MODELLING THE TRANSVERSE PHASE SPACE AND CORE EMITTANCE STUDIES AT PITZ

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Abstract

In this work we propose a method for reconstruction of the transverse phase space distribution of electron beams using data from slit scanning measurements. The suggested analysis procedure will be applied to slit scanning data taken at various operating conditions of the Photo Injector Test Facility at Zeuthen (PITZ). Transverse emittance values containing only a certain fraction of all particles in the distribution (core emittance) will be estimated and the results will be compared with simulations.

INTRODUCTION

The high electron beam quality needed for SASE FEL processes requires considerable effort in the characterization and the improvement of the electron source. The main research goal of the Photo Injector Test Facility at Zeuthen (PITZ) is the development of electron sources with minimized transverse emittance like they are required for the successful operation of Free Electron Lasers and future linear colliders [1]. The experimental set-up used for the measurements is shown in Fig. 1. It consists of a 1.5 cell L-band rf gun with a Cs_2Te photo-cathode, a solenoid system for compensating space charge induced emittance growth, a photo-cathode laser system capable of generating long pulse trains with variable temporal and spatial micro pulse shape, and an extensive diagnostics section. The transverse emittance measurements at PITZ are performed using a single-slit scan technique. A slit of 50 μm width is used to sample the initial transverse phase space distribution. The beam is transformed into small beamlets, which retain the uncorrelated divergence of the original beam. The beamlet profiles are observed on a screen situated at a distance L=1.01 m downstream, where the measured rms size $\tilde{\sigma}_{\rm i}$ of the $\rm i^{th}$ beamlet image directly corresponds to uncorrelated divergence $\tilde{\rm x}'_{\rm i} \cong \tilde{\sigma}_{\rm i}/{\rm L}$. The goal is to evaluate the rms emittance defined as $\epsilon_{\rm x,rms} = \sqrt{\langle {\rm x}^2\rangle\langle {\rm x}'^2\rangle - \langle {\rm xx}'\rangle^2}$, which requires the computation of the total (correlated and uncorrelated) divergence $\langle {\rm x}'^2\rangle$ as well as the correlation $\langle {\rm xx}'\rangle$. For practical use it is more convenient to apply an equivalent definition as derived in[3]:

$$\epsilon_{x,rms} = \sqrt{\langle x^2\rangle\langle \tilde{x}'^2\rangle} = \sqrt{\langle x^2\rangle\left\langle \frac{\tilde{\sigma}^2}{L^2}\right\rangle} \qquad (1)$$

The rms size $\sigma_{\rm x} = \sqrt{\langle {\rm x}^2\rangle}$ is measured directly by observing the beam profile on a screen with scintillating material inserted at the position of the slit mask. The typical emittance measurement at PITZ, as it is illustrated in Fig. 2,

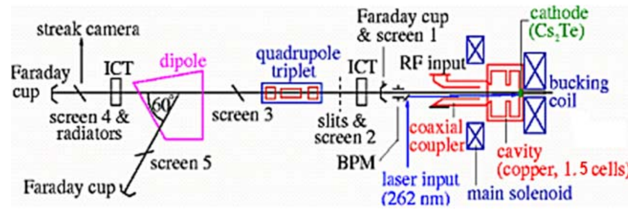

Figure 1: Schematic layout of PITZ.

consists of a beam size measurement at the slit mask position and of a transverse phase space sampling at three transverse positions [2] given by $\rm x_i = \langle x\rangle + 0.7\sigma_x \cdot i$, where i = {-1, 0, 1}.

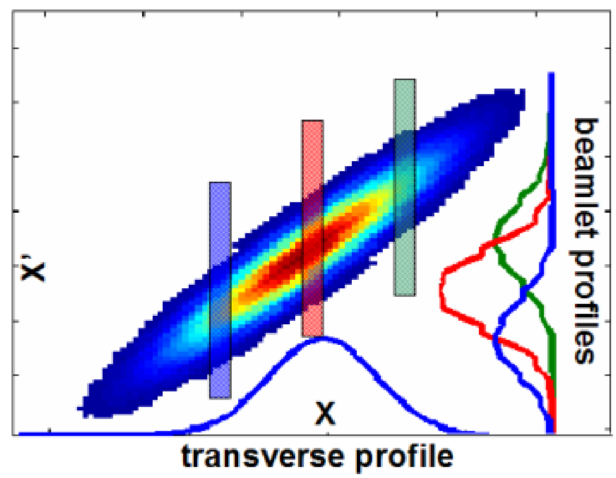

Figure 2: A schematic representation of the emittance measurement using the slit scanning technique at PITZ. The shaded stripes correspond to a phase space sampling by the slit. The beamlet profiles $\eta_{\rm meas}({\rm x_i}, {\rm x}')$ produced by the slit are observed on a screen after about 1 m drift. The beam transverse profile $\xi_{\rm meas}({\rm x})$ is measured at the position of the slit mask.

PHASE SPACE RECONSTRUCTION

The measurement procedure briefly described above provides a good estimation of the full (100%) beam emittance, although the process of emittance calculation does not require a detailed reconstruction of the phase space. However, in some FEL applications the particles in the outermost phase space region might stay out of the amplifier bandwidth and hence only the core of the distribution takes part in the FEL process. For this reason one might be interested in calculating the emittance only of a certain fraction of the particles (core emittance), which corresponds to the

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lasing part of the bunch. One possible approach to estimate the core emittance is to reconstruct the distribution $\mathrm{f(x, x')}$ of the electrons in the phase space using the data from the slit scan i.e. using the measured transverse beam profile $\xi_{\mathrm{meas}}(\mathrm{x})$ and the observed beamlet profiles $\eta_{\mathrm{meas}}(\mathrm{x_i, x'})$. The goal is to determine the function $\mathrm{f(x, x')}$ such, that its projection $\xi_{\mathrm{rec}}(\mathrm{x})$ onto the transverse axis fits to $\xi_{\mathrm{meas}}(\mathrm{x})$ as well as the beamlet profiles $\eta_{\mathrm{rec}}(\mathrm{x_i, x'})$ sampled from $\mathrm{f(x, x')}$ should fit to $\eta_{\mathrm{meas}}(\mathrm{x_i, x'})$. Let Λ be a parameterization of $\mathrm{f(x, x')}$. Then the phase space reconstruction reduces to a search of the parameters set Λ_0, which minimizes the sum:

$$R = R_\xi + R_\eta \tag{2}$$

where R_ξ and R_η are defined as:

$$R_\xi = \sum_n \Big(\xi_{rec}(x_n, \Lambda) - \xi_{meas}(x_n)\Big)^2 \tag{3}$$

$$R_\eta = \sum_{i=1}^{3} \sum_m \Big(\eta_{rec}(x_i, x'_m, \Lambda) - \eta_{meas}(x_i, x'_m)\Big)^2 \tag{4}$$

In the expressions above a summation instead integration is used since the beam measurements are done with CCD cameras of finite pixel size and therefore ξ and η are non-continuous binned distributions. If one considers the electron bunch as an ensemble of longitudinal slices each of them with different orientation in the transverse phase space, then the projected beam emittance will be determined by the common phase space area occupied by all slices. For the purpose of the phase space reconstruction, one can imagine a model, which formally resembles the case with the longitudinal slices. One assumes, that the transverse phase space shape is a superposition of an ensemble of N ellipses, each of them characterized by its phase space angle δ, semi axes $\{\mathrm{a, b}\}$ and charge Q. For the analysis presented in this paper the charge distribution in each ellipse was assumed to be gaussian in both x and $\mathrm{x'}$. However, it is important to note that the final result of the phase space reconstruction and hence of the calculated core emittance depends on the assumed charge distribution, where the distributions with longer tails might generate smaller core emittances.

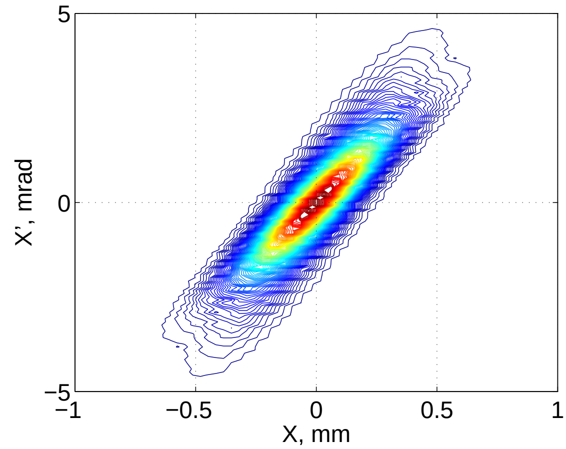

Figure 3: Reconstructed horizontal phase space based on slit scan data. The calculated 100% vertical emittance is ϵ_{x} = 1.4 mm mrad and the 90% core emittance is $\epsilon_{\mathrm{x,90\%}}$ = 1.0 mm mrad. For comparison the measured 100% emittance is ϵ_{x} = 1.3±0.1 mm mrad.

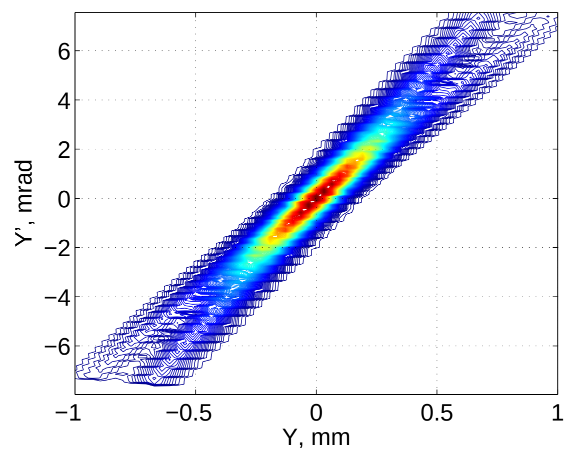

Figure 4: Reconstructed vertical phase space based on slit scan data. The calculated 100% vertical emittance is ϵ_{y} = 2.3 mm mrad and the 90% core emittance is $\epsilon_{\mathrm{y,90\%}}$ = 1.6 mm mrad. For comparison the measured 100% emittance is ϵ_{y} = 1.9±0.2 mm mrad.

CORE EMITTANCE ESTIMATIONS

In the proposed model the quantities $\Lambda \equiv \{\delta_\mathrm{i}, \mathrm{a_i}, \mathrm{b_i}, \mathrm{Q_i}\}$, i = 1..N, are considered as free parameters, which have to be determined by the minimization of the quadratic sum given in Eq. 2. The proposed procedure to calculate the transverse core emittance consists of three steps. At first one performs a phase space reconstruction based on the slit scan data. Then one applies a thresholding (as illustrated in Fig. 6) of the phase space distribution in order to remove a given fraction (e.g. 10%) of the particles. The third step is a calculation of the emittance of the remaining (e.g. 90%) core. In the examples shown in Fig. 3 and Fig. 4, the reconstruction algorithm was applied to slit scan data measured at a solenoid current, which corresponds to an over focused beam at the position of the emittance measurement system. The reconstruction was performed for both the horizontal and for the vertical phase space and the results are to be compared with the ASTRA [4] simulation, which is shown in Fig. 5. As an reasonable compromise between the needed computing time and the goodness of the fit, the number of the superimposed phase space ellipses was taken to be N = 3. A core emittance (90%) analysis was done using the slit scan data taken at PITZ, where the emittance at 1 nC bunch charge was measured as a function of the focusing solenoid current. The estimated 100%

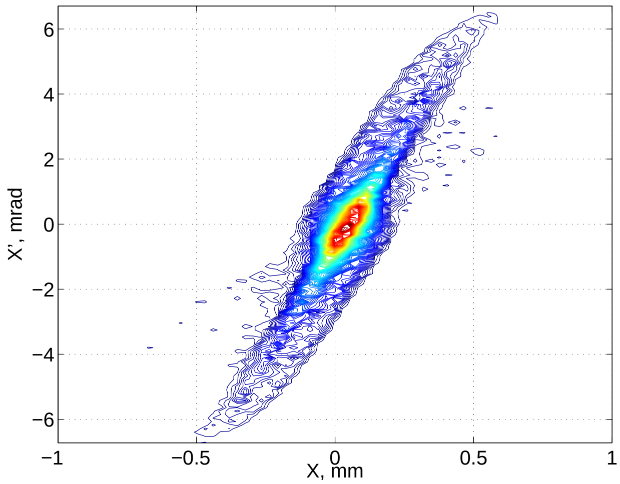

Figure 5: The phase space as predicted by ASTRA simulation for the same conditions as for the measurements analysed in Fig. 3 and Fig. 4: a gun gradient of about 45 MV/m, 1 nC bunch charge and rf phase corresponding to the phase of maximum energy gain Φ_{m}. The current in the main solenoid is set to 326 A, which corresponds to an over focused beam at the position of the slit mask. The UV laser pulse shape was a flat top of about 20 ps FWHM and about 5 ps rise/fall time. The 100% emittance is $\epsilon = 1.5$ mm mrad and the 90% core emittance is $\epsilon_{90\%} = 0.8$ mm mrad.

and 90% emittance values are presented in Fig. 7, Fig. 8 and compared with corresponding ASTRA simulations for injector parameters like the ones observed during the emittance measurements.

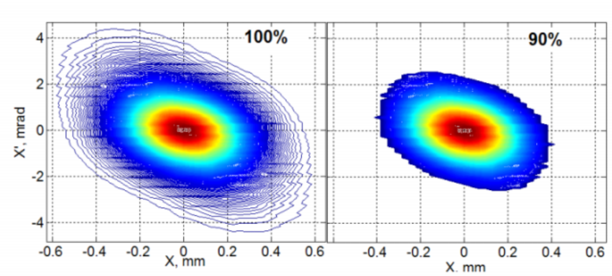

Figure 6: The figure shows the result of a thresholding of the phase space distribution. The graph in the left represents the full reconstructed distribution with an emittance of $\epsilon = 1.95$ mm mrad. In the right the remaining points are those, where the phase space density is above a certain threshold determined so that 90% of the particles are left. The corresponding core emittance is $\epsilon_{90\%} = 1.39$ mm mrad.

SUMMARY

A method for reconstruction of the transverse phase space distribution of electron beams using data from slit scanning measurements was proposed. A procedure to estimate the transverse core emittance was discussed. Following the suggested procedure slit scan data taken at PITZ were analyzed and 90% core emittance was calculated as a function of the solenoid current. Despite the good general agreement between the obtained results and the simulation one can think of further improvements in the model for the phase space reconstruction.

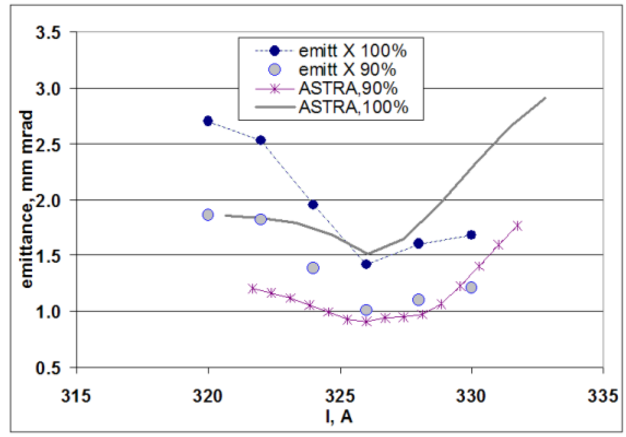

Figure 7: Estimated after phase space reconstruction 100% and 90% horizontal emittances are shown as a function of the solenoid current.

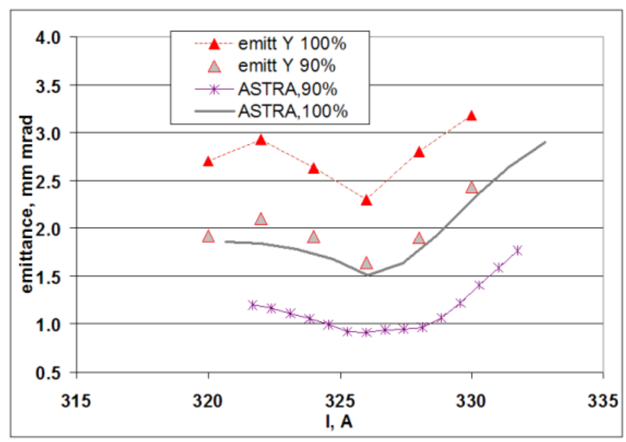

Figure 8: Estimated after phase space reconstruction 100% and 90% vertical emittances are shown as a function of the solenoid current.

ACKNOWLEDGEMENTS

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