Thermal emittance and response time of a cesium antimonide photocathode

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Measurements of the intrinsic emittance and response time of a Cs_3Sb photocathode are presented. The emittance is obtained with a solenoid scan technique using a high voltage dc photoemission gun. Photoemission response time is evaluated using a RF deflecting cavity synchronized to a picosecond laser pulse train. We find that Cs_3Sb has both small mean transverse energy, 160 ± 10 meV at 532 nm laser wavelength, and a prompt response time (below the resolution of our measurement) making it a suitable material for high brightness electron photoinjectors. © *2011 American Institute of Physics*. [doi:10.1063/1.3652758]

Energy recovery linacs and free electron lasers rely primarily on the photoemission process to generate high brightness electron beams. The choice of the photocathode material plays a critical role for low emittance beam production: an ideal photocathode has both small thermal (intrinsic) emittance and a sub-picosecond response time. High average current applications additionally require photocathodes with high quantum efficiency (QE) in a convenient (visible) spectral range. During beam operation in a 24/7 user facility, the photocathodes must be able to withstand an adverse environment in which positive ions inadvertently created by ionizing either the residual gas or desorbed molecules when the beam halo strikes the vacuum pipe are accelerated back towards the cathode surface, which may cause sputtering and removal of material.

Alkali-antimonides such as Cs_3Sb are well-known from the photomultiplier tube industry to have high QE in the visible spectral range. Unlike negative electron affinity materials which owe their high QE essentially to a monolayer of Cs adsorbed at the surface, these photocathodes are "bulk" materials and therefore possess superior lifetime as desired in the accelerator environment. Cs_3Sb has an additional appeal in that it is simpler to grow than the multialkalis such Cs_2KSb or Na_2KSb, yet it has a good response in the visible spectral range.

We detail a growth procedure for Cs_3Sb that reliably yields high QE of about 5% in the green. Thermal (intrinsic) emittance of this photocathode, a critical parameter for high brightness photoinjectors, is obtained using a solenoid scan technique from a 350 kV dc photoemission gun for 532, 473, and 405 nm laser wavelength excitation. The results are then compared with a simple photoemission model with the photoelectric work function being the only variable parameter. Finally, we evaluate the response time of Cs_3Sb using a direct time diagnostic similar in principle to a streak camera: a radio frequency (RF) deflecting cavity synchronized to a picosecond 520 nm laser system.

The Cs_3Sb photocathode preparation procedure is similar to those reported in the literature[1,2] with some modifications as necessary for the beam operation inside the high voltage dc photoemission gun. All photocathode growth is performed in a dedicated chamber[3] and subsequently transferred into the high voltage dc gun[4] equipped with a load-lock system. Heavily *p*-doped Si(100) substrates with a resistivity of 1–5 mΩ cm are first rinsed for 4 min in 2% hydrofluoric acid solution to remove the oxide layer. The cleaned substrate is then indium soldered to a molybdenum holder and secured in place by a crimped soft tantalum cap. Before the deposition of metals, the holder and substrate assembly is heated to 600 °C to remove the hydrogen passivation from the Si surface. Then the assembly is left to cool down and when the temperature is lowered to approximately 180 °C the evaporation of 10 nm of antimony film thickness is performed. At the end of the antimony deposition, the Cs evaporation is carried out until the photocurrent is maximized, and eventually starts to decrease, indicating an excess of Cs on the sample surface. During the Cs deposition stage, the holder temperature decreases from 160 °C to 125 °C, see Fig. 1. The photocathode assembly is then allowed to cool down to room temperature. We observe a sudden recovery of the QE that dropped from initial peak value of 3.5% down to 0.5% due to the over-cesiation of the surface when the Cs source is turned off. During the cooling down of the

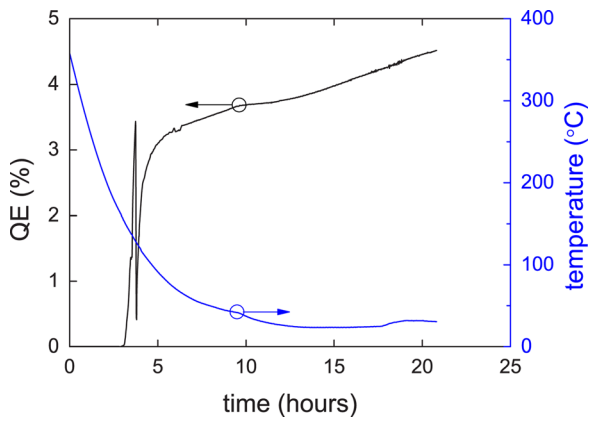

FIG. 1. (Color online) QE and the substrate temperature during the deposition.

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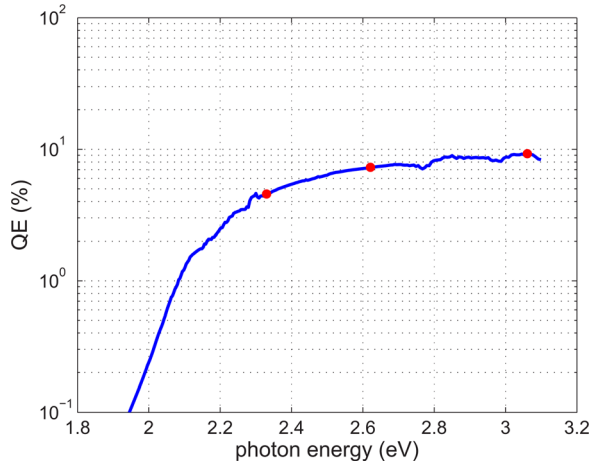

FIG. 2. (Color online) QE vs. laser wavelength.

photocathode, the QE continues to increase and after 15 h reaches a typical value of 4%–5% as monitored by a 532 nm laser.

The spectral response of the photocathode has been measured using a broadband source in conjunction with a monochromator. Fig. 2 shows the spectral response of the Cs_3Sb for wavelengths ranging between 400 and 700 nm. Specific laser wavelengths used in the measurement of the photocathode intrinsic emittance are indicated by dots. The activated photocathode is then moved to the high voltage dc gun. The QE map as obtained inside the gun vacuum system by scanning a focused 532 nm laser is shown in Fig. 3. The active region of the photocathode is limited to a 12 mm diameter region via a mask placed near the substrate during the deposition.

The experimental beamline and procedures we use to determine the thermal emittance are well documented.[5,6] In essence, a small dc laser is used to produce an electron beam free of space charge effects and the beam emittance is determined from the solenoid lens scan while the electron spot size is measured on a luminescent screen inserted in the beam path. Knowing the beam transfer matrices from the cathode allows us to determine not only the beam emittance but also the initial electron rms spot size, which is identical to the laser transverse profile when QE is perfectly uniform. This allows to include (small) effects of the spatially varying QE or account for uncertainties in the laser shape asymmetries. We use multiple laser apertures to obtain the thermal emittance, which is given by,

$$\epsilon_{n\perp} = \sigma_\perp \frac{\sqrt{\langle p_\perp^2 \rangle}}{mc} = \sigma_\perp \sqrt{\frac{\mathrm{MTE}}{mc^2}}, \tag{1}$$

where $\sigma_\perp$, $p_\perp$, and MTE are the initial electron rms spot size, transverse momentum, and mean transverse energy of the electron beam, respectively; m and c are the electron mass and the speed of light.

The results of measurements for Cs_3Sb are presented in Fig. 4. All these measurements were performed at 350 kV gun voltage. To assess Schottky correction to the work function, we have measured the thermal emittance at 3 different voltages 110 kV, 230 kV, and 350 kV. It was found to be the same within the uncertainty of the measurement. The 350 kV gun voltage corresponds to about 4 MV/m at the photocathode, which results in a Schottky correction to the work function of less than 0.1 eV.[7]

The mean transverse energy, an intrinsic property of the photocathode, is shown in Fig. 5. Following,[5] we write MTE in terms of the photon energy $h\nu$ and the photoemission threshold energy (photoelectric work function) $E_{th} = E_g + E_a$, which is the sum of the band gap energy E_g and electron affinity E_a,

$$\mathrm{MTE} = \frac{h\nu - E_{th}}{3}. \tag{2}$$

The measurements of E_{th} for Cs_3Sb vary noticeably in the literature, e.g., from 1.8 eV (Ref. 8) to 2.05 eV.[9] The spectral response of our photocathode, Fig. 2, indicates that $E_{th} = 1.9$ eV is a reasonable value for the photoelectric work function and it also yields a good agreement between the Eq. (2) and the measured MTE values. We note that E_{th} for both Cs_3Sb and CsK_2Sb are very close[9] and, therefore, the thermal emittance of the two photocathodes is expected to be similar. A possible deviation of the slope of the MTE for Cs_3Sb from $h\nu/3$ as seen in Fig. 5 may be an indication of

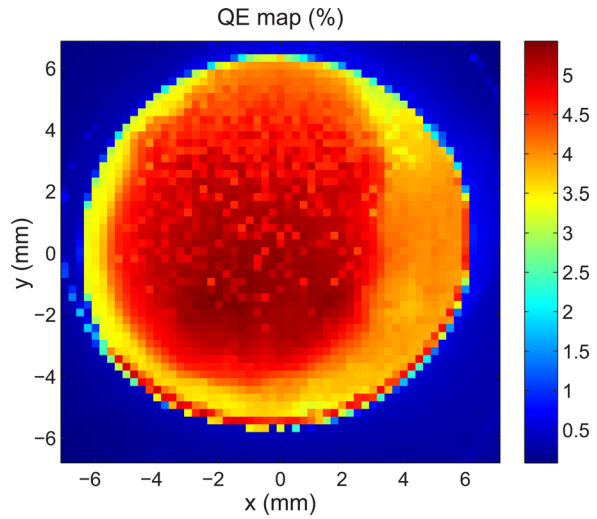

FIG. 3. (Color online) QE map of the photocathode inside the dc gun.

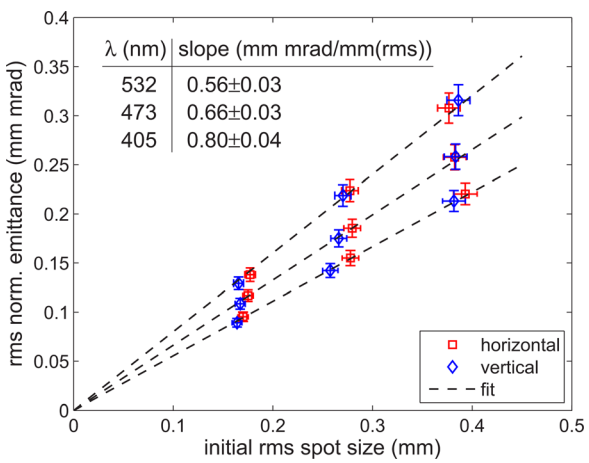

FIG. 4. (Color online) Thermal emittance for different wavelengths.

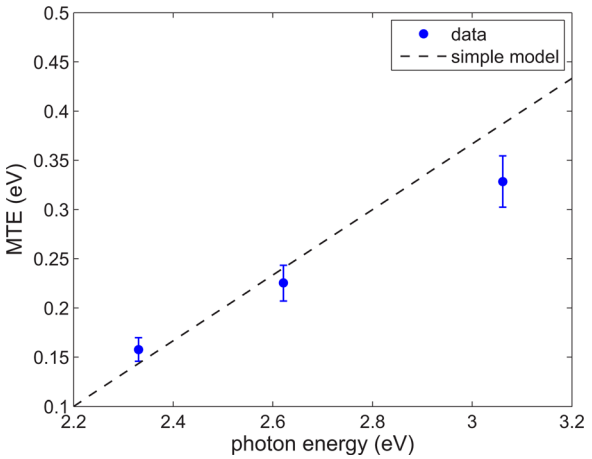

FIG. 5. (Color online) Measured MTE and Eq. (2) for $E_{th} = 1.9\,\text{eV}$ vs. photon energy.

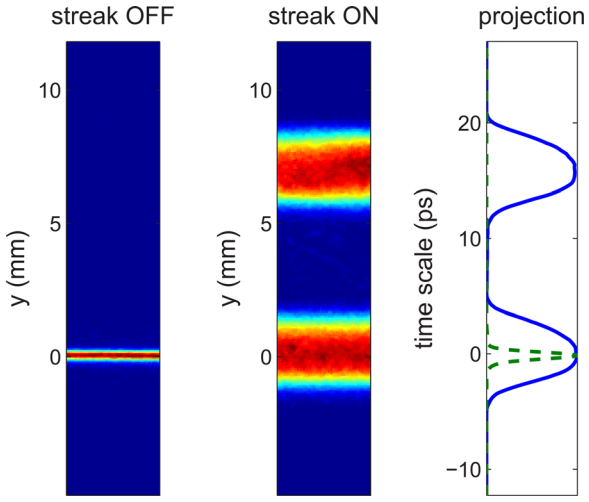

FIG. 6. (Color online) Response time measurement at 520 nm laser wavelength.

the energy loss due to scattering phenomena prior to the electron emission into vacuum or the anisotropic nature of the photoemission not accounted for in this simple model.

The response time of photocathodes is crucial when temporal laser pulse shaping is used to mitigate the effects of the space charge.[10] The photocathode must be able to support a prompt (~1 ps) rise and fall time of the laser pulse. To evaluate the response time from Cs_3Sb, we use a picosecond laser pulse train synchronized to 1.3 GHz RF master clock and an RF deflecting cavity which imparts a time-dependent vertical kick to the beam.[11] Vertical position on a view screen placed downstream of the RF deflecting cavity then corresponds to the time, a principle analogous to the operation of streak cameras. Fig. 6 shows the results of this measurement: the left and middle subplots show the beam image with the RF cavity OFF and ON, respectively, and the right subplot shows the projected intensity. To calibrate the time axis in this measurement, we have inserted a birefringent crystal of 15 mm thickness into the laser beam, which splits a single laser pulse into 2 with a known delay of 15.8 ps.[10] The FWHM of the individual pulse in Fig. 6 is 5 ps (right subplot). This can be fully accounted for by the known width of the laser pulse (1.7 ps), the laser to RF synchronization jitter (~2 ps) and the fluctuation of the gun voltage and the corresponding velocity and time arrival fluctuations (the dc gun is located 11 m from the RF deflecting cavity so that 10^{-4} voltage fluctuation at 350 kV causes the arrival time to change by 1 ps). We conclude that this Cs_3Sb photocathode has sufficiently prompt response time below the resolution of our system.

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