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BEAM ASYMMETRY STUDIES WITH QUADRUPOLE FIELD ERRORS IN THE PITZ GUN SECTION

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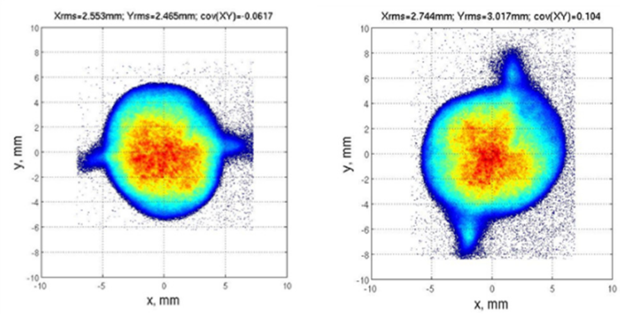
Abstract

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, such as wing structures and beam tilts were observed during many years of operation with different generations of guns. These cannot be explained by simulations with the rotationally symmetric gun cavities and symmetric solenoid fields. Based on previous coupler kick, solenoid field imperfection studies and coupling beam dynamics, the beam asymmetries most probably stem from anomalous quadrupole field error in the gun section. A thin lens static quadrupole model is applied in the RF gun section simulations to fit the position and intensity of quadrupole field errors by comparing the beam asymmetry directions in experiments and ASTRA simulations. Furthermore, by measuring the laser position movement at the photocathode and the corresponding beam movement at downstream screens, the integrated quadrupole field strength can also be extracted.

INTRODUCTION

The RF gun of PITZ is a rotationally symmetric 1.6 cell L-band cavity. The electron beam is generated at the cathode by a laser and then accelerated by gun cavity RF fields and focused by the solenoid field. From beam dynamics simulation with $E_z(z)$ and $B_z(z)$ field map in ASTRA [1], the beam transverse distribution is symmetric anywhere downstream the gun cavity, which is not exactly matching to the experimental results. During several years of operation with different generations of guns, the imperfect beams were always observed from experiments [2-3], such as beam tilt from transverse images, beam wing structures, asymmetric x and y phase space distributions and not round beam transverse distributions observed during emittance measurements. One of the most obvious asymmetric features is the beam wing structure shown in Figure 1 from experiment. For Figure 1 the experiment results were taken at High1.Scr1 (z = 5.277 m from cathode) with beam momentum of 6.18 MeV/c, bunch charge 480 pC and two polarities of the main solenoid (Imain) but the same current. The beam wings are at



(a) (b)

Figure 1: Beam images at High1.Scr1 (a) normal solenoid polarity (Imain = -360 A) and (b) opposite solenoid polarity (Imain = +360 A).

different orientations due to different rotation angle caused by different solenoid polarity.

From previous studies [4-5], the 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 uniform. The RF coupler kick optics can be modelled as a rotated quadrupole with focal length and rotation angle given in terms of complex voltage kicks. 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. Beam asymmetries from photo gun are also observed in other labs [8]. The feature of the beam transverse coupling from rotated quadrupoles can be observed from beam transverse distributions in experiment like the beam tilt in Figure 1. Linear coupling can be compensated in principle by additional rotated quadrupoles, but the beam dynamics for coupling effects must be known to perform a proper compensation [9].

QUADRUPOLE FIELD ERROR POSITION AND ROTATION ANGLE ESTIMATION

Experiments for Beam Wings Studies

For beam asymmetry studies, some dedicated experiments were done with different RF power in the Gun4.2 and solenoid current scan. Three values of power 5 MW, 3 MW and 1.5 MW in the gun were used. The beam wings appeared at High1.Scr1 by solenoid current scan and the clearest signals of beam wings are seen for Imain at 360 A, 290 A, 219 A respectively and other Imains have shown the beam tilted images for both polarities. The

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beam images with beam wing structure are shown in Figure 2 row 3 for different gun power. For each gun power, when changing the polarity of the solenoid, the beam wing directions are changed. The experiment settings and beam parameters are shown in Table 1.

Table 1: Experimental Settings for Beam Wings Studies

Power (MW)	**Gradient** (MV/m)	**|Imain|** (A)	**Charge** (pC)	**Maximum Momentum** (MeV/c)
5	54.2	360	502	6.18
3	42.2	290	502	4.86
1.5	31.4	219	334	3.69

Beam Wings Directions Fitting by Simulations with Rotated Quadrupole Model

For RF power of 5 MW in the gun, the beam wings appeared in different directions with both solenoid polarities. With Imain = -360 A, the beam wings are at about 12 degrees with respect to the anticlockwise direction and for Imain = 360 A the beam wings are at about 78 degrees. A rotated quadrupole model is added in simulations with scanning both the quadrupole positions along the beam line, the rotation angle and the strength. The rotation angle is scanned from 0 to 360 degrees with a step of 5 degrees for each position in order to fit the beam wings direction to that of the experimental images. The quadrupole model parameters are shown in Figure 2, with an effective length of 0.01 m. The simulated beam images at High1.Scr1 are investigated with both solenoid polarities as a function of the quadrupole rotation angle at the assumed kick location position. The quadrupole positions scanning range covered the whole possible area where a quadrupole like field could exist due to field imperfection reason. The range is from 0.12 m to 0.38 m at a step of 0.02 m. By fitting the beam wings direction for both solenoid current polarities from the simulation to experiment, two possible positions and corresponding rotation angles of the quadrupoles were found. One is shown at z = 0.18 m, with skew type (rotation angle 135 degree); another one is at z = 0.36 m, with normal type (rotation angel 0 degree). The simulated image results are shown in Figure 2, in row 4 and row 6. The beam wings structure appeared from simulation with quadrupole fields. The beam wings directions could fit to the experiment results very well with found quadrupole positions and rotation angle. For the skew quadrupole at z = 0.18 m, when change the solenoid polarity, the quadrupole polarity did not change, but for the normal quadrupole at z = 0.36 m, the quadrupole polarity changes together with the main solenoid polarity.

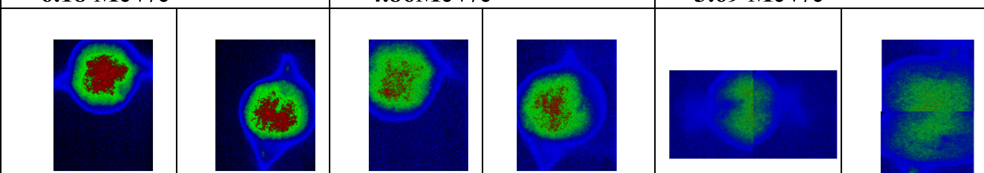
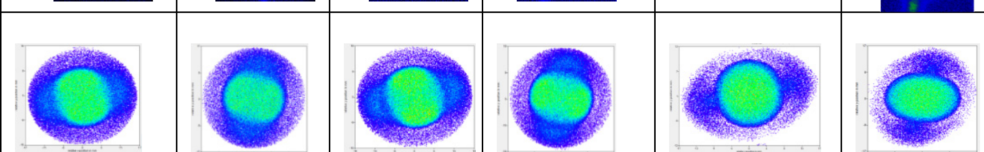
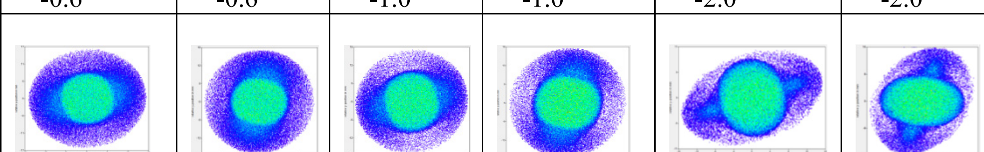
Imain	-360 A	+360 A	-290 A	+290 A	-219 A	+219 A
Beam momentum from experiment	**5 MW in the gun 6.18 MeV/c**		**3 MW in the gun 4.86MeV/c**		**1.5 MW in the gun 3.69 MeV/c**	
Experiment: Beam at High1.Scr1 at z = 5.277 m						
Simulation: High1.Scr1 with skew quad (rotation angle 135 degree) at z = 0.18 m						
K_{skew} (m^{-2})	-0.6	-0.6	-1.0	-1.0	-2.0	-2.0
Simulation: High1.Scr1 with normal quad (rotation angle 0 degree) at z = 0.36 m						
K_{normal} (m^{-2})	0.2	-0.2	0.3	-0.3	1.0	-1.0

Figure 2: Experimental beam images (row 3) and simulation results, with skew quadrupole located at z = 0.18 m (row 4) and with normal quadrupole located at z = 0.36 m (row 6). The row (5) and (7) are the quadrupole strength used in simulation when the beam wings structure appeared.

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QUADRUPOLE FIELD ERRORS STRENGTH ESTIMATION

Principle and Method for Estimating the Rotated Quadrupole Field Strength

In the PITZ gun section, because of the overlap of the RF and solenoid fields, also couplings from solenoid and quadrupoles field error are both existing, which causes the coupling problem to be more complicated. If we track the beam in a solenoid induced coordinate system, the coupling due to beam rotation induced by the main solenoid can be neglected. Beam transport in a solenoid will be rotated and the rotation angle can be defined by:

$$\emptyset = -\frac{1}{2}\int_{z_0}^{z} S(z)\,\mathrm{d}z, \quad S(z) = \frac{e}{P(z)} B_s(z)\,, \qquad (1)$$

where the solenoid field $B_s(z)$ starts from z_0. In the gun section, the beam momentum P(z) increases along the beam line, so the rotation angle along the gun section beam line depends not only on the solenoid field profile but also on the RF field profile. By varying the laser position at the cathode and observing the corresponding electron beam movements at downstream screens, the integrated quadrupole field strength can be extracted. The principle is shown in Figure 3: (a) laser positions at the cathode, (b) beam positions at the downstream screens in lab coordinate (x, y), (c) beam positions at downstream screens in solenoid induced rotation coordinate (x', y') without any other x-y coupling, (d) beam positions at downstream screens in solenoid induced rotation coordinate (x', y') with other x-y coupling (rotated quadrupole, et al). The beam relative positions in lab coordinate system transform to the solenoid induced coordinate system. By fitting the simulation results to experiment, the rotated quadrupole strength can be estimated.

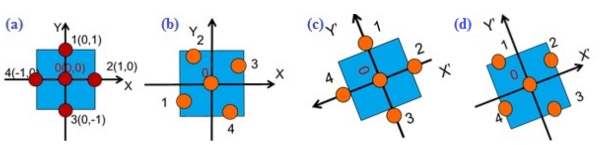

Figure 3: Sketch map of beam positions in different coordinate system.

Rotated Quadrupoles Strength Estimation for Gun with Solenoid

One important parameter for transforming the coordinates from the lab coordinate frame to the solenoid induced coordinates is the rotation angle induced by the solenoid field. So a beam imaging experiment by grid transverse shaping the laser beam at the cathode [3] was done to check the rotation angle with simulation. The experiment was taken with Gun4.2 operated at 5 MW with focusing solenoid currents. Laser RMS size is 0.3 mm and the bunch charge is 500 pC. The laser relative positions are as following: 10, (0.018, 1.001) mm, 20, (0.98, -0.001) mm, 30, (-0.008, -1.066) mm, 40, (-1.015, 0.073) mm, where 10 means laser relative position with laser position at 1 (up ~1 mm) minus laser position at 0 (nominal running position), other positions 20, 30, and 40 are in a similar way. The laser positions at VC2 (virtual cathode camera) and the beam positions at Low.scr3 (z = 1.708 m from cathode) are shown in Figure 4. We moved the laser to five positions, up and down, left and right and zero positions shown in Figure 4 (a) and observed the corresponding beam positions at Low.scr3 shown in Figure 4(b).

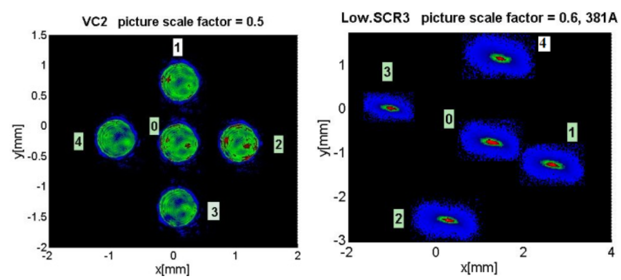

Figure 4: The laser positions at VC2 (a) and beam positions at Low.scr3 (Imain = -381 A) (b) in lab coordinate from experiment.

From the previous studies, we found two possible locations of kicks: skew quadrupole at z = 0.18 m and normal quadrupole at z = 0.36 m. So these two quadrupoles were used for changing the beam relative positions from simulation and try to fit to the experimental results, by which the quadrupoles strength can be estimated. The results are shown in Table 2 for two solenoid currents. It is shown with normal and skew quadrupoles the simulated beam relative positions are changed much closer to the experiment results, especially for laser position 30 fitting very well. The quadrupole strength was estimated to be: g_{skew} = -0.01 T/m, g_{normal} = 0.04 T/m for Imain = -356 A and g_{skew} = -0.01 T/m, g_{normal} = 0.09 T/m for Imain = -381 A, the quadrupole effective length is assumed to be 1 cm in simulation. In Table 2, the italics numbers are the fitting positions between experiment and simulation results with the rotated quadrupoles mentioned above, other non-italic numbers still have big discrepancy from simulation and experiment. Due to the source of the quadrupole error field are expected from gun coupler and solenoid field imperfections, there are anomalous quadrupoles and the field distribution is irregular. But in simulation we use regular quadrupole fields. Therefore in simulation we cannot fit all four positions to experiment at the same time with one group of normal and skew quadrupoles. By fitting position 30 and several other positions, the estimated quadrupole strength is still reasonable.

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Table 2: Experimental and simulated (with quadrupoles) beam relative positions in solenoid induced coordinate system.

P	-356A Simulation (x,y)(mm)	-356A Experiment (x,y)((mm)	-381A Simulation (x,y) (mm)	-381A Experiment (x,y)((mm)
10	(-0.11, -1.18)	(0.12, -0.73)	*(-0.20,* -2.21)	*(-0.17,* -1.49)
20	*(-1.08,* -0.11)	*(-0.93,* 0.35)	*(-1.97,* -0.20)	*(-1.97,* 0.57)
30	*(0.11, 1.18)*	*(0.10, 1.12)*	*(0.20, 2.21)*	*(0.21, 2.44)*
40	(*1.08*, 0.11)	(*1.02*, -0.13)	*(1.97, 0.20)*	*(1.91, 0.26)*

CONCLUSION

The beam tilt and wing structure observed from experiments can be reproduced by ASTRA simulations including a rotated quadrupoles model for different gun power and solenoid current and the wings directions can be fit rather good. These simulations were done with parameters completely the same as the experimental machine running settings. Two positions of the quadrupole-like error fields were found, one is at z = 0.18 m, which is most probably from the RF coupler field asymmetry and it's polarity does not depend on the solenoid polarity, another one is at z = 0.36 m, which is most probably from the solenoid field imperfection and it's polarity changes when changing the solenoid polarity. From moving the laser spot at the photocathode experiment, the method for estimating the rotated quadrupoles strength is validated and confirmed by simulation. Combining experimental and simulated results, the skew and normal quadrupoles strengths can be estimated to be on the orders of 10^{-4} T and it is also found that these quadrupole error fields are not regular and have anomalous distribution. These results are helpful for the further beam asymmetries compensation and optimization studies [10].

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