

# IN-SITU CLEANING OF METAL CATHODES USING A HYDROGEN ION BEAM\*

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## Abstract

Improving and maintaining the quantum efficiency (QE) of a metal photocathode in an s-band RF gun requires a process for cleaning the surface. In this type of gun, the cathode is typically installed and the system is vacuum baked to ~200degrees C. If the QE is too low, the cathode is usually cleaned with the UV-drive laser. While laser cleaning does increase the cathode QE, it requires fluences close to the damage threshold and rastering the small diameter beam, both of which can produce non-uniform electron emission and potentially damage the cathode. This paper investigates the efficacy of a low-energy hydrogen ion beam to produce high-QE metal cathodes. Measurements of the QE vs. wavelength, surface contaminants using x-ray photoelectron spectroscopy and surface roughness were performed on a copper sample, and the results showed a significant increase in QE after cleaning with a 1keV hydrogen ion beam. The H-ion beam cleaned an area approximately 1cm in diameter and had no effect on the surface roughness while significantly increasing the QE. These results and a comparison with theory as well as a scheme for installing an H-ion cleaner on an s-band gun are presented.

## INTRODUCTION

Metal photocathodes are commonly used in high-field RF guns because they are robust, straightforward to implement and tolerate relatively poor vacuum compared to semi-conductor cathodes. However metal cathodes have very low QE even at UV wavelengths, and still require some form of cleaning after installation in the gun. The most commonly used process for improving the QE is laser cleaning. In this technique the UV drive laser is focused to a small diameter close to the metal's damage threshold and then moved across the surface to remove contaminants. This method does improve the QE, but can produce non-uniform emission and potentially damage the cathode. Ideally a process which produces an atomically clean, but unaltered surface is needed.

In this paper we explore using a hydrogen ion (H-ion) beam to clean a copper cathode. We describe QE measurements over the wavelength range of interest as a function of integrated exposure to an H-ion beam, the data analysis and propose an in-situ installation compatible with existing s-band RF guns.

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## DESCRIPTION OF THE EXPERIMENT

### *Sample Preparation and Surface Roughness*

A sample 25mm in diameter and 2.5mm thick was prepared in the standard polishing technique using 0.25micron diamond paste. However, during its storage under hexane, the hexane had evaporated resulting in an oxidized carbon surface and a low initial QE (Figure 1).

The surface roughness was studied to determine if there was any change in the surface morphology due to the exposure to the H-ion beam. Atomic force microscope (AFM) measurements on a similarly treated sample gave the following results [1]. The Ra and Rq before treatment were 10.55nm and 13.09nm respectively, and the peak-to-peak roughness was 187.91nm. After exposure to H-ions the respective values were 12.48nm, 15.65nm and 118.76nm for one 50x50micron area and 10.19, 12.52 and 82.50nm for another 50x50micron area. Two areas were measured given the difficulty of repositioning the probe to exactly the same region on the sample when it has been removed and then reinstalled in the AFM.

### *QE and Surface Contamination Measurements*

After preparation the sample was placed in a load lock chamber separated by a valve from an X-ray Photoelectron Spectroscopy (XPS) measurement chamber. The XPS data provided the percentage coverage of carbon on the surface. The QE measurements and the H-ion cleaning were performed in the load lock chamber. The QE was determined with the sample biased at 18V and since there was a large gap (of order inches) to the nearest ground, the electric field on the sample was nearly zero. The sample was illuminated by light from a xenon arc lamp whose output was selected by a monochromator with a slit set to pass a wavelength range of 8nm. The transmission of the vacuum window and other optics were measured and used to determine the absolute QE. The H-ion beam was produced by a commercial saddle field ion source [2], whose beam energy was approximately 1KeV. Beam currents of 0.4, 0.7 and 2microamperes were used. Labview [3] software automatically scanned the wavelength in 2nm steps while collecting the photo- and background currents. The experiment determined the QE and the surface contamination as the sample was progressively exposed to the H-ion beam.

The data for the unbaked copper sample are shown in Figure 1. In other experiments it is standard practice to bake the sample to 230degrees C to clean the surface. In this case however, we were interested in the effects of H-

ion cleaning only and the initial bake was not performed. The results are quite dramatic, especially at the drive laser wavelengths of interest at 255nm and 263nm. Although the sample was exposed to a total integrated H-ion charge of 10.23mC, most of the benefit was achieved by 3.03mC. It should be noted that 250μJ at 255nm requires a QE of  $2 \times 10^{-5}$  to produce 1nC.

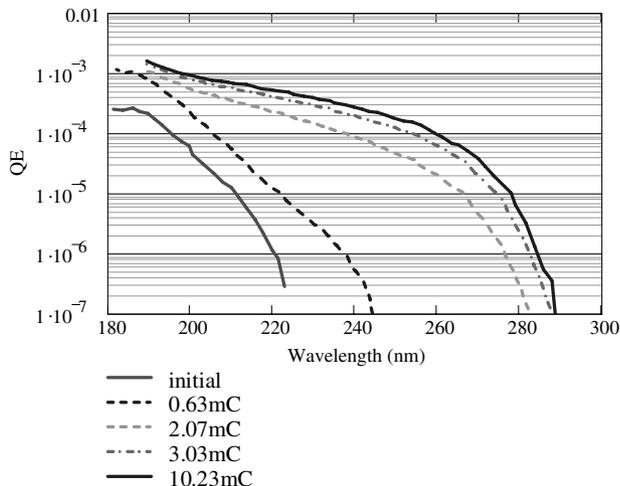


Figure 1: The QE for a copper sample vs. wavelength with increasing exposure to the H-ion beam.

## DATA ANALYSIS

The QE data were analyzed to obtain the work function using the method of Fowler [4]. This technique includes the effect of temperature at photoemission threshold by assuming a Fermi distribution for the electrons and comparing the data with the following function,

$$\ln\left(\frac{QE}{T^2}\right) = B + \ln\left(f\left(\frac{\hbar\omega - \phi}{kT}\right)\right)$$

where  $T$  is the electron temperature (assumed to be 300degK),  $k$  is Boltzman's constant,  $\hbar\omega$  is the photon energy, and  $\phi$  is the work function.  $B$  is a constant related to the electron density of states, the optical reflectivity and electron transport to the surface. The function  $f(x)$  results from integrals of the Fermi-Dirac function and is approximated by

$$f(x) = e^{-x} - \frac{e^{-2x}}{4} + \frac{e^{-3x}}{9} - \dots \quad \text{for } x \leq 0$$

$$f(x) = \frac{\pi^2}{6} + \frac{x^2}{2} - \left( e^{-x} - \frac{e^{-2x}}{4} + \frac{e^{-3x}}{9} - \dots \right) \quad \text{for } x \geq 0$$

Fowler showed that  $\phi$  and  $B$  are easily obtained by plotting the experimental  $\ln(QE/T^2)$  vs. the photon energy normalized to  $kT$ , and fitting with  $B + \ln(f((\hbar\omega - \phi)/kT))$ . Fowler plots are given for our six QE data sets in Figures 2, 3 and 4. The comparison with Fowler's theory is excellent with the exception of few cases. Figure 2 shows the data and theory for the initial, contaminated sample with 31% carbon coverage and after a short exposure to the H-ion beam (0.630mC). In these cases the fit has been biased to better match the threshold

region. We assume the discrepancy at higher photon energies results from additional electron states not accounted for by the Fermi-Dirac distribution. In fact, one might consider a two-component model to explain the data, in which one component is given by the Fermi distribution and another results from surface states such as plasmon resonances produced by the presence of contaminants or non-uniform QE across the surface.

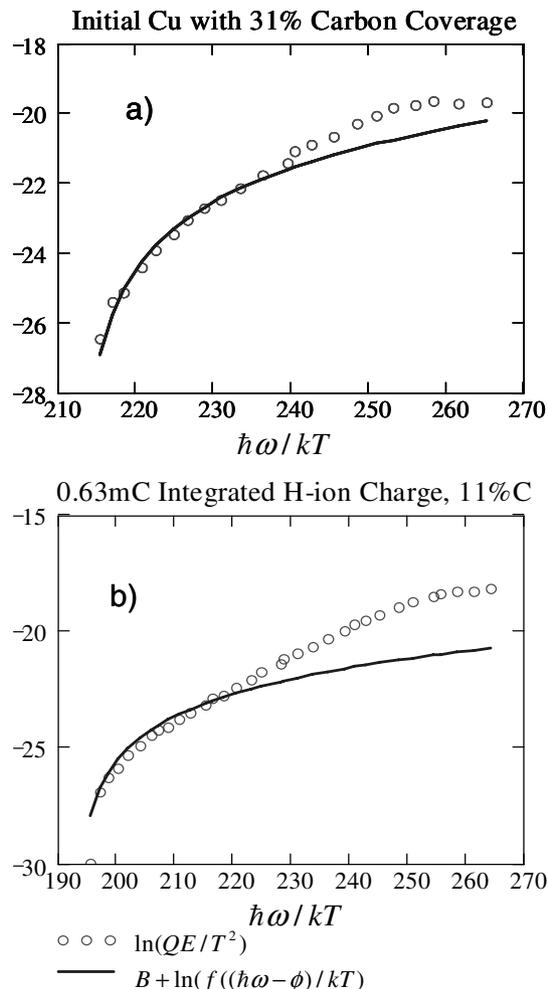


Figure 2: Fowler plots for: a) the initial sample with 31% carbon surface coverage, b) the same sample after exposed to 0.63mC of H-ion beam.

Another discrepancy is seen in Figure 4b. In this case the sample was baked at 230degrees C for 1hour after being cleaned by H-ions. The bake was expected to further improve the QE, instead the QE went down and the work function appeared to increase by 0.18eV. The Fowler plot indicates a poor fit at the lowest photon energies. Unlike the analysis in Figure 2, it seemed inappropriate to bias the fit to the low energies since this would grossly under-estimate the bulk of the data at higher energies. We speculate this bake re-contaminated the cathode either from outgassing of the surrounding adjacent chamber walls (only the sample was heated to 230degreesC) or by diffusion of material from the sample's interior.

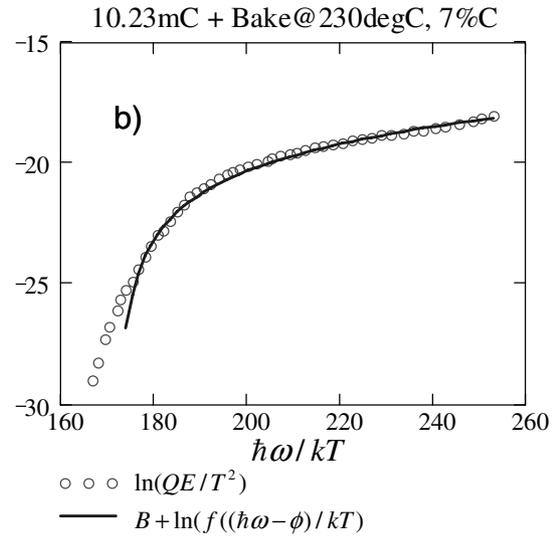
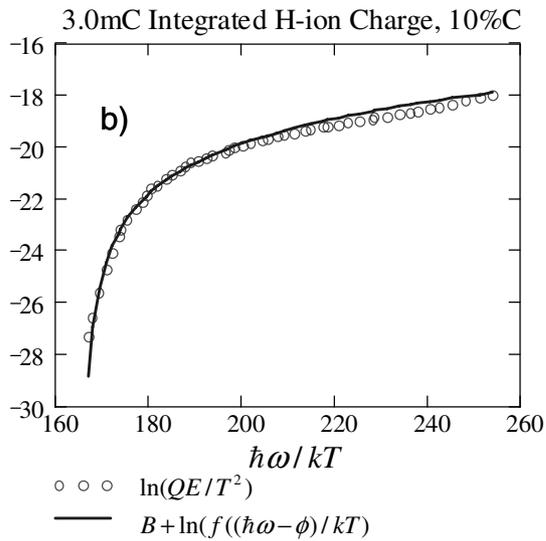
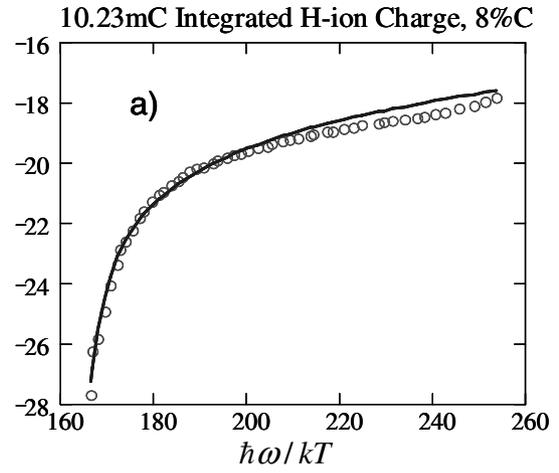
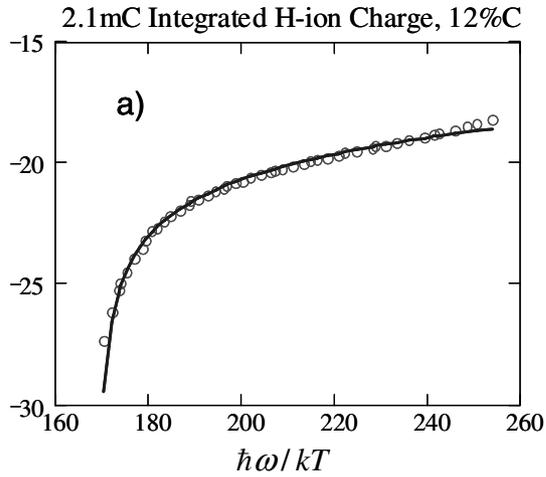


Figure 3: Fowler plots for sample exposed to a) 2.1mCoul of H-ions and b) after 3.0mCoul of H-ions.

Figure 4: a) Fowler plot after final integrated exposure of 10.23mCoul. b) The result of heating the sample to 230degC.

## DISCUSSION OF RESULTS

The work functions obtained for the copper sample as it was progressively cleaned by the H-ion beam are shown in Figure 5. The final work function was 4.31eV with an estimated systematic uncertainty of 0.2eV. There was an increase of 0.18eV when the sample was baked at 230degreesC as described above.

Comparison with an accepted work function for polycrystalline copper is difficult because of the large range quoted in the literature. Therefore an average work function was computed with a standard deviation based upon the reported values [5,6,7,8]. The resulting work function is 4.66+/-0.51eV. Thus our value of 4.31eV is in reasonable agreement.

In our previous work [9], the QE was computed using the free electron gas model of a metal and used the Fermi-Dirac distribution for the electron density of states [10]. This derivation of QE assumed the electrons are at zero temperature and imposed the requirement that the

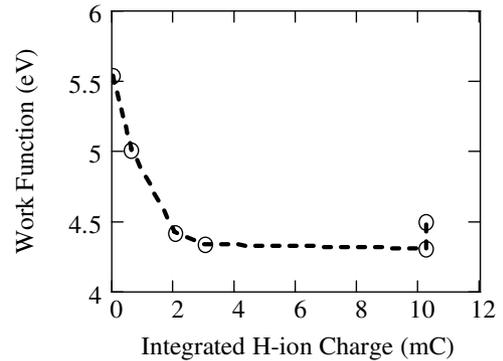


Figure 5: The copper sample work function vs. the accumulated H-ion charge.

escaping electron's momentum perpendicular to the surface,  $p_{\perp}$ , satisfy [11]

$$\frac{p_{\perp}^2}{2m} > \phi + E_F - \hbar\omega - \Delta\phi_{schottky}$$

where  $\phi$  is the work function,  $E_F$  the Fermi energy,  $\hbar\omega$  the photon energy.  $\Delta\phi_{schottky}$  is the barrier reduction due to the Schottky effect which is conveniently expressed in units of eV by [12]

$$\Delta\phi_{schottky} = 3.7947 \times 10^{-5} \sqrt{E(V/m)}.$$

Figure 6 compares measurements after H-ion cleaning with the Eqn. [4] of Ref. [9]. The red-curve is the QE computed at the same low field as the data was collected at, and generally over-estimates the measurement by a factor of 2.5. Possible explanations include a higher reflectivity than given in the literature (considered unlikely), electron-electron and electron-phonon scattering during transport to the surface[10], inefficient collection of electrons in the experiment (it's assumed that all are collected) or an error in the assumed electron density of states. These and other possibilities are being explored.

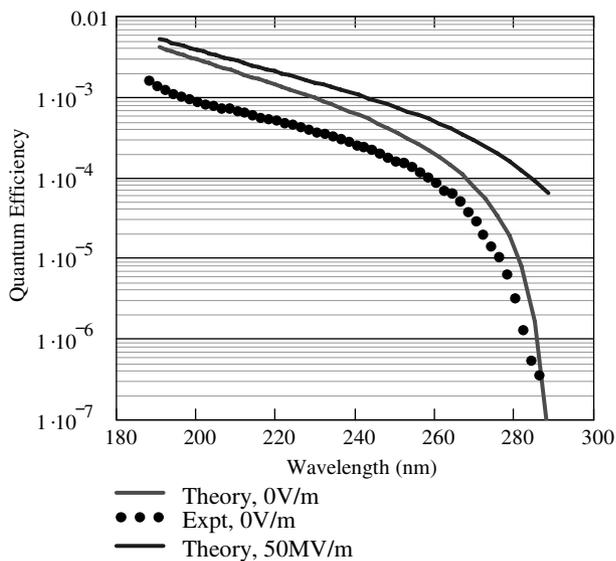


Figure 6: Plot comparing the measured (points) and computed QE's at low (red) and high (blue) applied fields.

Figure 6 also illustrates the Schottky enhancement of the QE for an applied field of 50MV/m. The 50MV/m corresponds to a RF gun with a peak field of 100MV/m but with the electron bunch being launched at 30degrees from the RF zero crossing. In this case, the QE increases approximately 2.2 times while the barrier decreases by 0.27eV. This increase can be applied to the measured QE's. For example, at 255nm the measured low field QE is  $1.2 \times 10^{-4}$  which becomes  $2.7 \times 10^{-4}$  in an operating gun. This QE is nearly 10-times the minimum QE specified for the Linac Coherent Light Source (LCLS).

Figure 7 shows a possible method for implementing a H-ion gun on existing 1.6cell, s-band guns. As nearly all such guns are built with grazing-incidence laser ports, we propose using one of these ports for directing the H-ion beam onto the cathode. As the vacuum pressure increases

to the  $10^{-4}$ Torr range during cleaning, a valve (not shown) is required downstream of the gun and solenoid to limit the affected beamline. In addition, the H-ion gun working distance is limited to approximately 15cm, thus transporting the beam through the solenoid is not possible. Work is in progress to investigate installing this type of cleaner on the LCLS gun.

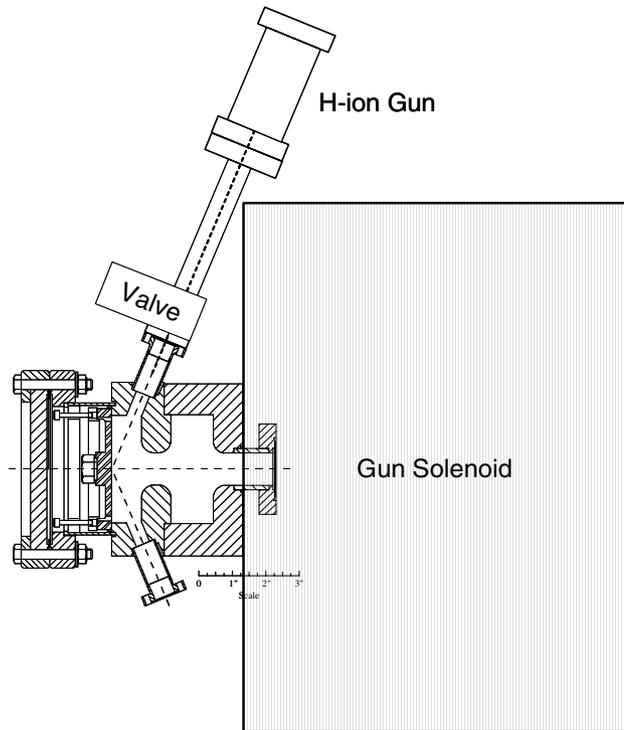


Figure 7: The proposed configuration for in-situ cleaning of the cathode in an s-band RF gun.

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