INVESTIGATIONS ON THE THERMAL EMITTANCE OF Cs_2Te PHOTOCATHODES AT PITZ*

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Abstract

The main objective of the Photo Injector Test facility at DESY in Zeuthen (PITZ) is the production of electron beams with minimal transverse emittance. The lower limit of this property of electron beams produced with a photocathode in an RF-gun is determined by the thermal emittance. To understand this crucial parameter for high performance FEL's, measurements under RF operation conditions for cesium telluride (Cs_2Te) photocathodes are done. Results for various accelerating gradients and the dependence on the laser spot size in the cathode plane are presented and discussed in this work.

INTRODUCTION

The thermal emittance determines the lower limit of the normalized emittance of electron beams in injectors. Cesium telluride (Cs_2Te) photocathodes are used at PITZ as sources for electron beams because of their high quantum efficiency (QE) and their ability to release high charge electron bunches in a high gradient RF-gun. In the past several theoretical and experimental studies on the thermal emittance of semiconductor photocathodes like Cs_2Te were performed [1, 2, 3, 4].

In Figure 1 a simplified overview of PITZ is given. The 1.5 cell L-band RF-gun is surrounded by a main and bucking solenoid for compensation of emittance growth due to space charge forces. Under normal operation conditions electrons are emitted from the Cs_2Te cathode by illumination with flat-top laser pulses with temporal FWHM $\approx$ 20 ps and $\lambda = 262$ nm wavelength. A 10 MW klystron provides gradients of about 60 MV/m at the cathode. This gradient is a necessary step toward achieving the required emittance for the European XFEL [5]. More details on the PITZ set-up can be found elsewhere [6].

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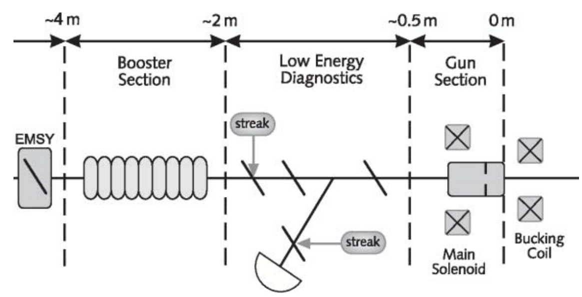

Figure 1: Simplified overview first part of PITZ

At PITZ it is not possible to measure the thermal emittance directly at the cathode. In order to estimate a thermal emittance, a normalized beam emittance has been measured for very low bunch charge and short laser pulses at the first emittance measurement system (EMSY1) 4.3 m downstream (Fig. 1) by the slit scanning technique [7].

In this contribution results from the emittance measurements performed at PITZ are presented for different rms laser spot sizes on the cathode and different accelerating gradients between 30 and 60 MV/m.

THEORETICAL ESTIMATIONS ON THE THERMAL EMITTANCE

The photoemission from semiconductors can be described by a three step model [8]. In the first step an electron from the valence band (VB) is excited to the conduction band (CB) by photon absorption. Due to the energy gap between the conduction and the valence band of $E_g = 3.3$ eV for Cs_2Te, the photon energy must be larger than 3.3 eV [8]. At PITZ a laser with a wavelength of $\lambda = 262$ nm ($E_{ph} \approx 4.72$ eV) is used for the electron excitation into the first density of states maximum in the CB, located 4.05 eV above the VB maximum [8]. The second step involves the electron transport to the surface. In the last step the electron is emitted into vacuum. For the emission process the electron has to overcome the potential barrier at the surface, which for semiconductors can be described by the electron affinity E_A (difference between the vacuum level and the minimum of the CB). For Cs_2Te E_A is in the order of 0.2 eV [8]. So the threshold photon energy for electron emission is $E_{thr} = E_g + E_A = 3.5$ eV. For PITZ and the above given photon energy this leads to an average kinetic energy of $E_{kin} = 0.55$ eV after emission. It is important to mention, that these results only hold for pure photoemission (i.e. no electric fields at the cathode) and for fresh Cs_2Te cathodes. If the cathodes are used in a photo-injector under operational conditions the electron affinity could be reduced by the high electric field at the cathode. On the other hand changes in the chemical composition of the cathode during operation can result in changed emission conditions (i.e. changed work function) [9].

Based on the argumentation given in [1], the kinetic energy of the emitted electrons can be determined by measuring the thermal emittance. Assuming an isotropic emission into the half sphere in front of the cathode surface the thermal emittance can be written in terms of the rms laser spot size σ_l at the cathode and E_{kin}.

$$\epsilon_{th} = \sigma_l \sqrt{\frac{2E_{kin}}{3m_0c^2}} \tag{1}$$

OPERATIONAL PARAMETERS

The thermal emittance ϵ_{th} adds quadratically to other emittance terms forming the measured transverse emittance ϵ_{meas}.

$$\epsilon_{meas} \approx \sqrt{\epsilon_{th}^2 + \epsilon_{SC}^2 + \epsilon_{RF}^2} \tag{2}$$

This relation has to be taken into account to adjust the operation conditions of the injector to perform thermal emittance measurements. The emittance growth caused by space charge forces reduces with smaller bunch charge. As compromise between small space charge and good signal to noise ratio during measurements, bunch charges of maximum 6 pC were used. The influence of the RF-field at the cathode during the emission on the emittance can be reduced by short gaussian laser pulses instead of flat-top temporal profiles, used for normal operation. The shortest pulses currently producible by the laser system at PITZ have a sigma of 3-4 ps. During measurements the gun RF-phase was adjusted to the phase of maximum mean momentum gain Φ_m. If not commented the data in this paper were obtained with the above mentioned operational conditions and the booster operating at maximal momentum gain. Usually slits of 10 μm width were used at the EMSY1.

EXPERIMENTAL RESULTS

The aim of the emittance measurements presented in this contribution, is to give an estimate on the kinetic energies of the emitted electrons for different RF-gradients at the cathode.

From the measured emittances as function of σ_l one can estimate the kinetic energy right after the emission from the

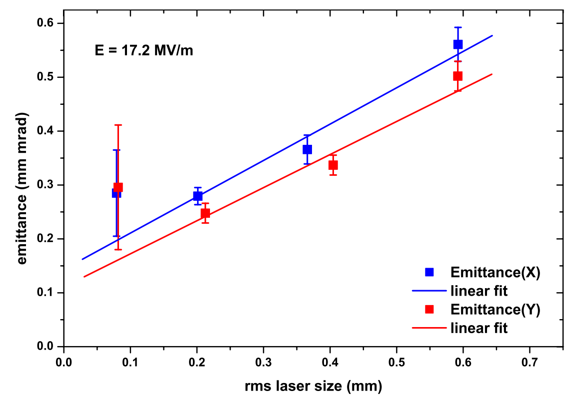

Figure 2: Results from emittance measurements as function of laser spot size for $E_0 = 30$ MV/m for cathode #83.3; symbols: data, lines: linear fit.

slope $(d\epsilon_{th}/\sigma_l)$ of a linear fit and considering equation 3, which results from the differentiation of equation 1.

$$E_{kin} = \frac{3}{2} m_0 c^2 \left(\frac{d\epsilon_{th}}{d\sigma_l} \right)^2 \tag{3}$$

The variation of the rms laser spot size at the cathodes was achieved by apertures of different diameters put into the laser beam line [10].

In Figure 2 measured emittances of Cs_2Te cathode #83.3 for an accelerating gradient of $E_0 = 30$ MV/m are presented. The field on the cathode during the emission process was determined by $E = E_0 \sin(\Phi_m - \Phi_0)$. The phase Φ_0 was estimated from the rising edge of the charge scan vs. RF-phase. For the current case this results in $E = 17.2$ MV/m. In addition to the experimental data, the linear fits are shown. The resulting kinetic energies for this and the other measured gradients are summarized in Figure 7.

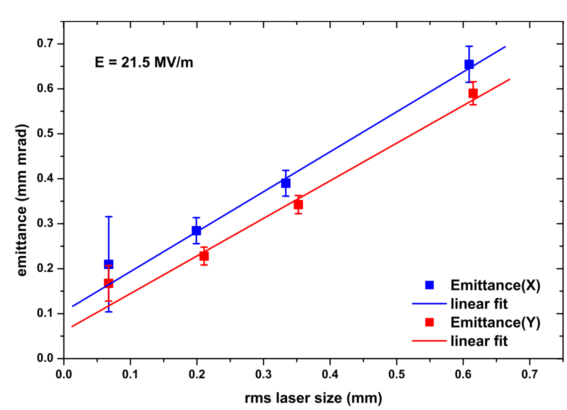

Figure 3: Results from emittance measurements as function of laser spot size for $E_0 = 35$ MV/m for cathode #83.3; symbols: data, lines: linear fit.

Figure 3 shows measured emittances together with the linear fits for an accelerating gradient of $E_0 = 35$ MV/m.

Although for both gradients the measured data can be described by a linear dependence from the rms laser size, deviations to the fits are not small, i.e for the smallest σ_l. A possible reason for the latter one can be the increased charge density of the electron bunch and therefore increased space charge forces. Also neither the data nor the fit end in zero emittance for $\sigma_l = 0$ mm, which could be caused by the accelerating RF-field, also at short laser pulses, and/or by a systematic error during the measurements.

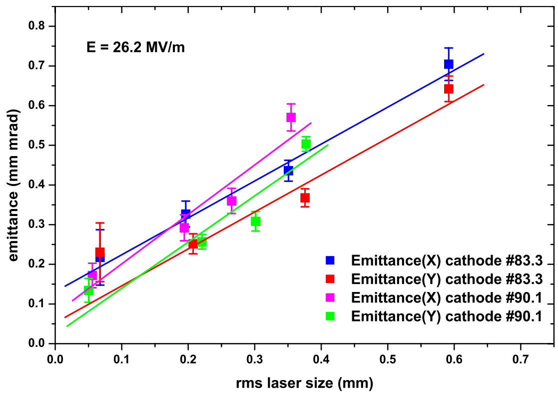

Figure 4: Results from emittance measurements as function of laser spot size for $E_0 = 40$ MV/m; blue and red symbols: data for cathode #83.3, green and magenta symbols: data for cathode #90.1

Figure 4 presents the emittances measured at $E_0 = 40$ MV/m for cathode #83.3 and #90.1. Identical measurements for $E_0 = 60$ MV/m are presented in Figure 6. The datasets were measured with the same operational conditions in the gun section, but the emittances of cathode #90.1 were obtained without booster and with a slit width at EMSY1 of 50 μm. Before the thermal emittance measurements on cathode #90.1, this cathode was used intensely with $\sigma_l = 0.36$ mm, and bunch charges of 1 nC were extracted during the whole period. A QE-map taken in the beginning of the thermal emittance measurements at $E_0 = 60$ MV/m (Fig. 5 right) clearly shows an area in the center region of the cathode with strongly reduced QE. The active area at the right plot in Figure 5 corresponds to the center of the photograph on the left side.

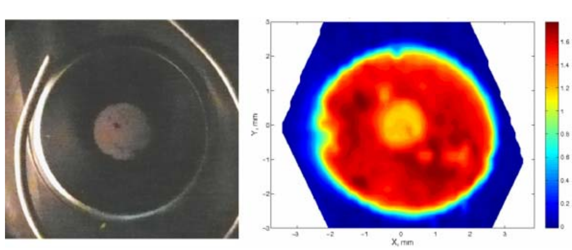

Figure 5: Photograph (left) and QE-map (right) of cathode #90.1

To avoid a mixing of regions with different QE during the emittance measurements, for cathode #90.1 data were only taken for $\sigma_l < 0.36$ mm. The fits in Figure 4 clearly show a different slope obtained from both cathodes, resulting in higher kinetic electron energies for cathode #90.1 (see Fig. 7). In contrary to that, in Figure 6 the slopes for both cathodes are comparable.

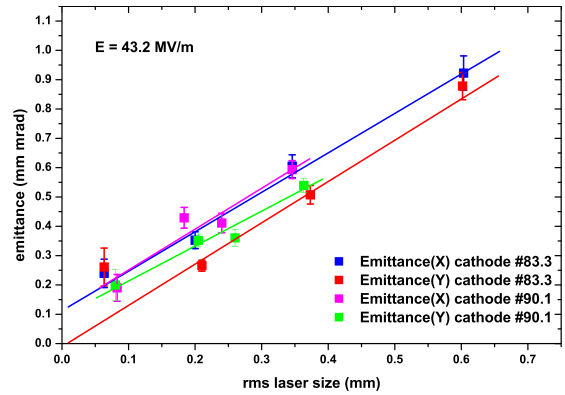

Figure 6: Results from emittance measurements as function of laser spot size for $E_0 = 60$ MV/m; blue and red symbols: data for cathode #83.3, green and magenta symbols: data for cathode #90.1

The kinetic energies obtained from the slopes of the linear fits to the data described above are summarized in Figure 7. Since there is no physical reason for different energies in X and Y direction after the emission, in the figure the geometrical averages of the kinetic energies in both transverse planes are presented. The plot clearly shows the influence of the electric field at the cathode on the kinetic energies, which already was observed for lower gradients [4]. For an accelerating gradient of 60 MV/m ($E = 43.2$ MV/m during emission) we find for both cathodes kinetic electron energies slightly above 1.2 eV. Despite the big uncertainties, this preliminary value is a factor of two higher than for the absence of the electric field (0.55 eV).

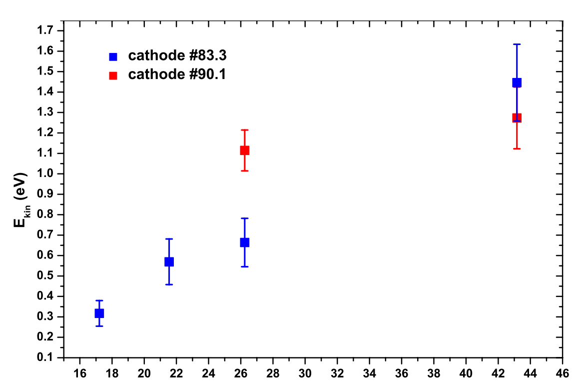

Figure 7: Kinectic electron energies as function of the field at the cathode; blue: cathode #83.3, red: cathode #90.1

SUMMARY

In this contribution measured transverse emittances for different rms laser spot sizes at the photocathode and different gradients are presented. For this measurements the charge was kept to values about 6 pC, and short laser pulses were used. From the thermal emittances the kinetic energies were estimated for two Cs_2Te cathodes. An increase of the kinetic electron energies after the emission with increasing electric field at the cathode was observed. For the highest acceleration gradient available we found kinetic energies of slightly above 1.2 eV. For better understanding of the measured data (i.e. why $\epsilon_{th}\,(\sigma_l = 0) \neq 0$), a more detailed analysis and a comparison with simulations is necessary.

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