DESIGN STATUS OF PAL-XFEL*

T.-Y. Lee†, Y. S. Bae, J. Choi J. Y. Huang, H. S. Kang, C. B. Kim, D. E. Kim, M. G. Kim, Y. J. Kim[a], I. S. Ko, J. S. Oh, Y. W. Parc, and J. H. Park
Pohang Accelerator Laboratory, San 31, Hyoja-dong, Pohang, Kyungbuk 790-784, KOREA
[a]Free Electron Laser Laboratory, Duke University, N.C. 27708-0319, USA

Abstract

Pohang Accelerator Laboratory has a plan to build an X-ray FEL machine. This new machine will utilize the existing 2.5 GeV injection linac to the storage ring by upgrading its energy up to 3.7 GeV or more. The target wavelength will be 3-4.5 Å and its third harmonic 1-1.5 Å will also be used. The project will proceed in two stages: In the first stage, a VUV SASE machine with 320 MeV will be constructed and tested for the proof-of-principle. The full X-ray machine will be constructed in the next stage.

INTRODUCTION

PAL-XFEL is the name of new project of Pohang Accelerator Laboratory (PAL) to build a new X-ray FEL machine based on SASE (self amplified spontaneous emission) scheme. This new machine will utilize the existing 2.5 GeV electron linac by increasing its energy to 3.7 GeV and upgrading the performance. The linac is currently used for injection to the 2.5 GeV storage ring of Pohang Light Source (PLS). The new linac energy will be 3.7 GeV. The overview of the PAL-XFEL project was reported previously [1]. For readers unfamiliar with the project, fundamental parameters of PAL-XFEL are listed in Table 1 and the machine layout is displayed in Fig. 1. At the moment, detailed design study and machine R& D are going on. In the figure, K2,...,K12 denote the currently used accelerating columns and X1,...,X9 denote the new accelerating columns that will be added to the existing linac. X3X denotes the X-band high harmonic cavity. We are going to build the new part of PAL-XFEL while still running PLS.

However, there have been a few modifications in the PAL-XFEL project. The first important modification is the target wavelength that will be used mainly. The X-ray community, which is the biggest synchrotron user community in Korea, has demanded that the target wavelength be in 1-1.5 Å range, which put quite a challenge for the PAL-XFEL design. Since the available linac energy of PAL is limited, we decided to utilize the high harmonic radiation of SASE. It is well known that the high harmonic radiations are also amplified to FEL by the so called nonlinear harmonic generation [2, 3]. The existence and usefulness of SASE higher harmonic radiation was verified experimentally in VUV-FEL at DESY [4]. According to calculation based on [5], the third harmonic radiation power is approximately 1% of the fundamental one.

* Work supported by Korean Ministry of Science and Technology
† tylee@postech.ac.kr

The fundamental wavelength of PAL-XFEL was determined to be 3 Å in which case the third harmonic becomes 1 Å. These wavelengths are achieved by using an in-vacuum undulator of 4 mm gap. Recently, we are considering an alternative choice in which the fundamental wavelength is 4.5 Å and the third harmonic wavelength is 1.5 Å. In this case, wider undulator period and gap (and thus out-vacuum undulator) are allowed and the undulator wakefield is smaller. Currently, we are estimating the two designs and the final decision is not made yet. Below, comparison of the two choices is given briefly.

Another important modification is the procedure of PAL-XFEL construction. The PAL-XFEL project will proceed in two stages. In the first stage, only a small 320 MeV SASE machine will be constructed. The purpose of this machine is to test and prove the design strategy of PAL-XFEL. Hence, this test machine (TM) will use the same undulator as PAL-XFEL. Only in the second stage, the full PAL-XFEL will be constructed. The design of TM is under active study. Brief introduction to the TM design will be given below. This status report will describe major modifications of the PAL-XFEL design briefly. The PAL-XFEL photo-injector status has been prepared separately [6, 7].

ALTERNATIVE UNDULATOR DESIGN

The point of the alternative undulator design is to relax the original design slightly and make the whole scheme safer. For the purpose, the fundamental radiation wavelength is changed from 3 Å to 4.5 Å, which makes the third harmonic wavelength 1.5 Å. This change makes some difference. The comparison of the two undulator designs is given in Table 2.

What advantages do we get from this alternative design over the original one? First of all, the undulator gap is relaxed from 4 mm to 7.8 mm, which is wide enough to allow an out-vacuum undulator. With out-vacuum undulator, the chamber inner gap would be 6.8 mm which gives wakefield 40 % smaller. The longitudinal wakefield induces relative energy spread in the bunch, which is inversely proportional to the electron energy E. The relatively low energy, 3.7 GeV, of PAL-XFEL as a hard X-ray FEL machine may make the undulator wakefield particularly serious. Hence 40% reduction of wakefield is not negligible.

Another advantage is related to the transversal coherence of the SASE radiation and explained by a number B=gain length/Rayleigh length. B measures how fast the transversal higher modes diffract out of the electron beam. One of the advantages of the SASE FEL radiation is the transver-

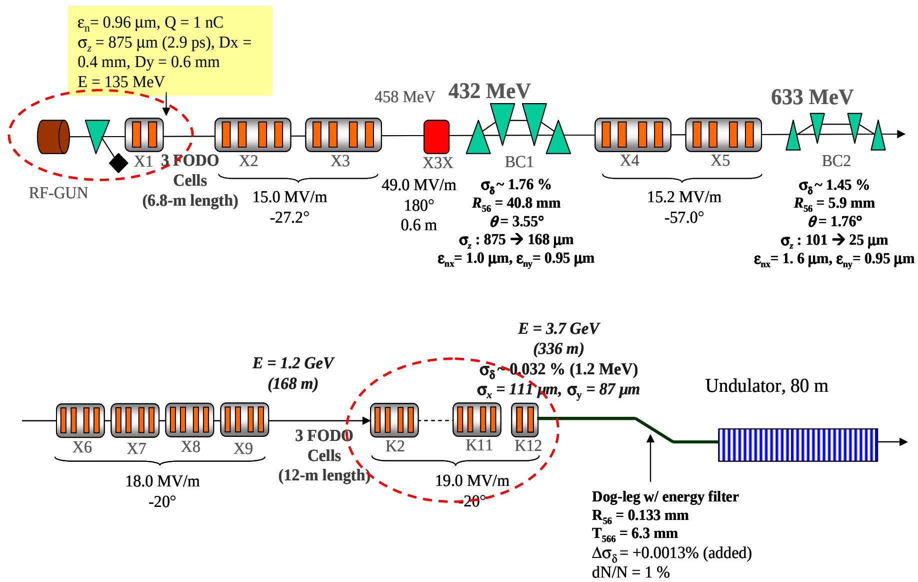

Figure 1: Layout of the PAL-XFEL injector and linac. K2,...,K12 denote the currently used accelerating columns and X1,...,X9 denote the new accelerating columns that will be added.

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	m
Peak undulator field	1.19	T
Undulator parameter, K	1.49	
Undulator gap	4	mm
Average β-function	10	m
FEL Parameters		
Radiation wavelength	3	Å
FEL parameter, ρ	5.7×10^{-4}	
Peak brightness	5×10^{31}	*
Peak coherent power	1	GW
Pulse repetition rate (Max.)	60	Hz
1D gain length	1.2	m
Saturation length, L_{sat}	45	m

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

Table 2: Comparison of the two undulator designs

Design	**Original**	**Alternative**
Wavelength	3 Å	4.5 Å
Third harmonic	1 Å	1.5 Å
Undulator	in-vacuum	out-vacuum
Undulator period	1.5 cm	2.2 cm
Undulator gap	4 mm	7.8 mm
Undulator parameter, K	1.49	1.52
FEL parameter	5.8×10^{-4}	6.6×10^{-4}
1-D gain length	1.2 m	1.5 m
Gain Length/Rayligh length	0.04	0.07
Saturation length	45 m	48 m
Peak power	2 GW	4 GW

sal coherence. However, the transversal coherence is not an intrinsic property of the undulator radiation but acquired by the amplification process in which all the transversal higher modes diffract out oh the beam while only the fundamental mode keeps growing. The bigger B is, the faster the higher modes diffract. It is true that B values of both the original design and the alternative design are not big enough compared with other machines such as LCLS. Figure 2 shows the power gain of the original design, while Fig. 3 shows that of the alternative design.

It is hard but possible to see that the power gain in Fig. 2 is not in a straight line but slightly over it. This indicates that the transversal higher modes do not diffract out fast enough and thus a small portion of it might remain at the final stage. Figure 3 shows a better case.

The third advantage of the alternative design is that its radiation power is bigger than that of the original design. As shown in Figs. 2 and 3, the peak radiation power of the original design is almost 2 GW while that of the alternative design is almost 4 GW.

The disadvantage of the alternative design compared with the original design is that its third harmonic radiation is 1.5 Å not 1 Å that is preferred by scientists working on organic samples. Those scientists include material scientists, biologists, organic chemists, and the number grows rapidly. The alternative design can provide 0.9 Å radiation

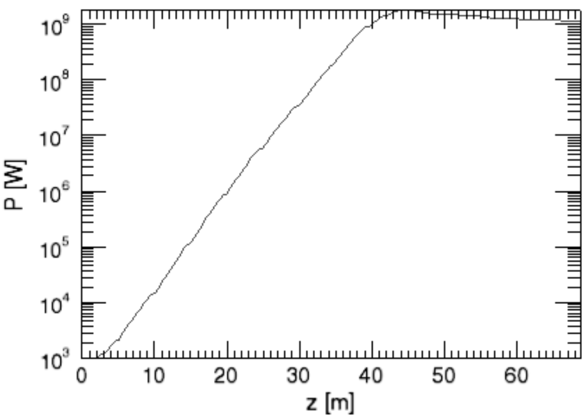

Figure 2: Power gain of the original undulator design.

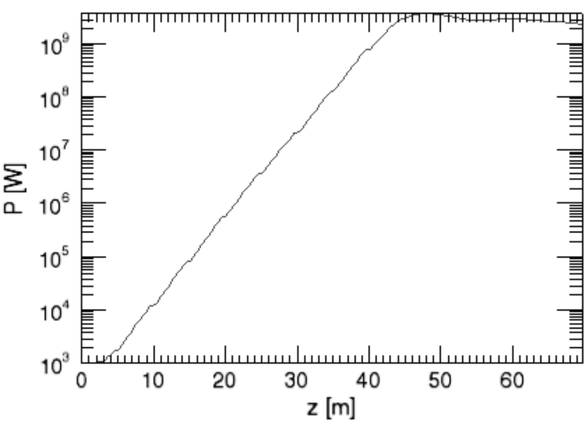

Figure 3: Power gain of the alternative undulator design.

as a fifth harmonic but its power is approximately 1/10 of the third harmonic radiation.

BUNCH COMPRESSOR DESIGN

The bunch compressor design is not fixed yet. There are a few issues still to be examined. One of the issues is the space charge in the bunch compressors. The ELEGANT code that is used in the linac design does not include the space charge effect and thus the space charge effect has not been checked seriously. It has been suggested that the second bunch compressor be in the higher energy region to make the space charge effect unimportant. A simulation study to estimate the space charge effect in the bunch compressors is going on.

Another important issue is the coherent synchrotron radiation (CSR). According to simulation, the electron distribution in the phase space is shifted slightly in the x, x' direction by CSR. This has to be fixed for the successful SASE FEL. A start to end simulation from the gun to the undulator was carried out. In case the CSR effect is off, the final radiation profile is very good as shown in Fig. 4, which was obtained with the alternative undulator design.

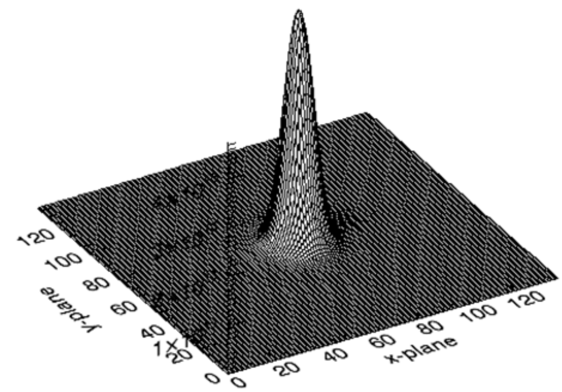

Figure 4: Radiation beam profile obtained from start to end simulation.

TEST MACHINE

The purpose of TM is to prove, in the low energy, that PAL-XFEL is achievable. It will not be used as a user facility. The reason why we need TM is that PAL-XFEL is challenging. It is challenging to generate hard X-ray (3 - 4.5 Å) SASE radiation with 3.7 GeV electron beam. The validity of the PAL-XFEL scheme will be proved by TM. TM will have a low energy of 320 Mev, lower than a tenth of PAL-XFEL energy, but the undulator will be the same as in PAL-XFEL except the total length. It will still adopt a pair of bunch compressors, but X-band higher harmonic cavity is not planned to be used at the moment. Beam parameters are chosen to give comparable magnitude of energy spread to the PAL-XFEL case. The optimal average β function of the undulator lattice is reduced from 10 m of PAl-XFEL to 5 m. A few fundamental parameters of TM are shown in Table 2.

Table 3: Parameters of the test machine

Parameters	Value	Unit
Electron energy	0.32	GeV
Peak current	0.7	kA
Normalized slice emittance	0.8	mm mrad
RMS slice energy spread	0.01 %	
Full undulator length	8	m
Average β-function	5	m
Radiation wavelength	28	nm
FEL parameter, ρ	3.4×10^{-3}	
1D gain length	0.2	m
Saturation length, L_{sat}	6	m

Since the high harmonic cavity is not used, the compressed bunch has a different shape from the PAL-XFEL case. The layout of TM is displayed in Fig. 5 and Fig. 6 shows the current distribution in a bunch at the test linac end.

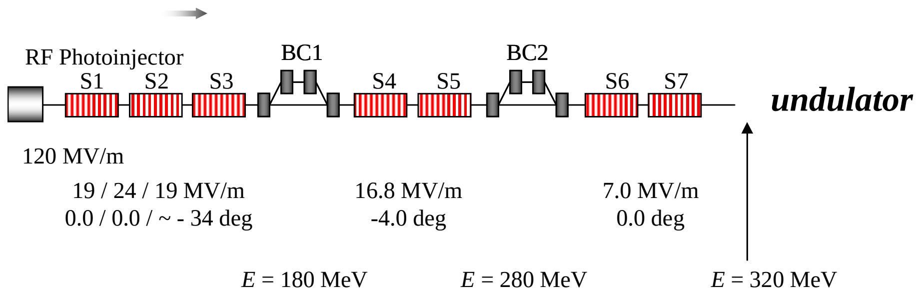

Figure 5: Layout of the test machine.

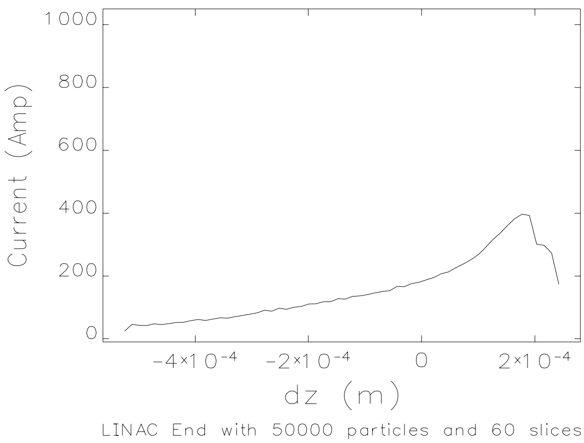

Figure 6: Current distribution in the linac end of the test machine.

SUMMARY

The progress of the PAL-XFEL design since the previous report [1] has been described. The bunch compressor design needs to be examined further with respect to the CSR and space charge effect. As for the undulator design, an alternative design has been described in comparison with the original design. The alternative design gives 4.5 Å fundamental radiation and 1.5 Å third harmonic, while the original design gives 3 Å fundamental and 1 Å third harmonic. The final decision for the undulator is not made yet. Also, an important change of the PAL-XFEL construction plan has been described. PAL-XFEL will be constructed in two stages. In the first stage, 320 MeV test machine will be constructed and the full 3.7 GeV machine will be constructed only in the second stage.

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