EMITTANCE FOR DIFFERENT BUNCH CHARGES AT THE UPGRADED PITZ FACILITY

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Abstract

Optimizations of electron sources for short-wavelength Free Electron Laser (FELs) at the Photo Injector Test facility at DESY, location Zeuthen (PITZ) have been continued with a new radio frequency (RF) gun cavity, a new post-accelerating Cut Disk Structure (CDS) booster cavity and several upgraded diagnostic components. The new booster cavity allows stable operation with higher acceleration and longer pulse trains than the operation with the previous TESLA type cavity. Electron beams with a maximum mean momentum of about 25 MeV/c can be produced with the setup described in this paper. Together with the upgraded RF system for the gun and the new CDS booster cavity, the electron beam stability was significantly improved. A large fraction of the measurement program in 2010-2011 was devoted to study the dependence of the transverse projected emittance on the bunch charge. Measurement results using this upgraded facility are reported and discussed.

INTRODUCTION

The Photo Injector Test facility at DESY, location Zeuthen (PITZ) is a test accelerator dedicated to study and optimize photo injectors for linac based X-ray FELs like the Free-electron LASer in Hamburg (FLASH) and the European X-ray Free-Electron Laser (European XFEL). Electron beam properties i.e. peak current, energy spread, and transverse emittance define the wavelength and gain of the FELs for a certain undulator period and length. In contrast to the beam peak current and the energy spread, the transverse emittance cannot be improved during the beam transport before entering the undulator. It is a crucial property of an electron beam which has to be optimized from the source. Therefore the optimization of electron sources to produce electron beams with small transverse emittance is a major research subject at PITZ.

Results of emittance optimization for the previous machine setup in 2008-2009, showed that the projected transverse emittance fulfills the requirement of the European XFEL injector. The geometric mean emittance[1] as small as 0.89 mm·mrad was obtained for a bunch charge of 1 nC [1]. Several upgrades of the PITZ beam line were carried out in 2010-2011. The upgrades included an exchange of a new gun cavity with an upgraded RF system, replacement of an old TESLA booster with a new CDS cavity, and the installation of a phase-space tomography module with its matching section and several beam diagnostic systems [2].

METHODS

Machine and Beam Characteristics

The PITZ facility utilizes a 1.6 cell L-band RF gun, operating in conjunction with two solenoids. The main solenoid is used to focus electron beams and to counteract space charge forces while the bucking solenoid is employed to compensate the longitudinal magnetic field at the cathode. The RF gun in this described setup has the same design, construction procedure and cleaning method as the one in the 2008-2009 setup but with different ratio between the peak RF field at the cathode and at the center of the second cell. This gun cavity has a field ratio of 1.08 while it was 1.05 for the previous one. The 1.3 GHz RF pulses are provided to the gun and the booster cavity by two separated klystrons at a repetition rate of 10 Hz. This gun cavity is capable to operate with a gradient of $\sim$60 MV/m at the cathode which corresponds to a peak RF power of about 6 MW. The gun RF phase stability was improved for this new gun cavity with a new 10-MW in-vacuum directional coupler installed after the T-combiner. Direct measurement and control of the combined forward and reflected RF waves allowed a feedback loop to control amplitude and phase slope of the RF pulse. The maximum gun phase fluctuation was measured to be 0.3^o (rms) compared to 4^o for the measured fluctuation of the gun in the 2008-2009 setup [3].

A Cs_2Te cathode at the backplane of the gun cavity is illuminated with UV laser pulses. The laser system based on Yb:YAG can produce 257 nm laser pulse trains of up to 800 micropulses with a spacing of 1 μs between the pulses [4].

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[1] The geometric mean emittance is given as a geometric normalized projected rms emittance, averaged over the two transverse planes.

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Each micropulse has a maximum energy of $\sim$10 μJ. A flat-top laser temporal profile with 21-22 ps FWHM pulse length and a rise- and fall-times of about 2 ps was used in all measurements discussed in this paper.

The new booster cavity is a great step forward for PITZ to study and optimize electron beam characteristics. The CDS booster cavity has been specially designed and constructed for operation with higher accelerating gradient, longer acceleration, and longer RF pulse, as compared to the previous TESLA cavity. Design parameters for the CDS booster are given in [5]. At present time it is operated with RF pulses up to 700 μs in length at a repetition rate of 10 Hz with a power of up to 5.5 MW, providing the momentum gain of $\sim$18 MeV/c. A low level RF system provides precise control of phase and amplitude using RF probes. The water cooling system keeps the temperature of the structure within 0.15^o C.

Measurements of electron beam momenta using dipole spectrometer magnets after the gun and the booster acceleration were performed as a function of the RF peak power. The results are plotted in Fig. 1. The RF phases of the gun and the booster cavities were set to be at the phases of maximum mean momentum gain (MMMG). A maximum mean momentum of $\sim$6.8 MeV/c was measured after the gun for an RF power of 6 MW. The final mean momentum of $\sim$25 MeV/c was achieved after the booster acceleration with an RF power of 5.5 MW. For all emittance measurements discussed in this paper, the booster phase was kept at the MMMG phase and the RF power was set to the maximum possible for both gun and booster cavity.

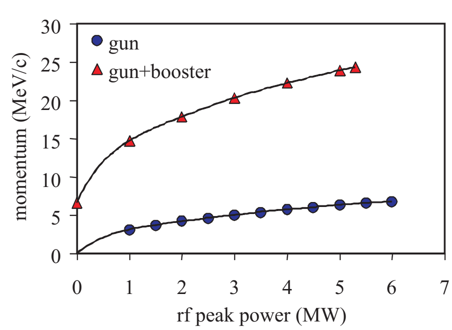

Figure 1: Measured beam mean momentum as a function of the RF power after acceleration with the gun (gun) and the booster (gun+booster). The RF peak power in the gun was set to the maximum value for the momentum measurements after the the booster acceleration.

Emittance Measurement and Analysis

The projected emittance and the phase-space distribution of the electron beam are measured using the single slit scan technique. Detailed information of the set-up and measurement procedure are described in references [6, 7]. All emittance measurements discussed in this paper were performed at the first Emittance Measurement SYstem station (EMSY1), located at 5.74 m downstream the photocathode. For each set of the measurement, the transverse beam size at the location of the slit mask was measured using a YAG screen equipped with a CCD camera and a suitable optical system. The slit scan procedure was carried out by continuously moving a 10-μm slit at constant speed to cut the beam in horizontal or vertical direction into thin slices. The beamlet images on a corresponding observation YAG screen at 2.64 m downstream of EMSY1 were recorded with a CCD camera at a fixed rate synchronously to the movement of the slit. The number of laser pulses in the train was adjusted to have sufficient signal intensity at the beamlet observation screen. The size and location of the beamlets on the observation screen were used to estimate the beam divergence.

The normalized transverse projected rms emittance can be calculated using the formula

$$\varepsilon = \beta\gamma\sqrt{\langle x^2\rangle \cdot \langle x'^2\rangle - \langle xx'\rangle^2}, \tag{1}$$

where $\beta\gamma$ is given by the electron beam energy, $\sqrt{\langle x^2\rangle}$ is the transverse rms beam size obtained by analyzing the projection of the (x, x') phase space distribution from the slit scan, $\sqrt{\langle x'^2\rangle}$ is the correlated divergence calculated from the measured size and location of the beamlets and $\langle xx'\rangle$ is the covariance term where the relative position of the beam line w.r.t. the corresponding slit position is taken into account. To correct for the underestimation due to a possible losses of the signal intensity at the tails of the phase-space distribution, a scaling factor $(\sigma_x/\sqrt{\langle x^2\rangle})$ is introduced to all emittance values discussed in this paper [7]. It is determined as the ratio of the rms beam size measured on the YAG screen at the slit location (σ_x) and the beam size estimated from the reconstructed phase space obtained from the beamlet images on the observation screen $(\sqrt{\langle x^2\rangle})$. The standard emittance formula in equation (1) becomes the so called scaled normalized projected emittance by applying this scale factor and is written as

$$\varepsilon = \beta\gamma\frac{\sigma_x}{\sqrt{\langle x^2\rangle}}\sqrt{\langle x^2\rangle \cdot \langle x'^2\rangle - \langle xx'\rangle^2}. \tag{2}$$

RESULTS AND DISCUSSIONS

Machine and beam parameters, i.e. laser transverse size at the cathode, main solenoid current and gun launch phase have to be optimized in order to minimize the projected transverse emittance. The dependence of the emittance on the laser transverse size at the cathode was experimentally studied. Circular beam shaping apertures with various sizes were applied to select the central part of the laser transverse distribution in order to vary the laser spot size at the cathode. The transverse shape at the cathode is flat. For each laser spot size, the main solenoid current was scanned to obtain the minimum emittance point.

The optimization started with a bunch charge of 1 nC and MMMG phases for both gun and booster cavities. The optimized results showed that the minimum geometric mean emittance of 0.83±0.03 mm·mrad was obtained for an rms laser spot size of $\sim$0.3 mm. It is noted that standard deviation values given in this paper were calculated from statistical measurements. The influence of the gun RF phase on

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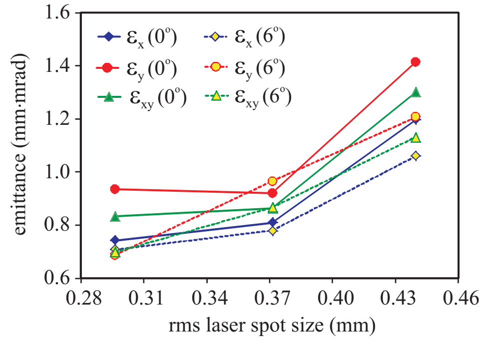

Figure 2: Measured emittance as a function of the rms laser spot size at the cathode for a bunch charge of 1 nC. The gun RF phases of 0^o and 6^o w.r.t the MMMG phase were used.

the emittance was investigated for the bunch charges of 1 and 2 nC. The measured emittance values as a function of the rms laser spot size for a gun launch phase of 0^o and $+6^o$ w.r.t. the MMMG phase of 1 nC bunch charge are shown in Fig. 2. The geometric mean emittance ε_{xy} is derived from $\varepsilon_{xy} = \sqrt{\varepsilon_x \varepsilon_y}$, where ε_x and ε_y are the horizontal and vertical emittance, respectively. The results in Fig. 2 reveal that the gun phase of 6^o delivered smaller measured emittance values than 0^o. One possible explanation is an effect of high space charge densities at the cathode during charge emission for small laser spot sizes at the gun phase of 6^o. An increase of the gun phase resulted in higher electric fields at the cathode surface and thus charge emission enhancement due to Schottky-like effect. Although the emittance value trended to decrease for the rms laser spot size smaller than 0.3 mm, it was not possible to produce 1 nC for smaller laser spots. Detailed study for the case of 2 nC bunch charge is presented in [8].

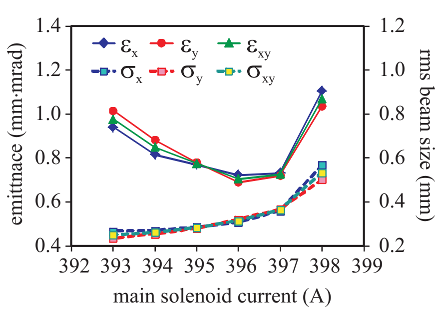

Figure 3: Measured emittance (ε) and rms beam size (σ) as a function of the main solenoid current for a bunch charge of 1 nC. The gun phase was at 6^o from the MMMG phase. The rms laser spot size at the cathode was 0.3 mm.

Optimization of the emittance as a function of the main solenoid current for the rms laser spot size of 0.3 mm and the gun phase of 6^o is illustrated in Fig. 3. The minimum emittance value was obtained for a main solenoid current of 396 A. Electron beam transverse distributions measured at EMSY1 and at the beamlet observation screen are shown in Fig. 4. An x-y asymmetric shape was observed at the beamlet observation screen (Fig. 4 right). The beam halo, low intensity tails of the transverse distribution, is clearly seen at this image. The cause of the asymmetry and beam halo is under investigation. The asymmetric ratio increased by a factor of about 1.3 for the drift length of 2.64 m. Measured phase-space distributions of the horizontal and vertical plane are shown in Fig. 5. Nine statistical measurements were performed and resulted in horizontal and vertical emittance values of 0.71$\pm$0.03 and 0.69$\pm$0.02 mm·mrad, respectively. This corresponds to a geometric mean emittance of 0.70$\pm$0.01 mm·mrad.

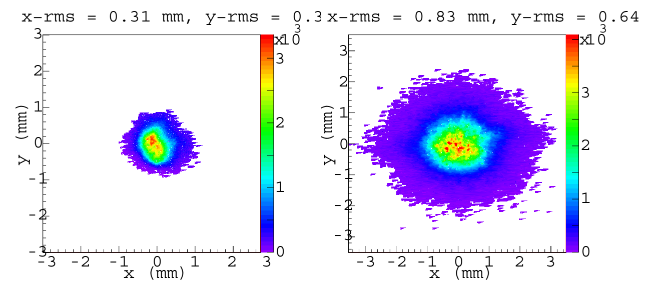

Figure 4: Transverse beam distribution on the YAG screens at EMSY1 (left) and at the beamlet observation station (right) for a bunch charge of 1 nC. The screens are located at 5.74 and 8.38 m downstream of the cathode, respectively.

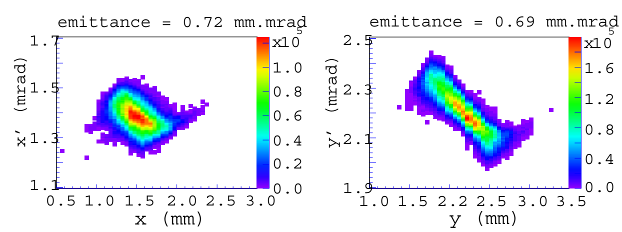

Figure 5: Measured horizontal (left) and vertical (right) phase-space distributions for a bunch charge of 1 nC.

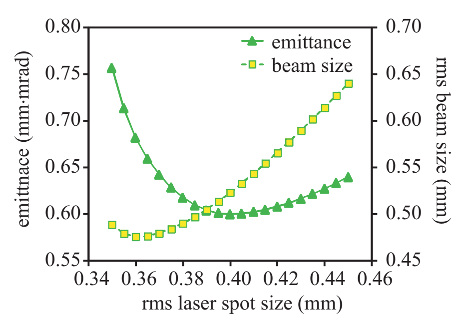

Figure 6: Simulated dependence of emittance and beam size at EMSY1 on the rms laser spot size for a bunch charge of 1 nC. The optimum rms laser spot size of 0.40 mm delivers the minimum emittance of 0.60 mm·mrad.

The measured minimum emittance value is ~16% larger than the simulated value, 0.60 mm·mrad, using the code ASTRA [9]. Moreover, the simulations yielded the optimum rms laser spot size of 0.4 mm and gun phase of around the MMMG condition while the experimentally optimization delivered the minimum emittance value for the rms laser spot size of 0.3 mm and 6^o w.r.t. the MMMG phase. The simulated dependence of the emittance and the

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beam size on the laser spot size at the cathode are presented in Fig. 6. The charge emission enhancement (Schottky-like effect) due to the presence of a high electric field at the cathode surface was not included in the beam dynamics simulations. This is one possible explanation for the discrepancy between the measured and simulated results.

Similar studies of the projected emittance were also performed for a bunch charge of 2, 0.25, 0.1 and 0.02 nC, respectively. The gun and the booster RF phases were set at the MMMG condition for these bunch charges. The measurement results show that the minimum geometric mean emittances of 1.56±0.08, 0.33±0.01, 0.21±0.01 and 0.12±0.01 mm·mrad were obtained for a bunch charge of 2, 0.25, 0.1 and 0.02 nC, respectively. A summary of the minimum measured emittance values as a function of the rms laser spot size for all bunch charges are shown in Fig. 7. The minimum geometric mean emittance of different bunch charges measured in this experiment are summarized and compared to the values obtained at the Linac Coherent Light Source (LCLS) injector [10, 11] in Fig. 8. Smaller emittance values were obtained at PITZ as compared to the LCLS injector beams. The gun phase for the PITZ data is noted by 0^o and 6^o w.r.t. the MMMG phase. A cut on the low intensity tails of the measured phase-space distribution to estimate the emittance as a function of the charge cut was performed and the results are presented in Fig. 9.

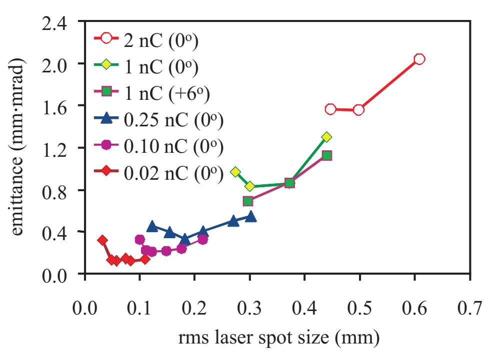

Figure 7: Measured geometric mean emittance (ε_{xy}) as a function of the rms laser spot size for different bunch charges. All emittance values were analyzed from the 100% rms phase-space distribution.

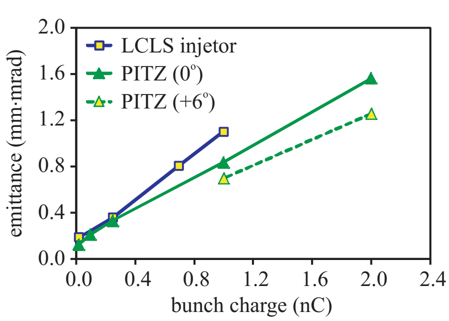

Figure 8: Comparison of measured geometric mean emittance (ε_{xy}) as a function of the bunch charge for PITZ and LCLS injector beams.

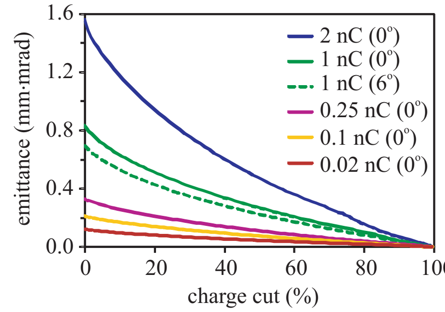

Figure 9: Geometric mean emittance (ε_{xy}) as a function of charge cut for different bunch charges.

CONCLUSION

The transverse projected emittance for different bunch charges was experimentally studied at PITZ in the run period 2010-2011. The reduction of the RF phase fluctuation from 4^o to 0.3^o (rms) resulted in a more stable phase for all pulses in the pulse train and thus a reduced smearing of the phase-space distributions. Together with the improvement of the laser optics in the transport line and removing of spurious magnetic fields in the beam line resulted in smaller emittances than the results measured with the setup in 2008-2009. The geometric mean emittances as small as 1.56, 0.70, 0.33, 0.21 and 0.12 mm·mrad were obtained for a bunch charge of 2, 1, 0.25, 0.1 and 0.02 nC, respectively. These emittance values are the smallest published values for FEL photo injectors, according to our knowledge.

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