WAKE FIELD EFFECT ON THE SASE PERFORMANCE OF PAL XFEL*

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Abstract

The PAL XFEL will supply coherent radiations from VUV to X-rays. X-ray FEL for 0.3 nm lasing requires a minimum 3-GeV driver linac and a 60-m long in-vacuum undulator with a narrow variable gap. The linac should supply highly bright beams with emittance of 1.2 mm-mrad, a peak current of 3.5 kA, and a lower energy spread less than 0.03%. The beam quality is degraded along the undulator trajectory due to the energy loss, the wake field, and the magnetic field errors, etc. Especially the wake field effect is most sensitive parameter due to the narrow gap of the undulator. The preliminary design details of undulators for PAL-XFEL are presented with parametric analysis. The SASE performance is analyzed using simulation tool SIMPLEX [1].

INTRODUCTION

PAL (Pohang Accelerator Laboratory) is designing a 4th generation light source, PAL XFEL, which is a coherent X-ray free electron laser (FEL) by utilizing an existing 2.5-GeV linac [2]. This source is based on the principle of Self Amplified Spontaneous Emission (SASE). A SASE-FEL radiations can give the images of the dynamic state of matter with atomic resolution in space and time that will allow very fast dynamic study such as non-equilibrium states and transitions between the different states of matter.

The linac should supply highly bright beams with emittance of 1.5 mm-mrad, a peak current of 3.5 kA, and a low energy spread less than 1 MeV (Table 1). By adding an RF photo-cathode gun, two bunch compressors, and a 1.2-GeV S-band injector linac to the existing 2.5-GeV PLS linac, the PLS linac can be converted to a SASE XFEL facility which supplies coherent X-ray down to 0.3-nm wavelength.

Table 1: Beam parameters of PAL XFEL

Maximum beam energy	3.7 GeV
Normalized emittance	1.2 μm
FWHM bunch length	0.23 ps
RMS energy spread	< 1 MeV
Maximum bunch charge	< 1.0 nC
Peak current	3.5 kA
Repetition rate	60 Hz

The SASE is only possible by low emittance and extremely dense electron bunches moving in an undulator magnetic field. The undulator is the most prominent FEL specific component. A short-period undulator will give a compact FEL machine for a short-wave radiation. An in-vacuum undulator is essential to produce coherent X-ray radiation at wavelengths down to 0.3 nm with 3-GeV beams.

The undulator parameters such as a period and a gap has to be optimized to get a short saturation length with reasonable margin. The SASE process should be analyzed including the practical situations such as beam degradation due to wake field, undulator misalignment, phase slip between undulators, undulator segmentation, etc.

PAL XFEL UNDULATOR

The fundamental radiation wavelength λ_x of an undulator is given by

$$\lambda_x = \lambda_u / (2\,\gamma^2)\,(1+K^2/2),$$

$$\gamma = E_0 / 0.511,\ K = 0.934\, B_u\, \lambda_u$$

where E_o is the beam energy in MeV, B_u is the peak magnetic field of the undulator in Tesla, and λ_u is the undulator period in cm. Either a short-period undulator or a high-energy beam can provide short-wave radiation. A short-period undulator will give a compact FEL machine for a short-wave radiation. An in-vacuum mini-gap undulator can keep reasonably large undulator parameter K to obtain a short saturation length. This idea was introduced by the SCSS project at SPring-8 [3].

Figure 1 shows the 0.3-nm XFEL curves with saturation lengths of 40, 50, 60 m and beam energy of 2.5, 3.0, 4.0 GeV, respectively. The one of possible solution that is reasonably economic, to meet the saturation length less than 60 m with margin is to use 3-GeV beam with a 3-mm gap and a 12.5-mm period for a undulator [4].

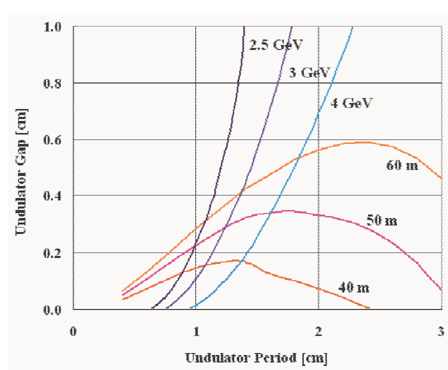

Figure 1: Undulator period and gap length for 0.3-nm SASE for saturation lengths (40, 50, 60 m) and beam energy (2.5, 3, 4 GeV).

Table 2 summarizes the FEL parameters for a 0.3-nm PAL XFEL. The undulator beta value of 10 is adjusted to obtain as short a saturation length as possible. Undulator saturation length is approximately 20 times the 3D gain

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length L_g. The undulator gap is increased from 3.0 to 3.5 mm to reduce the SASE degradation due to the increased energy spread caused by the wake field effect in this study. Therefore, the undulator saturation length is increased from 52 m to 61 m.

Table 2: FEL parameters for 0.3-nm PAL XFEL

Undulator period [mm]	12.5
Undulator gap [mm]	3.5
Undulator parameter, K	1.0
Undulator beta [m]	10
1D gain length [m], L_{1d}	1.72
3D gain length correction, η *	0.97
3D Gain length [m], L_g	3.35
FEL parameter	4.7e-4
Saturation length [m]	61
Peak power [GW]	1.1

* $L_g = (1+\eta)\, L_{1d}$

BASIC SASE PERFORMANCE

The betatron function of the undulator system of which average beta values in x and y directions are 9.4 m and 9.7 m respectively as shown in Figure 2. The undulator system is composed of 15-segmented undulators with 4.5m long each. The focusing lattice is FODO whose field gradient is 20 T/m with 0.11 m pole length. Each magnet is located in the drift spaces between the undulators.

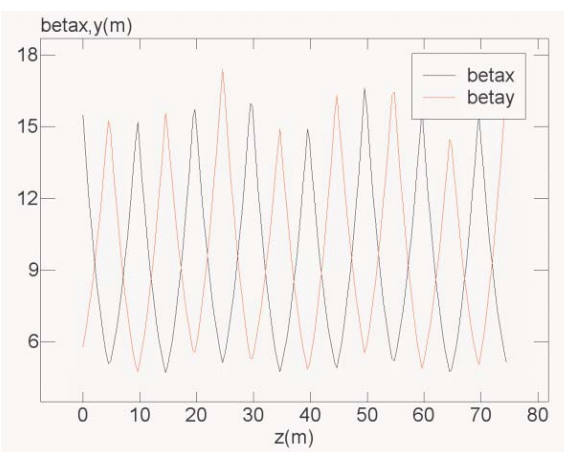

Figure 2: Betatron function of the undulator system.

Figure 3 shows the profile of a radiation power density along the undulator at 20 m, 40 m, 60m, 70 m, respectively. The radiation profile is well peaked and symmetrical in the centerline but the bottom level is rather broad and differs from a pure Gaussian distribution. The higher-order modes are possible to be amplified and contributed to this area. After saturation, the radiation energy is inversely transferred to the electron beam as shown in the figure (L=70 m).

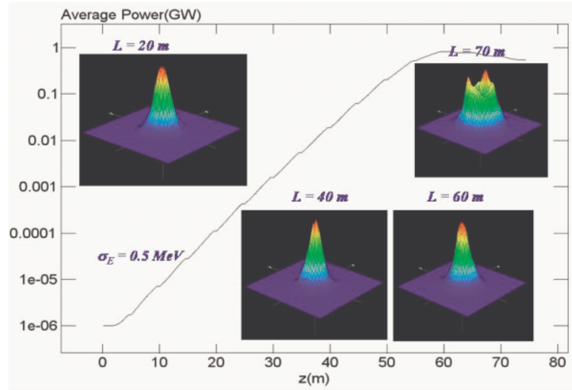

Figure 3: Power density profile along the undulator.

Figure 4 shows the gain dependence on the beam energy spread of the SASE process. The relative energy spread has to be smaller than the FEL parameter. The FEL parameter of the 0.3-nm PAL XFEL is 4.7e-4 as shown in the Table 2. The relative energy spread at 3 GeV is 1.7e-4 for 0.5 MeV. The relative energy spread of 3.4e-4 with 1.0 MeV energy spread is very close to the FEL parameter so that the gain becomes smaller as shown in the figure.

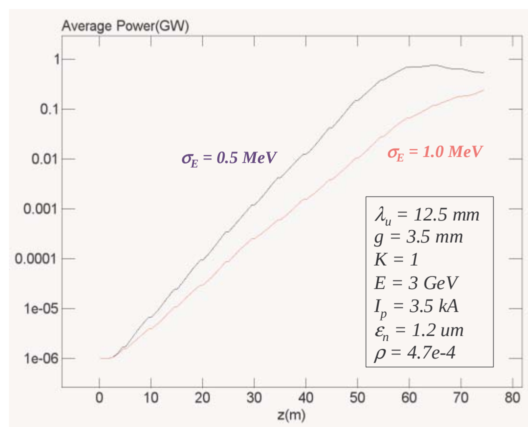

Figure 4: SASE performance vs. beam energy spread.

WAKE EFFECT AND OTHER CONSIDERATIONS

In order to smoothly transfer the beam induced wall current through the long undulator gap, nickel foil plated with copper is attached on the pole surface using the magnetic attractive force. The practical smooth surface on commercially available metal plate has a high aspect ratio of surface roughness, which makes the energy spread due to the surface roughness negligibly small enough. The energy spread caused by the wake field is given by

$$\langle \delta_E \rangle = e2NL \langle W \rangle / E, \quad \langle W \rangle \propto 1/a^2$$

where N is the number of electrons in the bunch, L is the undulator length, $\langle W \rangle$ is the energy loss due to resistive wall wake that is inversely proportional to the distance to the surface from the beam, E is the beam energy. The energy spread due to the resistive wake field on the electron beams in the undulator can be estimated by assuming the radius being equal to half of the gap and energy spread being half of the pipe radius [3]. For resistive wall wake evaluation, Cu resistivity of 1.68e-6 Ohm-m is used. The surface roughness is assumed the RMS height of 1 μm with correlation length of 50 μm.

Figure 5 shows the resistive and surface roughness wake fields as a function of aperture with the bunch charge of 1-nC. The roughness wake is relatively smaller than the resistive wall wake. The gap size of 3 mm and undulator length of 60 m give large projected energy spread due to the resistive wall wake. It may become more serious if we include AC conductivity. The wake effect has to be carefully examined to get the realistic SASE output estimation.

The emittance growth due to transverse resistive wall wake is less than 1% if the random oscillation is kept less than 20 μm with a Gaussian beam according to reference [4]. The gap size of each undulator can be adjusted to adjust the resonant condition for the reduced average beam energy due to the incoherent synchrotron radiation loss.

The length of each undulator has to be at least 2xLg (gain length) in order to release the tight tolerance of longitudinal and transverse misalignment [5]. However, this is rather long undulator to handle and it is hard to make small beta value. The achievable radiation power is reduced to 50% if the phase slip is π over the drift section between the adjacent segments or the radiation is cut off at the drift section. The jitter and sensitivity analysis on the combined parameter space is extensively studied in reference [6]. It is still necessary to analyse the hardware upgrade scheme and the stability requirements with related technical parameters.

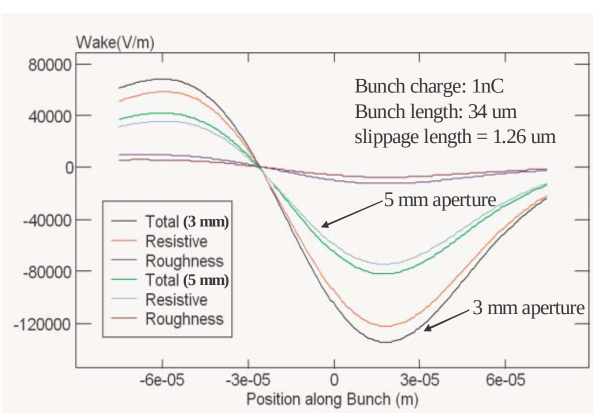

Figure 5: Resistive and surface roughness wakes.

SUMMARY

In the PAL XFEL, the electron beam is compressed and accelerated to a high energy up to 3.7 GeV. Even the emittance and energy spread is matched to the basic SASE requirements, the wake fields, misalignment, field errors make the SASE process complicated in the undulator. Especially the wake fields can degrade the SASE power that is sometimes critical issues to the femto-chemistry single-shot experimental users. Therefore the FEL physics should be more carefully analysed.

ACKNOWLEDGMENTS

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