MEAN TRANSVERSE ENERGY AND DEGRADATION MEASUREMENTS ON A CAESIUM TELLURIDE PHOTOCATHODE

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Abstract

Fourth generation light sources require high brightness electron beams. To achieve this a cathode with a high quantum efficiency and low intrinsic emittance is required while also being robust with a long lifetime and low dark current. Alkali-metal photocathodes have the potential to fulfil these requirements and, as such, are an important area of research for the accelerator physics community.

A Cs-Te photocathode grown at STFC Daresbury Laboratory is presented. Important photoemissive properties such as quantum efficiency (QE), mean transverse energy (MTE) and lifetime have been investigated using the Transverse Energy Spread Spectrometer (TESS). Elevated MTE beyond the Cs_2Te photoemission threshold is reported as well the QE decrease and MTE increase when a Cs-Te photocathode is subject to progressive oxygen degradation.

INTRODUCTION

X-ray free electron lasers (XFELs) require high brightness electron beams. The beam brightness, a key factor in FEL cost and performance [1], depends on the beam current, which should be maximised, and beam emittance, which should be minimised [2]. To achieve this, a photocathode with high quantum efficiency (QE) and a low mean transverse energy (MTE) is required. Caesium telluride, (Cs_2Te or more broadly Cs-Te), photocathodes fulfil these requirements, demonstrating measured levels of QE as high as 20 % at 266 nm and low MTE, all while being sufficiently robust to survive inside a electron gun [3]. As such, they are currently used in accelerator facilities around the world [4, 5].

The photocathode research group at the STFC Daresbury Laboratory are developing an Alkali-metal Photocathode Preparation Facility (APPF) [6] to supply Cs_2Te photocathodes to the CLARA accelerator [7]. In order to evaluate the suitability of a photocathode for use in a photoinjector and subsequently refine the photocathode growth recipe, comprehensive performance characterisation is required. To do this, we use Multiprobe [8] and the Transverse Energy Spread Spectrometer (TESS) [9, 10]. Multiprobe is equipped for surface preparation and characterisation and is able to measure QE. TESS measures the transverse energy distribution curve of a photocathode across a range of illumination wavelengths. From this, the MTE can be extracted [11], which is related to the photocathode's intrinsic emittance. We present data on the growth and performance characterisation of a Cs-Te photocathode grown at Daresbury Laboratory.

SAMPLE GROWTH

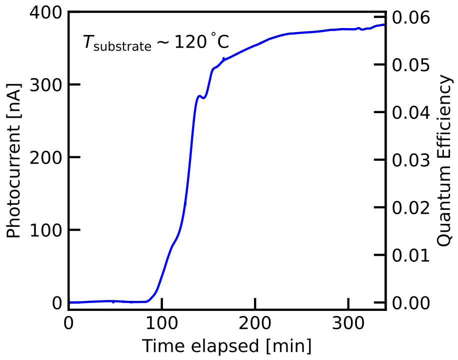

Figure 1: Measured photocurrent and quantum efficiency from the Cs-Te photocathode during caesium deposition.

A Cs-Te photocathode was grown in our APPF on a 6 mm diameter polycrystalline Mo substrate supplied by Surface Preparation Laboratory with a measured surface roughness of < 30 nm. The substrate was cleaned using 1.5 keV Ar^+ bombardment to remove surface oxygen and carbon. Tellurium and caesium were deposited sequentially with the substrate temperature held at approximately 120 °C. During tellurium deposition, surface reflectivity was monitored using a 265 nm LED pulsed at 190 Hz combined with a photodiode and a lock-in amplifier. Tellurium deposition was stopped when we measured an estimated 54 % drop in surface reflectivity. The substrate was then biased at -18 V and the caesium deposition commenced. The same LED and lock-in amplifier were then used to monitor the total yield photocurrent which is proportional to QE. Deposition continued until the photocurrent reached its maximum level, as shown in Fig. 1.

SURFACE CHARACTERISATION

The Cs-Te cathode was transferred using a UHV vacuum suitcase to the Multiprobe system for X-ray photoelectron spectroscopy (XPS) analysis. XPS spectra were taken using the unmonochromated Mg Kα line from a PSP Vacuum Technology CTX400 X-ray source and a Thermo Alpha 110 hemispherical analyser with the results shown in Table 1. The film consists of 61.8 % caesium, 29.4 % tellurium and 8.8 % oxygen. This gives an overall Cs:Te ratio of 2.12:1 and suggests that a significant proportion of the sample is the desired Cs_2Te. The Te spectra shows the Te is fully-bonded to Cs with no elemental Te or Te oxide detected. However, it was not possible to determine the exact Cs bonding environ-

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ment from the XPS data – multiple Cs-Te compounds are known to exist [12], in addition to elemental Cs. It was also not possible to determine how the oxygen is bonded to this cathode; however, given caesium's high affinity for oxygen [13], caesium oxide seems a likely candidate. Though not shown in Table 1, the molybdenum substrate was still visible in the XPS spectra. Given the typical XPS probing depth of ~10 nm, this shows that the thickness of the Cs-Te photocathode layer was significantly below the optimal thickness of approximately 65 nm [14].

Table 1: XPS Characterisation of the Cs-Te Photocathode

Region	Peak Position [eV]	Elemental Composition [%]
Cs 3d $^{5/2}$	725.3	31.6
Cs 3d $^{3/2}$	739.2	30.2
Te 3d $^{5/2}$	571.6	15.0
Te 3d $^{3/2}$	582.0	14.4
O 1s	531.1	8.8

PHOTOEMISSIVE PROPERTIES

Direct Quantum Efficiency Measurement

Table 2: Measured QE of the Cs-Te Photocathode

	266 nm	405 nm	266 nm Post Degradation
QE	4.6×10^{-2}	2.5×10^{-5}	2.5×10^{-2}

The QE was measured in Multiprobe using a 266 nm Crylas FQSS 266-Q4 laser pulsed at 1 kHz combined with a SR830 lock-in amplifier and high voltage anode. The same system was used for the post degradation measurement. In a separate system, the QE at 405 nm was measured using a 1 kHz modulated laser and the lock-in amplifier.

Mean Transverse Energy Spectral Response

The cathode was transferred to TESS using the vacuum suitcase. Transverse energy distribution curves were measured and MTEs extracted from 236 nm to 536 nm. By combining the light source power with the integrated photoemission intensity, correcting for MCP gain and exposure time, and calibrating to our measured QE at 266 nm, it is possible to estimate the QE across the dataset [9]. Figure 2 shows the two datasets taken, the first with progressive light source attenuation to avoid space charge, the second without.

Both datasets agree extremely well, apart from some small space charge effects at > 416 nm. At 266 nm the MTE is (240 ± 20) meV. As the incident photon energy decreases, the excess energy decreases, lowering the MTE, which we see for $E_{\mathrm{ph}} > 3.3$ eV. According to the Dowell-Schmerge (D-S) approximation, the MTE should equal $^1/_3$ the excess energy of the incident photons [15]. Using such a fit, the x-axis intercept is therefore the work function (WF) of the cathode. A D-S fit to the data for $E_{\mathrm{ph}} \geq 4.49$ eV gives an estimated WF = (3.93 ± 0.01) eV for the species responsible for this portion of the photoemission. We attribute this emission to Cs_2Te; however, the WF disagrees with the literature value of 3.5 eV [5]. Further study with additional samples is required to explore the reproducibility of this result.

Notably, the MTE begins to increase at energies below 3.3 eV. We attribute this to other low WF compounds, most likely Cs (WF = 2.14 eV [16]) and Cs_2O (WF = 1.4 eV [13]) which, as the Cs-Te components reach their emission threshold and beyond, become the dominant photoemissive species imaged by the TESS. This hypothesis is supported by the XPS in Table 1 showing a Cs:Te ratio exceeding 2:1 and the presence of oxygen. In the 2nd dataset a shoulder is seen in the estimated QE at < 3 eV. Similar behaviour has been reported previously [17] where additional Cs-Te compounds were suggested as the source of photoemission [12].

Finally, we note that even at the emission threshold, the MTE never reached the thermal limit of $k_B T = 25$ meV. This may imply high levels of surface roughness either from the sample preparation or the deposition process as sequential deposition has been shown to result in rougher surfaces than co-deposition [3]. Alternatively, it is possible that emission continues below 2.3 eV with the MTE approaching the thermal limit; however, the QE level of $< 10^{-9}$ may exceed the sensitivity of the TESS detector.

Mean Transverse Energy under Degradation

Degradation experiments were conducted in the TESS. When changing between gas species, the gas line was heated and thoroughly purged to maximise purity. Gas was admitted through a piezoelectric leak valve into the chamber from its base pressure of 3×10^{-11} mbar. The pressure was raised slowly from the low $\times 10^{-10}$ mbar regime to the high $\times 10^{-9}$ mbar regime, where the majority of the degradation data was acquired. The experiment was conducted at illumination under a single wavelength of 266 nm (4.64 eV). The MTE was measured and the relative change in the QE calculated. The Cs-Te photocathode was exposed to N_2 and then O_2. An additional measurement was taken on the Cs-Te the following day once the TESS chamber had recovered to its base pressure. A polycrystalline copper cathode was also exposed to N_2 as a control experiment. The results including the total chamber pressure are shown in Fig. 3.

On exposure to N_2, the Cu photocathode QE remained relatively constant, increasing by ~5 % which we ascribe to measurement drift due to the length of the data acquisition (typically 5 hours). The Cs-Te photocathode behaved similarly to the Cu photocathode; it was relatively constant yet the QE did increase overall, remaining slightly elevated the next day. This may highlight some changes in surface chemistry, but is most likely to be drift, as no change in the MTE was observed.

Conversely, exposure to O_2 is seen to drive significant degradation in the photoemissive properties of the Cs-Te cathode. A pressure spike when the piezoelectric leak valve

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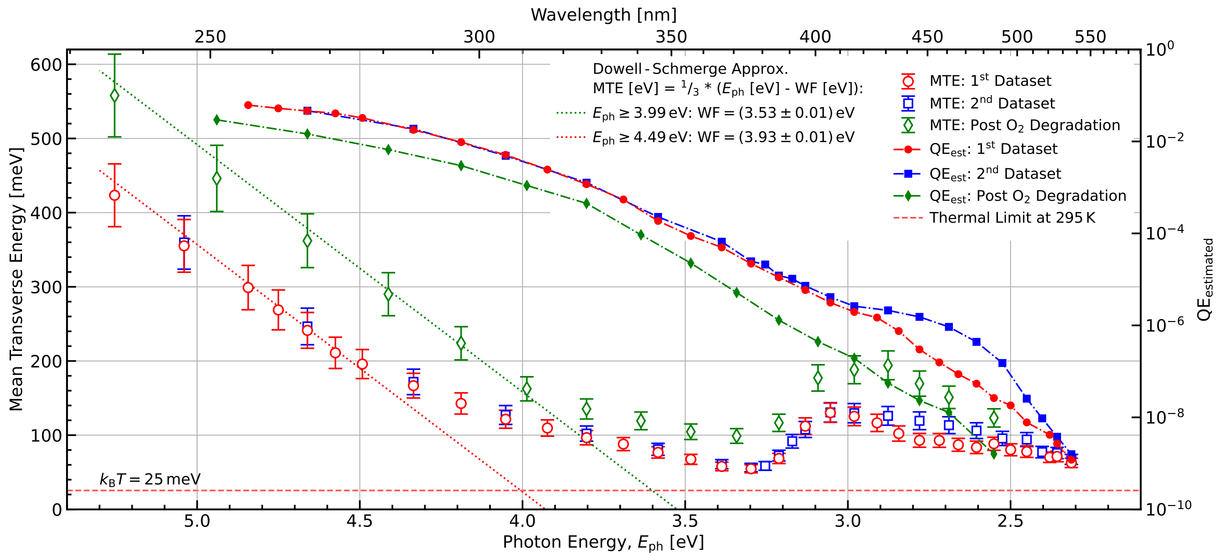

Figure 2: Mean transverse energy and estimated QE for a caesium telluride photocathode at room temperature.

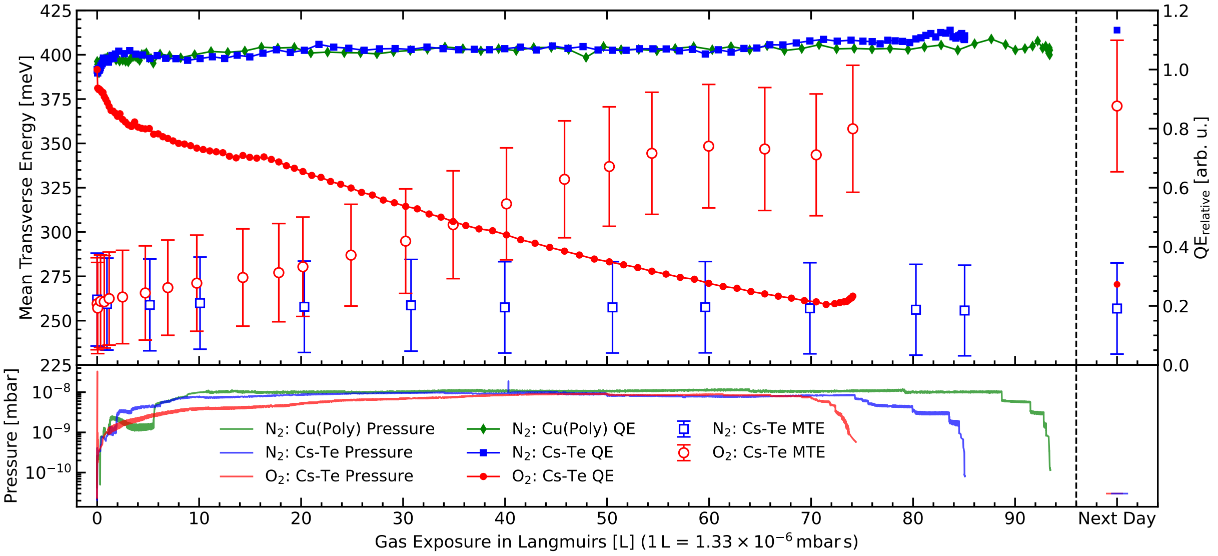

Figure 3: MTE and relative QE (**Top**) with chamber pressure (**Bottom**) for a caesium telluride photocathode exposed to progressive N_2 and O_2 degradation. The response for a polycrystalline copper sample exposed to N_2 is included as a control.

was first opened resulted in an instantaneous QE drop of 7 %. Once stabilized, the QE decayed rapidly at first, then more steadily over the following 75 L of O_2 gas exposure. During this, the QE of this photocathode is estimated to have fallen by approximately 73 %, a later measured value gives a QE of 2.5×10^{-2} (Table 2). Previous experiments have reported similar behaviour [18]. Meanwhile, the measured MTE of the photocathode increased throughout the gas exposure from 260 meV to 360 meV. This increased MTE is reflected across a wide range of photon energies as seen in Fig. 2. This behaviour is contrary to what one might expect from a metal photocathode where degradation results in a higher WF, resulting in lower QE and MTE [19, 20]. A D-S fit for $E_{ph} \geq 3.99$ eV gives a new WF = (3.53 ± 0.01) eV. While it appears that the presence of O_2 is reducing the effective WF of the Cs_2Te emission, resulting in higher excess energy and MTE, the exact processes occurring are unknown. As the sample degrades, we also anticipate an increased formation of low WF compounds with lower QE, such as Cs_2O. This behaviour could significantly impact the lifetime of a Cs-Te photocathode in a XFEL, where high brightness beams rely on both high QE and low MTE.

CONCLUSION

We have shown that the exposure of Cs-Te to O_2 drives a decrease in QE and an increase in MTE over a wide range of illumination energies through the creation of lower WF surface compounds. This may negatively impact electron beam brightness in 4th generation light sources, reducing the effective lifetime of Cs-Te photocathodes.

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