IMPLEMENTATION OF TOMOGRAPHIC DIAGNOSTICS AT PITZ

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Abstract

The Photo-Injector Test Facility at DESY, location Zeuthen, PITZ, develops electron sources capable of driving short wavelength FELs like FLASH and the European XFEL. The characterization of the source is mainly based on detailed measurements of the transverse phase space at the injector exit. Complementing the standard single slit scan technique, a module for tomographic diagnostics has been used as an additional device in the 2010/2011 run period, extending the possibilities of PITZ. The module allows measurements of the two transverse planes simultaneously with improved resolution for short pulse trains or even of individual bunches. The major difficulties towards the usage of the module are the conditions PITZ operates with - energies of only about 25 MeV, transverse emittance below 1 mm·mrad for a nominal charge of 1 nC, and thus, strong impact of the space-charge forces.

This work presents the first systematic studies done with the module. The measurement procedure is discussed together with experimental results.

INTRODUCTION

Measurements of the transverse phase space have an indispensable importance for FELs operating in high peak brilliance short wavelength regime. The European XFEL requires transverse emittance of 1.4 mm·mrad for bunch charge of 1 nC in front of the undulator which corresponds to 0.9 mm·mrad at the injector exit [1]. To characterize the electron sources capable to produce electron beams with such emittances, the European XFEL makes use of the Photo-Injector Test facility at DESY, location Zeuthen, PITZ. PITZ, schematically shown in Fig. 1, uses a normal conducting 1.6-cell L-band gun cavity as electrons are produced via photoeffect from a $\mathrm{Cs_2Te}$ cathode. The momentum after the gun is about 6.7 MeV/c and a booster cavity is used to increase the beam momentum up to about 25 MeV/c. Two solenoid magnets around the gun - main and bucking, are used to focus the beam at the entrance of the booster and to cancel remnant magnetic fields at the cathode plane. Measurements of the longitudinal properties of the electron bunches are performed in dispersive sections behind both of the accelerating cavities.

Until the 2010/2011 run period the measurements of the transverse phase space at PITZ were done mainly with a dedicated station directly behind the booster - EMSY1 in Fig. 1, deploying a single slit scan technique. A module for tomographic diagnostics and its preceeding matching section were recently installed [2, 3]. The module makes use of four observation screens, separated by FODO cells, as quadrupole magnets in the cells are used to rotate the beam in the transverse phase spaces and, thus, obtain projections under different equidistant viewing angles needed for a tomographic reconstruction. The rotations should be symmetric in the two transverse planes if the two of them are to be reconstructed simultaneously.

TOMOGRAPHIC MEASUREMENTS AT PITZ

The major obstacle for the tomographic measurements is the influence of space-charge forces associated with the small transverse emittance, the moderate beam energies and high charges. In the 2010/2011 run period PITZ has measured transverse projected normalized emittance smaller than 1 mm·mrad for bunch charges of 1 nC and the above mentioned momentum [4]. Consequently, according to the equation for laminarity of the beam[1] [2]

$$\Lambda_x = \frac{K}{2\varepsilon_x^2}\frac{X^3}{X+Y}, \tag{1}$$

where K is the generalized perveance[2], ε_x is the horizontal geometric emittance, X and Y - the horizontal and vertical envelopes, the beam dynamics is space-charge dominated for characteristic beam spot size of about 0.35 mm measured directly behind the booster. The space-charge term is about 3.5 times bigger than the emittance one ($\Lambda_x^{-1} = 3.5$). The tomographic measurement is based on a valid transport between the position of reconstruction - the first screen along the FODO lattice, and the positions where projections are taken - all four screens, and under the influence of space charge the transport matrices cannot be described in a straightforward manner. Therefore, the weight of the space-charge term needs to be decreased early upstream the

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[1] similar equation can be written by analogy for the vertical plane

[2] $K = \frac{2I_{peak}}{I_0(\beta\gamma)^3}$ for I_{peak} being the peak current, I_0 - the characteristic Alfven current, β and γ - the relative velocity and reduced energy.

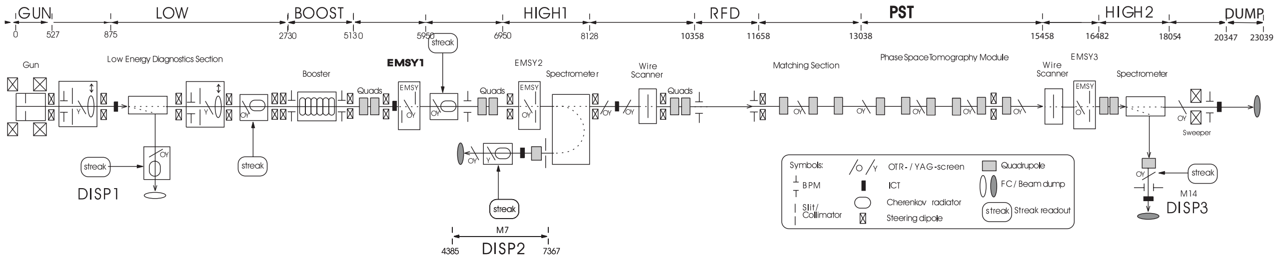


Figure 1: PITZ setup with installed matching section and a module for tomographic diagnostics.

beamline. For that purpose and in order to match the beam envelope parameters to the design optics of the FODO lattice, PITZ has installed a dedicated matching section equipped with quadrupole magnets. In general up to nine quadrupoles can be used but in the run period discussed the first two were excluded. With appropriate focusing strength of the matching magnets and the same beam parameters as above, using Eq. (1) it can be shown that along the tomography module the space charge and the emittance are in equilibrium and linear transport can be used for the reconstruction procedure ($\Lambda_x^{-1} \ll 1$).

As a first step of the matching MAD [5] is used. The input beam Twiss parameters are calculated from the phase-space distributions measured at the location of the first slit-scan station EMSY1 - about 7.3 m upstream the tomography module. MAD does not take into account the influence of the space charge and the emittance dilution along the matching section cannot be predicted. On the contrary, the transverse emittance can increase significantly along the matching section when the photo-injector is set to deliver optimized emittance [2, 6]. Therefore, the quadrupole gradients need to be optimized in an iterative procedure as on each iteration the beam sizes are measured on the four observation screens and the transverse emittance is calculated using multi-screen technique [2] in order to reach the design Twiss $\alpha_{x,y}$ and $\beta_{x,y}$. Figure 2 shows the evolution of the β-functions as in a typical matching.

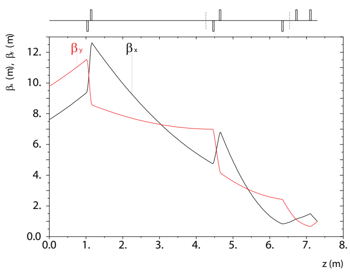
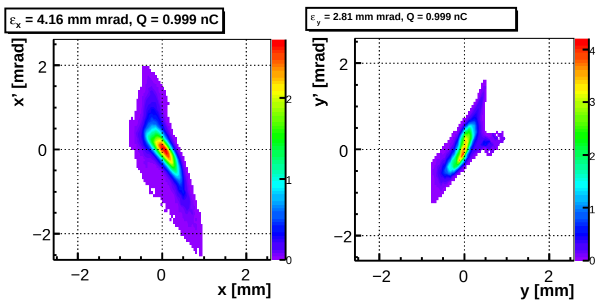


Figure 2: Typical evolution of the Twiss β-function along the matching section until the first screen of the tomography module. The *z*-axis is with respect to the starting position of the matching - EMSY1 from Fig. 1.

The tomographic reconstruction runs on the data from the last iteration with MENT [7] being the favoured algorithm [2].

MEASUREMENTS FOR NOMINAL BEAM PARAMETERS

Major part of the optimization and characterization of the source at PITZ is done for bunch charge of 1 nC and maximum achievable beam energy. A set of tomographic measurements were performed for such conditions together with slit scans at locations surrounding the tomography module - EMSY1 $(\mathrm{z} = 5.74\ \mathrm{m}$ from the cathode$)$ and EMSY3 $(\mathrm{z} = 16.606\ \mathrm{m})$. The reconstruction of the phase space takes place on the first screen of the module $(\mathrm{z} = 13.038\ \mathrm{m})$. A particular measurement is shown in Fig. 3. The current of the main solenoid, which is a crucial



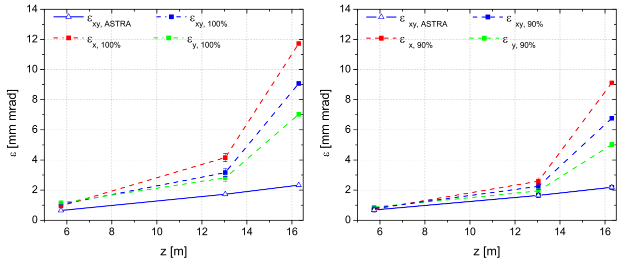
(a) Horizontal plane.

(b) Vertical plane.

Figure 3: Reconstructed phase-space distributions corresponding to current of the main solenoid for which minimum emittance on EMSY1 was measured.

parameter in the photo-injector optimization, corresponds to the one which delivers minimal transverse emittance on EMSY1 station. A remark that deserves to be noticed here is the opposite orientation of the two phase spaces - from Fig. 2 it can be seen that if at the entrance of the FODO lattice the beam is converging in the horizontal plane it is diverging in the vertical and, therefore, the reconstructed distributions should be nearly orthogonal.

The peculiar tails of the distributions develop further as the beam propagates downstream leading to a significant increase of the emittance as this is shown in Fig. 4 where the emittances obtained with the tomographic reconstruction are combined with the results from the slit scans. The measurements with single slits were done without having active quadrupole magnets. The solid blue line shows a numerical simulation with ASTRA [8] for adapted machine settings. The emittance, calculated from 90% of the inte-



(a) Evolution for 100% beam intensity.

(b) Evolution for 90% beam intensity.

Figure 4: Measured (dashed) and simulated (solid) emittance evolution for fixed laser transverse size and final beam momentum of 24.67 MeV/c. The emittance values calculated from the simulated ASTRA data take into account the full 100% distributions. The vertical emittance at EMSY3 is underestimated due to technical problems.

grated beam intensity reveals the strong contributions the tails have.

The data from this example is taken with a single pulse from the pulse train with good signal quality which proves the capability of the tomographic technique to measure individual pulses. For statistical purposes 20 consequent shots were taken from each screen as a combination of four images - one from each screen, was used for reconstruction.

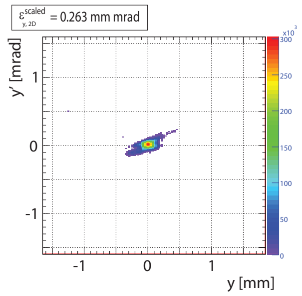
MEASUREMENTS FOR LOWER CHARGES

To confirm the capability to measure short pulse trains and verify the reconstruction, the transverse phase space was measured also for charges of 250 pC and 100 pC. Figure 5 shows the reconstruction of the vertical phase space for 250 pC bunch charge done at the location of EMSY1 and the first screen of the tomography module. As above, the main solenoid current corresponds to minimum emittance, measured at EMSY1. In both cases specific bifurcation of the phase space is revealed, demonstrating the reconstruction agrees well with the slit scan result in terms of features of the phase space. The tomographic measurement is shown also with 10% cut on the integrated intensity - Fig. 5(c), in order to emphasize the weight of the tails developing already at EMSY1 - about 35% of the emittance results from them.

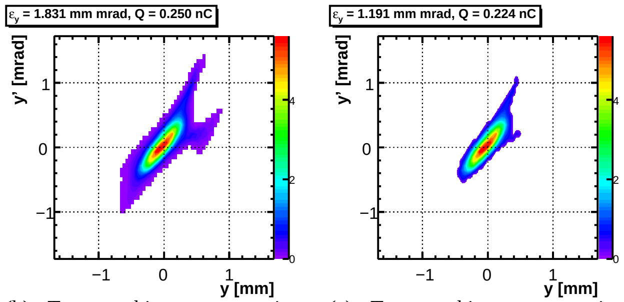
The data for the tomographic reconstruction uses two pulses per screen station while for the slit scan 14 pulses were necessary.

SUMMARY

The PITZ tomography module has been successfully installed and commissioned. The first measurements have shown the results are consistent with results from slit scans done on locations along the beamline surrounding the module. It has been shown that even though space-charge forces



(a) EMSY1 reconstruction.



(b) Tomographic reconstruction with 0.1% intensity cut.

(c) Tomographic reconstruction with 10% intensity cut.

Figure 5: Vertical phase space measured at EMSY1 (top) and on the first screen of the tomography module (bottom). 10% of the reconstructed integrated intensity is taken away for the distribution shown in Fig.5(c) resulting in 35% decrease of emittance.

are an issue along the matching section they can be dealt with and the two transverse planes can be reconstructed independently. Experimentally it was proven that measurements of single pulse from the pulse train are feasible.

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