STUDY OF PAL-XFEL WAKE FIELD EFFECTS WITH THE GENESIS CODE*

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Abstract

PAL-XFEL is the newly announced SASE FEL project that is going to achieve 0.3 nm wavelength radiation with 3.7 GeV electron beam. To overcome the relatively low energy of 3.7 GeV, short period and small gap in-vacuum undulator will be adopted. There has been worry about the wake field effect that this in-vacuum undulator may cause. The wake field effect of this in-vacuum undulator on the SASE process is studied in this paper and it is shown that the effect is not serious.

INTRODUCTION

Pohang accelerator Laboratory (PAL) is going to build a new x-ray FEL machine based on SASE (self amplified spontaneous emission) scheme. This new machine called PAL-XFEL will utilize the existing 2.5 GeV electron linac by upgrading its energy and performance. The linac is currently used for injection to the 2.5 GeV storage ring of Pohang Light Source (PLS). PAL-XFEL will cover from the soft x-ray radiation to the hard x-ray of 0.3 nm by upgrading the linac energy to at least 3.7 GeV. The soft X-ray FEL is named WFEL and the hard X-ray FEL is named XFEL. WFEL and XFEL will use the same undulator with different beam energy. A PAL-XFEL layout is shown in Fig. 1. It is well known that SASE FEL is quite a challenge; generation of extremely low emittance beam through photo-cathod RF gun, bunch compressing to an extremely short length, maintaining the low emittance to the end of the linac, and keeping the beam orbit as straight as possible in the undulator. But PAL-XFEL adds a few more scientific challenges. This is easily understood by comparing PAL-XFEL with another machine under construction, LCLS (Linac Coherent Light Source) [1], which uses 14.45 GeV electron beam that is four times bigger energy to obtain 0.15 nm radiation that is only half of the PAL-XFEL radiation. In other words, PAL-XFEL is going to achieve hard X-ray laser with a relatively low energy electron beam. To get an idea of scientific difficulties, recall that the resonant wavelength of an undulator is given by

$$\gamma_r = \frac{\lambda_u}{\gamma^2}\left(1 + \frac{K^2}{2}\right), \quad (1)$$

where λ_r is the resonant wavelength, λ_u the undulator period, γ the Lorentz factor, and K the undulator parameter. To obtain 0.3 nm radiation with 3.7 GeV, both the undulator period and the undulator parameter should be small enough to be allowed only for an in-vacuum undulator. Therefore PAL-XFEL will adopt an in-vacuum undulator with the undulator gap of a few mm. An important question that arises here is the wakefield. The small in-vacuum undulator gap will definitely cause some amount of wake field, bigger than that of an out-vacuum undulator. The undulator wake field does not increase the saturation length, but cause some slices radiate out of the target frequency and eventually reduces the output power. Can we secure some important portion of the radiation with the in-vacuum undulator? We will ask the question in this paper. First of all, the design parameters are listed in Table 1.

Table 1: Parameters of PAL-XFEL

Beam Parameters	**Value**	**Unit**
Electron energy	3.7	GeV
Peak current	3	kA
Normalized slice emittance	1	mm mrad
RMS slice energy spread	0.01 %	
Full bunch length	270	fs
Undulator Parameters		
Undulator period	1.5	cm
Segment length	4.5	m
Full undulator length	80 - 100	m
Peak undulator field	1.19	T
Undulator parameter, K	1.49	
Undulator gap	4	mm
FEL Parameters		
Radiation wavelength	3	Å
FEL parameter, ρ	5.7×10^{-4}	
Peak brightness	5×10^{31}	*
Peak coherent power	1	GW
Pules repetition rate (Max.)	60	Hz
1D gain length	1.2	m
Saturation length, L_{sat}	60	m

* photon/(sec mm^2 mrad^2 0.1%BW)

UNDULATOR

PAL-XFEL will use hybrid planar undulator. The hybrid material will be vanadium permendur. Then the peak field $\mathbf{B}$ is given by the fitting formula [2]

$$\mathbf{B} = 3.69 \times \exp\left[-5.07\frac{g}{\lambda_u} + 1.52\left(\frac{g}{\lambda_u}\right)^2\right], \quad (2)$$

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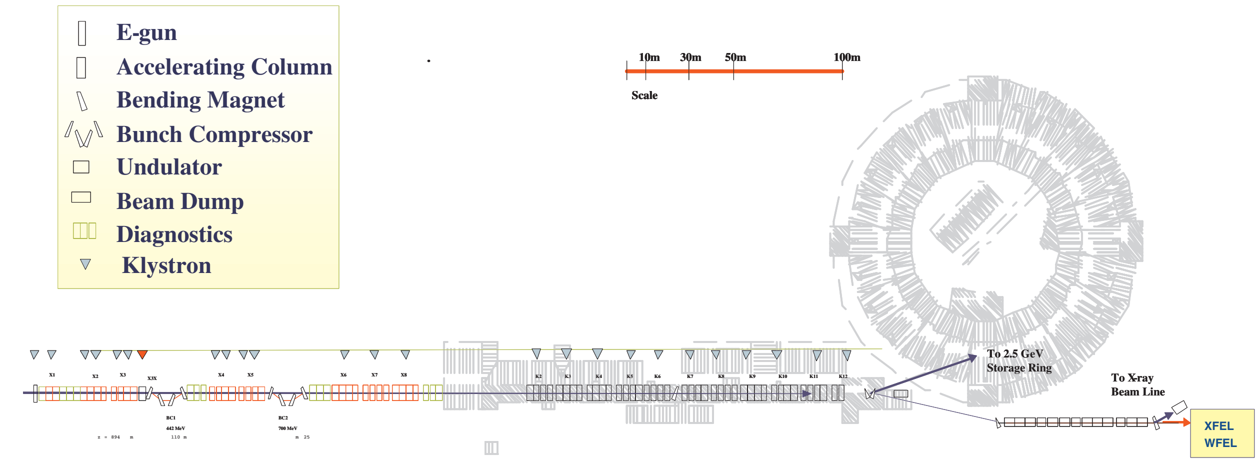

Figure 1: Layout of PAL-XFEL. The current linac building is shown in the figure. The beam transport dog-leg has approximately 0.5°, although it is exaggerated in the figure.

where g denotes the undulator gap. As shown in Table 1, the undulator period is 15 mm and the gap is 4 mm. The length of a segment is 4.5 m. Since this is an in-vacuum undulator, the role of beam pipe is played by metal plates covered on the magnet pols. Hence the cross sectional area of the beam pipe is not circular but rectangular, which helps to reduce the wake effect. To further reduce the wake field effect caused by AC conductivity, aluminum coating on the metal plate is considered seriously.

WAKE FIELD AND ENERGY SPREAD

An electron beam passing through the undulator excites both longitudinal and transverse wake fields. However, it is the longitudinal one that is mainly relevant for the FEL process. The longitudinal wake field causes the slices along the bunch to have slightly different beam energies. Then, according to Eq. (1), some slices radiate with resonant frequencies so different from the target one that the radiation is not useless and excluded. Hence the final number of photons with the target frequency will be reduced. The rms of the energy spread at the end of the undulator is given by

$$\sigma_\delta = \frac{e^2 N L (W_z)_{rms}}{E}, \tag{3}$$

where N is the number of particles in the bunch, L the length of travel, $(W_z)_{rms}$ the rms of the wake field with respect to its mean value. In order to have small energy spread, preferred conditions are:

- Small number of electrons (low charge) per bunch.
- Short undulator length.
- Small longitudinal wake field.
- High beam energy.

N should be big enough to achieve enough peak brightness and radiation power. Hence N should not be very small. Also the undulator length should be long enough for saturation. The potential problem of PAL-XFEL is that it has a relatively low energy. Also there has been continuous skepticism about the use of in-vacuum undulator in SASE FEL, because its small gap is expected to cause some amount of wake field, bigger than that of an out-vacuum undulator. The longitudinal wake function is inversely proportional to the undulator gap. Obviously, in-vacuum undulator gap is smaller than that of an out vacuum undulator. However the PAL-XFEL undulator gap (4 mm) is maximized. For example the inner radius of the LCLS undulator beam pipe is 5 mm, which is only 1 mm bigger than the PAL-XFEL undulator gap. Another important factor is the energy E. The PAL-XFEL energy is relatively low, approximately 4 times lower than the LCLS energy, and thus contributes a lot to σ_δ. To overcome this weakness, PAL-XFEL will use longer bunch length. Note that the wake function is given by [3]

$$W_z \propto \frac{1}{g(\sigma_z)^{3/2}}, \tag{4}$$

where σ_z is the rms of a Gaussian distribution. This relation was derived for the Gaussian distribution, but since it is possible to approximate a more realistic distribution with a Gaussian distribution, it is applicable to a flat beam. It is clear that the longitudinal wake function is smaller for a longer bunch. According to the current design, PAL-XFEL will use a bunch with full length of 80 μm, which is relatively long. Including this effect, we find that the PAL-XFEL wake field effect is not so bad.

SIMULATION

An estimation of the in-vacuum undulator wake field effect on the FEL performance has been carried out by using the GENESIS code [4]. Not only the resistive wake field but also geometric, inductive and synchronous wake effects are included in the simulation, although the resistive wake field is dominant. The inner geometry of the in-vacuum undulator is rectangular, but since the gap is much smaller than the undulator width and the bunch is very small, it is practically a set of parallel plates. The wake field of parallel plates is smaller than that of a round pipe, although the wake field shape is basically identical [5]. Hence the effect of parallel plates is to reduce the overall wake field effect by up to 50 %. However, we have so far used a round pipe in Genesis simulation in order to assume the worst case.

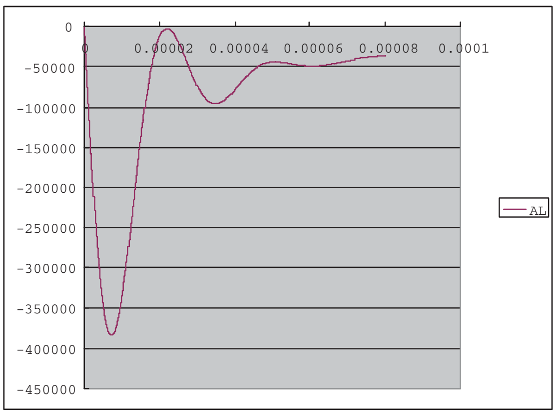

Figure 2: Wake field of a 2 mm round pipe with AL coating.

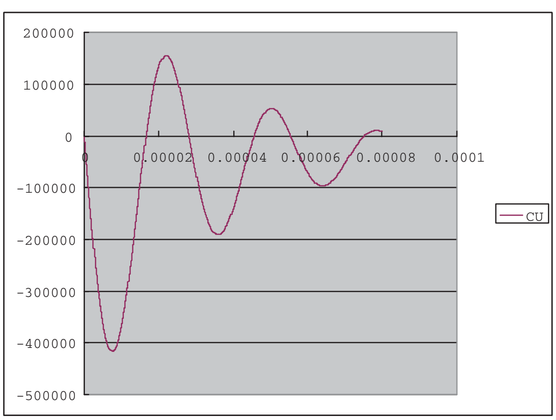

Figure 3: Wake field of a 2 mm round pipe with CU coating.

We have two choices for the coating material of the plates that cover the undulator poles, copper and aluminum. Aluminum has recently been studied in respect to the ac-conductivity related wake field effect. For a 2 mm radius round pipe, wake field for aluminum and copper coatings are displayed in Fig. 2 and Fig. 3 respectively. The bunch is flat with full bunch length of 80 μm. Both DC and AC-conductivity related wake fields are included in these figures.

The difference between the two wake fields is clear. The aluminum wake field has a strong head part but fattens at the tail. On the other hand, the copper wake field oscillates. The result of a time dependent Genesis simulation is displayed in Fig. 4 including the aluminum wake field of Fig. 2. In Fig. 4, s=0 is the tail and s=80 μm is the head. Most slices radiate while there is a part that radiates dominantly. With the realistic parallel plate configuration, the wake field will be smaller 20 - 50 %. Even with this exaggerated wake field, simulation shows that power grows smoothly and the radiation profile is clean enough. A far field profile at $z = 80$ m is shown in Fig. 5.

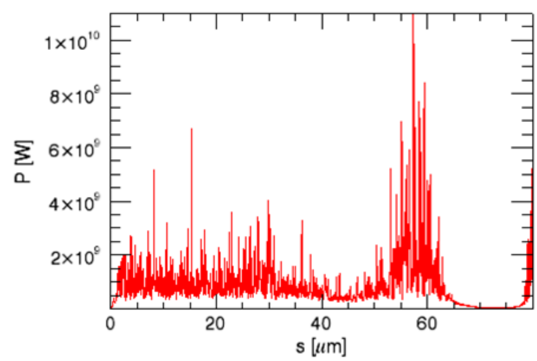

Figure 4: Time-dependent Genesis simulation over a bunch including the aluminum wake field.

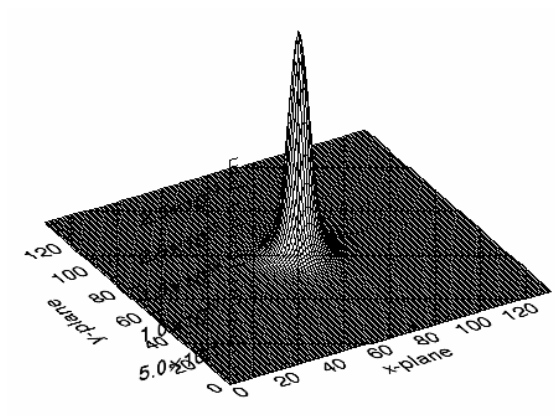

Figure 5: Projected far field radiation including the aluminum wake field at z=80 m

SUMMARY

The PAL-XFEL in-vacuum undulator does not cause fatal wake field effect that one might assume. First of all, the gap value 4 mm is not so small, only 1 mm smaller than the LCLS gap. Further the longer bunch than usual helps to reduce the wake field effect. The inner parallel plate geometry of an in-vacuum undulator helps to reduce the wake field effect, too. Genesis simulation shows that even with exaggerated wake field the SASE lasing proceeds well and the projected far field radiation profile is clean enough.

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