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STATUS OF THE PAL-XFEL CONSTRUCTION*

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Abstract

The PAL-XFEL, a 0.1-nm hard X-ray FEL facility consisting of a 10-GeV S-band linac, is being constructed in Pohang, South Korea. Its building construction was completed at the end of 2014. The installation of the 10-GeV linac started in January 2015 will be completed by the end of 2015 together with undulators and beam lines. The commissioning will get started in January 2016 aiming for the first lasing of hard X-ray FEL. We will report the current status, construction progress, and commissioning plans for the PAL XFEL project, including major subsystem preparations.

INTORDUCTION

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 follows and will be completed by the end of 2015. The FEL commissioning will get started in early 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, and three bunch compressors (see Table 1). 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.

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 [1]. The L1 section consists of two RF units each of which is comprised with one klystron and two S-band structures, while L2 has 10, L3 has 4, and L4 has 27 RF units each of which has one klystron, four accelerating structures, and one energy doublers. A laser heater to mitigate micro-bunching instability is placed right after the injector, and an X-band cavity placed right before the BC1.

Among the available five undulator lines in the undulator halls, only two undulator lines will be prepared during the construction period of Year 2011-2105: a hard X-ray FEL line (HX1) and a soft X-ray FEL line (SX1) as shown in Fig. 2. HX1 covers the wavelength of λ=0.06 - 0.6 nm using a 4 to 10-GeV electron beam, and uses linear polarization, variable gap, out-vacuum undulators. SX1 covers the wavelength of λ = 1.0 - 4.5 nm using a 3.15-GeV electron beam.

Figure 1: Picture of construction site taken in January 2015.

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	6.7 x 13.4 mm

To achieve the beam energy stability of below 0.02% and the arrival time jitter of 20fs for the PAL-XFEL, the linac RF parameters should be as stable as 0.03 degrees for the RF phase and 0.02% for the RF amplitude for S-band RF systems, and 0.1 degree / 0.04% for the X-band linearizer RF system. The pulse-to-pulse klystron RF stability is determined by the klystron beam voltage

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driven by a modulator. Therefore, the klystron modulator beam voltage should be as stable as 50 ppm for the 0.03 degree S-band RF and 0.1 degree X-band RF.

From the beginning of the project, three critical systems such as a low emittance injector, an ultra stable klystron modulator, and a variable gap out-vacuum undulator were being developed [2]. The requirement of undulator field accuracy is better than 2 x 10-4 and the undulator gap setting accuracy should be below 1 um. which are challenging issues not easy to realize.

In this paper, we will report the current status, construction progress, and commissioning plans for the PAL XFEL project, including major subsystem preparations.

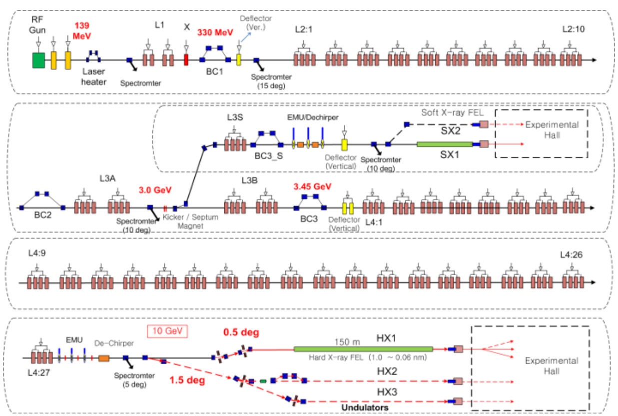

Figure 2: Schematic layout of PAL-XFEL.

CONSTRUCTION STATUS

Injector

The injector test facility (ITF) has been operational since 2012 for the low emittance injector R&D. ITF has the same configuration as the injector of the PAL-XFEL which consists of a PAL-design photo-cathode RF-gun and two S-band J-type accelerating structures [3]. Optimization study to clarify the effect of various sources such as laser beam profile and timing jitter on emittance is being carried out. A laser heater system consisting of a short undulator and four dipoles is being tested at ITF. ITF will be operational until July 2015, and then the gun and the two accelerating structures will be moved to the PAL-XFEL building. Afterward, a spare RF-gun and two dual-feed accelerating structures will be installed at ITF to continue the low emittance injector R&D.

Linac

The installation of S-band linac components along the 700-m long linac tunnel has been going on since January 2015. As of April 20th, 77 S-band accelerating structures out of 174, 13 energy doublers out of 42, and 16 klystron modulators out of 51 are installed. Figure 3 shows the waveguide network and S-band accelerating structures installed in the tunnel. Figure 4 shows the picture of an energy doubler and a 3-dB power divider. The energy doubler is designed to have two hole coupling to withstand the peak RF power up to 380 MW with 1 µs pulse length.


Figure 3: Picture of Linac tunnel.

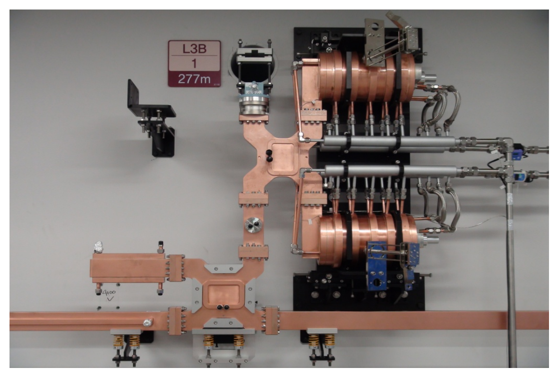

Figure 4: Picture of energy doubler and 3-dB power divider.

120 among 174 S-band accelerating structures are made by Mitsubishi Heavy Industry, Japan, and the remaining 54 units of the structures are being made by Vitzro-Tech, Korea. The S-band structure from Vitzro-Tech was confirmed to withstand the accelerating gradient of 27 MV/m at 60 Hz and generate the same level of dark current as the MHI structure. The Vitzro-Tech accelerating structure has a quasi-symmetric feed coupler with a racetrack geometry designed to have a smaller quadrupole kick than the round geometry type of MHI structure.

The operating temperature of accelerating structures is 30°C. Each RF unit has its own cavity temperature control system which uses heaters and a PLC controller to control the cooling water temperature. A total of 51 temperature control system will be installed. The temperature of supply water for the temperature control system is as stable as ±0.1°C and adjustable from 29 to 29.5°C depending on the RF pulse repetition rate. The cavity temperature should be precisely controlled within

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±0.02°C for Injector, ±0.05°C for L1 and L2, ±0.1°C for L3 and L4. The first cooling system installed at one of the L3 section shows that the temperature stability is within the specification.

A total of 51 klystron modulators were being constructed by two companies, POSCO-ICT and Dawon-Sys, Korea. The modulator using an inverter type high voltage power supply is capable of operating at 200 MW peak power and 60 Hz for the 80-MW, 4-us S-band klystron. The klystron beam voltage stability achieved by those companies is below 30 ppm better than the stability requirement of 50 ppm, while it is below 10 ppm at the PFN voltage. Figure 5 shows the klystron modulators installed at the linac klystron gallery.

A 50-MW X-band klystron (XL4 type klystron), X-band waveguide components, and an X-band linearizer cavity are being prepared by SLAC. The X-band cavity (H60GV3) is 0.6 m long and has a larger diameter to have a smaller wake loss even though it requires more RF power than the T53 structure.

Figure 5: Klystron modulators at the klystron gallery.

A total of 51 low level RF controllers including one X-band RF are being prepared by MOBIIS, Korea. The first S-band module delivered recently shows that the performance meets the requirement of 0.03 degrees for the RF phase and 0.02% for the RF amplitude. The LLRF system is also designed to have the function to monitor the klystron beam voltage signal for the pulse-by-pulse protection of the klystron.

The installation of accelerating structures, magnets, vacuum chambers, and klystron modulators is planned to be finished by the end of September 2015, when the linac tunnel is closed to start the RF conditioning.

Reference RF System

The reference RF system using a 1 5/8" coaxial RF cable is being installed from the timing room near the gun laser room down to the experimental hall, which is about 1 km long. The reference RF cable is enclosed into a specially designed duct which is temperature controlled by cooling water at 30°C. The original concept of the reference RF system is the dual operation of coaxial RF and pulsed optical timing system. The reason that RF only distribution is chosen in the early stage of operation is that engineering for pulsed optical timing system needs to be further improved for long-term operation. The pulsed optical timing system is being developed to be placed into operation in late 2016.

Undulator

For the PAL-XFEL the two undulator systems are under construction: 18 planar undulators for the hard X-ray line HX1 and 6 planar undulators with additional two EPUs for the soft X-ray line SX1. The two EPUs (Elliptically Polarized Undulator) will be used for polarization control and installed at the end as the last stages of lasing. An enough space is reserved in the undulator halls for the future upgrade to house a total of 28 undulators for HX1 and 15 undulators for SX1 (see Fig. 6).

The major parameters of the HX1 undulator are shown in Table 2. The undulator gap is 8.3 mm at minimum, and the undulator chamber aperture is 6.7 mm, large enough to make the wake field effects and the exposure of magnets to irradiation reduced. The parameters of the EPUs are under study now, and the magnetic pole gap is 10.0 mm with 44.0 mm magnetic period to match the resonance condition with the planar hybrid undulator for SX1 [4]. The installation of EPU is expected in 2017.

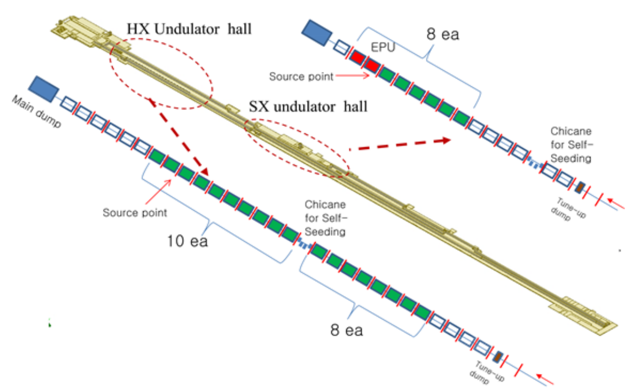

Figure 6: Undulator layout for HX1 and SX1. Green colour box represents an undulator to be installed.

To reduce the development efforts and period, the EU-XFEL design and technology [5] was adopted and further developed with some modification reflecting different magnetic periods and pole gaps. The modification done by PAL includes new magnetic design, EPICS IOC, and updated tolerances reflecting new parameters. In addition, precision tilt meters are attached to the girders to monitor parallel motion.

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Table 2: Major Parameters of the HX1 Undulator

Symbol	Unit	Nominal value
E	GeV	10.000
g	mm	8.30
λ_u	mm	26.0
L_{und}	m	5.0
λ_r	nm	0.1
B_{eff}	Tesla	0.8124
K		1.9727
Optical phase error	degree	less than 5.0

Delivery of the serially produced HX1 undulators is started in April 2015. As of April 20th, 3 HX1 undulators are delivered. The first undulator delivered from the company is under field measurement at the undulator field measurement lab (see Fig. 7) where the ambient temperature is as stable as ±0.1°C. The 250-m long undulator hall should be also as stable as ±0.1°C in ambient temperature, which will be tested soon (see Fig. 8). The installation of HX1 undulators is scheduled to start in June to be finished by the end of 2015.

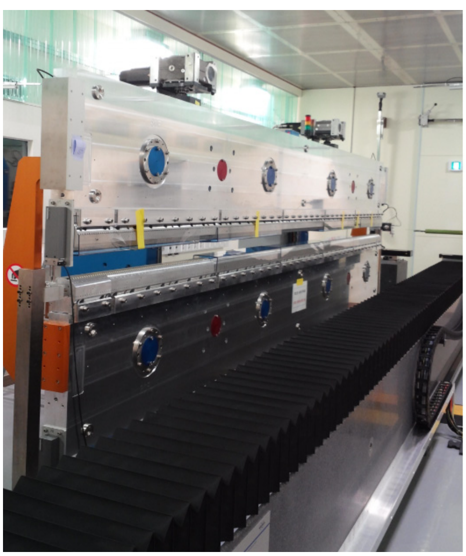

Figure 7: The first HX undulator under field measurement.

Hall scanning measurements and experiments to acquire the pole tuning effects as well as pole tuning experiments to improve the orbit and optical phase errors are carried out for the first undulator. Between each measurements, gap was opened to 100mm and closed to the measurement gap of 8.3 mm. The data scatter in the peak field is about ±1.5 Gauss maximum. This difference translates to approximate ±1.0 μm gap error. This error includes the mechanical hysteresis of the gap and the magnetic hysteresis of the pole, which is within our specification.

Figure 9 shows the calculated phase jitter after pole tuning. The calculated rms phase jitter was 2.6 degree rms which is less than the specification of 5.0 degree. Initial optical phase errors were very large because of girder deformations about 50 um. The corrected optical phase error is reduced to below 3.0 degree (rms) at the tuning gap. In production phase, we expect 1 day for vertical orbit correction, 1 day for correction of dominant quad components, 3 days for the phase/horizontal orbit tuning.

Figure 8: Picture of the 250-m long hard X-ray undulator hall. The ambient temperature control systems are mounted onto the right hand side wall.

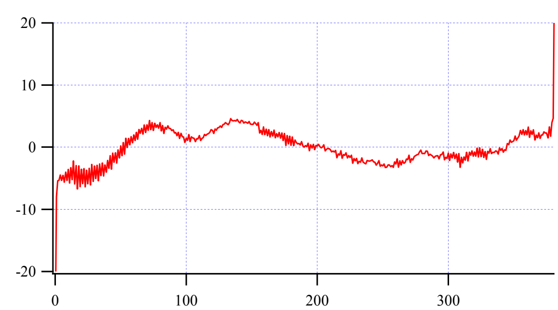

Figure 9: Optical phase error at the working gap of 9.5 mm. The vertical axis represents phase and the horizontal represents pole number.

Self-Seeding Section

A self-seeding section is allocated right after the 8-th undulator as shown in Fig. 6. PAL made a contract with ANL to develop a novel self-seeding monochromator for PAL-XFEL. Our self-seeding monochromator is a little different form the LCLS design. Two diamond crystals with (400) and (220) orientations will be mounted onto single holder to cover the photon energy from 5 keV to 10 keV. PAL and ANL focus on development of all diamond

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based crystal holder. The new holder might be resistive to thermal instability. The monochromator will be ready for installation in PAL-XFEL in Oct. 2016.

COMMIISIONING PLAN

The linac RF conditioning and the injector commissioning are scheduled in October to December 2015 (see Fig. 10). Injector Test Facility (ITF) will be operational until the end of July, since then the gun and the two S-band structures in ITF will be moved to the PAL-XFEL injector site. The on-going installation work will continue until September of 2015 for S-band accelerating structures and waveguide networks in the linac tunnel and for klystron modulators in the linac galley. The control system and the machine protection system will get ready before the linac RF conditioning starts in October 2015.

During the period of October to December 2015, the electron beam is able to be accelerated up to 135 MeV only at the Injector site, while the remaining section of the 700-m long linac will be only RF-conditioned. During the linac RF conditioning periods a 1-m thick concrete block will be placed at the end of linac tunnel to protect the undulator hall from radiation generated by dark currents from accelerating structures due to the RF conditioning. The installation work for undulators in the undulator hall, which is planned to start in June, will continue until the end of December. Debugging of the control system and the commissioning program will be carried out during those periods.

The first XFEL commissioning for HX1 is scheduled in early 2016 aiming for 0.3-nm radiation with 6-GeV beam at 10 Hz. The 2-nd FEL commissioning is scheduled in September to December 2016 for 0.1 nm hard X-ray FEL.

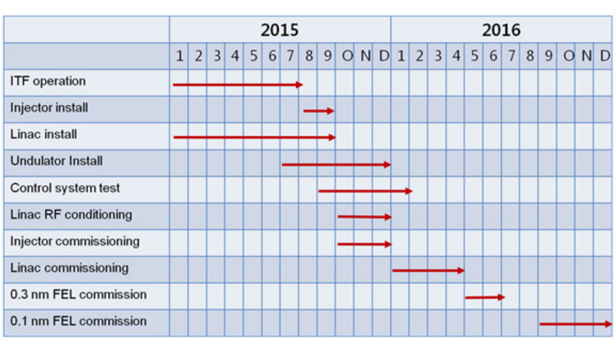

Figure 10: Schedule of installation and commissioning.

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