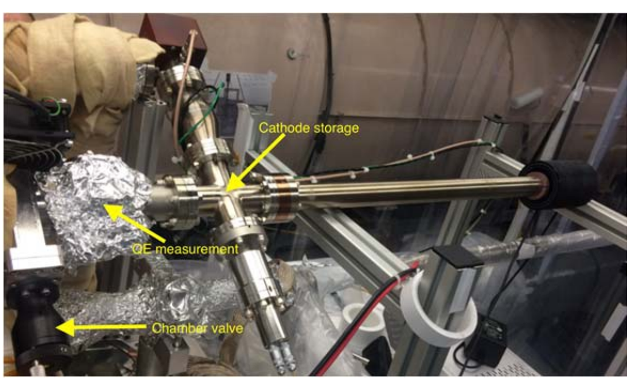


Figure 4: Cathode transfer chamber.

From 2015 to 2016, totally ten cathodes have been delivered to 112 MHz gun. Figure 5 shows the QE comparison before and after delivering cathode to RHIC tunnel. QE before transfer was measured once the QE has stabilized in the fabrication/transport system. The initial QE of the cathodes are in range of 6%~10% except one cathode (2.6) in which we cooled the mask cryogenically to reduce adhesion of cathode material in masked region of the puck. Seven cathodes had acceptable QE after the transfer from preparation chamber to RHIC tunnel and in storage for a week. Three cathodes lost QE before insertion into the gun due to either loss of power to the vacuum pump and resulting increase in the base pressure or mis-assembly of the garage. Figure 6 shows a typical QE evolution from cathode preparation chamber to before inserting into the gun. In this plot, the QE dropped about 2% in transferring and in load lock baking like from May 11th to May 14th. Then the QE is almost stabilized with the lifetime more than months.

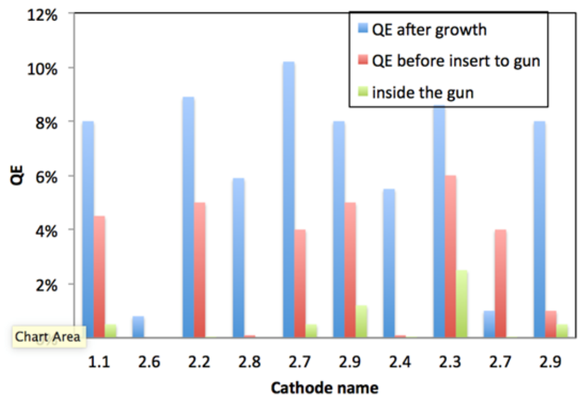


Figure 5: Cathode QE comparison: after growth, before cathode transfer (blue), before insertion into the gun (red) and inside gun after passing through the multipacting (green). The cathode with the same name means that the substrates were polished and reused again.

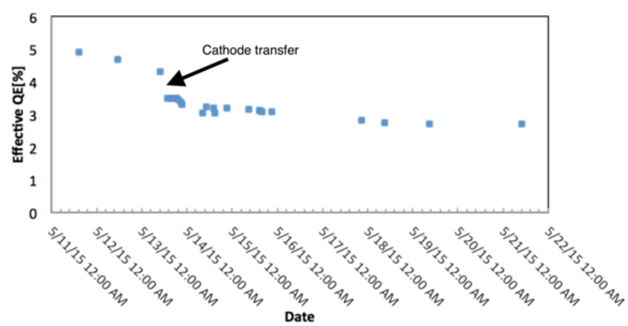


Figure 6: QE evolution in Cathode transferring and storage in the garage.

CATHODE PERFORMANCE IN SRF GUN

In 2016 run, 112 MHz gun has reached stable operation in CW mode at 1.7 MV without cathode, limited by a LHe load due to strong field emission. A cavity voltage as high as 2.0 MV could be reached in the pulsed mode [2]. We observed the multipacting after inserting the cathode into the gun. The typical multipacting voltage ranges from zero to 0.7 MV. The multipacting induced outgassing is the main reason for drastic reduction in the QE of the cathode. Three key steps were preformed to overcome the multipacting zones. i) Cover all the view-ports on the gun to make sure no ambient light could leak into the gun. This step is to reduce the initial electrons in multipacting. ii) Move the main coupler to strong coupling position and off set the center frequency to break the multipacting resonance. iii) Use pulse mode to boost gun voltage to desired range. This step reduces the number of vacuum spikes. After overcoming multipacting, the gun could operate with a gap voltage in the range of 0.8 MV to 1.3 MV.

The three steps are used in most of the cases. However, for different cathodes, specifics such as off center frequency and pulse voltage have to be fine-tuned in beginning. Thus, while searching for the optimum conditions, occasionally, the vacuum spikes to 10^{-6} torr scale, reducing the QE significantly. Figure 5 shows the cathode QE in the gun. QE of four cathodes dropped by orders of magnitude during the initial gun power ramp due to multipacting. Rest of them survived in power ramp when the multipacting zone was crossed in very short time and with few vacuum spikes. The QE for these cathodes is 1.1% and 2.5%.

Some cathodes, even with as low a QE as 0.1% after strong multipacting could survive in the gun for several weeks without further decay. Figure 7 shows the charge evolution for one ~0.1% QE cathode. Once the multipacting happen in boosting the power, the charge is significantly drops from > 100 pC to 10s pC. With the CW RF operation for couple hours, the charge recovered back to >100 pC again.

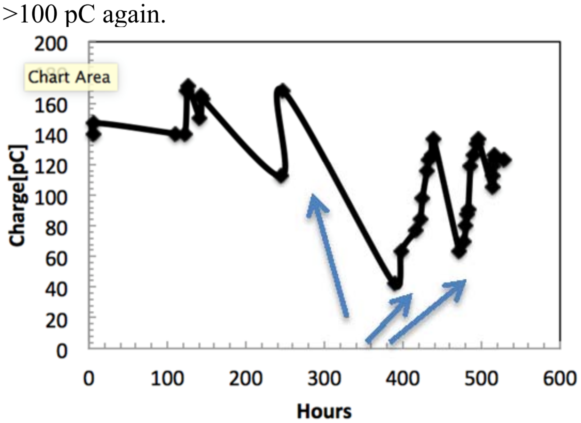
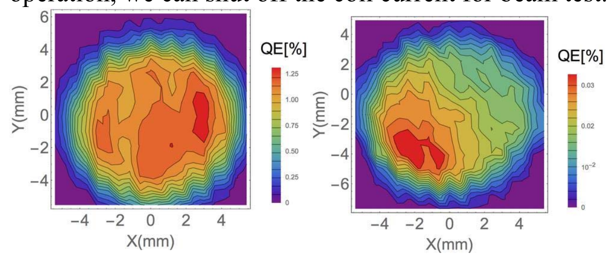


Figure 7: ~0.1% QE cathode charge evolution in three weeks. Blue array shows the QE reduction and recovery due to multipacting and beam emission.

The gun usually was shut down almost every couple days for regular RHIC maintenance to meet safety regulations. The cathodes with QE above 1%, are very sensitive to vacuum spikes that occur during the power ramp after such a shut down One cathode delivered QE above 1% in the gun with CW RF power for more than 1.5 days. The figure 8.a is the QE map of the cathode after operated in the gun (CW mode) for about 1.1 day. Then after a shut down, we had to ramp up the power in the gun again and faced a strong multipacting. After ramp up, the cathode QE dropped to 0.02%. Figure 8 b) shows the QE map after the multipacting. The QE recovered back to 0.1% in next a few hours of gun operation. One possible solution for eliminating the multipacting due to cathode, is adding a bucking coil at back of cathode to generate small magnetic field while boosting the power. Once the gun in CW operation, we can shut off the coil current for beam test.



(a) (b)

Figure 8: The QE map of the cathode inside the gun

With our 2.5% cathode, the gun delivered maximum 3.7 nC charge. Our bunch repetition frequency is 5 kHz and generated an average beam current of more than 15 uA.

DARK CURRENT FROM CATHODE

We also observed dark current after inserting the cathode in the gun, shown in Fig. 9. Obviously, the cathode generates high dark current. The dark current with and without the cathode were fitted to the equation (1) [3].

$$I = \frac{I_c}{(2\pi)^{\frac{1}{2}}} \left(\frac{E}{E_c}\right)^{2.5} e^{\frac{-Ec}{E}} . \qquad (1)$$

One solution for eliminating the dark current is to choose S20 cathode, which has higher work function.

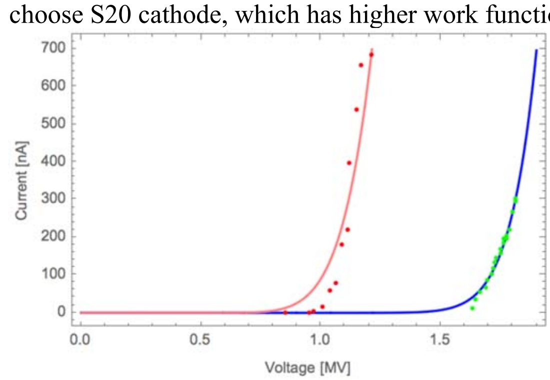


Figure 9: The dark current comparison with (Red) and without (Blue) cathode in CW operation.

CONCLUSION

The 112 MHz SRF gun was tested in 2015 and 2016 with K_2CsSb cathode. High charge bunches have been generated from the gun. We are able to fabricate high QE K2CsSb photocathode in one location and to deliver to RHIC tunnel a few miles away. Ways to eliminate the multipacting and dark current are under study.

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