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Characterization of the electron source at the photo injector test facility at DESY Zeuthen

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Abstract

The Photo Injector Test Facility at DESY Zeuthen (PITZ) was built to test and optimize electron sources for Free Electron Lasers and future linear colliders. The focus is on the production of intense electron beams with minimum transverse emittance and short bunch length as required for FEL operation. The experimental setup includes a 1.5 cell L-band gun cavity with coaxial RF coupler, a solenoid for space charge compensation, a laser capable to generate long pulse trains with variable temporal and spatial pulse shape, an UHV photo cathode exchange system, and an extensive diagnostics section. This contribution will give an overview on the facility and will mainly discuss the measurements of the electron beam transverse phase space. This will include measurements of the transverse and longitudinal laser profile, beam charge as a function of RF phase, and transverse emittance as a function of different parameters. The corresponding measurements of momentum and momentum spread as well as the RF commissioning results will be summarized. As a first application of the PITZ electron source it will be installed at the TESLA Test Facility Free Electron Laser at DESY Hamburg in autumn 2003.

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1. Introduction

First beam measurements at the photo injector test facility at DESY Zeuthen (PITZ) have been presented at earlier conferences [1,2]. Since then, the photo cathode laser system has been upgraded significantly and several operation periods have followed. The current near term goal of PITZ is to do a full characterization of the existing electron source and then to install it at the VUV-FEL at TTF2 in Hamburg in autumn 2003. The experience gained with the PITZ gun at Zeuthen and Hamburg will be the basis for the development of a more demanding injector for the recently approved X-FEL project. In this paper, an overview of the achieved experimental results is given and detailed measurements of the transverse beam emittance as a function of injector parameters are presented.

A schematic overview of the current PITZ installation is given in Fig. 1.

2. Achievements on RF commissioning

A smooth commissioning procedure yielded an operation with up to 900 μs long RF pulses at 10 Hz repetition rate and a gradient at the cathode of about 40 MV/m. That corresponds to a maximum average power of 27 kW in the gun cavity with 0.9% duty cycle. This long pulse operation fulfils the TTF2 requirements and no fundamental limit on the gradient has been detected yet.

The dark current in the gun cavity has been measured as a function of the accelerating gradient, main solenoid and bucking magnet currents [2,3]. Measurements were performed using Mo and Cs_2Te cathodes. A maximum dark current of 180 μA has been measured with a gradient on the cathode of about 40 MV/m and a main solenoid current of 200 A. In standard operation at higher solenoid fields the dark current is over focussed and the amount transported downstream is at least a factor of 2 smaller.

3. Upgrade of the laser system

The main achievement of the cathode laser upgrade at PITZ is a stable production of long laser pulse trains where each micro pulse has a flat top longitudinal profile. The laser is based on a diode-pumped pulsed oscillator synchronized with the RF. A diode-pumped amplifier chain and two flash-lamp-pumped booster amplifiers follow. A pulse shaper inserted between the oscillator and the diode-pumped amplifier chain allows for generation of temporal flat top pulses. The laser material is Nd:YLF operated at a wavelength of 1047 nm. Since the photo cathode requires ultraviolet radiation, the infrared laser pulses are converted to the fourth harmonic (262 nm) by means of two nonlinear crystals. The rising edge of the flat top pulses after conversion to the UV is presently in the order of 4–6 ps. A typical laser micro pulse longitudinal profile is shown in Fig. 2a. The laser is able to generate trains of micro pulses of up to 800 μs length.

The transverse profile of the laser beam is controlled by imaging a diaphragm onto the photo cathode. The RMS spot size can be varied from 0.3 to 1 mm. For the emittance measurements shown later, the measured RMS laser spot

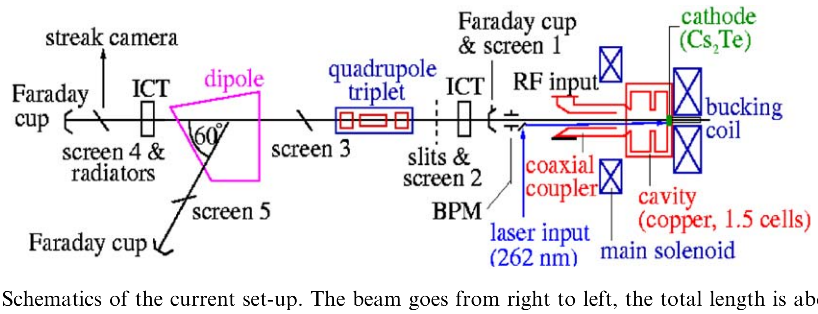

Fig. 1. Schematics of the current set-up. The beam goes from right to left, the total length is about 6 m.

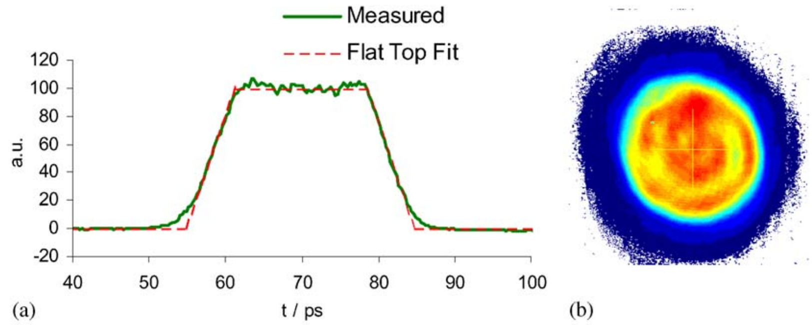

Fig. 2. (a) Temporal profile of the laser micro pulse measured at a wavelength of 524 nm using a streak camera. Ten laser pulses have been integrated. The dashed line shows a flat top fit with ~24 ps FWHM and 6 ps rise/fall time. (b) Transverse laser intensity distribution on the virtual cathode. Modulation depth ~20%.

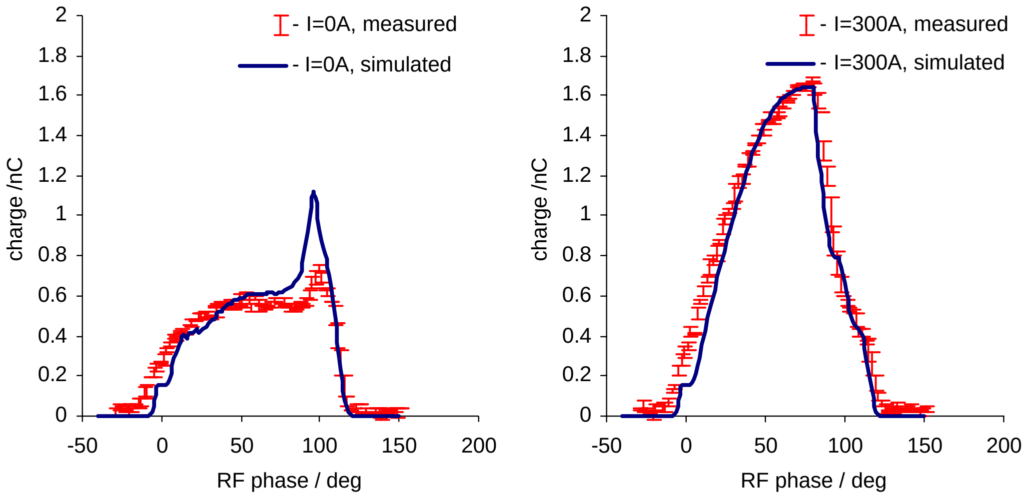

Fig. 3. Phase scans—detected beam charge as a function of RF phase for main solenoid currents of 0 (left) and 300 A (right), compared with simulations. Gradient at the cathode ~40 MV/m.

size on the cathode was $\sigma_x = 0.45 \pm 0.03$ mm and $\sigma_y = 0.52 \pm 0.03$ mm (see e.g. Fig. 2b).

4. Beam charge measurements

The charge of the electron bunch is measured with Faraday Cups and integrating current transformers (ICT). A basic measurement is the so called phase scan: the accelerated charge downstream of the gun measured as a function of launch phase, the relative phase of the laser pulses with respect to the RF.

The space charge effects on and near the cathode which depend on the laser pulse shape, the solenoid position and strength, and the acceleration gradient at the cathode determine the shape of the phase scan. Fig. 3 shows two-phase scans for main solenoid currents of 0 and 300 A. The data are compared to simulations [4]. The general agreement is fairly good, but there are differences in detail.

In order to have a defined comparison between measurements and simulations a corresponding reference RF phase Φ_0 has to be settled. To not rely on details of the comparison between the measured and simulated phase scans, the reference RF phase in our paper is chosen as the phase with maximum mean energy gain. This is easy and reliably defined using a beam transverse size vs. RF-phase measurement, as described in Ref. [2]. In the rest of this paper the RF phases will always be quoted with respect to this reference phase Φ_0.

5. Longitudinal phase-space measurements

The mean momentum and the momentum distribution of the electron beam were measured using the dipole spectrometer. For an accelerating gradient of ~ 42 MV/m and a beam charge of 1 nC a maximum mean momentum of ~ 4.7 MeV/c and a minimum momentum spread of ~ 30 keV/c were obtained. An electron bunch length of ~ 20 ps FWHM was measured using a streak camera and a Cherenkov radiator. For detailed results see Ref. [5].

6. Beam emittance measurements

Before starting emittance measurements numerous beam dynamics simulations have been performed. The emittance has been simulated for a 1 nC beam with a laser longitudinal profile of 25 ps FWHM and 5 ps rise/fall time. A homogeneous transverse laser profile with $\sigma_{x,y} = 0.45$ mm and an accelerating gradient at the cathode of 40 MV/m were assumed. The results for the above mentioned flat top laser profiles are shown in Fig. 4, the simulated minimum emittance is $\sim 1.6\pi$ mm mrad. Only changing the transverse laser shape to a Gaussian with the same $\sigma_{x,y}$ yields an emittance minimum of $\sim 5\pi$ mm mrad.

Measurements of the transverse emittance were performed using a single-slit scan technique. Beamlet profiles were observed 1010 mm downstream of a single-slit mask (1 mm thick tungsten plate, 50 μm slit opening) at screen 3 (see Fig. 1). Beamlets from three slit positions were taken into account for the emittance calculation (see Fig. 5).

Horizontal and vertical emittances were measured as a function of main solenoid current for a gradient at the cathode of ~ 40 MV/m. The RF phase has also been varied by $\pm 10°$ from the phase of maximum mean energy gain Φ_0. The laser power was tuned for 1 nC beam charge, readjusted for each RF phase chosen. The bucking coil was off during these measurements, so the magnetic field at the cathode is supposed to be small but not zero. Results of the measurements are plotted in Fig. 6.

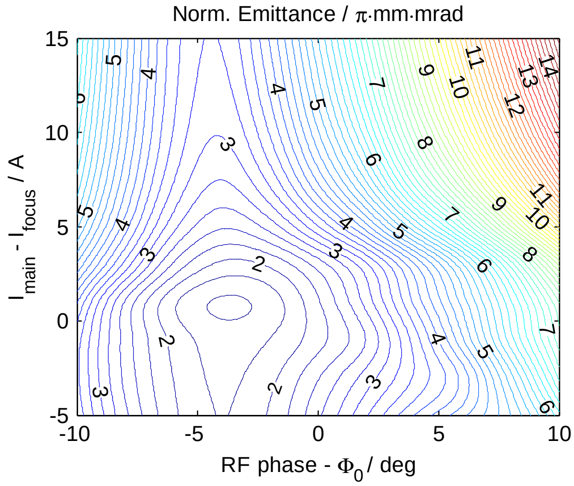

Fig. 4. Contour plot of simulated transverse normalized beam emittance as a function of RF phase and main solenoid current. The reference solenoid current corresponds to the conditions of electron beam focusing at screen 2.

The normalized beam emittance has been simulated using ASTRA for injector parameters close to the ones observed during emittance measurements. This includes the modelling of the measured transverse and longitudinal laser profiles. Results are shown in Fig. 7.

The coarse agreement between measurement and simulation (minimum emittances between 2 and 5 πmm mrad for different transverse laser profiles) is good. In detail, the usage of the measured transverse laser distribution as an input for the simulations results in a rotational asymmetry. At least a part of the disagreement between simulated and measured emittances can be explained by the fact, that the space charge routine used in ASTRA is based on a cylinder symmetric beam model. Another probable explanation comes from possible imperfections in slit orientation, which causes X–Y coupling resulting in increased measured emittances.

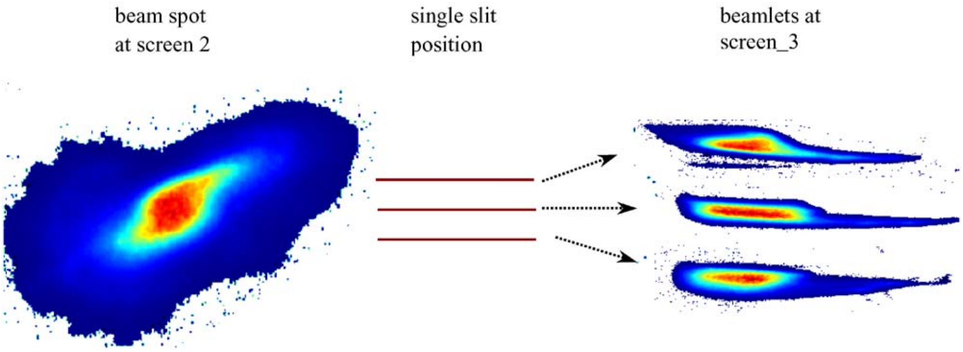

Fig. 5. Schematics of the single slit scan technique for the beam emittance measurement. After measurements of the beam position and beam size at screen 2, the size of the beamlets is measured at screen 3 for three slit positions: $y_n = \langle Y \rangle^{\text{screen2}} + n \cdot 0.7\sigma_y^{\text{screen2}}; n \in \{-1, 0, 1\}$.

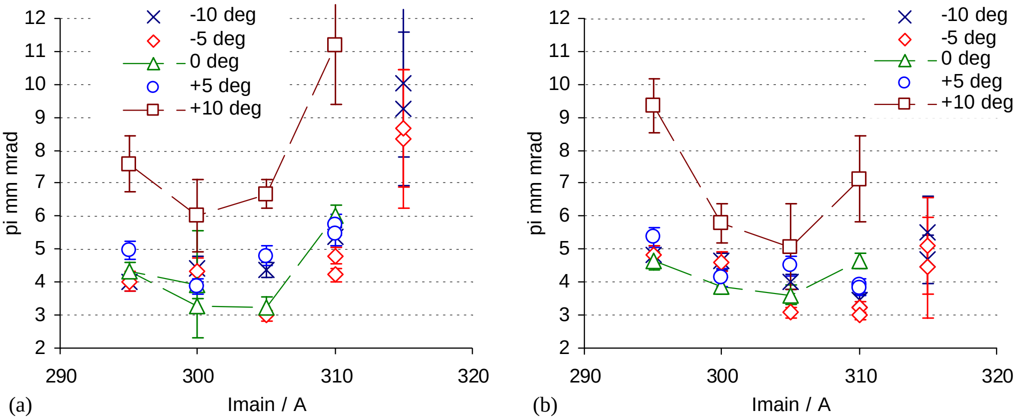

Fig. 6. Measured horizontal (a) and vertical (b) beam emittance as function of main solenoid current for different RF phases with respect to Φ_0.

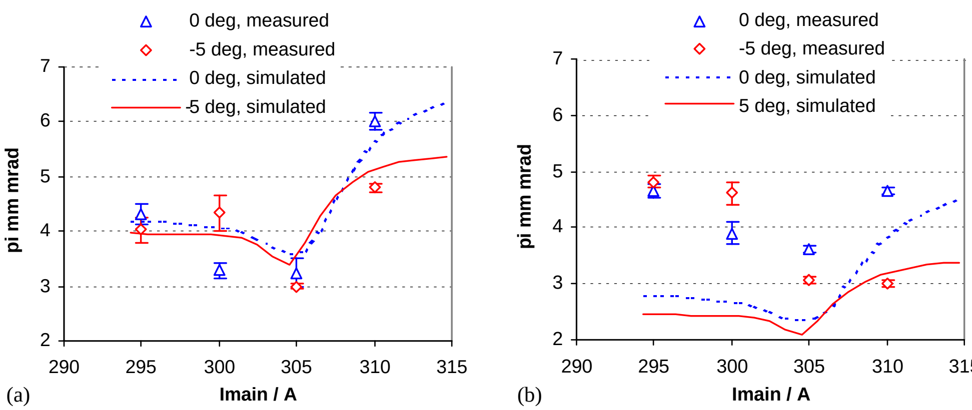

Fig. 7. Simulated horizontal (a) and vertical (b) beam emittance as a function of main solenoid current in comparison with measurements. RF phases are given with respect to Φ_0.

The next steps for optimizing the electron source include further improvement of the transverse laser profile and investigating the influence of the residual magnetic field at the cathode.

7. Conclusions

The experimental optimization and full characterization of the electron source at PITZ is ongoing. The current optimum machine parameters have been found. A normalized transverse beam emittance of 3π mm mrad for 1nC electron beam is measured with high stability and reproducibility. The simulations for the phase scan show reasonable agreement, while emittance simulations need further studies.

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