

Measurements of thermal emittance for cesium telluride photocathodes at PITZ*

V. Miltchev[†], J. Baehr, H.-J. Grabosch, J. H. Han, M. Krasilnikov, A. Oppelt,
B. Petrosyan, L. Staykov, F. Stephan, DESY, D-15738 Zeuthen, Germany
M. v. Hartrott, BESSY GmbH, Berlin, Germany

Abstract

The thermal emittance determines the lower emittance limit and its measurement is of high importance to understand the ultimate injector performance. In this contribution we present results of thermal emittance measurements under rf operation conditions for various Cs_2Te cathodes and different accelerating gradients. Measurements of thermal emittance scaling with the cathode laser spot size are presented and analyzed. The significance of the applied electric rf field in the emittance formation process is discussed.

INTRODUCTION

The main research goal of the Photo Injector Test Facility at Zeuthen (PITZ) is the development of electron sources with minimized transverse emittance like they are required for the successful operation of Free Electron Lasers and future linear colliders [1]. The experimental set-up used for the measurements is shown in Fig. 1. It consists of a 1.5 cell L-band rf gun with a Cs_2Te photocathode, a solenoid system for compensating space charge induced emittance growth, a photo-cathode laser system capable of generating long pulse trains with variable temporal and spatial micro pulse shape, and an extensive diagnostics section. The emittance characterization at PITZ is performed using the slit scanning method [2], which was used also for the thermal emittance measurements.

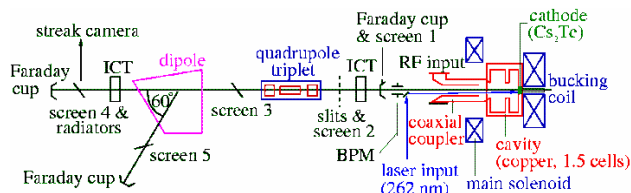


Figure 1: Schematic layout of PITZ.

The thermal emittance adds in quadrature to the other emittance contributions, thus it sets the lower limit for the transverse emittance of electron sources. Numerous theoretical and experimental studies have been dedicated to the

measurements of the thermal emittance as well as to solutions for reducing it. Everywhere the authors point out the high importance of thermal emittance measurements to understand and to improve the ultimate performance of injectors feeding linac driven FELs. Among the various possible photocathode materials, the semi conductive alkali telluride Cs_2Te shows high quantum efficiency, high robustness and long lifetime and therefore has been chosen for PITZ as well as for many other photoinjectors. For first time thermal emittance measurements for Cs_2Te photocathodes under real rf operating conditions were performed at PITZ and will be presented in the following sections. The thermal emittance depends [3] on the laser spot size, the momentum and the angular distribution of the emitted photoelectrons. Its typical value is small, usually in the range 0.3-0.7 mm-mrad and therefore it starts to play a significant role in the emittance formation, when the injector operating parameters have been fully optimized so that very low emittances of the order of 1 mm-mrad are about to be produced. It is important to note that the thermal emittance is a complex quantity influenced not only by the photocathode material properties but also by the parameters of the cathode UV laser and the accelerating field amplitude. In planning the measurements one has to consider the dependence on the laser spot rms size, on lowering the surface potential barrier due to the high rf field (Schottky effect) and on poisoning of the cathode due to increased vacuum pressure.

THERMAL EMITTANCE CALCULATION

The photoemission in semiconductors takes place in the following sequence [4]: Step 1: Absorption of a photon in the bulk material and excitation of electrons to the conduction band (CB). Since Cs_2Te is a semiconductor material with a band gap of $E_G = 3.3$ eV, a photon energy $E_{ph} > 3.3$ eV is required. The UV laser put into operation at PITZ generates photons at a wavelength of $\lambda = 262$ nm or $E_{ph} = 4.72$ eV. Step 2: Transport of excited electrons to the first maximum of the CB density of states, which for Cs_2Te is located at an energy of 4.05 eV above the maximum of valence band (VB). Step 3: Escape of the electrons into vacuum. In order to escape from the conduction band to the vacuum, electrons have to overcome the surface potential barrier given by the electron affinity E_A , which is defined as the energy difference between the vacuum level E_{vac} and the bottom of the conduction band. Thus, the threshold energy $E_T = E_{vac}$ for photoe-

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[†] velizar.miltchev@desy.de

mission is given by the sum of the band gap and the electron affinity: $E_T = E_A + E_G$. The threshold energy for Cs_2Te is measured [4] to be $E_T = 3.5$ eV and hence the electron affinity for a very fresh cathode can be estimated by: $E_A = E_T - E_G = 0.2$ eV (due to cathode contamination E_A might become larger). Since the electrons final state energy in Step 2 is on average $E_{CB} = 4.05$ eV, after escaping into the vacuum the electrons will have a mean kinetic energy of $E_k = E_{CB} - E_{vac} = 4.05 - 3.5 = 0.55$ eV. The above quoted value for the average kinetic energy of the emitted photoelectrons was estimated considering the measurements of Powell[4] performed with fresh cathodes and very low electric fields. However the actual value of E_k obtained when the cathode is operated in an rf gun with high accelerating gradient might be larger due to Schottky reduction of the electron affinity or lower due to poisoning of the cathode surface. Following the arguments in [3] one can derive a relation between the thermal emittance and photoemission parameters: the average kinetic energy of the emitted photoelectrons and the electron affinity. In the photoemission model considered in the following, one assumes that the electrons are emitted isotropically into the hemisphere over the cathode surface behind the potential barrier. The average kinetic energy of photoemitted electrons is defined as:

$$E_k = E_{CB} - E_G - E_A \quad (1)$$

The analysis presented in [3] yields the following relation for the normalized thermal emittance:

$$\epsilon_{th} = \sigma \sqrt{\frac{2E_k}{3m_0c^2}} \quad (2)$$

where σ denotes the rms laser spot size.

OPERATION PARAMETERS

As it was discussed above the thermal emittance adds quadratically to the other emittance terms to form the total emittance: $\epsilon_n \approx \sqrt{\epsilon_{th}^2 + \epsilon_{rf}^2 + \epsilon_{sc}^2}$. This relation has to be taken into account in order to determine the operation conditions needed to perform thermal emittance measurements. The main problem is that with the PITZ set up one can not measure the thermal emittance directly at the photocathode (inside the rf gun), but at the position of emittance measurement system, which is located about 1.62 m downstream. This means that one measures not only the thermal emittance but the contributions of rf and space charge as well. Under proper operation conditions the last two terms should be minimized so that $\epsilon_n \approx \epsilon_{th}$. The space charge contribution to the emittance rapidly scales up with the charge, which implies that the bunch charge should be set as close as possible to zero. On the other hand one has to keep the signal-to-noise ratio during the emittance measurement sufficiently high, which sets a lower limit to the charge. According to the practical experience a charge of about 3 pC is a reasonable compromise between these contradicting requirements. According to ASTRA [6] for this charge, the relative emittance increase due to self-fields

should not be larger than 5%. Regarding the contribution of the rf field it is helpful to recall that $\epsilon_{rf} \propto \sigma_t^2$, hence the laser pulse length σ_t has to be shortened to the possible limit. The laser system of PITZ can generate gaussian pulses of $\sigma_t \approx 3$ ps. A further reduction of the temporal extent of the laser pulses is not possible without major reconstruction of the system. According to the ASTRA simulation results the rf induced emittance growth is expected to be not more than 2% of the thermal emittance for pulse length of 3 ps. Taking into account that for the tiny charge of 3 pC the beam current $I \simeq Q/\sigma_t$ is just about 1 A, one can consider to lower the accelerating rf gradient in order to minimize the dark current and its impact on the emittance and the data analysis. For that reason most measurements were done at an accelerating field of about 32-34 MV/m, since the PITZ gun (with inserted Cs_2Te photocathode) then produces a negligible dark current of about $1 \cdot 10^{-4}$ A for a peak gradient of 34 MV/m. The gun rf phase for the measurements was always set to the phase of maximum mean energy gain Φ_m , although a large emittance variation with the rf phase for that small charge is not expected.

EMITTANCE SCALING WITH LASER SPOT SIZE

The final goal of these measurements is to estimate the average kinetic energy E_k of the electrons immediately after emission from the Cs_2Te photocathode. By differentiation of both sides of Eq. 2 one obtains a relation between energy of the electrons and the rate of increase of emittance with the laser spot size σ_r .

$$E_k = 1.5m_0c^2 \left(\frac{d\epsilon_{th}}{d\sigma_r} \right)^2 \quad (3)$$

Thus an estimate for E_k can be given, provided that the slope ($d\epsilon_{th}/d\sigma_r$) is known. It can be determined by measuring the emittance as a function of the laser spot size and then fitting a straight line through the measured data points. The emittance was measured vs. laser rms spot size using the slit scanning technique at a small bunch charge of 3 pC and a moderate gradient of about 32 MV/m. The variation of the laser spot size was realized by passing the initial laser beam through a circular aperture of changeable diameter. Two sets of measurements were taken for two different Cs_2Te cathodes: cathode No.60 (see Fig. 2) with quantum efficiency (QE) of about 1% at the time of the measurements and cathode No.61 (see Fig. 3) with QE of about 1.5%. Straight line fits through the measured data for the horizontal as well as the vertical emittance yield the following results for cathode No.60:

$$\frac{d\epsilon_{th,x}}{d\sigma_x} \simeq 1.3 \text{ mrad} \quad \frac{d\epsilon_{th,y}}{d\sigma_y} \simeq 1.1 \text{ mrad} \quad (4)$$

Taking into account Eq. 3 and since there is no reason to expect the energies obtained for both transverse planes to differ, one takes the average of the two as a final result with

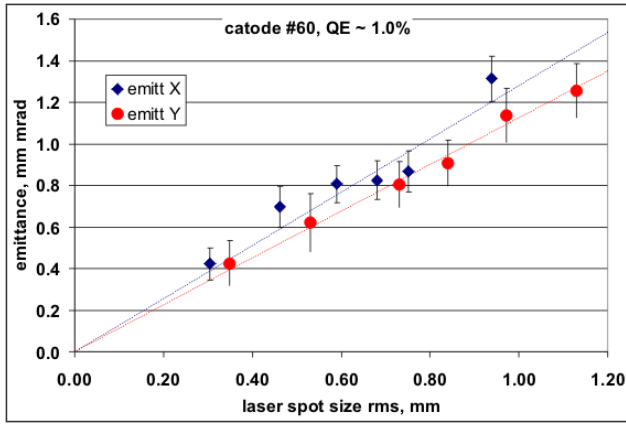


Figure 2: Measurements with cathode No.60.

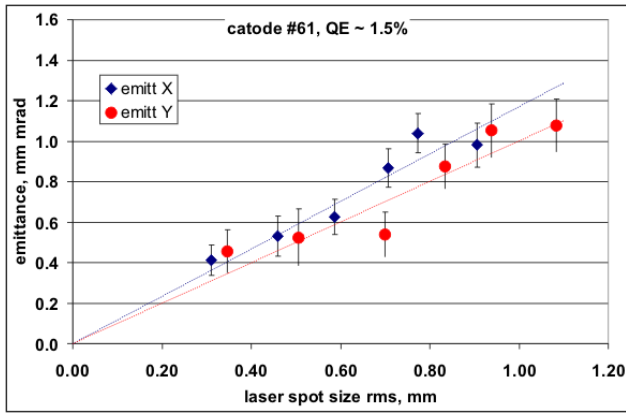


Figure 3: Measurements with cathode No.61.

an uncertainty equal to the standard deviation:

$$E_{k,\#60} = (1.1 \pm 0.2) eV \quad (5)$$

The same analysis applied to the emittance data taken with cathode No.61 yields the following results:

$$\frac{d\epsilon_{th,x}}{d\sigma_x} \simeq 1.2 mrad \quad \frac{d\epsilon_{th,y}}{d\sigma_y} \simeq 1.0 mrad \quad (6)$$

And the final result for cathode No.61:

$$E_{k,\#61} = (0.9 \pm 0.2) eV \quad (7)$$

The average kinetic energy of the emitted photoelectrons was estimated to be in the range 4.2-4.4 eV above the top of the valence band, which corresponds to 0.9-1.1 eV relative to the vacuum level. The expected value was about 4.05 eV, where a symmetric energy distribution curve of the photoemitted electrons was assumed. The slightly higher experimental result might be assigned to an asymmetry in the energy distribution.

THERMAL EMITTANCE DEPENDENCE ON ELECTRIC RF FIELD

The goal of these measurements is to study the dependence of the thermal emittance and hence the average ki-

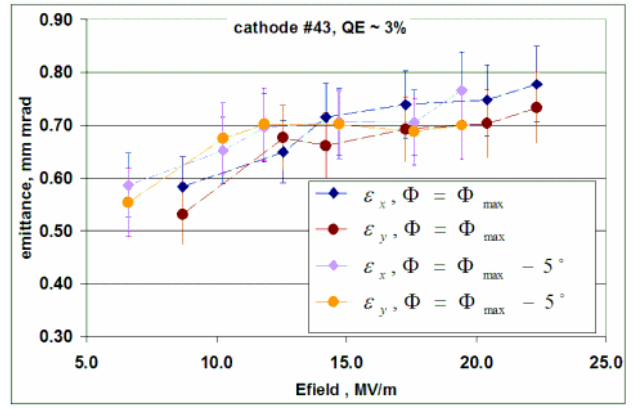


Figure 4: Measurements with cathode No.43. RF phase set to Φ_m and $\Phi_m - 5^\circ$. Laser spot size $\sigma_{x/y} = 0.55/0.54$ mm

netic energy of the photoelectrons as a function of the electric field E in the moment of photoemission. The measurements were done using the PITZ slit scanning technique. Since the same general requirements for the operation parameters apply as described above, a similar measurement procedure was followed. The electric rf field amplitude E_0 was varied in the range of 24 to 39 MV/m. For each value of E_0 the rf phase was adjusted to the phase of maximum mean energy gain Φ_m . Before each emittance measurement the beam charge was measured vs. rf phase. From the rising edge of that scan the zero crossing rf phase Φ_0 was determined and thus $E = E_0 \sin(\Phi_m - \Phi_0)$. The laser spot size was kept fixed. The bunch charge was set to 2-3 pC. Such measurements were done with a cathode of QE of about 3% and then repeated for a slightly different rf phase corresponding to $\Phi_{max} - 5^\circ$. The laser spot size was adjusted to $\sigma_{x/y} = 0.55/0.54$ mm. Results of these measurements are shown in Fig. 4. In all cases the thermal emittance increases with the accelerating field, which corresponds to a rising average kinetic energy of the photoelectrons. The experimental data can be analyzed assuming that the thermal emittance increase is due to a lowering of the electron affinity caused by the Schottky effect. The reduction of the electron affinity due to the Schottky effect for a semiconductor photocathode is described by the following expression [5] :

$$E_A = E_A(0) - \sqrt{\beta \frac{eE}{4\pi\epsilon_0}} \quad (8)$$

with β denoting an effective field enhancement factor and $E_A(0)$ is the electron affinity at zero electric field. In summary from Eq. 1, Eq. 2 and Eq. 8 one expects the following general relation between thermal emittance and applied electric field:

$$\epsilon_{th}^2 = A + B\sqrt{E} \quad (9)$$

i.e. a linear dependence between square of thermal emittance and square root of electric field. It is well known that the main problem in using semiconductor photocathodes in

an rf gun is the relatively short, compared with metals, lifetime due to contamination caused by residual gases. This photocathode degradation appears as monotonic QE decay with the time and can be explained with electron affinity increase due to passivation of the photocathode surface. Therefore the value of electron affinity $E_A=0.2$ eV, quoted before, is valid only for very fresh cathode. During the rf operation the electron affinity monotonically grows and might reach significantly larger values than the initial one [5]. The photocathodes used in the thermal emittance studies presented above were exposed to residual gases in the rf gun. For that reason it is interesting to give an estimate of their actual electron affinity at the time of the measurements. In order to do this, according to Eq. 9, one has to fit a straight line to the square of the measured thermal emittance ϵ_{th}^2 as a function of the square root of the rf field \sqrt{E} . The fit coefficient denoted as A in Eq. 9 is related to the actual value of the electron affinity at zero electric field. The replacement of Eq. 1, Eq. 2 into Eq. 8 and setting the electric field $E=0$ yields:

$$E_A(0) = E_{CB} - E_G - \frac{3 Am_0 c^2}{2 \sigma_r^2} \quad (10)$$

where $\epsilon_{th}(0) = \sqrt{A}$ denotes the thermal emittance at zero electric field. With these considerations the measured data for cathode No.43 were analyzed using the regression model introduced in Eq. 9. The results of the straight line χ^2 fits, plotted in Fig. 5 and Fig. 6, give the following value for A:

$$A = \epsilon_{th}^2(0) = (0.12 \pm 0.04) \mu m^2 \quad (11)$$

and subsequently by replacement in Eq. 10:

$$E_A(0) = (0.45 \pm 0.10) eV \quad (12)$$

The last result is in very good agreement with the value of 0.44 eV [5] obtained by measuring QE dependence on rf phase. The estimated high value of the electron affinity for cathode No. 43 (compared to 0.2 eV for very fresh not yet used cathode) is a clear indication of degradation of photoemissive layer due to residual gases in the rf cavity.

SUMMARY

The transverse emittance was measured for a very low charge of 2-3 pC, short laser pulses of σ_t about 3 ps and moderate accelerating gradients. According to simulations space charge and rf field contributions to the emittance should be negligible. The scaling of the transverse emittance with the laser spot rms size was measured using the single slit scanning technique. The thermal emittance was measured as a function of the applied field at the cathode, where monotonic increase with electric field due to the Schottky effect was observed. The electron affinity at zero accelerating field was estimated to be 0.45 ± 0.10 eV for a cathode with quantum efficiency of about 3%.

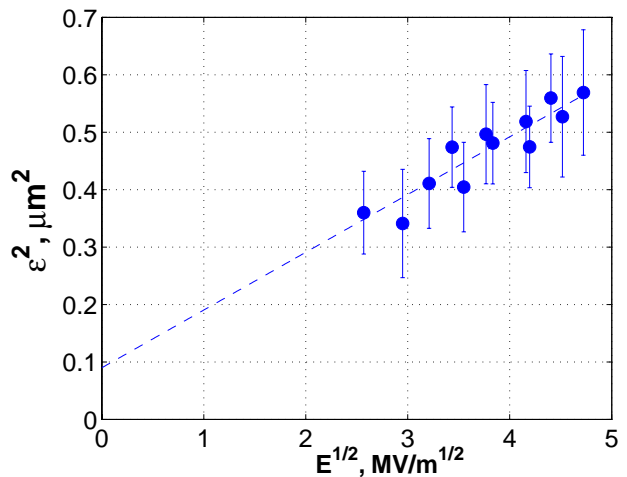


Figure 5: The fit yields: $\epsilon_{th,x}^2 = 0.09 + 0.10\sqrt{E}$

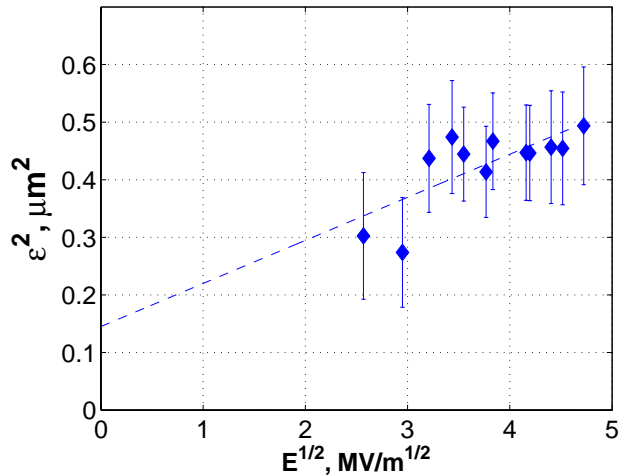


Figure 6: The fit yields: $\epsilon_{th,y}^2 = 0.15 + 0.07\sqrt{E}$

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