

Studies of Linear and Nonlinear Photoelectric Emission for Advanced Accelerator Applications

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Abstract

Various electron emission properties of accelerator photocathodes were studied using short pulse lasers. The quantum efficiencies (QE's) of copper and magnesium were compared before and after above-damage threshold laser cleaning. Changes in the emission properties of copper photocathodes used in the UCLA RF photoinjector gun were observed by mapping the QE's of the cathode surfaces. The electron yield of thin copper films resulting from back-side illumination was measured. Multiphoton (nonlinear) emission was studied as a means of creating ultrashort electron bunches, and an RF gun Parmela simulation investigated the broadening of such pulses as they propagate down the beam line.

I. COPPER AND MAGNESIUM QUANTUM EFFICIENCY MEASUREMENTS

In a radio-frequency (RF) photoinjector gun, short pulse electron beams are created using a laser pulse incident on a photocathode placed in a high RF field accelerating structure. The laser is synchronized with the RF cycle to achieve maximum acceleration and minimum energy spread of the electron bunch. For high peak currents, a photocathode material should be chosen which has a high quantum efficiency at the laser wavelength. It must also be robust to withstand the high RF fields and high incident laser intensity, and should have a smooth, nonreactive surface for uniform emission over long periods of operation.

Copper and magnesium are two materials commonly used in these devices.^{1,2} The work function of copper is 4.6 eV and thus ultra-violet (UV) laser pulses are required to achieve linear photoemission. In the UCLA RF gun¹ these pulses are created by frequency quadrupling an amplified Nd:YAG laser pulse to obtain 266 nm (4.7 eV photon energy) radiation. Magnesium has a 3.7 eV work function and therefore may exhibit a higher electron yield than copper. However, Mg is more reactive than Cu and subject to greater surface contamination which can hinder photoemission.

A DC field test gun was devised to measure the QE's of copper and magnesium photocathodes. Laser pulses of 266 nm wavelength, 50 ps pulsewidth, and 3 mm spot size were sent through a hollow anode onto the cathode sample at normal incidence. The anode was biased at +5 kV and located 3 mm from the cathode, resulting in an electric field of 1.6 MeV/m. In the actual RF gun the electric field is 100 MeV/m, which enhances the electron emission via the Schottky lowering of the

potential barrier. No such enhancement was observed in the DC gun. Thus the QE of a photocathode in the RF gun is typically an order of magnitude greater than that of the same cathode measured in the DC gun. The anode-cathode system of the DC gun was enclosed in a vacuum system at a pressure of 10^{-6} torr. The energy of each laser pulse was measured on line by a photodiode placed behind a UV mirror in the laser line. The emitted charge was measured by a charge preamplifier placed across a 1 M Ω load resistor.

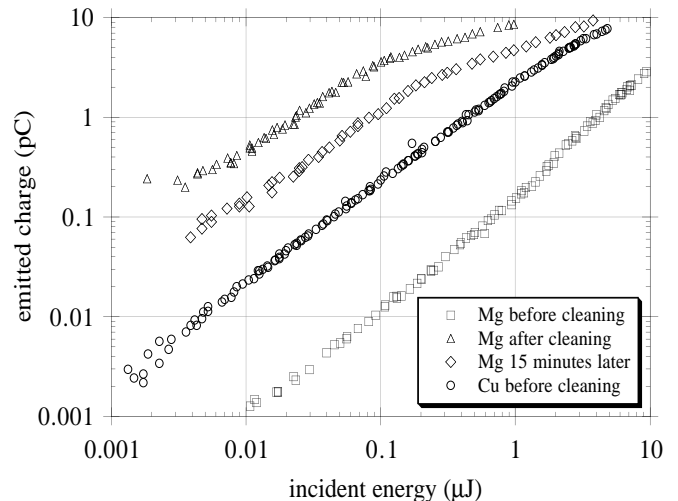


Fig. 1. Electron yields of Cu and Mg.

The cathodes were 1" diameter OFHC copper and 95% Mg-Zn-Al alloy samples hand polished to 1 μm . The QE of each sample was determined by varying the incident laser energy and measuring the corresponding emitted charge. For the single-photon (linear) photoelectric effect, the emitted charge should be directly proportional to the incident laser energy. The constant of proportionality of this relationship is the electron yield.

The results of the Cu and Mg measurements are shown in Fig. 1. The curves show the linear relationship between charge and laser energy at moderate charge levels -- at high charge levels the curves bend due to space charge saturation. Initially, the electron yield of copper was 2.2 pC/ μJ (QE = 1.0×10^{-5} electrons per photon) while the magnesium yield was only 0.15 pC/ μJ . We then performed above-damage threshold laser cleaning on the magnesium sample, and observed the electron yield increase to 33 pC/ μJ (a factor of 220 -- 15 times greater than Cu). However, within minutes the yield decayed to 10 pC/ μJ where it remained steady. Even in a vacuum of 10^{-6} the magnesium surface can quickly become contaminated and lose quantum efficiency. Similar cleaning on copper

showed a modest (factor of two) increase in QE but no such emission degradation over time. Although this technique enhances electron yield, the resulting damaged area may produce non-uniform emission which could impair the emittance of the accelerator beam.

II. CHANGES IN RF GUN PHOTOCATHODE EMISSION CHARACTERISTICS

In an RF photoinjector gun, the cathode is exposed to many adverse physical conditions: extreme RF fields, high voltage arcing during conditioning, impurities in the vacuum, and repetitive incident UV laser shots. These factors may induce physical changes on the surface of the photocathode which modify its photoemission characteristics. Such changes were observed for copper cathodes in the UCLA RF gun.³

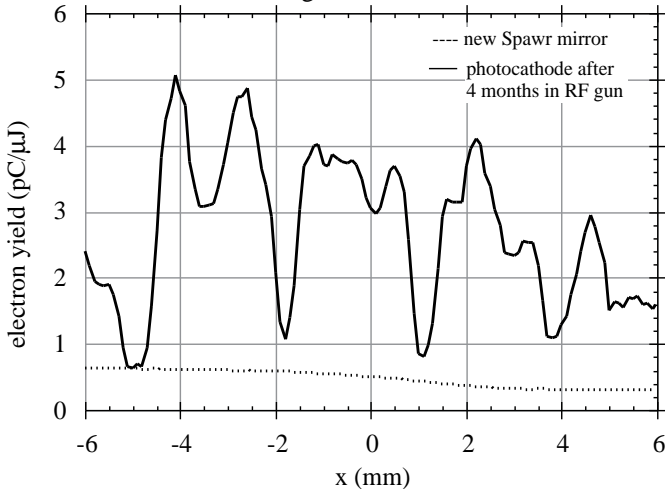


Fig. 2. Spawr polished RF photocathode.

In an attempt to understand the nature of these emission changes, the DC gun was used to create quantum efficiency maps of the cathode surfaces. This was done by focusing the input 266 nm laser pulse to a spotsize of approximately 100 μm , and then moving the cathode with the x,y feedthrough to illuminate different points on the surface.

The first cathode tested was originally polished by Spawr Industries to $\lambda/20$ for 10 μm light. It had been used in the RF gun for 4 months of operation, then removed after its quantum efficiency and emittance characteristics degraded. A QE surface map of this cathode after removal is shown in Fig. 2. Variations greater than a factor of five in the QE are observed across the surface. Such variations are not present on a newly polished Spawr copper mirror, shown for comparison.

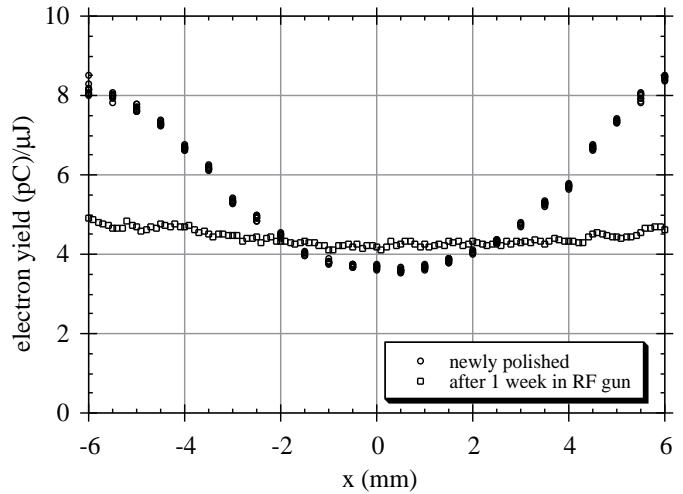


Fig. 3. Hand polished photocathode.

The second cathode was polished by hand to a 1 μm finish. It was installed in the RF gun for one week before its quantum efficiency and emittance characteristics began to deteriorate. Fig. 3 shows the QE maps of this cathode before and after the RF gun installation. Note that originally the electron yield was two times larger toward the edges of the cathode than at the center. This feature was not present for the new Spawr-polished mirror (Fig. 2), and thus seems to be a characteristic of the polishing method. After one week in the RF gun the QE map had changed, becoming fairly constant across the surface. No large scale variations were observed as on the previous cathode.

III. BACK ILLUMINATION OF THIN Cu FILMS

Synchronization of an electron bunch with a laser pulse is important in experiments such as the plasma beat wave accelerator. Using laser-induced photoemission to generate such electron bunches is an effective means of achieving this synchronization. However, if a photoinjector gun is part of an X-band or higher frequency linac, it may be difficult or impossible to illuminate the front surface of a photocathode with a laser pulse. If such a device is driven by a DC gun, it may be possible to circumvent this problem by employing a thin film photocathode that is illuminated from the back side of the film to produce electron emission from the front side. Although this technique will result in some loss of quantum efficiency, it may be useful in systems which do not require a high total charge.

To investigate this possibility, we measured the UV (266 nm) light transmission and electron emission properties of five different thicknesses of copper films. The measurements were done in the back illumination configuration of the DC gun. The films were deposited on 1" diameter fused silica windows and ranged from 270 \AA to 1490 \AA in thickness. The laser pulses propagated through the transparent substrate onto the back side of the copper film. The resulting photoelectrons were then collected on

the opposite (front) side by the hollow anode. A calibrated photodiode was placed after the hollow anode to measure the energy of the light transmitted through the film.

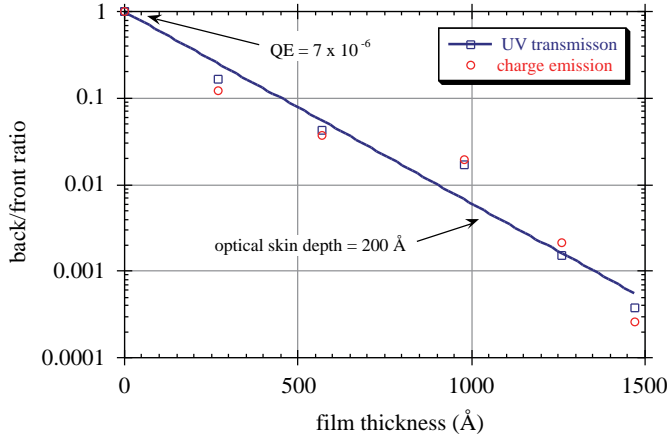


Fig. 4. Back Illumination of copper thin films.

The results are shown in Fig. 4. The exponential fit to the laser transmission data indicates an optical skin depth of 200 Å for 266 nm radiation. Note that the ratio of electrons emitted via back illumination versus front illumination is equal to the fraction of UV light transmitted through that film thickness. This shows that the number of electrons emitted from the front surface during back illumination is proportional to number of photons transmitted through the film to that surface. Thus the mean free path of the photoelectrons in the metal must be short compared to the optical skin depth -- only the electrons which absorb a photon very close to the front surface can be emitted.

Using back illumination on the 270 Å sample reduces the electron yield by a factor of eight due to the laser transmission losses through the film. A 266 nm laser system would then require 50 μJ of incident energy to produce 10 pC of charge. For a laser pulsewidth of 1 ps, the peak current would be 10 A. Thus reasonable currents can still be obtained with modest incident laser energies and pulsewidths, and even higher efficiencies could be achieved by using thinner photocathode films.

IV. MULTIPHOTON PHOTOEMISSION

For high laser intensities, photoemission of electrons can occur even for incident photon energies less than the metal work function. This can occur by an electron consecutively absorbing more than one photon in order to gain enough energy to overcome the surface potential barrier. The instantaneous electron current density emitted in such a process is given by the relation $J = a_n I^n$, where I is the laser intensity, n is the minimum number of photons required to overcome the metal work function, and a_n is a constant depending on the material and the photon energy. For a given laser pulsewidth and spotsize, this can be rewritten in terms of the emitted charge Q and the incident energy E as $Q = b_n E^n$.

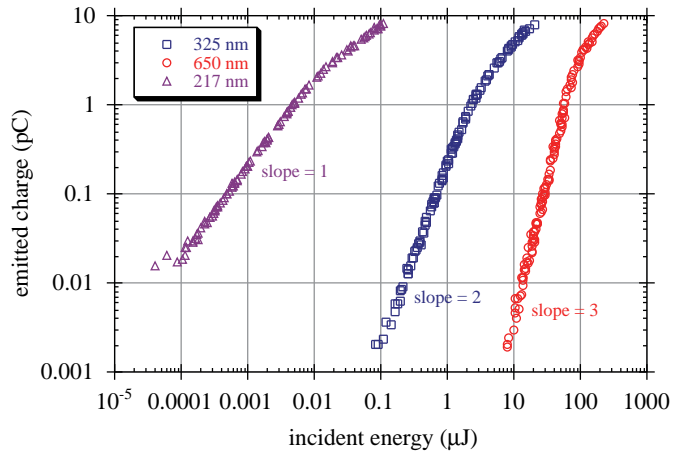


Fig. 5. Multiphoton emission from copper.

Multiphoton emission was investigated using the DC gun front illumination setup. An ultrafast dye laser and dye amplifier system were used to create incident laser pulses of 650 nm wavelength, 500 fs pulsewidth, and 3 mm spotsize. Second and third harmonic generation crystals could be placed in the laser line to generate 325 nm and 217 nm pulses. The photon energies for the 650, 325, and 217 nm wavelengths are 1.9 eV, 3.8 eV, and 5.7 eV respectively. These wavelengths produce 3-2-, and 1-photon photoemission processes in copper. The experimental charge vs. energy traces for these processes are shown in Fig. 5. The slopes of the lines on the log vs. log scale reflect the linear, square, and cubic dependence of the emitted charge on the laser energy for the three wavelengths. Multicolor, multiphoton emission has also been observed.⁴

V. ELECTRON TRANSPORT IN THE RF GUN

Multiphoton emission could be utilized in an RF gun to produce electron bunches that are narrower than the incident laser pulse. The I^n dependence of the photoemission current density implies that a gaussian laser pulse will produce a gaussian electron bunch that is narrower in time by a factor of \sqrt{n} . If a 500 fs FWHM laser pulse at 1.0 μm wavelength ($E = 1.2$ eV per photon) is used to induce photoemission on a copper cathode, the resulting 4-photon emission process will produce an electron bunch that is initially 250 fs in length. A Parmela simulation which modelled the UCLA RF gun was run to investigate the temporal broadening of 250 fs, 30 pC electron bunches of different spot sizes during transport through the gun (Fig. 6). The large spot size bunches were broadened by the fringe fields of the RF and solenoid, while the small spot size bunches were subject to a lesser broadening due to space charge (a factor of 2 for a 1 mm radius spot size). This space charge broadening could be reduced by using a laser pulse train to produce many charge bunches, each containing a fraction of the total charge necessary for the experiment. This method is currently being investigated.

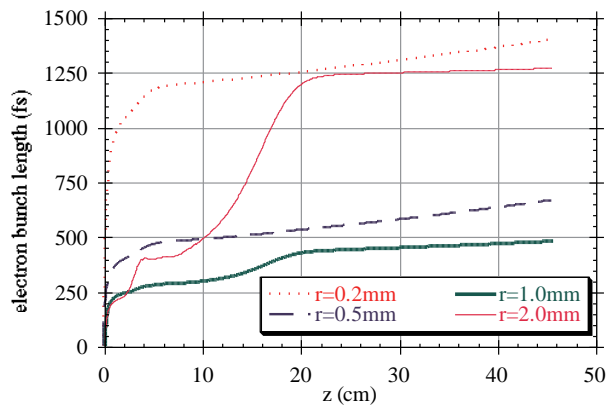


Fig.6. Electron bunch lengthening in the RF gun and transport line. The RF cells end at 8 cm and the focusing solenoid ends at 45 cm.

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