PAL-XFEL PROJECT*

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Abstract

Pohang Accelerator Laboratory has recently launched a new XFEL project. This PAL-XFEL will utilize the existing 2.5 GeV injection linac to the storage ring by upgrading its energy up to 3.7 GeV and using an in-vacuum undulator. It will have two beamlines that will cover both soft X-ray and hard X-ray of 0.3 nm. Scientific and engineering difficulties for PAL-XFEL are analyzed, and overall design philosophy and some details to overcome the difficulties are presented here.

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 the 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. In the figure, the current linac building is shown and the new 1.2 GeV linac is drawn outside the existing building. We are going to build the new part of PAL-XFEL while still running the storage ring. Our aim is to minimize the PLS downtime, which will require much managing ingenuity.

On the other hand, SASE FEL is quite a scientific challenge as is well known; the generation of extremely low emittance beam through a 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. PAL-XFEL adds a few more scientific difficulties. 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. This paper will describe the physical difficulties thus caused and the PAL-XFEL design strategy to overcome the difficulties. The focus will be on XFEL not WFEL, details of which will be omitted here.

PHYSICS ISSUES

To get an idea of physical difficulties that PAL-XFEL faces, recall that the resonant wavelength of an undulator is given by

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

where λ_r is the resonant frequency, 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 4 mm. There arise two important questions for PAL-XFEL in this respect:

- Is the electron beam energy high enough to ignite and keep the lasing?
- Is the in-vacuum undulator wake field small enough not to reduce the output radiation seriously?

The source of SASE process is the interaction between the overlapped electron beam and the radiated beam. The best condition is met when the two beams have comparable sizes. The radiated hard X-ray beam has small size and especially the transversal fundamental mode can be smaller than the electron beam. Hence the electron beam size should be small enough and the beam energy should be high enough as demonstrated by the relation $\epsilon = \epsilon_n/\gamma$ where ϵ_n is the normalized emittance. The size of 3.7 GeV electron beam is bigger than the fundamental mode of the 3 $\AA$ radiation. However, the computer simulation with GENESIS code [2] confirms that SASE process still proceeds properly and the saturation is reached at a reasonable length of 60 m. Details will be shown below.

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 undulator wake field does not increase the necessary saturation length, but causes the energy spread along the many slices in the bunch. Some slices may have bigger energy shift and radiate out of the target frequency eventually reducing the output power. The rms of the relative energy spread, with respect to the mean energy, at the end of the undulator is given by

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

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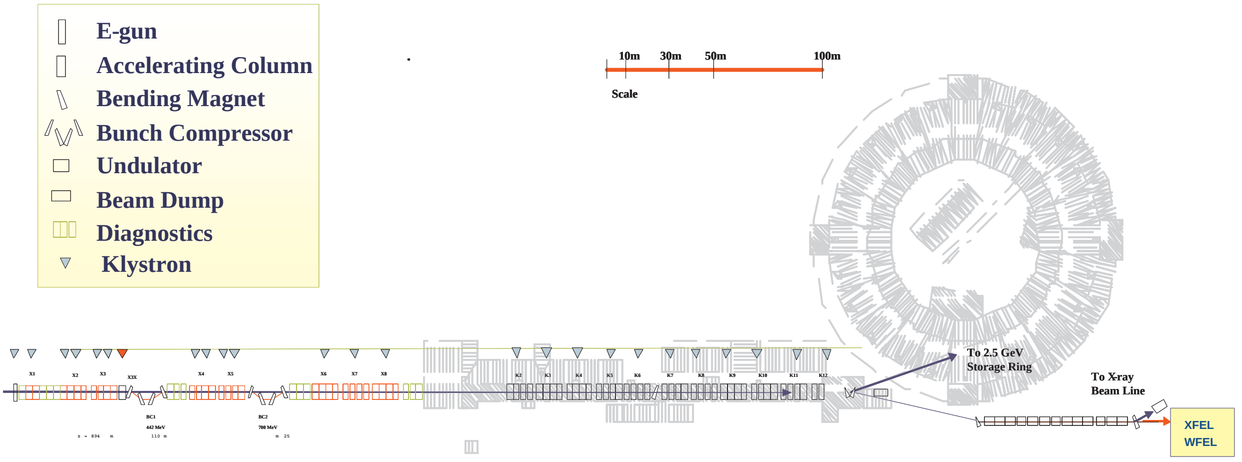

Figure 1: Layout of PAL-XFEL. The current linac building is shown in the figure. The beam transport dog-leg has approximately 0.5°, although it is exaggerated in the figure.

where N is the number of particles in the bunch, L the length of the undulator, $(W_z)_{rms}$ (in unit of V/Cm) the rms of the wake field with respect to its mean value. The undulator gap is a factor determining $(W_z)_{rms}$. Another shortcoming of low energy machine is that it makes the energy spread σ_δ bigger for the same amount of $(W_z)_{rms}$. We will overcome this difficulty by using longer bunches, which lowers the wake field. For a Gaussian distribution, $(W_z)_{rms}$ has the dependence of

$$(W_z)_{rms} \propto \frac{1}{a(\sigma_z)^{3/2}}. \tag{3}$$

The PAL-XFEL gap 4 mm is not so small, comparing it with the 5 mm chamber gap of LCLS. On the other hand, we will use bunch length almost twice as long as that of LCLS. Then, σ_δ^{PAL} is almost same level as σ_δ^{LCLS}. Furthermore, the parallel plate geometry of the undulator helps reduce the wake field effect further including the AC-conductivity related one [4]. Details of this wake field issue will be given below and elsewhere [5]. Fundamental parameters of PAL-XFEL is 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)

INJECTOR

In order to get hard X-ray SASE FEL, creating and keeping small emittance is uppermost. Therefore the photocathod RF gun is one of the essential elements for the success of SASE FEL. Our aim is to achieve normalized slice emittance of 1 micron or smaller for 1 nC bunch charge. The design pulse length is 10 ps and the final energy of the injector is 135 MeV. The PAL-XFEL photocathod gun is currently under development in collaboration with Brookhaven National Lab. (BNL). Currently the R&D place is in a test stand separate from the FEL site. Fabrication of solenoid magnets is finished and precision field measurements have been finished. Also Ti-Sapphire laser system has been installed and RF source system will be installed with in-house developed 66-MW klystron and a modulator with inverter PS. Details of PAL-XFEL injector design and R&D status are presented in a separate paper [6].

LINAC

Linac is composed of two sets of bunch compressors, one X-band accelerating section that is needed to compensate non-linearities, and conventional S-band accelerating columns. In the current design, the 1st bunch compressor

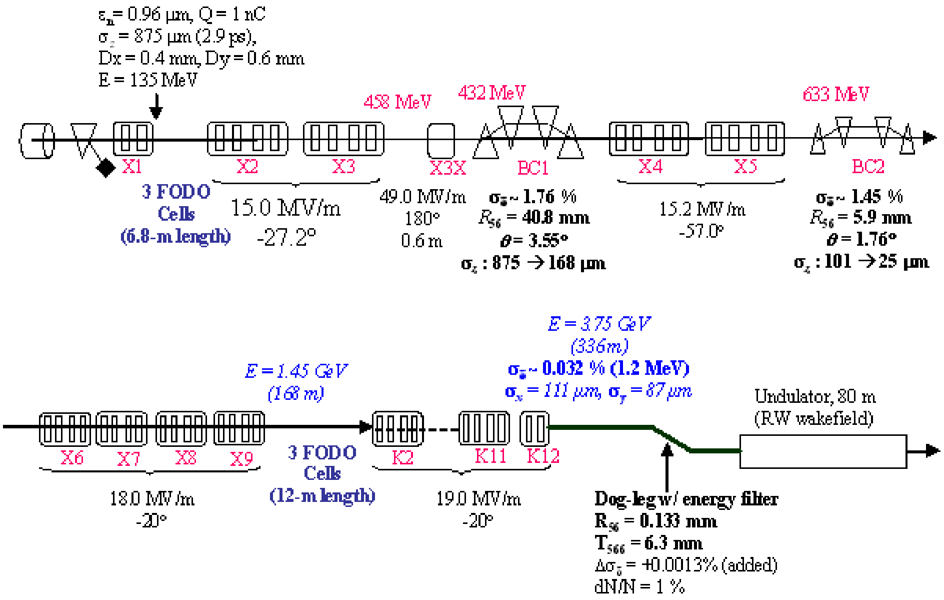

Figure 2: Layout of the PAL-XFEL injector and linac

(BC1) is located at the point of 430 MeV and the 2nd one (BC2) is located at 630 MeV. The X-band structure is located just before BC1. BC1 compresses the 10 ps injector output to around 200 μm and BC2 compresses it further to 80 μm. A layout of PAL-XFEL injector and linac is shown in Fig. 2. As is now well known, a serious problem in the bunch compressor design is the effect of coherent synchrotron radiation (CSR) in the bending magnets, especially the CSR instability which can develop for very cold beams [7, 8, 9]. The PAL-XFEL bunch compressors have also been designed to minimize the CSR effect. However, a possible use of a laser heater as a back-up plan is reserved. After BC2, the full bunch length of the almost rectangular beam is longer than 80 μm. This is a relatively long value, almost twice that of LCLS. As discussed in section 2, this long bunch helps to reduce the undulator wake field effect.

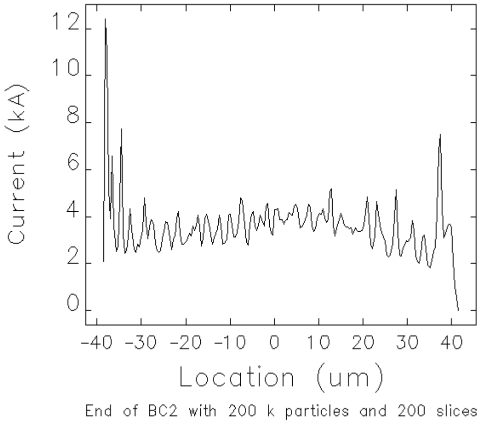

Figure 3: Slice peak current after BC2.

There are two FODO cells in the linac, one is 6 m long and places just after the injector and the other one is 12 m long and places right after the 9th accelerator column as shown in Fig. 2. These two FODO cells will be used for the diagnostic purposes. Graph of slice peak current is shown in Fig. 3. The peak current of most slices reaches 3 kA, the design value except the head and the tail. Also the graph of slice emittance is shown in Fig. 4. Note that most of the slice emittance is below 1 μm. Further design refinement may be necessary in the near future, but the current design already satisfies many expectations.

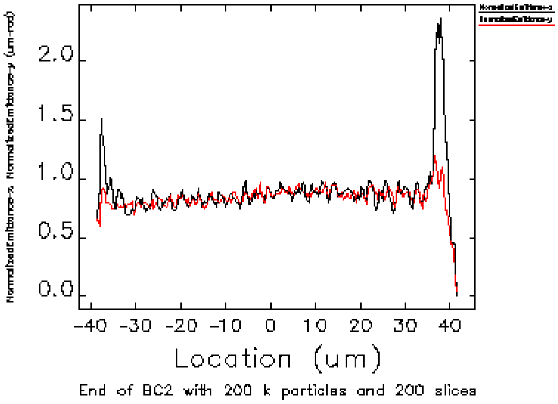

Figure 4: Slice emittance after BC2.

After the linac, there places 36 m long beam transport line to the undulator. It includes a dog-leg composed of 4 bending magnets, each of which bends 0.5°. The purpose of this dog-leg is to escape from the dark current coming from the gun. The dog-leg lattice has carefully designed to cause insignificant emittace dilution due to CSR (0.6 %) [10].

UNDULATOR

The PAL-XFEL undulator will be a hybrid planar undulator with the material of vanadium permendur. Basic parameters of PAL-XFEL are listed in Table 1. As shown there, each undulator segment is 4.5 m long. Between segments, a 0.5 m space is reserved for diagnostic equipments and a quadrupole for the beam focusing. Also, either a corrector magnet or trim windings on the quadrupole is planned. According to Genesis run, the saturation length is around 60 m, including the above diagnostic space, as shown in Fig. 5. The full undulator length would be 80 – 100 m to take care of possible errors. The radiation beam profile at 80 m of the undulator is shown in Fig. 6. It must be now clear that PAL-XFEL will work properly

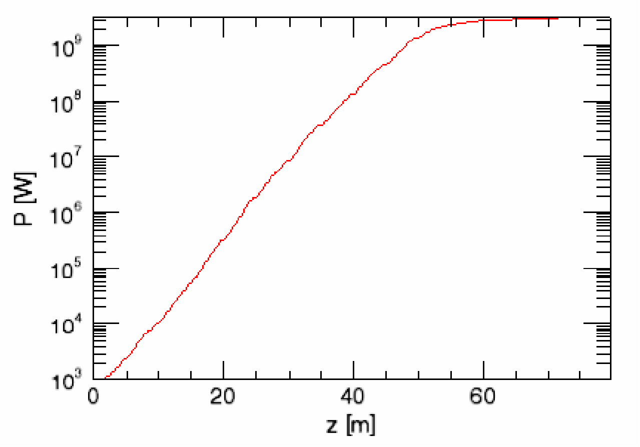

Figure 5: Power gain of PAL-XFEL.

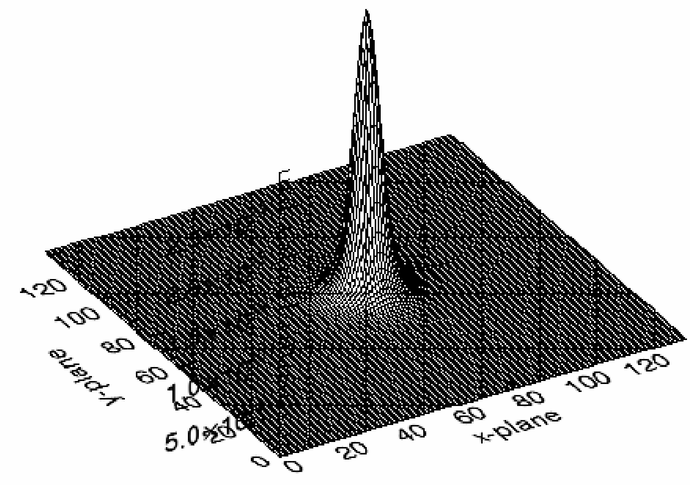

Figure 6: Radiation profile at z=80 m

SUMMARY

PAL-XFEL will provide 0.3 nm FEL with 3.7 GeV electron beam by expanding and upgrading the existing linac. Detailed design is still going on. It will use an in-vacuum undulator. The photo-cathod RF gun is under development. Linac has been designed to compress the bunch to a very short length and to keep the emittance below 1 mm mrad at the end of the linac. Undulator wake field effect is not so serious as one might consider. Simulation shows that the radiation power grows well exponentially and the saturation reaches at $Z = 60$ m. The saturation power is around 1 GW and the radiation profile is satisfactory even with including the wake field effect.

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