FEL PERFORMANCE WITH FOCUSING LATTICE MAGNETS ALIGNMENT ERRORS

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Abstract

At the European XFEL the alignment errors of the undulator section quadrupole magnets will be corrected by applying beam based quadrupole alignment methods. Numerical simulations of the SASE process have been conducted to evaluate the FEL power reduction due to residual quadrupole alignment errors. FEL simulations with focusing lattice errors allow choosing an optimal error correction method in terms of FEL performance.

INTRODUCTION

The study was conducted aimed at definition of the after correction error orbit influence on the European XFEL radiation parameters. This study is complementary to M. Vogt's work [1]. Beam based alignment method will be applied in FEL undulator section to correct focusing lattice quadrupoles initial alignment errors expected to be 300µm [1]. Precision movers are used to realign quadrupole magnets instead of correctors.

Using Beam Position Monitors (BPM) readings a correction algorithm is applied minimizing the difference between the orbits of two beams with different energies (dispersion free steering). Due to BPM finite resolution (~1µm), movers' precision (~1µm), and correction algorithms resolution some after correction errors of quadrupole magnets alignment remain. In order to evaluate FEL performance degradation due to quadrupole alignment residual errors numerical simulation of the SASE process was conducted applying GENESIS code [2].

FEL NUMERICAL SIMULATIONS

FEL process simulations taking into account quadrupole alignment residual error enable one to define requirements for orbit correction and finally tolerances for quadrupole magnets initial offsets, BPM resolution and movers precision. Simulation results should allow also validation of the correction algorithm used.

Correction procedure was simulated for the European XFEL SASE1 undulator line [3]. SASE1 FEL design parameters are presented in the Table 1.

Residual Misalignments

We conducted SASE FEL simulations with GENESIS introducing five groups of files containing samples of quadrupole magnets residual after correction misalignments provided by Mathias Vogt [1]. Those groups of files are named as "Best" with d = 0.5 µm, "Worst" with d = 50 µm and three "Intermediate" groups with d = 2, 5, 10 µm respectively (d is the dispersion).

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Table 1: SASE1 FEL Design Parameters

K value	3.3
Segment length [m]	5
Number of segments	33
Inter-segments drift space [m]	1.1
Total length [m]	201
Resonant radiation wavelength [nm]	0.1
# of quadrupole magnets	34
Total length [m]	201
FODO period length [m]	12.2
Av. Beta function [m]	32
Energy [GeV]	17.5
Energy spread [MeV]	1.5
Nornalized emittance [mm-mrad]	1.4

The parameters of the quadrupole magnets after-correction misalignments used in the simulation are given in the Table 2. A particular set of quadrupole magnets horizontal integrated dipole fields due to residual misalignments (Fig.1) are presented in the Fig. 2.

Table 2: Magnets Residual Misalignments Parameters

Dispersion	0.5	2	5	10
Mean misalignment	-0.34	-2.41	3.9	-5.05
RMS misalignment	3.92	14.7	12.2	76.1

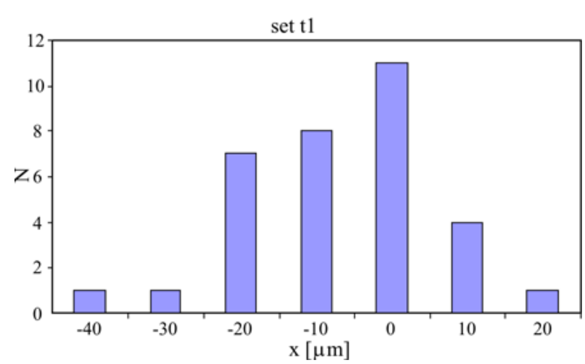

Figure 1: Distribution over values of typical set of residual misalignments.

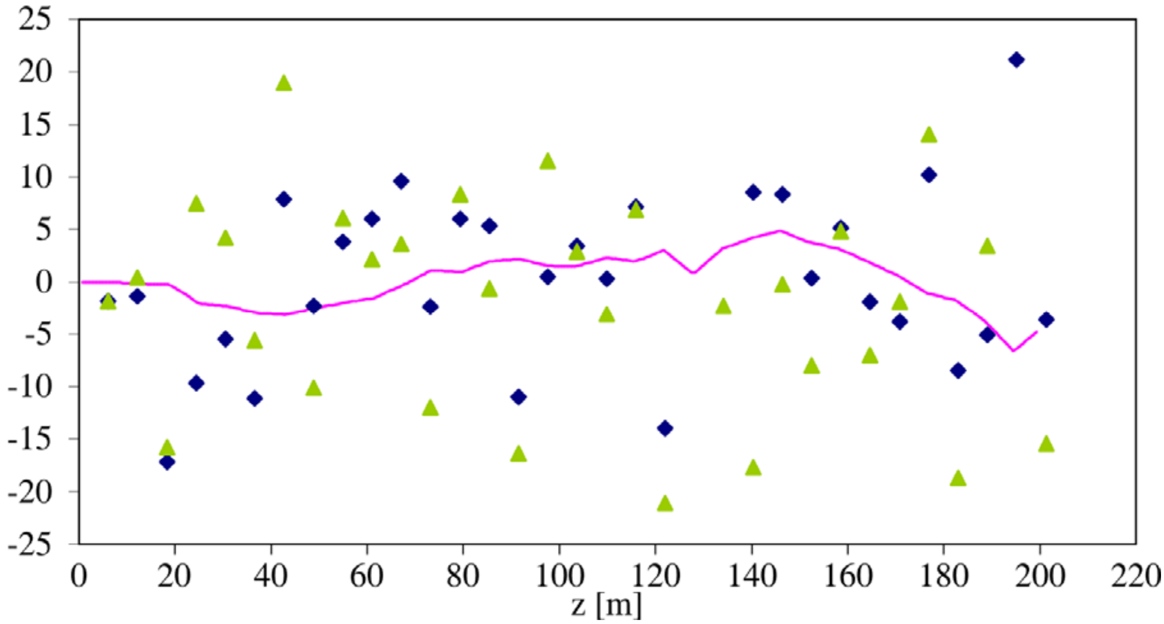

Figure 2: Beam trajectory in microns (solid line), magnets integrated fields in 10^{-6} Tesla-m units (triangles) and cumulative dipole field integral in 10^{-6} Tesla-m units (diamonds) in the presence of the quadrupole magnets alignment errors.

Dipole fields that arise from misaligned quadrupoles deflect the electron beam forcing it to perform zigzag motion in the undulator. Beam deflection at particular off–axis magnet depends on integral field of all previous magnets. Beam orbit deviation from the undulator axis is defined by beam second integral of the field. This behaviour of the beam error orbit is shown in the Fig. 1. It depicts the trajectory in the field of magnets with particular set of the misalignment corresponding to dispersion 0.5 μm.

Error orbit degrades FEL performance via a few mechanisms: a) beam wander in the transverse plane reducing beam–radiation overlapping, b) beam travels along zigzag trajectory instead of strait one and accumulates extra phase slippage with respect to radiation field, c) when beam changes its direction of the propagation micro bunches preserve their orientation and the emission of the radiation in the direction of the beam propagation decreases. The main effect is the reduction of the overlap between the radiation and electron beam due to its transverse deviation. The transverse size of the beam is ~36μm and error orbit maximal excursion from the undulator axis is about 5μm which corresponds to the 0.5μm dispersion (Fig. 2).

An efforts to simulate SASE FEL process for misalignments sets corresponding to so called “the worst” case with dispersion 50 μm showed that lasing was completely destroyed at early stages of the power growth process. That can be explained by the following.

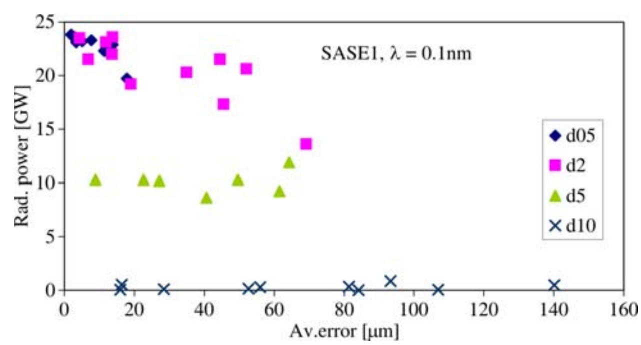

Figure 3: FEL radiation power vs. quadrupole magnets average alignment errors for various sets of random misalignments with different values of the dispersion (d= 0.5, 2, 5, 10 [μm]).

An analysis carried out by T. Tanaka et. al [4] indicates that after the dipole kick FEL gain length increases:

$$L_G \rightarrow L_G \Big/ \left(1 - \frac{\vartheta^2}{\vartheta_C^2}\right)$$

where ϑ is the kick angle and the critical angle corresponds the kick that completely destroys further radiation growth

$$\vartheta_C = \sqrt{\frac{\lambda_R}{L_G}}$$

where λ_R is resonant wavelength.

A gain length is calculated for SASE1 at =0.1nm is about 6.1m, that gives $\vartheta_C \approx 4\mu rad$, which corresponds to quadrupole misalignment $X_Q \approx 66\mu m$.

Meanwhile the FEL power is reduced according to formula:

$$P \sim P_0 e^{-\vartheta^2 \frac{d_c}{\lambda_R}},$$

where d_c is the distance over which correction is applied.

The various sets of the residual misalignments corresponding to the same value of the dispersion have nearly Gaussian distributions with parameters shown in the Table 2. Figure 3 shows that the radiation power level is strongly defined by the dispersion. Within the group of the misalignments sets corresponding to the particular value of the dispersion FEL power decreases slowly with the increase of the an average misalignment.

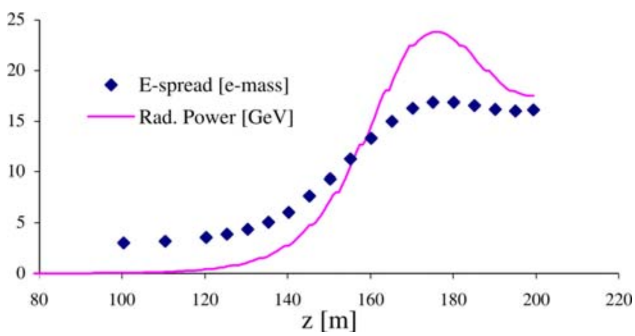

Figure 4: Beam energy spread and radiation power growth in the undulator. The curves sown correspond to corrected beams with dispersion 0.5 µm. Beam initial energy spread (~3 electron mass) widens in the result of the energy losses due to FEL radiation.

The beam initial energy spread increases along with energy losses via radiation since FEL radiation is stochastic process (Fig. 4). No emittance dilution can be observed since the dispersion was corrected.

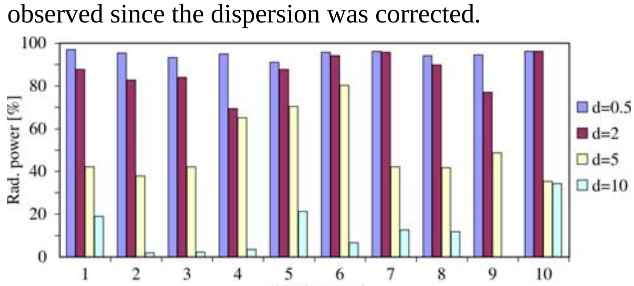

Figure 5: FEL radiation power vs. quadrupole magnets average alignment errors for various sets of random misalignments with different values of the dispersion (d= 0.5, 2, 5, 10 [µm]).

The main effect is the reduction of the overlap between the radiation and electron beam due to its transverse deviation. The transverse size of the beam is ~36µm and error orbit maximal excursion from the undulator axis is about 5µm which corresponds to the 0.5µm dispersion (Fig. 1).

The FEL radiation power reduction due to residual misalignments the of quadrupole magnets of the EXFEL SASE1 undulator are presented in the Fig. 5. The peak power values are randomly distributed with the parameters shown in Table 3.

Table 3: SASE Radiation Peak PowerA values and RMS Dispersions for the 10 Different Sets of Random Residual Misalignments.

Dispersion [µm]	**0.5**	**2**	**5**	**10**
Power [GW]	23.3	21.2	12.4	0.278
Power normalized [%]	95	87	51	1.1
RMS deviation [GW]	0.432	2.1	3.79	0.265

CONCLUSIONS

- SASE FEL simulations have been performed to define the impact of beam trajectory errors due to quadrupole magnets residual (after correction) misalignments on the FEL radiation.
- Trajectory errors arise from the technically feasible requirements of BPM resolution, movers' precision and in the result of realization of the different DF steering scenarios.
- 0.5 micron rms dispersion should be provided to ensure that radiation power reduction is ~ 5%.
- No beam offset and tilt at the undulator entrance have been considered. That leaves the room for the further development of the alignment algorithm.
- The study should be continued further together with simulation of the beam based alignment scenarios to find out the requirements for quadrupole magnets alignments errors, movers' precision, BPM resolution, their alignment accuracy and optimal arrangement.

The work is performed within the framework of DESY-CANDLE collaboration.

REFERENCES

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