METHODICAL STUDIES FOR TOMOGRAPHIC RECONSTRUCTION AS A NOVEL METHOD FOR EMITTANCE MEASUREMENTS AT THE PITZ FACILITY

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Abstract

The Photo-Injector Test Facility at DESY in Zeuthen, PITZ, is dedicated to the development of high brightness electron sources for linac-based FELs like FLASH and the European XFEL. A key parameter to judge on the beam quality for an FEL is the transverse phase space distribution, wherefrom the PITZ beamline is equipped with three Emittance Measurement Systems. In 2010 the diagnostics has been upgraded with a module for tomographic reconstruction comprising three FODO cells, each surrounded by two observation screens. The anticipated advantages of tomographic measurements are improved resolution for low charge beams and ability to evaluate both transverse planes simultaneously. Major operational challenges are the low beam energies the module will be used with - 15 - 30 MeV, strong space charge effects for high bunch charges and, consequently, difficulties to match the beam into the optics of the lattice.

This contribution presents studies on the performance of the module for different initial conditions as bunch charge and temporal laser pulse shape. Influence of residual noise on the quality of the reconstructed phase space is discussed.

INTRODUCTION

A major point for optimization of a photo-injector, capable to drive high brightness and short wavelength FELs, is the projected transverse emittance and, more generally, the transverse phase space. PITZ studies those using dedicated emittance measurement systems deploying the single slit scan technique. In the shutdown of 2010 a new module for transverse phase-space tomographic diagnostics has been added. Data with it is still to be taken. It consist mainly of three identical FODO cells, separated by observation screens [1]. The leading screen is the position where the transverse phase space density distributions are to be reconstructed. The cell length is rather short - 0.76 m, leading to an increased focusing strength of the quadrupoles within the FODO cells. Being a disadvantage for magnets with short effective length like the ones at PITZ, the strong gradients can facilitate low charge measurements in terms of improved quality of the measured signal data. Low charges are considered as an option to allow single spike lasing of an FEL [2]. Still, the numerical manipulation of data from a single low-charge pulse is challenging.

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This contribution presents simulation studies using ASTRA [3] on the performance of the tomography module for low bunch charges. Matching of the electron beam parameters to the optics of the FODO lattice is discussed for flat top and Gaussian shape of the initial temporal laser profile. These two cases represent different peculiar shapes of the transverse projections needed for the reconstruction and, therefore, require different matching conditions.

LOW CHARGE SIMULATIONS

According to the European XFEL requirements [4], the characterization of the electron source at PITZ aims to be done for laser pulses having a flat-top temporal profile with duration of 20 ps FWHM and rise/fall time of 2 ps. However, the laser system is capable to produce temporal profiles with variable pulse duration [5]. Here the cases of a flat-top pulse of a 20 ps FWHM and 2 ps rise/fall time and a Gaussian with $\sigma_\tau = 4.4$ ps, being the FLASH design value, are discussed for bunch charges of 20 and 100 pC. For each case the transverse beam emittance is optimized at the photo-injector exit, behind a booster cavity, where final energy is already reached. The optimization includes adjustment of the laser spot size onto the photo-cathode, phase of the gun cavity and the solenoid magnetic field. The peak accelerating field in the gun cavity is the PITZ working point of 60 MV/m and the booster gradient can be varied so that the electron beam reaches momenta in the range of 15 to 30 MeV/c. The transverse laser spot size is chosen so that it delivers projected emittance slightly bigger than the minimum possible one, but having slower increase towards the end of the beamline.

Multi-screen emittance calculations with a FODO lattice, simultaneously for the horizontal and the vertical transverse planes, require certain phase advance between the cells and, consequently, periodic particles' trajectories [6]. Since the geometry is fixed, one has to deliver the required beam parameters at its entrance. For PITZ the chosen phase advance is $\phi_{\mathrm{x,y}} = 45°$. The beam envelope matching is done with seven quadrupole magnets. As the study includes different beam momenta, the gradients of the last two magnets are kept fixed for any of these cases. They are chosen so that a cross of the Twiss β and α functions is ensured at about one FODO period before the entrance of the tomography module. At the same time these two magnets have strong influence on the Twiss α which is harder to adjust. According to simulations, a bunch originating from a Gaussian temporal profile is matched better if these two magnets have strong gradients, while for the flat top case they can also be relatively weak as compared to the first five.

For each of the cases below the matching includes a number of steps. An initial guess is made using hard-edge quadrupoles and excluding the otherwise present space-charge forces. This guess is then used in a second series of iterations where only the linear term of the space charge is taken into account and the quadrupole magnets are represented by their measured field maps. In this case the projected transverse emittance does not increase which is not true for the PITZ energy range. To correct for that, the final iterative steps are done including higher order terms of the particles' repulsion.

Flat-top Temporal Laser Profile

Figure 1 shows the Twiss β-functions along the tomography module for 20 and 100 pC bunch charges and beam momentum of 18.9 MeV/c. The mismatch[1] for the horizontal plane is bigger, resulting from the odd number of matching quadrupoles that cannot compensate simultaneously for the two transverse planes. Therefore, the transverse projected emittance also increases with a different slope. The corresponding mismatches from the design normalized phase space for the vertical plane are shown in Fig. 2(a) and Fig. 2(b). As expected, the higher charge is related to a stronger mismatch as the beam emittance is optimized. In general, the focusing strength along the FODO lattice might need additional adjustment in order to minimize the mismatch from screen to screen. Such is the case above for 20 pC and for a beam originating from a Gaussian temporal profile.

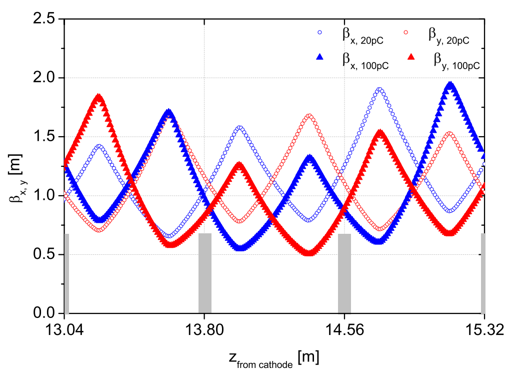
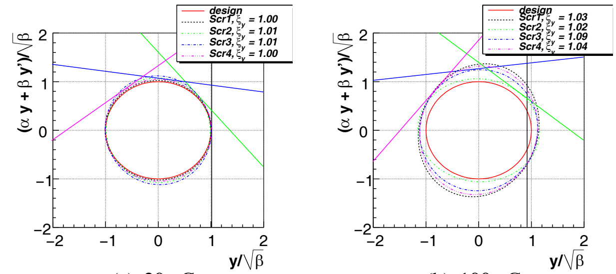


Figure 1: Twiss β-s along the FODO lattice for 20 and 100 pC. The grey rectangles represent the screen stations where the Twiss parameters should have the same values.

Gaussian Temporal Laser Profile

The β-functions for a Gaussian laser profile are shown in Fig. 3. Here the bunch charge is again 100 pC with slightly higher momentum of 20.6 MeV/c. The Twiss β-s are well matched onto the first screen but, despite the higher momentum, the mismatch increases along the lattice. In order to minimize it additional compensation is needed. The quadrupoles between the screens no longer form a strict FODO cell - the gradients are slightly different for a focusing and defocusing magnet.



(a) 20 pC. (b) 100 pC.

Figure 2: Normalized phase spaces for the vertical planes for 20 and 100 pC charges. ξ_i represents the mismatch on screen i with respect to the design phase space normalized to unity circle.

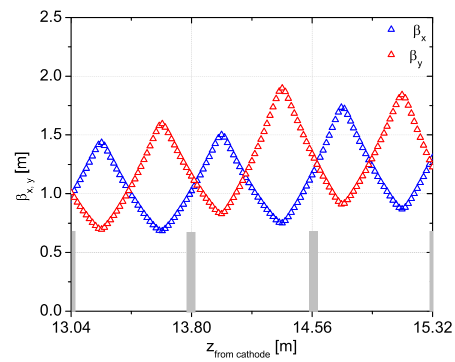


Figure 3: Twiss β-functions along the FODO lattice for 100 pC bunch charge and beam momentum of 20.6 MeV/c.

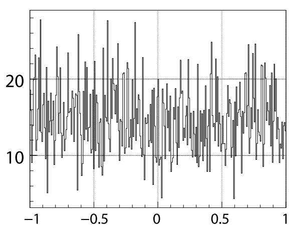
INFLUENCE OF RESIDUAL NOISE

The tomographic reconstruction requires projections of the (x, y) distributions at small and equidistant angular steps. The first condition cannot be achieved due to space limitations. The second is possible but hard to achieve as it was shown above. Another factor defining the outcome of the reconstruction is the quality of the data used. An (x, y) distribution can be deteriorated from the left-over noise or, on the contrary, signal that is taken away from the denoising procedures. To have a result representative for a low-charge measurement, the influence of the residual noise onto the projection data is shown for the 20 pC case flat-top laser profile, delivering the smallest mismatch.

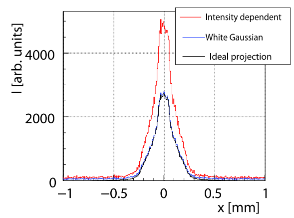
Noise models characteristic for a photodetector are white Gaussian noise and an intensity dependent one. In the first

[1] $\Delta\beta_x = \frac{\beta_{x,design} - \beta_{x,measured}}{\beta_{x,design}}$

case the additional signal contains equal power within fixed bandwith at some central frequency. In the case of intensity dependent one the pixel content is enhanced with some white Gaussian noise added to a Gaussian error with mean 0 and σ the original noise-free value. Figure 4(a) shows the spectral bandwidth of such a white Gaussian noise as the resulting projection deteriorated with those two types is given in Fig. 4(b). The MENT algorithms is chosen for



(a) White Gaussian noise with mean amplitude of 2^4.

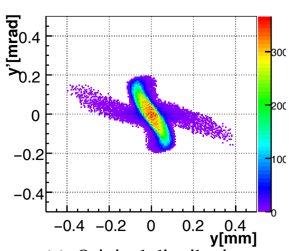


(b) Projections of an ideal (x, y) distribution, added white Gaussian noise and intensity dependant one.

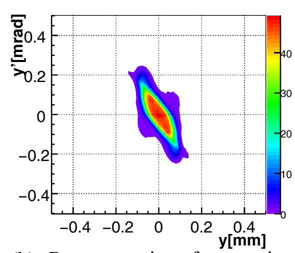
Figure 4: Additive noise enhancing the projected intensity.

the reconstruction as it has proven to deliver the smallest artefacts for limited number of input projections [7].

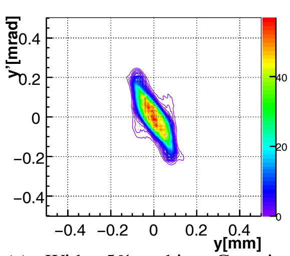
Figures 5(a), 5(b), 5(c) and 5(d) show an original simu-



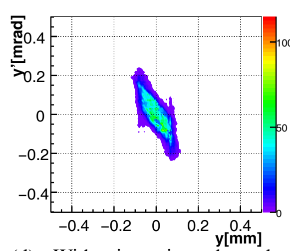
(a) Original distribution.



(b) Reconstruction from noise-free projections.



(c) With 5% white Gaussian noise.



(d) With intensity dependent noise including 5% white Gaussian one.

Figure 5: Original and result from reconstruction for ideal data and different noise models.

lated distribution and reconstructions resulting from noise-free projections and projections with noise added according to the models above. The weight of the white Gaussian noise is 5% of the maximum bin intensity as for the intensity dependent case this value increases up to eight times the underlying ones.

The emittance calculated from the noise-free reconstruction shows 11% overestimation as the low charge density in the tails is missing. The calculated norm [7] reveals about 30% more charge present from where one can draw a conclusion that the mismatch seen in Fig. 1 originates mainly from the beam halo. The reconstruction in Fig. 5(c) shows that smearing artefacts are introduced in the beam core, whereas the density in the tails is reduced. The vertical emittance is overestimated with 25% having about 33% more charge. As the added noise is stochastic, such a small difference is expected since the MENT is looking for areas representative in any of the projections. Nevertheless, both values will increase further if stronger deterioration is present. This can also be seen in the case where 5% intensity dependent noise is added. Here the core is entrirely smeared as about 49% more charge is restored. The emittance is overestimated with 22%.

CONCLUSIONS

As the quality of the matching is defined by RMS values, a Gaussian temporal profile, having extended tails, results in bigger mismatch. This was shown to be related to stronger overall focusing and, on the contrary to the flat-top case, the different constant slope of the β-functions along the FODO lattice.

The general conclusion on left-over noise for low-charge reconstruction is influenced mostly by the artefacts on the beam core even for a relatively good β-mismatch. A possible solution with longer pulse trains can be an outcome only in the presence of Gaussian noise.

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