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

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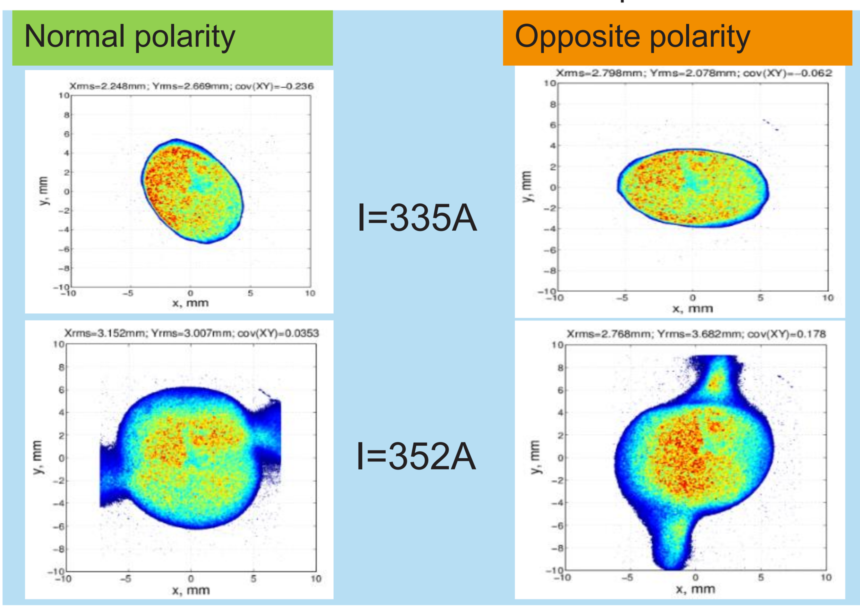
Introduction and motivition

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 RF guns. Based on previous studies [*FEL2017, Q.Zhao*], 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 4D beam matrix at PITZ and tested by simulation, which will give the residual beam coupling after gun quadrupole compensation and would be helpful for minimizing the 2D rms emittance by tuning compensation gun quadrupoles in experiment.

Figure 1: Beam images at High1.Scr1, the position is 5.277m away from cathode, laser RMS size 0.3 mm, 500 pC, 6.0 MeV/c. Measured results from Gun4.6 operation.



4D beam matrix:

$$\sigma^{4D} = \begin{bmatrix} <xx> & <xx'> & <xy> & <xy'> \\ <x'x> & <x'x'> & <x'y> & <x'y'> \\ <yx> & <yx'> & <yy> & <yy'> \\ <y'x> & <y'x'> & <y'y> & <y'y'> \end{bmatrix}$$

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

Coupling factor: $t = \dfrac{\varepsilon_x\varepsilon_y}{\varepsilon_1\varepsilon_2} - 1 \geq 0$

Quadrupole field errors effects on the 4D emittance and couplings factor

Simulation settings:

Gun 51.36 MV/m, solenoid 350 A, bunch charge 500 pC, laser rms size 0.3 mm; Gaussian beam. Beam momentum after gun: 5.87 MeV/c;

Booster: 17.2 MV/m, after booster: 20.874 MeV/c;

Qs at z=0.18 m, Qs is negative polarity;

Qn at z=0.36 m, Qn is related to solenoid, for normal current, Qn is positive polarity.

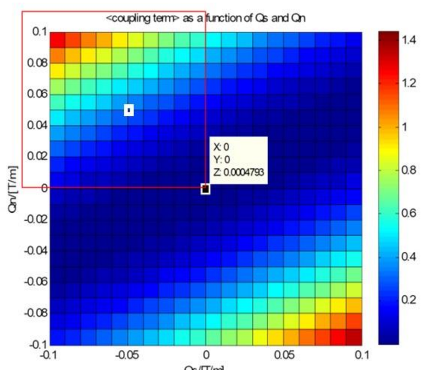
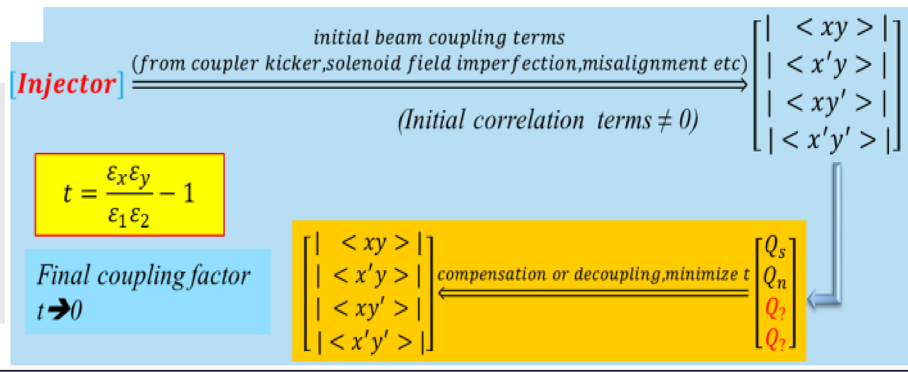


Figure2: Coupling factor as a function of Qs and Qn.

Table1: coupling factor for different Qs and Qn.

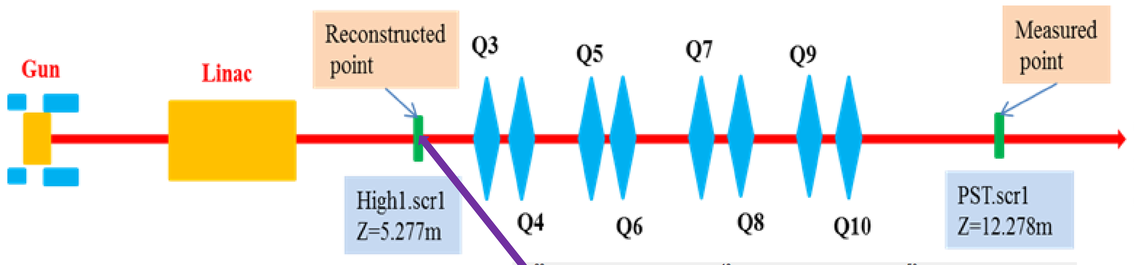
Qs	Qn	rmsemitx	rmsemity	intriemit1	intriemit2	Coupling factor
0	0	2.658e-05	2.555e-05	2.683e-05	2.529e-05	4.782e-04
-0.01	0.01	3.091e-05	2.325e-05	3.145e-05	2.251e-05	0.0147
-0.05	0.05	6.387e-05	3.244e-05	6.308e-05	2.465e-05	0.322
-0.1	0.1	8.269e-05	6.748e-05	6.726e-05	3.554e-05	1.3338

General procedure for injector decoupling and optimize the 2D rms emittance close to intrinsic emittance.



4D emittance measurement method----Multi-quads scan

Figure 3: PITZ beam line layout for multi-quads scan 4D emittance measurements.



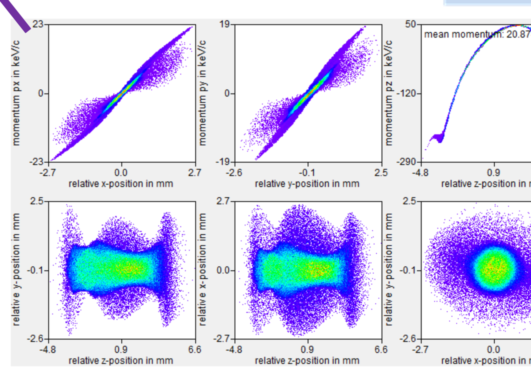


Figure 4: Coupled beam distribution at the reconstruction point induced by Qs=-0.1 T/m and Qn=0.1 T/m.

Figure 5: Reconstructed 4D beam matrix correlation terms from simulation studies with multi-quads scan method and compared with the initial ones.

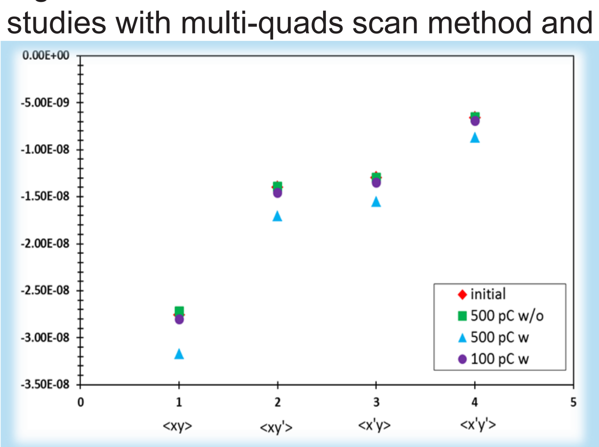


Figure 6: Beam optics design for multi-quads scan. The designed multi-qauds scan settings with MAD-X: first 7 scans for x plane measurement, the x plane phase advance scan from 10 to 120 and keep the y lane phase advance nearly constant and second 7 scans for y plane measurement and the phase advance scan vice versa, and the total 14 scans for correlation terms reconstruction.
The calculated <xx>, <yy> and <xy> for each scan.

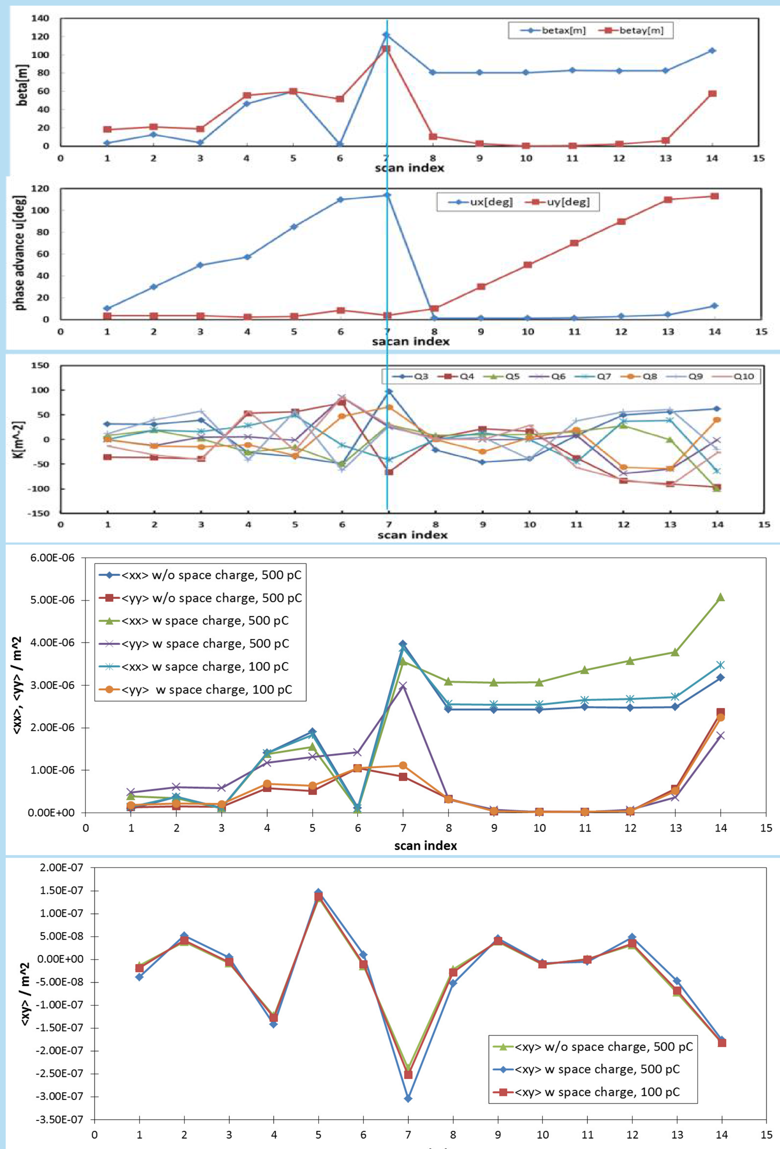


Table2: Initial and reconstructed correlation terms with multi-quads scan method.

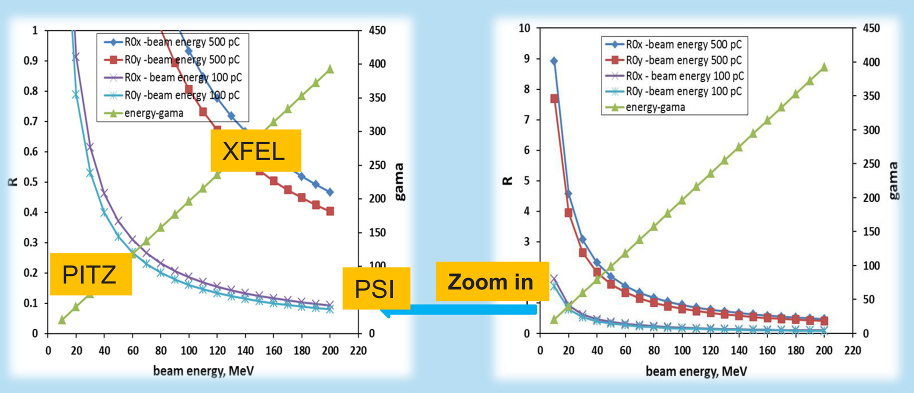
	<xy>	<xy'>	<x'y>	<x'y'>
Initial (goal)	-2.76E-08	-1.40E-08	-1.30E-08	-6.60E-09
500 pC w/o	-2.72E-08	-1.40E-08	-1.30E-08	-6.52E-09
500 pC w	-3.17E-08	-1.71E-08	-1.55E-08	-8.69E-09
100 pC w	-2.81E-08	-1.46E-08	-1.35E-08	-6.94E-09

Space charge effect:

The notion of space-charge dominated flow is quantified by comparing the space charge and emittance terms in the rms beam envelope equation for an ultra-relativistic beam in a drift space ($\gamma \gg 1, \beta = v/c \approx 1$). taking the ratio of the second to the first terms on the right-hand side of the envelope equation, we have a measure **(R)** of the degree of space-charge dominance over emittance in driving the evolution of the beam envelope.

$$\sigma_x'' = \frac{\epsilon_{nx}^2}{\gamma^2\sigma_x^3} + \frac{I}{\gamma^3 I_0(\sigma_x + \sigma_y)} \qquad R_{0x} = \frac{I\sigma_x^3}{\epsilon_{nx}^2 I_0(\sigma_x + \sigma_y)}$$

Figure 7: The calculated R as function of beam energy with above beam distribution.



4D emittance measurement method----rotated slits plus two quads scan

Figure 8: PITZ beam line layout for rotated slits plus two quads 4D emittance measurements.

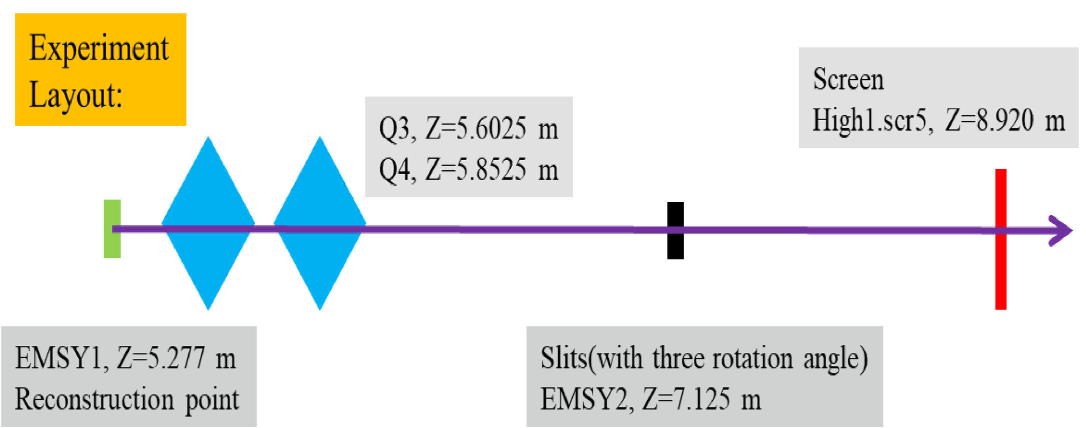


Table 3: Five groups of two quds settings.

	Q3, k / m^2	Q4, k /m^2
group1		
a	-21.5	19
b	-15	16
group2		
c	-10	8
d	10	-12
group3		
e	-10	8
f	-21.5	19
group4		
e	-25	33
f	-22	38
group5		
e	-45	43
f	-24	40

Figure 9: Condition k value for each group of two quads settings in simulations.

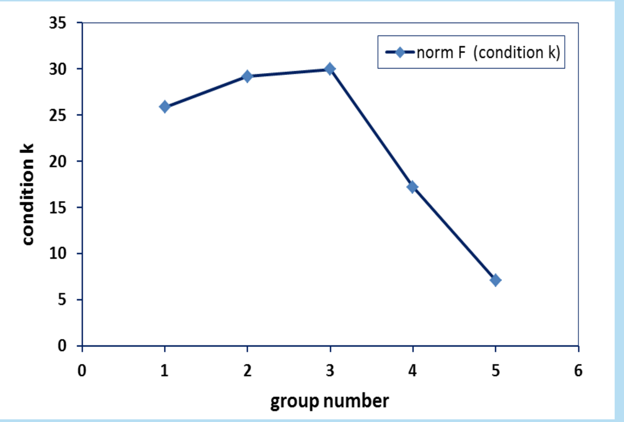


Figure 10: Reconstructed 4D beam matrix correlation terms from simulation studies with rotated slits plus two quads scan method and compared with the initial ones.

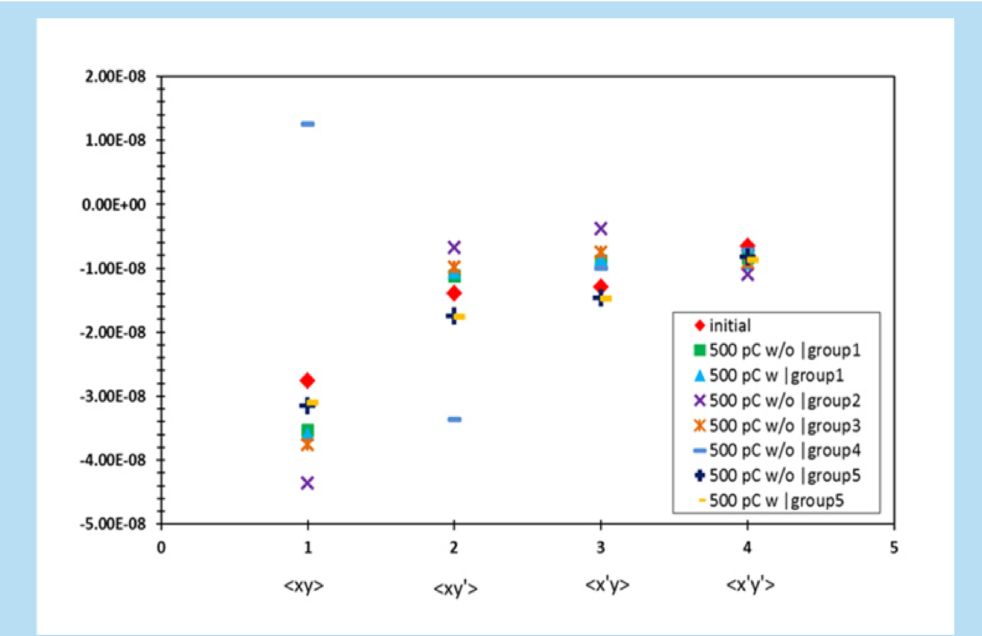


Table4: Initial and reconstructed correlation terms with rotated slits plus two quads scan method.

	<xy>	<xy'>	<x'y>	<x'y'>
Initial (goal)	-2.76E-08	-1.40E-08	-1.30E-08	-6.60E-09
500 pC w/o/ group1	-3.53192E-08	-1.1172E-08	-8.87733E-09	-8.37941E-09
500 pC w/ group1	-3.59878E-08	-1.0633E-08	-8.48221E-09	-9.23953E-09
500 pC w/o group2	-4.36E-08	-6.85E-09	-3.87E-09	-1.09E-08
500 pC w/o group3	-3.76E-08	-9.84E-09	-7.55E-09	-9.18E-09
500 pC w/o group4	1.26E-08	-3.37E-08	-9.94E-09	-7.12E-09
500 pC w/o group5	-3.15E-08	-1.75E-08	-1.47E-08	-8.31E-09
500 pC w group5	-3.10E-08	-1.77E-08	-1.48E-08	-8.76E-09

Summary and Conclusions

- The beam transverse coupling due to RF coupler kicker and solenoid field imperfection for PITZ was studied by simulation with quadrupole field errors model.
- The decoupling procedure of the beam transvers coupling with additional Qs and Qn is proposed and this procedure is valid for different kind of injector.
- Two methods for measuring the 4D beam matrix are proposed for PITZ beam line and tested by simulation.
  - ✓ For multi-quads scan method, it is precise for low bunch charge and for high bunch charge, the space charge effect on the quads scan should be taken into account. But this method is valid for European-XFEL injector 4D emittance measurement.
  - ✓ 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 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 Qs and Qn compensation quadrupoles.

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