Two-photon photoemission from a copper cathode in an X-band photoinjector

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This paper presents two-photon photoemission from a copper cathode in an X-band photoinjector. We experimentally verified that the electron bunch charge from photoemission out of a copper cathode scales with laser intensity (I) square for 400 nm wavelength photons. We compare this two-photon photoemission process with the single photon process at 266 nm. Despite the high reflectivity (R) of the copper surface for 400 nm photons ($R = 0.48$) and higher thermal energy of photoelectrons (two-photon at 200 nm) compared to 266 nm photoelectrons, the quantum efficiency of the two-photon photoemission process (400 nm) exceeds the single-photon process (266 nm) when the incident laser intensity is above 300 GW/cm². At the same laser pulse energy (E) and other experimental conditions, emitted charge scales inversely with the laser pulse duration. A thermal emittance of 2.7 mm-mrad per mm root mean square (rms) was measured on our cathode which exceeds by sixty percent larger compared to the theoretical predictions, but this discrepancy is similar to previous experimental thermal emittance on copper cathodes with 266 nm photons. The damage of the cathode surface of our first-generation X-band gun from both rf breakdowns and laser impacts mostly explains this result. Using a 400 nm laser can substantially simplify the photoinjector system, and make it an alternative solution for compact pulsed electron sources.

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I. INTRODUCTION

Single-photon photoemission is the standard photoemission process used in electron guns for both metallic [1] and semiconductor cathodes [2]. One usually chooses a laser wavelength such that the energy of a single photon just exceeds work function of the cathode material. Compared to semiconductor cathode, copper cathodes can sustain very high gradient electric fields, above 200 MV/m, survive poor vacuum conditions down to 10⁻⁷ torr scale, and have long lifetimes. Copper cathodes in radio frequency (rf) guns can recover from damage and pollution respectively by rf processing and laser cleaning. The copper cathode in the S-band gun of the Linac Coherent Light Source has been in use 24/7 for the past several years, the copper cathode in the X-band gun at this facility has been used for two and a half years. The assets of metallic cathodes are unfortunately counterbalanced by its flaws, particularly its low quantum efficiency (QE) of normally 10⁻⁵, and the necessity of using UV light. The low QE requires high pulse energy. This also prevents using copper cathodes in high repetition-rate electron guns, because the thermal

effects deteriorate its performance and even cause damage when operating at kHz to tens of kHz repetition rates.

We experimentally studied the two-photon emission on a copper cathode [3,4] to determine the adequacy of using a 400 nm wavelength, with a view to simplifying laser systems and a possibility of increasing the QE [5–8].

The work function ϕ of bulk copper is approximately 4.5 to 5.1 eV (we use 4.7 eV in this paper), it requires ultraviolet (UV) photons and rf fields to overcome its work function to generate photoelectrons with single photons. The emitted charge is linearly proportional to the input UV laser pulse energy, with an efficiency of QE. The QE of copper cathodes varies between 10⁻⁶ to 10⁻⁴, which depends on the surface roughness, the presence of contaminants, and the field applied. In this X-band gun, the copper cathode has a relatively low QE of 2×10^{-5} . It requires 100 μ J UV pulse energy to generate electron charge of 420 pC. Conventionally, UV pulses near 266 nm are usually obtained from sum-frequency generation between a 400 nm second harmonic generation (SHG) and a 800 nm fundamental from Ti:sapphire laser systems, where the conversion efficiency to the third harmonic is usually less than 15%. In this third-harmonic generation (THG) process, the THG pulse energy is proportional to the intensity cube of 800 nm fundamental, and any amplitude fluctuation is amplified in this nonlinear process. Although the pulse energy can be stabilized by feedback, it would add complexity to the laser system.

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When the peak intensity of laser pulses is sufficiently high, the multiphoton photoemission process can occur. Three-photon emission from a copper cathode has been observed with a higher QE than the single-photon emission when incident intensity is higher than 10 GW/cm^2 , and its mean thermal emittance is similar to UV photoemission at 266 nm [9]. Two-photon photoemission from a copper cathode has not been demonstrated before, it only needs a frequency doubling crystal compared to the THG system [10], and requires a similar intensity threshold to reach the same QE compared to three-photon emission, so that it could be a complementary method of generating photoelectrons.

Here we present a two-photon photoemission process from 400 nm laser pulses on a copper cathode. The 400 nm laser pulses are obtained by frequency doubling 800 nm fundamental from a commercial Ti:sapphire laser system. Its QE exceeds the single-photon process when the incident laser intensity is larger than 300 GW/cm^2 . We have demonstrated generating 100 pC bunch charge with 52 μJ incident laser pulse with laser beam size of 1 mm full width at half maximum (FWHM). The emitted charge scales with laser pulse energy squared, and is inversely proportional to the laser pulse duration at the same laser pulse energy.

II. EXPERIMENTAL APPARATUS, RESULTS, AND DISCUSSION

The experimental schematic is depicted in Fig. 1. The laser system is a commercial Ti:sapphire laser system. It consists of a Ti:sapphire oscillator (Tsunami, Spectra Physics) providing 20 nm bandwidth pulses at 800 nm, and a Ti:sapphire regenerative amplifier (Elite, Coherent) which amplifies the pulse energy to 4 mJ. The laser system has a repetition rate of 600 Hz, but is picked up at 300 Hz by an acousto-optic modulator. Chirped laser pulses of 200 ps pulse duration are then transported to the accelerator inside a cement tunnel 20-m downstream by an image-relaying system (lens 1 in Fig. 1). Mirror loss along the transport reduces the laser pulse energy down to 3 mJ. At arrival on the optical table adjacent to the accelerator, chirped pulses are compressed via a four-path single-grating compressor combined with a retroreflector. With 20 nm bandwidth, the pulse can be compressed down to 50 fs full width at half maximum (FWHM). Its pulse duration can be tuned by adjusting the path length between the retroreflector and grating, whose group velocity dispersion is $-5000 \text{ fs}^2/\text{mm}$. The pulse energy is 2.2 mJ after the compressor.

Pulse durations of 800 nm at the output of the compressor were measured by a single-shot autocorrelator, the compressor actuator position vs pulse duration is plotted in Fig. 2(a), the green curve is the theoretical calculation based on different group velocity dispersions, and it agrees well with the data. Some sample autocorrelation traces are

FIG. 1. Experiment schematic of the two-photon emission from a copper cathode of an X-band photoinjector (not to the scale). Lens 1 is the imaging relaying lens, lens 2 images an iris onto the cathode. HWP, half-wave plate; BS, beam splitter; VCC, virtual charge-coupled device camera; PS, phase shifter; RMO, radio master clock; YAGS, yttrium aluminum garnet screen; OTRS, optical transition radiation screen; PS, phase shifter; SLED, SLAC linac energy doubler. The solenoid has the bucking coil that makes sure the magnetic field on the cathode is zero. Klystron #1 supplies energy to SLED, which doubles the energy and lowers the repetition rate of the klystron output pulses. PS1 and PS2 adjust the amplitudes and phases of SLED output rf pulses to the gun, PS3 adjusts the phase of SLED output rf phases to the linac. YAGS collects charge on it, and is used to phase the 5.5 cell X-band rf gun. RMO provides the master radio clock to the laser oscillator and the klystron, which are both synchronized to the timing of the RMO.

shown in Fig. 2(b). These 800 nm fundamental wavelength pulses go through a $500 \mu\text{m}$ thick type-I beta barium borate (BBO) crystal ($\theta = 29.2^\circ$), and are frequency doubled to 400 nm. The phase matching bandwidth of this $500 \mu\text{m}$ SHG BBO crystal is 10 nm, which is lower for 20 nm of transform limited 50 fs FWHM pulse at 800 nm. The 10 nm lower bandwidth would elongate the pulse, but most of the energy is still in the main lobe, therefore, we still treat the 400 nm pulse duration as $1/\sqrt{2}$ of the 800 nm fundamental pulses in the later part of this paper. A half-wave plate (HWP) before the BBO crystal rotates the input polarization of the 800 nm fundamental, it changes the phase match condition, and adjusts the laser power. Two dichroic mirrors reflect 400 nm second-harmonic generation (SHG), transmit 800 nm fundamental, and pulse energy of the SHG is up to 0.9 mJ when the system is optimized. Then the laser beam overfills an adjustable iris, it is reflected by two metal mirrors, and goes through a 75 cm (later changed to 100 cm) focal length planoconvex lens (lens 2 in Fig. 1) to form a 2:1 (3:1) image on the copper cathode. A flip mirror can be inserted in the laser beam path to reflect the laser beam on a power meter to measure laser pulse energy. The laser beam is reflected by a

FIG. 2. Measured laser pulse durations and autocorrelations at 800 nm. (a) Compressor actuator position vs pulse duration in FWHM, dots are experimental data, and the green curve is fitted by a model based on group velocity dispersion of the single-grating compressor. (b) Sample autocorrelation traces for pulse duration of 60, 130, 300, and 500 fs FWHM.

50/50 beam splitter (later a dielectric mirror at 400 nm, in order to have more laser pulse energy on the cathode), part of it then enters the rf gun enclosure, and the other part goes into a virtual cathode, a charge-coupled device camera after sufficient attenuation. The pulse energy before the entrance vacuum window is up to 0.3 mJ (0.6 mJ) when laser system parameters are maximized. The vacuum window and the vacuum injection mirror are measured to have efficiency of 0.7, and the laser energy on the cathode is up to 0.2 mJ (0.4 mJ). The incident angle of the laser beam on the cathode is approximately 3° . The surface of the copper cathode has a R of 0.48 at 400 nm [11], and half of the light is reflected downstream the linac beam line. In the later part of this paper, when calculating the QE, unless otherwise specified, we only count photons that are not reflected from the surface of the cathode, whose pulse energy is $E(1-R)$.

The emittance is calculated from beam size measurements on an optical transition radiation (OTR) screen, varied by scanning the strength of a quadrupole magnet upstream of the OTR screen. The reflection of 400 nm SHG laser beam goes downstream to the OTR screen, and optical low-pass filters are installed to filter out the 400 nm for those quad-scan emittance measurements.

The X-band rf gun has 5.5 cells, it can provide up to 200 MV/m peak field gradient at the cathode, and it normally operates at 50 degree injection phase in this experiment. If not mentioned otherwise, the rf field value is the peak field value, and the operating point is 50 degrees from the zero crossing. The higher peak field on the cathode can freeze the Coulomb forces between electrons, and preserve the thermal emittance in the photoemission process. The performance of this X-band photoinjector was elaborated and discussed in [12]. In a n -photon photoemission process, the emitted current density and laser intensity at photon energy $h\nu$ can be described by the Fowler-Dubridge theory [13–16],

$$J_n(h\nu) = a_n A \left(\frac{e}{h\nu} \right)^n (1 - R_v)^n I^n T_e^2 F \left(\frac{n h \nu - e \varphi}{k_b T_e} \right), \quad (1)$$

where a_n is a constant related to the likelihood of n -photon photoemission, $A = 120 \text{ A/cm}^2 \text{ K}^2$ is the Richardson constant, e is the electron charge, R_v is the reflectivity of optical frequency ν , I is the laser intensity, T_e is the temperature on the surface of the cathode, k_b is Boltzmann's constant, φ is the work function of the cathode, $F(x) = \int_0^\infty \ln(1 + e^{-y+x}) dy$ is the Fowler function. In our experiment, $J_2(h\nu)$ stands for the current of two-photon emission with photon wavelength at nm, and $J_1(3/2 h \nu)$ stands for the current of single-photon emission at UV wavelength of 266 nm. $J_2(h\nu)$ becomes larger than $J_1(3/2 h \nu)$ when laser intensity is larger than a critical value I_{cr} , given by Eq. (2), this two-photon process has a higher electron yield compared to the single-photon photoemission process:

$$I_{cr} = \frac{\frac{2}{3} a_1 (1 - R_{3/2\nu}) F \left(\frac{3/2 h \nu - e \varphi}{k_b T_e} \right) h \nu}{a_2 (1 - R_v)^2 F \left(\frac{2 h \nu - e \varphi}{k_b T_e} \right) e}. \quad (2)$$

It was measured that $a_1 \sim 10^{-14} \text{ cm}^2 \text{ A}^{-1}$ [15] and $a_2 \sim 10^{-25} \text{ cm}^4 \text{ A}^{-2}$ [16], and assuming that the blue (400 nm) and UV (266 nm) light have reflectivity of 0.48 and 0.33 respectively, and temperature of electrons at several thousand K [17], we calculate the critical power to be $I_{cr} \sim 100 \text{ GW/cm}^2$. The highest peak intensity in our experiment is 80 GW/cm^2 , that is smaller than the damage threshold of copper [18]. However, it is also known that in the presence of the MV/m electric field, the damage threshold of copper could be 1 or 2 orders magnitude lower. Furthermore, at the laser pulse duration 40 fs FWHM at 300 Hz, at the critical power, the average fluence corresponds to 1.2 J/cm^2 , which is comparable to the ablation threshold of copper in air [19,20]. Most of the time, pressure of the gun vacuum is usually 10^{-9} torr. Thus, there was no immediate observable damage to the cathode. We did observe the decrease of the QE after eight hours. Processing of the gun several hours with rf power and without the laser beam can remove the contamination

FIG. 3. Electron bunch charge and absorbed laser intensity. (a) Incident laser pulse energy E vs electron bunch charge. (b) Incident laser intensity I vs electron charge density. The large scatter of data points mainly comes from the time jitter between the laser pulses and rf field inside the gun, it also comes from the amplitude and phase noise from the rf field itself. Both of them can change the instant field at the cathode, and change the QEs, thus the charges of electron bunches. Because this is an X-band photoinjector, therefore it is more sensitive to the phase noise compared to the traditional S-band photoinjectors. Meanwhile, the jittering of rf field changes the effective work function of the copper cathode, and also contributes to the large scatter of data in Figs. 3 and 4.

and recover the QE. Previous work has also demonstrated that the overall laser-induced damage threshold is higher at longer wavelength because of the lower effective cross section in the multistep multiphoton process [21].

We measured the laser power vs emitting charge, the laser power is measured on a power meter, and electron charge is collected by a Faraday cup just after the gun. In the experiment, we rotate a HWP before the BBO crystal to adjust the laser power. In Fig. 3(a), for blue circled data points, the last optic before the vacuum is a 50/50 beam splitter, and the beam spot size is 1.5 mm FWHM on the cathode; for green square and red diamond data points, this beam splitter is replaced by a dielectric mirror, and the beam sizes are 1.5 and 1 mm FWHM on the cathode respectively. It is apparent that electron charge scales as the square of laser pulse energy, as expected from a two-photon photoemission process. The dashed curves are quadratic fits of the data to guide the eye. Figure 3(b) plots the laser intensity vs electron charge density. The curve has a slope of 2.0 ± 0.1 , which confirms that the emitted charge is generated from a two-photon photoemission process. The curve of single-photon photoemission from UV at 266 nm with QE of 10^{-5} is also plotted on the same graph, it crosses the two-photon photoemission curve at a laser intensity of $I_{\text{cr}} \sim 300 \text{ GW}/\text{cm}^2$. The QE is relatively low when intensity is below the critical intensity I_{cr} , it reaches 10^{-5} at I_{cr} , and exceeds the typical single-photon QE of 10^{-5} when intensity is larger than I_{cr} . It is worth noting that the copper cathode has a reflectivity of 0.48 for 400 nm as reported in [11], thus, in order to utilize this high QE of the two-photon photoemission process, antireflection coating is required on the surface of the copper cathode.

We also measured the charge at different rf field gradients on the surface of the cathode. Higher gradient lowers the effective work function φ to $\varphi - \sqrt{\frac{e\beta E_0 \sin \theta}{4\pi\epsilon_0}}$, and

makes the photoemission process more efficient, where β is the enhancement factor, $E_0 \sin \theta$ is the rf field at injection phase θ , ϵ_0 is the absolute permittivity. We measured the photoemission at the field gradient of 140 and 200 MV/m as shown in Fig. 4, the enhancement factor is 1.5 in this experiment by fitting the data. Although higher field gradients increase dark currents, it increases the QE as well. The QE at 200 MV/m is substantially higher compared to its value at 140 MV/m.

We studied the photoemission at different input laser pulse durations as well. The charge emitted from a photocathode can be described by the following equation:

$$Q = J\tau A = C I^2 \tau A = C \frac{E^2}{\tau A}, \quad (3)$$

FIG. 4. Absorbed laser pulse energy $E(1-R)$ vs electron bunch charge. The dashed lines are quadratic fits of the data. The E_0 is the peak field, and the gun operates at 50 degrees from zero crossing. The reason for large scatter of data points is the same as in Fig. 3.

FIG. 5. Laser pulse duration and electron bunch charge. (a) Absorbed laser pulse energy $E(1-R)$ vs electron bunch charge at different pulse duration. (b) Laser pulse duration vs electron bunch charge at 30 μJ laser pulse energy, the dashed line is the fit of $1/\tau$, the error bars are calculated from Fig. 5(a).

where Q is the emitted charge, J is the charge current on the surface, τ is the laser pulse duration, A is the area of the laser spot area, I is the laser intensity, E is the laser pulse energy. Therefore, the charge is inversely proportional to the pulse duration. The pulse duration of the 800 nm fundamental can be tuned by adjusting path length in the pulse compressor, and the 400 nm SHG pulse duration is assumed to have $1/\sqrt{2}$ of the pulse duration as the 800 nm fundamental pulses, when the group velocity mismatch inside the 500 μm BBO crystal is negligible. We measured the bunch charge at different pulse durations with beam size σ of 0.4 mm. For the same pulse energy, shorter pulse duration has higher QE, because of its higher peak intensity. The data are depicted in Fig. 5; Fig. 5(a) shows the laser pulse energy vs bunch charge at laser pulse duration (266 nm) of 36, 43, and 57 fs FWHM. Figure 5(b) shows the laser pulse duration vs bunch charge at 35 μJ pulse energy; the data was derived from Fig. 5(a) where the pulse energy is 35 μJ . At this pulse energy, the emitted charge does scale inversely proportional to pulse duration τ , as expected from Eq. (3). From the data, it is calculated that $C = 5 \times 10^{-22} \text{ A m}^2/\text{W}^2$, which corresponds to $a_2 = 10^{-25} \text{ cm}^4/\text{A}^2$.

We have also measured the emittance at very low bunch charges as the thermal emittance from the copper cathode

downstream the linac at 70 MeV electron beam energy; the result is presented in Fig. 6. Figures 6(a) and 6(b) depict a typical laser beam spatial profile and laser beam size vs emittance at very small charge respectively. Electron beam size is measured on an OTR screen at various quadruple strengths, and emittance is calculated from the transfer matrix. Thermal emittance is given by $\epsilon_n = \sigma \sqrt{\frac{MTE}{m_e c^2}} = \sigma \sqrt{\frac{2h\nu - e\phi}{m_e c^2}}$, where σ is laser beam size (assuming that the spatial distribution obeys normal distribution $N(0, \sigma) \sim \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{r^2}{2\sigma^2}}$), MTE is the mean thermal energy, $h\nu$ is the photon energy, ϕ is the work function, e is the electron charge, m_e is the electron mass, and c is the speed of light.

The measured thermal emittance is approximately 2.7 mm mrad/mm, which is 60 percent larger compared to the theoretical predictions 1.7 mm mrad/mm, similar to the case of single-photon emission at 266 nm, and three-photon emission at 800 nm [9]. The large value of the thermal emittance can be understood by the poor surface uniformity of the cathode. After two years from commissioning, the cathode surface was noticeably damaged. Both rf breakdowns and too high fluence of short laser pulses generated ripple patterns and scratches on the cathode

FIG. 6. Laser beam spatial profile (a) and beam size vs emittance (b) at very low bunch charge. The red line is linear fit of the data.

surface. As electric field is normal to the surface of those irregular features, the transverse momentum spread increases, the emittance is 2.7 mm-mrad per rms mm.

We have demonstrated the two-photon photoemission on a copper cathode in an X-band photoinjector. The QE of the two-photon photoemission exceeds the single-photon process at a laser intensity of 300 GW/cm², the electron charge yield scales inversely with laser pulse duration at the same laser pulse energy. The two-photon photoemission requires a simpler laser system over a conventional UV laser system, and could be useful for future photoinjector applications.

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