CESIUM TELLURIDE AND METALS PHOTOELECTRON THERMAL EMITTANCE MEASUREMENTS USING A TIME-OF-FLIGHT SPECTROMETER

Daniele Sertore, Davide Favia, Paolo Michelato, Laura Monaco, Paolo Pierini,
INFN Milano - LASA, Segrate (MI), Italy

Abstract

The thermal emittance of photoemitted electrons in an RF gun is a crucial parameter for short wavelength FELs and future high luminosity electron colliders. An estimate of the thermal emittance of semiconductor and metal samples, commonly used as photocathodes, has been assessed using a Time-Of-Flight spectrometer. In this paper we present the analysis, based on angle resolved photoemission measurements, of both the cesium telluride (Cs_2Te) photocathode films as used at the TESLA Test Facility, and polycrystalline metals. These latter measurements, at different laser wavelengths, are used to validate both our experimental apparatus and the thermal emittance reconstruction technique developed.

INTRODUCTION

The high beam quality delivered from photocathode based RF photoinjectors has allowed, in the past few years, many SASE-FELs to reach saturation. The wavelength spectrum ranges from deep UV [1] to visible [2]. The photoinjector community is now working to further improve the beam quality by reducing the emittance of the generated beam and preserving it during its acceleration. Besides beam dynamics studies, the main fields of investigations are the longitudinal and transvers laser pulse shaping and the selection of proper photocathode materials. Among semiconductor photocathodes, alkali tellurides (Cs_2Te) show high Quantum Efficiency, high robustness and long lifetime. Metals such as copper and magnesium, less sensitive to surface pollution, are usually more demanding on laser performance because of their lower QE. The very high quality of the beam generated from present photoinjectors is now introducing a new parameter for the photocathode material selection: its thermal emittance, a measure of the electron distribution in the transverse position-momentum phase space at its generation.

In this paper, we present the first direct measurement of the thermal emittance from a Cs_2Te and an Ag sample performed using a Time Of Flight spectrometer. Differently from previous measurements on Cu [3] and Mg [4] in RF guns, our measurements are performed in a field-free region in the eV energy range.

EXPERIMENTAL SETUP

The experimental apparatus consists of a complex UHV system where the cathodes are grown and analyzed. The energy electron analyzer is based on a Time Of Flight spectrometer, with high energy resolution for electrons with low kinetic energies ($\Delta E/E$ = 0.8 % @ 1.9 eV) [5]. The analysis chamber configuration allows performing angle resolved measurements, a key feature for the reconstruction of the thermal emittance.

The light source for the photoemission experiment is a solid state Nd:glass laser (TWINKLE). The operational wavelengths are the 4th (264 nm) and 5th (211 nm) harmonic of the fundamental. The pulse length is 500 fs, measured using a technique based on self diffraction. The laser light enters the UHV chamber through Suprasil viewports. The laser energy is monitored during the measurements by a UV sensitive photodiode.

The Ag samples are machined out of a pure Ag sheet (99.97 %), optically finished, rinsed with alcohol. Before the measurements, the samples are baked out and cleaned with Ar ion sputtering.

The Cs_2Te samples are grown on a Mo substrate. The substrates are machined from a pure Mo sheet (99.95 %), optically finished and rinsed with alcohol. The samples are then heated up to 450 °C for 1 hour for cleaning and then cooled down to 120 °C for the cathode preparation. The photoemissive films are grown following the standard recipe [6] used for the TTF2 and PITZ2 photocathodes production.

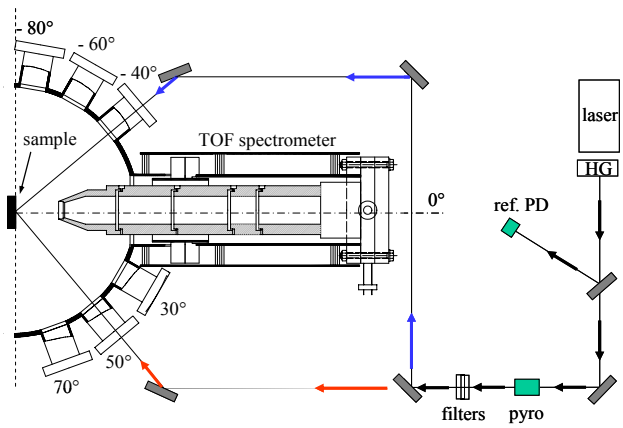

Fig.1. Sketch of the TOF analysis system. The sample is rotated at each angle to provide normal laser incidence.

RECONSTRUCTION ALGORITHM

The TOF apparatus allows to measure the momentum distribution of the photoemitted electrons. Due to the cylindrical geometry of the analysis chamber, we consider the following definition for the normalized emittance calculation:

$$\varepsilon_x = \frac{1}{2 \cdot c} \cdot \sqrt{\left\langle r^2 \right\rangle \cdot \left\langle \dot{r}^2 + \left(r \cdot \dot{\phi}\right)^2 \right\rangle - \left\langle r \cdot \dot{r} \right\rangle^2} \qquad (1)$$

where c is the speed of light, r is the radial position and ϕ is the azimuthal angle, $\dot{r}$ e $\dot{\phi}$ their time derivatives.

Furthermore, we assume that there is no correlation between the radial component of position and velocity at the photocathode. This allows dropping the second term in the square root. Then, the radial component of the electron velocity is related to the total electron kinetic energy E_{Kin} by:

$$\dot{r}^2 + \left(r \cdot \dot{\phi}\right)^2 = \frac{2 \cdot E_{Kin}}{m_0} \cdot \cos^2(\theta)$$

where m_0 is the electron mass and θ is the TOF collecting angle. If the laser has a spot characterized by an rms value σ, expression (1) is reduced to the evaluation of the following relation:

$$\varepsilon_x = \sigma \cdot \sqrt{\frac{\left\langle E_{Kin}(\theta) \cdot \cos^2(\theta) \right\rangle_{E_{Kin},\theta}}{2 \cdot E_0}} \qquad (2)$$

where $E_0 = m_0c^2$, and the average appearing inside the square root is performed over the distribution in energy and angle of the emitted electrons.

It is now necessary to determine the average term in equation (2). The TOF analyzer shown in Figure 1 can collect the electrons emitted at nine different angles from the direction of normal incidence, from 0° to 80° with a step of 10°. At each angular position, the emitted electrons are collected at a distance L_{TOF} in a laser-triggered microchannel plate (MCP) detector, in order to determine their energy distribution from the measure of the time of flight distribution. The energy distribution measured at each collection angle θ_n at the MCP detector area is then taken as representative of the electron emission within the solid angle underlying the spherical corona separating two successive angles, and the total number of counts is correspondingly scaled.

THERMAL EMITTANCE ESTIMATIONS

As explained in the previous section, we concentrated our effort in the estimation of the momentum distribution of the photoemitted electrons, assuming no correlation between position and momentum at the emission.

The measurement of the energy distributions of the photoemitted electrons at these low energies (in the 0 - 2 eV range) is particularly difficult, subject to many sources of instrumental errors and complicated by the uncertainties on the properties of the sample materials. Although the earth magnetic field was properly shielded, the different work functions of the sample and TOF system lead to contact potential effects and result in electric fields that perturb significantly the measurement. Even applying voltage difference to balance the contact potential, the stray electric and magnetic fields in the chamber limit the collection capabilities of the low energy part of the photoelectron spectra. Therefore, during the measurement, a bias voltage has been applied to the system to collect the complete spectrum of the photoemitted electrons. In the following, the zero value of the bias voltage corresponds to the balanced contact potential case between the TOF "nose" and sample.

Furthermore, the expected spectra depend on the sample properties (like density of states, work function, etc.), which are not fully available for Cs_2Te. For this reason, we calibrated the system with a known metal like silver, where precise data concerning the density of states in the conduction band and the work function are available in the literature. This measurement provided a test bed and a calibration [7] for the successive measurement of Cs_2Te samples.

During all measurements, the number of emitted electrons has been kept low enough (by applying calibrated attenuation filters on the laser beam) to consider the space charge effects negligible on the collected spectra. At all collecting angles, the laser is always normal to the sample. This configuration is similar to the usual condition in the RF gun where the laser shines nearly at normal incidence.

Metal (Ag)

The estimated thermal emittance of an Ag sample using the 4th harmonic of the Nd:glass is shown in Fig. 2. The values obtained can be compared with theoretical consideration assuming a gaussian distribution, isotropic in space, for the energy of photoemitted electrons. A typical spectrum from a silver sample is shown in the insert of Fig. 2. The spectrum fits to a Gaussian function centered at 0.28 eV with an rms width of 0.094 eV. The expected thermal emittance, with the above assumptions, is ε_{th} = 0.6 mm mrad for a rms laser beam radius of 1 mm.

Fig 2 shows also the independence of the measured thermal emittance from the bias voltage applied between the sample and the nose of the detector. The low value at 0 V is affected by an instrumental cut at very low energies (< 0.2 eV) and hence it is not included in the emittance estimation.

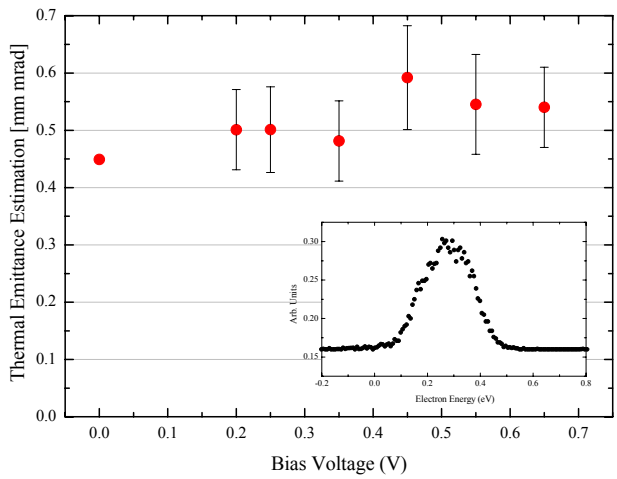

Fig. 2. Thermal emittance measured on Ag sample for a rms laser spot of 1 mm. The insert shows a typical spectrum of photoemitted electrons from Ag.

The estimated thermal emittance of Ag from our measurement is ε_{th} = 0.52±0.1 mm mrad for 1 mm rms spot radius, consistent with the expectation based on a gaussian emission spectra.

Semiconductor (Cs_2Te)

The measurements of Cs_2Te samples are shown in Fig. 3 for different bias voltages and for the two different laser wavelengths (λ = 264 nm and 211 nm). The Quantum Efficiencies at these two wavelengths are, respectively, 5.1% and 8.9 %. The standard QE reached after the film deposition – 12.1 % @ λ= 264 nm - has been reduced to the value reported above in a controlled way by oxygen exposure to reproduce the operational photocathode properties usually obtained in the RF gun.

The Cs_2Te thermal emittance estimation shows more statistical variation with respect to the silver case due to the lower work function of the semiconductor, resulting in stronger perturbations caused by the applied voltages needed to compensate the effect of the contact potentials. This limits the electron collection capabilities at different angles. The resulting effect – confirmed with electron tracking in the resulting field pattern - is a kinematic-induced difference of the collection angle with respect to emission and in a lower collection capabilities at large angles. For each data point, the error bar takes into account also the scattering of the results obtained applying different methods to compensate for these effects.

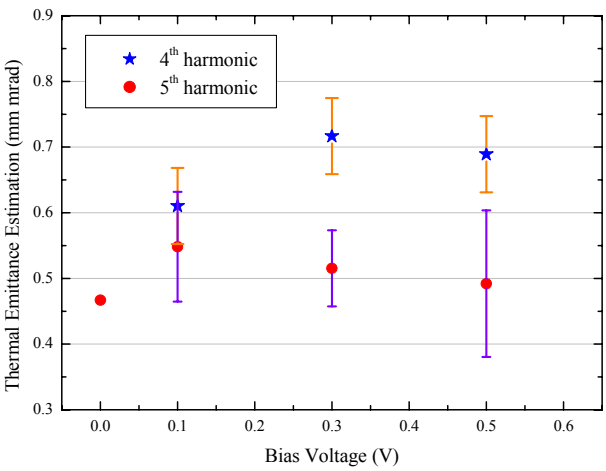

Fig. 3. Thermal emittance measured on a Cs_2Te sample at different bias voltages and at two wavelengths (λ=264 nm and 211 nm respectively for the 4th and 5th harmonic).

The estimated emittance for the 4th harmonic is constant and independent from the bias voltage. The increase in the error bars for higher values of the bias voltage is due to the lower counting rates at large angles, induced by the electric fields as explained above. We estimate, a thermal emittance at $\lambda = 264$ nm of $\varepsilon_{th} = 0.5 \pm 0.1$ mm mrad for 1 mm rms radius. This result is in agreement with previous theoretical estimations [8].

To further investigate the dependence of the emittance on laser wavelengths, we performed measurements using the 5th harmonic of the laser. The estimated thermal emittance at $\lambda = 211$ nm is $\varepsilon_{th} = 0.7 \pm 0.1$ mm mrad.

The increase of thermal emittance at higher photon energies is an expected phenomenon and can be explained by the fact that the spectrum of photoemitted electrons varies with the photon energies. Indeed the spectrum of the photoemitted electrons at the 4th harmonic has an electron count maximum at 0.5 eV, whereas at the 5th harmonic it has a maximum at 0.9 eV. The position of this maximum is related to the possible electron transitions and their probabilities in the material after laser excitation. Assuming, as suggested in Ref. [9], that the thermal emittance scales as the square root of the most probable energy, the ratio between the estimated thermal emittances at the 4th and 5th harmonic varies according to this simple scaling.

CONCLUSIONS

We have reported here the first measurement of the thermal emittance from Cs_2Te and Ag samples. The thermal emittance has been reconstructed using spectra of the photoemitted electrons collected at different angles with respect to the sample normal incidence.

Furthermore, the thermal emittance estimated for the Ag samples is in good agreement with the expected theoretical value assuming a gaussian photoemission spectrum. The Cs_2Te measurements are well within the expected values from a model previously developed, and are consistent with the requirements of ultra high brightness beam applications. Moreover, the estimated thermal emittance scales with wavelength in good agreement with the most probable value of the emitted energies of the photoelectrons.

REFERENCES

[1] J. Andruszkow et al., "First Observation of Self-Amplified Spontaneous Emission in a Free-Electron Laser at 109 nm Wavelength", PRL 85(18), p. 3825.

[2] S.V. Milton, "Measurements of exponential gain and saturation of SASE at the APS LEUTL", PAC 2001, p. 236.

[3] W. Graves et al., 'Measurement of the thermal emittance for a copper photocathode', PAC 2001, p. 2227.

[4] X. J. Wang et al., 'Mg cathode and its thermal emittance', LINAC 2002, p. 142.

[5] D. Sertore et al, "First energy spectra obtained with a Time-Of-Flight (TOF) electron spectrometer on Cs_2Te photocathodes", PAC 2001, p. 2420.

[6] P. Michelato et al., "Cs_2Te photocathode for the TTF Injector II", EPAC 96, THP068L.

[7] P. Michelato et al., "A novel spectrometer for laser-excited time- and angle-resolved photoemission spectroscopy", submitted to Measurement Science and Technology

[8] P. Michelato et al., "Thermal emittance estimation using a Time-Of-Flight spectrometer", EPAC 2000, p. 1669.

[9] J.D. Lawson, "The physics of charged particle beams", Oxford University Press, Oxford, 1988, p. 2