BEAM DIAGNOSTIC SYSTEM FOR PAL-XFEL

Changbum Kim*, Hyojin Choi, Jae-Young Choi, Jung Yun Huang, Heung-Sik Kang, Do Tae Kim, Byung-Joon Lee, Chang-Ki Min, PAL, Pohang, Korea

Abstract

The XFEL project in Pohang Accelerator Laboratory (PAL) requires low beam-emittance, ultra-short bunch length, high peak current, high stability of beam energy, and measurement and steering of beam trajectory within micrometers. Therefore, beam diagnostics for the self-amplified stimulated emission (SASE) XFEL should be, focused on attaining femto-second precision in the measurement of temporal beam parameters, and sub-micrometer precision in beam position measurement. Charge measurement and energy measurement are important as well. In this work, technical concepts regarding the diagnostic monitors will be summarized and present status of them will be described.

INTRODUCTION

The XFEL[1,2,3,4] is based on the principle of SASE that occurs due to on the generation, acceleration, and transport of unprecedently low-emittance, mono-energetic, high peak current electron bunches through the undulating magnetic field of an undulator array. When the XFEL beam parameters are well matched with XFEL conditions during the electron beam passes through the undulating magnetic field of undulator, the single XFEL mode among the spontaneous emission of synchrotron radiation gains exponential amplification along the undulator magnets. The SASE process is extremely sensitive to the electron beam parameters, so precise beam monitoring and feedback control of the beam parameters are very important in the operation of the XFEL machine. The proposed XFEL project in Pohang Accelerator Laboratory (PAL) requires low beam-emittance (< 1 μm·rad), ultra-short bunch length (~ 50 fs), high peak current (~ 4 kA), high stability of beam energy (< 0.01%), and measurement and steering of beam trajectory within micrometers (< 2 μm) [5].

Therefore, beam diagnostics for SASE XFEL should be, focused on attaining femto-second precision in the measurement of temporal beam parameters, and sub-micrometer precision in beam position measurement. Several beam measurement techniques have been developed for XFEL diagnostics in advanced XFEL study projects. Femtosecond bunch-by-bunch length measurement can be realized using a transverse deflecting cavity. Shot-to-shot variation of bunch length can also be monitored by measuring the coherent synchrotron radiation intensity radiated by femto-second electron bunches. Synchronization between the pump and probe beam for the pump-probe experiments can be achieved with femto-second precision by electro-optic detection of the beam arrival time. For the sub-micrometer beam position measurement, the nanometer beam position monitors (BPMs) developed for the international linear collider (ILC) can be utilized.

For the success of the PAL XFEL project, bunch-by-bunch measurements and control of electron and photon beam parameters must be obtained at critical locations - such as the low energy beam injector, bunch compressors - to achieve optimal tuning of the XFEL. For detailed understanding of the XFEL, beam emittance and beam energy spread should also be measured slice-by-slice along the bunch length. However, the existing diagnostics techniques used for the existing PLS machine, such as single bunch charge measurement, wire scanners, and optical transition radiators for beam size measurement, are also excellent diagnostic tools for the measurements of basic beam parameters in PAL XFEL.

DIAGNOSTICS SYSTEMS

Beam Position

Preservation of beam quality during beam transport, and lasing of the XFEL radiation through the undulator are guaranteed only when the electron beam trajectory is well aligned within the specified tolerance, which is about 10% of the beam size in the undulator. In PAL XFEL, trajectory alignment should be more precise because of the narrow gap (~ 5 mm) in-vacuum undulator. Beam trajectory must be maintained within 10 μm in the linear accelerator and within 2 μm in the undulator array.

The transverse position of the beam in the XFEL can be measured using two different types of BPM: a pickup electrode (stripline or button) BPM, or a cavity BPM. A stripline BPM has a wide dynamic rage with a good resolution and suitable for the use of beam position monitoring in a linac. A cavity BPM has an excellent resolution in a small dynamic range and is widely used in the undulator area. A prototype stripline BPM was developed for the test and installed in the PLS linac.

In the undulator line, because of the tight resolution requirements, cavity BPMs will be used together with the stripline BPM. Cavity BPM has been intensively studied for nanometer beam position measurement for the future International Linear Collider (ILC) [6]. In a cavity BPM, the amplitude of the TM110 mode, excited in the cavity by an off-centered beam, yields a signal proportional to the beam displacement and the bunch charge. Sub-micrometer resolution of the cavity BPM can be achievable, although the measurable range of the cavity BPM is very narrow, typically less than 500 μm.

A prototype cavity BPM has been developed for the ILC (KEK ATF) and XFEL in PAL [7]. A prototype cavity BPM installed in KEK ATF extraction beamline for the

* chbkim@postech.ac.kr

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test. The sensitivity and isolation of the cavity BPM were measured with the signal processing electronics. Real beam position was checked with two stripline BPMs installed upstream and downstream of the test cavity BPM. Beam intensity of 0.8×10^{10} e/bunch was measured by an integrating current transformer (ICT) installed at the end of the extraction beamline, and the nominal ATF bunch length is 8 mm. Sensitivity of the cavity BPM was measured to be 0.8 V/mm when the two port signals are combined. Isolation was better than 40 dB with real beam measurements. By comparing the correlation between output signals from two opposite ports of the cavity, the 100 nm resolution of position measurement was proved within the dynamic range of ± 50 μm [8].

Bunch Charge

An integrating current transformer can be used for the bunch-by-bunch charge measurement. In the linac section, a commercial integrating current transformer (e.g., Bergoz ICT) [9] will be used. This transformer measures bunch-by-bunch charge with 5 pC accuracy in a measurable range of 2 nC. For some non-critical applications, sum signal from each BPM can be used for the bunch charge measurement after appropriate calibration.

Transverse Beam Profile and Emittance

For the XFEL, the beam emittance should satisfy the diffraction limited beam relation [10]. Thus an accurate beam emittance measurement is an essential diagnostics to determine machine performance and provide corrective feedback. The emittance is correlated with beam size, so accurate beam size measurement is needed to infer beam emittance. For the beam size measurement, thin fluorescence crystals such as YAG(Ce), and CsI(Tl) are used to image the beam. Optical transition radiation (OTR) that is produced when a charged particle passes through a boundary of two materials having different dielectric constants, can be also used to measure the size of projected beam.

Because the OTR has sub-picosecond response time, femto-second bunch-by-bunch structures can be observed using OTR. Beam emittance is measured with OTR screen and a quadrupole magnet located in a non-dispersive section.

For the practical reasons that the quadrupole scanning method needs change of quadrupole strengths, which affects the stability of accelerator optics, and that each scan takes a long time, we will use four screens installed in a FODO lattice section to avoid changing quadrupole strengths during operation, and will measure beam emittance in a single pass of the beam. A wire scanner was fabricated for PAL XFEL study based on the KEK ATF design and a preliminary test conducted using a laser beam to simulate the electron beam showed good performance.

Because the XFEL performance depends on slice emittance of the bunch, so the diagnostic equipment must be capable of measuring the slice beam profile along the bunch. Slice emittance can be measured with the same setup used in the bunch length measurements system by combining an RF deflector and an OTR screen. The slice beam profile can be also measured by zero-phasing the accelerating column and passing the electron beam through an analyzing magnet in the dispersive sections [11]. As the energy is modified linearly along bunch length in the zero-phasing scheme, each slice of electron bunch makes an image on the OTR screen after passing the analyzing magnet.

Longitudinal Beam Profile

In the PAL XFEL, the electron bunch length at the photocathode will be ~ 10 ps, but will become shorter by the time it reaches the end of focusing solenoid coils. After the first accelerating column, it is compressed to ~5 ps. It is further compressed in the first bunch compressor (BC1) to 1.3 ps and finally to ~ 50 fs after the third bunch compressor (BC3). Because the bunch length varies along the accelerator components, an appropriate bunch length measurement tool should be selected at critical locations. A commercial streak camera, such as the Hamamatsu Fesca streak camera has a temporal resolution of < 200 fs, so it is a useful instrument for the measurement of spatio-temporal structure of electron bunch. SR or OTR [12] can be used for direct bunch length measurement using as streak camera. Because the resolution of the streak camera is limited to ~200 fs, alternative methods for bunch measurement should be used after the first bunch compressor. For the time-domain sub-picoseconds bunch length diagnostics, a transverse RF deflecting cavity (TCAV) will be used [13]. The RF deflector generates a transverse electric field to accelerate the beam in a vertical direction while the beam passes through the deflecting cavity. After leaving the cavity, the beam drifts further to the OTR target for imaging. At the OTR target, bunch length converts to vertical height and measured beam size shows bunch length. This kind of RF deflector is used for the diagnostics of sub-picosecond bunch length in TTF [2].

Autocorrelation of coherent synchrotron radiation (CSR) from a dipole magnet, or coherent transition radiation (CTR) from a metal foil target can be used for the bunch length measurement [14]. When the micro-bunching instability increases, the CSR or CTR amplitude increases quadratically in the spectrum with respect to bunch charge. This characteristic can be utilized as an on-line bunch length monitoring device by monitoring the intensity of the CSR using a pyro-electric detector during operation.

Recent progress on electro-optical (EO) bunch measurement technology using electro-optic crystals like LiNbO3, TiNbO3, ZnTe has been very successful [15]. As the electric field of a relativistic bunch propagates parallel with the electron bunch, high electric field from the electron bunch modifies the refractive index of the EO crystal. Bunch structure can thus be detected using a polarized laser as a probe pulse, and detecting the modification of polarization while the laser beam passes

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through the EO crystal. Although the resolution of this technology is limited by the dispersion of the laser light through the EO crystal, bunch-by-bunch single-shot measurement is possible without intercepting the beam. The beam signal detected by EO is a very important timing signal in measurement of the timing jitter, and in the synchronization of electron beam with the laser light and FEL radiation within a few femto-second precision. One type of electron beam arrival time jitter measurement depends on whether the laser beam incident on the EO crystal is ahead of or behind the beam. The ahead part or behind part of the laser beam experiences polarization modulation that can be detected by the optical analysing system, and the spatial variation of the detected signal is converted to the absolute time jitter. Measurement of 30 fs rms beam jitter has been achieved using the EO detection scheme [16]. Fine improvement of electro-optic measurement technique is one of the major research activities in FEL diagnostics. A balanced detection scheme using a ZnTe electro-optic crystal is under development for PAL XFEL. The vertical and horizontal polarization beam intensities of laser beam that impinges on the ZnTe crystal are changed due to the birefringence of the crystal induced from the transverse electric field generated by relativistic electron bunch.

Beam Energy and Energy Spread

The beam energy variation can be monitored with an OTR screen in the dispersive section. A larger OTR screen will be needed in the low-energy dispersive parts such as BC1, because the spread of the beam image will be large in the dipole magnets at low energy. As the XFEL performance depends on the slice parameters, so slice energy spread measurement is also very important. Slice energy spread and bunch length can be measured simultaneously by using the analyzing magnet to bend the RF-deflected bunch in the perpendicular direction. Separate beam analyzing stations will be installed for the beam energy and energy spread measurements during machine operation.

Undulator Diagnostics

In the PAL XFEL, tens of undulators will be installed to obtain saturated FEL radiation, so that their alignment is one of the critical issues. For the alignment, diagnostics module can be installed in-between two undulators. The alignment process is done as in the following. First, BPM, beam finding wire and OTR screen on a diagnostics module are aligned, and the synchrotron radiation from the align undulator is sent to downstream of undulator line. Next, the whole diagnostic module is moved to transverse direction and let the radiation place on the centre of OTR target, then the diagnostic module is align to the synchrotron radiation from the align undulator. Last, the electron beam orbit can be aligned to make overlapping between the electron beam and the synchrotron radiation by using two corrector magnets.

Important undulator parameters such as gain length and the intensity of the X-ray must also be measured along the undulator. Thus, beam diagnostics in the undulator line includes beam position monitors, bunch charge monitors, beam profile monitors and an X-ray profile and intensity monitor. FEL intensity can be measured using an appropriate photon beam pick-up like a thin metal wire or a crystal diffractor in the path of the electron and photon beam. Several ideas for precise characterization of XFEL radiation have been proposed and are being studied in the on-going XFEL projects [1,2,3,4]. Further developments of undulator radiation diagnostics for the PAL XFEL are also going.

SUMMARY

General descriptions on the special diagnostic techniques for the proposed PAL XFEL have been introduced. Development of methods to reliably and accurately measure sub-micrometer beam position measurement and sub-picosecond bunch length measurements is ongoing.

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