PSI XFEL SIMULATIONS WITH SIMPLEX AND GENESIS

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Abstract

The numerical simulation results of the SASE FEL process for PSI XFEL project are presented. The main purpose of the investigations using FEL simulation codes SIMPLEX and GENESIS is the reliable definition of the undulators design parameters (K value, period, segment length, number of segments) that provide desirable radiation characteristics such as wavelength, bandwidth, saturation length, peak power and the brightness.

INTRODUCTION

One of the approaches to significantly reduce the costs for the construction of an X-Ray FEL would be the use of new electron sources with reduced transverse beam emittance combined with sufficient peak current. In PSI XFEL project [1] this is supposed to achieve by developing a Low Emittance Electron Gun based on field emitter technology [2]. After a 250 MeV injector and first bunch compressor, the electron beam with normalized emittance of 0.2 mm-mrad is accelerated to the maximum energy of 6 GeV in two S-Band linear accelerators separated by the second bunch compressor. The compressed electron beam with 1.5 kA peak current is delivered at different energies to three undulator sections to produce SASE FEL (Fig.1). It is assumed that output radiation energy should be tunable between the limits ~0.124 and ~12.4 keV, which corresponds to the wavelength region 0.1 – 10 nm. The photon beam wavelength is tuned by electron energy and undulator gap variations.

Branch 1 undulator will produce linearly polarized FEL radiation with wavelengths starting of 0.1 nm to 0.3nm utilizing electron beam with the energy that can be varied up to 5.8 GeV. For that purpose a separate linear accelerator segment is foreseen. Branch 2 and branch 3 undulators' radiation fundamental wavelengths are also tuneable within the range of 0.3 – 1.0nm and 1.0 – 10nm correspondingly. They can produce radiation with both linear and circular polarization. Each of the undulator systems should be compact enough (~70 m) to fit the area anticipated for the construction of the PSI XFEL facility.

In those three FELs three different methods of the fundamental mode wavelength tuning will be applied. In the branch 2 and branch 3 undulators the gap is variable and additional linac segment enables one to change also the energy of the beam delivered to branch2 FEL.

At the design stage one can use the theoretical considerations [3] and the variational solution of the FEL dispersion relation equation [4] to obtain crude estimates for the most important FEL performance parameters. We carried out numerical simulation study of the FEL process applying two different three-dimensional simulation codes SIMPLEX [5] and GENESIS [6] to find out FEL design parameters. The main design parameters of the PSI XFEL project are presented in Table 1. The electron bunch charge is 0.2 nC, the rms length after BC1 and BC2 is 40 μm and the required energy spread is 0.5 MeV.

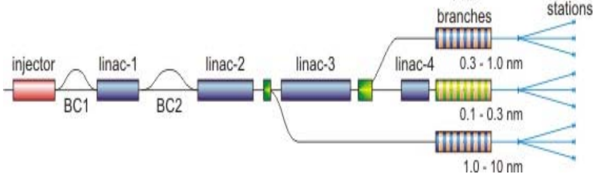

Figure 1: Schematic layout of the PSI XFEL.

Table 1: PSI XFEL main design parameters

FEL	Branch 1	Branch 2	Branch 3
Beam energy [GeV]	5.8-3.4	5.3– 4.5	3.7
Wavelength [nm]	0.1– 0.3	0.3 – 1.0	1.0 – 10
Wavelength tuning	energy	energy and gap	gap
Type	Planar	APPLE	APPLE
Period [mm]	15.0	36.6	52.0
Section length [m]	4.50	4.39	4.16
FODO period [m]	10.5	10.3	9.8
Beta function [m]	15	15	15
Saturation length [m]	31.4	40.5	35.4
Peak power [GW]	2 – 6	10 – 20	10 – 20

BEAM FOCUSING

Since the total length of each undulator system is important the numerical simulations have been performed to get the optimal value for the average beta function that minimizes the saturation length. The focusing lattice of each branch of the undulators is FODO type and comprised of a set of single focusing or defocusing quadrupole magnets inserted into every 75 cm drift section between the undulator segments.

Both analytical and numerical simulation studies indicate that saturation length decreases with the reduction of the average beta function. The SIMPEX simulation results for branch1 is presented in Table 2, where P is the peak power, L is the saturation length.

The same pattern is observed for all three undulators. The minimal possible values for the averate beta function

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are those corresponding to 90 degrees of phase advance per cell, namely 8.8m, 8.4m and 8.2m for the branch 1, branch2 and branch3 FELs respectively. Based on the simulation results by the SIMPLEX and GENESIS the optimal average beta function for branch 1 is chosen to be 10m, while it is 9m for branch 2 and branch 3.

Table 2: Branch 1 performance dependence on average beta function (λ=0.1nm, SIMPLEX simulations).

Av. beta	P	L
16	4.50	51.6
15	4.62	51.8
14	4.69	51.8
13	4.78	51.2
12	4.93	46.5
11	4.97	46.5
10	4.72	43.1

The choice of 10m beta function value reduces saturation length for branch 1 FEL by more than 20% (Fig. 2).

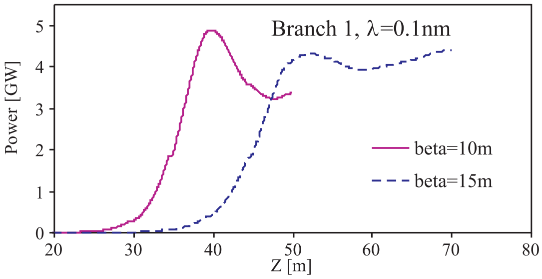

Figure 2: Power growth curves for branch 1 undulator.

SIMPLEX and GENESIS indicate somewhat different values for saturation lengths and saturation powers of three FELs branches. For comparison in table 3 and 4 the saturation length and saturation power are calculated by different codes.

Table 3: Performance of the FELs with optimised beta function (SIMPLEX simulations).

Branch	1	2	3	Branch3, λ_u=4.16cm
Wavelength (nm)	0.1	0.3	1.0	1.0
Av. β [m]	10	9	9	9
L_{sat} [m]	43	58	48	39
P_{sat} [GW]	4.7	12	16	16

Figure 3 and Table 3,4 (the last column) show further significant reduction of the branch 3 FEL saturation length if one decreases the undulator period from 5.2cm to 4.16cm.

Table 4: Performance of the FELs with optimised beta function (GENESIS simulations).

Branch	1	2	3	Branch3, λ_u=4.16cm
Wavelength (nm)	0.1	0.3	1.0	1.0
Av. β [m]	10	9	9	9
L_{sat} [m]	39	51	45	34
P_{sat} [GW]	5.1	11	14	13

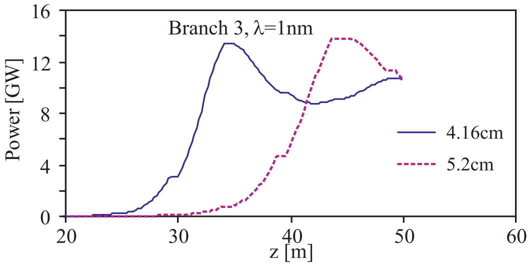

Figure 3: Power growth curves for branch 3 undulator with 5.2cm and 4.16cm undulator period.

PERFORMANCE SENSITIVITY TO BEAM PARAMETERS

To reach high performance the PSI XFEL undulators use electron beam with rather challenging parameters (Table 1). It requires much efforts to be invested into research and development to prove that electron beam with intended values of parameters such as beam emmitance, peak current, energy spread can be supplied to FEL.

Taking into account those considerations one should be ready to cope with the situations when some parameters will be different from their initial design values. We have done numerical simulations to reveal FEL performance parameters sensitivity to the electron beam parameters variations.

By means of the GENESIS simulations we investigated the behaviour of the branch 1 FEL performance parameters (saturation length and saturation power) when the electron beam normalized emittance varies from the design value 0.2 to 0.4 mm-mrad. It turned out that saturation length increases by ~70% and saturation power decreases by about 60% (Figure 4).

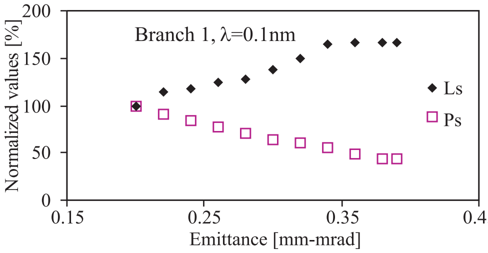

Figure 4: Saturation length (Ls) and power (Ps) (normalized to 39.3m and 5.1GW) dependence on the beam emittance.

Branch 1 FEL saturation length and saturation power dependence on the energy spread has been investigated in the energy deviation range from 0.5 to 1.0 MeV. Saturation power decreases steadily with the increase of energy spread to ~80% of its initial value. Saturation length increases with the rise of the energy spread by ~20%, though it does not demonstrate a smooth behaviour (Fig. 5).

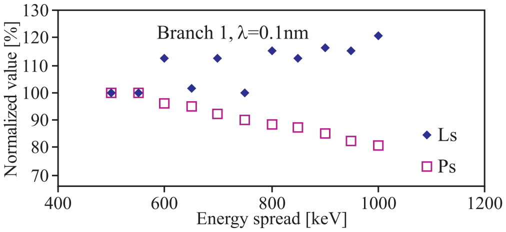

Figure 5: Normalized saturation length (Ls) and power (Ps) dependence on the beam energy spread.

Branch 1 FEL saturation length and saturation power dependence on the peak current is shown in Figure 6. Bunch charge was kept the same. In that case peak current value depends only on the bunch compression. With the decrease of the beam peak current down to 1kA, saturation length increases by 25 % while saturation power decreases twice.

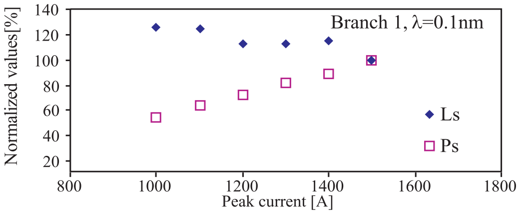

Figure 6: Normalized saturation length (Ls) and power (Ps) dependence on the beam peak current.

UNDULATOR TECHNOLOGY

For the construction of the branch 2 and branch 3 undulators the most appropriate alternative would be the hybrid design that uses NdFeB permanent magnets and soft iron blocks[6]. On the undulator axis the field can be calculated with using the formula

$$B = a \cdot \exp\left(\frac{g}{\lambda_u} (b + c \frac{g}{\lambda_u}) \right)$$

where g is the gap, λ_u is the period of the undulator. This formula can be used if $0.1 < g/\lambda_u < 1.0$. For the NdFeB hybrid undulators the coefficients $a = 3.694, b = -5.068, c = 1.52$ and if that technology for the branch 1 is used, the undulator gap will be 4.8mm. Even for in vacuum design one can expect that wake field effects would be essential. One can get rid of the problem if cryogenic permanent magnet technology is chosen [7]. The above-mentioned formula for the on axis field calculation remains intact with the coefficients $a = 8.62703, b = -8.1857, c = 5.9718$ and one gets an acceptable value for gap 6mm.

SUMMARY

PSI XFEL SASE simulations have been done using two different computer codes. Using preliminary design beam and undulators parameters FEL output parameters, such as saturation length and saturation power, have been obtained for all the three XFEL undulator systems branch 1, branch 2 and branch 3.

- Branch 1 undulator (0.1 - 0.3 nm) is chosen to be of planar type and its beam energy should be varied in the range from 5.8 GeV to 3.35 GeV if the tuning method is energy variation. Undulator gap is 6mm if cryogenic permanent magnet technology is used.
- Saturation length for all the three FELs can be significantly reduced (more than 20%) if an optimal value for the beta function is used. Based on simulation study results for the all three FELs operating in planar mode at shortest wavelengths one can suggest the following average beta functions: 10m for branch 1 FEL and 9m for branch 2 and branch 3.
- Branch 3 undulator (1.0 – 10 nm) total length can be reduced by shortening the undulator period from the current design value 5.2 mm to, for instance, 4.16 mm.
- The study branch 1 FEL performance dependence on the beam emittance shows that saturation length grows by about 70% and saturation power decreases by 60% with the increase of beam natural emittance from 0.2 to 0.39 mm-mrad.
- When beam energy spread changes from 0.5 MeV to 1.0 MeV saturation power decreases by 20%.
- If the peak current of electron beam delivered to branch 1 FEL is twice lower than the design value then FEL saturation length will be 25% longer while radiation peak power halves.

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