INVESTIGATIONS ON THERMAL EMITTANCE AT PITZ

M. Otevrel[1], M. Khojoyan[2], G. Asova[3], H. J. Grabosch, M. Gross, L. Hakobyan, Y. Ivanisenko,
I. Isaev[4], G. Klemz, M. Krasilnikov, M. Mahgoub, D. A. Malyutin, A. Oppelt, S. Rimjaem,
B. Petrosyan, A. Shapovalov[4], F. Stephan, G. Vashchenko, S. Weidinger,
DESY, 15738 Zeuthen, Germany
S. Lederer, DESY, 22603 Hamburg, Germany
D. Richter, HZB, 14109 Berlin, Germany

Abstract

The main aim of the Photo-Injector Test Facility at DESY, location Zeuthen (PITZ) is to develop and test an FEL photo-injector system capable of producing high charge electron bunches of lowest possible transverse emittance, which has a fundamental impact on FEL performance. Recent measurement results at PITZ showed a fairly small electron beam transverse projected emittance [1] which increased interest in the thermal emittance and its contribution to the overall electron beam emittance budget. Therefore thermal emittance was investigated at PITZ. Results of these studies are presented and discussed.

INTRODUCTION

The main goal of the Photoinjector Test Facility at DESY, location Zeuthen (PITZ) is to develop and test the RF accelerating source (RF gun) for the high brightness Free Electron Lasers (FELs) in particular for FLASH and the European X-FEL project. Essentially such a photoinjector system capable of producing electron bunches of high charge and lowest possible transverse emittance and supporting long pulse train operation provides increasing FEL performance and/or reduction of investment costs. One of the most important components of a photoinjector is the photocathode, which quality has high impact on overall system performance. Caesium telluride (Cs_2Te) photocathodes are used in PITZ photoinjectors for their high quantum efficiency (QE), which is needed for production of high charge bunches, and reasonable lifetime. A very important property of the emitted photoelectrons is their thermal emittance, which is a measure of their initial, spatially uncorrelated transverse momentum spread. This quantity is dependent on the applied laser photon energy as well as on surface properties of the photocathode and also on external electric field close to its surface, if applied.

THERMAL EMITTANCE

The electron emission goes essentially in following three steps [2]: 1) electron excitation by photon absorption, 2) electron drift towards the surface and finally 3) electron escape over the surface barrier – the electron affinity – into the vacuum. The probability of photon absorption $P(h\nu)$ is proportional to [3]

$$P(h\nu) \propto N_{fin}(E_{fin}) \cdot N_{ini}(E_{fin} - h\nu)\,, \qquad (1)$$

where N_{fin}, N_{ini} are densities of initial and final states respectively and E_{fin} is the final state energy level. Therefore the first absorption maximum appears for photon energy close to difference between the first Conduction Band Density of States (CBDOS) maximum and last Valence Band DOS (VBDOS) maximum levels. In case of Cs_2Te this energy is equal 4.75eV since the 1st CBDOS maximum is at +4.05eV [3] and the last VBDOS maximum is at -0.7eV [3], both with respect to the valence band maximum (see Fig.1). The laser system at PITZ consists of Yb:YAG laser [6] and two SHG crystals convert an IR laser pulse into UV of wavelength 257nm which corresponds to the photon energy of 4.82eV. The system is therefore well tuned to Cs_2Te cathodes. The vacuum energy level (again w. r. t. Cs_2Te VB maximum) is 3.5eV: the sum of the band gap (+3.3eV) and the electron affinity (+0.2eV). If we assume that the electrons undergo scattering also in the surface region, they will be emitted isotropically into a half-sphere over the cathode with *uniform* energy E_{kin} = 0.55eV (See Fig.1). Now using the definition of normalized emittance and considering the above mentioned assumption, following formula for the thermal emittance could be derived [4]:

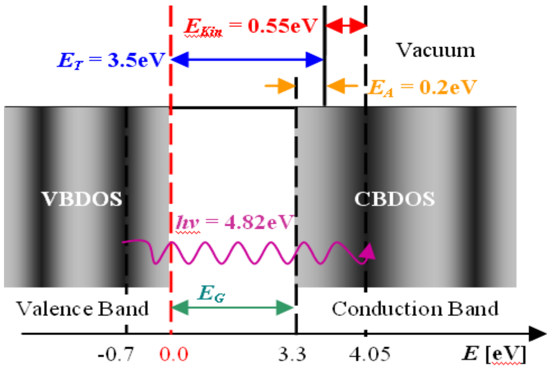

Figure 1: Schematic energy level diagram of Cs_2Te. The shadowed areas represent the density-of-states function.

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[1] marek.otevrel@desy.de

[2] On leave from YerPhI, Yerevan, Armenia

[3] On leave from INRNE, Sofia, Bulgaria

[4] On leave from MEPhi, Moscow, Russia

$$\varepsilon_{Th,i} = \sigma_{RMS,i}\sqrt{\frac{2E_{kin}}{3m_0c^2}} \qquad (2)$$

Here $\sigma_{RMS,i}$ is the RMS size of the laser spot x_i-projection. As already mentioned, this formula has been derived assuming that *all* emitted electrons have *the same* energy (and total momentum – let us denote it as p_0). This leads to "rectangular" probability distributions for the components p_x, p_y, p_z. The distributions are constant for $p_x \le p_0$, and zero otherwise. The RMS of such a distribution is equal to $p_0/\sqrt{3}$. It could be proven that if the RMS of the real probability distribution of p_0 is much less than mean p_0, the RMS of the momentum components will remain close to $p_0/\sqrt{3}$. Therefore the assumption for the thermal electrons to be mono-energetic is reasonable. In reality nevertheless the E_{kin} can significantly differ from the stated value of 0.55eV. First the electron affinity could be different due to impurities on the cathode surface and second, the kinetic energy would be higher due to Schottky effect caused by RF and space charge fields at the moment of emission. Since there is lack of certainty about the E_{kin}, the eq.2 can not be used for thermal emittance determination. In fact, it will be used to determine the E_{kin}, itself *from* the measured (ideally thermal) emittance to 1) check the theoretical approach and 2) give feedback to measurement results.

MEASUREMENT PROCEDURE

Measurement Setup

Since no direct thermal emittance measurement is available at PITZ, estimation on the average kinetic energy from Cs_2Te photocathode can be done by measurement of projected emittance at special machine setup. The emittance was measured using the slit scan method [1]. In Fig. 2 a simplified scheme of the PITZ setup could is shown. The electron bunch is created by means of (RF field assisted) photoemission and immediately accelerated gaining up to ca. 6.7MeV/c axial momentum by the RF field generated inside the 1.6 cell L-band copper cavity [1]. The beam is influenced by the main solenoid field for space charge effects compensation. There is also a bucking solenoid which compensates the magnetic field of the main solenoid at the cathode surface. Beam momentum is measured in the dispersive arm and the emittance is measured using the Emittance Measurement System (EMSY) Station and the Screen station marked as H1.Scr.4. (The Booster Cavity was not used for thermal emittance measurement.) For details on emittance measurement procedure and setup please see [1].

Considering Measurement Conditions

Obviously there are several contributions in the measured emittance budget and they add quadratically assuming mutual independence as follows:

$$\varepsilon_{Exp} = \sqrt{\varepsilon_{Th}^2 + \varepsilon_{SC}^2 + \varepsilon_{RF}^2 + \varepsilon_{SErr}^2} \qquad (3)$$

Here ε_{Exp} is measured emittance and ε_{Th} is the thermal emittance. The other contributions are 1) from RF field (ε_{RF}) caused firstly due to phase shift within a single bunch (of finite temporal length) and secondly due to phase and/or amplitude instability causing different conditions for subsequent bunches in a bunch train 2) from non-linear space charge effects (ε_{SC}) and finally 3) the systematic error ε_{SErr} is to be considered, associated e.g. with signal and camera properties, laser spot instability by means of position and intensity, the beamlet dimensions, the actuator position and speed precisions etc. The ε_{Exp} will be close to ε_{Th} if the ε_{Th} will be dominant among the other contributors. Therefore for the measurement a short pulse (affecting ε_{RF}) with as low charge (density) as possible (affecting ε_{SC}) should be used. The pulse temporal length is however limited by the native laser pulse length of ca. 1.2ps RMS and the charge density should be high enough to provide reasonable signal intensity (affecting ε_{SErr}). The signal intensity could be improved by considering a longer pulse train, but this might increase the ε_{RF} on the other hand.

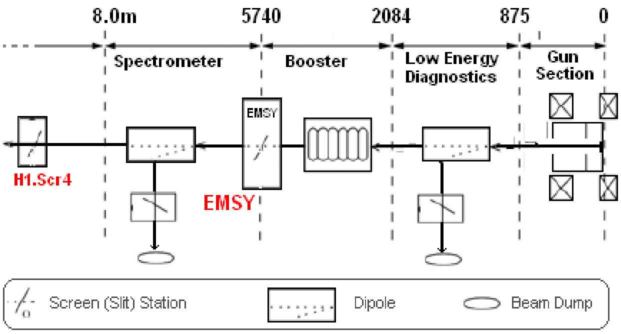

Figure 2: Simplified setup of the PITZ low section. (The beam goes from right to left).

The Scaling Factor

Obviously, if we cut the beam using a slit, the lowest-charge-density parts of the beam could hardly be detected at the observation screen. That would lead to emittance systematic underestimation. To partially compensate this effect, the resulting emittance was multiplied by a Scaling Factor (*SF*), which is defined as a ratio of beam spot RMS at the slit position and the X-RMS value of corresponding reconstructed phase space obtained: $SF \equiv \sigma_x/\langle x^2\rangle^{-1/2}$ [1].

Measuring Average Kinetic Energy

A standard approach how to determine the average kinetic energy at the cathode (E_{kin}) at PITZ is to measure the emittance as a function of laser spot size at special conditions allowing us to assume the measured emittance being close to the thermal emittance. Using eq.2 we can find following formula for the average kinetic energy of emitted electrons:

$$E_{kin} = \frac{3m_0c^2}{2}\left[\frac{d\varepsilon_{Th}}{d\sigma_{RMS}}\right]^2 \cong \frac{3m_0c^2}{2}\left[\frac{d\varepsilon_{Exp}}{d\sigma_{RMS}}\right]^2 . \quad (4)$$

Here $d\varepsilon/d\sigma_{RMS}$ is the slope of the corresponding emittance dependence on laser RMS spot size. Since there is no fundamental reason for kinetic energy to depend on the laser spot size, the slope should be constant w.r.t. σ_{RMS}. (The only possible non-linearity should be due to the last three terms in eq.3.) The charge of the bunch has been chosen that way to keep the charge density at the cathode constant. There is a serious problem connected to above mentioned approach however. Since the charge density is maintained constant, the space-charge relative contribution $\varepsilon_{Th}/\varepsilon_{SC} \equiv \kappa$ will approximately remain also constant. Therefore the measured emittance would be (if we neglect ε_{RF} and ε_{SErr})

$$\varepsilon_{Exp} = \left(1+\kappa^2\right)^{\frac{1}{2}}\varepsilon_{Th}, \quad (5)$$

and this factor will add to the slope. The impact to the kinetic energy will be large, since it depends on second power of the slope (eq.4). To deal with this problem a second complementary approach has been considered. Here the laser spot size was fixed (large) and the beam charge (density) was varied. Therefore, as the intuition suggests and simulations show, the κ is varied and there is also a region for charges low enough, where κ is almost negligible and therefore the measured emittance is no more dependent on bunch charge. The way how to determine the average electron kinetic energy is to fit the measured curve with a simulated one. The ASTRA [5] code was used for the simulations and the parameter was the average kinetic energy itself. Let us notice, that this approach also does not need to use eq.4, although it keeps some of the assumptions used to derive it (included in the ASTRA code).

RESULTS AND DISCUSSION

Fixed Charge Density Approach

In this paragraph the measurement results of the average kinetic energy of just-emitted (thermal) electrons will be presented. (All the measurements was done using cathode #11.3, which was inserted into the photo-gun two weeks before the measurements.) First focus will be on the results obtained from the slope analysis of the emittance dependence on the laser spot size RMS (eq.4). The charge density was kept constant here. Therefore the charge was kept proportional to laser spot size RMS squared as follows:

$$Q_{bunch} = D_i^{SC}\sigma_{RMS}^2 \quad (6)$$

In Fig.3 you can see the emittance - laser spot size dependences for two charge density coefficients. (D^{SC} = [0.96, 0.49] nC/(mm)^2). From the slope analysis (eq.4) following kinetic energies were obtained: 24.9eV for the higher charge density coefficient and 17.7eV for the lower one. Those values are incredibly far from the expected value of 0.55eV. There are a few possible explanations for such an observation. Firstly, and by far most importantly, the charge densities are quite high for both charge density coefficients which lead to significant κ values (eq.5). Secondly, since the charge varied with the laser spot size, bunch train lengths had to be accordingly adjusted due to the signal quality reasons. But unfortunately due to laser properties at the time of measurement the bunch charge was not constant within the train (an example shown in Fig.3b). Therefore for the smaller laser beam sizes the measured emittance was lower then expected, since the charge was adjusted for the first bunch in the train. This increased the slope and consequently (quadratically) the resulting E_{kin}. An additional expected effect, that the fit would not cross the *y*-axis (emittance) at the zero-point but below, was indeed observed as Fig.3 shows.

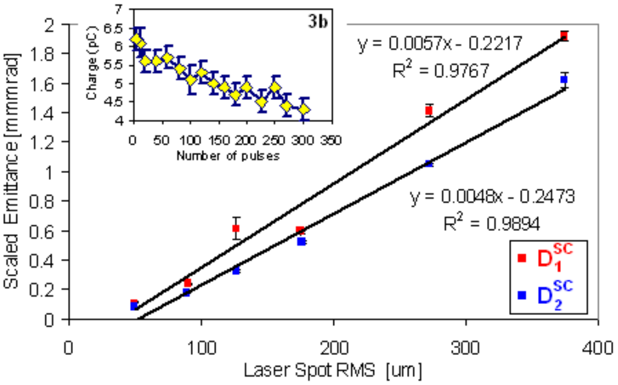

Figure 3: Measured emittance as a function of laser RMS size, keeping charge density constant.

Fixed Laser Spot Size Approach

As mentioned before, here the laser spot size was kept constant (Ø=1.50mm, σ_{RMS} =0.375mm) and the (scaled) emittance was measured as a function of the bunch charge. In fig.4 you can see the geometrical average of *x*- and *y*-scaled emittances $\varepsilon_{SC} = \sqrt{\varepsilon_{SC,x}\varepsilon_{SC,y}}$, together with the ASTRA simulations obtained for various average kinetic energies E_{kin}=[0.2, 0.55, 1.0]eV (The other parameters were matched to the experiment, 5*10^5 macro-particles used). One can see that for low-charge-end the emittance indeed does not depend on charge (or the dependence is weak) since the ε_{SC} significance diminishes. In this region, the experiment agreement with simulation prediction is satisfactory. For the higher charges there is a significant disagreement between experiment and simulation however. Unfortunately the

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region where the emittance is not dependent on charge could not have been reached due to prohibitive low signal intensity. Also the measured points in the low-charge region suffered more-or-less from low signal intensity, which could have lead to emittance underestimation. This effect was however significantly reduced by applying the above discussed scaling factor. On the other hand, for high charge region the beam lost its symmetry (resulting in *x*-*y* phase space coupling) and also shows artefacts due to causes not yet entirely understood. Those could not have been simulated and therefore the emittance growth due to those effects was not affecting the simulation results. In any case however the experimental results could be considered at least close to the theoretical predictions, since simulated curves for e.g. $E_{kin} = 0.2$eV and $E_{kin} = 1.0$eV are far beyond the error-bars (see Fig.4).

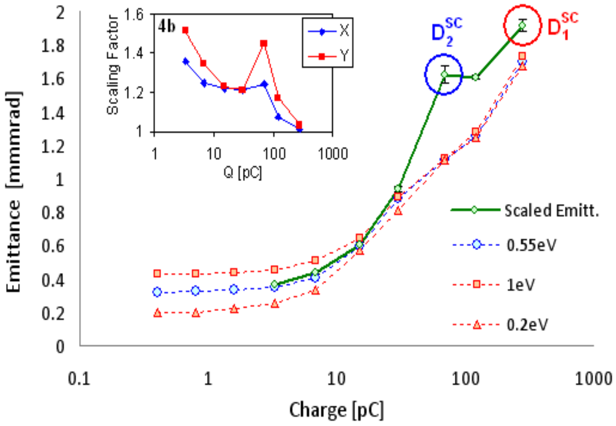

Figure 4: Measured and simulated emittance and the scaling factors as functions of charge density, keeping laser RMS size constant (σ_{RMS} =0.375mm). The Scaled Emittance shown is the geometrical average of measured *x*-and *y*-scaled emittances. Simulations were done for various average kinetic energies (0.2eV, 0.55eV, 1.0eV).

SUMMARY

The aim of the studies reported here was to estimate experimentally the thermal emittance of the just photo-emitted electrons from the cathode and check the results agreement with theoretical predictions. The analysis of measured emittance as a function of laser spot size for constant charge density led to much higher average kinetic energy for the emitted electrons (E_{kin}) than the value predicted by theory caused at least partially by the space charge effects. On the other hand the emittance measurements for large laser spot size and low bunch charge led to E_{kin} comparable to the theoretical value 0.55eV.

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