OPTIMIZATION OF THE FOCUSING LATTICE FOR EUROPEAN XFEL

V. Khachatryan#, V. Sahakyan, A. Tarloyan, V. Tsakanov, CANDLE, Yerevan, Armenia
W. Decking, DESY, Hamburg, Germany.

Abstract

Detailed knowledge of the impact of the undulator section focusing lattice on the FEL performance is an important issue to ensure the stable operation with reasonable tolerances. In this paper the results of numerical simulation studies for the European XFEL project are presented. The saturation length, saturation power and the spectral brightness of the SASE FEL are calculated for various focusing lattice arrangements. The numerical simulations are performed using the SIMPLEX and GENESIS codes.

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 nm. Five photon beam lines will deliver the X-ray pulses to the experimental stations.

External alternating-gradient quadrupoles are inserted into the undulator to provide sufficient focusing of the electron beam. The impact of different lattice solutions on the FEL performance has been investigated in [2] concluding that a FODO type lattice provides the best performance.

The European XFEL undulator system consists of 5 m long segments and the shortest FODO lattice period is obtained when one quadrupole magnet is installed in each inter-segment gap. For a finite beam emittance the electrons perform betatron oscillations and the transverse shape of the beam is modulated along the undulator modifying the FEL performance: saturation length, radiation power and brilliance. In addition, misalignments of the focusing lattice cause distortions of the beam orbit along the undulator, thus reducing the overlapping of electron and photon beams during the FEL process.

The electron beam transverse rms size and divergence as well as the disturbed orbit are determined by the quadrupole magnets spacing and the betatron phase advance per FODO cell. In this report we present the results of a study for various FODO cell arrangements along the undulator, including the scenario without external focusing quadrupoles. The numerical calculations are made using the GENESIS [3] and SIMPLEX [4] 3D codes. All simulations are performed for SASE1 and SASE 2 undulator systems [1] with the major parameters listed in Table 1.

Table 1: XFEL Specifications

Undulator parameters	SASE1	SASE2
Radiation wavelength [nm]	0.1	0.1-0.4
K value	3.3	2.8-6.1
Period length [cm]	3.56	4.8
Segment length [m]	5	5
Total length [m]	201	256
Number of FODO cells	17	24
Average beta (m)	32	46/15
Phase advance per cell (degree)	22.4	15/54

THE EFFECTS OF BEAM FOCUSING

Along with diffraction effects and beam energy spread the effects of the electrons betatron motion have to be taken into account when optimising FEL parameters. For a finite beam emittance ε the average rms transverse size and divergence of the beam in a symmetric FODO lattice in thin lens approximation can be evaluated analytically

$$\overline{\sigma_x^2} = \varepsilon\bar{\beta} = \varepsilon L\left(\frac{1}{\sin\mu} - \frac{1}{6} tg\frac{\mu}{2}\right)$$
$$\overline{\sigma_{x'}^2} = \varepsilon\bar{\gamma} = \varepsilon\frac{4}{L} tg\frac{\mu}{2} \qquad (1)$$

where L is FODO cell length, μ is the phase advance per cell, $\bar{\beta}, \bar{\gamma}$ are the average Twiss parameters per FODO cell. In high gain FEL the power gain-length L_G is approximately given by [5]

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho}(1+\Lambda), \qquad (2)$$

where ρ is the Pierce parameter scaled with the electron beam transverse size $\overline{\sigma_x^2}$, undulator K value and period length λ_u as $\rho \sim (K^2\lambda_u^2 / \overline{\sigma_x^2})^{1/3}$. The parameter Λ describes the effects caused by the beam energy spread, detuning and the beam transverse size and angular spread and can be found using Xie fitting formula [7]. The saturation power P_s is reached at saturation length of about $L_S \approx 20 L_G$ and is given by the total electron beam power P_{beam} as [5]:

#khachatryan@asls.candle.am

$$P_S \approx \frac{1.6}{(1+\Lambda)^2}\rho P_{beam} \tag{3}$$

For the long FODO cell length and the small phase advance (large average beta function, small divergence) a 1D theory predicts increasing of the saturation length and saturation power. However, the real XFEL performance requires careful 3D numerical simulations [3-5].

NUMERICAL SIMULATIONS: SASE 1

An approximate formula for the beta function that corresponds to the minimum gain length is given in [6]. Applying those expressions for the SASE1 parameters adjusted by the undulator "filling factor" of 1.22 we obtain $\overline{\beta} = 29$ m, which is close to the current design value of 32 m obtained through numerical simulation.

Figure 1 shows the results SIMPLEX simulations of the saturation length and power for SASE1 design (Table 1) for the average beta 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 $\overline{\beta} = 32\text{m}$.

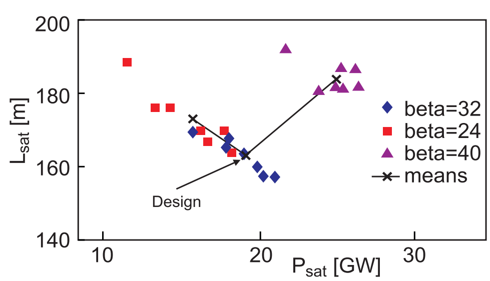

Figure 1: SASE1 saturation power and saturation length for various beta functions. (SIMPLEX).

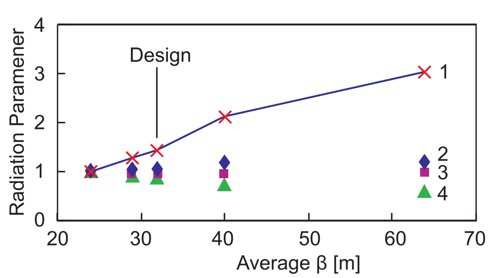

Figure 2: SASE1 normalized brilliance (1), saturation power (2), radiation rms size (3) and divergence (4) versus average beta.

Figure 2 presents the dependence of the normalised brilliance, saturation power, radiation rms size and divergence 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 an increase of the saturation length by ~12%, saturation power by ~30 % and the brilliance by ~35% with respect to design lattice with $\overline{\beta} = 32\text{m}$ (see also Table2).

Numerical simulations by SIMPLEX have been performed for the SASE1 lattice with a FODO cell length of 24.4 m (reducing the number of quadrupoles in undulator by factor of 2). The results of the steady-state simulations - averaged over 30 random seeds - are summarised in Table 2.

Table 2: SASE1 FEL performance parameters dependence on the FODO lattice spacing (SIMPLEX).

N_{cell}	β [m]	P_{Sat} [GW]	L_{Sat} [m]
17	24	15.72	173.3
17*	32	19.15	162.4
17	40	25.11	183.7
9	32	18.5	165.1
9	40	23.44	173.4

In comparison with the nominal design lattice (*), the FODO cell arrangement with two undulator segments per cell and a betatron phase advance of 37 degree (beta average 40 m) give rise in saturation power by about 20% while the saturation length increases by about 7 %.

One of the most important FEL radiation parameters is the brilliance. It is possible to calculate the brilliance by processing the results of GENESIS time dependent simulations. To investigate the impact of the focusing lattice arrangement the GENESIS simulations have been carried out for the SASE1 undulator. Keeping the current design layout of the SASE1 undulator unchanged we evaluated the radiation saturation power and the brilliance for the FODO lattice arrangements with 24.4 m (9 cells) and 36.6 m (5 cells) cell lengths. The results are given in Table 3 along with the design performance (*). The simulations indicate that an average beta of 64 m corresponds to the highest brilliance.

Table 3: 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

Of special interest for the SASE1 performance is the case with switched-off pair of quadrupoles after every second focusing (defocusing) magnet (active FODO cells 5, cell length 36.6 m). The simulation predicts an increasing of the brightness by 13% with about the same radiation power for the phase advance per cell of about 34 degree ($\overline{\beta} = 64\,\mathrm{m}$). This option could be realized easily with the current SASE1 focusing lattice design during the commissioning stage.

NUMERICAL SIMULATIONS: SASE 2

Extensive GENESIS simulations have been performed for SASE2 for radiation wavelengths of 0.1 nm and 0.4 nm and FODO lattice arrangements with 12.2 m and 24.4 m cell lengths. Saturation length and brilliance for various average beta functions are presented in Fig. 3 and Fig. 4.

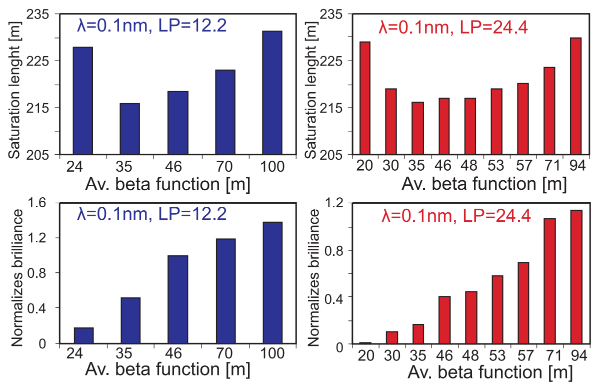

Figure 3. SASE 2 saturation length and saturation power vs average beta for two FODO cell length: 12.2 m (left) and 24.4 m (right). Radiation wavelength: 0.1 nm.

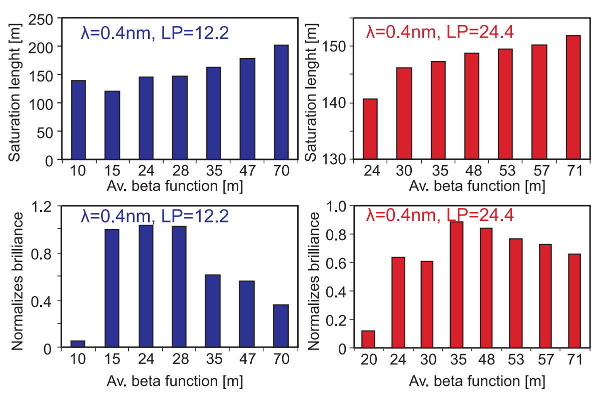

Figure 4. SASE 2 saturation length and saturation power vs average beta for two FODO cell length: 12.2 m (left) and 24.4 m (right). Radiation wavelength: 0.4 nm.

As it is seen from Fig.3, for 0.1 nm wavelength in comparison with the nominal design (Table 1) the FODO arrangement with 24.4 m cell length and beta average of 70 m give rise in brilliance by about 10 % while the saturation length increases only by 3 %. For 0.4 nm wavelength operation mode, the optimal performance with reduced number of cells is reached for a beta average of 35 m. In comparison with the nominal lattice the saturation length increases by 17 % (147 m) and the brightness decreases by 10 %.

SASE PERFORMANCE WITHOUT STRONG FOCUSING

Though it is common knowledge that for an FEL operating in the X-ray region focusing by external lattice is necessary, the problem of the FEL performance operating with no strong regular focusing in the undulator 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 FEL radiation with significantly worse performance compared to the design values. The horizontal and vertical beta variations along the SASE2 beamline are presented in Fig. 5.

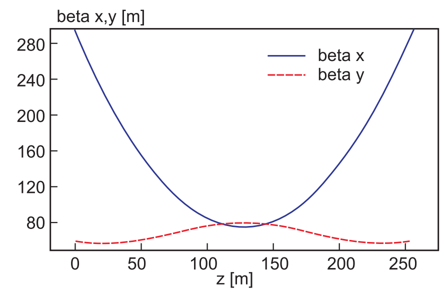

Figure 5: The horizontal /vertical beta functions in SASE2.

SIMPLEX steady-state simulations indicate 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 4: 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
SASE2	0.4 nm	1.84	0.59

CONCLUSIONS

The design value of the SASE1 FEL average beta function provides the lowest saturation length, while higher average beta function (e.g. 40m) results in higher saturation power. The obtained numerical simulation results suggest that for SASE1 and SASE2 a reduction of the number of quadrupoles is possible without degradation of the FEL performance in terms of radiation power and brilliance.

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