BEAM OPERATION OF THE PAL-XFEL INJECTOR TEST FACILITY*

J.-H. Han†, J. Hong, J. H. Lee, M. S. Chae, S. Y. Baek, H. J. Choi, T. Ha, J. Hu, W. H. Hwang, S. H. Jung, C. B. Kim, C. H. Kim, I. Y. Kim, J. M. Kim, S. H. Kim, H. S. Lee, S.-J. Lee, Y. Y. Lee, C.-K. Min, G. Y. Mun, D. H. Na, S.-J. Park, S.-S. Park, Y. J. Park, Y. K. Son, H. R. Yang, H.-S. Kang, I. S. Ko,
Pohang Accelerator Laboratory (PAL), Pohang, 790-834, Republic of Korea

Abstract

The Pohang Accelerator Laboratory X-ray Free electron Laser (PAL-XFEL) project was launched in 2011. This project aims at the generation of X-ray FEL radiation in a range of 0.06 to 6 nm for photon users with a bunch repetition rate of 60 Hz. The machine consists of a 10 GeV normal conducting S-band linear accelerator and five undulator beamlines. The linac and two undulator beamlines will be constructed by the end of 2015 and first FEL radiation is expected in 2016. As a part of preparation for the project, an Injector Test Facility was constructed in 2012. Since December 2012, beam commissioning is being carried out to find optimum operating conditions and to test accelerator components including RF, laser, diagnostics, magnet, vacuum and control. We present the status of beam commissioning and components tests at the test facility.

INTRODUCTION

The Pohang Accelerator Laboratory X-ray Free-Electron Laser (PAL-XFEL) project was started in 2011 [1–3]. This project aims at the generation of X-ray FEL radiation in a range of 0.06 to 6 nm for users. The machine consists of a 10 GeV electron linac and five undulator beamlines. The linac is based on the normal-conducting S-band technology, which has been used for the 3 GeV full energy injector linac of PLS-II, the 3rd generation light source at PAL, over 20 years [4]. As Phase-I of PAL-XFEL, one hard X-ray undulator beamline with two experiment stations and one soft X-ray undulator beamline with one experiment station are under preparation. Both hard and soft X-ray undulator systems are variable-gap, out-vacuum type.

This new machine is being built on the northern hill of the PAL campus (see Fig. 1). The building construction was started in autumn 2012. The building will be ready by December 2014. Accelerator components will be installed from January 2015 during the year. The machine is capable of 60 Hz operation with a single bunch initially. Upgrade to 120 Hz as well as two micro-bunch is foreseen as next phase in a few years. A fast kicker to divide electron pulses into the two undulator beamlines is considered as future upgrade as well. PAL-XFEL commissioning will be started from winter 2015. Beam commissioning will be carried out at a repetition rate of 10 Hz for the first year of operation mainly due to the operation budget. First FEL is foreseen in early summer 2016.

At the beginning of the project in 2011, the construction of the Injector Test Facility (ITF) was started [5]. The facility was built in the extended building of the PLS-II full energy injection linac as shown in Fig. 1. The concrete tunnel, RF gallery, laser clean room and control room were prepared.

The RF system, accelerator components, laser system and control system were installed from summer to autumn 2012. The first beam was generated and transported to the beamline end in December 2012. Emittance measurement was started in spring 2013. Since then, beam test of diagnostics has been carried out.

In this paper, we describe the construction, component installation, beam test of diagnostics and beam property measurement. Some experiment results are shown even though empirical optimization is ongoing.

BUILDING

At the northwestern end of the PLS-II linac building, there has been a multi-purpose test area. This test area is now utilized as the Accelerator Test Facility (ATF) of PAL-XFEL. At ATF, high power modulators, klystrons, low level RF modules, accelerator structures, RF power douplers (SLAC energy doubler, SLED) and SiC loads are tested.

This test area was extended in 2012 for ITF. The extended floor area is about 30 m long and 14 m wide. A concrete tunnel with 1.5 m thickness was built in ITF. The inner area of the tunnel is 19.2 m long and 3.5 m wide. The view of the ITF tunnel and gallery is shown in Fig. 2. The roof of the tunnel is removed for installation work in the photograph. During the operation, the roof is covered with the concrete plates for radiation safety.

A laser clean room was constructed on the same floor of the tunnel and gallery. Temperature and humidity is controlled in the room. On top of the laser room, a control room was constructed.

ACCELERATOR DESIGN

The ITF accelerator was designed for the test of the first 9 m of the PAL-XFEL linac. An S-band (2.856 GHz) photocathode gun and two 3 m long S-band (2.856 GHz) constant-gradient traveling-wave structures are used for electron beam generation and acceleration. The layout is shown in Fig. 3.

Even though the PAL-XFEL injector will have three S-band accelerating structures, the design using two structures was adopted at ITF. After the two structures beam energy is

* Work supported by The Ministry of Science, ICT and Future Planning of the Korean Government
† janghui_han@postech.ac.kr

ISBN 978-3-95450-133-5

Figure 1: Areal view of the Pohang Accelerator Laboratory site in July 2014. The PAL-XFEL building under construction is shown at the left side. The circular building at the top right is the PLS-II ring. The full energy injector linac is connected to the ring. The end of the linac, the accelerator and injector test facilities (ATF and ITF) of PAL-XFEL are located. The insertion device test laboratory (IDL) is located in the storage building located at the north of PLS-II. In the PLS-II ring, the photon test facility (PTF) is located.

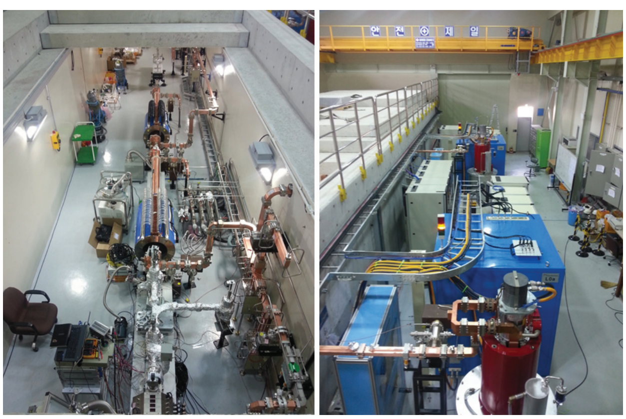


Figure 2: Injector Test Facility (ITF) of PAL-XFEL. The accelerator components are installed in the tunnel (left). The RF systems, magnet power supplies other facility control systems are installed in the gallery (right).

high enough for emittance measurements, diagnostics tests and laser heater test. With two structures a space for the installation of diagnostics and other test stands is allowed.

An electron beam is generated at the copper cathode, which is the central part of the gun cavity back plane, by a drive laser pulse. The beam is accelerated through the gun cavity with a 120 MV/m maximum field at the cathode on the beam axis. At the gun exit, the beam energy becomes 5.7 MeV. Immediate downstream of the gun a solenoid is positioned for beam focusing. Between the gun and first accelerating structure there are an integrating current transformer (ICT), a spectrometer dipole and screen, two screens for beam image measurement, a stripline beam position monitor (BPM) and three sets of beam steerers.

The first accelerating structure starts at 2.2 m from the cathode. Between the structures a stripline BPM and a set of steerers are positioned. 0.92 m long solenoids are installed around the structures. The first solenoid is mainly for beam matching at the structures and the second for beta-function control at the components downstream. After further acceleration through two S-band structures, the beam energy becomes up to 140 MeV.

Table 1: Nominal Operation Parameters of ITF

Laser/cathode	
Laser profile	Gaussian
Fwhm length	3 ps
Rms size	0.2 mm
Gun	
Peak field at cathode	120 MV/m
Beam launch phase from 0-crosing	38°
Accelerating section	
Gradient of 1st section	21 MV/m
Gradient of 2nd section	24 MV/m
Phase of 1st section from on-crest	−10°
Phase of 2nd section from on-crest	0°
Nominal electron beam	
Bunch charge	200 pC
Fwhm bunch length	3 ps
Normalized transverse emittance	0.6 mm mrad
Mean energy	137 MeV

ISBN 978-3-95450-133-5

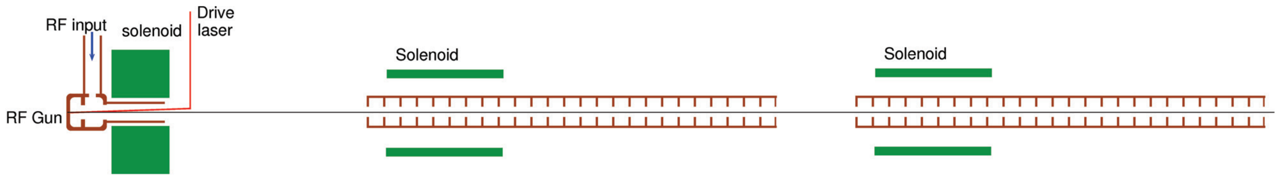


Figure 3: ITF accelerator layout with the gun and two accelerating structures.

ACCELERATOR COMPONENTS

RF Gun

The baseline gun has been developed at PAL, which consists of 1.6 cells and a high power RF coupler on the side of the second cell with a length of half a wavelength. Both cells have a round shape. Two RF input holes are made with mirror symmetry and two additional pumping holes reduce the high-order modes of the RF field [6]. The peak accelerating field at the cathode is designed to be 120 MV/m and the beam energy at the gun exit is 5.7 MeV [7].

The cavity body was made by diamond machining oxygen free copper. Machining was done at a local company, Hanatech. Cleaning and vacuum brazing were carried out in PAL. RF tuning was mainly done by controlling the cell length before the final brazing.

The first gun used for the Injector Test Facility (ITF) was the gun produced in 2011 for the test at the Gun Test Facility (GTF), which was located in the underground ATF area for the gun test far advance to the PAL-XFEL project [8]. This GTF gun was used for the first beam generation at ITF. An improved gun, named Gun1-0, in terms of brazing and tuning process was produced in spring 2013. Gun1-0 installed in the ITF tunnel is shown in Fig. 4. Gun1-0 was used for the ITF beam operation from summer 2013 to summer 2014. In September 2014, another gun, named Gun1-1, will be installed at ITF. This gun will be used later for PAL-XFEL beam commissioning as well.

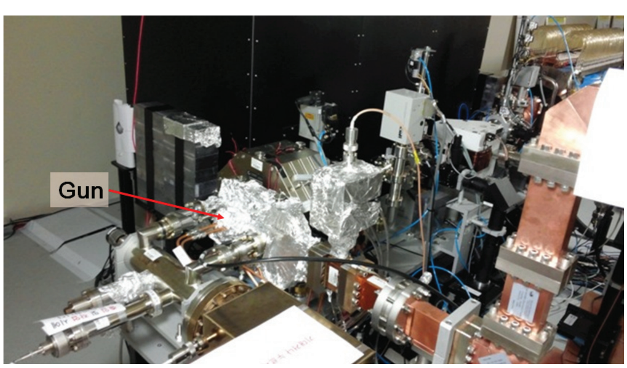


Figure 4: RF gun installed in the ITF tunnel.

High power RF test was done for Gun1-0 with the full peak power of 13 MW and repetition rate of 60 Hz. The RF pulse length was 2 μs. RF breakdown did not take place even though the test period was only a few hours. At nominal operation the gun operates at 10 Hz, 12 MW and 1.75 μs.

A focusing solenoid is positioned after the gun for the emittance compensation process. The solenoid was manufactured by RadiaBeam Technologies. Almost the same design of solenoids have been used for the GTF gun and for the gun of the femtosecond terahertz beamline in PLS-II.

A next stage gun development, targeting the achievement of a lower transverse emittance as well as a higher peak current, is ongoing [9]. This gun will provide an electron beam with a lower transverse emittance by optimizing the gun cell length and focusing solenoid position [10, 11]. With an exchangeable cathode plug, damaged cathodes can be replaced with a fresh one easily. Cathodes with high quantum efficiency and/or low thermal emittance will be tested at the gun.

Laser

The Ti:sapphire laser system is a commercial regenerative amplifier from Coherent Inc [12]. The pulsing rate of the seed laser (Coherent Mira) is set to 79.333 MHz which is synchronized to the master oscillator. A regenerative amplifier (Coherent Legend Elite) is used to generate pre-amplified output with about 150 ps and 120 Hz repetition rate. A post-power amplifier is employed to boost the output power up to 2.5 W with an rms noise of 0.24 %. The center wavelength is 770 nm. The wavelength is tripled for the beam generation at the gun.

Figure 5 shows the results of UV (257 nm) laser pulse length measurement using synchronized cross correlation with a femtosecond IR pulse. Various UV pulse length was used for electron beam generation. The transverse shape of a laser pulse and the effect to the beam parameter are discussed in Ref. [7]

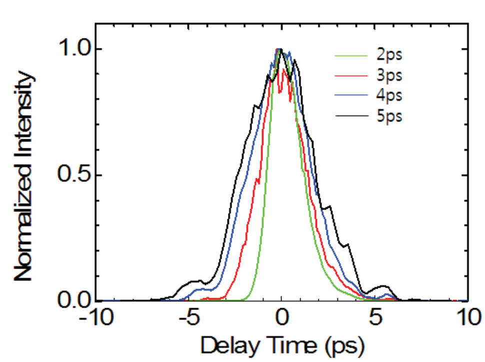


Figure 5: Pulse length measurement using cross correlation method.

ISBN 978-3-95450-133-5

The laser clean room is located at the north wall of the linac tunnel. Figure 6 shows the view of the laser room. Laser pulses generated in the laser room are transported through a hole in the ITF tunnel wall to the laser table in the tunnel. A pin hole and optics are installed on the laser table in the tunnel for the transverse beam shaping. The laser position at the cathode is remotely controlled using two mirrors .

Figure 6: Laser system in the laser clean room.

Photocathode

The oxygen-free copper which is part of the gun cavity back plane, is used as photocathode. At nominal operating condition, a quantum efficiency (QE) of order of 10^{-5} is measured. Laser cleaning was tried using an IR (760 nm) laser pulse as well as a UV (253 nm) lase pulse. An IR laser pulse with hundreds ps length was found be most useful up to now. After the IR laser cleaning, the QE of the cathode was recovered from 4.0×10^{-5} to 1.3×10^{-4} and stayed without QE drop for a few months [13]. More systematic study is planned in September 2014.

Accelerating Structures

Two 3 m long S-band constant-gradient traveling-wave structures, manufactured by Mitsubishi Heavy Industries, are installed in the ITF tunnel (see Fig. 7). The structures have J-type high power RF coupler for reducing the dipole mode in the coupling cell [14]. Since the coupler cell has a round shape, the quadrupole mode remains. It seems to be the reason of beam emittance rise when the second structure is on. Study on the effect to a beam is ongoing.

Both structures have 0.9 m long focusing solenoids, which were manufactured by Keum Ryong Tech, a local company. These solenoids are used for beam matching at the structures and downstream components.

RF SYSTEM

Two S-band klystrons from Toshiba (E37320) feed high power RF to the gun, two accelerating structures and deflecting cavity. The maximum power of the klystron is 80 MW with a pulse length of 4 μs. The first klystron feeds the gun and first accelerating structure. The second feeds the second structure and RF deflector (see Fig. 8). The maximum

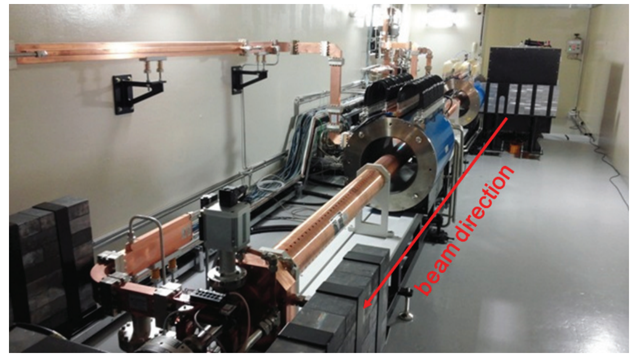


Figure 7: Accelerating structures and focusing solenoids installed in the ITF tunnel.

repetition rate of the RF systems is 60 Hz. 6 dB and 8 dB

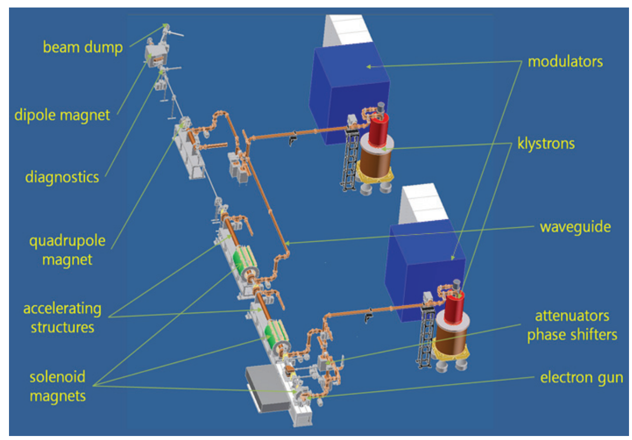


Figure 8: Main components of accelerator beamline and RF systems. The concrete tunnel wall between the accelerator beamline and RF stations is not shown.

RF power dividers are installed at the first and second RF stations, respectively. Higher power is sent to the accelerating structures. Lower power is delivered to the gun or RF deflector.

For the independent RF operation of the gun a high power RF attenuator and a phase shifter are installed in the waveguide to the gun. For the RF deflector, a vacuum gate valve is installed before the cavity coupler in addition to an attenuator and a phase shifter because only few kW RF power in the deflector can induce a transverse kick to a beam. Both attenuators and phase shifters were manufactured by Nihon Koshuha.

Two high power pulse modulators were manufactured by a Korean company, DAWONSYS. The maximum power of the modulators is 200 MW (400 kV, 500 A) with a flat top width of 4 μs.

Two low level RF (LLRF) modules consisting of both phase and amplitude detector (PAD) and phase and amplitude controller (PAC) units were manufactured by Mobiis, a Korean company. More detail on the LLRF modules is found in Ref. [15] The solid state pre-amplifiers amplify a 2.856 GHz pulse from the LLRF module to 800 W for the

ISBN 978-3-95450-133-5

klystron operation. The pre-amplifiers are manufactured bu SUNGSAN, a Korean company.

DIAGNOSTICS

Screen Station

100 μm thick 1 inch YAG screens are installed normal to the beam direction. a 200 nm aluminum layer on a 100 μm silicon substrate, installed 45° to the beam axis, reflects beam images horizontally to the view port parallel to the beam axis. BAUMER TXG50 GigE cameras with 5M pixels and a 2/3 inch CCD sensor are used.

The original version of ITF screen station was manufactured by RadiaBeam Technologies. A new version of screen station is under preparation for the use at PAL-XFEL, with considering the European XFEL/DESY and SwissFEL screen station designs (see Fig. 9). The new version has a target geometry for the reduction of coherent optical transition radiation (COTR).

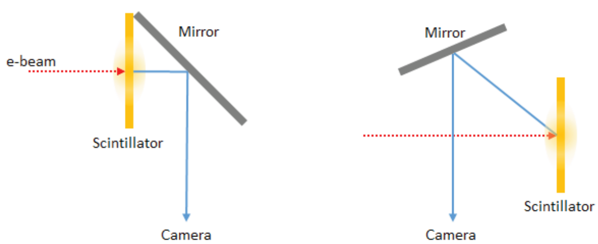


Figure 9: Geometry of screen station. The original design (left) manufactured by RadiaBeam Technologies and the new design (right) for reducing the COTR.

Spectrometer Dipole

Two spectrometer systems are installed for beam energy measurement. Both systems consist of a dipole for beam bending, a drift vacuum tube and a screen.

The first dipole is installed between the gun and first accelerator column for the gun commissioning. Beam launch phase of the gun is found with this spectrometer by means of beam energy measurement as function of gun RF phase. The dipole is a sector magnet which bends a beam by 90°.

The second dipole is installed at the end of the ITF beamline. The dipole is a sector magnet which bends a beam by 30° for a beam energy measurement up to 150 MeV.

Integrating Current Transformer

Two Bergoz integrating current transformers (ICTs) were installed, one after the gun and another before the beam dump at the end of the beamline. Since signal from the ICTs was interfered by high level of noise, it was difficult to read beam signal using the controller. The first ICT after the gun was replaced with Turbo-ICT from Bergoz Instrumentation. Bunch charge is now measured clearly using the Turbo-ICT without background noise problem.

Beam Position Monitor

Seven stripline beam position monitors (BPMs) are installed. One BPM is located before the first accelerating structure to monitor the position of a beam entering the accelerating structure. Three BPMs are located between the first and second structures, after the second structure, and before the RF deflector, respectively. These four BPMs are used for beam operation purpose.

Other three BPMs are installed on the BPM test stand at the rear part of the ITF beamline (see Fig. 10). Using this BPM test stand, the performance of BPM electronics was evaluated. Libera Brilliance Single Pass and Libera Single Pass E from Instrumentation Technologies showed 3 μm and 1.5 μm resolution for 200 pC electron beam, respectively. μTCA based BPM electronics produced by SLAC showed about 3 μm resolution using a divided signal from a 200 pC beam. All tested BPM electronics satisfy the PAL-XFEL BPM resolution requirement, 5 μm at 200 pC.

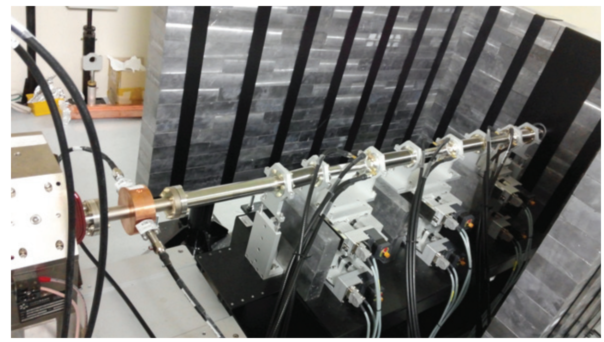


Figure 10: Diagnostics test stand at ITF.

This test stand will be used for the test and beam-based calibration of new BPM pick-ups as well. A new type of BPM pick-ups will be installed in this autumn.

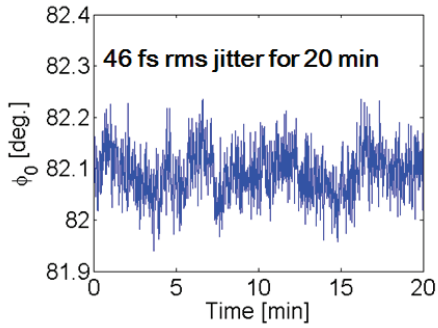
Beam Arrival Time Monitor

A cavity type of beam arrival time monitors (BAMs) are installed before the BPM test stand as shown in the left side of Fig. 10. Resonance takes place when an electron passes through the single cell S-band cavity. The RF signal is collected with two pick-up antenna at the cavity cylindrical wall. The signal is analyzed using one channel of the LLRF module installed at the second RF station. The BAM resolution is about 10 fs. More detail on the BAM will be found in Ref. [16]. Figure 11 shows analyzed signal from the beam arrival time monitor. This measurement was carried out during the pulse optical timing test [17].

RF Transverse Deflector

An RF transverse deflecting cavity is installed about 2 m downstream of the second accelerating structure (Fig. 12). This 1 m backward traveling-wave structure deflects an electron bunch vertically. This deflector was used for the dechirper experiment [18] and slice emittance measurement. It will be used for laser heater test in winter 2014. This

ISBN 978-3-95450-133-5



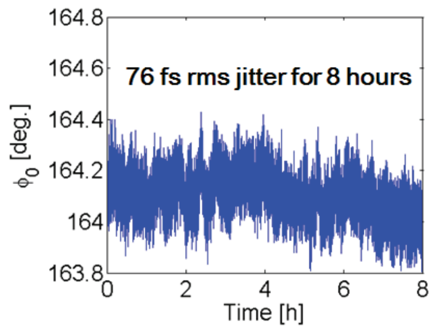


Figure 11: Measured signal from the beam arrival time monitor during the pulsed optical timing test for a short term (top) and a long term (bottom).

deflector will be moved to PAL-XFEL and installed after the first bunch compressor where the beam energy is 350 MeV.

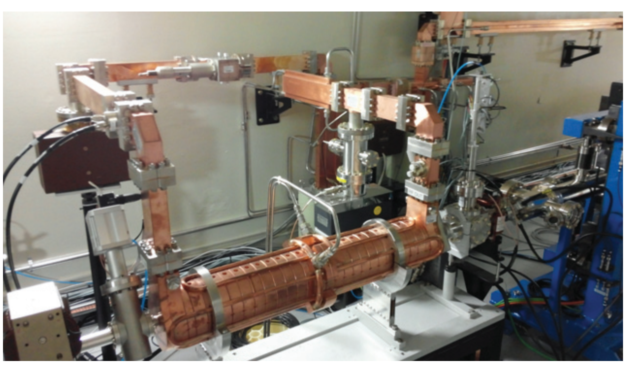


Figure 12: RF transverse deflector installed in the ITF tunnel.

EMITTANCE MEASUREMENT

Projected Emittance

Projected emittance was measured by scanning the strength of the third quadrupole [19, 20]. The beam image was measured using the screen immediate upstream of the second (high energy) spectrometer dipole. The distance between the quadrupole and screen is 2.6 m. Measured emittance was normalized by diving with the beam energy measured with the second spectrometer dipole and screen downstream. An example scan of quadrupole strength for emittance measurement is shown in Fig. 13.

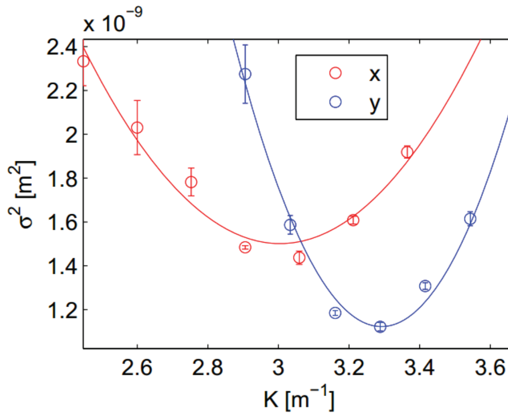


Figure 13: An example of single quadrupole scan for projected emittance measurement. Current of the third quadrupole was scanned and the beam image was measured with the screen 2.6 m downstream.

Figure 15 shows the history of emittance measurements at 200 pC bunch charge for the past 18 months. The values in the plot are the quadratic means of the horizontal and vertical emittance values. For each measurement point, gun solenoid field was optimized for best emittance compensation condition. For the measurements, various drive laser size and length, RF phases of the gun and first accelerating structure, RF amplitude of the gun, and current of the accelerating structure solenoid were used.

Figure 14 shows the emittance measurement with various radius and pulse length of drive laser. For each measurement, gun RF phase and gun solenoid current were optimized. This result does not agree with numerical simulation. An electron beam generated with a 5 ps laser pulse length has a smaller emittance compared to the 3 ps case according to numerical simulation using the ASTRA code [21]. The reason is under investigation.

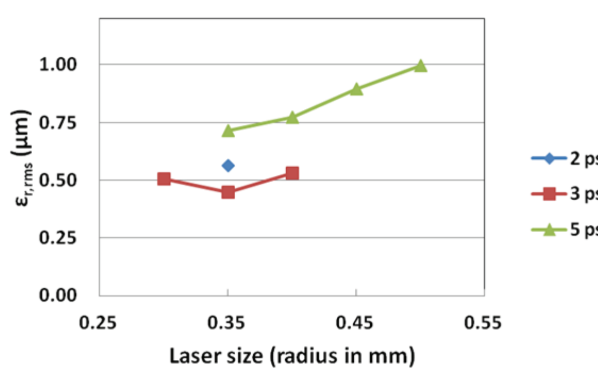


Figure 14: Projected emittance (95% rms) for various radius and pulse length of drive laser at 200 pC bunch charge.

During the first few months of ITF operation, measured emittance values varied much. However, at good measurement conditions emittance values below 0.5 mm mrad was measured (see Fig. 15). Recent measurements do not show

ISBN 978-3-95450-133-5

a low emittance. We are studying possible reason including components alignment.

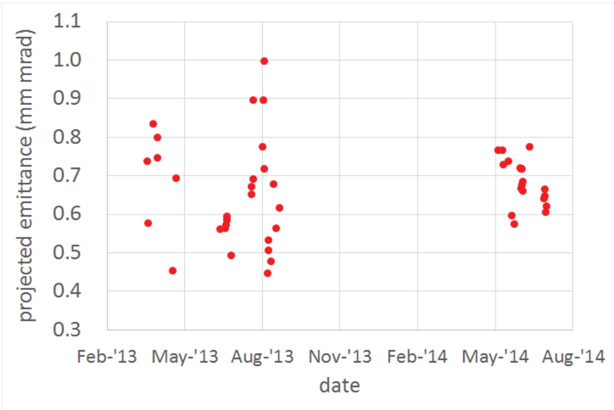


Figure 15: Projected emittance (95% rms) measured with 200 pC beams at ITF from early 2013 to summer 2014.

For the period of October 2013 to April 2014, beam test of stripline BPM, laser cleaning, and other maintenance were carried out instead of systematic emittance measurement.

Slice Emittance

Slice emittance for the horizontal direction was measured by streaking a bunch vertically using the RF deflector [22]. As for projected emittance, the third quadrupole was used for beam focusing and the last screen was used for beam image measurement. Figure 16 shows an example measurement at 200 pC. Slices were divided for equal charge. Each slice has a 10 pC charge. The measurement condition was not fully optimized yet.

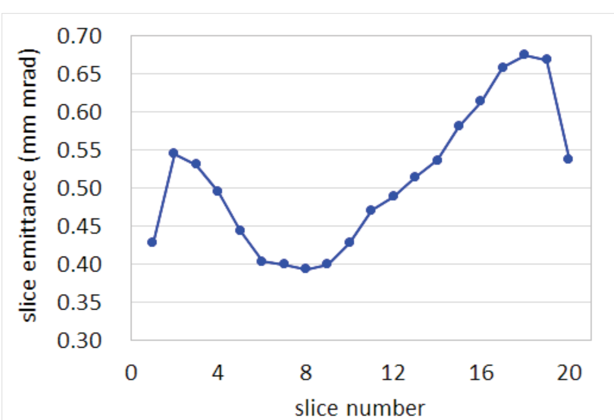


Figure 16: Slice emittance (95%) for the horizontal direction measured by streaking vertically using the RF deflector. The right side corresponds to the bunch head.

Systematic measurements of slice emittance as well as projected emittance are planed in September 2014.

OTHER BEAM TESTS

Dechirper

A 1 m long dechirper system was produced for the test of energy chirp control. The beam experiment was successfully carried out at ITF with SLAC and LBNL physicists in August 2013 [18, 23].

Laser Heater

A laser heater system will be installed in the ITF tunnel in September 2014. Beam commissioning will be carried out and operating condition will be found in winter 2014 for the efficient commissioning at PAL-XFEL. Laser heater components such as laser heater undulator (see Fig. 17), bending magnets and vacuum chamber are ready for installation. A small fraction of an IR pulse (770 nm) from the gun laser system will be sent to the laser heater.

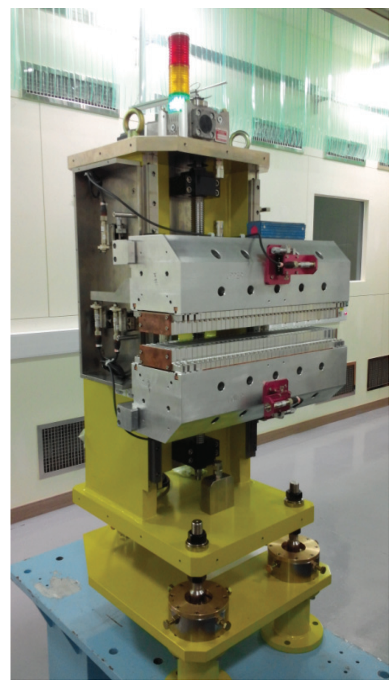


Figure 17: Laser heater undulator. The undulator magnetic field is being measured in the insertion device test lab.

Cavity BPM

Cavity BPM test is foreseen in autumn 2014. The cavity BPMs, which were fabricated at PAL, will be used in the undulator lines of PAL-XFEL for a position reading resolution better than 1 μm [24].

SUMMARY

The PAL-XFEL Injector Test Facility (ITF) was built in 2012 for beam commissioning of the injector in advance to the construction of the PAL-XFEL main linac. Beam test of the RF system, drive laser and diagnostics required for the PAL-XFEL main linac is also another important role of ITF.

ISBN 978-3-95450-133-5

Projected and slice transverse emittance is being measured with various machine parameters. Diagnostics test using electron beams was done successfully. Beam commissioning of the ITF accelerator including new guns and diagnostics will be continued.

REFERENCES

[1] J.-H. Han et al., "Status of the PAL-XFEL project," in *Proceedings of 3rd Int. Particle Accelerator Conf.*, New Orleans, 2012, p. 1735.

[2] H.-S. Kang et al., "Current status of PAL-XFEL project," in *Proceedings of 4th Int. Particle Accelerator Conf.*, Shanghai, 2013, p. 2074.

[3] I. S. Ko and J.-H. Han, "Current status of PAL-XFEL project," in *Proceedings of 27th Linear Accelerator Conf.*, Geneva, 2014, MOIOB03.

[4] S. H. Nam et al.,"Upgrade of Pohang Light Source (PLS-II) and challenge to PAL-XFEL," Synchrotron Radiation News 26, p.24 (2013).

[5] S. J. Park et al., "Construction of injector test facility (ITF) for the PAL XFEL," in *Proceedings of 4th Int. Particle Accelerator Conf.*, Shanghai, 2013, p. 2220.

[6] M. S. Chae et al, "Emittance growth due to multipole transverse magnetic modes in an rf gun," Phys. Rev. ST Accel. Beams 14, 104203 (2011).

[7] J. Hong et al., "Beam measurement of photocathode RF-gun for PAL-XFEL," in These Proceedings: Proc. 36th Int. Free-Electron Laser Conf., Basel, 2014, THP011.

[8] J. Hong et al., "High-power Beam Test of an RF Gun for the PAL-XFEL," in *Proceedings of 3rd Int. Particle Accelerator Conf.*, New Orleans, 2012, p. 1539.

[9] J. Hong et al., "Development of photocathode RF-gun at PAL," in *Proceedings of 35th Int. Free-Electron Laser Conf.*, New York, 2013, p. 279.

[10] J.-H. Han et al., "Design of a high repetition rate S-band photocathode gun," Nucl. Instr. and Meth. A 647, 17 (2011).

[11] J.-H. Han, "Design of a low emittance and high repetition rate S-band photoinjector," Nucl. Instr. and Meth. A 757, 1 (2014).

[12] C.-K. Min et al., "Development of low-noise picosecond laser system for Cu photocathodes," PAL-PUB/2014-002, PAL, 2014.

[13] C.-K. Min et al., "Recovering damaged Cu photocathodes by pulsed laser cleaning," PAL-PUB/2014-001, PAL, 2014.

[14] S. Miura et al., "Development of S-band accelerating structure," in *Proceedings of 34th Int. Free-Electron Laser Conf.*, Nara, 2012, p. 153.

[15] J. Hu et al., "Experimental test of the prototype LLRF systems for PAL-XFEL," in *Proceedings of 5th Int. Particle Accelerator Conf.*, Dresden, 2014, p. 2462.

[16] J. Hong et al., "Bunch arrival time monitor for PAL-XFEL," in *Proceedings of 3rd Int. Beam Instrumentation Conf.*, Monterey, 2014, MOPOD016.

[17] C.-K. Min et al., "Current status of development of optical synchronization system for PAL XFEL," in *Proceedings of 2nd Int. Beam Instrumentation Conf.*, Oxford, 2013, p. 772.

[18] P. Emma et al., "Experimental demonstration of energy-chirp control in relativistic electron bunches using a corrugated pipe," Phys. Rev. Lett. 112, 034801 (2014).

[19] M. Chae et al., "Simulation for new injector test facility of PAL-XFEL," in *Proceedings of 34th Int. Free-Electron Laser Conf.*, Nara, 2012, p. 117.

[20] M. Chae, "Study on electron beam optimization at PAL-XFEL injector test facility," PhD Thesis, POSTECH, 2014.

[21] K. Flöttmann, "ASTRA, A Space Charge Tracking Algorithm," ver. 3.0, `http://www.desy.de/~mpyflo/Astra_dokumentation/`

[22] J. H. Lee et al., "Slice emittance measurement using rf deflecting cavity at PAL-XFEL ITF," in These Proceedings: Proc. 36th Int. Free-Electron Laser Conf., Basel, 2014, THP013.

[23] H.-S. Kang and J. Hong, "A beam test result of corrugated structure for passive linearizer," in These Proceedings: Proc. 36th Int. Free-Electron Laser Conf., Basel, 2014, TUP093.

[24] S. Lee et al., "Design of the X-band cavity beam position monitor," J. Korean Phys. Soc. 63, 1322 (2013).

ISBN 978-3-95450-133-5