EFFECT OF JITTER AND QUADRUPOLE ALIGNMENT ERRORS ON SASE FEL PERFORMANCE

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Abstract

Numerical simulations of the radiation process at the European XFEL project are presented. The impact of the beam centroid initial jitter and quadrupole misalignments on the saturation length and saturation power is investigated using the simulation codes SIMPLEX and GENESIS. The influence of trajectory steering in the presence of BPM misalignments on the FEL performance is analyzed. The study is performed for the SASE 1 undulator designed for 0.1 nm radiation wavelength.

INTRODUCTION

The European X-Ray FEL project [1] is aiming to generate ultra-short pulses of spatially coherent photon beams with wavelength down to 0.1 nm and the brilliance of about 10^{33} ph/mm^2/mrad^2/0.1%BW. After acceleration in the main linac the 17.5 GeV energy electron beam with normalized projected emittance of 1.4 nm and relative energy spread of 10^{-4} enters the hundreds meters long undulator sections with external focusing lattice. Up to five photon beam lines deliver the X-ray pulses to the experimental stations.

Although the physics of the SASE FEL process is well understood [2], the impact of the beam jitter, quadrupoles misalignment and field errors on the saturation length and the output radiation power require extensive numerical simulations to evaluate the real facility performance. The influence of undulator and quadrupole errors on the FEL performance has been evaluated numerically in [3].

In this report the results of a numerical study for the SASE1 undulator section are presented using the three-dimensional time-dependent simulation codes GENESIS [4] and SIMPLEX [5]. This study is complementary to the previous work and includes the effects of beam centroid initial jitter, quadrupole misalignments and trajectory steering on the saturation length and radiation power.

The main design parameters of the electron beam and the undulator section performance for the SASE1 beamline is presented in Table 1. The SASE1 beamline consists of 33 undulators that are arranged in 17 FODO cells. The length of a single undulator is 5 m and the total length of the beamline is about 200 m. Each quadrupole is associated with a Beam Position Monitor (BPM) and provides horizontal and vertical dipole steering of the electron central trajectory by moving the quadrupole itself.

Table 1: SASE1 FEL design parameters

Electron energy [GeV]	17.5
Bunch length (RMS) [µm]	25
Bunch charge [nC]	1
Normalised emittance [mm-mrad]	1.4
Energy spread [MeV]	1.5
Undulator K value	3.3
Beam line total length [m]	201
Resonant radiation wavelength [nm]	0.1
FODO period length [m]	12.2
Average Beta function [m]	32

BEAM CENTROID INITIAL JITTER

The investigation of the FEL performance sensitivity to the beam spatial and angular jitter is an important issue to derive the stability and trajectory feedback criteria.

Fig.1 presents SASE1 steady state simulations of the radiation power for a matched electron beam and perfectly aligned components of the beam line. The gain length of about 170m and the saturated radiation power of 22.5 GW are predicted by both GENESIS and SIMPLEX.

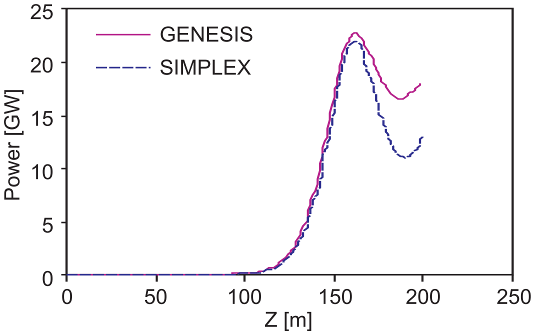

Figure 1: Radiation power for SASE1 obtained with steady state simulations by GENESIS and SIMPLEX.

The angular and spatial offsets of the electron beam trajectory at the entrance of the undulator will deteriorate the FEL performance by decreasing the overlap of the electron beam and its radiation in the transverse phase space. The electron bunch performs transverse oscillations in the external focusing field while the radiation is obviously insensitive to the focusing lattice

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fields. The betatron phase advance phase per FODO cell in SASE1 is about 21 degree, so the beam with initial space or angular offsets performs one complete oscillation through the beam line. Figure 2 presents the beam trajectory along the beamline for various beam initial offsets in terms of rms beam size σ_x at the entrance to undulator.

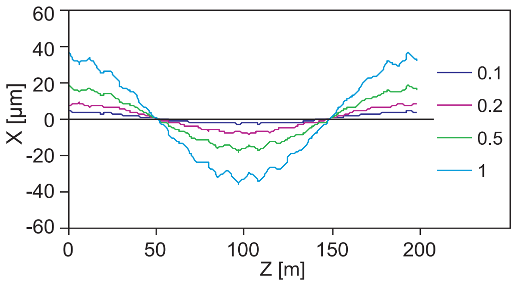

Figure 2: Trajectories with initial transverse offsets.

Figures 3 presents the radiation power and saturation length dependence on the initial transverse space $r = (x^2 + y^2)^{1/2}$ and angular $r' = (x'^2 + y'^2)^{1/2}$ offsets of the beam for $(x = y, x' = y')$.

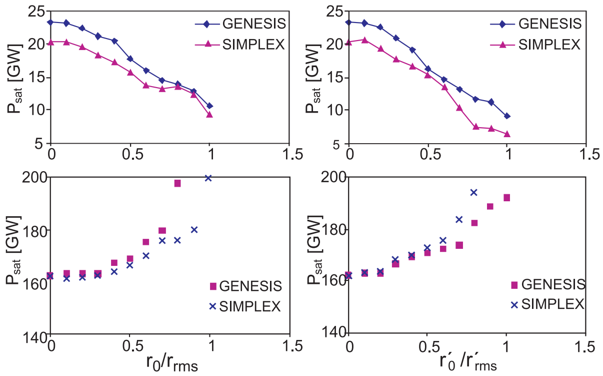

Figure 3: Saturation power (top) and saturation length (bottom) versus beam initial space (left) and angular (right) offsets.

Both GENESIS and SIMPLEX simulations show up to ~50% decrease of the radiation power at saturation for one sigma initial offset of the beam (σ_x=36.2 μm, $\sigma_{x'}$=1.13 μrad). Initial beam offsets also increase the saturation length. For the spatial offsets GENESIS shows more sensitivity than SIMPLEX, while in the case of angular offsets it is vice versa. Table 2 presents sensitivities of the saturation power and saturation length parameters to beam centroid transverse phase space offset in units of beam one standard space σ_x and angular $\sigma_{x'}$ deviations obtained by time-dependent simulations.

Table 2: SASE1 performance sensitivity to beam offsets

Offsets [σ_x,$\sigma_{x'}$]	$\Delta P_{sat}/P_{sat}$	$\Delta L_g/L_g$
0.1, 0.1	0.051	0.015
0.2, 0.2	0.19	0.031
0.3, 0.3	0.39	0.069
0.4, 0.4	0.54	0.12
0.5, 0.5	0.64	0.22
1.0, 1.0	0.99	0.69

QUADRUPOLE MISALIGNMENTS AND TRAJECTORY STEERING

One of the basic conditions for SASE FEL process is the matching of the electron beam to the angular and transverse phase space characteristics of the single electron radiation in the undulator. The effects of quadrupole misalignments increase the effective apparent beam phase space as the beam trajectory is disturbed along the undulator. The radiation parameters are strongly affected by the disturbed electron orbit in undulators since

- kicks draw away the electron beam from the inner and the most intense part of the radiation;
- radiation from electrons is produced at a certain angle with respect to reference direction (undulator axis);
- electrons have phase discrepancies with the radiation propagating along the reference axis.

For misaligned quadrupoles in the undulator the electron beam central trajectory x_c is disturbed. The effective phase space area $< A >$ of the disturbed trajectory in thin lens approximation is given by

$$< A >= 8N_{cell} \frac{\langle x_c^2 \rangle}{L_{cell}} tg \frac{\mu}{2}$$

with N_{cell} number of FODO cells in the beam line, L_{cell} the FODO cell length and μ the betatron phase advance per cell. The rms value of the quadrupole misalignments that yield a disturbed central phase ellipse equal to the diffraction limited photon beam emittance is then given by $A^2 = \lambda / 4\pi$. For SASE 1 beam line (λ=0.1nm) this corresponds to 2 μm of rms quadrupole misalignments.

The quadrupole magnets misalignment influence on various parameters of the FEL radiation (number of radiated photons, spot size, divergence, and bandwidth) is investigated using GENESIS time dependent simulations.

In particular, Fig. 4 shows the dependence of the SASE1 saturation power on the rms quadrupole misalignments for 10 random seeds. The solid line indicates the average effects for 10 random seeds. The resulting variation of the normalized brilliance is presented in Figure 5. Due to increase of the radiation size and divergence the brilliance decreases in a faster pace than the saturation power.

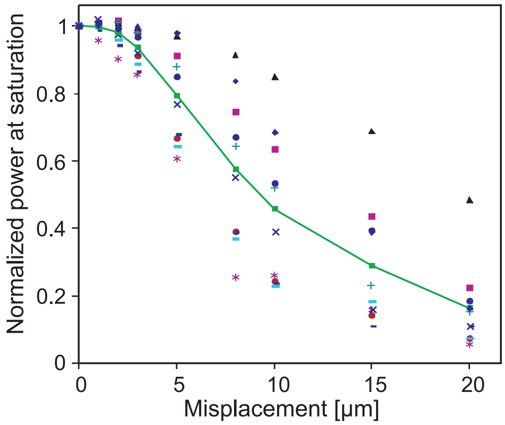

Figure 4: The saturation power versus quadrupole rms misalignments for 10 random seeds.

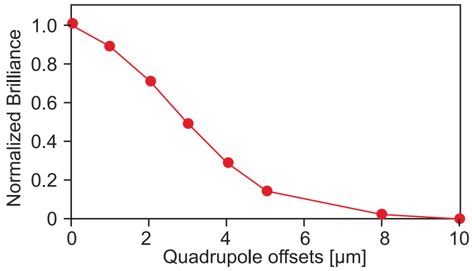

Figure 5: Radiation brilliance versus quadrupole rms misalignment (GENESIS time-dependent simulations).

To improve the FEL performance the trajectory is steered to BPM centers using beam based alignment technique. As a result the beam centroid follows an error trajectory through the centers of the BPMs within the undulator. In Figure 6 an error trajectory is shown where 32 BPMs have been randomly misplaced with an rms offset of $\sigma = 3$ µm.

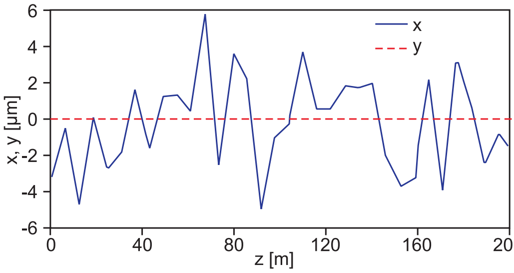

Figure 6: Corrected centroid trajectory following the horizontally misaligned BPMs with 3 µm rms offset.

The beam is steered towards the BPM centers with one corrector for every BPM. The resulting steered trajectory is in the range of ± 6 µm. Figure 7 presents steady state simulations of radiation power and saturation length for various BPM rms offsets and different seeds.

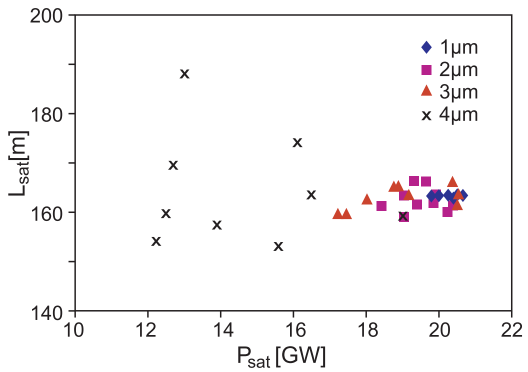

Figure 7: Saturation power and saturation length for various BPM rms offsets (10 different seeds).

The steady state simulation indicates that even a misalignment of 1 micron may yield a certain decrease of the saturation power, while the saturation length remains rather unchanged. Those results seem counterintuitive, since one would expect the saturation length to increase with the increase in BPM misalignments. However SIMPLEX time-dependent simulations of the SASE1 FEL give similar results (Table 3).

Table 3: Dependence of the normalized saturation power and saturation length on the BPM rms offsets

σ_x [µm]	$\langle P_{sat}/P_0 \rangle$	$\langle L_{sat}/L_0 \rangle$
1	0.98	1.00
2	0.95	0.995
3	0.93	0.998
4	0.72	1.001

CONCLUSIONS

The degradation of the FEL performance caused by the injection jitter, quadrupole and BPM misalignments has been studied numerically. It is shown that these imperfections strongly affect the radiation power and saturation length and have stringent requirements down to few µm for the components rms misalignments.

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