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**PHOTOEMISSION USING FEMTOSECOND
LASER PULSES***

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Photoemission Using Femtosecond Laser Pulses

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ABSTRACT

Successful operation of short wavelength FEL requires an electron bunch of current >100 A and normalized emittance < 1 mm-mrad. Recent experiments show that RF guns with photocathodes as the electron source may be the ideal candidate for achieving these parameters. To reduce the emittance growth due to space charge and RF dynamics effects, the gun may have to operate at high field gradient (hence at high RF frequency) and a spot size small compared to the aperture. This may necessitate the laser pulse duration to be in the subpicosecond regime to reduce the energy spread. We will present the behavior of metal photocathodes upon irradiation with femtosecond laser beams, comparison of linear and nonlinear photoemission, and scalability to high currents. Theoretical estimate of the intrinsic emittance at the photocathode in the presence of the anomalous heating of the electrons, and the tolerance on the surface roughness of the cathode material will be discussed.

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I. Introduction

In recent studies, it became clear that extending the FEL to wavelength shorter than $1000\text{\AA}$ requires a good quality and high brightness electron beam source preferably operating at high duty cycle. A preliminary study [1] indicates that for a $1\text{\AA}$ FEL operation, the electron bunch should have a bunch length of 40 fs with an energy spread of $<0.2\%$, a normalized emittance $<0.12\pi\text{-mm-mrad}$, a current $>2\text{ kA}$ with a total charge of 40 pC emitted from a radius of 0.3 mm. The present BNL RF photocathode gun has achieved 2 nC in $\sim 5\text{ ps}$ with an energy spread of 0.4% and a normalized emittance of $4\pi\text{-mm-mrad}$ from a radius of $\sim 0.5\text{ mm}$. Improving these performance to meet the FEL operation below the $1000\text{\AA}$ regime may require substantial modification to the RF gun design. In this paper, we describe the results of an ongoing research on metal photocathodes in DC extraction field. A femtosecond laser is used to generate the high current electron beam directly. The high peak power femtosecond laser beam facilitate the nonlinear photoemission thereby easing the requirement of UV photon for metal cathodes. However, additional emittance growth due to the heating of the electrons imparted by the ultrashort laser and the surface roughness of the metal might degrade the quality of electrons. Detail of these phenomena will be discussed.

In a previous study, [2] we have proposed a scheme to examine the possibility of the nonlinear photoemission process overtaking the linear process to give better quantum yield using ultrafast lasers, and identify some possible complications. Since the quantum efficiency increases as P^{n-1} , where P is the incidence laser intensity and n is the order of the multiphoton process, higher electron yield with short pulse duration can be obtained from multiphoton photoemission before the laser intensity reaches the damage threshold. Figure 2 compares the linear versus nonlinear processes from different metal photocathodes which we have studied. For the same laser power density, quantum efficiency of the nonlinear photoemission is expected to over take that of the linear process at $\sim 10^{10}\text{ W/cm}^2$. In this study, we will attempt to address this possibility.

II. Experimental Setup

The laser oscillator used in this experiment is a colliding pulse mode-locked (CPM) dye laser operating at the center wavelength of 625 nm ($\sim 2\text{ eV}$) with a pulse duration of $\sim 100\text{ fs}$, at a repetition rate of $\sim 80\text{ MHz}$ and an average power of $\sim 25\text{ mW}$ per beam, with a total of 2 output beams. One of the oscillator output beam is subsequently amplified in a dye cell using a N_2 laser as the pump source to generate $2\text{ }\mu\text{J}$ of energy at 625 nm

with a pulse duration of 280 fs at 10 Hz repetition rate. Measurements were made both with the CPM oscillator alone and with the added amplifier to achieve the high electron current density. Figure 1 shows the complete experimental setup.

The laser beam is directed to an experimental cell containing the cathode and an anode with a DC extraction gradient of ≤ 10 MV/m at a pressure of 10^{-8} to 10^{-9} Torr. The electrons leaving the cathode are measured with an electrometer when the quasi-CW CPM oscillator is used. To examine the behavior at higher electron current with the amplified CPM laser, the charge output from the cathode is measured for each pulse using the pulse shaping technique. Data are collected on a digital oscilloscope for further analysis.

III. Results and Discussion

A. Femtosecond Laser Oscillator - Low Charge Regime

Several photocathodes were investigated and some of the results are shown in Figure 3. Since the incident photon energy (2 eV) is lower than the work function of the metals investigated (4 to 4.5 eV), multiphoton process are invoked and the order of the measured nonlinearity is in agreement with the number of photons required to overcome the work functions. Under simple scaling law, the quantum efficiency for multiphoton mediated electron emission increases as P^{n-1} , where P is the intensity of the laser beam on the photocathode and n is the nonlinearity of the process. The maximum current density with this optical arrangement is ~ 2 A/cm² from surface-plasmon enhanced electron emission of a Au metal film. [3] This yields a quantum efficiency of $\sim 10^{-7}$ at laser intensity of $\sim 10^7$ W/cm², while typical non-enhanced quantum yield with 2 eV photon is $\sim 10^{-9}$. Using this nonlinear process, we have obtained the electron and the corresponding laser autocorrelations, see Figure 3. The electron high-order correlated signals strikingly resemble those of the laser pulse width. No surface damage and no thermally-assisted photoemission is observed from the photocathodes. Therefore, higher current output with more intense femtosecond laser beam seems possible.

B. Amplified Femtosecond Laser - High Charge Regime

In this initial study, only optically polished coppers have been investigated. A charge of 60 fC has been obtained when the copper photocathode is irradiated with ~ 2 μ J of 625 nm, ~ 280 fs, 10 Hz repetition rate laser beam focused to a spot size of $\sim 100 \times 70$ μ m². The corresponding current and current density are 0.25 A and 3.4 kA/cm². The dependence of the charge on the laser input intensity (see Figure 3, [•]), indicates a nonlinearity between

1 and 2 photon process. The quantum efficiency based on these results is $\sim 10^{-7}$ at the laser intensity of $\sim 10^{11}$ W/cm². Scaling of the low intensity data to this intensity level leads to an expected quantum efficiency of $\sim 10^{-5}$ at a corresponding current density of 10^6 A/cm². The discrepancy between the results using low and high laser intensity are currently under investigation.

To examine the photoelectrons at the UV wavelength regime, the output of the amplified CPM laser was frequency doubled using a BBO crystal to 4 eV. After proper filtering, the 4 eV beam is loosely focused on the Cu photocathode. The intensity dependence of the charge (Figure 3, [+]) indicates a 1-photon process. The maximum charge extracted under these conditions is ~ 100 fC from an area of $\sim 90 \times 60$ μm^2 . Since the pulse duration is expected to be ~ 200 fs at 313 nm, a peak current of 0.6 A and a maximum current density of ~ 10 kA/cm² are then achieved. The quantum efficiency is $\sim 10^{-6}$, which is in reasonable agreement with other measurements using 4.66 eV photon. Based on these preliminary measurements, UV photon seems to be more effective than visible photon in extracting electrons from metals even at these high intensity. More experiments are in progress to examine the photocathodes under femtosecond UV laser illumination.

IV. Intrinsic Emittance Growth Due to Hot Electron Generation

One consequence of using ultrashort laser pulses to study laser interaction with metal is the generation of hot electrons on the metal surface. [4] Since the electronic heat capacity is small and the photon pulse duration is shorter than the electron-phonon interaction time, the temperature of the electrons become out of equilibrium with the lattice phonons. Therefore, significant laser-induced thermoelectrons are generated which might broaden the energy and momentum spectra of the emitted electron, and hence, the emittance. However, laser damage to metal photocathodes can be avoided with ultrashort laser pulse even at fairly high intensity level. This phenomenon requires more attention when experiments are done with amplified femtosecond lasers.

Figure 5 shows a numerical calculation of electron and lattice temperature profiles based on a heat diffusion model through two coupled differential equations. At the typical operating intensity in our measurement, 10^{11} W/cm², the laser-induced electron temperature rises to ~ 0.4 eV in a duration of < 1 ps for copper. While at 10^{12} W/cm², the electron temperature approaches 1 eV. This temperature rise, however, are tolerable in a typical RF photoinjector. The excess kinetic energy of the electron in photoemission process is $\text{K.E.} = nh\nu - \phi$, which is typically a few tenths of a eV. Hence, the kinetic energy of the electrons due to photon energy and thermal energy due to hot electrons are expected to be

comparable, if the assumption that the intrinsic emittance, $\epsilon = \frac{1}{2}r_c\sqrt{\frac{kT}{mc^2}}$, can be applied to the hot electrons.

V. Intrinsic Emittance Growth Due to Surface Roughness

The effect of the extraction field on the transverse energy of the photoelectrons can be attributed to the energy acquired as they escape the surface and arrive at a plane where the field is normal to the macroscopic surface. This effect is related to the smoothness of the surface and the modification of the direction of the field lines due to the roughness. For surface irregularity much less than the wavelength of the RF wave, the field lines behave as in DC. For any single conical irregularity with a cone opening angle β , the electrons experience a field normal to the microscope surface once they leave the surface. Figure 7 shows the variation of the *transverse* component of the field at a distance very near the tip of the microscope surface for a cone angle ranging from 0° (a delta-like sharp point) to 180° (a perfectly smooth surface). From this calculation, it can be seen that for $\beta = 60^\circ$, typical for a metal mirror, and an applied field of 100 MV/m, an electron travelling a distance of $10\text{\AA}$ in this field would acquire an energy of 3.5 eV at $100\text{\AA}$ away from the microscopic surface. This 3.5 eV would contribute to the intrinsic transverse emittance. Comparison of the contributions to the transverse velocity by various effects indicate that the surface roughness may be the predominant contributor to the emittance of the high brightness electron source, which is a pre-requirement of short wavelength FEL operation.

Recently, preliminary emittance measurements done at BNL with a rather severely optically damaged, and many conical irregularity, Cu photocathode in the RF cavity indicate that no adverse emittance growth is observed. This result tends to suggest that perhaps the actual photoemission is only occurring at the tip of each conical surface. Therefore emittance is very much preserved. Detailed investigation, both experimental and theoretical, are needed to understand the role of surface roughness in emittance measurements.

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Fig.1 Experimental setup for nonlinear photoelectric emission

Fig.2 Comparison of Linear vs. Nonlinear Photoemission

Peak Electron Current Density (A/cm^2)

Peak Laser Power Density (W/cm^2)

Fig.3 Nonlinear Photoemission Using Femtosecond Laser

Fig.4 Electron (—) and Laser (---) Temporal profiles

Fig.5 Amplified CPM laser pulse

Fig.6 Calculated Electron (—) and Lattice (--) Temporal Profiles

Fig.7 Transverse field on the surface of the irregularity, normalized to the applied field for difference distance from the surface

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