X-RAY FREE ELECTRON LASER PROJECT OF POHANG ACCELERATOR LABORATORY*

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Abstract

The PAL XFEL is designed to generate 0.06-nm wavelength coherent X-ray by using self-amplified spontaneous emission mechanism from a 10-GeV electron linear accelerator, which is required to generate high brightness electron beam with 0.2 nC charge, normalized emittance of 0.5 μm-rad, and peak current of over 3 kA in order to reduce the required length of undulator for saturation below 70 meters. The radiation that is coherent and a few tens of femto-second long will cover hard X-ray (0.06 ∼ 1 nm) as well as soft X-ray in the ranges of 2∼5 nm. Advanced X-ray free-electron laser concepts are also being considered in the design: self-seeded operation for narrow band spectrum as well as attosecond X-ray pulse generation using the energy modulation of electron beam by optical laser beam. The baseline design of 0.06-nm femtosecond XFEL radiation generation as well as attosecond 0.1-nm XFEL radiation generation will be presented.

INTRODUCTION

Pohang Accelerator Laboratory (PAL) is proposing an X-ray free-electron laser facility that is designed to generate 0.06-nm wavelength coherent X-ray by using self-amplified spontaneous emission mechanism from a 10-GeV electron linear accelerator, which consists of a 135 MeV injector with 6-MeV photo-cathode RF-gun, two chicane-type bunch compressors (BC1 and BC2), 10-GeV S-band linac, and 85-m long in-vacuum undulator (see Fig. 1). The locations of BC1 and BC2 are at 420 MeV and 2.8 GeV, respectively, which was determined in balances of longitudinal space charge force and coherent synchrotron radiation effect. The emittance of electron beam from the RF-gun is as small as 0.4 $\mu m - rad$ at the beam charge of 0.2 nC, and the bunch length is about 5 ps at the exit of 135-MeV injector. After BC2, the bunch length is reduced to below 50 fs to get the bunch current of 3 kA or higher. A 0.6-m long X-band cavity with the accelerating gradient of 47.5 MV/m is used to linearize the non-linear longitudinal phase-space.

We have chosen a beam energy of 10 GeV and in-vacuum type undulator to get 0.06-nm (20 keV) radiation with the undulator shorter than 70 m. The undulator period is 2 cm and the undulator gap for 0.1 nm is 4 mm when the

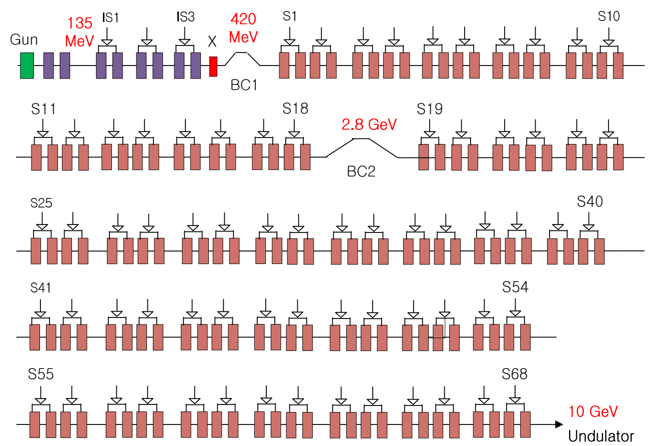

Figure 1: Layout of PAL-XFEL. BC1 and BC2 represent first and second chicane-type bunch compressor.

undulator parameter is 2.35. The saturation length in Table 1 is calculated with MingXie's formula.

We are also considering a 20 pC operation with 0.15 μm-rad emittance beam to get much shorter FEL photon length below 5 fs. The accelerating gradient of S-band linac is 27 MV/m, which is achieved by using one klystron and one sled for two 3-m long accelerating structures.

We are also considering an ESASE(Enhanced SASE) scheme to get atto-second 0.1 nm FEL radiation, which uses optical laser beam to introduce an energy modulation into electron beam.

The length of linac is 550 meters, the beam transport line to undulator is 80-m long, the undulator hall is 130-m long to accommodate a wiggler and a chine for the EASE scheme, and the XFEL beam line consisting of front-end (50 meters) and experimental hall (60 m) is 110 meters long. The total length of the facility is 870 meters.

START-TO-END SIMULATION

Start-to-end simulation was done by using PARMELA code for injector [1], Elegant code for linac [2], and Genesis code for SASE process in undulator [3]. The electron beam properties at the entrance of undulator calculated by the Elegant code (see Fig. 2) show that the slice current is around 3 kA, the slice emittance in both horizontal and vertical directions is smaller than 0.5 mm-mrad, and the incoherent energy spread is smaller than 1.0×10^{-4} with the coherent energy spread being much smaller than the FEL

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Table 1: Parameters of PAL XFEL

	Parameter	Value
	FEL radiation wavelength [nm]	0.1 / 0.06
Linac	Beam energy [GeV]	10
	Beam charge [nC]	0.2
	Beam emittance [mm-mrad]	0.5
	Peak current at undulator [kA]	3.0
	Relative energy spread	1.0×10^{-4}
Undulator	Undulator period [cm]	2.0
	Undulator gap for 0.1 nm [mm]	4.0
	Undulator parameter for 0.1 nm, K	2.35
	Undulator gap for 0.06 nm [mm]	5.7
FEL	FEL parameter	4.9×10^{-4}
	RMS Photon length [fs]	< 50
	Saturation length for 0.1 nm [m]	45
	Saturation length for 0.06 nm [m]	68

parameter of 4.9×10^{-4} as well. The electron bunch length at the entrance of undulator is as small as 20 μm ($\approx 60 fs$).

Figure 3 shows the genesis code simulation result for (a) 0.1 nm FEL and (b) 0.06 nm FEL using the electron beam described in Fig. 2. There is a difference in data representation between (a) and (b), which is that 0.1 nm data is averaged over the beam slices while 0.06 nm data is maximum among slice bunches. It is seen from the figure that the saturation length for 0.06-nm XFEL is below 70 meters.

ATTO-SECOND XFEL GENERATION

The saturation length of the SASE process is $L_g \propto \epsilon^{5/6}/I_p{}^{1/2}$. Increasing the peak current (I_p) and keeping the emittance (ϵ) through the bunching process with a very small charge beam can make it possible to decrease L_g. It is observed in the photo-cathode RF-gun of LCLS that when the beam charge at the gun is 20 pC, the emittance decreases to 0.15 μm-rad. If the peak current after the laser-modulated bunching is over 8 kA, and the emittance is kept below 0.5 um-rad, it is possible to decrease the saturation length from 45 m to 30 m for 0.1 nm XFEL radiation. The number of undulator periods for 30-m long undulator is $30\ m/2.0\ cm = 1500$, and the total slippage distance is $1500 \times 0.1\ nm = 150\ nm = 0.5\ fs$.

The ESASE scheme consists of a wiggler with two periods, a four-dipole chicane, and 800-nm Ti-Sappire laser. The resonant interaction between laser beam and electron beam takes place in the wiggler. Following the idea of the EASE scheme of ref. [4], we did a simple calculation of micro-bunching through an energy modulation in wiggler with optical laser beam. The parameters of the ESASE scheme was determined such as wiggler period of 45 cm, the undulator parameter of 50, and the momentum compaction factor, R_{56}, of 0.6 mm (see Table 2). Figure 5 shows the micro-bunching of electron beam by laser beam. The first graph is relative energy spread for one laser wavelength before wiggler, the second after wiggler, the third after chicane, and the last is the electron distributions after

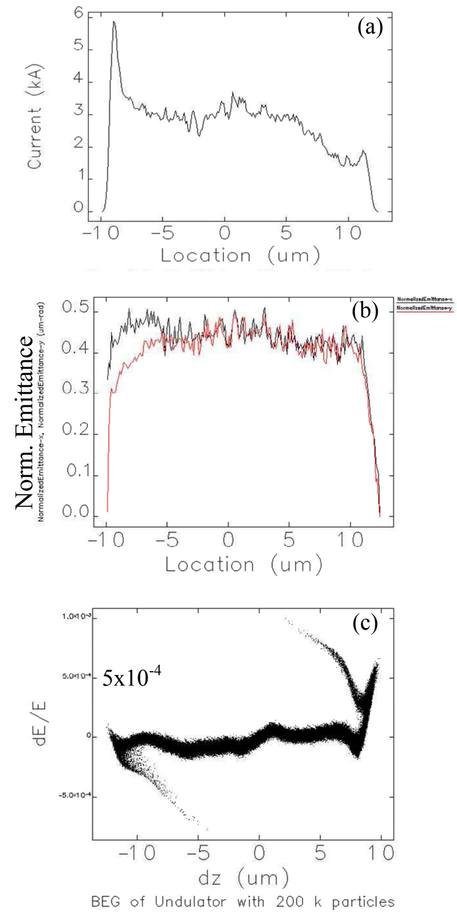

Figure 2: 10-GeV / 0.2 nC electron beam properties at the entrance of undulator: (a) current profile, (b) normalized emittance, and (c) longitudinal phase space. In (b) the black and red lines represent the horizontal and vertical emittances, respectively.

chicane, which indicates that the bunch length is as short as 500 as.

Table 2: Parameters of ESASE Scheme

Parameter	Value
Electron energy, E	10 GeV
Number of wiggler period, N_w	2
Wiggler period	45 cm
Undulator parameter	50
Laser wavelength	800 nm
Undulator parameter	50
Wiggler field	1.093 T
Momentum compaction factor, R_{56}	0.6 mm
Laser power	5.0 GW

Start-to-end simulation with 200 pC beam instead of 20 pC was carried out for the ESASE scheme. Figure 6 shows the 10-GeV / 0.2 nC electron beam properties at the entrance of undulator passing through the laser-beam interaction. The 800-nm laser pulse length is 6 fs rms and the laser

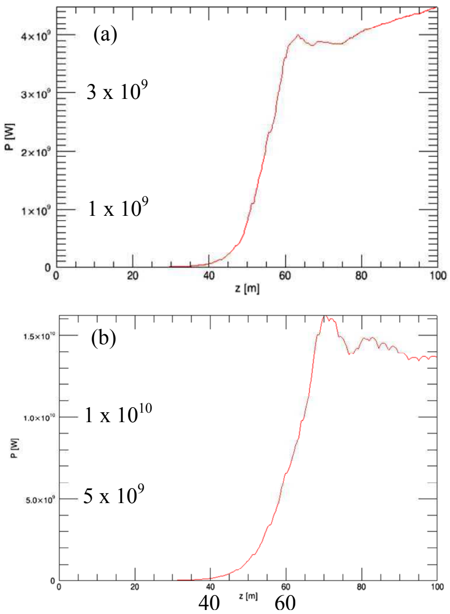

Figure 3: Genesis code simulation result for (a) 0.1 nm FEL and (b) 0.06 nm FEL. The electron beam energy is 10 GeV, and the beam charge is 0.2 nC.

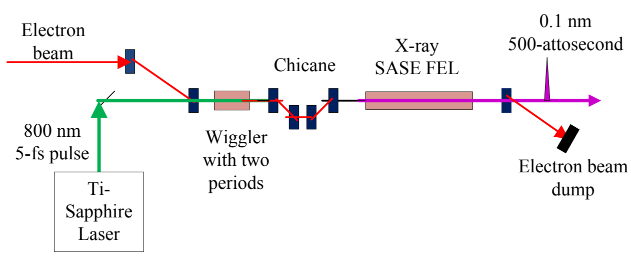

Figure 4: ESASE Scheme for atto-second XFEL radiation.

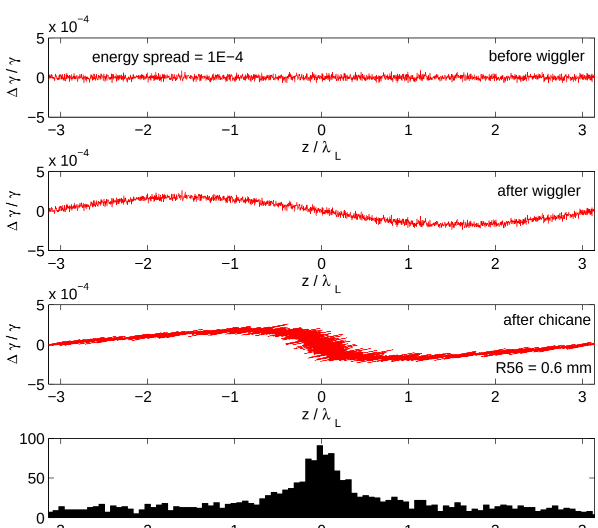

Figure 5: Micro-bunching by laser modulation. The first graph is relative energy spread for one laser wavelength before wiggler, the second after wiggler, the third after chicane, and the last is the electron distributions after chicane.

power is 10 GW. The current profile at the mid of bunch after chicane shows that the peck current reaches over 10 kA. The emittance increase at the mid of bunch is negligibly small, below 0.7 μm-rad. The interesting thing is the large current peak at the tail of bunch, which is over 25 kA. It is not due to laser beam but due to the energy chip at the tail of the bunch from 5 to 6 μm as shown in Fig. 6(b), which is compressed to sub fs in the chicane for the ESASE scheme. The emittance at the tail of bunch grows to 1.2 µm·rad.

Figure 7 shows the genesis code simulation result for 0.1 nm FEL using the electron beam described in Fig. 6. Four peaks of atto-second XFEL radiation are developed by ESASE technique at the mid of bunch and the largest peak is developed at the tail of bunch at z=20 meters of the undulator. At z=40 meters, the first peak at the tail of bunch reaches up to 2×10^9W even though the emittance grows to 1.2 μm-rad. The second two-peaks by the ESASE process reach 1.5×10^9W. The first peak is unexpected one in the ESASE process. But it looks very short, about 1 fs.

SUMMARY

A 0.06 nm PAL-XFEL design was done with a 10 GeV linac and in-vacuum undulator. Beam dynamics calculation shows the design parameters are achievable. Beam dynamics calculation of the ESASE scheme shows that atto-second 0.1-nm XFEL generation is achievable from 200 pC e-beam. The unexpected radiation peak with atto-second length is observed in the simulation, which will be revisited soon. Beam dynamics calculation of atto-second X-ray generation from 20-pC beam will be done to compare with the 200-pC case.

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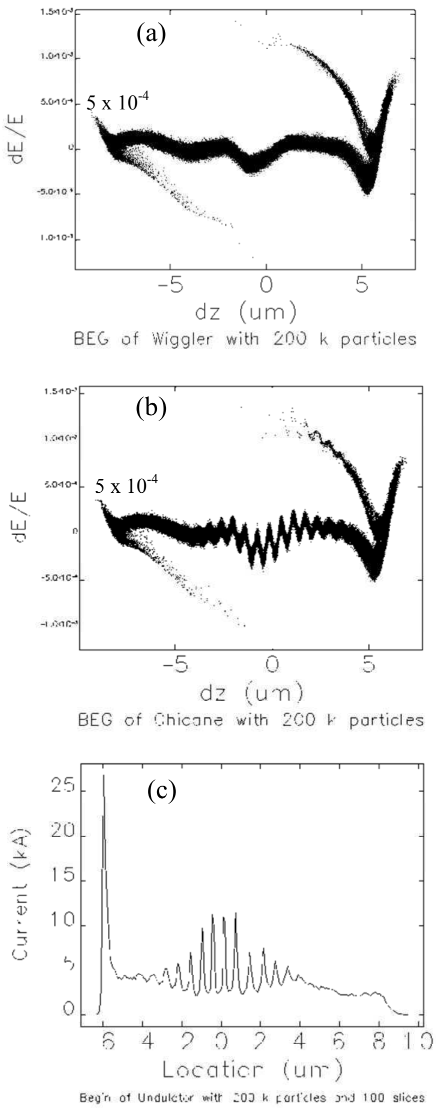

Figure 6: 10-GeV / 0.2 nC electron beam properties at the entrance of undulator via the laser-beam interaction: (a) longitudinal phase space before wiggler, (b) longitudinal phase space after wiggler, and (c) current profile after chicane.

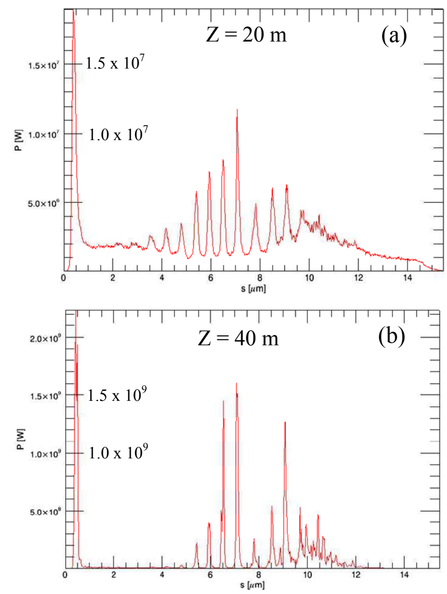

Figure 7: 0.1 nm SASE output at two different location of undulator: (a) 20 m, (b) 40 m.