STATUS OF THE PAL-XFEL*

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Abstract

The construction of the PAL-XFEL was completed at the end of 2015 and the FEL commissioning started from the beginning of 2016. The commissioning aims for the lasing of 0.5 nm FEL in the first campaign by July 2016, and for the lasing of 0.1 nm hard X-ray FEL in the second campaign by December 2016. The commissioning results of the 0.5 nm FEL lasing will be presented.

INTRODUCTION

The Pohang Accelerator Laboratory (PAL), Pohang, South Korea, is developing a 0.1 nm SASE based FEL, named PAL-XFEL, for high power, short pulse X-ray coherent photon sources. It is adjacent to the existing 3-rd generation light source, PLS-II, which was upgraded to a 3-GeV/400-mA/6-nm facility in 2010 (see Fig. 1). The PAL-XFEL project was started from 2011 with the five-year total budget of 400 MUSD, its building construction completed by the end of 2014, and successively the installation of linac, undulator, and beam line followed and was completed in January 2016. The FEL commissioning started in April 2016.

The PAL-XFEL includes a 10-GeV S-band normal conducting linac, which is 700 m long and consists of a photocathode RF gun, 174 S-band accelerating structures with 50 klystron/modulators, one X-band RF system for linearization [1], and three bunch compressors (see Table 1 and Fig. 2). Beyond the 10-GeV linac, a 250-m long hard x-ray undulator hall follows. An experimental hall, which is 60-meters long and 16-meters wide, is located at the end of the facility. The total length of the building is 1,110 meters.

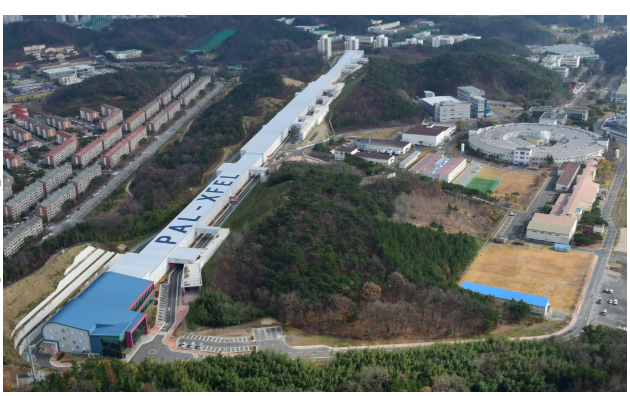

Figure 1: Picture of PAL-XFEL building.

The PAL-XFEL linac is divided into four acceleration sections (L1, L2, L3, and L4), three bunch compressors (BC1, BC2, BC3), and a dogleg transport line to undulators as shown in Fig. 2 [2]. A laser heater to mitigate micro-bunching instability is placed right after the 135 MeV injector, and an X-band cavity is placed right before BC1. A soft X-ray FEL branch line is located at 3 GeV point of the 10-GeV linac.

Originally, 0.3 nm FEL lasing was planned in the first campaign. But, the cavity BPM electronics essential for the undulator line were not fully functional, only 14 out of the minimum number of 22 for 20 undulators. We had to use only 12 undulators, therefore, decided to get lasing of 0.5 nm FEL instead of 0.3 nm.

Table 1: Parameters of PAL-XFEL

Linac	
FEL radiation wavelength	0.1 nm
Electron energy	10 GeV
Slice emittance	0.5 mm-mrad
Beam charge	0.2 nC
Peak current at undulator	3.0 kA
Pulse repetition rate	60 Hz
Electron source	Photo-cathode RF-gun
Linac structure	S-band normal conducting
Undulator	
Type	out-vacuum, variable gap
Length	5 m
Undulator period	2.6 cm
Undulator min. gap	8.3 mm
Vacuum chamber dimension	13.4 x 6.7 mm

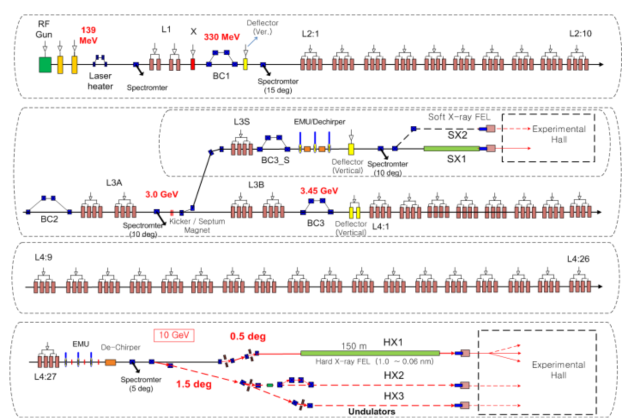

Figure 2: Schematic layout of PAL-XFEL.

LINAC COMMISSIONING

The installation of accelerating structures, magnets, vacuum chambers, and klystron modulators for the 10-

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GeV linac was finished at the end of October 2015 (see Fig. 3), when the linac tunnel was closed to start the RF conditioning for the accelerating structures. While the RF-conditioning was under way in linac, we continued the installation work in the undulator section. To do this we installed the 1-m thick concrete block at the end of linac tunnel to make the undulator hall safe from radiation.

The installation of undulator section was complete in January 2016. After getting an approval of accelerator operation from the Radiation Safety Control Agency in April, we began the accelerator commissioning starting from the 135-MeV injector on April 14. One day after we got the first beam from the RF-gun we achieved a 135-MeV beam at the injector. We continued the beam acceleration to the next RF sections of L1, L2, L3, and finally L4 to achieve a 10-GeV beam. It took only 11 days to accelerate the beam up to 10 GeV and transport to the linac end, BAS3H, which is 715 m away from the gun (see Fig. 4).

Figure 3: Picture of Linac tunnel.

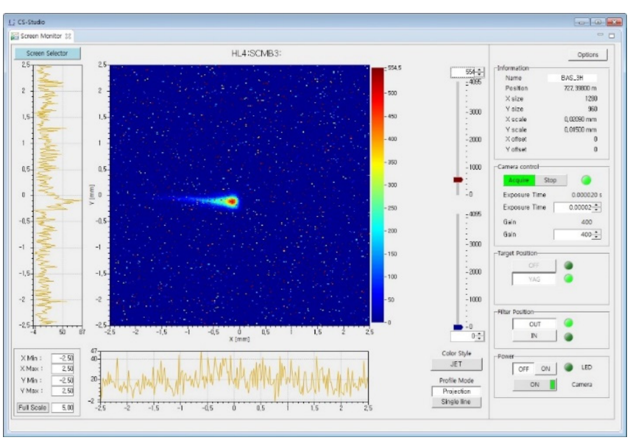


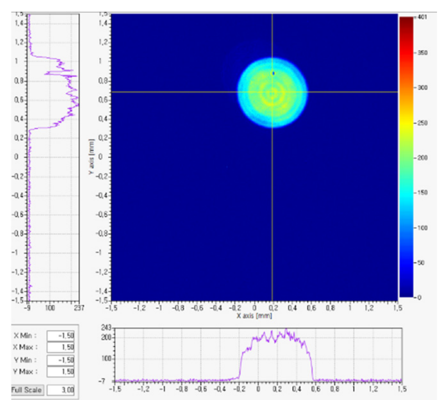
Figure 4: 10-GeV beam image captured at the BAS3H screen monitor of Linac.

Injector

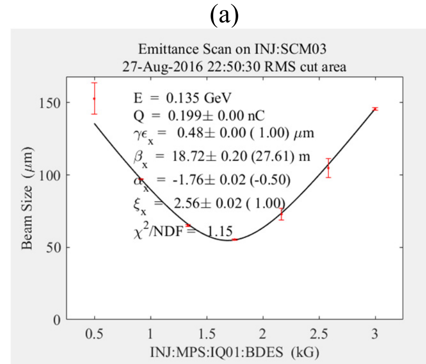
The injector consists of the PAL-design photo-cathode RF-gun and two S-band J-type accelerating structures [3], and a laser heater system consisting of a short undulator and four dipoles (see Fig. 5).

The transverse profile of UV laser beam for the gun is changed to cut Gaussian from uniform distribution, which enables us to achieve the best projected emittance of 0.48 mm-mrad (h) and 0.42 mm-mrad (v) at the beam charge of 200pC (see Fig. 6). It was 0.88 mm-mrad and 058 mm-mrad for horizontal and vertical direction, respectively, with the uniform distribution. The poor emittance is thought to be because the uniform distribution tends to have density modulation in radial direction.

Figure 5: Picture of 135 MeV Injector.



(a)



(b)

Figure 6: (a) Transverse profile of UV laser beam for the gun, (b) horizontal emittance of 135 MeV Injector.

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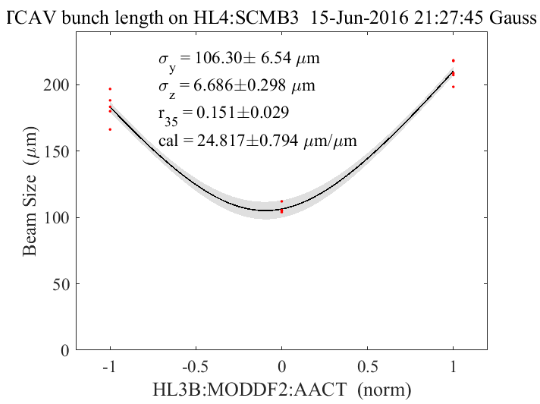
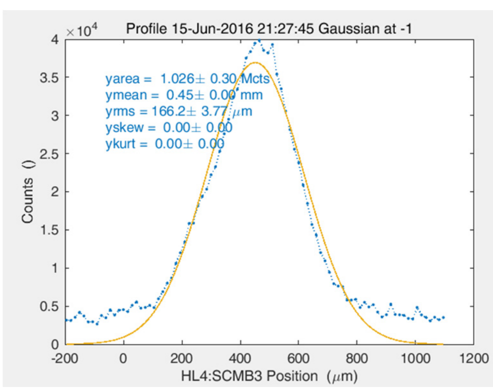
Linac

Only two bunch compressors (BC1, BC2) among three are used for bunch compression to simplify the bunch compression. The bunch length measured with a deflecting cavity located downstream BC3 is 6.68 um (22 fs), which corresponds to the peak current of 3.07 kA at the beam charge of 170 pC (see Fig. 7).



(a)



(b)

Figure 7: (a) TCAV bunch length measurement, (b) longitudinal distribution of bunch.

FEL COMMISSIONING

For the PAL-XFEL the two undulator lines are prepared: 20 planar undulators for the hard X-ray line, HX1, and 7 planar undulators for the soft X-ray line, SX1. The installation of HX1 undulators into the 250-m long undulator hall was finished in January 2016 (see Fig. 8). A self-seeding section is allocated right after the 8-th undulator of HX1. In the first place the hard X-ray FEL, HX1, was commissioned because of the priority issue. The soft X-ray FEL will be commissioned after we succeed in lasing of 0.15 nm hard X-ray FEL, maybe in December.

0.5 nm FEL Lasing in June

On 19 May 2016 the 10-GeV beam was farther transported to the tune-up dump which is located at the entrance of the undulator line HX1, 794 m away from the gun. We carried out the optimization study to have better beam profiles in transvers and longitudinal directions for the beam transport through the 126-m long small gap undulator chambers.

We need at least 22 cavity BPMs functional for the 20 undulators. But, the available BPM electronics were only 14 in late May. After we installed the cavity BPM control electronics, we tried to send the beam thorough 20 undulators down to the main dump, which was successfully done on June 2nd. Then, we carried out the cavity BPM calibration with the cavity BPM mover. Each cavity BPM pick-up is equipped with its own mover with the maximum moving distance of +/- 1.5 mm for both horizontal and vertical directions [4, 5]. And then, the undulator BBA was done with four different beam energies of 4.0, 5.12, 6.2, and 9.97 GeV. Since only 14 cavity BPMs are functional, the BBA is applicable to the upstream 12 undulators (see Fig. 9).

Figure 8: 20 undulators installed in the hard X-ray undulator hall (HX1).

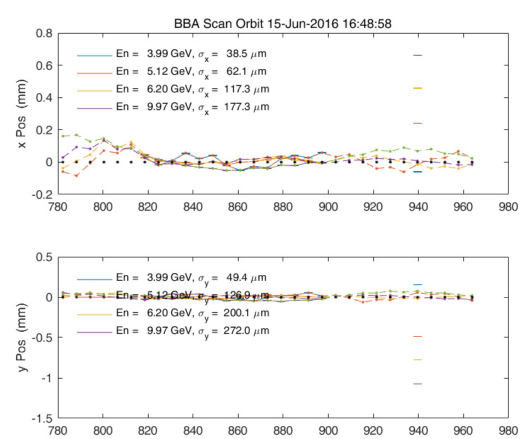
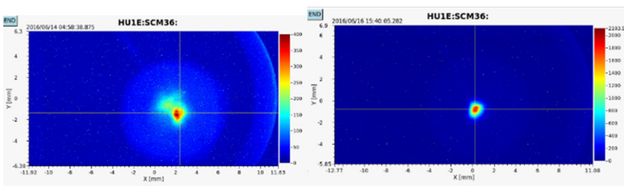


Figure 9: Scan obit of undulator BBA.

After we establish the orbit along the undulator, we tried to get lasing of 0.5 nm FEL with the 4-GeV electron beam, which was successful to get the first FEL beam on June 14th (see Fig. 10(a)). After we improved the beam, we got the brighter FEL beam (See Fig. 10(b)).



(a) (b)

Figure 10: Lasing of 0.5 nm FEL: a) the first light, b) the brighter one.

FEL Lasing in August

After the summer maintenance of July, we re-started the FEL commissioning in mid-August. Very soon we could realize the lasing of 0.5 nm FEL. This time we use the smaller gap of undulator, 9 mm, for the higher K-value of 1.87. It was 9.5 mm with the undulator parameter of 1.75 in the FEL commissioning of June. The FEL beam intensity is increased by a factor of 6 compared to that of June based on the beam image intensity (see Fig. 11). The number of functional cavity BPM electronics are same as of June. But, by relocating one BPM electronics to the upstream side we can use 13 undulators for FEL lasing.

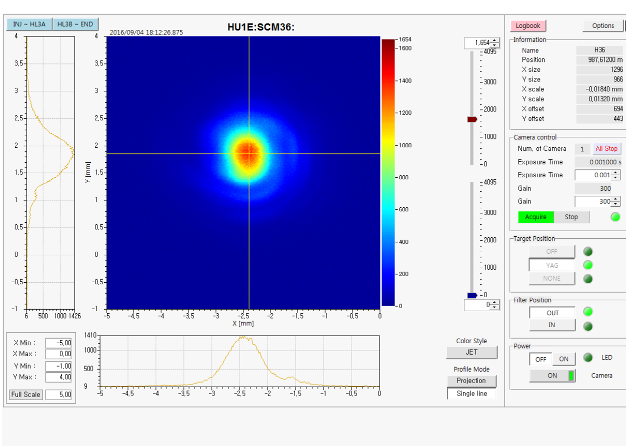


Figure 11: The brightest FEL of 0.5 nm.

The FEL beam is delivered to beamline for calibrating a double crystal monochromator as well as the beamline commissioning. As the fundamental photon energy is 2.19 keV and out of range of DCM, we decided to use third harmonics, 6.58 keV, for the photon beam measurement. Figure 12 shows the spectrum of 3-rd harmonics obtained by using a single shot spectrometer. The blue line is 10 shots average data and the red is the single shot data. The measured bandwidth is 0.45 %. For single shot measurement we use a bend (R=100 mm) Si(111) Sliver with the dimension of 15 mm x 5 mm x 0.01 mm and a PyLoN detector. Figure 13 shows the multiple profiles of the single shot spectrum of 3-rd harmonics.

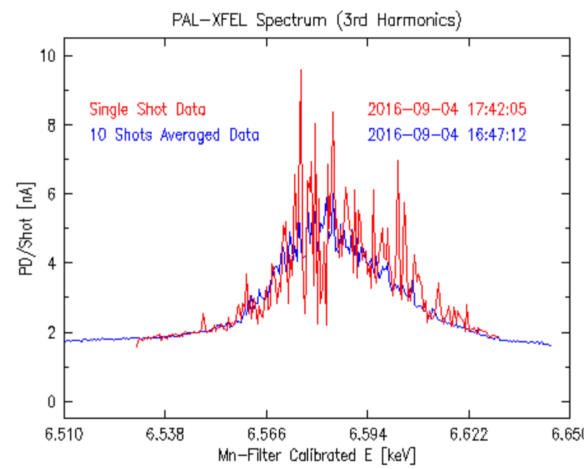


Figure 12: The spectrum of 3-rd harmonics obtained by using a single shot spectrometer.

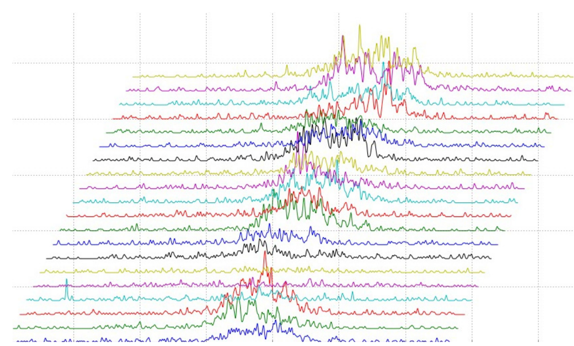


Figure 13: Multiple profiles of the single shot spectrum of 3-rd harmonics.

We carried out the K-tuning using DCM and a downstream photo-diode for 13 undulators. The electron beam energy is increased to 8 GeV because we need a higher photon flux from a single undulator for the better spectrum. Figure 14 shows the phot-diode current as a function of undulator gap for undulator HU105. To find the K-matched undulator gap we use a fitting method (b) rather than a peak derivative method (a) [6]. We found that the undulator gaps determined by K-tuning are too much different from the undulator field measurement data [7]. The worst case of the differences is as high as 30 um. We will investigate why those differences come out.

We set the gaps of all 13 undulators at the undulator gap numbers determined by the K-tuning for the design

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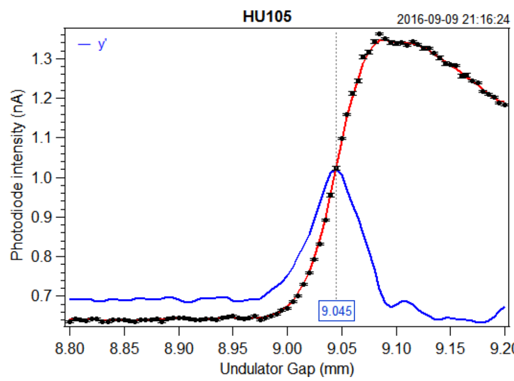
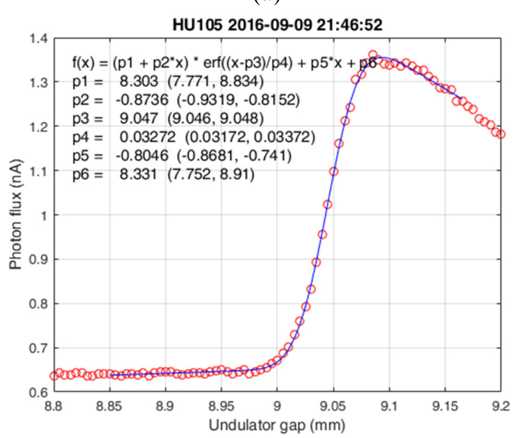
undulator K. And using the same beam energy of 8 GeV, we tried to get lasing. Successfully, we got a lasing even though it is very weak. Its wavelength is as short as 0.14 nm, calculated from the beam energy and the undulator K value (see Fig. 15).



(a)



(b)

Figure 14: Photo-diode current as a function of undulator gap for undulator HU105: a) peak derivative (b) fitting method.

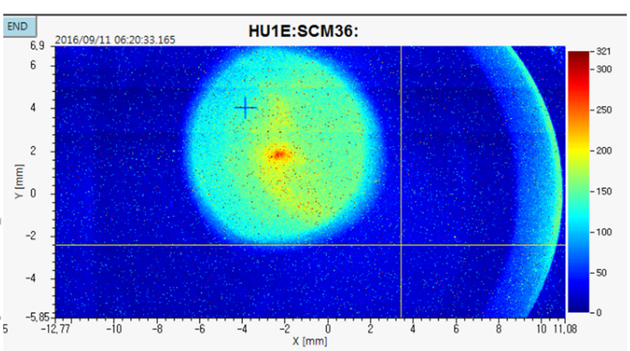


Figure 15: Lasing of 0.14 nm FEL.

CONCLUSION

Even though we could not use all 20 undulators for the hard X-ray undulator line, we could get lasing of 0.5 nm FEL and even 0.14 nm. All the cavity BPM electronics are expected to be functional by early October 2016. Since then we will be able to move forward to get lasing of 0.15 nm FEL with higher intensity. The study of K-tuning and phase matching is under way. When it is fully understood for our system, we expect the saturation of 0.15 nm FEL to be realized by the end of 2016.

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