Quantum Efficiency Measurements of a Copper Photocathode in an RF Electron Gun*

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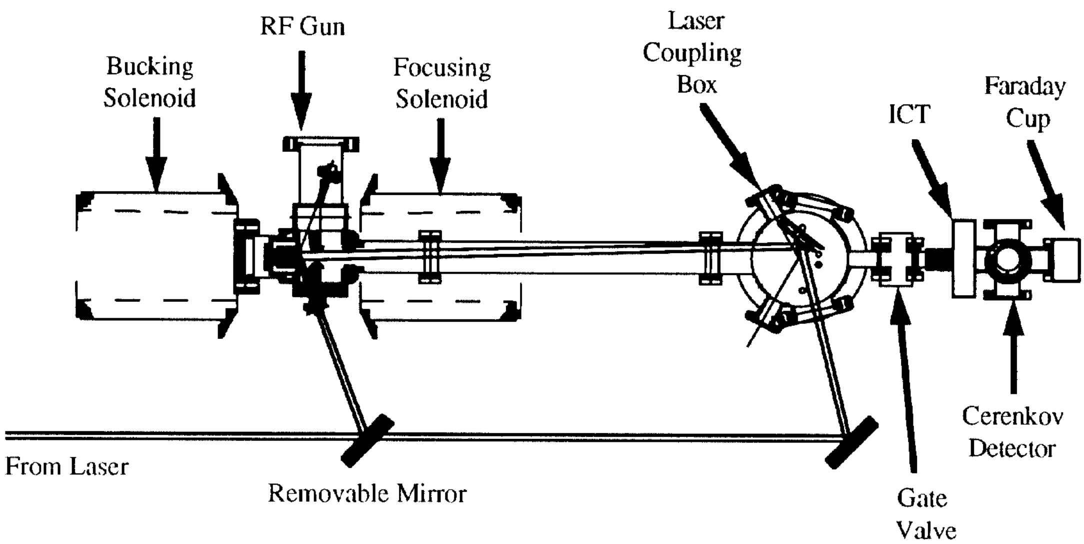

Figure 1: Diagram of the experimental setup

Abstract

A 4.5 MeV photocathode RF Gun has been commissioned at UCLA. A photo-injector drive laser produces sub 2 ps pulses of UV (λ=266 nm) light with up to 200 μJ/ pulse, and illuminates a copper cathode. The photoelectrons are accelerated to an energy of 3.5 MeV within the gun. The electron beam charge is measured as a function of laser energy using an integrating current transformer (ICT). We present measurements of quantum efficiency as a function of laser polarization for injection angles of 2° and 70° with respect to the cathode normal. At 70° incidence a 50% enhancement in quantum efficiency (> 10^{-4}) is observed for p-polarized light over s-polarized light.

I. INTRODUCTION

The photocathode quantum efficiency is a fundamental parameter in laser driven rf guns. It has been shown that the quantum efficiency depends on the wavelength, injection angle, and polarization of light used in producing electrons[1]. Furthermore, the quantum efficiency is strongly affected by experimental conditions such as the cathode surface, vacuum conditions, and the applied electric field[2].

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In most experiments, special consideration is given to the collection of all the charge produced by the injected photons. Since our goal is to create an electron beam, we measure the charge contained in the electron beam at the output of the rf gun and use it in the calculation of quantum efficiency. Therefore, this measurement defines an effective quantum efficiency of the photo-injected rf gun system which incorporates the collection efficiency of the beam.

II. EXPERIMENTAL SETUP

The photoinjector consists of a Cu photocathode placed at the endwall of the 1/2 cell in a 1 1/2 cell rf gun. After completion of the measurements, the field balance between the 1/2 cell and the full cell was measured to be 1:1.8. This limits the maximum electric field at the cathode to less than 50 MV/m. A solenoid is used to transport the beam to various beam diagnostics. The experimental setup is depicted in Figure 1.

For single photon photoemission, the photon energy must exceed the work function of Cu (4.65 eV)[3]. The photoinjector drive laser was designed to produce < 2 ps laser pulses at 266 nm (4.66 eV) with 200 μJ/pulse. This is accomplished using chirped pulse amplification and compression of a mode-locked YAG laser and frequency upconverting using two KD*P doubling crystals.

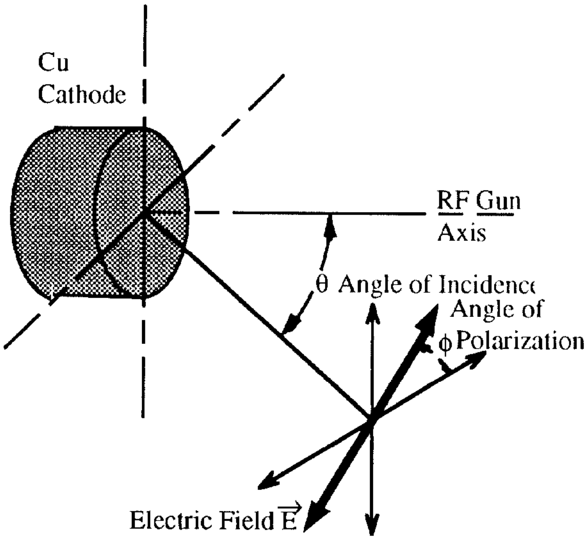

Figure 2: Laser injection geometry

The laser injection geometry is shown in Figure 2. The polarization angle ϕ is the angle the electric field makes with respect to the plane of incidence. Therefore, 0° corresponds to p-polarized light and 90° corresponds to s-polarized light. A 1/2 waveplate allows continuous rotation of the laser polarization through a full 360°. The angle θ is the angle of incidence of the laser beam with respect to the beam axis of the electron gun. We are limited to only two angles of injection, 70° and 2°.

The electron charge is measured with two independent diagnostics, the Faraday cup and the ICT. Both these diagnostics agree with each other to within 10%. Because the Faraday cup collects significant amounts of dark current, the ICT was used to measure the photo-induced charge per pulse free of the dark current background. A phosphor screen was used to ensure the position of the electron beam was on axis near the center of our diagnostics. The beam energy was measured to be 3.5 MeV using a dipole spectrometer.

The Cu cathode received no special surface preparation. After machining, the cathode was installed in the rf gun and baked at 100°C with the gun under vacuum. High power rf conditioning was used to reach a vacuum level of 10^{-9} Torr.

During operation of the gun, the laser spot was focused to sub mm spot sizes on the cathode. The high intensity of the laser pulses damaged the cathode surface further complicating the emission process. The damaged spot is centered on the cathode and therefore all quantum efficiency measurements were made for photoemission from the damaged area.

III. EXPERIMENTAL RESULTS

Measurements of collected charge vs laser energy for three representative cases are shown in Figure 3. From these measurements it is clear that saturation of the charge occurs at laser energies above 50 μJ. Therefore values of quantum efficiency η are taken in the low charge limit. Linear fits for laser energies below 25 μJ are presented and labeled with the quantum efficiency (η) corresponding to the slope of the line. From these fits, an enhancement in quantum efficiency of 50% is observed for 70° p-polarized over 70° s-polarized light.

Measurements of charge vs laser energy were obtained for various polarization angles. For 2° injection, changing the polarization angle did not affect the charge collected. However, for 70° injection, measurements resulted in curves of similar shape to those of Figure 3 but which lie in between the 70° s-polarized and 70° p-polarized curves depending on the angle of polarization. Figure 4 shows the polarization dependence of collected charge for a laser energy of 100 μJ. Identical plots are found at different energies. The functional form of this enhancement fits a $\cos^2\phi$ dependence which implies that the enhancement is dependent on the energy of p-polarized light rather than its electric field.

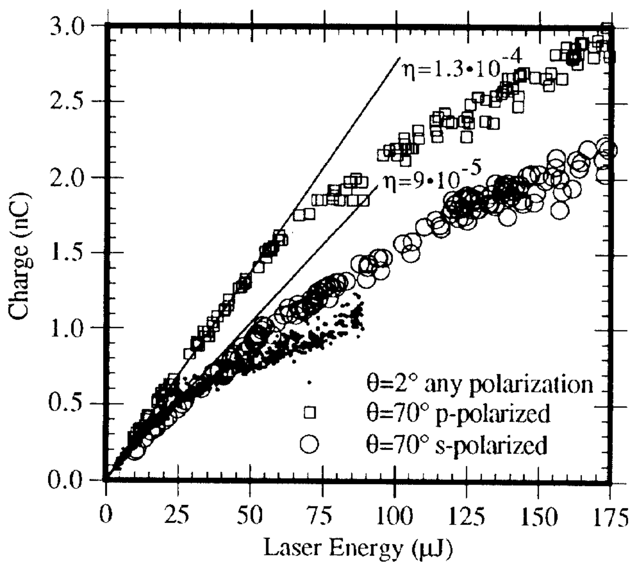

Figure 3: Quantum efficiency measurements

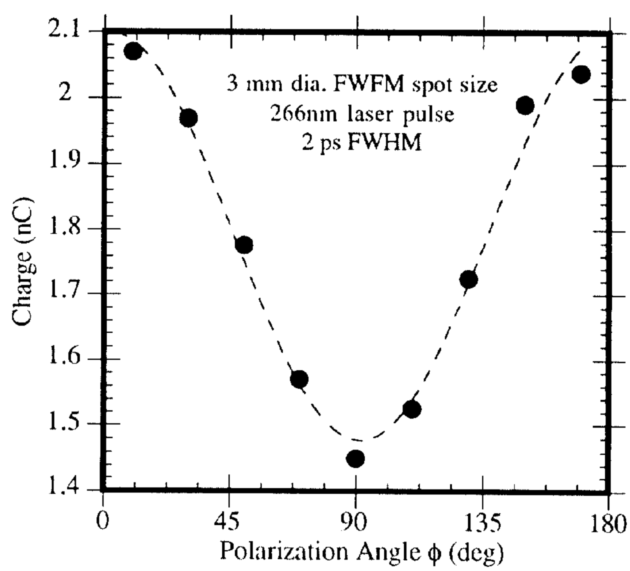

Figure 4: Charge measurements at 70° injection vs polarization angle

For laser spot sizes less than 3 mm in diameter, it was possible to inject the laser pulses at 2° incidence without impinging directly on the damaged area of the cathode. Careful quantum efficiency measurements were not taken under these conditions however a factor of 3 decrease in the quantum efficiency was observed from the undamaged portions of the cathode.

IV. DISCUSSION

Quantum efficiencies of $1x10^{-4}$ are surprisingly high for photoemission from Cu using 266 nm light (4.66 eV) since the photon energy is very close to the work function of Cu (4.65 eV). The quantum efficiency of Cu has been measured to be $1.5x10^{-5}$ using 248 nm light [4] and $6x10^{-5}$ using 193 nm light [5]. Typically the quantum efficiency is higher for light of shorter wavelength. Using the Fowler-Dubridge theory for photoemission [6], these previous measurements of quantum efficiency can be scaled for our wavelength of 266 nm predicting $\eta \approx 10^{-8}$. The quantum efficiency can be increased in large electric fields (>10 MV/m) through the Schottky effect. In order to increase η from 10^{-8} to 10^{-4} electric fields of almost 1 GV/m are necessary at the cathode surface. As was mentioned above, macroscopic fields at the cathode of only 50 MV/m were reached, however, in the damaged area electric field enhancement factors of 20 are possible due to the surface roughness. The enhancement of quantum efficiency from the damaged area over undamaged area could explain the factor of 3 decrease in quantum efficiency observed as the laser spot was directed away from the damaged area.

A more recent measurement of quantum efficiency ($1.4x10^{-4}$) for polished, clean Cu with low applied fields using 266 nm laser pulses was reported by Srinivassan-Rao *et al* [2]. Although this value agrees with our measurement, it implies that field enhanced emission did not occur and does not explain the difference in photoemission between the damaged and undamaged parts of the cathode.

The Fowler-Dubridge theory for one photon photoelectric effect predicts a linear dependence of charge production on incident laser energy. However, the measured charge vs laser energy manifests a saturation of charge output for laser energies above 50 μJ. The saturation can be explained by space charge effects near the cathode surface. When the electrons are produced by the laser pulse, they are emitted as a thin disk from the cathode: approximately 80 μm thick and 1 mm in diameter corresponding to the laser spot size on the cathode. The space charge electric field between the electron bunch and the cathode can be approximated by a surface charge density and its image charge in the cathode. Using this simple model, a space charge field equaling the accelerating field of 50 MV/m results from only .25 nC of charge. This value agrees with the 0° data.

The particle accelerator code, PARMELA[7], has been used to model this space charge effect. This code calculates the space charge forces between a user specified number of test particles as the particles are accelerated from the cathode in an rf gun. However, experimentally the space charge problem is complicated by the cathode damage. Because of this damage, most of the electrons could be produced from microemitters on the cathode surface. At these emitters the space charge could be worse. Despite these limitations in the computer modeling, the PARMELA simulation showed saturation similar to that of experimental data.

The increase in quantum efficiency for p-polarized vs s-polarized injection is probably due to the difference in the reflectivity of copper at these polarizations. The reflectivity of a copper mirror was measured as a function of incident angle for both s and p polarized 266 nm light. According to the generalized Fowler-Dubridge theory, η is proportional to absorbed laser energy. A 90% increase in absorption was measured for p-polarized light over s-polarized light predicting a 90% improvement of the quantum efficiency for p-polarized injection. The measured enhancement was only 50%. This discrepancy could be due to a difference in the relative reflectivities of the damaged cathode in comparison to those of the copper mirror.

V. CONCLUSIONS

The quantum efficiency measurement of Cu in a rf gun resulted in $\eta = 1x10^{-4}$. The photoemission from Cu under macroscopic electric fields of 50 MV/m appears to be enhanced by damage on cathode. However, for charge levels greater than .25 nC the quantum efficiency is reduced by space charge near the photocathode. Despite the limitations imposed by space charge, up to 3 nC is produced from the electron gun. For 70° laser injection, p-polarized light results in a 50% increase in quantum efficiency over s-polarized light probably due to their relative reflectivities.

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