Journal of Physics: Conference Series

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Studies of space charge dominated electron photoemission at PITZ

To cite this article: Mikhail Krasilnikov *et al* 2019 *J. Phys.: Conf. Ser.* **1238** 012064

Studies of space charge dominated electron photoemission at PITZ

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Abstract. Photoemission in modern high brightness electron sources is under studies at the PITZ photo injector. Space charge dominated photoemission in the presence of high RF field at the semiconductor photocathode is studied. By utilizing core and halo particle distributions based on measured radial laser profiles, simulations reproduce the behaviour of the measured emission curves for a wide range of RF gun parameters within the measurement uncertainties for Gaussian laser pulses. But applying this model to the case of long flattop photocathode laser pulses revealed discrepancies between experimental data and simulation results. Corresponding emittance simulations have been compared to measurements for both temporal profiles of the photocathode laser.

1. Introduction

High brightness electron sources are key components for the successful operation of modern Free Electron Lasers (FELs) like the European XFEL and FLASH. A high brightness electron source for such modern applications requires rather high bunch charge and very small transverse normalized emittance. For the European XFEL photo injector 1 nC electron bunches with ~20 ps length and normalized emittance of <1 mm mrad should be generated from the RF gun operated at high field (~60 MV/m) at the Cs_2Te photocathode. Modern RF-guns are mature technology demonstrating such a high performance. Since more than 15 years the Photo Injector Test facility at DESY in Zeuthen (PITZ) develops and optimizes high brightness photo injectors [1].

The key component of the PITZ accelerator is an L-band 1.6-cell RF-gun, as illustrated in Fig. 1. It consists of a 1.3 GHz copper cavity operated in π-mode with coaxial RF power coupler and supplied with a pair of focusing solenoids. A molybdenum cathode plug of ∅16 mm with Cs_2Te film of ∅5 mm is inserted in the cavity back wall.

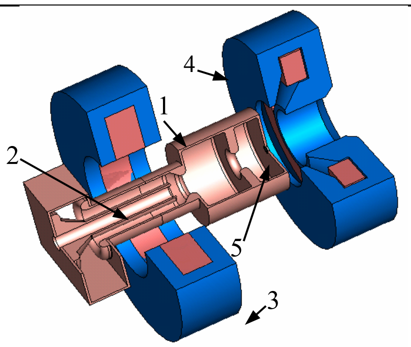

Figure 1. Sketch of the PITZ RF-gun:
1– gun cavity,
2– coaxial power coupler,
3– main solenoid,
4– bucking solenoid,
5– photocathode (Cs_2Te).

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Experimental minimization of the transverse emittance for a wide range of electron bunch charges resulted in optimum photo injector parameters which correspond to the space charge dominated regime of photoemission from the Cs_2Te cathode. At the same time beam dynamics optimization using photo injector parameters corresponding to the experimentally tuned ones results in a more relaxed space charge effect during electron bunch photoemission. Moreover direct plugging of experimental parameters into beam dynamics simulations (ASTRA, [2]) results in strong space charge effect at the cathode and therefore to the significant dilution of the simulated beam emittance.

For more precise description of the space charge dominated dynamics in the RF-photoguns other beam measurements have to be simulated in a consistent way. One of such measurements is the so-called emission curve – dependence of the accelerated bunch charge on the photocathode laser pulse energy for fixed other parameters of the RF-gun (gradient, launch phase, laser pulse length, etc.) Discrepancies between experimental data and simulation results have been observed already for these measurements. In order to bring beam dynamics simulations closer to experimental results several improvements in the emission modelling have been implemented. A core and halo model for transverse photocathode laser distribution helped to reduce the discrepancy between measured and simulated emission curves [3]. Nevertheless, there are still remaining discrepancies, especially for the flattop temporal profile of the photocathode laser pulse. These discrepancies can be dedicated to the space charge dominated photoemission processes.

2. PITZ measurements with flattop photocathode laser pulses

The main goal of the PITZ measurements campaign of 2011 was minimization of the transverse projected normalized emittance for the flattop temporal profile of the photocathode laser pulse [1]. This optimization has been performed for a wide range of bunch charge (20 pC-2 nC) by tuning of key photo injector parameters – main solenoid current/peak field, RF-gun launch phase, laser pulse transverse spot at the photocathode. The laser pulse temporal profile of ~21 ps FWHM and the gun peak field at the photocathode of ~60.5 MV/m were fixed during these studies. A single slit scan technique has been used to measure the transverse phase space at the position of the 1st emittance measurement station (z=5.74 m) [1]. The results of emittance optimization for 1 nC bunch charge are shown in Fig. 2, where projected normalized emittance is shown as a function of the rms spot size of the photocathode laser pulse. For each laser spot size the main solenoid current and RF gun launch phase have been optimized. This yielded the optimum phase to be +6° w.r.t. the gun phase of the Maximum Mean Momentum Gain (MMMG). In contrary, the optimized simulated setup corresponds to the MMMG phase. Corresponding temporal profile and transverse distribution of the photocathode laser pulse for the optimum setup are shown in Fig. 3.

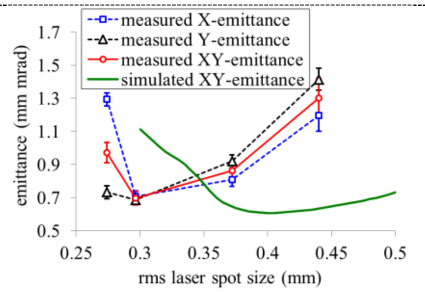

Figure 2. Transverse normalized projected emittance optimized for various rms spot sizes of the photocathode laser and for 1 nC bunch charge [1].

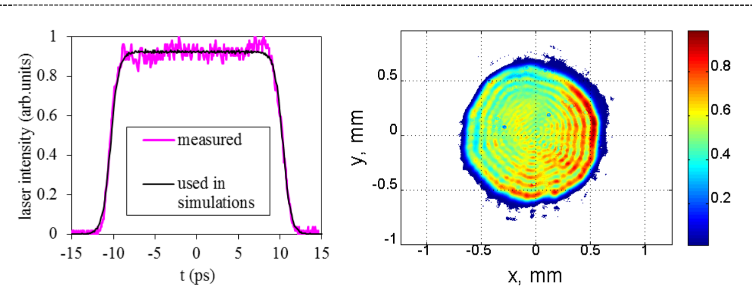

Figure 3. Left: photocathode laser temporal profile measured with an optical sampling system. Right: photocathode laser transverse distribution obtained from the image taken with CCD camera at the location optically equivalent to the photocathode position.

Beam dynamics optimization have been performed for the experimental setup assuming smooth flattop temporal profile with corresponding FWHM and rise/fall times and a radially homogeneous transverse distribution of the photocathode laser pulse. The corresponding curve is shown in Fig. 2 as well. Already from this comparison it appears a significant discrepancy between experimentally optimized rms laser spot size (~0.3 mm) and the results of ASTRA [2] beam dynamics simulations (~0.4 mm). Moreover, direct plugging of the best experimental laser rms spot size into the simulations with radial homogeneous distribution results in a very strong space charge effect already at the photocathode. Thus even the measured bunch charge cannot be reproduced and the simulated transverse phase space of the electron beam is strongly deteriorated. In contrary, the measured emittance is minimized for these settings. The measured beam transverse distribution and phase spaces [1] are shown in Fig. 4. Beam x-y asymmetry in transverse distribution as well as between horizontal and vertical phase spaces have been recently studied and the reason was found to be related to RF power coupler kick and main solenoid imperfections [4].

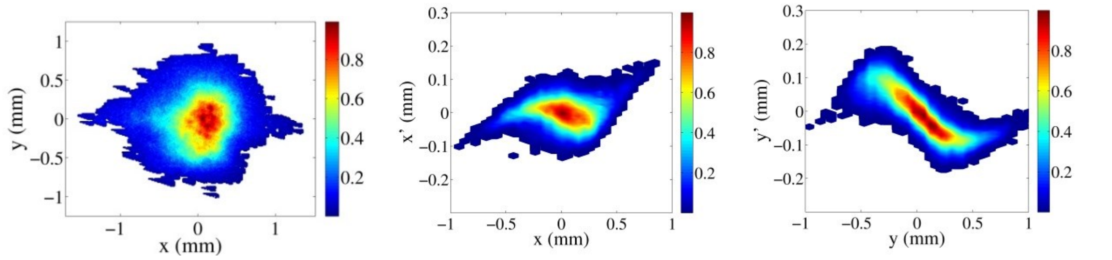

Figure 4. Left plot: 1 nC electron beam transverse distribution measured at the location of the emittance measurements (z=5.74 m from the photocathode). Measured horizontal (middle plot) and vertical (right plot) phase spaces correspond to the normalized rms emittance values: $\varepsilon_{x,n} = (0.72 \pm 0.06)$ mm mrad , $\varepsilon_{y,n} = (0.60 \pm 0.04)$ mm mrad [1].

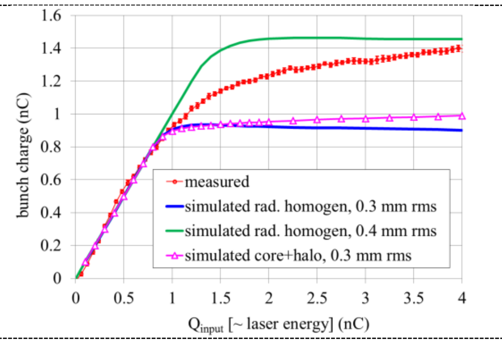

Figure 5. Dependence of the accelerated bunch charge on the photocathode laser pulse energy: measured and simulated for various transverse laser distributions.

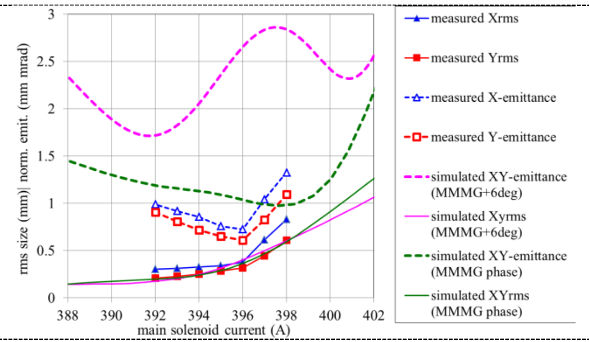

Figure 6. Measured and simulated rms transverse size and normalized transverse emittance of the electron beam versus current of the main solenoid for 1 nC bunch charge.

Besides emittance measurements several complimentary experimental curves have been taken. The emission curve for the best emittance photo injector conditions is shown in Fig. 5. The horizontal axis in this plot has been normalized w.r.t. the linear part of the emission curve (so-called QE-regime): $Q_{input} = QE \cdot E_{laser}$. Replacing the laser transverse distribution (Fig. 3, right) by radial homogeneous profile with the same rms size of 0.3 mm and applying it to ASTRA simulations yielded earlier saturation of the emission curve (blue curve). Corresponding emission curve for the laser rms size of 0.4 mm (the best simulated setup – the minimum of the green curve in Fig. 2) shows rather late saturation and working point (1 nC) would lie in the linear emission regime. The presence of a transverse halo in the photocathode laser (Fig. 3, right) could be responsible for exceeded charge measured in the saturation region. The transverse core and halo photocathode laser model [3] has been suggested in order to explain the experimental data. Unfortunately this resulted only in a small increase of the charge in the beam halo obtained from these simulations (pink curve in Fig. 5). Corresponding results of the simulated rms beam size and emittance are shown in Fig. 6 as a function of the main solenoid current compared to measurements [1]. In order to illustrate an impact of the RF gun launch phase also results of simulations for the MMMG gun phase are shown in Fig. 6. The main solenoid calibration (peak field vs. current) has been modified by ~0.5% in order to provide a better agreement between simulated and measured curves of the rms electron beam size. Transverse distribution of the photocathode laser (core and halo model) used in ASTRA simulations and results of these simulations for the optimum setup (with gun phase of MMMG+6°) are shown in Figs. 7 and 8. For results of simulations with radial homogeneous laser profile and gun MMMG phase see Fig. 8 in [1]. Double-fan shape of the simulated phase space is correlated to the two-maxima in the beam current profile. These results are distinct signatures of the strong space charge effect. Discrepancies between simulations and measurements (Fig. 4) are clearly seen and still not yet fully understood.

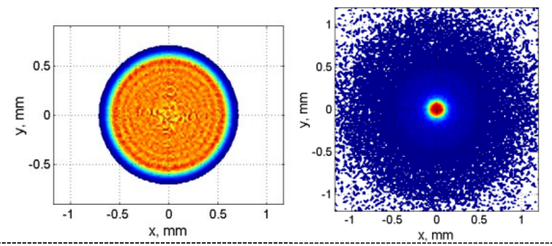

Figure 7. Left: Photocathode laser transverse distribution with applied core and halo model. Right: simulated electron beam transverse distribution at z=5.74 m.

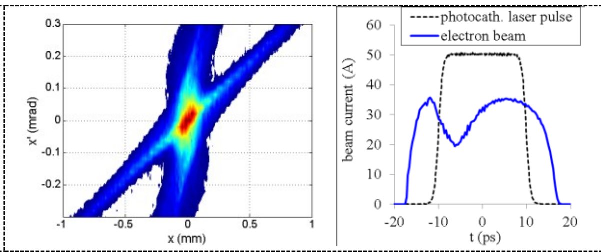

Figure 8. Left: simulated transverse phase space, $\varepsilon_{x,n} = 2.6$ mm mrad. Right: simulated beam current profile at z=5.74 m compared to the temporal profile of the photocathode laser pulse.

3. PITZ measurements with Gaussian photocathode laser pulses

Similar measurements have been performed at PITZ in 2015 but the emittance was optimized for different photo injector parameters, namely for 0.5 nC bunch charge (1 nC in 2011) and for photocathode laser pulses with Gaussian temporal profile of ~11.5 ps FWHM (in contrast to the flattop with 21 ps FWHM used in 2011). The position of the 1st emittance measurement station was shifted upstream to z=5.277 m from the photocathode. Another difference to the 2011 results is the experimental optimum gun phase was found to be close to the MMMG phase what well agrees with simulations. The measured laser transverse distribution is shown in Fig. 9 (left) together with core and halo modeled input distribution for ASTRA simulations (right plot in Fig. 9). Results of emission simulations are shown in Fig. 10. Here, the improvements from the core and halo model w.r.t. the radial homogeneous distribution are clearly observed.

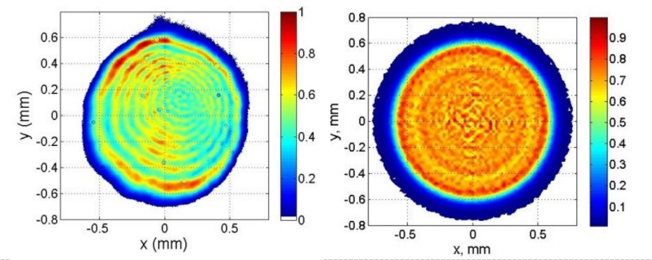

Figure 9. Photocathode laser transverse distributions: measured (left) and used in beam dynamics simulations with applied core and halo model (right).

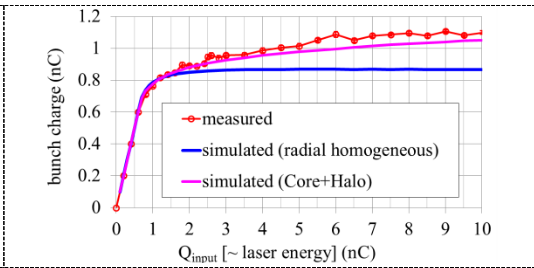

Figure 10. Emission curves: measured and simulated for various transverse laser distributions.

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Simulated dependencies of the electron beam transverse rms size and emittance on the main solenoid are shown in Fig. 11 together with corresponding measurements [5]. A pair of specially designed gun quadrupoles has been used during this measurement campaign. This resulted in a more round beam (Fig. 12) and more equal horizontal and vertical phase spaces (Fig. 13). Corresponding simulated electron beam distribution and phase space are shown in Fig. 14. A better agreement is achieved for the electron beam transverse distribution whereas the simulated transverse phase space is still deviating from the measured one when the largest part of this discrepancy results from the low intensity tails of the phase space distribution. Overall, this setup corresponds to a good agreement on the transverse rms beam size in Fig. 11. The horizontal displacement between measured and simulated emittance curves still remains, but the vertical offset became smaller. The better agreement for this emittance measurement setup could be also partially related to the fact that the working point (bunch charge of 0.5 nC) lies well within the linear regime of the emission curve (Fig. 10).

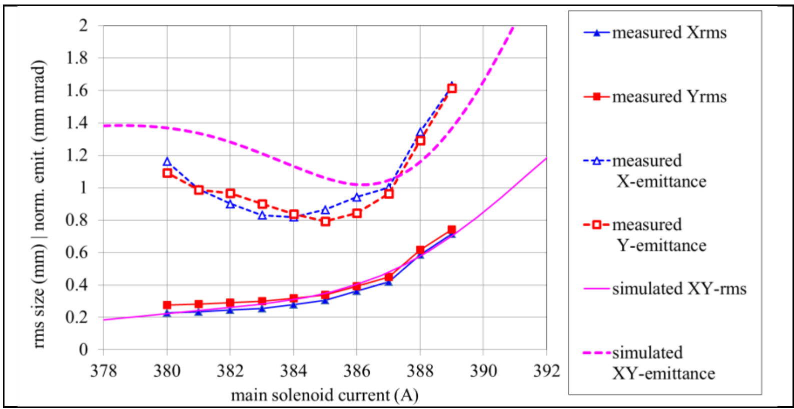

Figure 11. Measured and simulated transverse rms size and normalized emittance of the electron beam versus current of the main solenoid for 0.5 nC bunch charge and photocathode laser pulses with Gaussian temporal profile of 11.5 ps FWHM and 0.3 mm rms spot size.

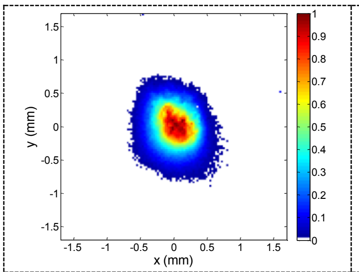

Figure 12. Measured transverse distribution of electron beam at 5.277 m from the photocathode.

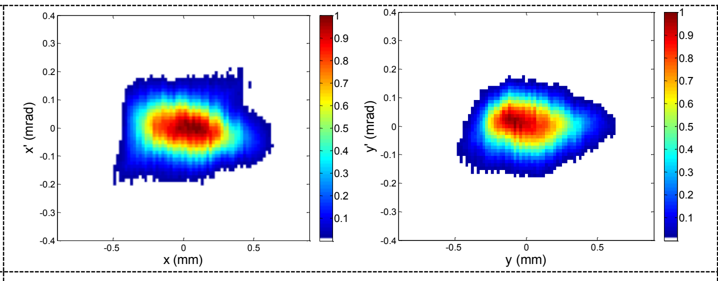

Figure 13. Measured horizontal (left) and vertical (right) phase space of the electron beam. Normalized rms emittance values: $\varepsilon_{x,n} = (0.82 \pm 0.04)$ mm mrad, $\varepsilon_{y,n} = (0.84 \pm 0.04)$ mm mrad. [5].

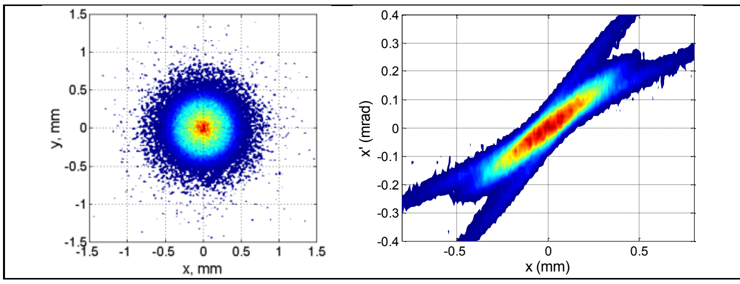

Figure 14. Transverse electron beam distribution (left) and transverse (horizontal) phase space (right) simulated for the optimum experimental conditions. Normalized rms emittance 1.1 mm mrad.

4. Conclusions

Space charge dominated photoemission is under studies at the PITZ photo injector. Discrepancies between experimental data and beam dynamics simulations have already been observed for the generated bunch charge for the optimum photo injector parameters. This also leads to strong disagreement between simulated transverse phase spaces of the electron beam and corresponding experimental data. Applying the model of the photocathode laser pulse transverse core and halo strongly improves this discrepancy for laser pulses with Gaussian temporal profiles, but for the case of flattop laser pulses it still remains significant. Further investigations are ongoing towards better emission model for the beam dynamics simulations as well as by preparing more detailed photoemission measurements.

5. References

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