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4D TRANSVERSE PHASE SPACE CHARACTERIZATION OF HIGH BRIGHTNESS ELECTRON BEAMS AT PITZ

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Abstract

The Photo Injector Test facility at DESY in Zeuthen (PITZ) utilizes slit scan technique as a standard tool for reconstruction of horizontal and vertical phase spaces of its space-charge dominated electron beams. A novel method for 4-dimensional transverse phase space characterization, known as Virtual Pepper Pot, is proposed at PITZ, that can give insight to transverse beam phase space coupling. It utilizes the horizontal and vertical single slit scans to form pepper-pot-like beamlets by careful crossing and post-processing of the slit scan data. All the elements of the 4D transverse beam matrix are calculated and used to obtain the 4D transverse emittance and coupling factor. The proposed technique has been applied to the experimental data with coupled beam phase space in order to demonstrate the diagnostic capability. The loss of signal at tails of the beamlets due to low signal-to-noise (SNR) ratio is considered in the algorithm and the systematic error resulting from crossing of the beamlets is also explored.

INTRODUCTION

The Photo Injector Test facility at DESY in Zeuthen (PITZ), was established as a test stand for the electron sources for Free electron Laser in Hamburg (FLASH) and the European X-ray Free Electron Laser (XFEL) [1]. Free Electron Lasers (FELs) require high brightness electron beams to generate short wavelength and high intensity coherent radiations. Therefore, a detailed characterization of the beam is required in both transverse and longitudinal planes to ensure small transverse emittance and high peak current.

The PITZ facility currently consists of two tunnels; tunnel 1 contains the main beam line and tunnel 2 is the recent upgrade for THz generation [2] and radiation biology research [3]. The PITZ accelerator consists of a normal conducting L-band 1.6-cell copper gun cavity with a Cs_2Te photocathode. It can produce up to ~6.5 MeV electron bunches with variable bunch lengths and up to several nC charge. The electron beam is further accelerated by a Cut Disk Structure (CDS) booster cavity to an energy of up to ~22 MeV. Downstream the accelerating structure, the beamline consists of different diagnostics.

Characterization of the electron bunch transverse phase space is done by a slit scan technique [4]. The set up at PITZ known as emittance measurement system (EMSY) consists of a horizontal and vertical slits and an observation screen. PITZ has three horizontal and vertical phase space measuring setups namely EMSY1, EMSY2 and EMSY3 at different locations along the beamline. Virtual Pepper Pot (VPP) is a novel method that is introduced at PITZ for 4D phase space measurements [5]. It utilizes data from horizontal and vertical slit scans to construct 4D transverse phase space and calculate 4D emittance. VPP has an additional advantage that it can give insight to transverse beam phase space coupling in order to understand it and possibly minimize or eliminate it.

In this paper, 4D Transverse Phase Space (TPS) characterization will be introduced and then VPP technique will be explained taking the case of 250 pC beam. The methodology of charge cut caused by noise in the experimental data will also be described along with its application to the VPP algorithm. The method will then be applied to the experimental data generated from a transverse truncated Gaussian laser and rotated by gun quadrupoles in order to show its 4D diagnostic capability. The systematic errors of the method will be described too.

TRANSVERSE PHASE SPACE CHARACTERIZATION

The particle transverse motion can be characterized in transverse phase space by its transverse canonical coordinates i.e. particle position (x, y) and mechanical momenta (p_x, p_y). This 4-dimensional phase space (x, p_x, y, p_y) is used to understand and quantify the quality of electron beam for accelerator design and phase space manipulations. Most of the published work on 2D sub phase space i.e. (x, p_x) and (y, p_y) does not consider coupling between transverse planes. Beamline elements such as normal quadrupoles, dipoles, and accelerating cavities are non-coupling elements and hence horizontal and vertical beam dynamics remain decoupled. But interplane correlations are introduced by solenoids, skew quadrupoles, RF kickers and magnetic component imperfections which need to be characterized by 4D diagnostics. Hence the projected distribution parameters along the beam line depend on these correlations as well. 4D beam matrix that describes the transverse statistical properties of the beam is:

$$\sigma^{4D} = \begin{pmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle xy \rangle & \langle x'y \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle xy' \rangle & \langle x'y' \rangle & \langle yy' \rangle & \langle y'^2 \rangle \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy}^T & \sigma_{yy} \end{pmatrix} \tag{1}$$

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where x and y are horizontal and vertical coordinates respectively and x' and y' are their corresponding angles. The matrices σ_{xx} and σ_{yy} describe the 2D horizontal and vertical trace spaces respectively and σ_{xy} describes the cross plane coupling. Projected RMS geometric emittances ϵ_x and ϵ_y are quantities which are used to characterize the transverse beam quality and correspond to RMS phase space areas from projections of the particle distribution onto the plane. Their values are equal to the square root of determinant of $\sigma_{\mu\mu}$ and they are invariant under linear uncoupled symplectic transformations.

$$\epsilon_\mu = \sqrt{\langle\mu\mu\rangle\langle\mu'\mu'\rangle - \langle\mu\mu'\rangle^2} \tag{2}$$

where μ refers to either x or y. If the beam is transversely decoupled ($\sigma_{xy} = 0$), the 2D beam matrices are sufficient to characterize the beam. But if not, one can calculate correlation term and find 4D emittance.

$$C_{xy} = \sqrt{\langle xy\rangle\langle x'y'\rangle - \langle xy'\rangle\langle yx'\rangle} \tag{3}$$

$$\epsilon_{4D}^2 = \epsilon_x^2\epsilon_y^2 - C_{xy}^4 \tag{4}$$

The coupling term definition as proposed in [6] can be used to quantify the degree of coupling in the transverse planes.

$$C = \frac{\sqrt{\epsilon_x\epsilon_y}}{\epsilon_{4D}} - 1 \tag{5}$$

VIRTUAL PEPPER POT TECHNIQUE

Virtual pepper pot is a novel method that is recently established at PITZ for 4D phase space measurements. It is called virtual because there is no actual pepper pot plate, rather the slit scan data is used to generate pepper pot like mask and beamlets. This technique eliminates the mechanical design considerations imposed by small beams at PITZ (0.2 mm-0.3 mm RMS) but relies on stable machine operation due to multi-shot measurement procedure. This section describes the VPP technique with the help of an example. The concept of charge cut will be introduced and the systematic errors of VPP will be briefly discussed.

Methodology

At PITZ, EMSY1 is located at a distance of 5.277 m from the electron gun. It consists of an actuator that holds a screen named EMSY screen, a 50 µm slit and a 10 µm slit in both horizontal and vertical planes. Downstream this station, there is another screen known as beamlet collector screen after a drift space of 3.133 meters. This generates the slit scan data that is offline utilized for VPP technique. Basically, the horizontal and vertical beamlets are crossed and the pixel-wise minimum of beamlets' intensity is taken to generate a pepper pot like beamlet. The known slit positions at the EMSY screen are used to generate a pepper pot like mask. All the beamlets and mask images are normalized by the sum of pixels of corresponding beamlet images. For the purpose of illustration, every 10^{th} horizontal and vertical beamlet is crossed and the generated VPP mask and beamlets are shown in Figure 1. For data analysis, every 3^{rd} beamlet was crossed to have more statistics along with reasonable processing time.

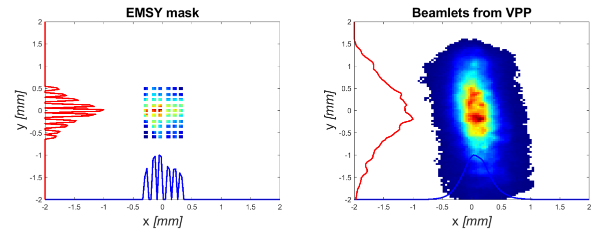

Figure 1: After crossing every 10^{th} horizontal and vertical beamlet (a) VPP mask formed from known slit positions and beam distribution at that screen (b) VPP beamlets where the hot spots show the center of beamlets with overlapping beam surrounding them

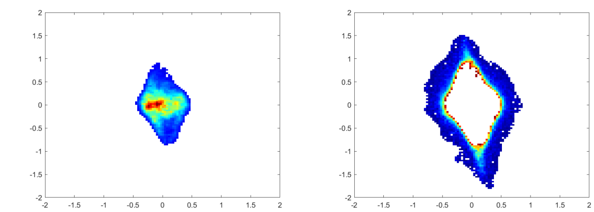

Figure 2: Charge cut applied to a coupled beam distribution at slit position (a) core (b) halo

Charge Cut

When the horizontal or vertical slits scan the EMSY beam, the number of bunches in a pulse train are set such that the beam has good SNR for the central beamlet image but the screen is not saturated. Therefore, when the slit is at the beginning or the end of the EMSY beam image, generally known as tails, there is either no signal detected at the beamlet collector screen or very poor signal observed with low SNR. Therefore, the phase space constructed for such a signal will have some charge cut. At PITZ, this is generally compensated by applying a scaling factor to the emittance values as discussed in [7]. For the case of VPP, charge cut at the tails was quantified and then a corresponding 2D cut was applied on the EMSY image. Basically, for a horizontal slit scan, the sum of pixels of beamlet as a function of slit position is fitted to the beam image projection at the horizontal plane. The fit is carried out using nonlinear programming solver *fminsearch* in Matlab. The same procedure is applied to the vertical scan and the common beam core is used to generate the VPP mask. Figure 2 shows an example of a beam core and halo after charge cut.

This procedure gives the core beam at EMSY screen which actually contributes to the beamlets at beamlet collector screen. In other words, with the current set up, VPP gives TPS and the related beam parameters for the core of the beam. There is further work forseen at PITZ for horizontal and vertical slit scan with tunable number of bunches in order to have improved signal for every beamlet image. This will also eliminate or minimize the charge cut and hence enable 4D diagnostics of the beam including halo.

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Systematic Errors

There are also some systematic errors in the VPP technique that need to be addressed. A VPP beamlet contains particles from the common part of the horizontal and vertical crossing beamlet. This area contains not only particles that emerged from the square-like VPP mask position but also some particles from the neighboring area of diverged beamlets. These *foreign particles* can slightly increase the weight and variance of the VPP beamlet. In addition, the number of beamlets selected to be crossed can be more dense in central part of the EMSY mask and beamlets as they have more weight. Another point of consideration is the EMSY mask sub-images size. The size of slit is 50 µm and the pixel size of screen is approximately 35 µm. This makes the sub-images pixel round off to 1 or 2 pixels. In order to have a uniform mask, the sub-images were extrapolated to have size 2 × 2.

EXPERIMENTAL DATA AND RESULTS

A 250 pC beam was generated from a truncated Gaussian laser and the solenoid current was kept constant. The experimental data was generated with coupling introduced in the beam in the transverse plane using 2 gun quadrupoles [8]. A combination of normal and skew quadrupole was kept such that the current amplitude I_o was constant but the angle was varied. Eq. 6 shows the relation.

$$I_{q,norm} = I_o \cos\theta, I_{q,skew} = I_o \sin\theta \tag{6}$$

The rotation angle θ ranged from $-90°$ to $90°$ with a step size of $10°$. The horizontal and vertical slit scans' data was taken for all these 19 cases. This was later fed offline to the VPP tool to generate $\epsilon_x, \epsilon_y, \epsilon_{4D}$ and coupling plots as shown in Figure 3. It was observed from the investigation of the 4D phase space that the coupling introduced by the main solenoid was compensated by the gun quadrupoles at an angle of $10°$.

Preliminary studies were done to show the trend of the 4D emittance values and coupling factor. The exact numbers are sensitive to the possible systematic errors in the methodology. Also, the tool will be applied in future to more data sets to show statistical errors. Figures 4 and 5 show the 4D phase space of a $10°$ and $90°$ coupled beam, respectively. The halo part of the phase space is missing due to charge cut. The core of phase space (y, x') has undergone a $90°$ rotation. Due to the coupling in this plane, the horizontal and vertical phase space correlation is also affected.

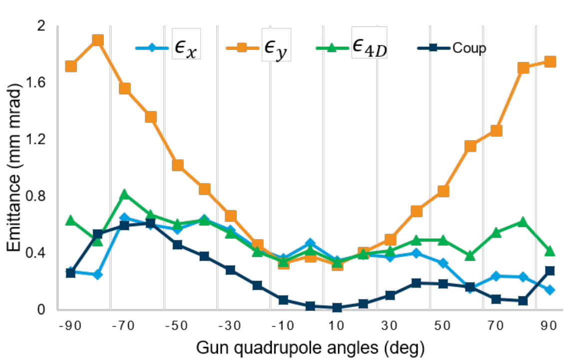

Figure 3: 4D-emittance and coupling factor for beam rotated by gun quadrupoles

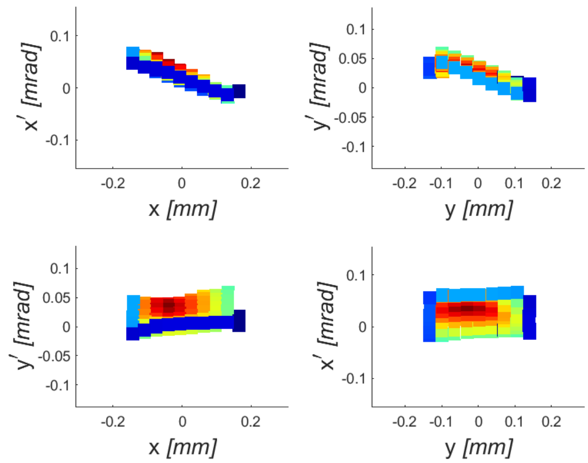

Figure 4: Reconstructed 4D TPS using VPP tool for core part of the coupled beam with quadrupole rotation angle 10°

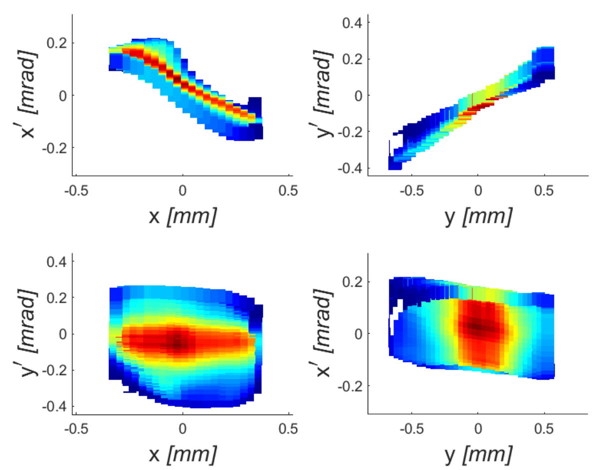

Figure 5: Reconstructed 4D TPS using VPP tool for core part of the coupled beam with quadrupole rotation angle 90°

CONCLUSION AND OUTLOOK

The virtual pepper pot technique is the recent diagnostic tool set up at PITZ for 4D TPS diagnostics. The gun quadrupoles rotation angle scan data which coupled the transverse phase space was analysed to prove the diagnostic capability of the method. The results gave 4D emittance, coupling factor and insight to cross planar coupling with its phase space reconstruction. This concludes that the source of rise in emittance comes from the cross planar coupling and in order to remove or minimize it, the optimum approach would be to fine tune the quadrupoles' current. Furthermore, the tuning of number of bunches during slit scan can enable reconstruction of tails as well. The systematic errors associated with the crossing of slits can be quantified in order to increase precision of results.

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