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XFEL PERFORMANCE ACHIEVED AT PAL-XFEL*

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Abstract

The hard X-ray free electron laser at Pohang Accelerator Laboratory (PAL-XFEL) successfully completed the commissioning of SASE and started user operation in late 2016. Since then, the facility has demonstrated excellent stability with very small timing jitter of about 20 fs, and commissioned the self-seeding system over a wide range of photon energies, etc. In this talk, we presents status of PAL-XFEL including recent commissioning results for self-seeded XFEL.

INTRODUCTION

After the first lasing of hard X-ray in the PAL-XFEL was observed on June 14, 2016, the saturation of hard X-ray FEL of 0.144 nm was achieved on November 27, 2016. The PAL-XFEL has become one of the major facilities providing intense and coherent X-ray lights since the start of the official user beam service on June 7, 2017 [1].

The PAL-XFEL consists of 10 GeV normal conducting S-band RF linac and two undulator lines for generating hard X-ray and soft X-ray coherent photons [1]. The linear accelerator can generate up to 10 GeV electron beam at maximum 60 Hz beam pulse rate for generating hard X-ray laser light in the range from 2 keV to 14.5 keV. The PAL-XFEL has a branched linac line to deliver electron beam around 3 GeV to the soft X-ray undulator line.

Figure 1 shows the pictures inside the PAL-XFEL. This 10 GeV linear accelerator based on S-band normal conducting RF technology consists of five sectors of a injector and four accelerating sectors which are connected by the three bunch compressors for increasing the peak currents of electron bunches.

Figure 1: The Photographs inside the PAL-XFEL.

The S-band photo injector generates low emittance electron beams by using the carefully controlled laser beams in temporal and spatial profile. The PAL-XFEL photo-cathode gun has a unique design to reduce multipole field components which dilute beam emittance. The UV laser beam has a cut Gaussian profile in transverse. Typical projected beam emittance at the gun is lower than 0.5 mm-mrad at 250 pC bunch charge.

In PAL-XFEL linac 50 S-band klystron RF modules are running to drive 174 S-band accelerating structures. The 42 RF modules in from L2 to L4 sector use the energy doublers which are tuneable remotely for maximum RF power gain. Especially one X-band RF module is used to drive higher harmonic cavity which acts as a linearizer. Every RF module is controlled by low-level RF controllers in amplitude and phase [1]. The PAL-XFEL linac shows excellent pulse to pulse RF stability performance to make low jitter FEL performance [2]. The undulator section consists of 20 planner undulators of 26 mm undulator period for hard X-ray FEL and 7 planner Undulators of 35 mm undulator period for soft X-ray FEL. These undulator are 5 m in length and have a variable gap [3].

FEL OPTIMIZATION

It is required for the purpose of increasing the achievable power at saturation that to decrease the emittance of the electron bunch before the undulator lines and to maximize spatial and spectrum overlap between electron and photon beam during FEL lasing.

The low emittance electron beams generated from the photo cathode gun are compressed by using three magnetic chicane bunch compressors. It is well known that horn shape non-uniform current profiles are generated during this bunch compression, which dilute the initial low beam emittance because of severe coherent synchrotron radiation. In PAL-XFEL operation these horn current parts are cut out by using the beam collimator installed at the middle of the first bunch compressor. Figure 2 shows typical slice beam emittance measurement at the screen monitor of the downstream of the first bunch compressor. The slice emittances are smaller than 0.5 mm-mrad.

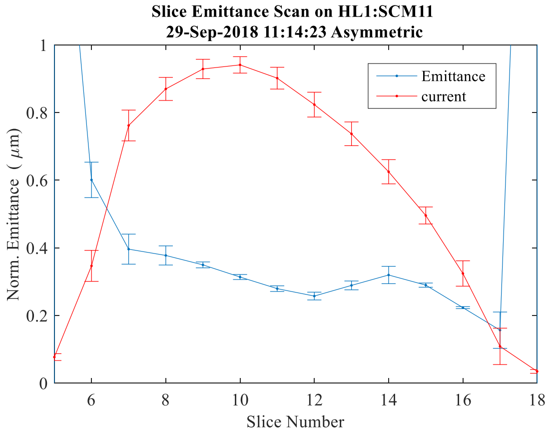

Figure 2: Typical slice emittance measurement result.

Since the PAL-XFEL uses three bunch compressors to obtain shorter bunch length of about 30 fs, CSR is weaker compare to the case of two step bunch compressor scheme. After these large dispersive region it is generally required to match beam to periodic lattice. In PAL-XFEL five quadrupoles in the upstream of the undulator line are used to match beam to the periodic FODO lattice in the hard X-ray undulator line. We used four wire scanners which is installed along the undulator line to measure Twiss parameters. Figure 3 shows a typical matching result. The horizontal and vertical mismatch factors are 1.01 and 1.02, respectively, which means that beam is nearly perfectly matched.

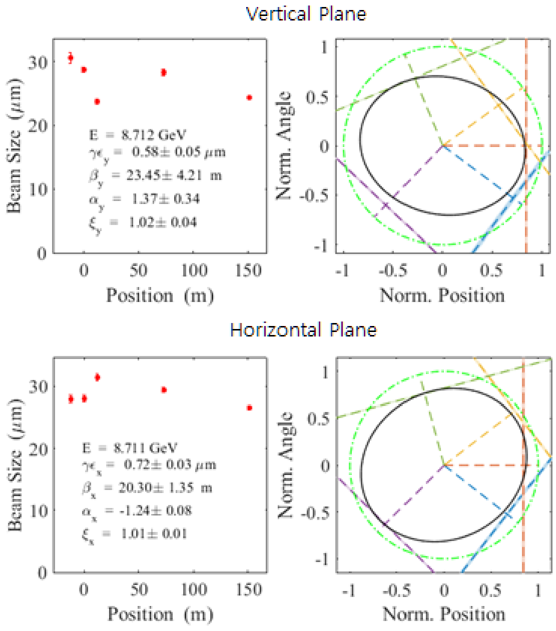

Figure 3: Typical result of undulator lattice matching.

We performed beam based alinement for the main linac and the undulator lines. The linac is aligned by using the one to one alignment method after the duration for maintenance. On the other hand, the undulator line is aligned after every user beam service shift or the duration for maintenance because it is critical to FEL intensity.

In order to maximize the spatial and spectral overlap between electron beams and photon beams, we utilized several schemes to tune undulators. To find the undulator field mid-plane we adjust the vertical offsets for each undulator to maximize the FEL intensity. Each undulator's gap is also tuned by using double crystal monochromator which is installed after undulator line, which makes the gaps have same undulator K value [3]. To compensate the phase mismatch between two adjacent undulators, we tune the each phase-shifter to get maximum FEL intensity [4]. We also applied tapering method to increase the FEL intensity. The gaps of early several undulators are linearly tapered, and the gaps of the rest undulators are tapered in quadrature scale by using the user friendly GUI control program realized on the CSS and the EPICS.

MACHINE PERFORMANCE

Table 1 shows the machine performance of the PAL-XFEL in hard X-ray. The photon energy range in the hard X-ray undulator line, HX1, is from 2 keV to 14.5 keV. We have successfully achieved saturated 14.5 keV FEL with 2.8 x 10^{11} photons per shot in 2018 [5]. The PAL-XFEL can supply FEL beams from 2 keV to 4 keV, in tender X-ray range, which is only available at the PAL-XFEL presently. It is expected to extend the research area using this tender X-ray FEL. We achieved the pulse FEL energy of around 1 mJ in the range from 3 to 14 keV, and maximum around 2 mJ at the 9.7 keV FEL. Typical FEL pulse duration is 10 ~ 35 fs in full width half maxim, which is depend on the beam parameters but we can control the pulse duration by using emittance spoiling slotted foil method even though the FEL intensity decreases. Figure 4 shows typical long term FEL intensity. The FEL power stability is smaller than 5 % in rms, and the FEL position stability is also under the 10 % of the photon beam size. The central wavelength jitter and electron beam energy jitter are 0.024 % and 0.015 %, respectively. These stable FEL performances are due to mainly excellent RF stability features of the PAL-XFEL.

Table 1: PAL-XFEL Hard X-ray FEL Performances

Parameter	Value
photon energy	2.0 ~ 14.5 keV
FEL pulse energy	1.9 mJ @ 9.7 keV
FEL pulse duration	10 ~ 35 fs (FWHM)
FEL power stability	< 5 % (RMS)
FEL position stability	< 10 % of beam size
FEL central wavelength jitter	0.024 %
E-beam energy jitter	< 0.015 %
E-beam arrival time jitter	< 15 fs
FEL beam availability	~ 95 %

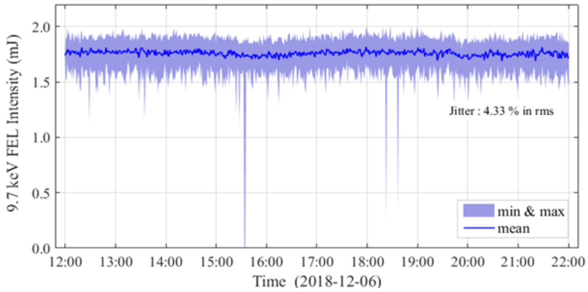

Figure 4: Long term FEL pulse energy for 10 hours.

The arrival time jitter of the electron beam measures smaller than 15 fs. This feature has been also confirmed through the observation of the Bi(111) phonon dynamics experiment in 2017 year [2]. The typical measured arrival time jitter is around 15 fs in 2018 year as shown in Fig. 5, which is achieved by improving the stability of the RF system. The long term drift of the arrival time results in slow drift of the reference time in user experiment such as pump probe, but it is possible to correct the timing error by using simple feedback control system.

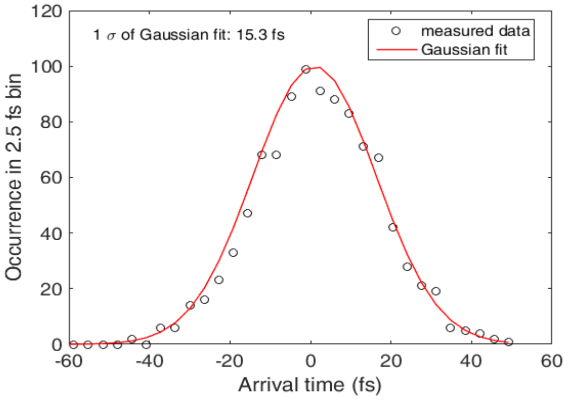

Figure 5: Typical beam arrival time jitter measured in 2018 year.

SELF-SEEDED HARD X-RAY FEL

The PAL-XFEL has been designed to be operated in not only self-amplified spontaneous emission mode but also the self-seeded mode for hard X-ray. To realize the self-seeding scheme in the PAL-XFEL, PAL collaborated with APS to design a diamond crystal monochromator since 2015. The diamond crystals were fabricated by TISNCM, Russia, and were checked at APS. The monochromator was fabricated by Korean company based on the engineering design of PAL under the collaboration with the experts of APS. The whole system has been installed in February 2018 in the HX1 undulator line as shown in Fig. 6.

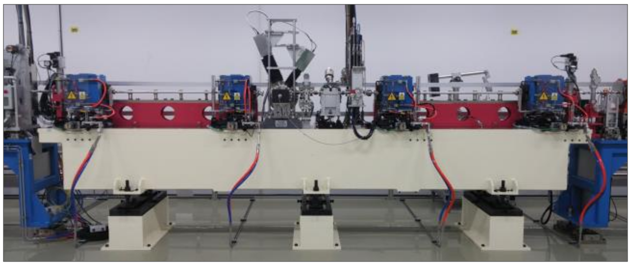

Figure 6: Photograph of the self-seeding system installed in the hard X-ray undulator line.

The self-seeding system consists of the chicane bending magnets and the diamond crystal monochromator. The PAL-XFEL uses the HXRSS with a single-crystal wake monochromator method as self-seeding scheme like as LCLS [6]. We calibrated the crystal offset with undulator radiation for 8.4 keV with 40 pC of low charge electron beam in May 2018. For the case of nominal bunch charge of 180 pC, we calibrated the crystal offsets with crossing points of self-seeding collaborating with the experts from ANL, LCLS, and EuroXFEL in Oct. 2018. In Nov. 2018, we succeeded to observe HXRSS FEL for 3.5 keV with a 30 μm thin diamond crystal and for 14.4 keV under the collaboration with LCLS and ANL. The 14.4 keV HXRSS FEL energy measured around 0.4 mJ compared to the SASE FEL energy of 1 mJ, but the peak intensity of the HXRSS FEL is 6 times stronger than that of SASE FEL, and the bandwidth of the HXRSS FEL is 35 times narrower than that of SASE FEL. The detailed commission results will be reported soon.

CONCLUSION AND OUTLOOK

The PAL-XFEL is successfully operated with very stable and reliable performance since the achievement of saturation of hard X-ray FEL in 2016. By using the procedures for optimization of linac and undulator such as lattice matching, undulator beam based alignment, undulator gap tuning, undulator field mid-plane adjusting, phase shifter tuning, and undulator tapering, the PAL-XFEL has become world class hard X-ray FEL facility.

The PAL-XFEL has unique features which are distinguished from other facilities such as low jitter and tender X-ray capability. Recently the commissioning of the HXRSS FEL in the PAL-XFEL has been accomplished. It is planed that the user service of HXRSS FEL will be opened soon after internal pilot experiments.

ACKNOWLEDEMENTS

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