PHASE SPACE MEASUREMENTS WITH TOMOGRAPHIC RECONSTRUCTION AT PITZ

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Abstract

The major objectives of the Photo-Injector Test Facility at DESY in Zeuthen, PITZ, are research and development of high brightness electron sources suitable to drive FELs like FLASH and the European XFEL. In the 2008/2009 run period the facility has been operated with a new photocathode laser system and a dry-ice cleaned RF gun cavity. Characterization of the transverse phase space of the electron source has been performed in details using a single slit scan technique with a dedicated Emittance Measurement System. In preparation for the forthcoming run, a number of quadrupole magnets have been installed and tomographic reconstruction with data from quadrupole scans with two magnets has been carried out in a semi-parallel manner to the slit scans.

This contribution summarizes the experience from the phase-space tomographic reconstruction with nominal beam conditions. Advantages and drawbacks of the measurement procedure and the analysis are discussed. The results are compared to the ones obtained with the slit scans.

INTRODUCTION

The PITZ facility is a photo-injector test stand, dedicated to the optimization of electron sources suitable to drive high peak brilliance short wavelength FELs. In the run period 2008/2009 PITZ has been operated with a newly installed Yb:YAG photocathode laser system and a dry-ice cleaned 1.6 cell RF gun cavity. The mean momentum after the gun has been about 6.5 MeV/c and a normal conducting TESLA type booster cavity has been used to accelerate the electron beam to energies of about 14 MeV. The longitudinal phase space can be measured after each of the two cavities. The characterization of the transverse phase space is done after final energy has been reached. The general PITZ setup used in the 2008/2009 period is described in details in [1].

Studies of the transverse phase-space density distribution have the highest priority at PITZ. Therefore there are a number of dedicated emittance measurement systems - EMSYs, along the beamline. An EMSY comprises horizontal and vertical actuators with slits, employing the so called slit scan technique [2]. Two major advantages of the slit scan are the possibility to obtain phase-space portraits and the eligibility of linear transport for an emittance dominated beamlet between the slit position and the beamlet observation screen. On the other side, the two orthogonal transverse planes cannot be resolved simultaneously. Moreover, the measurements are sensitive to the signal to noise ratio, wherefrom low charges require long bunch trains which are prone to machine instabilities. Measurements from the last run period presented in [3] show the effects of such instabilities.

In the current shutdown a new module for transverse phase-space tomographic diagnostics has been installed downstream the first two EMSY stations usually used in measurements until now - see Fig. 1. It consists mainly of four screen stations as each two of them surround a FODO cell [4]. As measurements with this setup require the beam envelope trajectory being matched to the optics of the FODO lattice, there is a set of quadrupole magnets upstream used to deliver the needed Twiss functions at the entrance.

Compared to the slit scan, the tomographic reconstruction with such a setup gives the possibility to measure the density distributions for the two transverse planes simultaneously, provided that both of them are well matched. The strong focusing facilitates improved signal quality and, therefore, low bunch charge measurements. The expected major impact in such a case have fluctuations between pulses in different pulse trains rather than fluctuations within a single macro-pulse. The nominal bunch charge PITZ is operating with is 1 nC for beam momenta below 30 MeV/c. Assuming maximum momentum, normalized transverse emittance below 1 mm mrad and a peak current of about 50 A, the beam dynamics is dominated by space-charge forces and the matching for such conditions is challenging. The conditions proved not to be easier for low charges when the beam parameters are optimized for minimum emittance at the injector exit, where the beam has reached final energy [5]. Assuming the Twiss parameters are matched at the entrance of the FODO lattice, the emittance and space charge are closer to equilibrium inside the tomography module. Except the hard but needed good matching, another drawback of the measurement procedure

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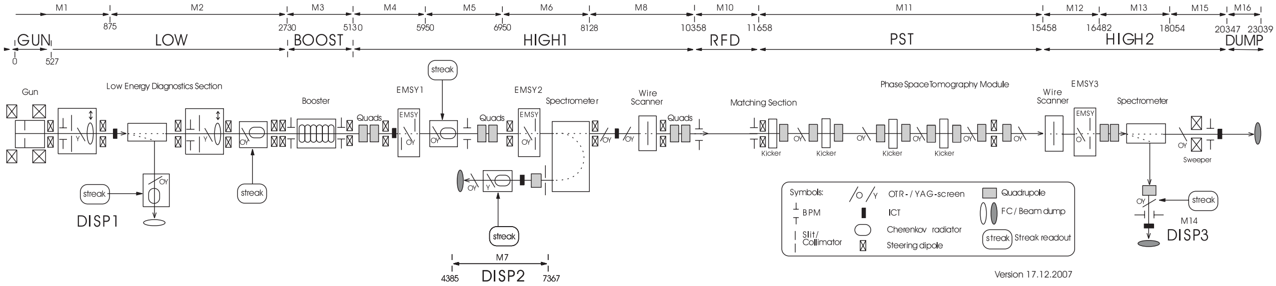


Figure 1: PITZ setup upgraded with the tomography section. In the run period 2008/2009 the last module of the diagnostics setup has been the C-band dipole magnet.

is the requirement for valid linear transport between the position of reconstruction and the observation screens.

The first six quadrupole magnets shown in Fig. 1 have already been installed for the 2008/2009 run. This contribution presents methodical measurements of the transverse phase space using only a pair of them and the tomographic reconstruction technique. As in the single slit, the two transverse planes cannot be measured simultaneously because only one quadrupole is being scanned. Beforehand the setup and simulations are presented.

The algorithm selected for the reconstruction is Maximum Entropy as it has proven to be superior over a number of others tested [6].

METHODICAL SIMULATIONS OF DOUBLE QUADRUPOLE SCAN RECONSTRUCTION

For the sake of consistence the phase-space reconstruction is needed to be done at the same location where emittance is measured experimentally - EMSY1. However, in the upgraded PITZ beamline, the quadrupole magnets are positioned so that the first magnet behind the booster cavity and a second one behind the EMSY1 station have to be used. In Fig. 1, those are the first and the third magnets along the beamline. Therefore, the reconstruction is done about 10 cm in front of the first quadrupole, where no electro-magnetic fields are present, and the resulting distribution is then linearly transported through a drift space to the EMSY1 position.

The first magnet is scanned in order to rotate the beam in the phase space being measured, while the second magnet is kept fixed so that the phase advance for the non-scanned plane stays nearly constant and a beam waist is avoided to counteract strong space-charge forces. Its focusing strength has to be sufficient so that defocusing introduced by the first magnet is minimized.

The observation screen is chosen according to the bunch charge and energy. It has to be far enough to resolve the beam divergence and at the same time close enough to minimize space-charge effects. The screen position also defines the range of rotations of the beam in the phase space as the tomographic theory requires infinitesimally small angular steps over full π between the observation and reconstruction positions. As an example to study the method, simulations with ASTRA [7] for 14.8 MeV/c beam momentum and 500 pC bunch charge show that a drift space of about 1.7 m between the scanning quadrupole and the observation screen is needed and this distance scales with energy and charge. The phase advance and the spot sizes for the two transverse planes as a function of the applied current of the scanning quadrupole are shown in Fig. 2. The step, with which the current of the scanning quadrupole is changed, is chosen so that it is feasible in practice. Due to the resolution of the optical system the spot size should not be smaller than about 40μm, wherefrom phase advances below 10° for the scanned plane are practically not realistic. Fig. 3(a) shows the original distribution as from simulations and Fig. 3(b) is the resulting reconstruction using all the available projections from Fig. 2 for which $\sigma_y > 0.04$ mm and which cover almost the full $(0, \pi)$ region.

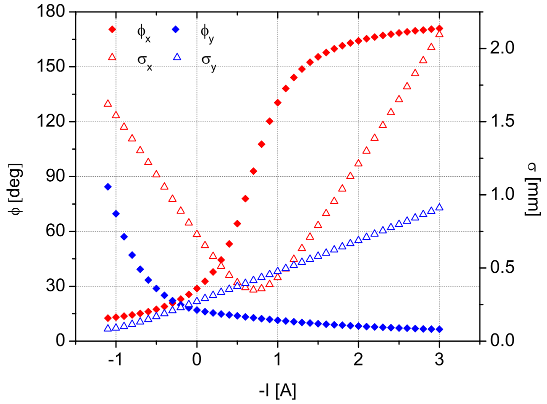
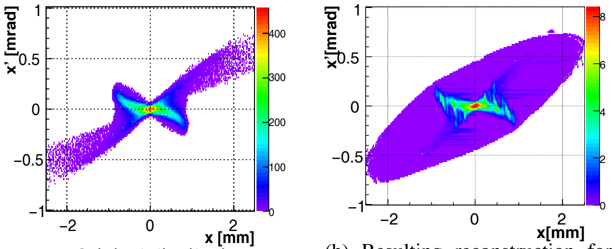


Figure 2: Simulated phase advances and spot sizes versus quadrupole current.

The emittance of the reconstructed distribution shows an overestimation of 0.3%. The smearing artefacts in the tails of the distribution are introduced by the usage of projections for which the phase advance for the non-scanned plane is not in the flat region in Fig. 2. In Fig. 4 only pro-

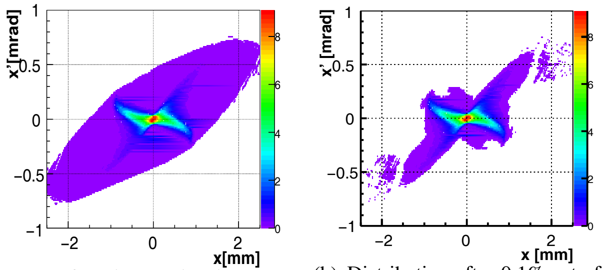


(a) Original distribution.

(b) Resulting reconstruction for rotations $\phi_x = [13^\circ, 170^\circ]$.

Figure 3: Simulated original and reconstructed transverse distributions.

jections for which the vertical phase advance is below 20° are used. The resulting area of the phase space is underestimated with 9% while, at the same time, artefacts in the quality of the reconstruction are decreased. The intensity of the low density halo in terms of total intensity is below 0.1% of the maximum one with which the emittance is underestimated with 10%. The corresponding area after such an intensity cut is shown in Fig. 4(b). Such a cut does not discard those histogram bins whose content is below the mentioned 0.1% of the maximum intensity. Instead, the overall intensity is reduced as a constituent of the same fraction is subtracted from each bin, i.e. a layer of thickness proportional to the amplitude of any bin of the 3D distribution is peeled off.



(a) Artefacts in the tails disappear and the emittance value is underestimated by 9%.

(b) Distribution after 0.1% cut of the maximum intensity.

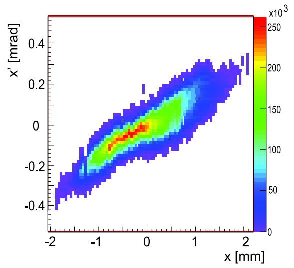
Figure 4: Reconstruction using only those projections for which the vertical phase advance varies slightly. The horizontal phase advance is in the range 25 - 167°.

MEASUREMENTS

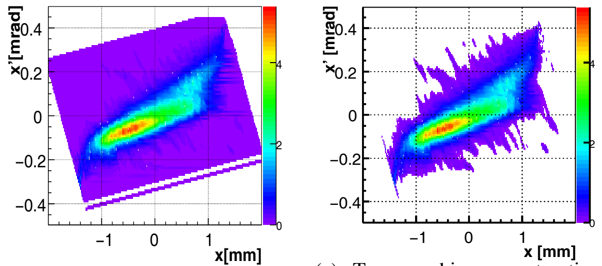
The nominal temporal laser pulse shape PITZ operates with is flat top. The measurements presented here have been done for 23 ps FWHM and 2.3 ps rise and fall times. The transverse laser profile is uniform with corresponding initial pulse rms spot size $\sigma_{\mathrm{xy}} = 0.44\,\mathrm{mm}$. This is bigger than the one for which minimum emittance at the injector exit has been obtained as presented in [3]. As in the standard measurement procedure a solenoid scan around the beam focus has been done. A slit scan and a quadrupole scan have been performed for the different solenoid magnetic fields. The bunch charge is 1 nC with a final momentum of 14.7 MeV/c.

The slit scans have been done with an average of 35 bunches in the pulse train to obtain high quality signal, while for the quadrupole scan a single bunch has been used. The camera settings have been kept the same in both cases. The observation screen for the quadrupole scan is about 3.2 m downstream the position of reconstruction in front of the first quadrupole and about 1.7 m behind the second quadrupole used.

Fig. 5(a) shows the transverse trace-space distribution for the minimum emittance obtained with the slit scan technique during the solenoid scan. The value calculated with the slit scan data is 1.07 mm mrad. The corresponding tomographic reconstruction using 15 horizontal projections of the spatial (x, y) distribution is given in Fig. 5(b). Here the resulting emittance is 1.33 mm mrad. The wide low intensity area shows the maximum range where charge is expected to be found. Considered as charge, its contribution to the total area is very low as this can be seen in Fig. 5(c). Here intensity equivalent to only 5 pC of the total charge has been removed resulting in normalized horizontal emittance of 1.3 mm mrad. If the equivalent of about 50 pC is taken away, the emittance is decreased to 1.06 mm mrad or nearly the same as from the slit scan. The corresponding density distribution is shown in Fig. 6.



(a) Single slit scan result, $\varepsilon_{\mathrm{x}} = 1.07\ \mathrm{mm\ mrad}$.



(b) Tomographic reconstruction result, $\varepsilon_{\mathrm{x}} = 1.33\ \mathrm{mm\ mrad}$.

(c) Tomographic reconstruction result with 0.5% intensity cut, $\varepsilon_{\mathrm{x}} = 1.3\ \mathrm{mm\ mrad}$.

Figure 5: Horizontal trace spaces. The distributions are reconstructed with data from single slit and double quadrupole scans.

Comparing the slit scan result and the last figure, one could conclude both methods agree fairly well on the fea-

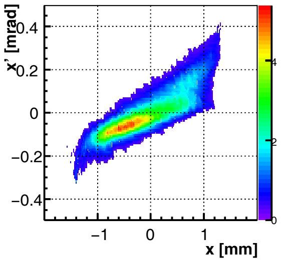
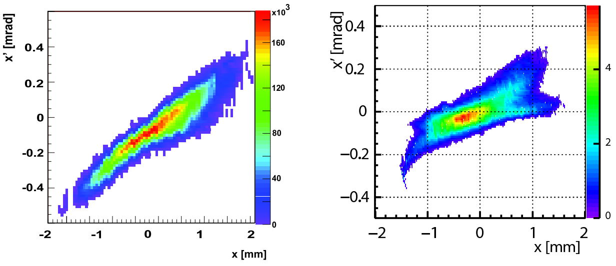


Figure 6: Reconstruction result after 5% intensity cut. The emittance is about the same as from the single slit scan.

tures of the dense non-symmetric core enclosed within the green area. Similar non-symmetric elongated tails are present in both results as well. The reason for the discrepancy in the values of the emittance in the original reconstruction can be explained with machine imperfections at the time those measurements have been taken. The transverse laser spot on the cathode has been measured to have inhomogeneous distribution, leading to off-axis center of gravity and possible different focusing conditions for particles far off. The steering along the beamline also acts in a different manner to such different clouds of particles. At the same time the density of those off-center particles might be sparse enough so that the slit scan is not able to distinguish them from noise as this is seen in Fig.5(c). The reconstruction algorithm would discard such clouds of low intensity if they are not representative for each of the used quadrupole focusing conditions. Otherwise, they will lead to smearing artefacts and overestimation of the phase-space area.

The possibility that different parts of the beam follow different focusing conditions can be seen also in reconstructions away from the optimized solenoid for which the slit scan shows almost no low-density tails in the phase-space distribution like the ones shown in Fig. 7(a). In this case the focusing effect of the quadrupole magnets shows clearly a diluted X-shape beam even when the 5% intensity cut is applied - Fig. 7(b). The quadrupole scan delivers emittance of 1.09 mm mrad which is in agreement with the emittance from the slit scan, despite that part of the charge is not present.



(a) Slit scan result.

(b) Tomographic reconstruction result with 0.5% intensity cut.

Figure 7: Horizontal trace spaces for an overfocused beam.

SUMMARY AND OUTLOOK

The presented work summarizes the experience obtained in order to study the possibility for tomographic reconstruction using a pair of quadrupole magnets. Basic measurement requirements have been derived from simulations and data have been taken to verify the image processing and reconstruction algorithm. Despite the inhomogeneous transverse laser spot on the photocathode, present during the data taking, the comparison between the slit and the quadrupole scan delivered understandable results. Such measurements can be done more regularly after the dedicated tomography module is in operation so that results from different techniques can be cross-checked.

REFERENCES

[1] G. Asova et al., “Status of the Photo-Injector Test Facility at DESY, Zeuthen site”, proceedings IPAC 2010, Kyoto, Japan

[2] L. Staykov, “Characterization of the transverse phase space at the Photo-Injector Test Facility in DESY, Zeuthen site”, PhD thesis, Universität Hamburg, 2008

[3] S. Rimjaem et al., “Measurements of transverse projected emittance for different bunch charges at PITZ”, these proceedings

[4] G. Asova et al., “Design considerations for phase space tomography diagnostics at the PITZ facility”, proceedings DIPAC 2007, Mestre, Italy

[5] J. Saisut et al., “Low charge simulations for phase space tomography diagnostics at the PITZ facility”, these proceedings

[6] G. Asova et al., “Tomographic reconstruction of a beam phase space from limited projection data”, proceedings ICAP2009, San Francisco, USA

[7] K. Flöttmann, http://www.desy.de/˜mpyflo/