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BEAM TRANSVERSE COUPLING AND 4D EMITTANCE MEASUREMENT SIMULATION STUDIES FOR PITZ

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Abstract

The Photo Injector Test Facility at DESY, Zeuthen site (PITZ) was built to test and optimize high brightness electron sources for Free Electron Lasers (FELs) like FLASH and the European XFEL. Although the beam emittance has been optimized and experimentally demonstrated to meet the requirements of FLASH and XFEL, transverse beam asymmetries were observed during operation of the RF guns. Based on previous studies [1], the beam asymmetries most probably stem from beam transverse coupling by quadrupole field errors in the gun section. A pair of normal and skew gun quadrupoles was successfully used for reducing the beam asymmetries in experiment. In this paper, we discuss the beam transverse coupling between X and Y planes due to quadrupole field errors and its impact onto horizontal and vertical rms emittance. Multi-quads scan and two quads with rotated slits scan were proposed to measure the 4D beam matrix for PITZ and tested by simulation, which will give the residual beam coupling after gun quadrupoles compensation and would be helpful for minimizing the 2D rms emittance experimentally.

INTRODUCTION

During several years of operation with different generations of guns, the transverse beam asymmetry was always observed from experiments in PITZ [1-3]. From previous studies [4-5], a PITZ gun RF coupler kick was found from RF field simulations. In the transition region from the coupler to the gun, the RF field distribution is not circularly symmetric. The RF coupler kick optics can be modelled as a rotated quadrupole and a rotated quadrupole near the coupler is effective at compensating for the coupler kicks, cancelling both the coupling emittance and the astigmatic focusing [6-7]. Another source of the beam asymmetries may come from solenoid field imperfections [8]. The feature of the beam transverse coupling from rotated quadrupoles can be observed from beam transverse distributions in experiment. These effects will result in an increase of the 2D rms emittances. For FELs this would imply a deterioration of the laser performance. Linear coupling can be compensated in principle by additional rotated quadrupoles [9-10].

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QUADRUPOLE FIELD ERRORS EFFECT ON THE 4D EMITTANCE AND COUPLING TERMS SIMULATION STUDIES

4D Emittance and Coupling Factor

In order to know the compensation quadrupoles strength and how much the coupling is decoupled, a full four-dimensional (4D) beam matrix measurement becomes necessary to measure precisely and possibly further correct the transverse coupling.

The 4D beam matrix, shown in formula (1) describes the transverse statistical properties of the beam:

$$\sigma^{4D} = \begin{bmatrix} <xx> & <xx'> & <xy> & <xy'> \\ <x'x> & <x'x'> & <x'y> & <x'y'> \\ <yx> & <yx'> & <yy> & <yy'> \\ <y'x> & <y'x'> & <y'y> & <y'y'> \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy}^T & \sigma_{yy} \end{bmatrix} \quad (1)$$

And the 4D emittance is determined by (2):

$$\varepsilon_{4D} = \varepsilon_1 \varepsilon_2 = \sqrt{\det(\sigma^{4D})} \quad (2)$$

where x and y are the horizontal and vertical coordinates, respectively, x' and y' are their derivatives with respect to the longitudinal coordinate, and the ε_1, ε_2.are intrinsic emittance [11-12]. The matrices σ_{xx} and σ_{yy} describe the 2D horizontal and vertical motions, and σ_{xy} describes the cross-plane coupling. If one or more elements of σ_{xy} are nonzero, the beam is x-y coupled and the projections onto the x and y planes exhibit an increase of the observed emittance values. The transverse coupling contribution to the 2D rms emittances can be quantified by the coupling factor (3),

$$t = \frac{\varepsilon_x \varepsilon_y}{\varepsilon_1 \varepsilon_2} - 1 \geq 0 \quad (3)$$

Where ε_x, ε_y are the x and y plane 2D rms emittance. For t = 0 the beam is decoupled and for t > 0 the beam is transversely coupled.

Quadrupole Field Errors Effect on the Coupling Simulation Studies

Based on quadrupole field errors model [3], it is possible to study these kinds of field errors effect on the coupling factor t and to show how the 2D rms emittance increases by the quadrupole field errors. The simulation was done by ASTRA [13] and the machine settings are as follows: gun gradient is 51.36 MV/m, solenoid current is 350 A (arbitrary one, not the optimized current), bunch charge is 500 pC, and laser rms size is 0.3 mm with longitudinal Gaussian distribution. Beam momentum after gun is 5.8 MeV/c and after the booster is 20.8 MeV/c. A pair of normal and skew quadrupole field errors are modelled and added in the simulation and placed in the correspond-

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ing positions: Qs (skew) at z = 0.18 m (the distance from cathode); Qn (normal) at z = 0.36 m, and the effective length of both are 1 cm. By scanning the Qs and Qn strengths, range from -0.1 T/m to 0.1 T/m, one can get the influence on the beam distribution at High1.Scr1. From the simulated beam distribution, the beam matrix correlation terms and coupling factor t can be calculated for each pair of quadrupole field errors settings. The coupling factor as a function of Qs and Qn is shown in Fig. 1, and in the red square, it's the normal case for PITZ operation (Qs is negative polarity and Qn is positive polarity). When the Qs becomes from 0 to -0.05 T/m and Qn increases from 0 to 0.05 T/m, the coupling factor increased from 0.000479 to 0.322 (shown in white squares), and the coupling contribution to the 2D rms emittance is about 15% increase.

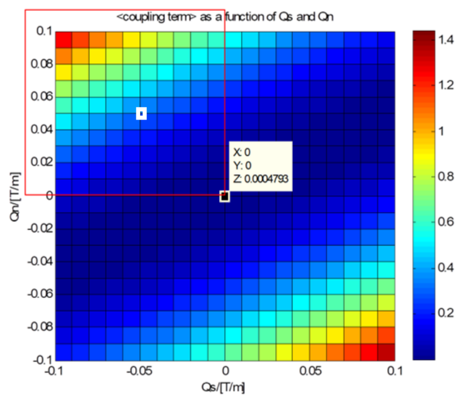

Figure 1: Simulation results for the coupling factor (colour code) as a function of Qs and Qn.

4D EMITTANCE MEASUREMENT METHOD SIMULATION STUDIES

Multi-quads Scan Method

First method to measure the 4D beam parameters is based on the multiple-optics/single-location approach: the beam parameters (<xx>, <yy> and <xy>) are measured at a single position and quadrupole strengths are changed to generate the required optics for the 4D measurement. Here we propose using the multiple-quadrupole scan technique to optimize the optics for the 4D measurement, which results in a minimization of the error of the reconstructed parameters. The reconstruction algorithm and detailed information are referred in [11, 14].

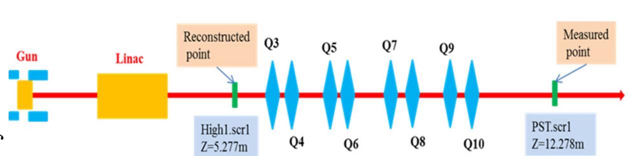

Figure 2: layout of the PITZ beam line for simulation studies of the multi-quads scan method for 4D emittance measurements.

The PITZ beam line used for this measurement is shown in Fig. 2. The reconstruction point is at High1.Scr1, the measured point is at PST.Scr1, and eight quadrupoles (Q3-Q10) are used for scanning. The machine settings are the same as before and Qs and Qn are chosen as -0.01 T/m and 0.01 T/m, respectively, which give a beam coupling and with the calculated coupling factor t = 0.014. The reconstruction point is chosen at EMSY1, because normally the 2D beam emittance and Twiss parameters are measured at this position by slits scan. It is convenient to match the beam optics by multi-quads for experiment. The basic requirements on the multi-quads scan for these measurements is to scan the phase advance between the optics reconstruction position and the measurement screen in one plane over 180 degree (if possible) and keep it constant in the second plane and the beam size at the measurement position has to be big enough for measurement. For described above set up, the phase advance scan can be from 10 to 120 degree. The designed multi-quads scan settings with MAD-X [15] are shown in Fig. 3: first 7 scans for x plane measurement and second 7 scans for y plane measurement. The total 14 scans are used for correlation terms reconstruction.

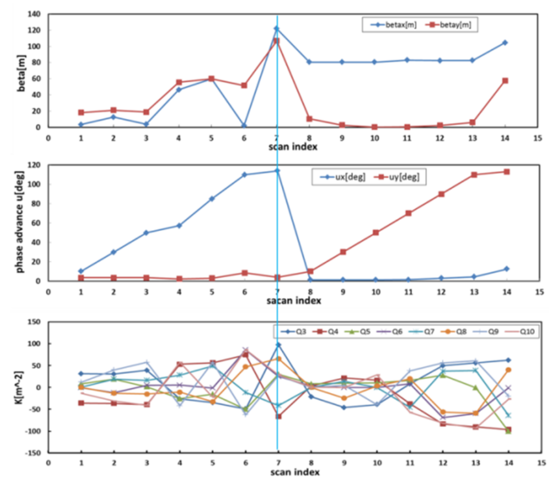

Figure 3: Beam matching for multi-quads scan method for simulation studies: beam size (β_x, β_y) at measured point, phase advance (μ_x, μ_y) between reconstructed point and measured point, and eight quads (Q3-Q10) settings for each scan.

Due to the low beam energy in PITZ, for 500 pC bunch charge, the space charge effect cannot be neglected. Therefore, the simulation studies are done for three cases, 500 pC bunch charge without space charge, 500 pC bunch charge with space charge and 100 pC bunch charge with space charge. The multi-quads settings are the same for the three cases. The reconstructed correlations terms in 4D beam matrix for the three cases are shown in Fig. 4. Compared with the initial values of the correlation terms, the 500 pC without space charge and 100 pC with space charge can be precisely measured with this method, but for 500 pC with space charge, this method has some errors and the correlation terms are over estimated. For the coupling factor, the initial beam has 0.0140, for the 500 pC without space charge case, it is 0.0142, for the 500 pC with space charge, it is 0.0075 and for 100 pC with space charge, it is 0.0113.

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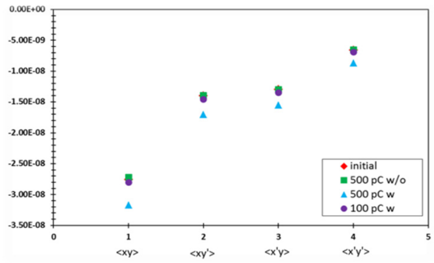

Figure 4: Reconstructed 4D emittance correlation terms from simulation studies with multi-quads scan method and compared with the initial ones.

Rotated Slits Plus Two Quads Scan Method

Another 4D emittance measurement method, rotated slits plus two quads scan is also investigated for the PITZ beam line by simulation. The detailed algorithm of this method is referred in [12]. For this method, three slits, 0 degree, 90 degree and one more rotated slit(not 0 or 90 degree) and two quadrupoles are needed. For the PITZ beam line, the experimental layout is shown in Fig. 5. The reconstruction position is chosen at EMSY1, same as previous method and only two quadrupoles Q3-Q4 are used, the slits are at EMSY2 position, and the beamlet measurement position is at High1.Scr5. For the current PITZ set up, this method only needs one more slit install at EMSY2 with 45 degree (in this study) rotation angle, which is easy to implement in PITZ set up and also the Fastscan software for slits scan emittance measurement can be used directly. For the simulation studies, the machine settings are the same as before. The reconstruction position and the coupled beam distribution (to be reconstructed) induced with Qs = -0.1 T/m and Qn = 0.1 T/m are also same with previous method used in simulation.

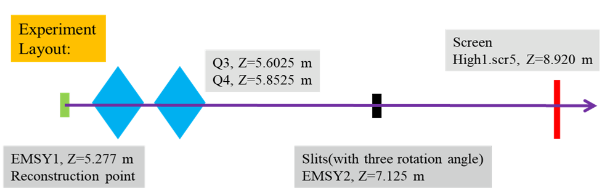

Figure 5: Layout of PITZ beam line used for the simulation study of the 4D emittance measurement with rotated slits plus two quads.

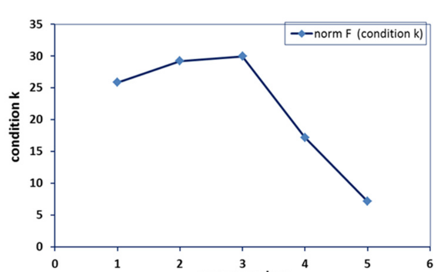

Figure 6: Condition k value for each group of two quads settings in simulations.

A pair of quadrupoles with two different settings ($Q3^a$&$Q4^a$ and $Q3^b$&$Q4^b$) is used for the scan. We can do the three slits scan respectively both for a and b settings. From described above six measurements, the 4D beam matrix at reconstruction point can be reconstructed completely and reliably. Minimum measurements is four, 0, 90 and 45 degree slits scan with a settings and 45 degree slits scan with b settings.

For this method, the most important is the determination of the two quads settings, which is determined by condition number k [12]. Well-conditioned matrices have condition numbers which are close to 1.0. Two different quadrupoles settings are selected by varying in brute force search method and from which we need to get 100% beam transmission from reconstruction point to the measurement screen and reasonable beam size at slit and screen. From simulation we tried five groups settings of the two quadrupoles, which meet the above requirement, and the condition number k for each group is shown in Fig. 6. For group 5 settings, the condition number k is the smallest.

The reconstructed correlation terms of the 4D beam matrix are shown in Fig. 7 for each group of two quadrupoles settings. Compared with the initial correlation terms value, for group 5 settings, the reconstructed values are most close to the initial value. Furthermore, the simulation was done with and without space charge for 500 pC bunch charge. It is clearly shown that the space charge has less effect for the 4D beam matrix correlation terms measurement.

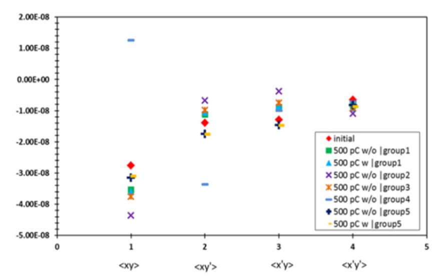

Figure 7: Reconstructed 4D beam matrix correlation terms from simulation studies with rotated slits plus two quads method and compared with the initial ones.

CONCLUSION

The beam transverse coupling due to RF coupler kick and solenoid field imperfection for PITZ was studied by simulation with quadrupole field errors model. These quadrupole field errors would increase the 2D rms emittance. Two methods for measuring the 4D beam matrix are proposed for the PITZ beam line and tested by simulation. For multi-quads scan method, it is still affected by the space charge effect, thus good for low bunch charge measurement at PITZ. But it is valid for European-XFEL injector 4D emittance measurement with high beam energy. The second method is rotated slits with two quads scan, the simulation results show it is possible to get approximate results with good quads settings and the space charge has less effect on the 4D emittance measurement. This method is easy to implement for the PITZ accelerator. Beam transverse coupling and 4D emittance measurement simulation studies are helpful for PITZ to fully experimentally optimize the 2D rms emittance with gun compensation quadrupoles [10].

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REFERENCES

[1] Q. Zhao *et al*., "Beam asymmetry studies with quadrupole field errors in the PITZ gun section", in *Proc. FEL'17*, WEP010.

[2] M. Krasilnikov *et al*., "Experimentally minimized beam emittance from an L-band photoinjector", *PRST-AB*, vol. 15, 100701, 2012.

[3] M. Krasilnikov, Q. Zhao *et al*., "Investigations on electron beam imperfections at PITZ", Proc. of LINAC'16, MOPLR013.

[4] I. Isaev, "RF field asymmetry simulations for the PITZ RF Photo Gun", DPG-Frühjahrstagung Wuppertal, 9 March 2015.

[5] Y. Chen *et al*., "Coaxial Coupler RF Kick in the PITZ RF Gun", in *Proc. FEL'17*, WEP005.

[6] M. Dohlus et al., "Coupler kick for very short bunches and its compensation", in *Proc. EPAC'08*, pp. 580-582, Genoa, Italy.

[7] D. Dowell, "Analysis and cancellation of RF coupler-induced emittance due to astigmatism". Report no. LCLS-2 TN-15-05, SLAC, 2015.

[8] J. Schmerge, "LCLS gun solenoid design considerations", Report no. SLAC-TN-10-084, SLAC, 2010.

[9] H. Wiedemann, *Particle Accelerator Physics*, Third Edition, pp 605-620.

[10] M. Krasilnikov *et al*., "Electron beam asymmetry compensation with gun quadrupoles at PITZ", in *Proc. of FEL'17,* WEP007.

[11] Eduard Prat and Masamitsu Aiba. Four-dimensional transverse beam matrix measurement using the multiple-quadrupole scan technique. PRST-AB 17, 052801, 2014.

[12] C. Xiao, M. Maier, X. N. Du, P. Gerhard, L. Groening, S. Mickat, and H. Vormann. Rotating system for four-dimensional transverse rms-emittance measurements, *PRAB 19*, 072802, 2016.

[13] K. Floettmann, ASTRA particle tracking code, `http://www.desy.de/~mpyflo/`.

[14] Florian L¨ohl, Measurements of the Transverse Emittance at the VUV-FEL, Diploma thesis, 2005.

[15] MAD-X, `http://madx.web.cern.ch/madx/`.