IMPACT OF FOCUSSING LATTICE TO EUROPEAN XFEL SASE1 PERFORMANCE

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Abstract

Time dependent simulations for the European XFEL SASE1 beamline for various FODO lattice quadrupole spacing in undulator section are presented. The dependence of radiation main parameters, saturation lengths, saturation power and brilliance on the betatron phase advance and the FODO lattice arrangement in undulator section are studied and compared with the case based on design focusing lattice. Impact of the trajectory correction and electron beam main parameters on the SASE FEL performance is discussed.

INTRODUCTION

In the European XFEL [1] intense coherent radiation will be produced at wavelengths down to 0.1 nm in long undulator sections. The maximum energy of the electron beam from the driving linac is 17.5 GeV with a normalized emittance of 1.4 mm-mrad. Five photon beam lines will deliver the X-ray pulses to the experimental stations.

The effective radiation and electron beam interaction that drives the SASE FEL process is highly conditioned by the space-angular distribution of the electron beam along the undulator section along with the diffraction effects and the beam energy spread [2]. The beam rms transverse size and divergence evolution along the undulator is influenced by the focusing lattice, i.e the phase advance per FODO cell and the cell length (quadrupole spacing). The SASE1 undulator section design is based on the minimum available FODO cell length of 12 m, implying the focusing quadrupoles spacing after each 5 m long undulator segment and the design average beta function of 32 m.

Due to betatron oscillations the transverse shape and the angular spread of the electron beam are modulated along the undulator modifying the FEL performance: saturation length, radiation power and brilliance. In addition, the beam disturbed orbit due to misalignments reduces the overlapping of electron and photon beams during the FEL process.

In this report we present the results of SASE1 performance study for various phase advance and the FODO cell arrangements along the SASE1 undulator section, including the scenario without external focusing quadrupoles. For comparison, the saturation power with beam based trajectory correction is given.

The numerical calculations are made using the GENESIS [3] and SIMPLEX [4] 3D codes. The design specifications of SASE1 are listed in Table 1.

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Table 1: Margin SASE1 Design Specifications

Undulator parameters	SASE1
Radiation wavelength [nm]	0.1
K value	3.3
Period length [cm]	3.56
Segment length [m]	5
Total length [m]	201
Number of FODO cells	17
Average beta [m]	32
Phase advance per cell [degree]	22.1

BETATRON PHASE ADVANCE AND FODO CELLS ARRANGEMENT

For the real undulator focusing lattice, the space-angular distribution of the electron beam modifies the FEL performance, and the optimum focusing lattice and the betatron phase advance can be evaluated based on the SASE FEL numerical simulations for various FODO cell arrangements [5].

Figure 1 shows the simulations results (SIMPLEX) of the radiation saturation length and power for SASE1 undulator section with nominal FODO lattice and the average beta functions of 24 m, 32 m and 40 m. The simulations are performed for 10 different random seeds of beam initial phase space distribution. As follows, the saturation power increases with high average beta, while the saturation length reaches the minimum at $\bar{\beta} = 32\text{m}$.

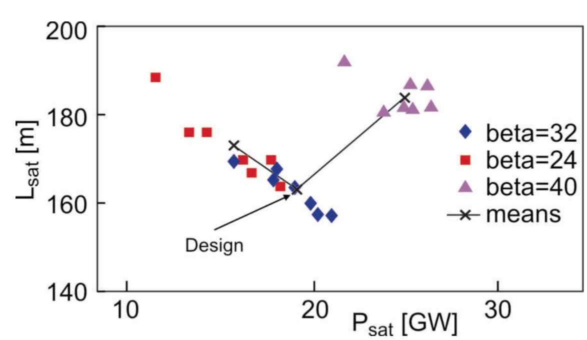

Figure 1: SASE1 saturation power and saturation length for various beta functions (SIMPLEX).

One of the most important FEL radiation parameters is the brilliance. The radiation brilliance can be calculated by processing the results of GENESIS time dependent simulations.

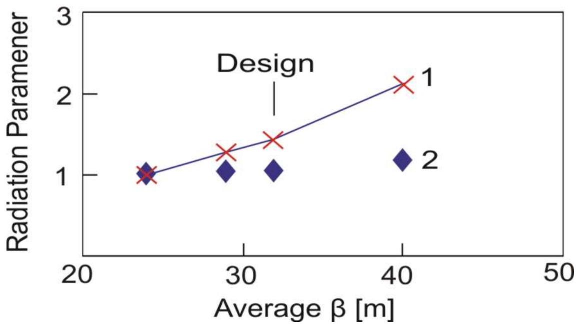

Figure 2: SASE1 normalized brilliance (1) and saturation power (2) versus average beta.

Figure 2 presents the dependence of SASE1 normalised brilliance and saturation power on the average beta function obtained by the time-dependent GENESIS simulations. Fig. 1,2 show that the reduction of the phase advance per cell to 17 degrees ($\overline{\beta} = 40\text{m}$) for the SASE1 nominal lattice leads to the increase of the saturation length by ~12%, saturation power by ~30 % and the brilliance by ~35% with respect to design lattice with betaron phase advance of 22.1 degree ($\overline{\beta} = 32\text{m}$).

The time dependent GENESIS simulations are performed to evaluate the SASE1 radiation saturation power and brilliance for undulator section with 5 and 9 periodic FODO cells. The results are given in Table 2 along with the design performance (*) with 17 FODO cells in undulator section.

Table 2: SASE1 saturation power and brightness for various FODO lattice arrangements (GENESIS)

N_{cell}	β [m]	P_{Sat} [GW]	Brilliance
17*	32	1	1
9	32	0.91	0.745
9	64	0.971	1.14
9	128	0.557	0.716
5	64	1.09	1.13
5	128	0.819	0.897

The simulation results predict that with less quadrupole magnets and longer spacing (smaller number of FODO cells), the proper choice of the phase advance per cell, the SASE FEL performance is comparable with the design one. The case with switched-off pair of quadrupoles (active quadrupole spacing after three undulator segments) is of special interest for the SASE1 performance. This option could be realized easily with the current SASE1 focusing lattice design during the commissioning stage.

ORBIT CORRECTION AND OFF-QUADRUPOLES OPERATION

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 quadrupole misalignments disturb the beam trajectory strongly affecting the radiation characteristics [6].

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. The beam is steered towards the BPM centers with one corrector for every BPM. Figure 3 presents steady state simulations of radiation power and saturation length for various BPM rms offsets and 10 different BPM misalignments random seeds.

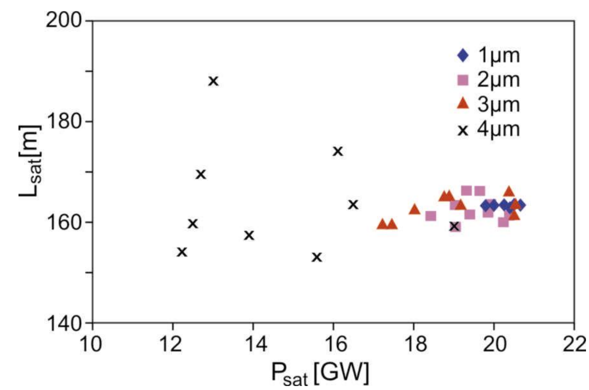

Figure 3: Saturation power and saturation length for various BPM rms offsets (10 different seeds).

The steady state simulation indicates that even 1μm BPMs rms offset may yield certain decrease of the saturation power, while the saturation length remains rather unchanged. SIMPLEX time-dependent simulations of the SASE1 give similar effect: the saturation power drops by about 30% for the BPM rms offset of 4 μm.

The problem of the FEL performance operating with no regular external focusing in the undulator section is of great interest. In the commissioning stage, if all quadrupoles are turned off, only so called natural focusing by the undulator field takes place and one gets a worse FEL performance compared to the design option. SIMPLEX steady-state simulations indicate (Table 3) that for SASE1 and SASE2 operating at the 0.1 nm wavelength the saturation length remains the same while the saturation power decreases by about 40-50 %.

Table 3: SASE FEL performance without quadrupoles

FEL	Wavelength	L_{sat}	P_{sat}
SASE1	0.1 nm	0.98	0.61
SASE2	0.1 nm	1.02	0.53

However, as follows from Fig.3 and Table 3 the off-quadrupole operation and design option with 5 μm BPM rms misalignments are comparable from the saturation length and power points of view.

FEL SENSITIVITY TO BEAM MAIN PARAMETERS

The tolerable beam main parameters budget is an important issue to provide the reliable facility operation. In this section we present the results of our study for the SASE1 performance (saturation length L_{st} and saturation power P_{st}) sensitivity to beam main parameters: energy, bunch charge and peak current.

By means of the SIMPLEX steady-state simulations we investigated the behaviour of the FEL performance when the electron beam energy varies from 15 to 20 GeV. In Figure 4 the dependence of saturation length and power on electron beam energy for SASE1 are presented. It turned out that saturation length changes from –17% to 31% and saturation power changes from 22% to –22% compared with the design values for SASE1.

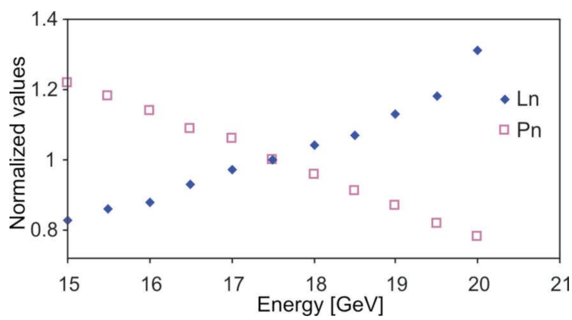

Figure 4: The normalized saturation length (Ls) and power (Ps) dependence on the beam energy.

Saturation length and saturation power dependence on the bunch charge have been investigated in the charge deviation range from 0.9 to 1.1 nC. For SASE1 the saturation length changes from 1% to -9% and saturation power changes from -17% to 20% compared with the design values for SASE1. In Figure 5 the dependence of saturation length and power versus bunch charge are presented for SASE1.

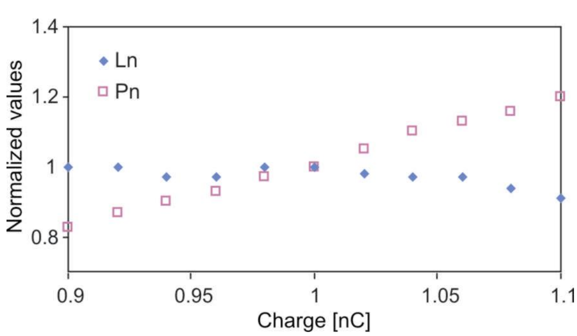

Figure 5: Normalized saturation length (Ls) and power (Ps) dependence on the bunch charge.

Saturation length and power dependence on the peak current (4.5-5.5 kA) for SASE1 is shown in Fig. 6. Bunch charge was kept the same, equal to 1 nC, while the bunch rms length varies within 10% range. The saturation length and saturation power for SASE1 changes from 7 % to –6 % and from –20 % to 20 % respectively.

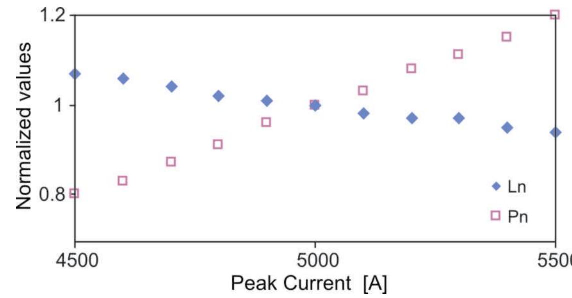

Figure 6: Normalized saturation length (Ls) and power (Ps) dependence on the beam peak current.

CONCLUSIONS

Time dependent simulations for European XFEL SASE1 undulator section have been performed to study the impact of the external focusing lattice and the beam main parameters sensitivity to radiation saturation length, saturation power and brilliance.

The numerical results for SASE1 undulator section, based on SIMPLEX and GENESIS simulations, show the following:

- The reduction of the betatron phase advance per FODO cell to 17 degree leads to the increase of the saturation length by ~12% and saturation power by ~30%.
- A good performance of the SASE FEL main parameters (saturation length, saturation power and brightness) can be obtained with less FODO cells in undulator section by the proper choice of the betatron phase advance per cell (average beta).
- The radiation saturation power with off-quadrupole operation is comparable to misaligned design performance with electron beam orbit correction down to 5 μm rms offset at BPMs.
- The sensitivity of the radiation saturation power is within ±20% for the beam energy, charge and peak current variation of ±10%.

The results of this study can be used for obtaining SASE1 optimal performance during the European XFEL commissioning stage.

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