MULTIPHOTON EMISSION FROM CESIUM TELLURIDE PHOTOCATHODES

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Abstract

The High-Brightness Electron Source Lab (HBESL) at Fermilab operates an L-band RF gun (1.3-GHz) that incorporates a Cesium Telluride (Cs_2Te) photocathode illuminated by an ultra-short (sub-100 fs) laser pulses. In this contribution we report recent studies on exploring the electron beam emission using 800 nm laser pulses (instead of the 266 nm nominal wavelength used for linear photoemission).

INTRODUCTION

Photocathodes are excellent sources for production of short electron bunches [1]. Production of short bunches is possible due to the advancements in the drive laser pulse times combined with availability of fast-response photocathodes. Photoemission allows generating higher charges compared to field- and thermionic emission, and also with small beam transverse emittance. One good parameter to characterize the performance of a photocathode is quantum efficiency (QE), which is defined as the number of electrons emitted for a unit photon. Cesium Telluride is considered to be an exceptionally high QE (up to 20 %) semiconductor photocathode [2]. The work function of Cs_2Te 4.6 eV corresponds to the laser wavelength of 266 nm falling in the ultraviolet (UV) region. Since most of the commercially available lasers include lasing media with high gain in the infrared (IR), frequency up-conversion to the UV is generally done for linear photoemission from metallic and some semiconductor cathodes. For titanium sapphire based laser systems (λ~800 nm), UV pulses for photoemission are obtained from frequency tripling of IR pulses using a two-stage process consisting of a second harmonic generation (SHG) stage followed by a sum frequency generation (SFG). In order to preserve the short pulse duration during the up-conversion process, both stages generally use thin BBO crystals which results in low IR-to-UV conversion efficiency typically < 10%. In this paper we present preliminary results toward attempting to generate electron bunches with commensurate charge directly using the amplifier IR pulse. We specifically report on the observation of two-photon emission from Cs_2Te.

PHOTOCATHODE THEORY

Spicer developed the first model in 1958 to explain photoemission in semiconductors, which is commonly referred to as the Three Step Model, which models the photoemission mechanism as a bulk effect [3]. In the first step, an electron absorbs a photon and gets excited from the valence band to the conduction band. In the second step, the excited electron transports to the surface. In the third step, the electron escapes to the vacuum level resulting in emission. The QE equation for a semi-infinite photocathode slab is given by [3]

$$QE = [1 - R]\frac{\frac{\alpha_{PE}}{\alpha}P_E}{1+\frac{1}{\alpha L}}$$

Where R is the reflectivity of the material; α is the intensity attenuation coefficient of the photocathode material; α_{PE} represents the coefficient of absorption for the vacuum level, or the number of electrons that are excited to the vacuum level that can possibly photoemit per unit laser intensity available; L is called the escape length which represents the strength of the electron scattering; P_E is the probability that an electron at the surface with sufficient energy to escape, escapes. Here all the parameters are functions of $h\upsilon$. Fowler-Dubridge model is derived for photoemission for metallic photocathodes based on similar approach. It is the first step (photo-absorption and excitation) that distinguishes between single-photon emission from multiphoton emission. Once the electrons get excited, the rest of the processes viz. electron transport to the surface and electron escape remain the same. In single photon emission the intensity dependence of QE goes away. But in multi-photon emission α_{PE} additionally depends on the intensity of the light (temporal) besides $h\upsilon$, as the non-linear "simultaneous" absorption of multiple photons (of lower energy) has to occur to excite an electron to the vacuum level. Hence shorter laser pulses are required for higher order photoemission.

EXPERIMENT

The experiment reported in this paper was carried at the high brightness electron source laboratory (HBESL). The HBESL facility consists of a 1.5 cell L-band 1.3 GHz RF gun powered by a 3 MW klystron. The photocathode drive laser consists of a broadband (200 nm) Octavius oscillator followed by a SpectraPhysics regenerative amplifier. The amplified IR pulse typically has 100 fs duration. The IR-to-UV SHG and SFG conversion processes incorporate respectively a 0.300 and 0.150 mm BBO crystals. The crystal thicknesses were optimized with SNLO and short UV pulse (130 fs), and were measured using a polarizing-gating UV FROG. The produced pulses were short enough to enable the production of uniformly charged ellipsoidal bunches using the blow-out regime [4]. A schematic of the experimental setup used for our experiment appears in Fig. 1. A 4 mJ amplified laser pulse is sent to the HBESL accelerator

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vault where it is converted to UV. The laser energy can also be measured prior to the injection into the accelerator beamline using an energy meter and a calibrated diode. A virtual cathode – a one-to-one optical image of the photocathode, located outside of the vacuum – enables the measurement of the laser transverse distribution on the photocathode. The laser hits the Cs_2Te photocathode under normal incidence angle. The charge emitted from the photocathode can be collected by a Faraday cup (FC) located immediately downstream of the gun; see Fig. 1. The FC was calibrated with an integrated current transformer (ICT) at high charge (nC) values and is used to measure the low charge values associated with the bunches produced via multiphoton emission.

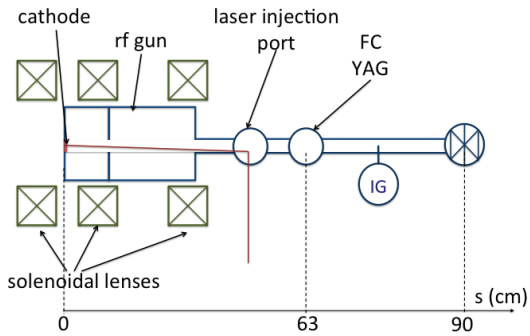

Figure 1: Overview of the HBESL electron source area. The IR pulse is injected through the laser injection port. The legend is *FC*: Faraday cup, *IG*: ion gauge, *YAG*: Yttrium Aluminum Garnet scintillating screen.

The produced bunch charge downstream of the RF gun strongly depends on the relative phase between the laser and the gun's RF field. Figure 2 shows the measured charge as a function of the launch phase referred with respect to the RF master oscillator. For this measurement the amplified IR laser pulse was directly sent to the cathode. The three traces correspond to three different laser transverse spot sizes of 3, 5 and 7 mm.

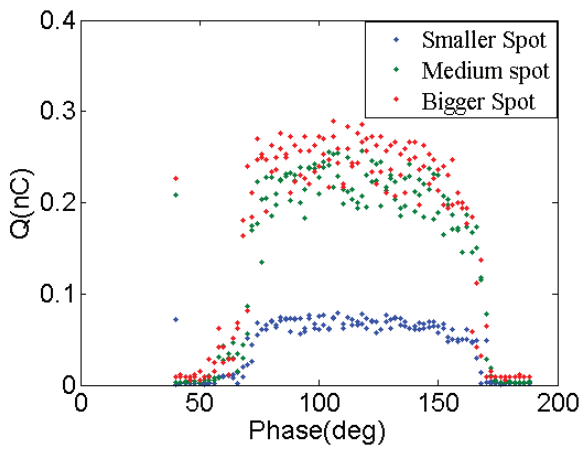

Figure 2: Charge dependence on laser phase relative to the gun (with an arbitrary phase offset). The blue, green, and red traces correspond respectively to laser spot diameter of 3, 5 and 7 mm on the photocathode.

The shape of the phase scan traces confirms that the charge emitted is from photoemission. Figure 3 shows the charge yield in the Faraday cup as a function of the laser energy for the same three different laser spot sizes.

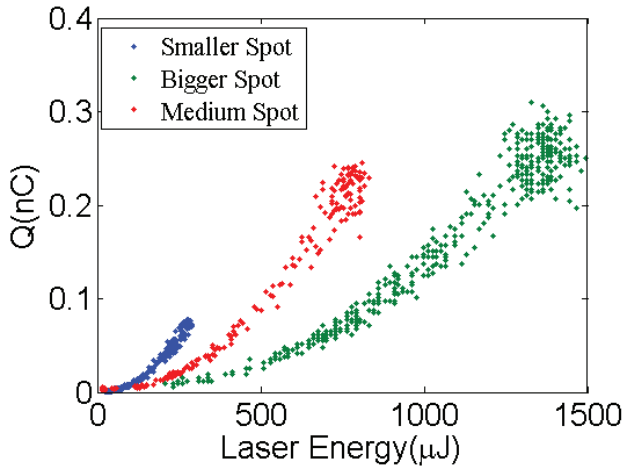

Figure 3: Charge variation as a function of laser energy for the three laser spot sizes considered in Fig. 2.

The stronger nonlinear dependence of the charge on the laser energy for the smaller spot size indicates that higher energy flux (J/m^2) produces higher charge in photoemission from the IR laser. Taking the laser's transverse density to follow a Gaussian distribution, smaller spot sizes obtained by clipping a larger spot impinges a higher laser flux for a given total laser energy and hence produces higher charge. The nonlinear signature of the charge–energy traces reported in Fig. 3 hint to a nonlinear photoemission process. To further quantify the dependence of the charge on the laser energy, we plot Fig. 3 on a log-log scale; see Fig. 4. The overall linear regression of the data confirms that the charge scales as $Q \propto I^2$ (where I is the laser intensity) suggesting that two-photon emission is the dominant process rather than the anticipated three-photon emission [5]. Some data points at lower charge/energy values with possible higher contribution from background noise (represented by '+') were omitted for linear curve fitting.

Photoemission is an independent process from charge acceleration, but the charge yield out of the RF gun which has a practical importance depends on the accelerating gradient in the gun due to the different electron beam dynamics. Figure 5 shows the log-log plots of charge vs. laser energy for different accelerating gradients (AD values) for the medium laser spot size. For a given logarithmic curve $logy = nlogx + C$, the coefficient A of $y = x^n$ can be calculated by using the relation $A = exp(C)$. In our case, $n = 2$ and A is the quadratic

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coefficient. The inset in Fig. 5 shows the variation in the quadratic coefficient with the accelerating gradient.

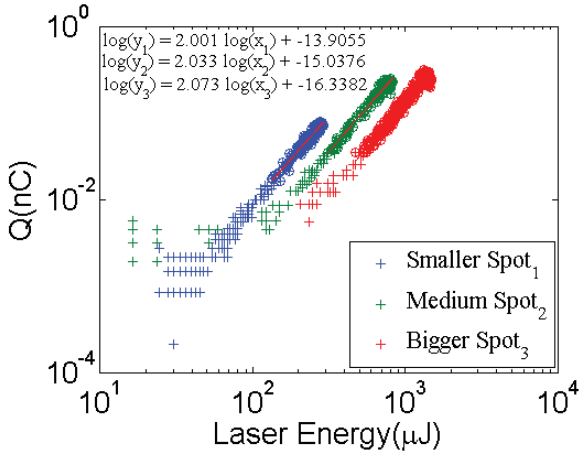

Figure 4: Logarithmic plots corresponding to the data presented in Fig. 3.

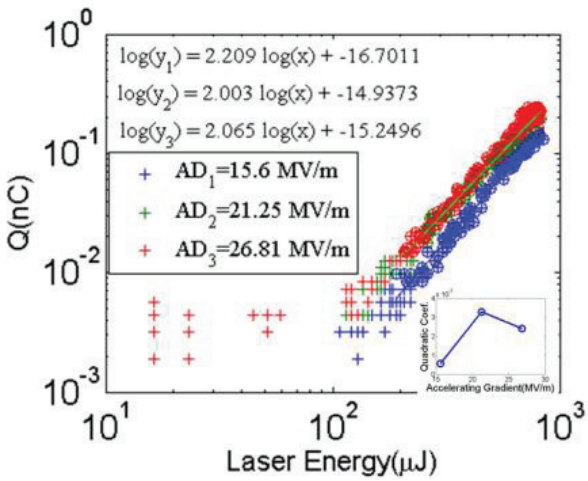

Figure 5: The effect of the accelerating gradient on the charge yield. Inset: The variation of the quadratic coefficient with the accelerating gradient.

Experimentally, we calculate the QE of a photocathode based on the correlation between the charge emitted Q by the given photocathode and the corresponding drive laser energy E as follows

$$QE \quad \frac{n(e)}{n(p)} \quad \frac{Q/\bar{e}}{E/hc\lambda^{-1}} \quad \frac{Q}{E}\left(\frac{hc}{\lambda\,\bar{e}}\right)$$

Where $n(e)$ is the number of electrons emitted, $n(p)$ is the number of photons impinged, λ is the wavelength of the drive laser, $\bar{e}$ is the electronic charge, λ is the wavelength of the laser, h is the Plank's constant, c is the velocity of light. Rewriting the above equation in more convenient units of charge and energy for the two wavelengths (of drive laser) of interest viz. 800 nm (IR) and 266 nm (UV) we get

$$QE_{UV} \quad 4.7\times10^{-6}\left(\frac{Q[pC]}{E[\mu J]}\right)$$

$$QE_{IR}(E) \quad 1.56\times10^{-6}\left(\frac{Q[pC]}{E[\mu J]}\right)$$

Figure 6 shows the charge vs. UV laser energy for the single photon emission from Cs_2Te.

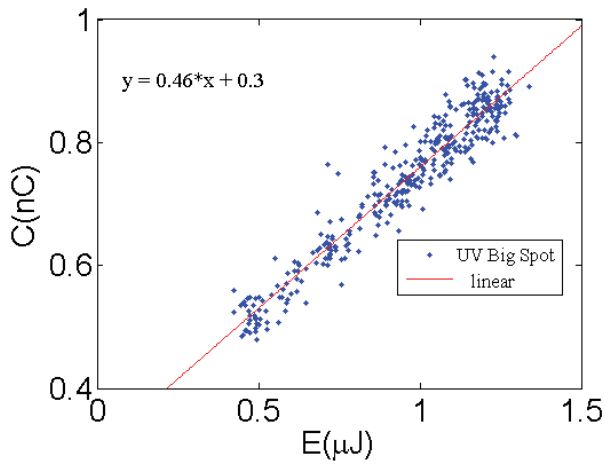

Figure 6: Charge vs. UV laser energy for Cs_2Te (single photon emission).

Typically, the QE is not defined for multiphoton emission as the ratio is not a constant like in the case of single photon emission. Or in other words increases with the laser energy, which possibly makes multiphoton emission preferable to obtain higher charge values at higher drive laser energy values, when compared to single photon emission. But we can define QE_{IR} as a function of E as in the previous equation and compare with that of UV.

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