Beam asymmetry compensation at DESY photoelectron guns

I Isaev, M Krasilnikov, Q Zhao
Deutsches Elektronen-Synchrotron DESY, 15738 Zeuthen, Germany

E-Mail: igor.isaev@desy.de

Abstract. Quadrupole fields are considered as an option for beam asymmetry compensation for L-band photoelectron guns used at DESY. The quadrupoles dedicated for the installation at a gun coupler region have three designs. The first two designs were installed and tested with photoelectron beam. The designs of the quadrupoles and experiments results are presented.

1. Introduction
One of the most suitable electron sources for modern Free-electron Lasers (FELs) is a photoelectron gun. A photoelectron gun combines electron generation utilizing photoemission and direct acceleration in the RF cavity. Photoemission allows the generation of higher current densities than in the case of thermionic cathodes and also provides better control over the transverse and longitudinal electron pulse distributions.

The Photo-Injector Test Facility at DESY in Zeuthen (PITZ) is built to develop, operate and characterize electron sources meeting the requirements for FELs operated in the SASE regime as Free-electron LAser in Hamburg (FLASH) [1] and the European X-ray Free Electron Laser (European XFEL) [2]. The requirements include a projected transverse normalized RMS emittance below 1 mm mrad, an RMS bunch length below a few mm and a nominal bunch charge of 1 nC [3].

The tests of the photoelectron gun at PITZ showed that the gun is able to provide required emittance, but at the same time, the optimal parameters (charge, transverse laser spot size, solenoid current) for the smallest emittance were different compared to simulations.

Additionally, during emittance measurements at PITZ an electron beam asymmetry was observed. The asymmetry was found for the beam transverse profile as well as for phase space pictures. The electron beam emittance shows additional undesirable tails that disclose the beam asymmetry (see figure 1).

![Figure 1](image.png)

Figure 1. Asymmetric transverse electron beam shape (left), and asymmetric X and Y phase spaces (middle and right) observed during emittance measurements at PITZ.
2. Beam asymmetry investigations

During electron beam asymmetry investigations a number of experiments for identification of the asymmetry source were performed [4].

The experiment on Larmor angle showed that the beam asymmetry source should be located around the region of coaxial coupler transition to the full cell of the gun. In the same region, the main solenoid is installed. Additionally to this experiment, simulations on the 'back-tracking' particle were performed [5]. Similar to the Larmor experiment, the particle tracking was carried out for two polarities of the main solenoid current (positive and negative). The simulations showed that the distributions of the mentioned particles coincide at the place. That was revealed during the Larmor experiment. The orientations of the particles distributions at this place are 45 deg. This fact is a hint that the beam asymmetry source feature a quadrupole structure.

Based on the insight and experience from other laboratories [6], there were performed thorough simulations on the beam asymmetry modeling [7]. In the simulations, the beam asymmetry source was modeled by a pair of quadrupoles. Position, strength and rotation angle of the quadrupoles were optimization parameters for fitting simulated beam shapes to the beam transverse profile images obtained from the experiment.

The simulations showed that the beam asymmetry can be modeled by the pair of quadrupoles. In this case, the first quadrupole must be located at position 0.18 m (the region of a coaxial coupler to the full cell) downstream the cathode, with skew orientation (45 deg for negative current polarity or 135 deg for positive current polarity). The polarity of the first quadrupole should not vary with changing the main solenoid polarity. The second quadrupole must be located at the position of 0.36 m (around the center of the main solenoid, but slightly shifted towards the downstream end). The quadrupole must have normal orientation, and the polarity should change together with the change of the main solenoid polarity.

The simulations results lead to the idea of building a quadrupole able to compensate the asymmetrical field that produces the beam asymmetry, and might be mounted onto the gun, which was already installed in the tunnel.

3. The first design of the gun quadrupoles

As the most suitable option (among single-wire and PCB quadrupole designs), air-coil based gun quadrupole design was selected (depicted in figure 2). As the only appropriate location for the quadrupole installation was selected the coaxial coupler near the gun-coupler flange.

![Figure 2. The view of the first design of the gun quadrupole: CAD model (left) and the corresponding produced quadrupole (right).](image)

The coil parameters were chosen according to the magnetic field simulations performed in CST Studio [8]. Using the simulation results, there was produced a quadrupole with the following parameters: aluminium frame, four air coils made of 0.56 mm thick copper cable with 180 windings, two thermal switches with non-magnetic screws and threshold at 80 deg C to prevent overheating. The quadrupole was fixed at the coaxial coupler by a radiation hard cable tie. The quadrupole was connected to the
power supply (with current stabilization) with a current limit of 3 A. The field measurements in a laboratory showed good consensus of the simulations and measurement results.

Since the quadrupole frame of the first design has only four coils, there were performed two series of the measurements, particularly with normal and skew quadrupole installations. The orientation change of the quadrupole was done by hands with the operation interruptions and tunnel access. The measurements were performed for 5 MW peak power in the gun, maximum mean momentum gain RF phase, 500 pC bunch charge, 1.2 mm laser transverse spot size, main solenoid current of 335 A (the solenoid current at which beam asymmetry mostly pronounced) at normal and opposite polarities, the bucking solenoid and the booster were switched off. The results showed that the normal-oriented quadrupole can make beam shape more round, but only for normal polarity of the main solenoid current, while the beam at opposite solenoid polarity becomes less round. The same situation was observed with the skew-oriented quadrupole.

4. The second design of the gun quadrupoles
The promising results of the first design of the gun quadrupoles tests and additional time slot for new tests allowed to create a second design of the gun quadrupoles, to produce and to test it.

The second design extends the previous design by additional air coils on an aluminium frame. The further differences are: two quadrupoles are placed on a single frame (each of the quadrupoles supplied separately), the number of copper cable (0.56 mm) windings was reduced to 140, because the geometry of the coils was changed to have as strong as possible quadrupole gradient (which is 0.0117 T/m at 1 A). In analogy to the first design, the quadrupole consists of two thermal switches with a threshold of 80 deg C. Initially, the quadrupole was fixed at the gun coaxial coupler by a radiation-hard cable tie, but later the fixation was exchanged to an aluminium clamp (because later the quadrupole was kept for standard operation). The CAD model and images of the second design of the quadrupole are presented in figure 3.

4.1. The transverse beam profile measurements
The transverse beam profile measurements were performed with the same settings as for the first quadrupole design (5 MW in the gun and switched off booster). The beam measurements with quadrupole showed the possibility to obtain symmetric beam profiles for both polarities of the main solenoid. For the case of the most round beam, the polarity of the normal-oriented quadrupole (Gun Q1) changes its polarity with changing polarity of the main solenoid, while the polarity of the skew-oriented quadrupole (Gun Q2) did not show this behavior. This result agrees with beam asymmetry modeling by two quadrupoles [7].

4.2. The emittance measurements
In order to correctly set quadrupole currents for the emittance measurements, the transverse beam shape scan adjustments were performed. During the adjustments, beam transverse profile pictures were
taken for different quadrupoles settings at two screens: screen station used for slit masks, and the screen used for beamlets collection. Afterward, the quadrupoles currents were selected to have the most round beam on both screens at the same time. The resulted currents are Gun Q1 = -0.6 A and Gun Q2 = -0.5 A.

For the emittance measurements adjustments the so-called solenoid scan was performed, meaning that the emittance and beam sizes dependencies are measured vs the main solenoid current. The emittance measurements were performed at following PITZ parameters: laser transverse spot size = 1.2 mm, charge = 500 pC, gun power = 6.5 MW, booster power = 3 MW, Gaussian laser temporal profile = 11.5 ps, bunch length = 15.8 ps. Emittance measurements vs solenoid current for the case of 0 currents of the gun quadrupoles and the optimized beam shape at two screens are presented in figure 4 (left bottom plots).

![Figure 4](image)

Figure 4. Emittance measurements results with the second gun quadrupole design: emittance values and beam sizes vs main solenoid currents (top pictures), beam profiles and phase spaces (left bottom pictures), beam parameters (table).

It is evident that in the case where the quadrupoles are applied, the values of the X and Y components of the emittance, and the beam sizes, are closer to each other, than in the case without any quadrupoles. It is also visible at the beam projection and X and Y phase spaces presented in figure 5 (left bottom). The transverse profile of the beam became symmetric as well as X and Y phase spaces approach closer to each other. Additionally to the emittance reduction by 10 %, all beam parameters became more symmetrical.

4.3. Copies of the second quadrupole design for XFEL and FLASH

The two copies of the gun quadrupoles were produced and installed at European XFEL in August 2017 and at FLASH at the end of 2017.

The emittance measurements with the gun quadrupoles at European XFEL injector were performed in October 2017. For the measurements the quadrupole scan technique was used. Due to the quick process of the emittance measurements, it was possible to perform the quadrupole scan for different combinations of the gun quadrupoles currents and produce an emittance map. The measurements results are presented in figure 5.
5. Results of emittance measurements with the second gun quadrupole design at European XFEL. QLN and QLS are quadrupoles names at XFEL, which correspond to Gun Q1 and Gun Q2 names at PITZ.

The smallest value of emittance was obtained at gun quadrupoles currents of -0.3 A and -0.1 A for normal and skew quadrupoles, correspondingly. The emittance value was reduced by 20%. Also, the beam profile became more round.

5. Outlook and the third design of the gun quadrupoles

The next step of the gun quadrupoles development is the third design, which is dedicated for the installation at a location that is closer to the gun cavity (between coaxial coupler flange and the gun cavity). The design was optimized to fit the quadrupole to the more tight space in this region (see figure 6). The third design gun quadrupole is already installed at current gun cavity at PITZ.

The combination of the second and the third designs of the gun quadrupoles supposed to decrease the beam emittance even more than it was already obtained with only the second design quadrupole.

Figure 5. Results of emittance measurements with the second gun quadrupole design at European XFEL. QLN and QLS are quadrupoles names at XFEL, which correspond to Gun Q1 and Gun Q2 names at PITZ.

Figure 6. The view of the third design of the gun quadrupole: CAD model (left) and the corresponding produced quadrupole (right).

References
[1] FLASH project: http://flash.desy.de/
[2] XFEL project: http://xfel.desy.de/
[3] Altarelli M et al 2006 XFEL: The European X-Ray Free-Electron Laser. Technical design report DESY-06-097
[4] Isaev I 2014 Stability and performance studies of the PITZ photoelectron gun. PhD thesis, Universität Hamburg
[5] Krasilnikov M 2016 Update on Beam Imperfections Studies at PITZ PITZ Collaboration Meeting
[6] Schmerge J 2010 LCLS Gun Solenoid Design Considerations SLAC Technical Note SLAC-TN-10-084
[7] Quantang Z 2016 Simulations with rotation quads model for beam asymmetry studies (updated) PITZ physics Seminar
[8] CST software: https://www.cst.com