# COMPACT X-RAY FREE ELECTRON LASER PROGRAM AT THE PAL

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*Abstract*

We propose a compact X-ray FEL program at the PAL (Pohang Accelerator Laboratory), PAL-XFEL. PAL operates a 2.5-GeV electron linac as a full-energy injector to the PLS (Pohang Light Source) storage ring. It will be possible to produce coherent X-ray radiation as short as 0.3 nm with the linac upgrade for the beam energy of 3 GeV and an in-vacuum undulator system. The third harmonic enhancement technique will be applied to obtain 0.1-nm radiation. The design goal is for the undulator to be less than 60 m in total length. This paper presents the basic study and design details for the proposed PAL-XFEL.

## INTRODUCTION

LCLS [1] at SLAC and TESLA-XFEL [2] at DESY are in the detailed design stages with government funding approval. These SASE-XFEL facilities are expected to be operational by 2008 and 2012, respectively. Those projects require large-scale accelerators with 14 to 20-GeV electron beams and very long undulator systems with 113 to 175-m lengths.

PAL is operating a 2.5-GeV electron linac, the 3rd largest in the world, as a full-energy injector to the PLS storage ring. The linac is regularly injecting these beams to a storage ring twice a day for 5 minutes per injection. In its design stage, PAL was designed to use multi-application beams concurrently.

The scientific users require X-ray source with a radiation wavelength of 0.1 nm and a pulse length of 20 fs (FWHM). The existing 2.5-GeV linear accelerator can be upgraded to beam energy of 3.0 GeV and a bunch length of 100 fs (RMS) with reasonable cost. Public consensus requests project period of less than 5 years within 2010 and total hardware cost of about 40 M$.

It will be possible to produce coherent X-ray radiation as short as 0.3 nm with an in-vacuum mini-gap undulator. The third harmonic enhancement technique on the electron beam or advanced X-ray laser optics can be applied to obtain radiation wavelengths of 0.1 nm. The design goal is for the undulator to be less than 60 m in total length. Figure 1 shows PAL site layout and X-ray FEL plan. The femto-second FIR source will use 80-MeV electron beam from the multi-purpose test linac to generate a radiation of 1-20 μm. The SASE FEL source will use 3.0-GeV electron beam to generate X-ray laser of 0.1-0.3 nm and VUV FEL of 1-5 nm. Nominal beam parameters for the PAL-XFEL linac are summarized in Table 1. The beam bunch length of 10 ps (FWHM) is compressed to 235 fs (FWHM) with bunch charge of 1.0 nC, which gives the peak current of 4 kA.

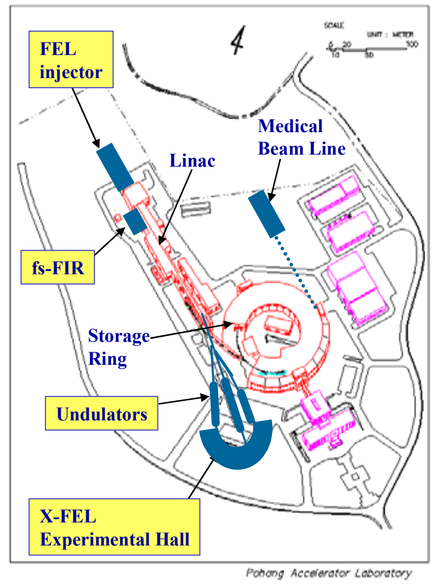


Figure 1: PAL site layout and X-ray FEL plan.

Table 1: Beam parameters for PAL-XFEL

| | |
|---|---|
| Beam energy [GeV] | 3.0 |
| Normalized emittance [mm-mrad] | 1.5 |
| Peak current [kA] | 4.0 |
| Bunch charge [nC] | 1.0 |
| FWHM bunch length [fs] | 235 |
| Energy spread [%] | 0.02 |

## UNDULATOR DESIGN

The fundamental radiation wavelength $\lambda_x$ of an undulator is given by

$$\lambda_x = \frac{\lambda_u}{2\gamma^2}(1 + K^2/2), \quad \gamma = E_o/0.511, \quad K = 0.934 B_u \lambda_u ,$$

where $E_o$ is the beam energy in MeV, $B_u$ is the peak magnetic field of the undulator in Tesla, and $\lambda_u$ is the undulator period in cm. Either a short-period undulator or a high-energy beam can provide short-wave radiation. However, the value of K should be reasonably large to obtain a short saturation length. An in-vacuum mini-gap undulator can meet this requirement. This concept was introduced by the SCSS project at SPring-8 [3].

The peak magnetic field $B_u$ of a 45° magnetized undulator with $H = \lambda_u/2$ is calculated by

$$B_u = \frac{4\sqrt{2}B_r}{\pi} \sum_{n=1,5,9}^{\infty} \frac{1}{n}(1 - e^{-2n\pi H/\lambda_u}) e^{-n\pi g/\lambda_u} ,$$

where $B_r$ is assumed 1.19 Tesla with $Nd_2Fe_{14}B$ magnets, H is the block height, and g is full-gap length.

Table 2 summarizes undulator parameters for a 0.3-nm PAL-XFEL. The undulator beta value is adjusted to obtain as short a saturation length as possible. Undulator saturation length is approximately 20 times 3D gain length $L_g$. We will use 13 units of 4.5-m long undulator. Table 3 lists the X-ray radiation parameters. Due to the rather higher emittance, the 3D gain length is twice the 1D gain length [4].

Table 2: Undulator parameters for 0.3-nm XFEL

| | |
|---|---|
| Period [mm] | 12.5 |
| Gap [mm] | 3.0 |
| Peak magnetic field [T] | 0.97 |
| Undulator parameter, K | 1.14 |
| Beta [m] | 15 |
| Saturation length [m] | 52 |

Table 3: X-ray radiation parameters

| | |
|---|---|
| FEL parameter | 0.00043 |
| 1D gain length [m], $L_{1d}$ | 1.35 |
| 3D gain length correction, η* | 0.97 |
| Gain length [m], $L_g$ | 2.67 |
| Peak power [GW] | 2.1 |
| Peak brightness [x $10^{32}$]** | 1.4 |

* $L_g = (1+\eta) L_{1d}$
** photons/sec-mm$^2$-mrad$^2$-0.1%BW

The 3D gain length correction and 3D gain length according to normalized emittance are shown in Fig. 2. In general, the electron beam emittance is required to be equal or less than the natural emittance of the FEL radiation. The gain correction factor of PAL-XFEL is a bit larger than the one of LCLS and TESLA XFEL due to rather large normalized emittance relative to the natural radiation emittance. However, due to the small periodic length of an undulator, the gain length becomes small. Therefore, it is possible to realized compact X-ray FEL by an in-vacuum undulator with small period and rather a low energy linear accelerator.

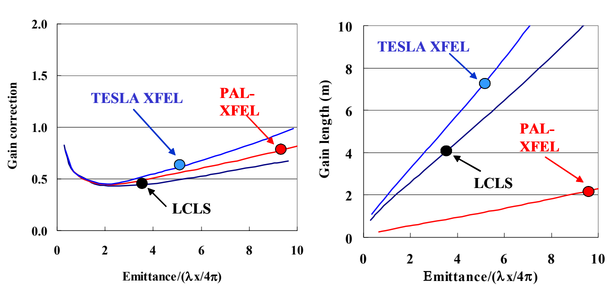


Figure 2: Gain length and gain correction factor.

The solid line 'PAL-XFEL' in Fig. 3 shows the expected peak brilliance of the fundamental radiation of PAL-XFEL. The three circles on the line correspond to beam energies of 2.0, 2.5, and 3.0 GeV. The peak brilliance of PAL-XFEL is $10^{12}$ time higher than the U7 undulator radiation from the PLS 3rd generation storage ring. The spontaneous radiation from the undulator of PAL-XFEL is hard X-ray and $10^{10}$ times brighter than the synchrotron radiation from the PLS bending magnet.

The 'PAL VUV FEL' uses a conventional undulator with a period of 3 cm and a gap length of 1.2 cm to generate 1-4 nm VUV radiation by changing the beam energy from 1.5-3.0 GeV. The 'PAL 0.1-nm XFEL' denotes the 0.1-nm PAL-XFEL with the third harmonic enhancement technique employing an additional undulator with a shorter periodic length.

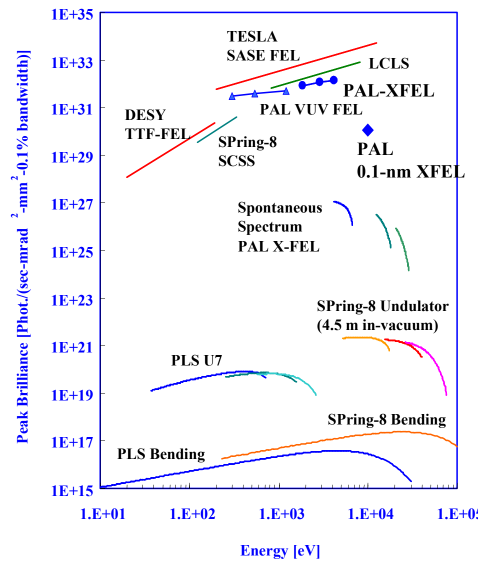


Figure 3: Peak brilliance for PAL-XFEL.

## ACCELERATOR DESIGN

Existing 2.5 GeV S-band PLS linac can be converted to X-ray FEL driver with a new S-band photo-injector, and a new S-band FEL injector linac, two bunch compressors. Figure 4 shows a possible upgrade layout of the PAL linac including a new 0.5-GeV injector and a new undulator system (U1 to U13). The injector consists of a low-emittance laser-driven photocathode-gun, three S-band accelerating modules (X1, X2, X3), and two bunch compressors, BC1 and BC2.

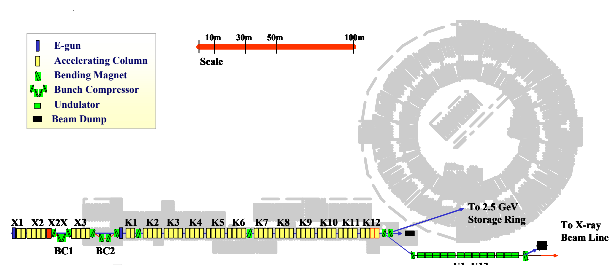


Figure 4: PAL-XFEL compression and acceleration.

The S-band photo-injector is consisted of a Cu cathode and 1.6-cell S-band RF cavity. Table 4 shows beam condition at the cathode. The photoelectron beam is generated by 10-ps, 500-μJ, and 260-nm UV laser. It is accelerated to 7 MeV by a high gradient field of 120 MV/m within 0.168-m length. The high gradient acceleration is essential to preserve the beam emittance under high space charge force at the low energy.

Table 4: Beam condition at the cathode

| | |
|---|---|
| Bunch length | 10 ps (FWHM), 2.9 ps (rms) |
| Rise time (10-90%) | 0.7 ps |
| Spot size | 0.6 mm (rms) |
| Thermal emittance | 0.6 μm |
| Peak gradient | 120 MV/m |
| Peak solenoid field | 2.71 kG at 19.1 cm |

Against projected parameter dilution due to CSR and chromatic effect, adopted lattice design concepts are as follows: long drift space for small bending angle; large energy spread and large compression factor at BC1; small compression factor at BC2; strong focusing lattice around BC to reduce CSR induced emittance growth; small quadrupole length around BC to reduce the chromatic effects; small beta-function at BC1 entrance; large beta-function at BC2 entrance. Against slice parameter dilution due to the micro-bunching instability, following design concepts are adopted: normal 4-bend chicane instead of S-type chicane; large uncorrelated energy spread at BC2 by putting the BC2 at low energy region. Figure 5 shows the layout of two bunch compressors and a new accelerator.

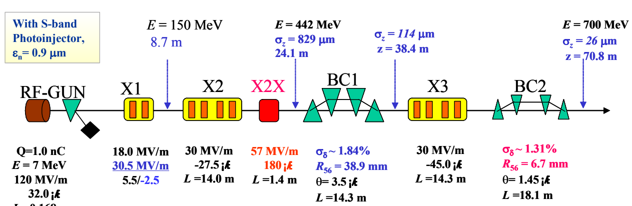


Figure 5: BCs and a new accelerator layout.

The beam parameter is obtained by the ASTRA simulation considering the space charge force at low energy. Lattice is designed by using ELEGANT code from X2 accelerating unit to the end of existing linac. The existing quadrupole magnets along the main linac are optimized as it is.

Table 5 shows the design parameters of bunch compressors. BC2 layout is almost same as BC1: dipole length is 0.3 m; the drift length is 5 m; total chicane length is 12.2 m. All uncorrelated energy spread is estimated at +/-0.1 mm core. The bunch length at the center of BC2 is 70 μm and the transverse beam size is 1.74 mm. By adding a 300-μm slit at this location, the bunch length can be further reduced less than 20 fs.

At the end of linac, beam size is 68.1 μm ($\sigma_x$), and 61.9 μm ($\sigma_y$); bunch length is 26 μm; emittance is 1.116 μm ($\varepsilon_{nx}$) and 1.004 μm ($\varepsilon_{ny}$). Figure 6 shows that the beam qualities at the end of linac are well matched to the requirement for FEL lasing.

Table 5: Design parameters of bunch compressors

| Parameter | BC1 | BC2 |
|---|---|---|
| Beam energy | 442 MeV | 700 MeV |
| Relative energy spread | 1.84% | 1.31% |
| Uncorrelated energy spread | 9.2e-6 | 4.3e-5 |
| Bending angle | 3.50 deg | 1.45 deg |
| Momentum compaction $R_{56}$ | 38.9 mm | 6.70 mm |
| Initial rms bunch length | 820 μm | 114 μm |
| Final rms bunch length | 114 μm | 26 μm |
| Compression factor | 7.2 | 4.38 |
| Initial projected emittance | 0.90 μm | 1.01 μm |
| Final projected emittance | 1.01 μm | 1.12 μm |

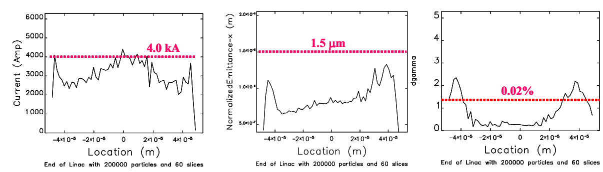


Figure 6: Beam quality at the end of linac.

## FUTURE PLAN

The wake field effect on the electron beams in the undulator and the beam quality degradation due to the magnet field error are sensitive to FEL process. The jitter and sensitivity analysis on the combined parameter space is to be intensively followed. Hardware upgrade scheme of existing linac is to be examined. Stability requirements and related technical parameters are analyzed.

## SUMMARY

PAL is proposing a $4^{th}$-generation light source, PAL-XFEL utilizing an existing 2.5-GeV linac. The in-vacuum undulator is optimized for short saturation length within 60 m for 0.3-nm PAL-XFEL. We have optimized the PAL-XFEL lattice by adding an S-band RF photo-injector, an injector linac, and two bunch compressors, to the existing 2.5-GeV PLS linac. Optimized parameters of PAL-XFEL are very promising to generate 0.3-nm X-ray laser source.

## ACKNOWLEDGMENTS

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## REFERENCES

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