RECENT EMITTANCE MEASUREMENT RESULTS FOR THE UPGRADED PITZ FACILITY*

S. Rimjaem†, G. Asova‡, J. Bähr, C. Boulware, H.J. Grabosch, M. Hänel, L. Hakobyan§, Y. Ivanisenko, M. Khojoyan§, G. Klemz, M. Krasilnikov, M. Nozdrin¶, B. O'Shea‖, M. Otevrel, B. Petrosyan, S. Riemann, J. Rönsch, A. Shapovalov**, R. Spesyvtsev, L. Staykov‡, F. Stephan, G. Vashchenko††, DESY, Zeuthen, Germany
K. Flöttmann, S. Lederer, S. Schreiber, DESY, Hamburg, Germany
D. Richter, HZB, Berlin, Germany
I. Will, MBI, Berlin, Germany

Abstract

At the Photo Injector Test facility at DESY, Zeuthen site, (PITZ) development and optimization of high brightness electron sources for Free Electron Lasers (FELs) like FLASH and the European XFEL are performed. In 2008, the PITZ facility was substantially upgraded. A new 1.6-cell L-band RF-gun cavity treated with an improved surface cleaning technique, a new photocathode laser system allowing shorter rise and fall times of the flat hat temporal distribution and several new diagnostics components have been installed. Since the transverse emittance is a key property of high brightness electron sources a major part of the measurement program at PITZ is devoted to the transverse phase space optimization. Recent results of emittance measurements using the upgraded facility are reported and discussed in this contribution.

INTRODUCTION

At the PITZ facility, the electron source optimization process has been continued. The major upgrade realized in 2008 is an important step towards improved sources for high power and short-wavelength FELs like FLASH and the future European XFEL. The facility consists of an 1.6-cell L-band photocathode RF-gun and solenoid coils for space charge compensation, a normal conducting copper TESLA booster cavity and various beam diagnostic systems for the characterization of electron beam properties. The production of electron beams with a small transverse emittance is the most challenging research task at PITZ. The research activities at PITZ aim to produce, optimize and characterize an electron beam with a small normalized projected transverse emittance. The goal is to reach the XFEL specifications of 0.9 mm mrad at a bunch charge of 1 nC. In summer 2007, a transverse emittance of ε_x = 1.25±0.19 mm mrad in the horizontal plane and ε_y = 1.27±0.18 mm mrad in the vertical plane has been measured for a 100% rms phase space distribution with the previous setup (PITZ1.6) [1, 2].

Starting in autumn 2007, the PITZ beamline and related components were upgraded toward the so called "PITZ1.7" setup to extend the ability of the facility to produce even smaller emittance beams. The main changes were an exchange of the gun cavity (from gun prototype 3.2 to 4.2), a new photocathode laser system, a position shift of the booster cavity by about 0.6 m downstream and modifications of several diagnostic systems [3, 4]. A schematic layout of the current setup is shown in Figure 1.

EMITTANCE MEASUREMENT AT PITZ

The transverse emittance and phase space is measured at PITZ using the single slit scan technique [1, 2]. The Emittance Measurement SYstem (EMSY) consists of horizontal and vertical actuators with 10 and 50 μm slits masks and YAG/OTR screens for the beam size measurement. The slit mask angle can be precisely adjusted for the optimum angular acceptance of the system. Three EMSY stations are located in the current setup as shown in Figure 1. The first EMSY station (EMSY1) behind the exit of the booster cavity is used in the standard emittance measurement procedure. It is at 5.74 m downstream the photocathode corresponding to the expected minimum emittance location.

For this technique, the local divergence is estimated by transversely cutting the electron beam into thin slices. Then, the size of the beamlets created by the slits is measured at the YAG screen at some distance downstream the EMSY station. The 10 μm slit and a distance between the slit mask and the beamlet observation screen of 2.64 m are used in the standard emittance measurement. The normalized rms emittance is calculated using the formula:

$$\varepsilon_n = \beta\gamma \frac{\sigma_x}{\sqrt{\langle x^2 \rangle}} \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle x x' \rangle^2}. \qquad (1)$$

The Lorentz factor $\beta\gamma$ corresponds to the electron beam energy, while $\langle x^2 \rangle$ and $\langle x'^2 \rangle$ are the second central moments of the electron beam distribution in the trace phase space obtained from the slit scan, $x' = p_x/p_z$ is the angle of the single electron trajectory with respect to the whole beam trajectory, and σ_x is the rms beam size measured at the slit location. The factor $\sigma_x/\sqrt{\langle x^2 \rangle}$ is applied to correct

* This work has partly been supported by the European Community, contract RII3-CT-2004-506008 and 011935, and by the 'Impuls- und Vernetzungsfonds' of the Helmholtz Association, contract VH-FZ-005.

† sakhorn.rimjaem@desy.de
‡ On leave from INRNE, Sofia, Bulgaria
§ On leave from YerPhI, Yerevan, Armenia
¶ On leave from JINR, Dubna, Russia
‖ On leave from UCLA, USA
** On leave from MEPHI, Moscow, Russia
†† On leave from NSC KIPT, Kharkov, Ukraine

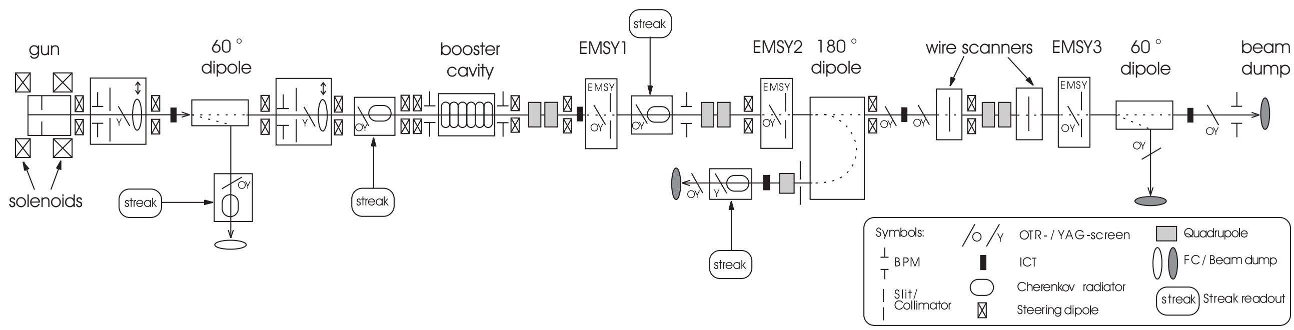

Figure 1: Layout of the current Photo Injector Test facility at DESY, Zeuthen site, (PITZ).

for possible sensitivity limitation of low intensity beamlets. In the emittance measurement setup and procedure, intrinsic cuts have been minimized by e.g. using highly sensitive screens, a 12 bit signal resolution CCD-camera and a large area of interest to cover the whole beam distribution. Therefore, emittance value is called 100% rms emittance.

DISCUSSION OF SIMULATION RESULTS

A new photocathode laser was developed by the Max-Born Institute and has been installed at PITZ in autumn 2008. It delivers UV laser pulses with a wide variety of temporal profiles. The new laser has been designed to allow a faster rise and fall time of the longitudinal flat hat shape compared to the previous laser system. A pulse shaper based on multicrystal birefringent filters produces a temporal flat hat shape with rise and fall time as short as 2 ps and a length of 24 ps FWHM (see Figure 2). The temporal profile of the output UV pulses is measured using an new installed optical sampling system (OSS). Detailed information of the upgraded laser system can be found in reference [5].

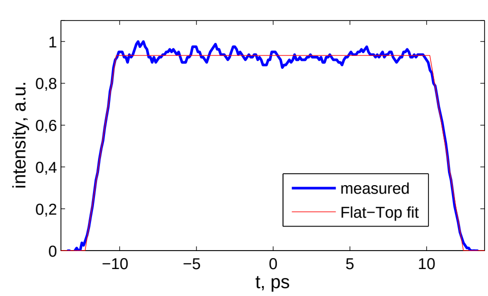

Figure 2: Measured laser temporal profile (UV). The rise and fall times are 2.0 ps and 2.2 ps respectively, the FWHM width is 22.5 ps. The data are extracted from a fit to the profile (red curve).

In the previous setup, the laser had a so-called "M-shape" temporal profile with 6-8 ps rise and fall time and about 24 ps FWHM with a dip (∼25%) in the middle. The pulse shaper of the new laser system is flexible enough to reproduce the same M-shaped longitudinal profiles. This allows a comparison of the emittance achieved in 2007 with the present new setup. With the new setup and the same M-shaped longitudinal profile as in 2007, an emittance of ε_x = 1.28±0.20 mm mrad and ε_y = 1.29±0.15 mm mrad has been measured [6]. This result is in a very good agreement with the emittance values measured in 2007 with the exception of the gun launch phase. The smallest emittance is now obtained at a launch phase increased by +6 degree compared to the 2007 data.

In the following, we concentrate on the measurements with a flat hat profile and a rise and fall time of 2 ps. Simulations suggest an improvement of the projected emittance for flat laser pulses with short rise and fall time. An optimized temporal laser profile measured using the OSS for a pulse length of 22.5 ps (FWHM) and a rise and fall time of 2 ps is shown in Figure 2. To study the dependence of electron beam performance on the transverse laser spot-size, a beam shaping aperture (BSA) is used. The transverse shape of the laser beam is round and flat. Simulations using the computer code ASTRA [7] have been performed to study the dependence of the emittance on laser spot size, gun phase, booster phase, and solenoid magnetic field.

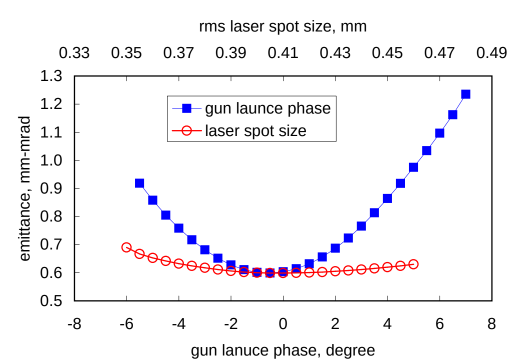

Figure 3: Simulated dependence of the emittance on gun phase and laser spot-size for the flat hat laser of 23 ps FWHM and 2 ps rise and fall time.

As an example, the simulated dependence of the emittance on the gun phase, the laser spot size, and the solenoid peak field for the flat hat laser of 23 ps FWHM and 2 ps rise and fall time are shown in Figure 3 and 4. The gun launch phase is defined such that 0 degree corresponds to the maximum energy gain. The optimistic kinetic energy of 0.55 eV is used in simulations. The simulation results suggest that the smallest emittance is achieved with a gun phase of -0.5 degree, a laser spot size of 0.405 mm (rms), and a solenoid peak field of 230.6 mT. This solenoid peak field corresponds to the current of 4 A above the current where the smallest beam size is obtained (see Figure 4). The booster phase is kept on-crest for these simulations. Figure 5 shows the simulated evolution of the rms beam size and normalized projected emittance along the beamline (z-position). The emittance at the position of the EMSY1 station (z = 5.74 m) is expected to be 0.6 mm mrad.

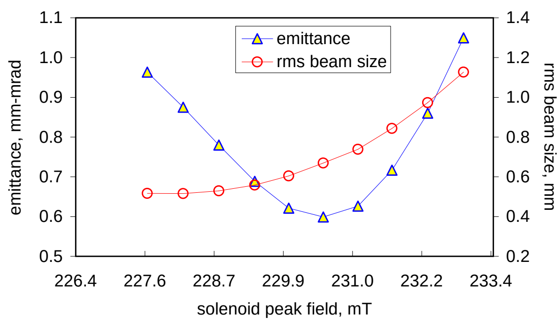

Figure 4: Simulated dependence of the emittance and the rms beam size on solenoid peak field. The range of the solenoid field on the x-axis corresponds to the current range of 12 A.

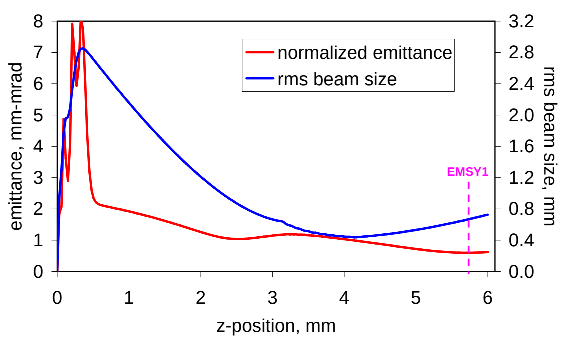

Figure 5: Simulated rms beam size and normalized projected emittance evolution along the beamline. The position of the emittance measurement station (EMSY1) is indicated.

MEASUREMENT RESULTS

Emittance Optimization

In the emittance optimization procedure, the beam emittance is measured as a function of the main solenoid current. The bucking solenoid current is set to compensate the longitudinal magnetic field at the cathode for each main solenoid current. In the rough slit scan procedure, the slit is moved in steps of 200 μm over the beam for a given solenoid current. For the solenoid current yielding the lowest emittance value, the emittance is remeasured using detailed scan with step size of 50 μm and more statistics (more images taken). The solenoid scans have been performed for different laser spot sizes at the cathode and different gun launch phases. The momenta of the beam after the gun and the booster acceleration are measured using spectrometers with screen stations in the dispersive arm downstream the RF-gun and in the first dispersive arm downstream the booster cavity. The RF-gun is driven with a forward power of 6.9 MW resulting in a gun gradient of about 60 MV/m on the cathode surface. This results in a beam momentum of 6.68 MeV/c for the phase of maximum momentum gain ("on-crest"). The booster phase was kept on-crest during the measurements and resulted in a beam momentum around 14.5 MeV/c.

In the initial experiments, the electron beam transverse distribution with the longitudinal M-shape laser distribution (see previous section) showed a hollow structure and a tilted-beam profile at EMSY1 [6]. Investigations on the laser and the electron beamline revealed several problems. The tilted beam structure could be significantly reduced by removing different magnetizable components from the electron beamline. The transverse laser distribution at the cathode is improved by replacing several optical components in the laser beamline. After these fixes, the measured emittance with a flat hat laser profile was indeed reduced. For the detailed scan, the minimum emittance of $\varepsilon_{xy} = \sqrt{\varepsilon_x \varepsilon_y}$ = 1.11±0.15 mm mrad was measured at a gun phase of +6 degree off-crest while the measurement at the gun on-crest phase resulted in an emittance of ε_{xy} = 1.26±0.16 mm mrad. In both cases, the laser spot size is 0.35 mm.

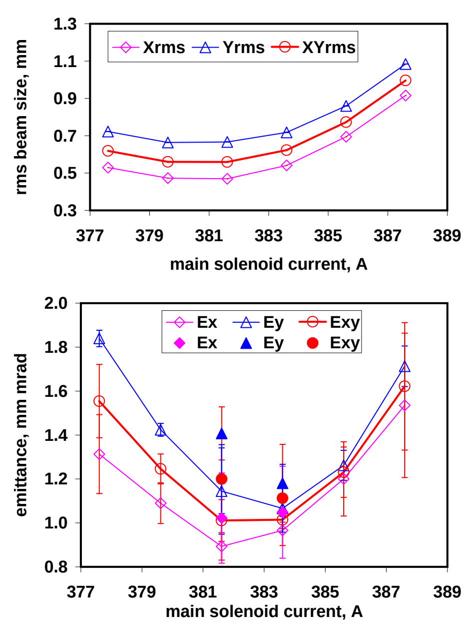

Figure 6: Measured beam size (top) and normalized projected emittance (bottom) vs. main solenoid current at EMSY1 station for a laser spot size of 0.35 mm, gun phase of +6 degree off-crest and booster phase on-crest (opened symbols for fast scan and solid symbols for detailed scan).

As an example, the rms beam size and the emittance as a function of the solenoid current is shown in Figure 6 for the +6 degree off-crest gun phase case. The smallest emittance is measured 2-4 A above the solenoid current where the smallest beam size is measured. This result is in a good agreement with the prediction from the simulation (see Figure 4). The reconstructed electron beam transverse phase space measured at the best emittance point is illustrated in Figure 7 and the emittance measurement results are summarized in Table 1.

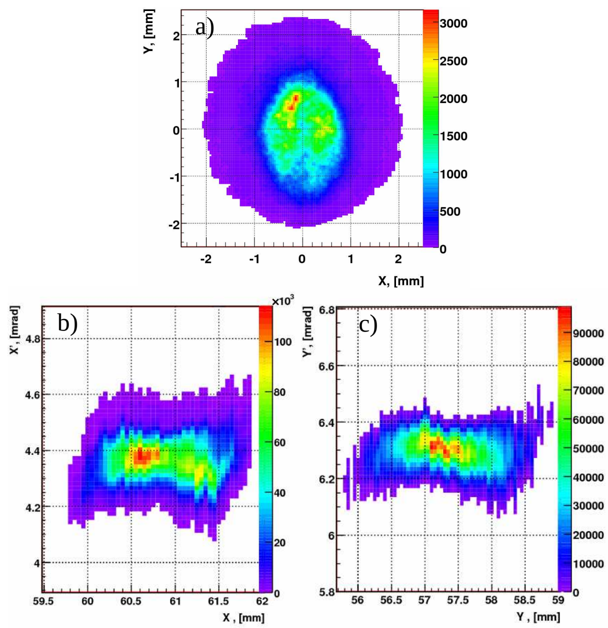

Figure 7: Transverse distribution (a), horizontal (b), and vertical (c) phase space of the best emittance point. The measured maximum longitudinal momenta of the beam for this best point were 6.61 MeV/c after the gun acceleration and 14.6 MeV/c after the booster acceleration.

Table 1: Summary of the Emittance Value for the Detailed Scans

gun phase	ε_x (mm mrad)	ε_y (mm mrad)	ε_{xy} (mm mrad)
on-crest	1.17±0.17	1.37±0.19	1.26±0.16
+6^o off-crest	1.05±0.21	1.18±0.18	1.11±0.15

Discussion

Main differences between the obtained optimum machine setup and the simulations are the gun launch phase, the laser spot size, and the smallest emittance value. Comparing the simulations (Figure 3 and 5) with the measurements (Figure 6) shows that the measured emittance is about twice as large as expected from simulations. This discrepancy is being investigated. Some possible reasons are

- a jittering of the amplitude and phase of the RF-gun over the pulse train results in a beam position, momentum, and phase space jitter
- a missing knowledge concerning the booster field profile under the RF-power (a very poor cooling of the booster cavity) may lead to the simulations which do not correspond to the measurement condition
- a limitation in the laser climatization results in the laser energy drift effecting the charge instability

The jitter of the RF amplitude and phase complicates not only the emittance measurement but also the procedure for the machine setup, introducing some uncertainty to the gun phase definition. Stabilization of the RF amplitude and phase from shot to shot and over the long RF pulse train is especially difficult for the present gun setup. The RF is fed from a 10 MW klystron via two arms and a combiner to the gun. With the absence of a directional coupler after the combiner, the low level RF (LLRF) regulation has built the vector sum using the forward and reflected RF-power measured in both arms. Study on the LLRF stabilization is underway. Replacement of the TESLA booster cavity with a new designed cut disk structure (CDS) booster cavity is planned in the next shut down. Improvement of the laser climatization is also foreseen.

CONCLUSION AND OUTLOOK

The current emittance measurement results at PITZ showed that a small emittance is achieved by applying a flat hat laser profile. However, the simulations predict an even smaller emittance than the results from the measurements. The experimental program to optimize the electron beam properties will be continued to study the discrepancy between results from the simulations and the measurements for the gun launch phase, the laser spot size and for the minimum emittance value.

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