OPTIMIZING THE PITZ ELECTRON SOURCE FOR THE VUV-FEL

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Abstract

The goal of the Photo Injector Test Facility at DESY Zeuthen (PITZ) is to test and optimize electron sources for Free Electron Lasers and future linear colliders. At the end of 2003, the first stage of PITZ has been successfully completed, resulting in the installation of the PITZ RF gun at the Vacuum Ultra Violet - Free Electron Laser (VUV-FEL) at DESY Hamburg. The main results achieved during the extensive measurement program are discussed in this paper. A minimum normalized beam emittance of about 1.7 π mm mrad (geometrical average of horizontal and vertical emittance) for 1 nC electron bunch charge has been reached by optimizing numerous photoinjector parameters, e.g. longitudinal and transverse profiles of the photocathode laser, RF phase, main and bucking solenoid current. The second stage of PITZ, being a large extension of the facility and its research program, has started now. Recent progress on the PITZ developments will be reported as well.

INTRODUCTION

Electron bunches required to drive a SASE FEL must have a high phase space density: typical requirements on transverse normalized emittance are 1-2 π mm-mrad. The goal of PITZ is to produce a high quality electron beam capable of meeting the demands of present and future FELs.

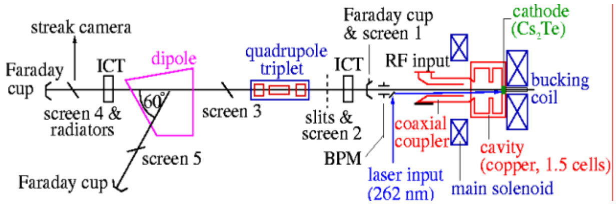

Figure 1: Layout of the PITZ.

The experimental setup consists of a 1.5 cell L-band RF gun with a Cs_2Te photocathode, a solenoid system for compensating space charge induced emittance growth, a photocathode laser system capable to generate long pulse trains with variable temporal and spatial micro pulse shape, and an extensive diagnostics section. The first stage of the PITZ project has been successfully completed by the end of 2003. A schematic outline of the PITZ experimental setup is shown in Fig. 1. PITZ parameters achieved during conditioning and operation are listed in Table 1.

Table 1: Achieved PITZ parameters.

RF	Frequency	1.3 GHz
	Accel. Field on the cathode	40-42 MV/m
	Max. RF pulse length	900 μs
	Repetition rate	1-10 Hz
	Max. average power	27 kW
	Max. duty cycle	0.9 %
Photocathode laser	Temporal profile: length (FWHM) rise/fall time	 18-26 ps 4-8 ps
	Transverse size (rms)	0.3-1 mm
	Max. pulse train length	800 μs
	Micro pulse spacing	1 μs
Electron beam	Bunch charge	0.003 – 8 nC
	Max.long.momentum	4.7 MeV/c
	Min.long.mom.spread (rms) @ 1nC	33 keV/c
	Min. norm. emittance (rms) @ 1nC: $\varepsilon_x / \varepsilon_y$ $\sqrt{\varepsilon_x \cdot \varepsilon_y}$	1.9 / 1.5 π mm mrad 1.7 π mm mrad

The PITZ measurement program includes various aspects: electron beam charge, longitudinal momentum and momentum spread, bunch length, transverse beam size and normalized beam emittance have been measured for a wide range of photoinjector parameters [1, 2, 3].

The start-up conditions for the VUV-FEL on normalized beam emittance have been fulfilled. A minimum beam normalized transverse emittance of 1.5-1.7 π mm mrad has been achieved for a 1 nC electron beam by optimizing of the photocathode laser properties together with RF field and solenoid parameters.

PHOTOCATHODE LASER

The use of RF photoinjectors has placed the burden of producing high quality beams on the photocathode lasers.

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The challenge of a photocathode laser system is to produce phase locked, stable, high intensity, short UV pulses of high spatial and temporal quality. Beam dynamics simulations yield an optimum photocathode laser shape to be: flat-top longitudinal profile (20 ps FWHM, 2 ps rise/fall time), homogeneous round transverse shape with $\sigma_{x,y}$=0.75 mm [4].

The operation experience shows that the temporal and transverse laser profiles are a key issue for the successful production of high quality electron beams. For example, a longitudinal flat-top profile yields a significant reduction of the electron beam emittance [1,5,6] and longitudinal momentum spread [3,7] compared to a Gaussian shaped profile. A typical temporal laser profile measured using a streak camera is shown in Fig. 2a. For comparison, a typical Gaussian profile (used for thermal emittance measurements at PITZ) is shown at the same plot as well. The transverse profile of the laser beam is controlled by imaging a diaphragm onto the cathode. A typical intensity distribution on the photocathode is shown in Fig.2b.

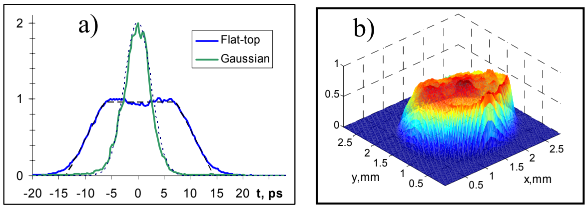

Figure 2: a) Example of a temporal laser profile: flat-top (20 ps FWHM). For comparison a Gaussian profile (3 ps rms) is shown as well. b) Transverse laser intensity distribution on the photocathode: σ_x / σ_y=0.51/0.63 mm.

EMITTANCE OPTIMIZATION

The emittance optimization has been performed for a wide range of photoinjector parameters. The strategy of the optimization is illustrated by Fig. 3.

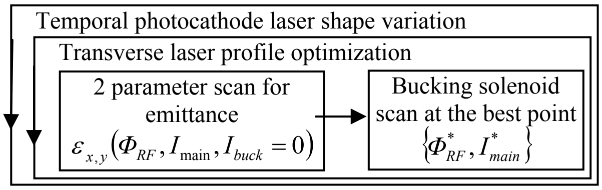

Figure 3: Strategy of the emittance optimization.

The most time consuming optimization step is a two-parameter scan: the measurement of the emittance as a function of the RF launch phase and the main solenoid current: $\varepsilon_{x,y}\left(\Phi_{RF}, I_{\mathrm{main}}\right)$. During this scan the bucking solenoid was off: the magnetic field at the cathode is small but not zero. The last optimization step is then a fine tuning of the bucking solenoid current for the best point $\left\{\Phi^*_{RF}, I^*_{main}\right\}$ to further reduce the emittance.

The transverse emittance has been measured using a single-slit scan technique [2]. The slit mask is a single 50 µm wide slit in a 1 mm thick tungsten plate. The beamlet profiles are measured 1010 mm downstream at screen 3 (see Fig. 1). The slit is moved transversely through the beam. Beamlets from three positions were taken into account for the emittance calculation [2].

For the emittance optimization, a reference RF phase is required. We chose the phase of the maximum energy gain Φ_0 as this reference. The beam size measured as a function of the RF phase yields a reference phase close to Φ_0 (for more details of the method refer to [1,2]). The measured horizontal and vertical emittances as a function of the RF phase and the main solenoid current are shown in Fig. 4.

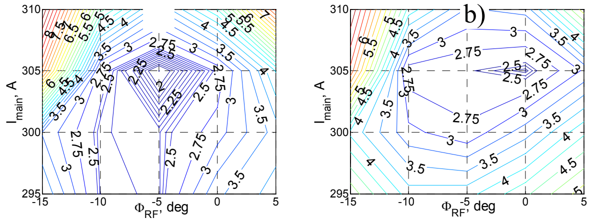

Figure 4: Contour plots of the measured horizontal (a) and vertical (b) normalized beam emittance [π mm mrad] as a function of the RF phase and the main solenoid current.

The maximum longitudinal momentum measured for this scan was 4.71 MeV/c. The laser power was readjusted for each RF phase to produce 1 nC beam.

ASTRA simulations [8] of the beam emittance for parameters close to the experimental ones have been performed. The results of the simulated emittance as a function of the RF phase and the main solenoid peak field are shown in Fig. 5a as a contour plot. Zero RF phase corresponds to the launch phase Φ_0 with a maximum mean energy gain. The emittance has been simulated for a 1 nC beam with a laser longitudinal profile of 22 ps FWHM and 4.3 ps rise/fall time. An accelerating gradient at the cathode of 42 MV/m was assumed. A homogeneous round transverse laser profile with $\sigma_{x,y}$=0.575 mm has been taken for the simulations, even though the real laser spot is asymmetric with σ_x=0.51 mm, σ_y =0.63 mm. For comparison, the measured effective transverse emittance $\varepsilon_{tr} = \sqrt{\varepsilon_x \cdot \varepsilon_y}$ is plotted in Fig. 5b.

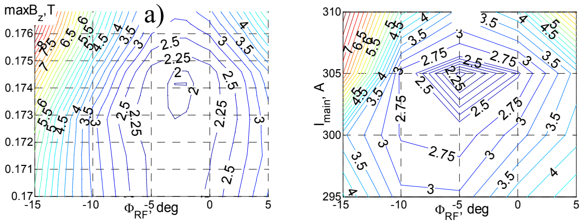

Figure 5: a) Contour plot of the simulated emittance [π mm mrad] as a function of RF phase and main solenoid peak field (maxB$_z$). b) Contour plot of the measured effective transverse emittance as a function of the RF phase and the main solenoid current.

There is good agreement between the measurements and simulations of the emittance, despite the fact, that we could not model precisely the asymmetric transverse laser beam profile. It should be noticed again that no bucking solenoid field has been applied during these measurements as well as for the simulations. The last optimization step is the adjustment of the bucking solenoid in order to compensate the remnant magnetic field on the cathode. For this, a main solenoid current of 305 A and a RF phase corresponding to (Φ_0-5 deg) have been chosen. The resulting emittance as a function of the bucking solenoid current is plotted in Fig. 6a. In addition to the horizontal and vertical emittance, an effective transverse emittance $\varepsilon_{tr} = \sqrt{\varepsilon_x \cdot \varepsilon_y}$ is shown as well. The minimum effective transverse emittance has been measured for a bucking solenoid current of 20 A. This corresponds to the current, where the field on the cathode is compensated to zero.

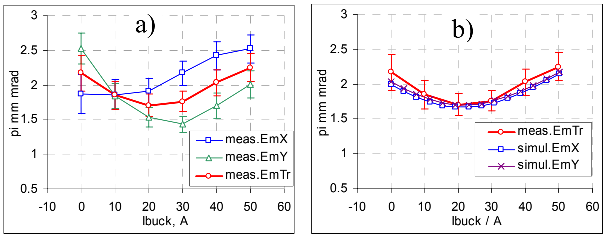

Figure 6: a) Measured transverse emittance as a function of bucking solenoid current. The RF phase is Φ_0-5 deg, the main solenoid current is 305 A. b) Simulated emittance as a function of the bucking solenoid current compared to measurements.

The data is in a good agreement with emittance simulations and therefore one can conclude that the beam dynamics in the PITZ photoinjector is in general understood. The transverse rms beam size and emittance along the beam line simulated for the best parameter set obtained experimentally are shown in Fig. 7a.

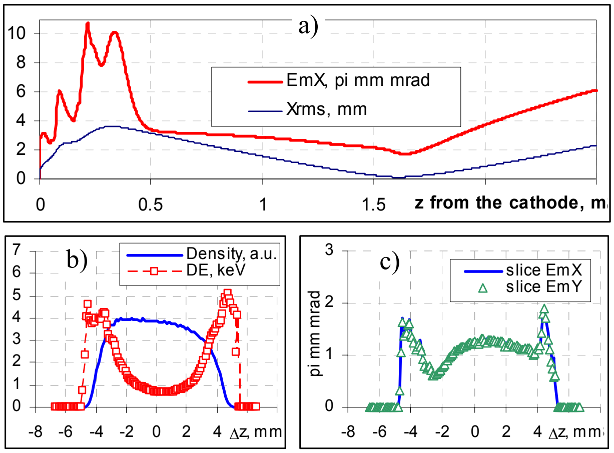

Figure 7: a) Simulated horizontal rms beam size and emittance along the beam line for the optimum parameter set. b) Bunch density distribution and slice energy spread for z=1.62 m. c) Slice emittance distribution inside the bunch at z=1.62 m.

Simulated beam slice parameters at z=1.62m (location of the emittance measurements) are shown in Fig. 7b,c.

During the emittance optimization it turned out, that due to an alignment problem, the laser mirror in the vacuum vessel (“laser input” in Fig. 1) has been close to the electron beam. An influence of the mirror on the beam dynamics has been observed. Steering the electron beam away from the mirror results in a significant emittance reduction of 0.6-1 π mm mrad. This is in good agreement with numerical simulations of the effect [9]. All the emittance measurements presented above have been done with the beam steered away from the laser mirror, still keeping full charge transmission.

CONCLUSION AND OUTLOOK

The PITZ electron source for the VUV-FEL has been studied in a wide range of critical parameters. A systematic optimization yielded a minimum vertical beam emittance of 1.5 π mm mrad and 1.7 π mm mrad for the effective transverse emittance measured at 1 nC beam charge. Simulations show a general agreement with the measured data, but some experimental features, such as laser inhomogeneity and beam line details (e.g. the laser mirror) need more detailed study. In order to further improve the PITZ electron source, the foreseen next steps foreseen are further improvements of the photocathode laser properties, higher accelerating gradients in the gun, thermal emittance studies etc. Being a large extension of the PITZ research program, the second stage of the project includes the installation of a booster cavity for studying the emittance conservation during acceleration, as well as an extended diagnostics section for the detailed photoinjector characterization.

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