TRANSVERSE EMITTANCE MEASUREMENTS AT THE PHOTO INJECTOR TEST FACILITY AT DESY ZEUTHEN

V. Miltchev*, K. Abrahamyan†, G. Asova‡, J. Bähr, G. Dimitrov§, H.-J. Grabosch, J.H. Han, M. Krasilnikov, D. Lipka, A. Oppelt, B. Petrosyan, D. Pose, S. Riemann, L. Staykov, F. Stephan
DESY, Zeuthen, Germany
M.v. Hartrott, D. Richter, BESSY GmbH, Berlin, Germany
J.P. Carneiro, K. Flöttmann, S. Schreiber, DESY, Hamburg, Germany
P. Michelato, L. Monaco, D. Sertore, INFN Milano-LASA, Segrate (MI), Italy
I. Tsakov, INRNE Sofia, Sofia, Bulgaria
I. Will, Max-Born-Institute, Berlin, Germany
W. Ackermann, S. Schnepp, S. Setzer, TU Darmstadt, Darmstadt, Germany

Abstract

This contribution summarizes the transverse emittance studies done at the Photo Injector Test Facility at Zeuthen (PITZ) for producing an electron beam that meets the requirements of the VUV-FEL. Systematic measurements of the beam emittance in a wide range of parameters (e.g. bunch charge, rf phase, solenoid fields) will be presented and compared with simulations.

INTRODUCTION

The main goal of PITZ is the development of electron sources for Free Electron Lasers. Since the first production of photoelectrons in January 2002 several upgrades have been realized. An important step was the transition from temporal gaussian laser profile to flat top distribution in the spring of 2003. This change was motivated by the resulting significant emittance reduction, which will be demonstrated in the first part of this paper. In the second part of the paper the optimization of the rf gun toward the VUV-FEL requirements is summarized. In the third part the measurements of thermal emittance are discussed and finally some of the latest emittance measurements are presented.

MEASUREMENTS WITH VARIOUS TEMPORAL PROFILES OF THE UV LASER PULSE

The emittance was measured as a function of the main solenoid current using gaussian temporal profile of the laser pulse of 6.0±1.0 ps FWHM. The bunch charge was set to 0.49 ±0.02 nC. The radial laser beam profile was about flat top, but with a modulation depth of ∼20 % , σ_x = 0.53 ±0.02 mm, σ_y = 0.65 ±0.02 mm. The rf phase ϕ was set to the phase with maximum mean energy gain ϕ_m. This phase ϕ_m will be used as a reference phase throughout this paper. The electric field gradient on the cathode surface was about 41 MV/m. A single slit scanning tech-

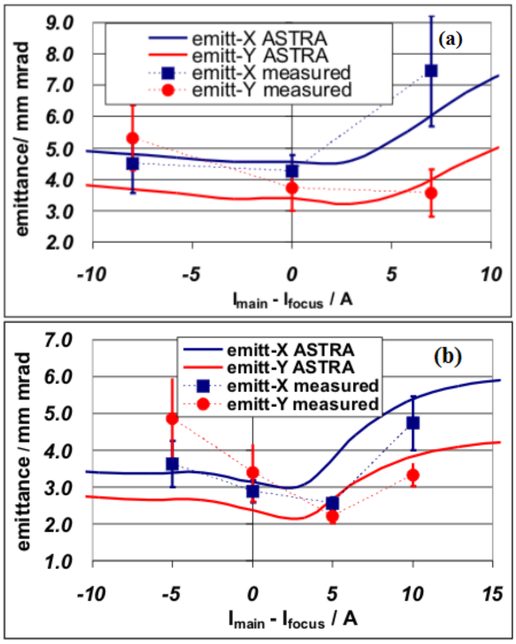

Figure 1: Projected normalized emittance as a function of the main solenoid current I_{main}: (a) for a bunch charge of 0.5 nC and a gaussian laser pulse with a length of 6.3 ps FWHM, and (b) for a bunch charge of 1.0 nC and a flat top laser pulse with a length of 23 ps FWHM. I_{focus} denotes the solenoid current to focus the beam on the position of the slit mask.

nique was used for the emittance measurements [1, 3]. Results of the measurements compared with ASTRA [4] simulation are presented in Fig. 1(a). The minimal emittance is about 4 mm mrad. Since the emittance scales with the charge, we expect the emittance for the gaussian

* velizar.miltchev@desy.de
† on leave from YERPHI, Yerevan, Armenia
‡ on leave from INRNE Sofia, Sofia, Bulgaria
§ on leave from INRNE Sofia, Sofia, Bulgaria

case at 1 nC to be even larger. The same set of measurements has been repeated with a flat top longitudinal laser pulse profile of 23.0±1.0 ps FWHM. The bunch charge was set to 1.00±0.02 nC. The laser beam transverse sizes are: σ_x=0.52±0.02 mm, σ_y=0.63±0.02 mm. The rf phase was set to ϕ_m; the electric field gradient on the cathode was about 42 MV/m. The parameters have not yet been optimized for minimum emittance, these measurements are to compare flat hat with gaussian laser pulses. The measurements compared with an ASTRA simulation are presented in Fig. 1(b). The minimal emittance is about 2.3 mm mrad. Since the measurement conditions for both solenoid scans are about the same, a flat hat laser profile yields a more than two times smaller emittance than the gaussian profile.

EMITTANCE OPTIMIZATION TOWARD VUV-FEL REQUIREMENTS

After the upgrade of the laser system an extended measurement program was carried out at PITZ in order to characterize and optimize the VUV-FEL rf gun (cavity prototype #2) for TTF [2, 5].

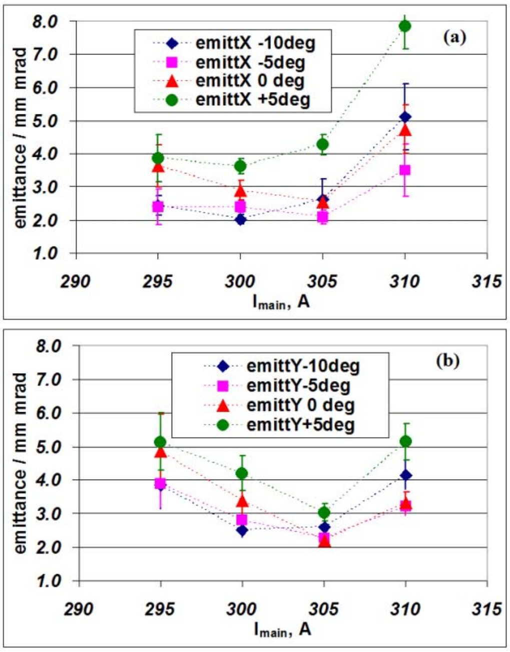

Figure 2: Projected normalized horizontal (a) and vertical (b) emittance for different main solenoid currents and gun phases $\phi - \phi_m = -10°$, $-5°$, $0°$, $+5°$. The bunch charge is 1.0 nC.

Optimization strategy

As a first optimization step, the emittance for a bunch charge of 1 nC is measured as a function of the main solenoid current $I_{\rm main}$ for the rf phases $\phi - \phi_m = -10°$, $-5°$, $0°$, $+5°$ at a maximum accelerating gradient on the cathode of 42 MV/m. During this first optimization step the magnetic field at the photo-cathode was not compensated by the bucking solenoid. Later on, for the settings $\{I_{\rm main}, \phi\}$ with the smallest emittance, the bucking solenoid current has been fine tuned. During the measurements, the laser temporal and transverse properties were frequently monitored and adjusted. The laser pulse temporal profile was a flat top of 18 to 23 ps FWHM with a rise and fall time of 5 to 7 ps. The transverse shape was slightly asymmetric: σ_x = 0.50 to 0.52 mm, σ_y = 0.61 to 0.63 mm.

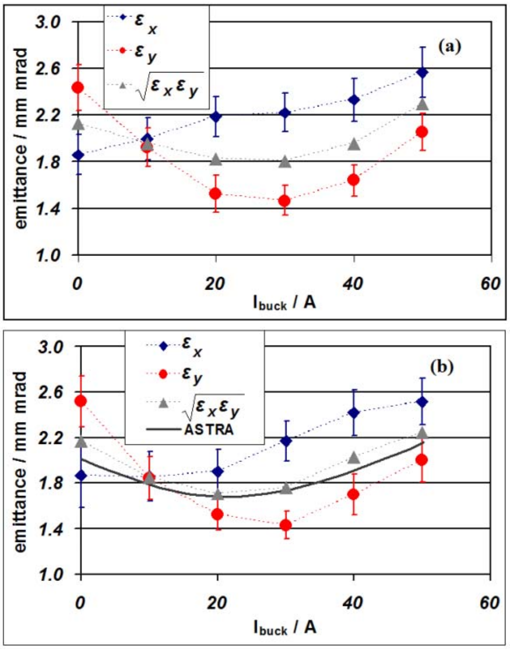

Figure 3: Projected normalized emittance for different bucking solenoid currents. The bunch charge is 1.0 nC, the main solenoid was set to 305 A. The the gun phase is: (a) $\phi - \phi_m = 0°$, and (b) $\phi - \phi_m = -5°$. The horizontal and vertical emittance as well as their geometrical average are shown. The solid line in the lower graph represents a corresponding ASTRA simulation at the geometrical average.

Results of the solenoid and phase scans

According to the strategy described above, the emittance was measured as a function of the main solenoid current for various rf phases. Results of these scans are presented in Fig. 2. The smallest emittance is about 2 to 2.5 mm mrad measured in both transverse planes for a main solenoid current of 305 A and for rf phases $\phi - \phi_m = 0°, -5°$.

Further optimization by scanning the bucking solenoid

As pointed out, for the measurements plotted in Figure 2 the residual magnetic field on the photo cathode has not been compensated. Therefore, additional scans with the compensating bucking solenoid were performed for the settings with the smallest emittance: $\{305\,\mathrm{A},\, \phi - \phi_m = 0°\}$ and $\{305\,\mathrm{A},\, \phi - \phi_m = -5°\}$. The results are shown in Fig. 3. Error contributions of the background noise [3], finite optical resolution and statistical fluctuations are all taken into account and propagated to the final measurement errors represented with the error bars. As shown in [5] and in Fig. 3(b) the experimental data agree well with simulations. The smallest vertical emittance is 1.5 mm mrad, a minimum geometrical average $\sqrt{\epsilon_x \epsilon_y}$ of 1.7 mm mrad is obtained.

Impact of vacuum components

The PITZ experience shows that the impact of the vacuum components on the beam emittance should be studied and must be in the list with optimization items. For the first of the two sets of measurements shown in Fig. 4, the electron beam has been horizontally shifted with respect to its design orbit. The beam is steered 6 mm closer to the laser vacuum mirror then the nominal distance of 12 mm. This metallized glass mirror is being charged up by the beam and dark current and the resulting electrostatic field affects

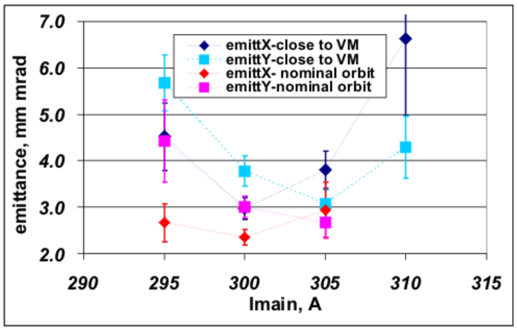

Figure 4: Impact of the laser vacuum mirror (VM) on the emittance. The bunch charge is 1.0 nC, the gun phase $\phi - \phi_m = -5°$.

the beam quality. As it is demonstrated in the second measurements set in Fig. 4 an emittance reduction of 0.5 to 1.0 mm mrad is achieved by steering the beam away from the vacuum mirror. A detailed simulation study of this phenomena [6] agrees well with the presented measurements.

THERMAL EMITTANCE MEASUREMENTS

The thermal emittance is limiting the emittance reach in photo-cathode rf guns. Therefore, its measurement is of high importance to understand the ultimate performance limit of rf gun based electron sources. The thermal emittance measurements use a laser pulse with a gaussian temporal profile of 6 to 8 ps FWHM. Simulations with ASTRA show that for these short pulses the emittance growth due to the rf field should be negligible ($\leq 2\,\%$) compared to the expected thermal emittance ϵ_{th}. The final goal of the measurements is to estimate the average kinetic energy E_k of the electrons emitted from the $\mathrm{Cs_2Te}$ photo-cathode. An emission model introduced in [7] is assumed, such that:

$$\epsilon_{th} = \sigma\sqrt{\frac{2E_k}{3m_0c^2}} \tag{1}$$

Hence,

$$E_k = 1.5 m_0 c^2 \left(\frac{d\epsilon_{th}}{d\sigma}\right)^2 \tag{2}$$

where σ denotes the r.m.s. laser spot size.

Emittance scaling with the laser spot size

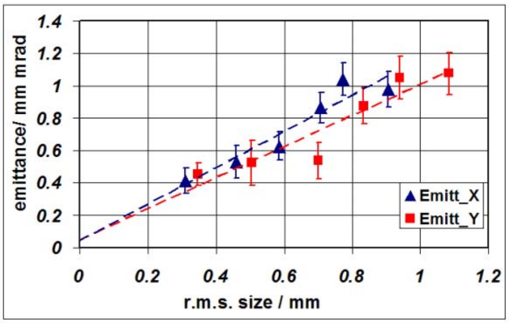

Figure 5: Transverse emittance vs. laser spot r.m.s. size measured with the slit scanning technique at 3 pC.

Figure 5 shows the normalized emittance for different r.m.s. laser spot sizes measured with the single slit scanning method at a charge of about 3 pC and an accelerating gradient at the cathode of 32 MV/m. For these conditions (tiny charge, low gradient) simulations predicts an emittance growth of less than 5 % due to space charge effects. From a straight line fit one obtains $\frac{d\epsilon}{d\sigma}$ =1.0 to 1.1 mrad. Inserting the fit values into Eq. 2 yields:

$$E_k = 1.5 m_0 c^2 \left(\frac{d\epsilon}{d\sigma}\right)^2 = 0.8 \pm 0.1\, eV \tag{3}$$

For comparison a second set of measurements similar to the set presented in Fig. 5 has been done using the solenoid scan method to determine the emittance. The analysis of the solenoid scan data takes into account the evolution of beam energy along the magnetic axis as well as space charge effects and yields about the same kinetic energy as the slit technique.

Dependence of the emittance on the accelerating gradient

The emittance was measured at a charge of 2 to 3 pC as a function of the accelerating field E at the cathode. The single slit scanning technique was used for these measurements. The electric field amplitude E_0 was varied in the

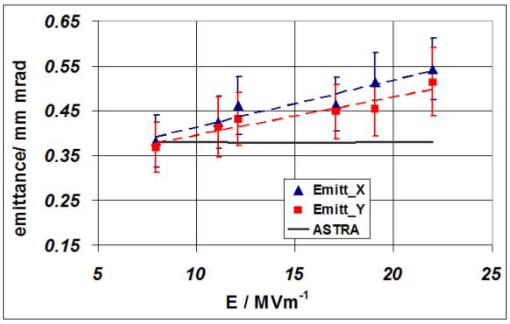

Figure 6: Emittance as a function of the accelerating field on the cathode surface E for a charge of 2 to 3 pC.

range from 24 to 37 MV/m. The laser spot size of σ_x= 0.46 mm, σ_y= 0.51 mm was kept fixed. The solenoid current was adjusted such that the beam was focused on the position of the slit mask. The rf phase ϕ was set to ϕ_m for each measurement. In addition, before each measurement the charge was measured as a function of the rf phase. From the rising edge of the phase scan the zero crossing phase ϕ_0 was determined. Finally the applied field at the cathode is calculated as $E = E_0 sin(\phi_m - \phi_0)$. The results presented in Fig. 6 show an increasing emittance with the accelerating field. The simulation predicts a constant emittance. It includes the beam dynamics in the rf gun, but does not scale the kinetic energy of the emitted electrons with the applied field at the cathode. The increasing thermal emittance corresponds to a rising kinetic energy of the emitted electrons. This phenomena can be explained by assuming a modified Schottky effect [8].

RECENT MEASUREMENTS WITH CAVITY PROTOTYPE #1

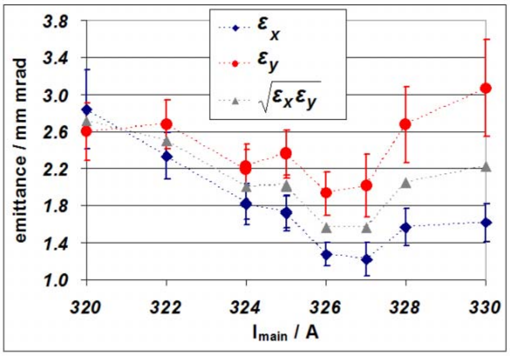

Figure 7: Measurements with cavity prototype #1.

After cavity prototype #2 was fully characterized at PITZ and installed at TTF, cavity prototype #1 was put into operation at PITZ in the beginning of 2004 [2] followed by the rf conditioning [9]. The beam dynamics optimization is ongoing. Figure 7 shows emittance measurements done for a bunch charge of 1 nC at the current stage of optimization.

SUMMARY

The impact of the temporal laser pulse profile on the emittance has been demonstrated. A longitudinal flat top laser pulse yields a significantly better emittance than a gaussian shape. The characterization of the rf gun cavity for the VUV-FEL was presented. The smallest normalized projected emittance is measured with 1.5 mm mrad in the vertical plane. The smallest geometrical average emittance of both transverse planes is 1.7 mm mrad. Measurements to estimate the thermal emittance have been done using a very small bunch charge and moderate accelerating gradients. The average kinetic energy of the emitted photo electrons is estimated to be 0.8±0.1 eV. An increasing of the thermal emittance with the accelerating field on the cathode has been observed. The characterization of the next cavity at PITZ is ongoing and shows promising results.

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