MEASUREMENTS OF TRANSVERSE PROJECTED EMITTANCE FOR DIFFERENT BUNCH CHARGES AT PITZ

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Abstract

Transverse projected emittance optimization is one of the main research activities at the Photo Injector Test facility at DESY, Zeuthen site (PITZ). The emittance measurement program in the 2008/2009 run period concentrated on the measurement using a single slit scan technique. The photocathode laser profile was optimized yielding small emittance. In standard projected emittance measurements, a flat-top temporal profile was used. For the nominal 1 nC bunch charge, emittance values down to less than 1 mm-mrad were measured. Emittance optimizations for lower charges were also conducted using the same measurement setup and procedure as for the case of 1 nC. Optimizations and measurement results of the transverse projected emittance for the bunch charges of 1, 0.5, 0.25 and 0.1 nC are presented and discussed in this paper.

INTRODUCTION

High brightness electron sources require electron beams of high quality for both transverse and longitudinal phase space. The transverse emittance is one of key parameters for linac based Free Electron Lasers (FELs), which must be optimized from the source. At PITZ, electron sources to produce electron beams with a small emittance have been developed and optimized yielding the beam requirements for FLASH and the European XFEL. Details of the PITZ setup and components in the 2008/2009 run period were described in [1]. In the last run period, small emittance values fulfilled the European XFEL beam parameters were measured. Emittance optimizations for various machine and beam parameters were carried out. In this paper, measurement results of the transverse projected emittance are reported and discussed for four different bunch charges. The flat-top cathode laser temporal profile [2] was used for this study. Measurements using Gaussian laser pulses were also performed and the results are presented in another contribution to these proceedings [3].

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MEASUREMENT METHODS

Methodics and Instruments

Transverse projected emittance and phase space of electron beams with different bunch charges are measured at PITZ using the single slit scan technique [4, 5]. The Emittance Measurement System (EMSY) consists of YAG/OTR screens and 10/50 μm slit masks. The screens are used to measure the beam size and the slit masks are used to transversely cut the beam into thin slices. The local divergence is estimated by measuring the size of the beamlets created by the slit on an observation screen downstream the slit location. The EMSY station, used during the standard emittance measurement, is located at 5.74 m downstream the photocathode. This location is an expected minimum emittance location obtained from simulations. The beamlet observation screen is positioned at 2.64 m downstream the EMSY station.

A 2D-scaled normalized projected RMS emittance formula is used to calculate emittance values [6]. A scaling factor is applied to the standard emittance formula. It is determined as the ratio of the RMS beam size measured at the slit position and the beam size estimated from the slit location and the beamlet intensity on the observation screen. This factor is always slightly larger than 1. It is employed to correct for the low intensity losses at tails of the density during the measurement of the beamlets in order to not under-estimate the emittance values. More details about instruments, techniques and procedures of the emittance measurement at PITZ are given in [5, 4, 6].

Optimization of Machine and Beam Parameters

A flat-top laser pulse length of 20-25 ps FWHM and 2-4 ps rise/fall time was used in the measurements presented in this paper. The transverse laser spot size at the cathode was varied from 0.05 to 0.44 mm using a set of apertures in the laser beamline to optimize the emittance values. The number of laser pulses was adjusted to have a good beamlet intensity at the observation screen.

The gun accelerating gradient at the cathode was set to be about 60 MV/m. This corresponded to a measured maximum momentum of 6.68 MeV/c for the gun launch phase of maximum mean momentum gain (MMMG). The gun phase was optimized to obtain the minimum emittance value. The optimization results showed that the minimum emittance values were obtained at the gun phase of +6 degree with respect to the MMMG phase. The measured mean momentum corresponding to this phase was 6.67 MeV/c.

The booster cavity phase was set at the MMMG phase during the measurements. Electron beams with a maximum mean momentum of 14.5 MeV/c after the booster acceleration were used in the measurements of the 1 nC bunch charge. For lower bunch charges, more laser pulses were used. This required a longer RF pulse length for the booster cavity. Due to a limitation of the booster cooling capability for the long RF pulse operation, a lower booster gradient was used in the cases of lower bunch charges. Beams with a maximum mean momentum of 12.3 MeV/c were used in the measurements for bunch charges of 0.5, 0.25 and 0.1 nC.

RESULTS AND DISCUSSIONS

Emittance Optimization

Transverse projected emittance as a function of the RMS laser spot size was measured for each bunch charge. The main solenoid current was scanned to define the minimum emittance point, while the bucking solenoid current was set to compensate the magnetic field at the cathode. Measurement results of the normalized projected emittance as a function of the RMS laser spot size for the bunch charges of 1, 0.5, 0.25 and 0.1 nC are shown in Fig. 1. There are some differences in the measured horizontal and vertical emittance values. It is possibly due to an asymmetric shape of the booster cavity at the RF waveguide input location. Asymmetric electromagnetic fields due to an opening in the wall of the booster cavity may introduce a vertical kick to the beams. This in general leads to a bigger beam size in the vertical plane and consequently to a bigger emittance. However, this is not the case for small laser spot sizes, which may due to an emission feature of a space charge dominated case.

Summary of the minimum measured value of the so-called geometrical emittance for all four bunch charges are shown in Fig. 2 and Table 1. The geometrical emittance value (ε_{xy}) is obtained from $\varepsilon_{xy} = \sqrt{\varepsilon_x \varepsilon_y}$, where ε_x and ε_y are the horizontal and the vertical normalized projected emittance. A so-called geometrical RMS laser spot size (σ_{xy}) is defined from $\sigma_{xy} = \sqrt{\sigma_x \sigma_y}$, when σ_x and σ_y are the horizontal and the vertical RMS laser spot size. All emittance results in Fig. 1, Fig. 2 and Table 1 are for the so-called 100% RMS value, where the cut in charge and phase space distribution are not performed. The geometrical emittance as small as 0.89 mm-mrad was achieved for the 1 nC bunch charge. This value fulfills the goal emittance at the injector for the European XFEL.

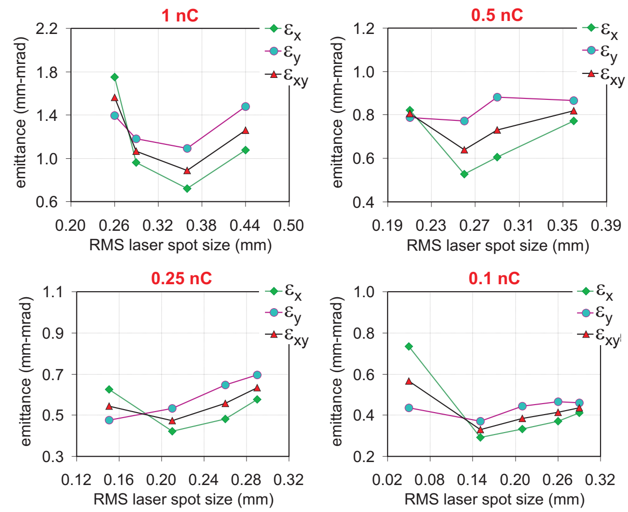

Figure 1: Measured normalized projected emittance as a function of the RMS laser spot size for the bunch charges of 1, 0.5, 0.25 and 0.1 nC.

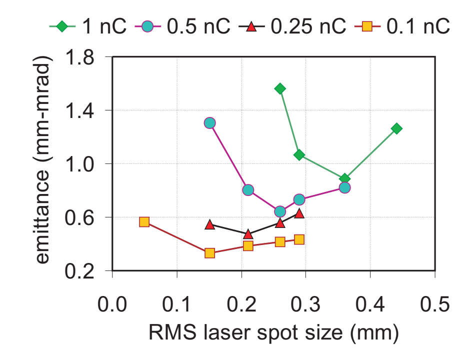

Figure 2: Measured normalized geometrical projected emittance (ε_{xy}) as a function of the RMS laser spot size for the bunch charges of 1, 0.5, 0.25 and 0.1 nC.

Table 1: Minimum measured normalized projected emittance for four different bunch charges (Q).

Q **(nC)**	**1**	**0.5**	**0.25**	**0.1**
σ_{xy} (mm)	0.36	0.26	0.21	0.15
ε_x (mm-mrad)	0.721±0.013	0.528	0.421	0.293
ε_y (mm-mrad)	1.089±0.020	0.773	0.533	0.371
ε_{xy} (mm-mrad)	0.886±0.011	0.639	0.474	0.330

Core Emittance

Core emittance values were estimated by removing 10% of the total bunch charge from the low intensity tails of the measured transverse phase space distribution. This corresponds to removing electrons, which probably do not contribute to the FEL lasing process. Examples of phase space distributions for 100% and 90% change intensity for the case of 1 nC are shown in Fig. 3. The estimation results show that the 90% geometrical RMS emittance as small as 0.67 mm-mrad can be achieved. By applying the charge intensity cut to the emittance analysis, the minimum geometrical emittance for four bunch charges as a function of the charge cut were obtained and are illustrated in Fig. 4. One interesting case is the 0.25 nC with 5% charge cut, which the normalized projected emittance of about 0.4 mm-mrad can be obtained. This value is comparable to the measured normalized projected emittance at the Linac Coherent Light Source (LCLS) X-ray FEL [7].

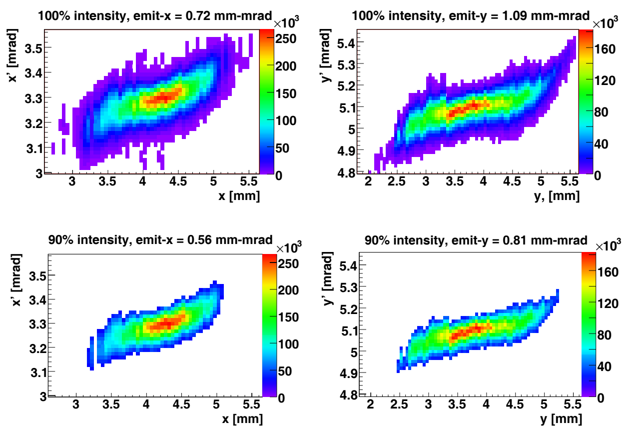

Figure 3: Horizontal (left) and vertical (right) phase space distributions for 100% and 90% charge intensity for the bunch charge of 1 nC.

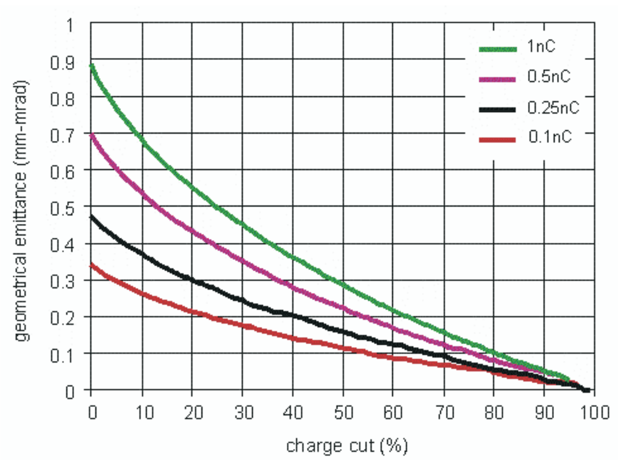

Figure 4: Minimum normalized geometrical emittance (ε_{xy}) as a function of charge cut for the bunch charges of 1, 0.5, 0.25 and 0.1 nC.

Stability of Emittance Measurements

During the emittance measurements, strong fluctuations of the gun phase at a given position within the train as well as over the pulse train were observed [8, 9]. Statistical measurements for the same machine setting were performed for the bunch charge of 1 nC using the optimum main solenoid current. The error bars given in Table 1 for the 1 nC case were determined within ∼30 minutes measurement time.

Longer term emittance stability was checked with the same machine setting as the case of the minimum emittance but with the laser pulse length of about 4 ps shorter. The laser temporal pulse shape was also not absolute stable during the run period. This resulted in emittance values larger than the optimum case. The results of the stability check are presented in Fig. 5. The RMS fluctuations of emittance value of about 4-7% were observed for the measurement time of about 3 hours. The RMS beam size jitterings were measured to about 3-4%. The long term stability measurements were performed over 4 days and the results are shown in Fig. 6. The RMS emittance fluctuations of 6-8.5% were observed.

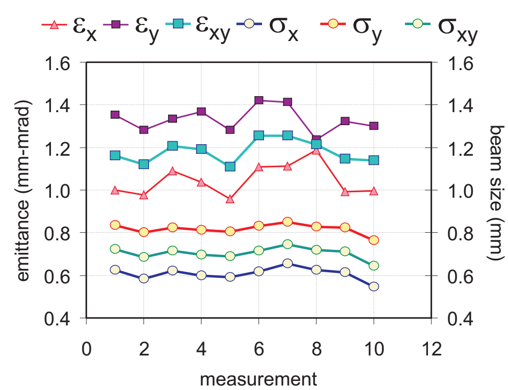

Figure 5: Stability check of the measured emittance and beam size for the measurement time of about 3 hours.

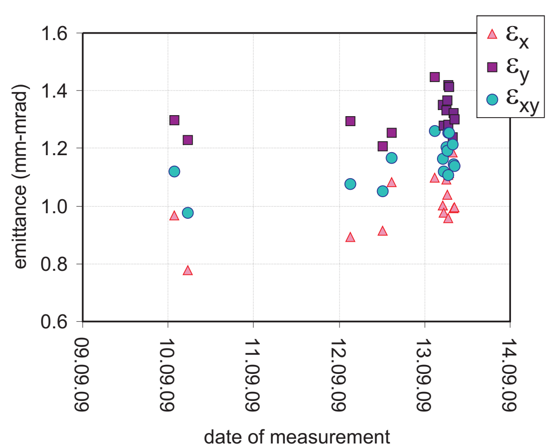

Figure 6: Fluctuations of the measured emittance for the operation time over 4 days.

ASTRA [10] simulations were performed to study the influence of different parameters on the emittance value. Emittance values of all four bunch charges were simulated as a function of the RMS laser spot size, the gun launch phase and the solenoid magnetic field. The simulations included machine and beam parameters according to the experimental conditions. The laser temporal profile of about the measured value was used. The gun and the booster accelerating gradient were adjusted to obtain the same maximum mean momentum as the measurement case. A theoretical electron kinetic energy of 0.55 eV was used in simulations for all bunch charges.

Simulated projected emittance values as a function of the RMS laser spot size for all four bunch charges are shown in Fig. 7. The results suggest that the minimum emittance for the cases of 0.5, 0.25 and 0.1 nC can be obtained for the laser spot sizes similar to the measurements. The simulated minimum emittance in the case of 1 nC is obtained at a larger laser spot size than the measurement case. The simulation results show that the smallest emittance in the case of 1 nC bunch charge is achieved with the RMS laser spot size of about 0.4 mm. Unfortunately, the same laser spot size could not be produced experimentally due to the limitation of available apertures.

There are discrepancies between the measured and the simulated minimum emittance values. Two hypotheses are considered to be the main reasons of the mismatch between measurements and simulations. The first hypothesis is the machine instabilities, especially the gun launch phase fluctuation. This instability is considered to be the source of the fluctuation of the measured electron beam size and emittance [6, 8, 9]. Since the emittance measurements were not a single shot and even evolving the pulse train for the intensity integration, the gun phase jittering can cause a smearing of the phase space distribution and results in a larger measured emittance. The second one is probably due to the missing knowledge concerning the booster cavity field profile under the high RF power operation. Studies on the discrepancies between the measured and the simulated emittance are required. Some studied results for the case of 1 nC bunch charge were presented in [6]. More investigations for lower bunch charges are ongoing.

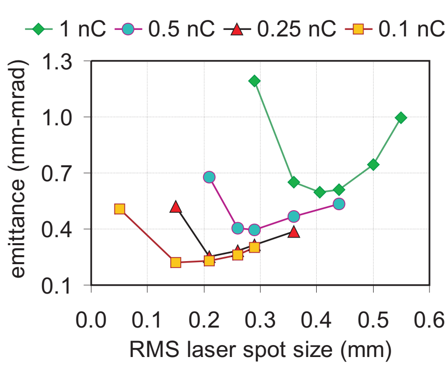

Figure 7: Simulated normalized projected emittance as a function of the RMS laser spot size for the bunch charges of 1, 0.5, 0.25 and 0.1 nC.

CONCLUSION AND OUTLOOKS

Emittance of electron beams produced by using the flat-top temporal laser pulses was measured for the bunch charges of 1, 0.5, 0.25 and 0.1 nC. Small emittance values fulfilled the requirements of the European XFEL were achieved. However, some discrepancies of the measured values from the simulation results were observed. The machine instabilities are considered to be one of the sources of the mismatch of the measurement and simulation results. Investigations on the machine instabilities, especially the fluctuation of the gun launch phase, are ongoing. Another reason can be due to an insufficient knowledge concerning the booster cavity field profile under the RF power.

Further investigations will be continued in the next run period using a newly installed RF gun and booster cavities. The gun phase stability is foreseen to be improved for the new gun cavity with a new 10-MW in-vacuum directional coupler [11, 12]. A direct monitoring and control of the combined forward and reflected RF waves should allow an RF feedback control for the new setup. A known field profile of a new booster cavity and an effective cooling system are certainly great steps forward for PITZ. These should lead to an improvement in the simulation knowledge and a more flexible booster operation.

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