BEAM INSTRUMENTATION FOR X-ray FELs*

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Abstract

The performance of X-ray Free-electron lasers depends strongly on the achieved quality of the high brightness electron beam and its shot by shot stability. The requirements and challenges of the instrumentation needed to tune and optimize such electron beams will be discussed. Of particular interest are measurements of the beam orbit, emittance, energy, and bunch length and the different measurement techniques for these transverse and longitudinal beam parameters and their implementation for routine operation will be addressed in detail, particularly the necessary instrumentation to fulfill different user requirements in terms of beam energy and bunch length. Specific requirements for the initial commissioning, routine optimization and feedback applications will be presented as well.

INTRODUCTION

The development of ultra-high brightness electron beams at GeV energies to drive free electron lasers from EUV [1, 2, 3] to hard X-ray wavelengths [4] requires instrumentation suitable to measure such beams. Table 1 lists the basic parameters of the three hard X-ray SASE FEL facilities in operation or under construction, LCLS [5], SCSS [6], and E-XFEL [7].

Table 1: X-Ray SASE FEL Projects

	LCLS	SCSS	XFEL
Repetition rate (Hz)	120	60	10
Bunch train rate (MHz)	-	-	5
Energy (GeV)	13.6	8	17.5
X-ray wavelength (nm)	0.15	0.1	0.1
Charge (nC)	0.25-1	0.3	0.1-1
Bunch length (μm)	8-20	25	20
Peak current (kA)	3.4	5	2.5
Undulator length (m)	100	100	130
Undulator β (m)	30	30	32
Beam size (μm)	30	45	35
3-D Gain length (m)	3.5	3.7	10

Beam diagnostics for such accelerators has to operate within an energy range of a few MeV in the gun and injector areas of the accelerator up to the several GeV level in subsequent acceleration, bunch compression, and undulator regions of the FEL. The diagnostics must also be suitable for a charge range of 100s of pC up to several nC, although recently low charge operation at only 10s of pC has proven to be a viable machine configuration providing extremely short electron and photon beams of only a few fs length [8].

Resolution requirements for the instrumentation used for beam orbit and emittance diagnostics are given by the rms beam size which for typical β-functions from 10 to 100 m and a high brightness beam of 1 μm normalized emittance can be as small as only a few 10s of μm. This requires the resolution of screens and wire scanners to be as good as 10 μm. A necessary photon beam stability out of the undulator of 1/10th of the beam size translates into upstream BPM resolutions of only a few μm. Precise beam-based alignment of undulator segments to the few μm level needed for optimum FEL performance results in the need for cavity BPMs with sub-μm resolution.

For the longitudinal beam parameters, the desired energy stability and energy spread of the electron beam needed for suitable FEL gain are related to the dimensionless FEL efficiency parameter ρ which is typically of the order of 10^{-4} for an X-ray FEL. The FEL bandwidth is of the same order and hence the beam energy spread and stability have to be measured better than a certain fraction of this number. Measurements of the beam energy in a chicane with commonly about 10 cm dispersion require thus a position sensitivity of 10 μm, similar to beam orbit measurements. Alternatively, the induced time delay from an energy deviation in a chicane of $c\Delta\tau = R_{56}\Delta E/E$ can be used to deduct beam energy by a measurement of bunch arrival time before and after the chicane. This requires such monitors to have time resolutions of 10s of fs for typical few cm R_{56} values. An even better resolution is desired for arrival time monitors to provide beam timing information for the FEL user stations. The bunch length needs to be measured over a wide range from the initial ps lengths in the injector area to 10s of fs after the bunch compressors or even down to a few fs in the LCLS case for operation in the shortest low charge mode. A further requirement for machines operating with a bunch train is to resolve beam parameters within the bunch train to provide input for intra-bunch feedback systems.

Diagnostic systems employed in user machines or in development will be discussed in more detail with examples from different facilities and their usefulness and performance for both machine commissioning and daily operation will be illustrated. Diagnostics used for the measurement of the X-ray beams will be discussed elsewhere [9].

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TRANSVERSE DIAGNOSTICS

Beam Position Monitors

Besides current transformers or toroids to measure bunch charge, beam position monitors are the most heavily used diagnostics in machine commissioning and tuning to establish the beam orbit through the machine and to maintain it through feedback systems once it's optimized. Commonly employed beam position monitors are of button, strip line, or cavity type. At FLASH about 72 BPMs with 10 μm resolution and electronics designed for 0.5 to 1 nC are in use which are mostly strip line with some button types in the low energy and undulator sections, and cavity BPMs in the cold modules with 40 μm resolution. The electronics is being upgraded to enable beam operation down to 50 pC and it is planned to upgrade the undulator BPMs to cavity types being tested for E-XFEL with 1 μm resolution [10]. They operate at 3.3 GHz and have a low Q of 70 to resolve beam position within the bunch train as needed for intra-bunch feedback [11]. The present FLASH BPM system has a high reliability enabled by regular maintenance and provides easy access for operators to store orbits and to recover previous settings for changes in machine settings.

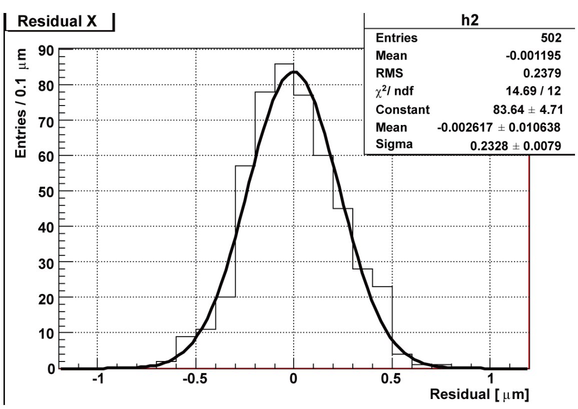

Figure 1: Position correlation between three SCSS cavity BPMs, corresponding to less than 200 nm resolution [12].

The cavity BPM design for XFEL/SPring8 which the E-XFEL is based on operates at 4.76 GHz and has a dipole and monopole cavity for signal normalization. The spatial resolution is better than 200 nm (see Fig. 1) and the monopole cavity also provides a phase measurement with less than 25 fs rms resolution [12].

The LCLS accelerator has about 180 BPMs installed which are mostly strip lines except for the cavity BPMs throughout the undulator. Variable attenuators in the strip line BPM electronics [13] enable a charge range from several nC to the 10 pC level, although the resolution worsens from normally about 3 μm above 50 pC to 25 μm at 20 pC. Long term stability is reached by applying calibration pulses between beam pulses to constantly self-calibrate the BPM electronics. The sub-μm resolution required for the BPMs in the undulator [14] is reached with a dipole/monopole cavity design operating at 11.4 GHz and was measured to be less than 300 nm [15]. The cavity BPM system for the undulators is quite reliable, although they require regular recalibration about every few weeks by moving the undulator support girders and subsequent beam-based alignment to determine their offsets [16]. Both BPM types are heavily used in multiple transverse feedbacks and the strip line BPMs in various dispersive regions provide beam energy measurements for the longitudinal feedbacks [17]. Beam synchronous data of multiple orbits from deliberate orbit oscillations or beam jitter enables machine optics verification during machine commissioning and determination of RF or magnet noise sources during routine operation.

Beam Profile Monitors

Measurements of beam emittance and β-matching throughout the accelerator requires either single shot beam profile monitors or multi-shot wire scanners. If 2D distribution are needed for temporally sliced measurements via deflecting cavities, only screens can be used. For profile monitors, commonly used are either fluorescent screens made of crystals or powder from YAG and other materials or metal foils and wafers to generate optical transition radiation (OTR). Fluorescent screens are preferable for their high sensitivity at low energies of few MeV where the OTR efficiency is poor. At higher energies where beam sizes are smaller YAG screens suffer from saturation effects at charge densities of a few $\mathrm{nC/mm^2}$ and limited resolution due to blooming and finite crystal thickness. For electron beams with moderate brightness OTR screens can be used instead. Highly compressed bunches with small emittance though exhibit strong coherent effects (COTR) and prohibit beam profile measurements with OTR [18]. Alternatives and mitigation schemes are discussed in [19].

At FLASH more than 20 such OTR screens are installed with zoom optics for up to 10 μm resolution and 8 bit CCD fire-wire cameras. They are used mainly in beam commissioning for emittance measurement and tuning [20], and for matching into bunch compressors and the undulator. The final matching procedure though has to be done without full compression because coherent radiation effects impede the profile measurement at certain compressor settings. The two Powdered YAG screens in the gun area are used for gun commissioning, but they are only useable for limited periods of time due to beam and dark current induced outgassing. Future upgrades to gigabit ethernet cameras to avoid radiation damage of the tunnel based PCs are being considered.

The LCLS accelerator utilizes a total of about 20 YAG and OTR screens with 12 bit camera link CCD cameras and 50 - 10 μm fixed pixel resolution depending on location. The YAG screens consist of 100 μm thick crystals and the OTR screens of 1 μm thick aluminum foils. YAG screens are used in the gun region for gun commissioning and their high sensitivity enables imaging of the cathode quantum efficiency at very low charges around 10 pC. Another YAG screen in the injector spectrometer is used to measure the longitudinal phase space in combination with a transverse deflecting cavity. The injector OTR screens are the main emittance tuning tool and are regularly used to optimize injector performance. Their sensitivity is even suitable for low charge operation and enables slice emittance measurements of 10 pC beams [8]. Only the OTR screens in the injector prior to the first dogleg are useful for operations due to the COTR effects from the ultra-bright compressed beam further down. The OTR screen in main beam dump with a large beam profile has been replaced with a YAG screen and shows beam profiles comparable to the profiles from the adjacent wire scanner.

Wire Scanners

The use of wire scanners enables a less intrusive diagnosis than screens, but such measurements are multi-shot and do not sample 2D distributions. They usually employ one or more wires made of tungsten or carbon with thicknesses of the order of 10 μm which are driven through the beam with a stepper motor. The beam profile is then recorded with beam loss monitors over multiple bunches.

Several OTR stations and the undulator section at FLASH are equipped with wire scanners, but the low repetition rate of the macro pulses makes them less favorable for normal operation and since they agree well with the OTR measurements, the latter are mostly used. For the E-XFEL a new design for a fast wire scanner is being developed using linear motors with speeds up to 1 m/s to sample the bunch profile within a single bunch train of less than 1 ms length [21].

The situation is different for LCLS where the ultra-high brightness of the compressed beam makes the OTR screens unreliable and wire scanners provide the only measurement of transverse beam profiles downstream of the injector. Four areas, in the injector, after each bunch compressor, and upstream of the undulator are equipped with multiple wire scanners for beam emittance measurements and three wire scanners in dispersive regions enable energy spread measurements. Each wire scanner has a wire card with a horizontal, vertical, and 45° wire and moves along a perpendicular 45° axis, so that different ranges of the stepper motor sample different projection planes. Profiles are obtained from fiber loss monitors and ionization chambers. Very important for obtaining reliable profiles is the synchronous shot-by-shot measurement of the beam orbit close to the wire to correct the wire position in the data analysis for transverse orbit jitter during the duration of the scan [22]. The 120 Hz repetition rate allows for rather fast scans and a measurement of the beam emittance in both planes with four wires takes less than five minutes. The development of new wire scanners is pursued to mitigate vibration issues in the present design and also significantly improve the scan speed with separate wires per plane and independent actuators for insertion and scanning.

LONGITUDINAL DIAGNOSTICS

Measurement and stabilization of bunch length and arrival time are both important to reach the kA peak currents needed for FEL saturation and to provide timing information and synchronization for FEL user experiments. Bunch length measurements are either based on coherent radiation emission or on techniques to map the longitudinal phase space onto transverse coordinates with deflector cavities.

Deflector Cavities

A transverse deflecting RF cavity [23] provides a very direct measurement of the bunch length with highest resolution to date at the 10 fs level at the cost of a large installation with RF source and cavity. The deflecting cavity imposes a time dependent transverse kick onto the beam which can then be measured on a downstream screen with 90° phase advance as transverse offset. The temporal calibration is simply done by changing the RF phase of the structure and observing the resulting offset on the screen. It is beam intercepting but can be set up for parasitic use with fast kickers.

The S-band deflecting cavity installed at FLASH is used in conjunction with either an off-axis screen and single bunch kicker straight ahead or another screen in a dispersive section downstream for longitudinal phase space with 20 fs temporal and 1.4×10^{-4} energy resolution. The cavity is used to study and set up bunch compression schemes [24] mainly with the dispersive screen because the straight off-axis screen is impeded by strong COTR effects.

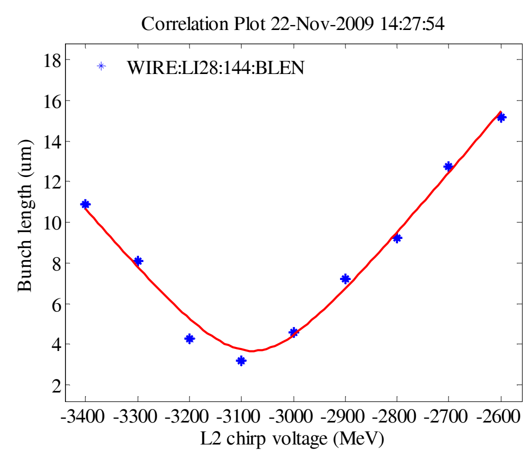

Figure 2: Scan of the LCLS rms bunch length after the second bunch compressor vs. chirp voltage in the L2 linac [22].

Two deflecting cavities are used in the LCLS accelerator, one 67 cm short in the injector and one 2.4 m long after the second bunch compressor to measure both initial and final bunch length after compression. With the injector cavity, slice emittance on an OTR screen and longitudinal phase space on a YAG screen in the injector spectrometer are also frequently measured. The originally intended off-axis

OTR screen and kicker for the main linac deflecting cavity are not usable and instead nearby wire scanners are used to avoid COTR effects. The correction of the shot-by-shot orbit jitter induced by the deflecting cavity becomes particularly important because the timing jitter can exceed the bunch length several times. With this method bunch lengths of 10 fs (see Fig. 2) have been measured [22] and this setup is used to calibrate the relative bunch length monitors for the feedback system. An X-band deflector is planned for installation downstream of the undulator with estimated 10 times better resolution than the S-band system. Its purpose is to measure the length of the ultra-short sub-μm long bunches at 20 pC as well as to obtain high resolution measurements of the longitudinal phase space of the spent electron beam to study the time resolved SASE process.

Bunch Length Monitors

A fast and single shot non-intercepting bunch length diagnostic is provided with detectors integrating the coherent radiation spectrum emitted by the electron beam over a wavelength range suitable for the respective bunch lengths. The source of coherent radiation can be edge and synchrotron radiation from bend magnets or diffraction radiation from screens close to the beam. Such diagnostics deliver a signal sensitive to bunch length which roughly scales with peak current and can thus be used for feedback on upstream accelerator phases. The absolute calibration needs to be obtained by other means like a deflecting cavity.

Such systems are implemented at FLASH as bunch compression monitors (BCM) after each of the two bunch compressors and the dogleg and use coherent diffraction radiation from slit screens. A fast 1 MHz readout from the pyroelectric detectors provides single bunch resolution within the bunch train [25]. These monitors perform very reliable and are used for slow phase feedbacks on the accelerating structures preceding the two bunch compressor, although issues of coupling between the feedbacks remain.

The relative bunch length monitors employed at LCLS use edge radiation from the last dipole in each bunch compressor which is the extracted downstream from the beam by an annular mirror. The integrated FIR spectrum above 100 μ is measured with pyroelectric detectors [26]. The raw detector signal is calibrated by measuring the absolute bunch length with the deflector cavity to generate a peak current value for the longitudinal feedback [17]. The measured noise of the monitor is better than 3% [27]. Since this integrating bunch length monitor does not distinguish well enough the shortest LCLS bunches, a single shot with low spectral resolution is being developed to measure the bunch shape of the ultra-short 20 pC bunches at LCLS. It follows a similar concept as the grating spectrometer implemented at FLASH [28], but it is designed as a prism spectrometer and utilizes a pyroelectric detector array. The setup is designed for the 1 - 40 μm wavelength range [29].

Bunch Arrival Monitors

Using a pick-up electrode or resonant cavity, an electron beam induced signal can be used to determine the bunch arrival time with respect to a RF distribution system.

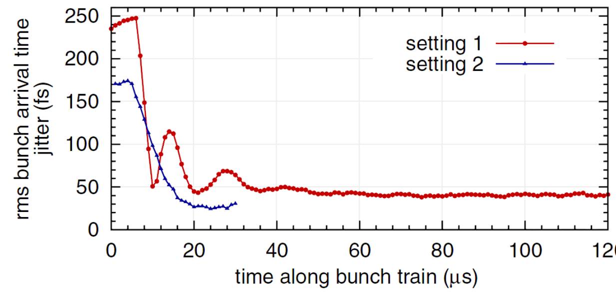

Figure 3: Beam arrival time jitter reduction to 20 fs with intra-bunch feedback at FLASH [30].

Bunch arrival monitors (BAM) [31] have been developed at FLASH which use a 4 button beam pick-off. The beam signals are compared to the fiber distributed reference laser pulses (5 fs stability) by encoding them onto the laser amplitude with an electro-optic modulator and sampling them with a 108 MHz ADC. Less sensitivity to laser amplitude jitter is achieved by operating at the zero-crossing of the amplitude modulation and the arrival time of each bunch in the train can been measured with 5 fs resolution [30] at 5 locations throughout the accelerator. The system is being used for feedback of the gun laser timing as well as for an RF amplitude feedback because the arrival time downstream of a bunch compressor depends on the beam energy. The fast acquisition rate of the monitors enables an intra-bunch feedback [32] on a FPGA based controller board and the arrival time jitter can be reduced from 60 to 20 fs rms within the bunch train (see Fig. 3). The system is still being developed and needs experts for operating.

A different system developed at LCLS for the bunch arrival time [33] uses a monopole mode phase cavity resonant at 2805 MHz whose signal is down-mixed with the main S-band frequency at 2856 MHz and digitized with a 16 bit ADC. The resolution of the arrival time measurement is estimated to 15 fs by comparing signals from the two adjacent phase cavities. The phase cavities provide timing information for the user experiments for off-line data analysis.

Synchrotron Radiation Monitors

The beam energy and energy spread can be measured directly with a synchrotron radiation monitor (SRM) inside a compressor chicane. The system installed at FLASH both provides the beam centroid via a multi-anode PMT and the beam size from an ICCD for a single bunch out of the bunch train [34]. The PMT signals are digitized at 1 MHz to give the centroid beam energy for each bunch in the train and provide an energy resolution of better than 10^{-4}. The SRM is being used in a feedback system [35] with a learning feed forward algorithm to reduce energy variation within the bunch train from 4×10^{-3} to 1×10^{-4}.

Diagnostic Integration & Automation

Reliable diagnostics which is well integrated into the accelerator control system becomes more and more necessary to accommodate frequent changes to the machine configuration as requested by the photon users. The LCLS controls software provides tools for automated configuration changes and one example is shown in Fig. 4 where the electron beam energy was gradually changed over a large range while the beam was maintained by the feedback systems.

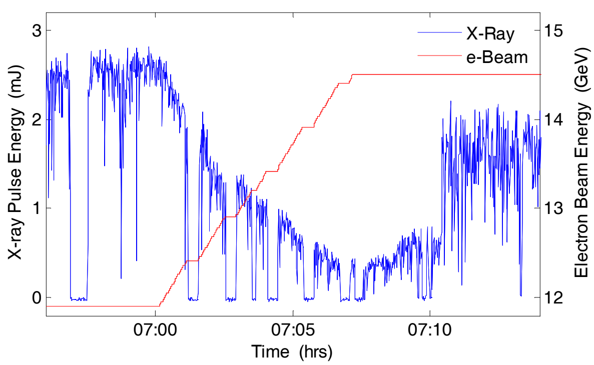

Figure 4: LCLS X-ray pulse energy during energy ramp from about 12 to 14.5 GeV. The jump in photon energy around 7:10 is due the recalibration of the gas detector [36].

SUMMARY

Electron beam diagnostics for X-ray FELs meets the main requirements needed for successful commissioning and reliable operation as a user facility at both FLASH and LCLS. Further development is being undertaken for diagnostics of ultra-bright electron beams to measure bunch length at the fs level and to have reliable measurements of 2D distributions. Measurement and stabilization of electron and x-ray beam at the fs level and their synchronization to laser systems for the x-ray users pose another challenge.

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