MEASUREMENT OF THE PROJECTED NORMALIZED TRANSVERSE EMITTANCE AT PITZ*

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Abstract

The main objective of the Photo Injector Test facility at DESY in Zeuthen (PITZ) is the production of electron beams with minimum transverse emittance at 1 nC bunch charge. PITZ consists of a photo cathode RF gun, solenoids for compensation of the space charge induced emittance growth and a booster cavity. In order to study the emittance evolution along the beam line three Emittance Measurement SYstems (EMSY's) were installed downstream of the booster cavity [1]. In a first operation period in October 2006 the emittance was measured for gun gradients of about 40 MV/m. A new gun cavity is presently installed at PITZ and conditioning up to a gradient of 60 MV/m is ongoing. In this work we present recent results from measurements of the normalized projected transverse emittance of the electron beam. The emittance is measured using the so called single slit scan technique. Measurements are presented for different gun and booster gradients, solenoid strengths and initial beam size at the photocathode.

INTRODUCTION

Major goal of PITZ is the development and optimization of electron sources that fulfill the requirements for SASE FEL's such as FLASH and XFEL. The optimization process is conducted by extended numerical simulations using ASTRA [2], and closely followed by research and development of appropriate instruments for electron and laser beam characterization (see [3, 4]).

A simplified scheme of PITZ is shown on Figure 1. It consists (right-to-left) of a 1.5 cell L-band RF gun equipped with a Cs_2Te cathode, pair of solenoids for space charge compensation, low energy beam diagnostics, a booster cavity, high energy diagnostics including three EMSY's (installed at 4.3, 6.6 and 9.9 m downstream the cathode) and a beam dump. A photocathode laser system provides carefully shaped laser pulses with variable transverse diameter and flat hat longitudinal distribution (see [4, 5]).

In this paper we present results from the emittance measurements made in October 2006 and summer 2007 using two different gun cavities:

- prototype 3.1 conditioned in summer 2006 and optimized in October 2006 up to the maximum requirements for FLASH with a peak power of 3.5 MW resulting in gun gradient of about 40 MV/m [6];
- prototype 3.2 which was conditioned and optimized this summer with a peak power of up to 6.9 MW resulting in a gun gradient of ∼60 MV/m [7].

For gun prototype 3.1 the emittance was measured using the three existing EMSY's as a function of the main solenoid focusing current for various booster phases. For prototype 3.2 the emittance was measured only at the first EMSY (distance from the cathode 4.3 m) for various beam sizes at the cathode and different energy gain from the booster. In addition the optimized settings for gun 3.1 were applied to gun 3.2 and the emittance was measured, the results are compared and discussed.

EMITTANCE MEASUREMENT SETUP

The transverse emittance at PITZ is measured using the so called *single slit scan* technique. A schematic representation of the technique is shown on Fig. 2. For this technique the uncorrelated local divergence is estimated by cutting the electron beam into thin slices and measuring their size on a screen after propagation in a drift space. The so called sheared normalized RMS emittance is then calculated using the following definition [8]:

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

Here $\langle x^2 \rangle$ and $\langle x'^2 \rangle$ are the second central moments of the distribution of the electrons in the so called trace phase space where $x' = p_x/p_z$ represents the angle of a single electron trajectory with respect to the whole beam trajectory[1]. The RMS beam size is measured on an additional OTR or YAG screen at the position of the slits. The uncorrelated divergence is obtained by analyzing the profiles of

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[1] valid for small momentum spread within the bunch, otherwise more precise definition should be used (i.e. [9]).

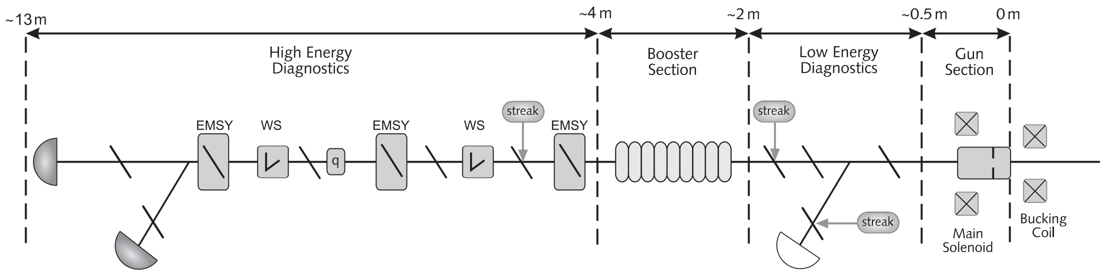

Figure 1: Layout of PITZ.

the beamlets produced from the slits which drift some distance L_d downstream. There the spatial distribution of the beamlets corresponds to the local uncorrelated divergence, $\langle x'^2\rangle_{local}$ which can be derived from the size of the beamlet using:

$$\sqrt{\langle x'^2\rangle_{local}} = \frac{\sqrt{\langle x_b^2\rangle}}{L_d}. \tag{2}$$

Here $\sqrt{\langle x_b^2\rangle}$ is the RMS size of the beamlet on the screen after distance L_d. The total uncorrelated divergence of the beam is estimated by a weighted average of several measurements of the local divergence taken from different locations across the beam:

$$\langle x'^2\rangle = \sum_{i=1}^{N} w_i \cdot \langle x'^2\rangle_i. \tag{3}$$

The Lorentz factors $\beta\gamma$ is measured using a dispersive section downstream of EMSY.

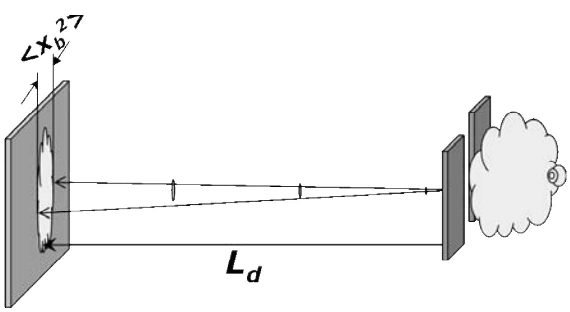

Figure 2: Schematic representation of the single slit scan technique.

The measurement system was optimized to measure emittance as low as 1 mm.mrad for 1 nC charge per bunch with precision better than 10 % (see [10]). The slits are mounted on two orthogonal actuators which host also the YAG and OTR screens for transverse beam distribution measurements. Single slit masks with slit opening of 10 and 50 μm and thickness of 1 mm. Rotating and goniometric stages are providing precise angular adjustment of the actuators for improved angular acceptance of the system.

EMITTANCE MEASUREMENTS

On Fig. 3 the evolution of the beam emittance as simulated with ASTRA[2] is shown for the two different accelerating gradients, 40 and 60 MV/m, used for the measurements. The simulation parameters are set close to PITZ machine parameters, shown in Table 1. The curves look different since for 40 MV/m the goal of the optimization was to have the slowest rise of the emittance along the beam axis in order to resemble the conditions for emittance conservation. At 60 MV/m the goal was to have the minimum emittance at 4.3 m downstream the cathode (location of EMSY1).

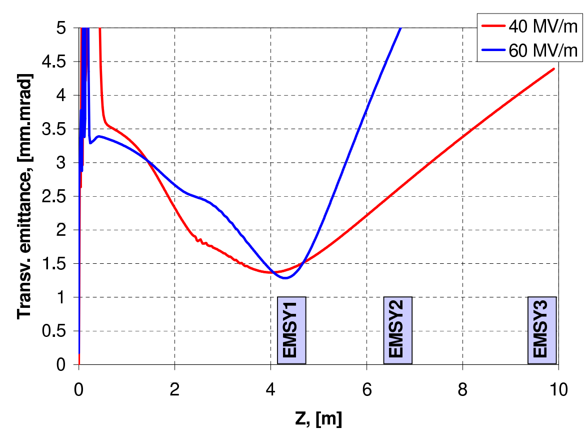

Figure 3: Emittance evolution along the beamline for two different gun gradients.

40 MV/m accelerating gradient at the cathode

The characterization of gun 3.1 was done with maximum input power of 3.5 MW. Therefore, all the emittance measurements were made with a maximum accelerating gradient of about 40 MV/m which resulted in a maximum mean beam momentum right after the gun of up to about 5 MeV/c. In addition, at solenoid currents below 280 A, the full beam size at z=1.0 m was approaching 12 mm which is the size of the vacuum chamber at the low energy dispersive arm located at this position (see Fig. 1). This was a further limitation to our available optimization range.

[2]all the RF phases are relative to the phase of maximum mean momentum gain in ASTRA

Table 1: Machine parameters for emittance measurements.

par.	gun 3.1	gun 3.2	Units
E_{acc}	43	∼60	MV/m
ϕ_{gun}	-2	0	deg
I_{main}	274-290	365-376	A
P_{mean}	12.85	11 to 14.8	MeV/c
$\phi_{booster}$	0 to -20	0	deg
XY_{ini}	0.51	0.33 to 0.55	mm
r_t/f_t	6-8	6-8	ps
$FWHM$	∼18	∼20	ps

On Fig. 4 the dependence of the projected normalized transverse emittance on the current in the main solenoid at three different locations along the beamline is shown. All other injector parameters are fixed as shown in the Table 1, $\phi_{booster}$ = ϕ_{ref}-10 deg. A minimum is visible for EMSY1 around $I_{main} = 282$ A. For the other two stations the minimum of the emittance could not be characterized because of the above mentioned limitations in the optimization range. Another notable fact is the large disagreement between the results at EMSY3, $I_{main} = 284$ A, and the simulations shown on Fig. 3. This can be explained by a large error of the beam size measurements due to the fact that the beam at EMSY3 is of a size comparable with the screen. Also the narrow dipole chamber in the low energy section could cause a dilution of the phase space.

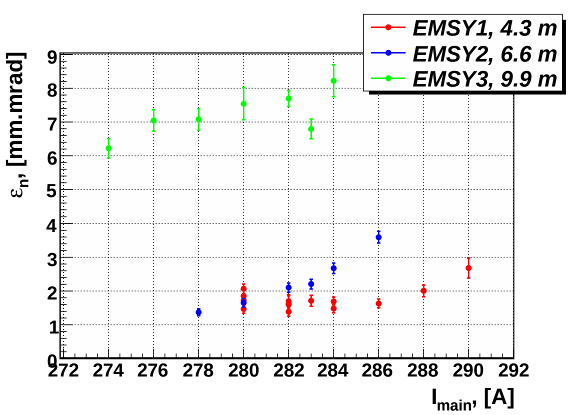

Figure 4: Emittance as a function of the current in the main solenoid. Gun at 40 MV/m and booster phase with respect to the maximum acceleration phase is -10 deg.

On Fig. 5 a comparison between gun 3.1 and 3.2 is shown, the machine settings were set such to reproduce the conditions during the measurements with gun 3.1, namely the mean momentum from the gun (4.95 MeV/c), final momentum after the booster (12.85 MeV/c) and the laser spot size on the cathode (initial beam size ~ 0.51 mm). Altough there is agreement within the error bars between the minimum values, $\varepsilon_{n,3.1} = 1.37 \pm 0.14$, $\varepsilon_{n,3.2} = 1.54 \pm 0.15$, there is obvious large discrepancy between the minimum

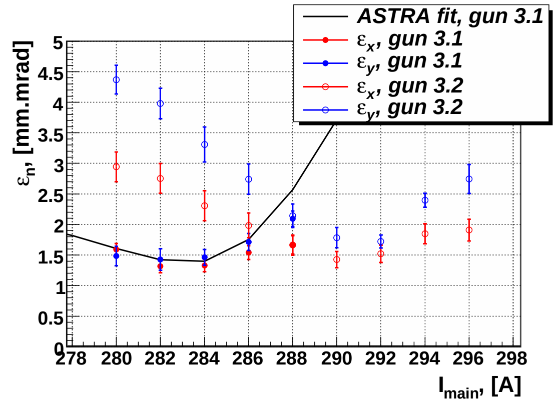

Figure 5: Comparison of the measurement with gun 3.1 and gun 3.2 as well as with ASTRA simulations for the gun 3.1 case. The machine was set to have the same mean momentum at about 40 MV/m, booster phase with respect to the maximum acceleration phase is -5 deg, initial beamsize is 0.5 mm.

position with respect to I_{main} of about 8 A. This large discrepancy is still to be understood.

60 MV/m accelerating gradient at the cathode

For the gun 3.2 the RF power in the cavity was increased up to the limit of our RF system ($\sim$ 7 MW in the gun). This corresponds to an accelerating gradient of about 60 MV/m or mean beam momentum after the gun up to 6.5 MeV/c However the problem with the aperture at the low energy dispersive arm remained therefore we decided to use only the first EMSY (z=4.3 m) and to optimize for lowest emittance at this location. One of the optimization parameters was initial beam size (laser spot size at the cathode) The main solenoid current (I_{main}) was scanned around the beam waist at EMSY1. The energy gain from the booster cavity was varied such that the final beam momentum was tuned to 9.5, 11.0, 13.0 and 14.5 MeV/c.

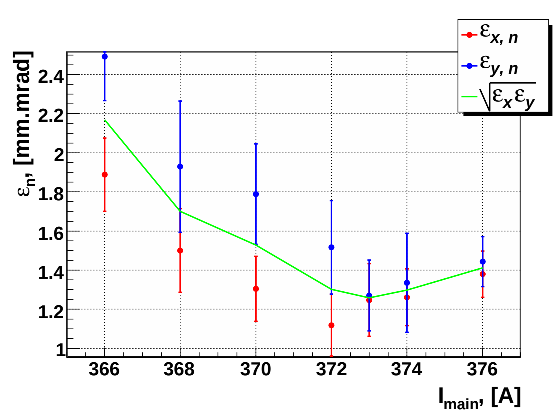

Figure 6: Emittance as a function of the main solenoid focusing strength. Gun 3.2, mean momentum after the booster 14.45 MeV/c.

On Fig. 6 one sees the dependence of the projected emittance on the focusing strength of the main solenoid. The geometrical average minimum of the measured emittance is 1.26 ± 0.18 mm mrad. Analog scans have been performed at different momentum gain from the booster. For fixed laser parameters, gun gradient and phase, as well as booster phase the minimum emittance obtained from a scan of I_{main} is shown in Fig. 7 as a function of the momentum gain in the booster.

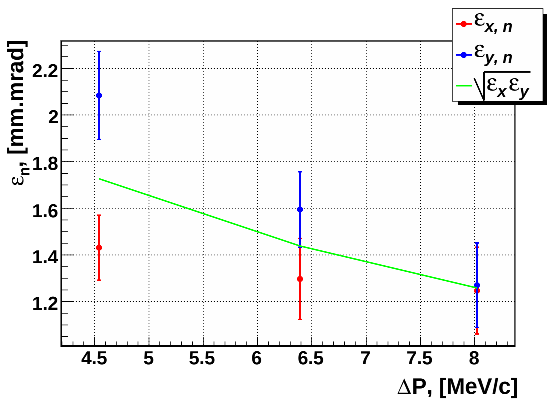

Figure 7: Minimum of the emittance as a function of the momentum gain in the booster.

The beam emittance has been re-measured in details for the best machine parameters: $P = 14.45$ MeV/c, $I_{main} = 373$ A, $XY_{ini} = 0.33$ mm. A very good reproducibility of about 2-3% has been demonstrated. Furthermore we did a very detailed scan with the slit technique, using as small as 25 μm separation between the individual slit positions. The phase space distribution is shown on Fig. 8. To the authors knowledge this image has unprecedent resolution in the trace space for such beam parameters. The ultimate resolution of our current system is estimated to be 36 μm x 15.4 μrad.

CONCLUSIONS

Gun 3.1 was conditioned up to 40 MV/m and characterized resulting in normalized beam emittance of 1.37 ± 0.14 mm mrad.

Corresponding machine parameters were applied to gun 3.2 at 40 MV/m yielding 1.54 ± 0.15 mm mrad.

Gun 3.2 was conditioned up to 60 MV/m and delivered minimum transverse normalized emittance of 1.26 ± 0.18 mm.mrad.

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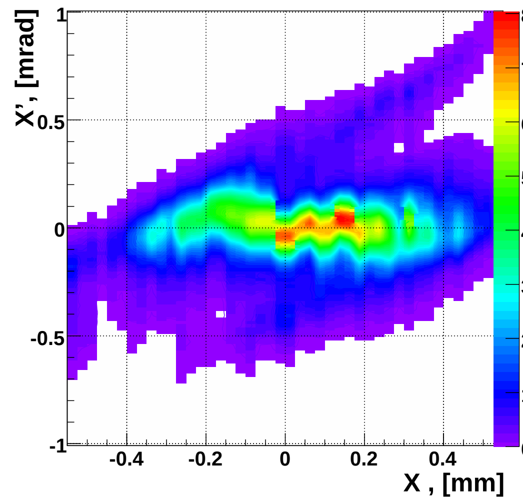

Figure 8: Phase space distribution at $P = 14.45$ MeV/c, $I_{main} = 373$ A, on crest phases of gun and booster.

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