DESIGN CONSIDERATIONS FOR PHASE SPACE TOMOGRAPHY DIAGNOSTICS AT THE PITZ FACILITY*

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Abstract

A major goal of the Photo Injector Test Facility at DESY in Zeuthen (PITZ) is to build and to optimise high brightness electron sources for SASE FELs where the detailed knowledge of the phase-space distribution of the electron beam is very important.

The current upgrade of the PITZ facility includes a diagnostic section suitable for transverse phase space tomography and multiscreen emittance measurements. The designed module should be capable of operation over a range of beam momenta between 15 and 40 MV/c. It mainly consists of four observation screens with three FODO cells in between them. An upstream section of a number of quadrupoles is used to match the electron beam Twiss parameters to the tomography section.

The design considerations of the tomography section and results from numerical simulations will be presented in this contribution.

INTRODUCTION

The Photo Injector Test Facility at DESY in Zeuthen (PITZ) will be upgraded to operate with higher beam energies in early 2008. The upgrade also implies extended diagnostics, including a tomography section for detailed analysis of the transverse phase-space density distribution of the electron beam. At a later stage the tomography module will be equipped with an RF deflecting cavity to study the transverse distributions and measure emittance of longitudinal slices for selected electron bunches [1].

The tomography module will consist of three FODO cells and four diagnostic stations for beam size measurements. It has previously been shown that 45° phase advance between the cells delivers the smallest emittance measurement errors using four screens [2]. Since the beam in general does not have the necessary size and slope on the first screen, a matching section is necessary. Both the tomography and the matching sections have been designed in a collaboration between STFC Daresbury Laboratory and DESY. Preceding iterations of the design can be found in [3].

In this paper some major aspects concerning the design of the tomography module are reviewed as follows: The first section justifies the choice of the physical layout; this is followed by general considerations of the matching section and then two different examples of matching are given, confronted with an ideal case where no space charge forces are acting on the beam (zero current). Phase space reconstruction from ASTRA-simulated [4] distributions provides the final results.

DESIGN LAYOUT OF THE TOMOGRAPHY SETUP

The proposed tomography setup is shown schematically in Fig. 1. It consists of a number of matching quadrupoles, which will be discussed later, and the three identical symmetric FODO cells at the end. In a previous design iteration a quadrupole effective length of 0.06 m was assumed but, due to stringent space restrictions, shorter quadrupoles with an effective length of 0.04 m and a physical one of 0.062 m have been chosen now. Geometrically the minimum drift allowed between two adjacent quadupoles is 0.26 m but the drifts between the quadrupoles in the first two cells and the one between the quadrupoles in an identical cell upstream, used for matching, have to accommodate kicker magnets for extraction of a single bunch from the bunch train. From the point of view of motion stability, the quadrupole effective length allows the use of any drift for which $|\cos\mu = \frac{T_{11}+T_{22}}{2}| \leq 1$, where T is the transport matrix from screen to screen and μ is the phase advance, up to a maximum 0.46 m. Thus, a cell length of 0.76 m was chosen. As it can be seen from Fig. 2, for the ideal case of zero current phase advance, the maximum RMS size excursion does not exceed 0.15 mm for a normalised emittance of 0.99 mm·mrad and beam energy of 32 MeV and on a screen the Twiss parameters are $\beta_{x,y} = 0.99$ m, $\alpha_{x,y} = \mp 1.12$.

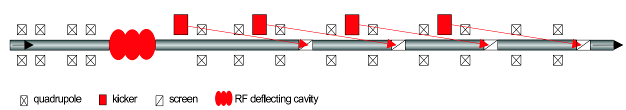

Figure 1: Tomography and matching setup (not to scale). Two more upstream quadrupoles are not shown.

Numerical simulations excluding particles' self-repulsion, for quadrupoles with effective lengths of 0.06 m, show smaller β-mismatch [1] on the screens in

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[1] $\Delta\beta[\%] = \frac{\beta_{designed}-\beta_{measured}}{\beta_{designed}} \cdot 100$

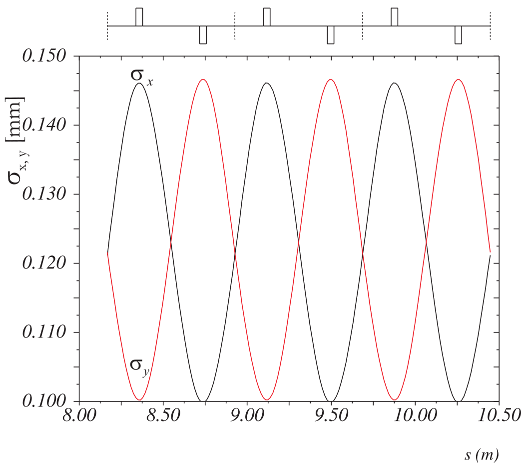

Figure 2: RMS beam size inside the FODO lattice for a beam with zero current. The abscissa coordinates are shifted with respect to the entrance of the matching section so that $s = 0$ corresponds to the beginning of the drift space in front of the first matching quadrupole.

comparison to the case of 0.04 m effective length. The mismatch increases when decreasing the energy which clearly shows that the space charge term dominates over the emittance term in the equations of motion. For beam momentum of 32 MeV/c the space charge term is 10 times the emittance one and decreasing the energy to 15 MeV leads to 50 times bigger space charge term. Thus, the matching procedure should be based on the equations of motion including space charge and emittance terms.

MATCHING OF THE ELECTRON BEAM TO THE TOMOGRAPHY SECTION

Matching of space charge-dominated beams implies minimisation of a 'cost function' which takes into account the beam size X(z), Y(z) and slope X′(z), Y′(z) and generalised perveance[2], including the kinetic energy and the beam peak current as a ratio between the bunch charge and length.

Initially five quadrupoles used for matching were assumed but they are not sufficient with the effective length we are planning to use. There is a possibility to include up to a further four magnets, located in an upstream straight section. Two independent approaches and setups were evaluated in order to obtain a matched beam on the first screen in the presence of self repulsive forces.

Initially ASTRA was used to track the electron beam along the full setup shown in Fig. 1 - seven matching quadrupoles, excluding the self-field repulsion. This would represent the ideal solution to be achieved. Including the space charge afterwards gives an idea of what the beam size mismatch is and where the effects have strongest influence.

[2] $K = \frac{I_{peak}}{I_{Alfven}} \cdot \frac{2}{(\beta\gamma)^3}$

The defined cost function is

$$\Delta^2 = (\delta X'_w - \delta X'_{wo})^2 + (\delta Y'_w - \delta Y'_{wo})^2 + (\sigma_{x,w} - \sigma_{x,wo})^2 + (\sigma_{y,w} - \sigma_{y,wo})^2,$$

where w denotes simulation with space charge included, wo - with space charge forces switched off, and

$$\delta U' = \frac{\sigma_{U,z_{start}} - \sigma_{U,z_{end}}}{z_{end} - z_{start}},$$

with U being either X or Y for both w and wo, z_{start} and z_{end} refer to the beginning and the end of the drifts surrounding the quadrupoles taken into account. The cost function has to be minimised in a number of iterations where the strength of each magnet for zero current is corrected with a predefined value

$$\delta k = \frac{L}{L_{eff}} \cdot \frac{K}{R^2},$$

where L is the overall length the space charge forces are acting on, L_{eff} is the quadrupole effective length, K is the perveance and R is beam radius. δk can be changed in each successive iteration to a value where the value of Δ is smaller. This iterative procedure has to include not less than two quadrupoles at a time. The process is rather time consuming since it requires evaluation of the results but in this way the mismatch was decreased down five times inside the FODO lattice, while without correction no periodic solution was obtained. An example of the results inside the FODO lattice is shown in Fig. 3 The beam was

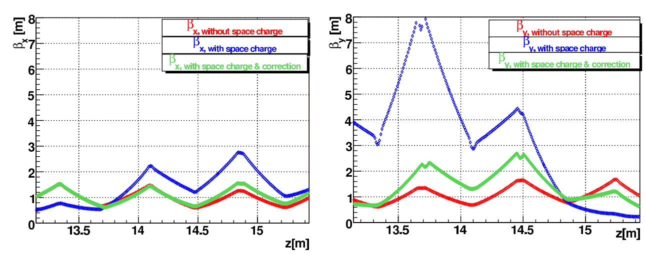

Figure 3: β_x (left) and β_y (right) along the tomography section.

also matched with the help of TRACE-3D [5] for the same layout of quadrupoles. The agreement in the resulting mismatch between the two methods is rather good. In both cases the periodicity in one of the transverse planes is better than in the other.

This can be seen as well using a different matching setup - excluding the first magnet from the previous case and including one more upstream. The result is shown in Fig. 4 - here the periodic solution for one plane was very good, while for the other it was not found. Inverting the polarity swaps the results for the two planes. Since the tomographic reconstruction requires recording (x, y) projections for both planes, the reconstruction error will depend strongly on the mismatch for either of the transverse planes if they are coupled.

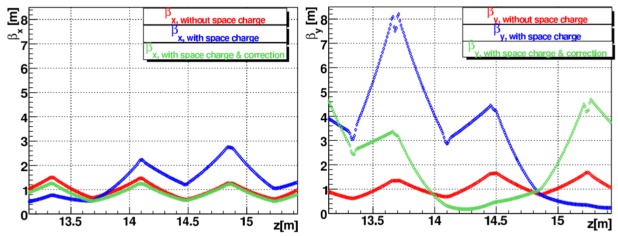

Figure 4: β_x (left) and β_y (right) along the tomography section. Inverting the quadrupoles' gradients along the tomography and matching sections delivers the same periodic solution for β_y.

PHASE SPACE RECONSTRUCTION FROM NUMERICAL DATA

Electron beam distributions have been numerically generated (using ASTRA), matched and tracked along both sections for the two matching setups described here. The four (x, y) on-screen distributions obtained are used as an input for the adopted Maximum ENTropy (MENT) [6] reconstruction algorithm. Results from (x, y) reconstruction onto (y, y') with the first setup, where the beam matching is worse in this same plane (see Fig. 3), are presented in Fig. 5. Fig. 6 shows results from the second setup, again in the plane with stronger mismatch (see Fig. 4).

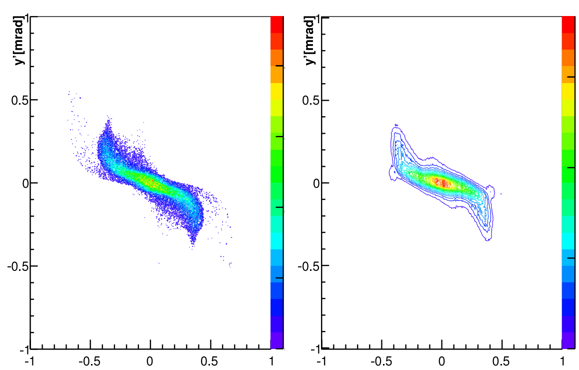

Figure 5: Original (left) and reconstructed (right) phase space in (y, y') plane.

Visually there is a good agreement with respect to the slope of the ellipses, but this is not the case for the size when there is a strong mismatch. The disagreement between the reconstructed and the ASTRA-generated distributions in terms of emittance, RMS size and the covariance are summarised in Table 1.

CONCLUSIONS

The present work reviews some basic considerations concerning a tomography diagnostics setup at the PITZ facility, particularly with regard to space charge effects. It has been shown that a space charge-dominated beam can be successfully matched (if done separately in both planes) but work still has to be done in order to easily obtain this result in both planes simultaneously. Reconstruction results for two different matching cases have been presented with good agreement in terms of phase space RMS radius, slope and covariance between the simulated and reconstructed distributions when the beam size mismatch is minimised.

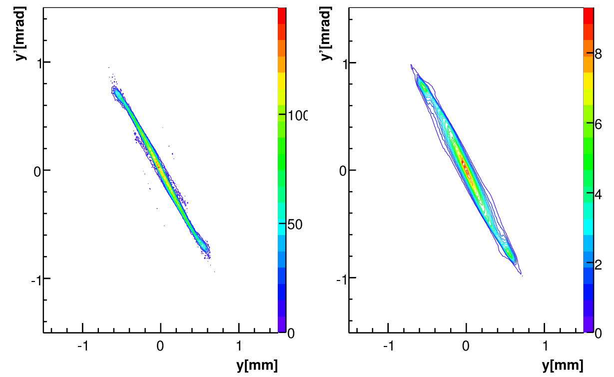

Figure 6: Original (left) and reconstructed (right) phase space in (y, y') plane.

Table 1: Disagreement between the ASTRA-simulated and the reconstructed result (matching case 1, 2 referred to with subscripts).

	Original	Reconstructed	Disagreement [%]
$\sigma_{y,1}$	0.26	0.24	7.7
$\sigma_{yy',1}$	-0.03	-0.03	-
$\varepsilon_{y,N,1}$	1.21	1.18	2.6
$\sigma_{y,2}$	0.3	0.3	-
$\sigma_{yy',2}$	-0.12	-0.13	8.3
$\varepsilon_{y,N,2}$	1.24	1.48	19

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