BEAM COMMISSIONING OF PAL-XFEL*

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Abstract

The Pohang Accelerator Laboratory X-ray Free electron Laser (PAL-XFEL) project aims at the generation of X-ray FEL radiation for photon users. The machine consists of a 10 GeV normal-conducting S-band linear accelerator (linac) and two undulator beamlines initially. The hard X-ray beamline will provide FEL radiation between 0.6 and 0.1 nm or shorter. The soft X-ray line will provide FEL radiation between 4.5 and 1 nm. The linac and hard X-ray beamline construction was complete by the end of 2015. The installation of the soft X-ray line is ongoing. High power RF conditioning of the linac started in late autumn 2015. Beam commissioning of the linac started in April 2016. We report the beam commissioning status.

INTRODUCTION

The PAL-XFEL project started in 2011 in order to construct an X-ray free electron laser (FEL) user facility. PAL-XFEL will be open for users in early 2017 with X-ray FEL radiation in a range of 0.1 to 4.5 nm. Shorter X-ray wavelength range, 0.1 to 0.6 nm, will be covered with the hard X-ray undulator beamline which is extended from the 10 GeV linac end. Longer wavelength range, 1 to 4.5 nm, will be covered with the soft X-ray undulator line which is branched at the 3.15 GeV point between the 2nd and 3rd bunch compressors of the main linac. The PAL-XFEL layout of Phase-1 is shown in Fig. 1 and the parameters are summarized in Table 1.

Table 1: PAL-XFEL Parameters

Undulator line	Hard X-ray	Soft X-ray
FEL wavelength	0.1 ~ 0.6 nm	1 ~ 4.5 nm
e-beam energy	4 ~ 10 GeV	3.15 GeV
Slice emittance	0.4 mm mrad	0.6 mm mrad
Peak current	3 kA	2 kA
Undulator type	Planar	Planar
Undulator period	26 mm	37 mm
Undulator min gap	8.3 mm	10 mm
Repetition rate	60 Hz	60 Hz

The injector consists of a 1.5 cell S-band photocathode gun and two S-band 3 m long constant gradient traveling-wave accelerating columns. The peak field of the gun is 120 MV/m at the cathode. The gun cavity is fed with a klystron with a 25 MW peak power. In reality, about half, 12 MW, of the 25 MW maximum power to feed the gun. The RF pulse length of the gun is 2.5 μs. The gun cavity has a 1.5 coupling factor and a 15 MHz mode separation between the 0 and π modes [1]. The accelerating columns operate at 20 MV/m and 25 MV/m accelerating gradient, respectively. Each column has its own RF station. The cathode is the back wall of the copper gun cavity and the quantum efficiency is about 2.5×10^{-4}. 253 nm UV laser pulse is used for electron beam generation. The UV pulse energy is about 5 μJ for 200 pC beam at the nominal operating condition. A focusing solenoid is located immediate downstream of the gun for emittance compensation. Each accelerating column in the injector has a 0.9 m long solenoid around the column for beam focusing.

The beam is accelerated through the S-band linear accelerator (linac). The linac has 164 S-band accelerator columns. The average accelerating gradient is about 20 MV/m. 43 high power RF stations feed the columns. Each RF station has a modulator, a low-level RF control module, a solid state amplifier and a klystron, The high power RF klystrons generate a 80 MW peak RF power with a 4 μs pulse length. The klystrons are operated by modulators with a 200 MW peak power. In the L1 section, two columns are fed by one RF station. In the L2 to L4 stations, four columns are fed by one RF station with an energy doubler (SLED). More detail on the PAL-XFEL RF system is found in [2]

The accelerator components were installed during the full year in 2015. High power RF conditioning started in November 2015 from a 0.1 μs RF pulse length and a 1 Hz pulse repetition rate during the night and weekend while component installation continued during the daytime. The RF power was increased gradually as the reflected power and vacuum in the accelerating column and waveguide are monitored. An automatic conditioning program controlled the modulator voltage. Once the klystron output reached the 80 MW peak power, the pulse length was increased to up to 4 μs step-by-step. By April 2016, all of the RF stations are fully conditioned at a 10 Hz repetition rate. RF conditioning to 60 Hz will be continued during the night while beam commissioning during the day.

Three bunch compressors are used for the bunch compression from few ps at the injector to few tens fs at the linac end. Each compressor has a magnetic chicane with four bending magnets. The bending magnets in one chicane are serially connected to one magnet power supply. Each magnet has a trim coil for trajectory correction. The second and third bending magnets are on a horizontally movable support. In between the second and third bends of each bunch compressor, a beam position monitor, a horizontal collimator, a slotted foil, and a screen are installed.

Twenty undulator segments are installed in the first hard X-ray undulator beamline. The hard X-ray undulators have a

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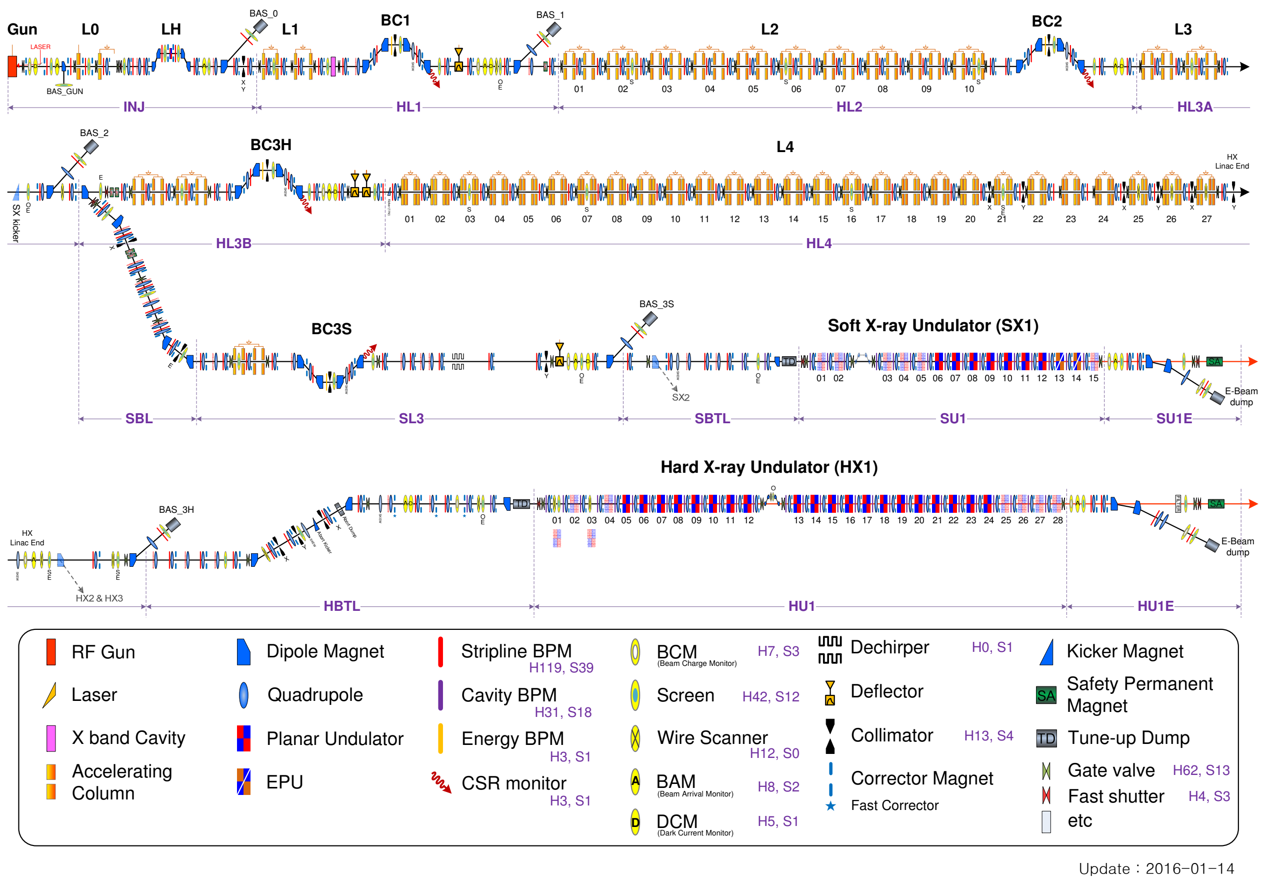

Figure 1: PAL-XFEL accelerator layout. Some of the components are to be installed in the coming years.

26 mm undulator period [3]. The gap is controlled remotely within 1 μm repeatability and the minimum gap is 8.3 mm. The height is controlled remotely, too. Seven undulator segments are installed in the soft X-ray undulator beamline. The soft undulators have a 37 mm undulator period and a minimum gap of 10 mm. Both hard and soft X-ray undulators are planar type. A self-seeding section is installed in the hard X-ray undulator line. Two more elliptically polarizing undulators are planned to be installed at the soft X-ray beamline in the coming years.

Total 211 beam position monitors (BPMs) are used for the electron beam position measurement. 49 of them are cavity type BPMs which can measure the beam position with sub-micrometer resolution in the undulator beamline. 10 bunch charge monitors are installed for the bunch charge measurement from the gun as well as beam loss monitoring though the accelerator. With 54 screen monitors with YAG and/or OTR screens the beam profile are measured. 6 spectrometer dipole systems are located at the gun section, laser heater, BC1, soft X-ray branch, BC3S and hard X-ray linac end. At both beam dumps at the ends of the hard and soft X-ray beamlines, the beam energy can be measured with the screens also. Three S-band deflector systems after BC1, BC3H and BC3S are used to measure the bunch longitudinal phase space. The deflectors streak the beam vertically depending on time. More detail on the PAL-XFEL beam diagnostic system is found in [4]

Beam commissioning started on 14th April 2016. The start of the commissioning was delayed by several months due to the radiation safety permission from the government. On the first commissioning day, a beam was accelerated to over 135 MeV at the injector end. Electron beams were accelerated up to 10 GeV at the linac end on 25th April. Since then, detailed parameter tuning of the injector and linac is ongoing. Undulator commissioning will start in the coming weeks. The 10 GeV linac and hard X-ray undulator beamline are being commissioned first. The soft X-ray branch from the main linac and the soft X-ray undulator beamline will be commissioned in the second half of 2016. In this paper, we report the beam commissioning for the past 3 weeks and future plans.

INJECTOR

The accelerator components of the injector were commissioned at the PAL-XFEL injector test facility (ITF) from late 2012 to summer 2015 [5]. Most of the components at ITF were transported into the PAL-XFEL tunnel. The vacuum mirror, screen and correctors were replaced with new designs for PAL-XFEL. A brand new micro-mover for

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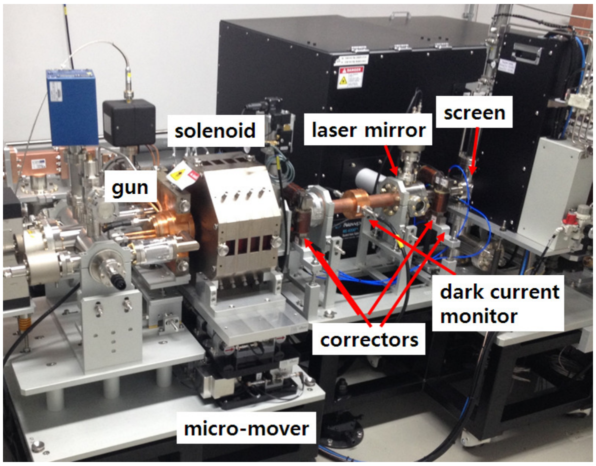

Figure 2: Gun section photo taken in the PAL-XFEL tunnel.

the gun solenoid was installed. The gun section is shown in Fig. 2.

Gun RF Phase Scan

To find the designed operating condition, the gun RF phase with respect to the drive laser pulse was scanned. Bunch charge as a function of RF phase was measured with the bunch charge monitor installed in the gun section (Fig. 3). To have a repeatability to select the operating gun phase, we first set the nominal bunch charge to 200 pC at a thought-to-be operating phase. Then, we carried out a phase scan and measure the bunch charge with the bunch charge monitor. Then, we put the phase producing a 10 pC charge, which is one twelfth of the nominal bunch charge, as 0-crossing phase. A new nominal phase was set by adding 44° from the 0-crossing phase for the case of 120 MV/m gun maximum RF field.

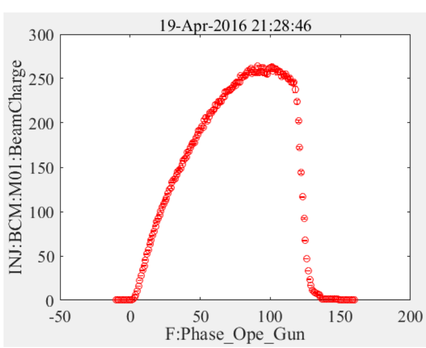

Figure 3: Bunch charge as a function of gun RF phase relative to drive laser pulse. 0-crossing phase is 5° here.

The beam energy was measured with the gun spectrometer dipole, which bends the beam 90° from the main beamline. Beam energy was also measured as a function of gun RF phase (Fig. 4).

Cathode Cleaning using IR Laser

Laser cleaning of the cathode surface was carried out by using IR (760 nm) laser pulses. The IR laser pulses were branched from the gun driver laser before the main part interring into the third harmonic crystal for the UV conversion. The IR pulse energy was controlled during cleaning by monitoring the vacuum in the gun. The pulse energy was about 1.5 mJ and the transverse size was about 0.13 mm. After each cleaning process, the quantum efficiency of the cathode was measured by scanning a 0.15 mm diameter UV laser pulse over the cathode area. Before the cleaning, there were high QE spots on the cathode (left in Fig. 5). After the cleaning, the QE of the cathode area became uniform (right in Fig. 5). The QE map were made by scanning a UV laser pulse over 4 mm by 4 mm around the cathode center. The cleaning was carried out by scanning an IR laser pulse with 0.1 mm step over 3 mm by 3 mm around the cathode center. During the cleaning, the IR pulse energies were increased as 1.10, 1.16, 1.21 and 1.39 mJ. Up to the 3rd cleaning, the gun vacuum was kept at low 10^{-10} mbar. The vacuum exceeded 1×10^{-9} mbar during the 4th cleaning process, but the vacuum recovered to below 1×10^{-10} mbar immediately after the cleaning.

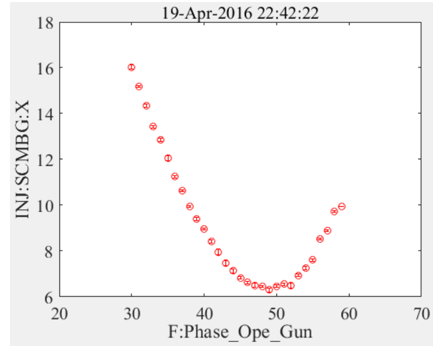

Figure 4: Beam energy as a function of gun RF phase relative to drive laser pulse. The y axis is the beam position on the gun spectrometer screen. Lower y values correspond to higher beam energy. Note that 0-crossing phase is 5°.

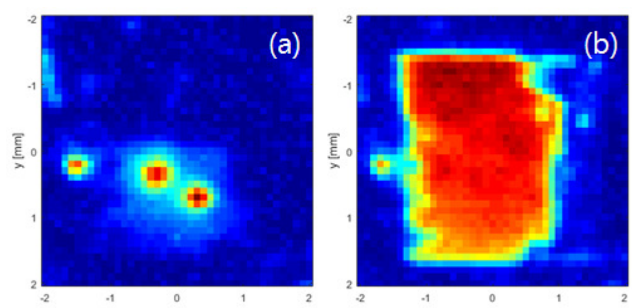

Figure 5: Quantum efficiency maps of the cathode before laser cleaning (a) and after 4th laser cleaning (b). After the cleaning, the QE became about 2.5×10^{-4} over 2×2 mm around the cathode center.

Beam-Based Drive Laser Alignment

After the laser cleaning, drive laser position was aligned to the cathode center, that is, the gun RF field center. For the

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alignment, the RF field was reduced from 120 to 90 MV/m in order not to have dark current on the gun screen. All the magnets in the gun section, including the gun solenoid and correctors, were switched off not to affect the beam trajectory.

The alignment was carried out by using high RF phases around 110°, where the emitted electron beam from the cathode travels through the gun cavity forth, back and forth again because the beam phase delay is so large and therefore the trajectory sensitivity to the starting position error is large. The drive laser position on the cathode for the minimum beam position variation at the screen over 10° around 110° RF phase was found.

Beam-Based Gun Solenoid Alignment

After the drive laser beam-based alignment, the gun phase was back to the nominal phase but the low gun gradient (90 MV/m) was used for no dark current at the screen. The alignment was carried out by scanning gun solenoid current from 80 to 115 A. Around 100 A solenoid current beams were focused on the screen. The beam position and size change at the gun screen for solenoid current variation was measured as shown in Fig. 6. For each trial, the solenoid position was changed using the micro-mover. Compared to the original position, the final position of the solenoid was shifted 0.2 mm to the right and 0.06 mm to the bottom.

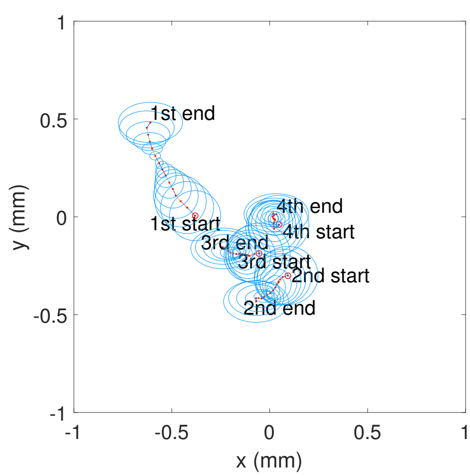

Figure 6: Beam position movement on the gun screen during gun solenoid current scan. The pale blue lines are the rms size of the beam divided by 10. In between each step the gun solenoid was moved by using the micro-mover.

Emittance Measurement

The injector emittance was measured by scanning the quadrupole current immediate downstream of the L0-2 column and the YAG screen 3.8 m downstream of the quadrupole. Very first emittance optimization is being carried out by changing the gun solenoid and drive laser beam size. Laser pulse length, gun RF gradient, RF gun phase, L0 RF gradient, L0 RF phase and L0 solenoid current are optimization parameters. The best measured values of normalized transverse emittance at the injector is 0.79 and 0.42ṁm mrad (95% rms) in the x and y directions, respectively. A laser beam diameter of 0.95 mm and a laser pulse length of 3 ps fwhm were used.

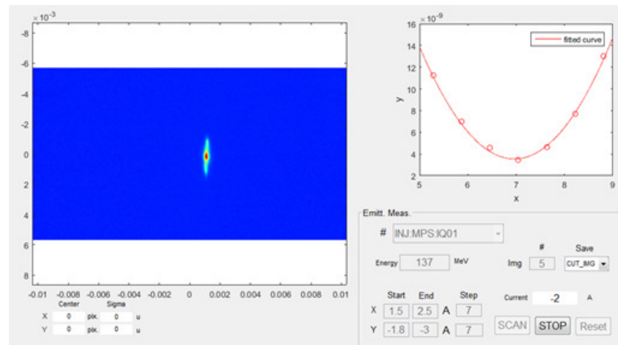

Figure 7: Emittance measurement program to scan the quadrupole current and measure the beam size at the screen.

LINAC

Since RF conditioning started several months ahead, beam acceleration through the linac was made without difficulty. The timing of the RF stations to the gun drive laser was synchronized roughly before the start of beam commissioning. On the 12th day of beam commissioning, a 10 GeV beam was accelerated to the linac end.

The RF on-crest phases were found by measuring the beam energy at the spectrometer dipole systems as scanning the cavity RF phase (see Fig. 1). The RF stability is being monitored and is well below 0.1% and 0.1 for the most RF stations° [6]. Fine tuning of the RF system is being done to achieve the design stability, 0.02% in amplitude and 0.03° in phase.

Phase Space Linearization using X-band

By using the X-band (11.424 GHz) cavity installed upstream of BC1, the beam curvature produced from the S-band gun and L0 to L1 (see Fig. 8a) was linearized in longitudinal phase space (see Fig. 8b). The longitudinal phase space was measured by using the S-band deflector and spectrometer dipole downstream of BC1.

Bunch Compression

The bunch compressors are horizontally movable. The first bunch compressor (BC1) was fixed to 5° during the first commissioning. For bunch compression by a factor of 3, the RF phase of the L1 linac was set to -15° from on-crest (see Figs. 8b and c). More systematic commissioning of BC1 with emittance measurement as a function of bunching factor is to be done in the coming weeks.

Commissioning of BC2 started. The longitudinal phase space is measured by using the S-band deflector downstream of BC3H and the spectrometer dipole at the linac end. During the first commissioning only the first two bunch com-

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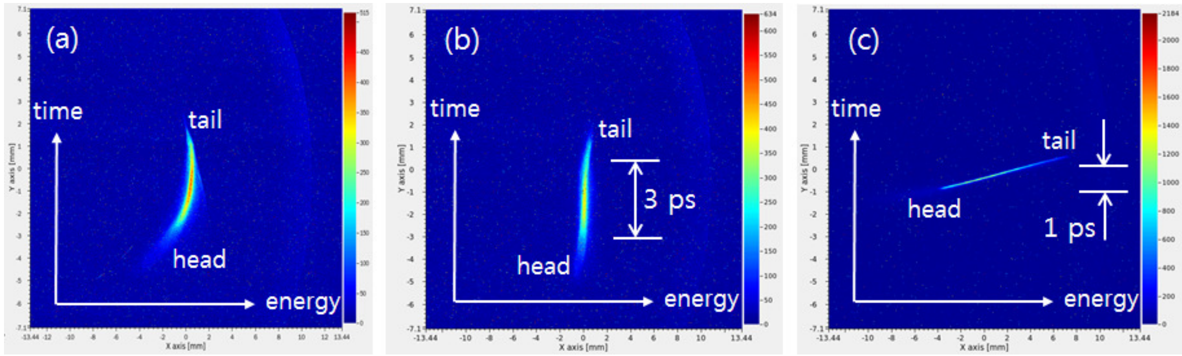

Figure 8: Longitudinal phase space of a beam. The bunch profiles were measured at the screen in the dipole spectrometer using the S-band deflector downstream of the 1st bunch compressor. The measurements were carried out with L1 phase on-crest and the X-band cavity off (a), L1 phase on-crest and the X-band on for linearization (b), and L1 phase $-15°$ off-crest for 3 times bunch compression (c).

pressors (BC1 and BC2) are used in order to minimize commissioning effort. Using BC3 will be considered as more find tuning of the PAL-XFEL linac proceeds.

ONGOING COMMISSIONING TASKS

Emittance measurement in the injector is ongoing for optimizing the injector parameters discussed earlier. Electron beam alignment through the injector and linac, betatron matching and dispersion correction are ongoing. Commissioning of the beam diagnostics and control system as well as stability test of the RF and magnet systems with beam are ongoing commissioning tasks.

When cavity BPMs, which are installed in the undulator line for a sub micrometer resolution, electronics are available, an electron beam will be sent through the undulator line. Electron beam trajectory correction will be tried by both electron beam [7] and spontaneous radiation [8] based methods. Undulator commissioning including undulator and phase shifter steering tables, beam-based undulator height alignment, undulator K value measurement and phase shifter gap optimization will be continued.

SUMMARY

PAL-XFEL construction and high power conditioning of the RF systems are ready. Beam commissioning started on 14th April 2016. The starting date was delayed mainly due to the radiation safety permission from the government. However the commissioning proceeds without difficulty up to now. 10 GeV full acceleration was achieved and fine tuning of the accelerator including emittance optimization is being carried out. SASE optimization for both hard and soft X-ray beamlines will be done in 2016. X-ray FEL user service will start early 2017.

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