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Abstract

Metal cathodes installed in rf guns typically exhibit much lower quantum efficiency than the theoretical limit. Experimenters often use some sort of in situ technique to "clean" the cathode to improve the QE. The most common technique is laser cleaning where the laser is focused to a small spot and scanned across the cathode surface. However, since the laser is operated near the damage threshold, it can also damage the cathode and increase the dark current. The QE also degrades over days and must be cleaned regularly. We are searching for a more robust cleaning technique that cleans the entire cathode surface simultaneously. In this paper we describe initial results using multiple techniques such as several keV ion beams, glow discharge cleaning and back bombarding electrons. Results are quantified in terms of the change in QE and dark current.

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IN-SITU CLEANING OF METAL PHOTO-CATHODES IN RF GUNS

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Metal cathodes installed in rf guns typically exhibit much lower quantum efficiency than the theoretical limit. Experimenters often use some sort of in situ technique to "clean" the cathode to improve the QE. The most common technique is laser cleaning where the laser is focused to a small spot and scanned across the cathode surface. However, since the laser is operated near the damage threshold, it can also damage the cathode and increase the dark current. The QE also degrades over days and must be cleaned regularly. We are searching for a more robust cleaning technique that cleans the entire cathode surface simultaneously. In this paper we describe initial results using multiple techniques such as several keV ion beams, glow discharge cleaning and back bombarding electrons. Results are quantified in terms of the change in QE and dark current.

INTRODUCTION

The LCLS RF gun requires fields up to 120 MV/m to achieve the desired emittance of 1 µm with 1 nC of charge in a 10 ps bunch. The high field requires the use of a Cu cathode to avoid breakdown at the cathode joint. The LCLS laser can produce 250 µJ of energy at 255 nm which will require a QE of 2 10^{-5} to generate 1 nC of charge. The theoretical QE for a clean Cu surface using a 263 nm photon is 33 10^{-5} with a 100 MV/m rf field and 8.4 10^{-5} with no applied field [1]. However, measurements at the SLAC Gun Test Facility (GTF) with multiple cathodes indicate the QE of Cu can vary from as low as 10^{-6} to nearly 10^{-4} at 100 MV/m. In addition the QE is not constant over the laser spot leading to increased emittance from the non-uniform space charge forces.

Our experience with laser cleaning [1] has convinced us to search for a better technique that cleans the entire surface simultaneously, does not increase the dark current and is easily repeatable. Here we report QE and dark current measurements before and after using multiple techniques intended to clean the metal surface and increase the QE.

IN-SITU TECHNIQUES AND RESULTS

One of the simplest proposed cleaning methods is to heat the entire gun and drive off any surface contaminants with thermal energy. This was motivated by a test where a small Cu sample was heated in a vacuum chamber to 230 C for 100 minutes which increased the QE over 2 orders of magnitude [2]. All four Cu cathodes installed at the GTF have been baked after installation to 200 C for several days, resulting in measured QEs that range from 10^{-6} to nearly 10^{-4} at 60 MV/m.

Ion Beam Cleaning

Previously we reported QE measurements on Cu samples before and after exposing the sample to a few keV ion beam [3]. The measured QE as a function of illumination wavelength with no applied field agreed very well with the theoretical Cu QE [4] after dosing the sample with up to 10 mC of charge. XPS measurements showed the primary contaminant was carbon.

This ion gun could not be installed on the GTF gun due to interference with the gun solenoid. The SLAC ARDB rf gun is nearly identical to the GTF gun but with more clearance between the gun and solenoid. Thus the ion gun, model number ZMB7C from Micro Photonics Inc., was installed on the ARDB rf gun. The two rf guns have interchangeable cathode plates but the lasers operate at slightly different wavelength. The ARDB drive laser wavelength is 266 nm and the GTF wavelength is 263 nm.

The ion gun was installed on one of the two laser ports in the half cell as shown in Figure 1. The beam has a direct line of site to the cathode through an oval opening in the cavity side wall measuring 0.433" X 0.25" with approximately a 70° angle of incidence at the cathode. The beam size at the cathode is approximately 1 cm in diameter.

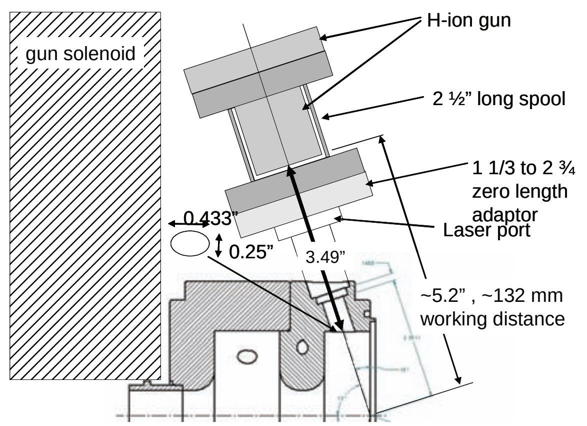

Figure 1: Layout of the ion gun and rf gun. The gun is installed on a laser port with a direct line of site to the cathode.

The QE was measured prior to the ion gun installation and was only 0.4 10^{-5} at 60 MV/m. The rf gun was vented using LN_2 tank boil-off and the ion gun installed. Before the ion gun was operated the QE was re-measured and found to have increased nearly an order of magnitude to 3 10^{-5}. The ion gun was then operated for 40 minutes at 2 keV and 2µA for a total integrated charge on the cathode of nearly 5 mC. After pumping out the hydrogen the QE was measured and found increased to 6 10^{-5} with no increase in the dark current. The ion gun was operated for a second time for 2 hours at 4 µA for a total dose of 29 mC but the QE decreased back to 3 10^{-5}. An additional 7 mC dose (1 hour at 2 μA) did not change the QE. The dark current was not affected by the hydrogen ion beam.

Although the QE increased initially after the first hydrogen ion beam cleaning, the subsequent QE was unchanged at 3 10^{-5} at MV/m. This is significantly lower than the 10 10^{-5} measured on the Cu samples at the same wavelength with no applied field [3]. The most interesting result was the substantial increase in QE after the gun was vented. This was also observed at the GTF and will be discussed in the next section.

The hydrogen was replaced with Argon and the ion gun operated for 30 minutes at 2-2.5 keV between 1.5-3 μA for a total dose of 3 mC. The dark current was measured but the rf system failed before the QE could be measured. The total integrated dark current more than doubled from 1.6 nC prior to the Argon cleaning to 3.4 nC after cleaning with a peak field of 105 MV/m. The peak dark current in the macropulse went from 1.1 mA to 2.6 mA.

The poor results compared to the test samples may partially be explained due to misalignment of the ion gun and thus limited cleaning at the center of the cathode. The 70° angle of incidence of the ion beam relative to the rf gun cathode is 33° larger than tested on the Cu samples which may also limit the effectiveness of the ion beam cleaning. It is also theorized that contaminants removed from other areas exposed to the ion beam migrate to the cathode instead of getting pumped out of the gun.

Glow Discharge Cleaning

Glow discharges are commonly used to clean vacuum vessels [5-6] and optical components [7]. Glow discharges have also been used to clean Cu accelerator structures such as the AFEL linac [8], an eleven cell photo-injector/linac. There it was observed that the glow was largely confined to a single cell, but could be moved to different cells through small changes in the rf drive frequency used to excite the glow discharge.

This technique was implemented on the GTF gun using both hydrogen and an oxygen-helium mixture (90% He and 10% O_2). Gas can flow into the gun through either the half cell via the laser port or the full cell via the waveguide and is pumped out the beam exit port of the gun with a scroll pump. The discharge is started using an rf source connected to the waveguide. We have used both a 25 W CW rf source and a pulsed 1 kW rf source with 30 μs pulse length, 200 Hz repetition rate and 5 W average power. The rf frequency can be adjusted to control the location of the glow discharge by shifting between the π mode excitation at 2856 MHz to confine the glow to the full cell or exciting the 0 mode at 2852.5 MHz to confine the glow to the half cell.

The QE of the cathode was 0.5 10^{-5} at approximately 80 MV/m after the gun was vented with LN2 boil-off to install the leak valves used to introduce the gas. The first discharge was on for about 1 hour using hydrogen flowing into the full cell at a pressure at the inlet of approximately 300 mTorr and excited with the CW rf source at 2856 MHz. The QE increased significantly to 6 10^{-5} and further increased to 8 10^{-5} after a second hour with the glow discharge. Then we switched to the 0 mode frequency of 2852.5 MHz with all other parameters constant and the QE dropped over one order of magnitude to 0.3 10^{-5}. Multiple glows at 2856 MHz at pressures ranging from 30-600 mTorr had no effect on the QE. This was an attempt to control the mean free path and thus the number of ions that reach the cathode from the glow discharge in the full cell.

We theorized that with the glow in the half cell we had actually added carbon to the surface possibly by removing carbon from the stainless tubes attached to the laser ports on the half cell. Therefore we tried to add oxygen to the system to help remove the carbon [7]. After a glow with the oxygen and helium gas at a pressure of 200 mTorr with the CW rf source at 2856 MHz the QE dropped to 0.01 10^{-5} which is the lowest value we have ever observed. An identical glow discharge with hydrogen restored the QE to 0.3 10^{-5}. It appears the oxygen attached to the surface but did not bond with the carbon and the hydrogen glow discharge removed the oxygen but apparently is not energetic enough to remove the carbon. We tried to increase the hydrogen ion's energy by using the 1 kW pulsed rf source for one hour and the QE increased to 0.8 10^{-5}. However later glows with the pulsed rf source cause the QE to decrease.

In an attempt to flow more hydrogen through the half cell we installed a leak valve on the laser port and then flowed directly into the half cell instead of into the full cell from the waveguide. However, the QE decreased every time we glowed with the gas flowing into the half cell possibly indicating some sort of contamination introduced through this leak valve. We also tried to glow with the hydrogen flowing into the half cell and the rf frequency adjusted to 2852.5 MHz so the glow was confined in the half cell but this time the QE had an insignificant change.

The only consistent result was an increase in the QE nearly every time we vented the gun with LN_2 boil-off. In one case the QE increased from 0.08 10^{-5} to 1 10^{-5} after venting and in another case it increased from 0.3 10^{-5} to 2 10^{-5}. The QE would slowly decrease after every glow and then increase after it was vented. We theorize that a contaminant in the LN2 boil-off, perhaps H_20, attaches to the surface and reduces the work function or modifies the surface states to increase the QE. Subsequent hydrogen glow discharges then remove this contaminant which reduces the QE but leave the primary contaminant untouched. This "doping" of the surface was also observed on the ARDB cathode after venting the gun.

The dark current emitted from this cathode actually decrease. Prior to the glow discharge the total integrated dark current at a field of 95 MV/m was 250 pC with a peak current of 0.3 mA. The final charge was only 100 pC with a peak current of 0.1 mA. The Fowler-Nordheim field enhancement factor decreased from 120 to 90 but the emitting area increased nearly an order of magnitude. The dark current decrease occurred after the glow discharge at 2852.5 MHz.

Electron Bombardment of the Cathode Surface

The possibility of cleaning photo-cathodes with electrons was also investigated. A very simple method using electrons is possible by selecting a laser arrival time such that the electrons do not exit the gun but actually reverse direction and strike the cathode. These back bombarding electrons have been extensively studied in thermionic rf guns [9-10].

By adjusting the laser arrival time, the energy of the back bombarding electrons can be controlled as shown in Figure 2 where the energy of the electrons exiting the gun and those returning to the cathode are plotted as a function of laser phase for a peak field on axis of 95 MV/m. Electrons that reverse direction in the full cell are emitted at a laser phase between 93 and 117°. Electrons emitted at a phase greater than 119° reverse direction in the half cell and thus typically have lower energy at the cathode. Interestingly there are two narrow phase regions where the electrons actually reverse direction twice and finally exit the gun. This phenomenon is observed experimentally when the emitted charge versus laser phase is carefully measured. The emitted charge falls to zero around 115° and then a small peak reappears around 120°. Of course the exact phase where the charge turns on and off depends on the rf field amplitude and the laser pulse length.

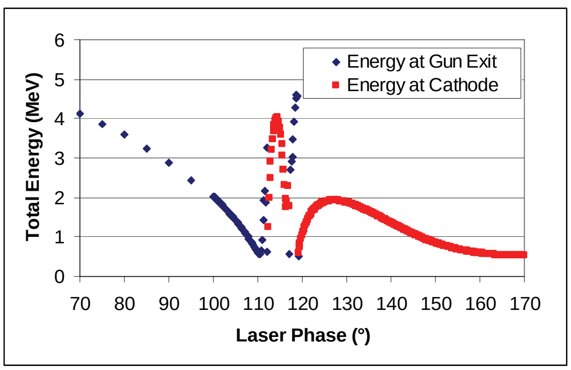

Figure 2: Simulation of the electron energy at the gun exit as a function of laser phase is plotted as diamonds. The squares show the energy of the electrons that return and strike the cathode.

Experiments were conducted with a Mg cathode and 3000 back-bombarding pulses with an estimated total charge of approximately 1 μC. The initial experiment used a laser phase of 140°, which should produce an electron with a kinetic energy of 0.85 MeV striking the cathode. No change in the QE was detected. The laser phase was adjusted to 160° and later to 125° corresponding to a kinetic energy of the bombarding electrons at the cathode of 0.076 MeV and 1.4 MeV. In all cases no measurable effect on the QE was observed. Back bombarding electrons also had no effect on the measured dark current.

The total dose of the electrons is over a factor of 1000 less than the ion beam dose and is possibly insufficient to produce a measurable effect on the QE. Plus the electron beam size may be larger when it returns to the cathode further limiting the total charge available for cleaning. The electrons may also penetrate too deep to remove surface contaminants.

CONCLUSIONS

Glow discharge cleaning appears to remove some surface contaminants without increasing the dark current. However, at least one contaminant, which is assumed to be carbon, was not removed but rather appears to have increased. Introduction of a small amount of water vapor may allow removal of carbon. The hydrogen ion beam has the potential to remove all contaminants but the initial results showed no improvement in QE possibly due to misalignment of the ion beam or migration of contaminants. The electron beam bombardment had no effect on the QE or dark current possibly due to the low amount of charge per unit area incident on the cathode.

It is clear that additional diagnostics are necessary to understand the surface chemistry. We hope to add an RGA to the vacuum system to understand what species are present. Plus the surface contaminant coverage of the cathode should be measured using a technique such as XPS when the cathode is removed from the rf gun. It is important to understand which contaminants are present since this information can help determine what technique is best suited to remove them. In addition it is desirable to measure the QE versus wavelength to understand the contaminants effect on the emission process. The wavelength dependent QE gives detailed information regarding the work function and density of surface states.

Perhaps a combination of techniques such as heating, glow discharge, ion beams and doping will be required to produce a clean metal cathode with high QE. We will continue to study various cleaning techniques and the effect on the cathode QE, dark current and lifetime.

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