FIRST RESULTS WITH TOMOGRAPHIC RECONSTRUCTION OF THE TRANSVERSE PHASE SPACE AT PITZ

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Abstract

The development of high brightness electron sources capable to drive FELs like FLASH and European XFEL is a major objective of the Photo-Injector Test Facility at DESY, location Zeuthen, PITZ. A key parameter used to define the beam quality at PITZ is the transverse phase-space density distribution and its evolution along the beamline. Complementary to the standard phase-space measurement setup using slit-scan stations, a module for tomographic diagnostics has been commissioned in 2010/2011. It consists of four observation screens separated by FODO cells and an upstream matching section. The expected advantages of the tomography method are the possibility to measure both transverse planes simultaneously and an improved resolution for low charges and short pulse trains. The fundamental challenges are related to strong space-charge forces at low beam momentum of only 25 MeV/c at PITZ, being an obstacle to obtain beam envelope parameters well-matched to the optics of the FODO lattice.

This contribution presents the first practical experience with the phase-space tomography module. Results of first measurements are presented as well.

INTRODUCTION

The Photo-Injector Test Facility at DESY, location Zeuthen, PITZ, is dedicated to the development and optimization of electron sources capable to drive high peak brilliance short wavelength FELs. PITZ is based on a normal-conducting L-band RF gun cavity where electrons are produced via photoeffect from a $\mathrm{Cs_2Te}$ cathode. Additional acceleration is obtained with a booster cavity. The space between the two cavities and downstream the booster is occupied by extensive diagnostics components as shown in Fig. 1.

In the run period 2010/2011 PITZ was operated with newly installed and conditioned 1.6-cell gun [1] and 14-cell booster cavities [2]. The accelerating gradient at the cathode surface was about 60 MV/m with which a maximal mean momentum after the gun of about 6.7 MeV/c could be reached. The booster cavity was operated with a nominal peak power of 5.5 MW providing final beam momentum of about 25 MeV/c. The characterization of the transverse phase space was done directly after the booster cavity - denoted with EMSY1 on Fig. 1, where slit scans are deployed.

In addition to the gun and the booster, the beamline was upgraded with a module for phase-space tomographic diagnostics, marked with PST in Fig. 1. The setup consists mainly of four observation screens separated by FODO cells [3]. Together with the analysis based on tomographic reconstruction, the module will be used as a standard measurement technique downstream the beamline, complementary to the single slit scan used at PITZ. Opposed to the slit scan, the tomographic measurement is expected to facilitate measurements of a single micropulse per screen with improved signal-to-noise ratio. Therefore, the method is less sensitive to fluctuations within a macropulse and gives the possibility to evaluate shot-to-shot beam and machine instabilities. Measurements of the two transverse planes simultaneously are attainable provided that both of them are well matched to the optics of the FODO lattice so that the phase advances from screen to screen are 45°. The major challenge to be able to perform a tomographic reconstruction is the significant impact of the space-charge forces related to the small emittances, high bunch charges and moderate beam energies PITZ operates with.

This work presents the initial experience with the tomography module and results for different bunch charges. Some of the results are compared to ones obtained upstream using slit scan technique at EMSY1. For all the measurements the phases of the gun and the booster are adjusted for maximum mean momentum gain and the temporal laser profile is a flat top with FWHM of ∼22 ps and rise/fall times of ∼2 ps.

PRECONDITIONS FOR TOMOGRAPHIC MEASUREMENTS

The input data used for the reconstruction of the (x, x', y, y') phase space are projections of the spatial (x, y) distribution on each of the four screens and the transport matrices defined by the FODO lattice. A requirement for a successful reconstruction with minimized artifacts is the equidistant angular spacing between the locations where projections are taken. The setup requires a phase advance of 45° between the screens for the two trans-

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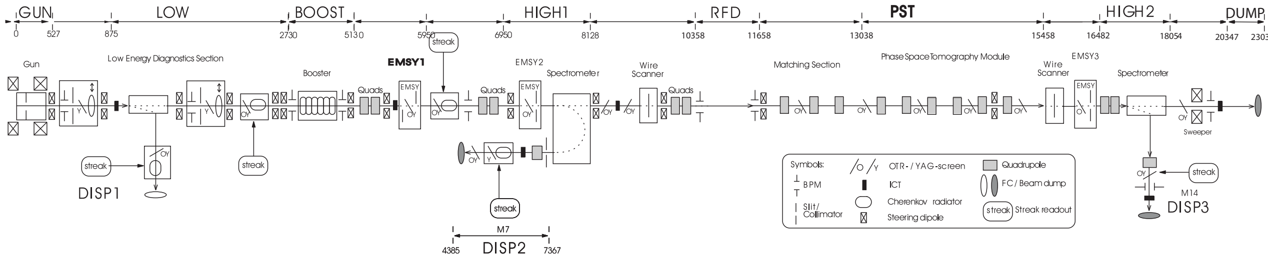
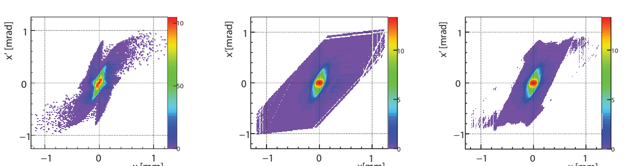


Figure 1: PITZ setup in the run period 2010/2011 - major components being the gun and booster cavities, low- and high-energy spectrometer dipoles, emittance measurement systems EMSY and a module for tomographic diagnostics PST.

verse planes, and, therefore, Twiss parameters fixed on the screens. As in general the actual beam Twiss parameters are different from the design ones, an upstream matching section of up to nine quadrupole magnets is provided in order to adjust them on the first screen. Due to machine considerations seven matching quadrupoles were involved in the matching in the 2010/2011 run period.

The beam envelope matching is based on the measured beam sizes on the four screens along the tomography module. Knowing the transport between any two screens, a multiscreen approach is used to obtain a reasonable estimation of the emittance and the Twiss parameters on the first screen and the emittance increase from the position of EMSY1 downstream along the matching section.

The Maximum ENTropy (MENT) [4] algorithm was chosen as a more accurate reconstruction technique given the limited number of projections as compared to a number of others tested [5]. MENT outlines areas of the underlying phase-space density distribution having different probability to be occupied by charge. This is shown in Fig. 2 where an original distribution with 1 nC bunch charge, numerically tracked with ASTRA [6] from the gun down to the last screen of the tomography module, is reconstructed using MENT. The colour scheme in the original distribu-



(a) Original phantom distribution, $\varepsilon_x = 1.17\,\mathrm{mm.mrad}$.

(b) Reconstruction result using MENT, $\varepsilon_x = 1.21\,\mathrm{mm.mrad}$.

(c) 0.1% of the integrated intensity from the MENT reconstruction is removed, $\varepsilon_x = 1.19\,\mathrm{mm.mrad}$.

Figure 2: Simulated original and reconstructed transverse distributions on the first screen of the tomography module. Excluding 0.1% of the integrated intensity does not lead to a significant underestimation of the emittance.

tion in Fig. 2(a) represents the number of particles per bin whereas in the reconstruction result in Fig. 2(b) it corresponds to the probability to have particles in that range of the phase space. The weight in the rim of Fig. 2(b) increases further if more rotations of the beam in the phase space are used [7]. The contribution of this rim to the emittance is negligible as shown in Fig. 2(c) where 0.1% of the integrated intensity from the reconstruction result is removed corresponding to about 1 pC equivalent charge. The decrease in emittance is 2% with respect to the initial reconstruction while the visual representation improves. For the reconstructions shown in the following 0.1% of the integrated intensity is cut out.

MEASUREMENTS AT NOMINAL CHARGE OF 1 nC

Emittance Evolution along the Beamline

To verify the validity of the tomography technique the transverse phase space was measured for a bunch charge of 1 nC at the locations of EMSY1 ($z = 5.74$ m from the cathode), on the first screen of the tomography module ($z = 13.038$ m) and behind it on the station denoted with EMSY3 in Fig. 1 ($z = 16.303$ m). The rms spot size of the laser on the photo-cathode was chosen to be 0.4 mm - bigger than the one for which the emittance minimum at the location of EMSY1 was experimentally obtained [8], so that the difficulties related to the influence of space-charge forces during the matching are expected to be smaller. The beam momentum was 24.66 MeV/c. A particular feature of the beam in the discussed run period was asymmetry of the transverse distribution, stronger pronounced with the distance from the cathode as it can be seen in Fig. 3 where the transverse beam profile is shown at the location of EMSY1, the observation screen of EMSY1 and on EMSY3. Quadrupole magnets were not used when measurements with EMSY1 or EMSY3 were performed. The reasons for such asymmetry are still examined with a likely explanation being machine imperfections.

Figure 4 shows the phase-space distributions for the two transverse planes obtained with slit scans (top), corresponding to the beam profiles from Fig. 3(a) and 3(b), and with tomographic reconstruction (bottom). The main solenoid current of 390 A corresponds to 1 A higher current than the one with which minimum emittance on EMSY1 was obtained. The small tails visible already on EMSY1

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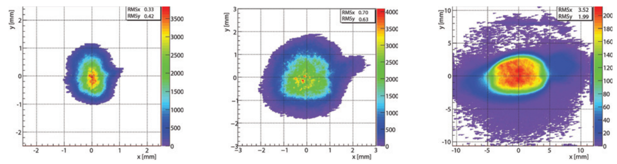
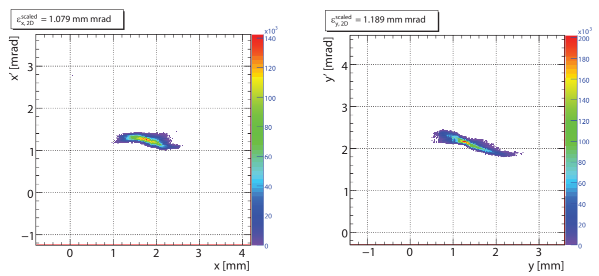
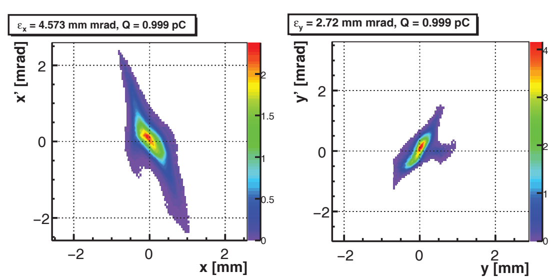


(a) $z = 5.74$ m, EMSY1, $\sigma_x/\sigma_y = 0.79$. (b) $z = 8.387$ m, beamlets observation screen for EMSY1, $\sigma_x/\sigma_y = 1.26$. (c) $z = 16.303$ m, EMSY3, $\sigma_x/\sigma_y = 1.77$.

Figure 3: Transverse beam profiles evolution along the beamline. The satellites in the horizontal plane were stronger pronounced downstream.



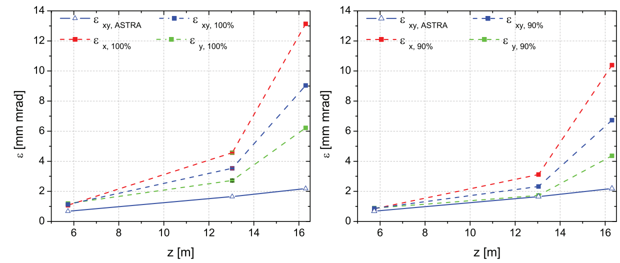
(a) Horizontal distribution on EMSY1. (b) Vertical distribution on EMSY1.



(c) Reconstruction of the horizontal plane. (d) Reconstruction of the vertical plane.

Figure 4: Phase-space distributions at EMSY1 (top) and on the first screen of the tomography module (bottom) for 1 nC, beam momentum of 24.66 MeV/c, laser spot size of 0.4 mm, main solenoid current of 390 A. The horizontal axis on EMSY1 data is with respect to the position of the beamlet on the observation screen.

develop downstream and their contribution to the overall emittance becomes significant in terms of rms values as on the first screen of the tomography module the tails of the distributions are well pronounced. Figure 5 shows the summarized results, together with the numerical predictions for the same photo-injector setup as used in the measurements, for 100% and 90% of the integrated reconstructed intensity. The measurement results for 90% of the beam intensity for the vertical plane correspond to the ASTRA simulations until the tomography setup. The asymmetry of the profiles could not be included in the ASTRA simulations. The error bars on the results from the tomographic measurement represent the statistical deviation from the analysis of 20 consecutive macropulses on each of the four screens as each



(a) Emittance evolution for 100% of the reconstructed intensity. (b) Emittance evolution for 90% of the reconstructed intensity.

Figure 5: Measured (dashed) and simulated (solid curve) emittance evolution for the injector setup as for Fig. 4. The emittance values calculated from the simulated ASTRA data take into account the full 100% distributions. The measured vertical emittance at EMSY3 is underestimated due to technical problems.

macropulse contains a single bunch which delivers intensity sufficient to use the full dynamic range of the grabbing cameras. There are no statistical measurements for EMSY1 and EMSY3 and the slit data were taken with 7/15 pulses on EMSY1 and 2/11 pulses on EMSY3 for the horizontal/vertical planes respectively. The emittance values from the slit scans are calculated as in [8], whereas the tomographic method uses the reconstructed 2D distribution.

Emittance Dependence on the Laser Spot Size

The transverse phase space was measured as a function of the laser spot size on the photo-cathode in order to estimate the effect of the laser transverse size on the emittance. The results from the measurements, together with the expectations from particle tracking with ASTRA, are summarized in Fig. 6. Each point corresponds to the solenoid current delivering optimum emittance at EMSY1 as obtained using slit scans. The beam momentum was in the range 24.6-25.2 MeV/c. Considering the 90% emittance the simulations correctly predict the trend of the dependence. More details on the results from the slit scans can be found in [8]. Measurements for bigger laser spot sizes were not performed due to inhomogeneous emission from the photo-cathode.

MEASUREMENTS FOR BUNCH CHARGE OF 100 pC

The transverse phase space was measured also for a bunch charge of 100 pC. The transverse laser profile on the photo-cathode was kept fixed with an rms spot size of 0.125 mm and the solenoid current was varied. The beam momentum was 24.76 MeV/c. The results for 100% and 90% of the reconstructed intensity are summarized in Fig. 7. Phase-space distributions for the horizontal plane for 100% of the reconstructed density for the smallest and

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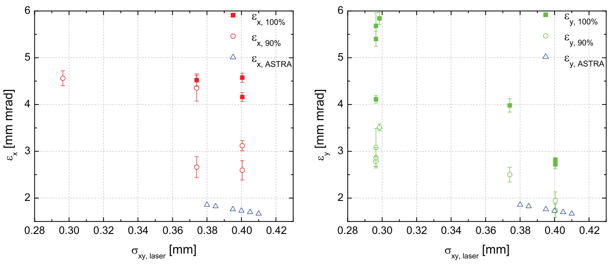


(a) Horizontal emittances. (b) Vertical emittances.

Figure 6: Measured and simulated emittances on the first screen of the tomography module as a function of the transverse laser spot size. The emittance value for 100% of the integrated intensity for laser spot size of 0.3 mm is not included in the plot for the horizontal plane due to a big mismatch.

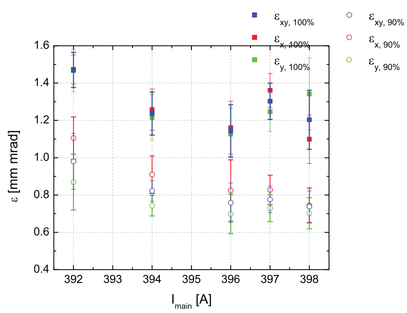
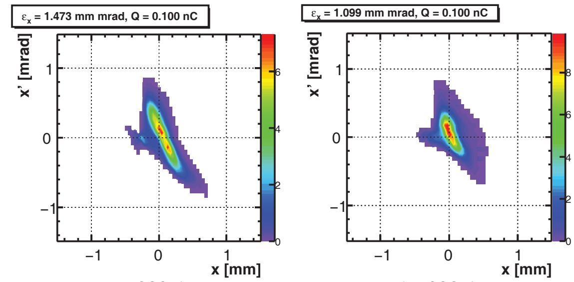


Figure 7: Measured horizontal (red), vertical (green) and geometrical emittances (in blue) for 100% and 90% of the equivalent charge density. The error bars correspond to statistical fluctuations within 20 machine shots.

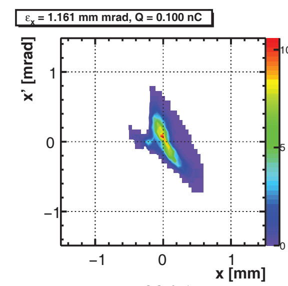
the biggest solenoid currents and the current delivering smallest emittance on EMSY1 are given in Fig. 8. The tails on the beam distributions were observed also for this case.

CONCLUSIONS

A module for phase-space tomographic diagnostics was successfully installed and commissioned at PITZ. First measurements were done revealing particular features of the phase-space distributions downstream the beamline. Those features could not be seen on the slit scan results directly behind the booster cavity with good resolution but nevertheless they were expected due to the structure of the transverse spatial beam distribution. The emittance calculated from the tomographic reconstruction was shown to fall between the emittances obtained in front of the module and behind it where slit scans were used. The advantages of the method to measure the two transverse planes simultaneously for short pulse trains and improved resolution for low charges were experimentally confirmed.



(a) 392 A. (b) 398 A.



(c) 396 A.

Figure 8: Reconstruction of the horizontal plane for 100 pC bunch charge. The distribution at the bottom for 396 A corresponds to minimum emittance measured at EMSY1.

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