THE EFFECT OF SPACE CHARGE ALONG THE TOMOGRAPHY SECTION AT PITZ

G. Kourkafas[*], M. Khojoyan, M. Krasilnikov, D. Malyutin, B. Marchetti, M. Otevrel, F. Stephan,
G. Vashchenko, DESY, 15738 Zeuthen, Germany
G. Asova, INRNE-BAS, 1784 Sofia, Bulgaria

Abstract

The Photo Injector Test facility at DESY, Zeuthen site (PITZ) focuses on testing, characterizing and optimizing high brightness electron sources for free electron lasers. Among various diagnostic tools installed at PITZ, the tomography module is used to reconstruct the transverse phase-space distribution of the electron beam by capturing its projections while rotating in the normalized phase space. This technique can resolve the two transverse planes simultaneously with an improved signal-to-noise ratio, allowing measurements of individual bunches within a bunch train with kicker magnets.

The low emittance, high charge density and moderate energy of the electron bunch at PITZ contribute to significant space-charge forces which induce mismatches to the reconstruction procedure. This study investigates how the phase-space transformations and thus the reconstruction result are affected when considering linear and non-linear self-fields along the tomography section for the design Twiss parameters. The described analysis proposes a preliminary approach for including the effect of space charge in the tomographic reconstruction at PITZ.

INTRODUCTION

A wide range of noble research areas and applications rely on the effective operation of Free Electron Lasers (FELs). The performance of an FEL depends significantly on the quality of the electron beam already from its source, i.e. the photo injector. For a beam of certain charge, a detailed knowledge of its transverse phase-space distribution provides important information which determines the machine settings downstream and the properties of the resulting FEL light.

The Photo Injector Test facility at DESY, Zeuthen site (PITZ) can accelerate electron bunches of 24 ps FWHM and 1 nC nominal charge up to energies of around 25 MeV, delivering a normalized rms transverse emittance smaller than 1 mm·mrad [1]. For the measurement of the transverse phase-space distribution two approaches are employed at PITZ: the slit-scan technique [2] and the tomographic reconstruction. The latter makes use of the basic principle of tomography which requires a number of rotated projections of a sample in order to reconstruct it.

Transverse Phase Space Tomography at PITZ

The tomography section of the PITZ beamline (Fig. 1) currently consists of six quadrupole magnets, forming a so-called FODO lattice which is used to rotate the beam by 180° in the transverse phase space. Additionally, four intercepting screens ideally at equidistant phase advance values capture the beam profile, providing the spatial projections of the beam at each transverse plane. These projections are then used as input to a reconstruction algorithm, known as Maximum ENTropy (MENT) [3], together with their corresponding transfer matrices w.r.t. the point of reconstruction (indicated as screen #0 in Fig. 1). These matrices provide the mathematical description of the transformation of the phase space at each screen. The outcome is the reconstruction of the phases-space distribution of both transverse planes simultaneously at the first screen of the tomography section, around 8 m downstream the cavity which provides the final acceleration. More details on the design of the tomography lattice and its preceding matching section can be found in [4, 10].

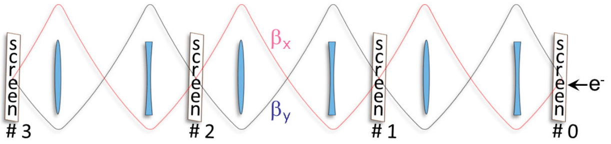


Figure 1: Schematic layout of the tomography section at PITZ. The beam propagates from right to left through six focusing and defocusing quadrupoles represented as lenses. Four intercepting screens capture projections of each transverse phase plane ideally at equidistant phase advance values as indicated by the plotted β-functions.

Space-Charge Effect at PITZ

The electron bunches typically produced at PITZ lay in a space-charge dominated regime where the moderate kinetic energy cannot compensate for the high charge density. Consequently, the space-charge induced defocusing becomes non-negligible.

The current reconstruction procedure at PITZ neglects this effect, resulting in an incorrect consideration of the beam dynamics along the FODO lattice. As a result, the calculation of the phase-space transformations is affected, leading to an incorrect reconstruction of the captured projections. For this reason, simulations were carried out in

---

[*] georgios.kourkafas@desy.de

order to quantify the impact of space charge along the tomography section.

SIMULATION WALK-THROUGH

The ultimate goal of these simulations was to reconstruct the phase-space distribution of an electron bunch with and without the consideration of the space-charge forces along the tomography lattice and to compare the results with the original distribution.

In its general form the space-charge force has no analytical expression, making its calculation possible through macroparticle-based codes, which are very demanding in computing resources. Only under certain assumptions, the linearization of the self-fields becomes valid and a formulation can then be derived which approximates the effect of space charge on a set of the statistical moments of the beam [5, 6]. The V-Code software [6] offers an implementation of the latter approach and was used for the linear space-charge tracking of the moments up to second order. The consistency of this model on the specific application is of great interest, as it can provide incomparably faster results. For the reference macroparticle tracking A Space Charge Tracking Algorithm (ASTRA) [7] was used.

A characteristic phase-space distribution of a photoinjector was tried to be generated as input for the reconstruction. Therefore, ASTRA was tuned to provide a bunch of 1 nC charge, 24.7 MeV/c momentum and emittance value equal to the result of a past slit-scan measurement. Moreover, the Twiss parameters at the entrance of the tomography section were adjusted to match the design values ($\beta_{x,y} = 0.999$, $\alpha_{x,y} = \pm 1.125$), resulting in the distribution shown in Fig. 2(a) and 3(a). It is important for the interpretation of the simulation results to notice the differences between the two phase planes.

The strengths of the tomography quadrupoles were set as currently implemented, i.e. according to the matching solution for 45° phase advance between each screen as provided by the Methodical Accelerator Design (MAD) software [8], which neglects space charge. Under this focusing, horizontal and vertical projections of the generated bunch at each screen of the tomography lattice were acquired from ASTRA, using a fine 3-D space-charge grid (60×60×120) on 500000 macroparticles.

The reconstruction of the above projections under different space-charge treatments (no space charge, linear space charge, non-linear space charge) requires the respective transformation matrices for each case. Given the input beam and the quadrupole strengths, the simulation of the beam transport along the tomography lattice for each tracking approach allows the calculation of the transfer matrices at each screen from the following formula [9]:

$$M_n = \begin{pmatrix} \sqrt{\frac{\beta_n}{\beta_0}}\left(cos\phi_n + \alpha_0 sin\phi_n\right) & \sqrt{\beta_n\beta_0}sin\phi_n \\ -\frac{1+\alpha_n\alpha_0}{\sqrt{\beta_n\beta_0}}\sin\phi_n + \frac{\alpha_0-\alpha_n}{\sqrt{\beta_n\beta_0}}\cos\phi_n & \sqrt{\frac{\beta_0}{\beta_n}}\left(cos\phi_n - \alpha_n sin\phi_n\right) \end{pmatrix} \quad (1)$$

where the index 0 refers to the reconstruction point and $n = 0, 1, 2, 3$ to each projection screen, α and β are the Twiss parameters and ϕ is the phase advance, given by:

$$\phi_n = \int_{z_0}^{z_n} \frac{\mathrm{d}z}{\beta(z)} \quad (2)$$

where z is the longitudinal position along the beamline.

The final reconstruction result for each tracking case is presented in Fig. 2(b), 2(c) and 2(d) for the horizontal plane and 3(b), 3(c) and 3(d) for the vertical plane.

SIMULATION RESULTS

The reconstruction of such complicated distributions from only four projections is expected to smear out the fine details observed in the original ones, creating the need of a quantitative property for the comparison. The reconstructed emittance, summarized in Table 1 together with the relative error w.r.t. the original emittance for each phase plane, will serve this purpose.

Table 1: Simulated Normalized Emittance Values

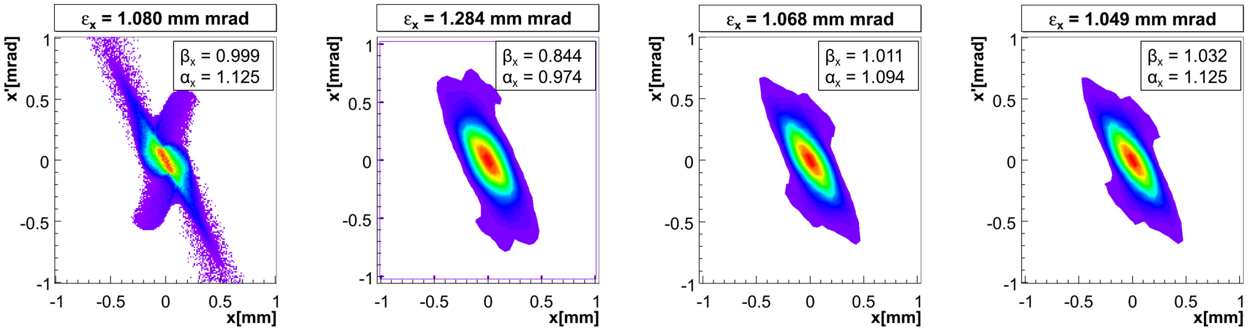
	Norm. emittance [mm·mrad] **Relative error (%)**	
Original	1.080 (-)	3.321 (-)
Reconstruction without space charge	1.284 (+18.9%)	3.588 (+8.0%)
Reconstruction with linear space charge	1.068 (-1.1%)	3.229 (-2.8%)
Reconstruction with non-linear space charge	1.049 (-2.9%)	3.225 (-2.9%)
	***x* plane**	***y* plane**

A significant error of up to 19% is introduced when space charge is neglected. The deviation is considerably bigger for the horizontal plane compared to the vertical due to the more dense concentration of the particles in the x plane, as observed in its phase-space distribution ($\sigma_x < \sigma_y$).

On the other side, any tracking which considers space charge matches the reconstructed emittance within 3%. In addition, a shearing appears in the reconstructed distributions which brings their slope ($\theta = tan^{-1}(\frac{2\alpha}{\gamma-\beta})/2$) closer to the original value. The emittance difference between the two space-charge implementations is smaller than 2%.

Counterintuitively, the results from the linear space-charge reconstruction match better the original values than the ones from the general space-charge tracking. Possible reasons for this result are the correlated emittance growth introduced by ASTRA in the presence of external fields [7], the shorter tracking step which is achievable with V-Code and the treatment of the low intensity tails by the reconstruction procedure.

Another value with useful information is the shift of the phase advance at each screen location when space charge is



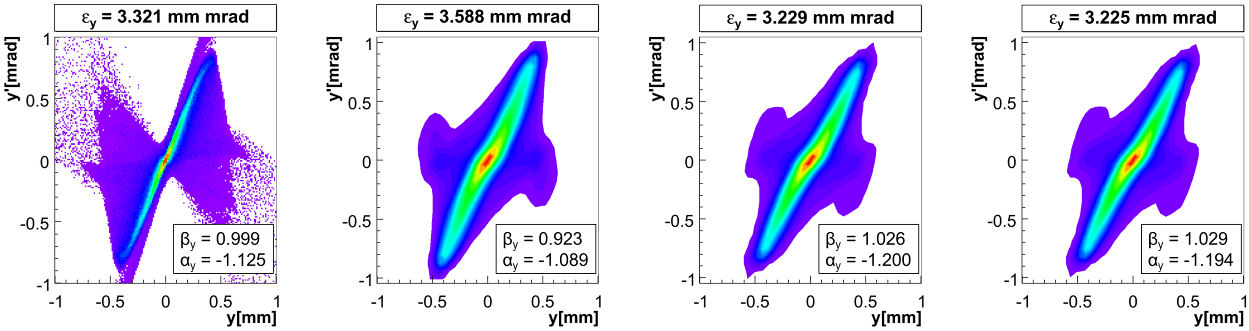
(a) Original distribution.

(b) Reconstructed distribution **without** space charge.

(c) Reconstructed distribution with **linear** space charge.

(d) Reconstructed distribution with **non-linear** space charge.

Figure 2: Horizontal plane of the original and reconstructed phase-space distributions with their corresponding normalized emittance values and Twiss parameters.



(a) Original distribution.

(b) Reconstructed distribution **without** space charge.

(c) Reconstructed distribution with **linear** space charge.

(d) Reconstructed distribution with **non-linear** space charge.

Figure 3: Vertical plane of the original and reconstructed phase-space distributions with their corresponding normalized emittance values and Twiss parameters.

taken into consideration. It quantifies the phase defocusing which is induced by space charge and indicates the projection angle mismatch at each screen when reconstructing in the normalized phase space. These values are summarized in Table 2 for each phase plane and tracking approach. Most observations from the comparison of the reconstructed distributions can be predicted by these figures in a qualitative way. It is worth to mention the 25° maximum mismatch at the last projection screen.

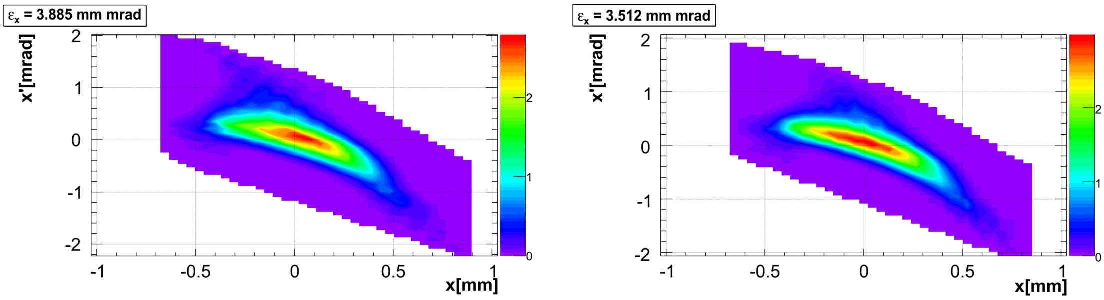
Table 2: Phase Advance Shift due to Space Charge

	Screen #1	 #2	 #3
***x* plane**			
Linear space charge	-1.9°	-11.1°	-23.3°
Non-linear space charge	-1.3°	-11.6°	-25.0°
***y* plane**			
Linear space charge	-1.6°	-7.9°	-14.5°
Non-linear space charge	-1.5°	-8.3°	-15.2°

APPLICATION TO EXPERIMENTAL DATA

The strategy developed for the simulation can also be applied to the existing experimental data [10]. While the quadrupole strengths and the projections are given for each dataset, a description of the incoming beam at the entrance of the tomography section is also necessary. An estimation of the transverse statistical moments of the beam at this position is available after performing a quadrupole-scan, a multi-screen measurement or a tomographic reconstruction with the current implementation which neglects space charge [10]. For the estimation of the longitudinal moments a new technique has recently been developed at PITZ [11].

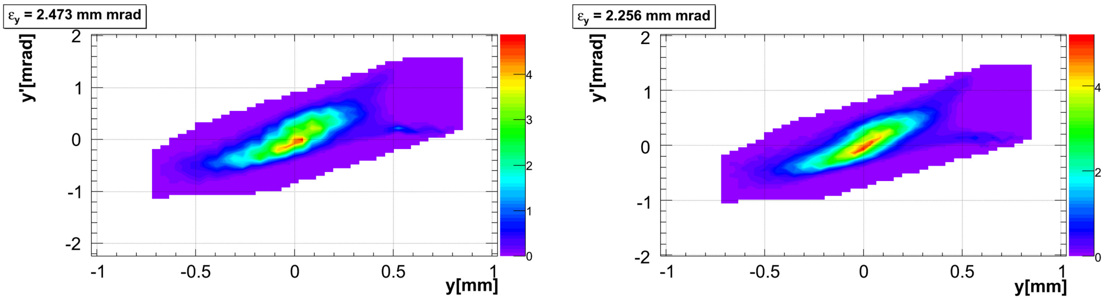
A measurement of a beam with 1 nC charge and 24.7 MeV/c momentum was reanalyzed using the old reconstruction result and the estimated longitudinal parameters from ASTRA for the description of the input beam. Since there is no significant deviation between the different space-charge tracking methods, as mentioned before, only the result from V-Code is presented in Fig. 4 and 5, together



(a) Result without space-charge consideration.

(b) Result with linear space-charge consideration.

Figure 4: Reconstruction of measured data without vs. with space-charge consideration - *x* plane.



(a) Result without space-charge consideration.

(b) Result with linear space-charge consideration.

Figure 5: Reconstruction of measured data without vs. with space-charge consideration - *y* plane.

with the old reconstruction which neglects the self-fields. Additional ASTRA simulations showed that the result is almost independent on the exact shape of the initial distribution for the specified set of moments.

A comparison of the reconstructed distributions shows smoother lines and less pronounced artifacts around the beam core when space charge is taken into consideration. The calculated emittance drops by ∼10% for both planes, in agreement with the simulation result for the vertical distribution which had similar rms beam size.

SUMMARY

For an electron bunch of 1 nC charge and 24.7 MeV/c momentum, space charge can considerably affect the beam transport along the tomography section at PITZ. Depending on the spatial distribution of the particles, additive phase-advance mismatches of up to 25° lead to an error of up to 19% in the reconstructed emittance when space charge is not accounted for. This error can be reduced to 3% when taking the self-fields into consideration, with negligible differences between the available implementation models. The linear space-charge model proves to provide a representative tracking of the tomography section of PITZ.

The application of the developed analysis to experimental data seems to improve the reconstruction result. Still, a new matching procedure which implements this analysis needs to be developed for the tomography lattice in order to obtain projections at equidistant phase advance values.

REFERENCES

[1] M. Krasilnikov et al., “Experimentally minimized beam emittance from an L-band photoinjector”, Phys. Rev. ST Accel. Beams 15, 100701 (2012).

[2] L. Staykov, “Characterization of the transverse phase space at the photo-injector test facility in DESY, Zeuthen site”, PhD thesis, Universität Hamburg, 2012.

[3] J. Scheins, “Tomographic Reconstruction of Transverse and Longitudinal Phase Space Distributions using the Maximum Entropy Algorithm”, TESLA Report 2004-08, May 2004.

[4] G. Kourkafas et al., “Tomography module for transverse phase-space measurements at PITZ”, DITANET2011, Seville, November 2011.

[5] C. Allen and N. Pattengale, “Theory and technique of beam envelope simulation”, LA-UR-02-4979, January 2002.

[6] S. Franke, W. Ackermann, T. Weiland, “A Fast and Universal Vlasov Solver for Beam Dynamics Simulations in 3D”, ICAP09, San Francisco, September 2009.

[7] `http://www.desy.de/∼mpyflo`

[8] `http://mad.web.cern.ch/mad`

[9] M. Minty and F. Zimmermann, “Beam Techniques - Beam Control and Manipulation”, USPAS lectures, June 1999.

[10] G. Asova, “Tomography of the electron beam transverse phase space at PITZ”, PhD thesis, INRNE, Bulgarian Academy of Sciences, Sofia, 2011.

[11] D. Malyutin et al., “First results of a longitudinal phase space tomography at PITZ”, FEL2013, Manhattan 2013, TUPSO47