OVERVIEW OF BEAM INSTRUMENTATION ACTIVITIES FOR SwissFEL

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Abstract

SwissFEL will provide users with brilliant X-ray pulses in 2017. A comprehensive suite of diagnostics is needed for the initial commissioning, for changes to the operating point, and for feedbacks. The development of instrumentation for SwissFEL is well underway, and solutions have been identified for most diagnostics systems. I will present here an overview of the instrumentation for SwissFEL, and give details on some recent developments.

INTRODUCTION

A comprehensive diagnostics suite has been designed to assist in the commissioning and operation of SwissFEL [1]. The normal-conducting accelerator will run at a repetition rate of 100 Hz, generating two electron bunches separated by 28 ns in each RF pulse. The bunch charge can be adjusted between 10 and 200 pC, depending on the operation mode. A significant effort has been put into designing instrumentation suitable for the low-charge mode, which generates the smallest signals in the pick-ups, but has the tightest tolerance goals.

Instrumentation for SwissFEL has been tested at the SwissFEL Injector Test Facility [2]. Detailed measurements demonstrate the suitability for the SwissFEL design parameters [3].

CHARGE MONITORS

For calibration of the FEL photon pulses, an absolute charge measurement accuracy of 1% is desired. We currently have two possibilities: 1) in-house developed BPMs; 2) Bergoz Turbo-ICT-2 with BCM-RF-2 readout electronics. The BPM is a highly sensitive but not a calibrated device. The charge related signals of the BPM still need to be calibrated. The Turbo-ICT-2 is a calibrated device. It is an upgrade of the Bergoz Turbo-ICT with 2-bunch resolving capability and can accomplish these requirements with negligible beam position and bunch length dependence. It is insensitive to dark current due to its fast readout of the beam induced current (3 ns) at higher bandwidth. The resolution of the Turbo-ICT-2 is comparable to that of the BPM at charges > 10 pC (Fig. 1). Hence, the ICTs can still be mounted with the BPMs in every dispersive section of the machine and used to calibrate the BPMs.

The second option for calibrating the BPMs is the Bergoz ICT with BCM-IHR readout electronics. This is a calibrated device that gives the total charge in an integration window of 5 µs and cannot resolve the two bunches at SwissFEL. It measures the total charge, including the dark current. The single-shot resolution of this device is 20 pC; however, it can be used to calibrate the BPMs by first measuring the dark current and subtracting this value from the total integrated charge, one bunch at a time, to ascertain the charge of a single bunch.

BEAM POSITION MONITORS

SwissFEL will use cavity beam position monitors (BPMs) to align the beam along the linac, and to measure the electron energy in dispersive sections [4]. The proper alignment of the beam is important to reduce emittance growth due to wake fields, and to ensure overlap of the electron bunch with the radiation in the undulators. The BPMs consist of dual-resonator cavities. The dipole cavity determines the position, while the monopole cavity is used as a charge reference measurement. This measured charge value is also used for other monitors that exhibit a strong bunch charge dependence, such as bunch compression monitors.

There will be three types of cavity BPMs in SwissFEL, taking into account vacuum chamber diameters of 38, 16, and 8 mm in the gun, the linac and the undulator lines, respectively. For the cavities designed for a vacuum chamber diameter of 38 and 16 mm, a frequency of 3.3 GHz and a low quality factor of about 40 was chosen to minimize the crosstalk between the two bunches separated by 28 ns. The BPMs with 8 mm diameter will be deployed in the undulator lines, where only single bunches will be present in each RF pulse. For this reason, a higher quality factor will be chosen.

The resolution of the BPMs has been determined by comparing the measurements of several monitors installed in series. The residual of the SwissFEL cavity BPM (BPM16) is 0.8 µm rms for a 0.35 mm beam offset (Fig. 2).

BUNCH ARRIVAL MONITORS

Two bunch arrival monitors (BAMs) have been commissioned in the SwissFEL Injector Test Facility [5]. The first BAM upstream of the bunch compressor (FINXB-DBAM10) was commissioned in 2012. Two pick-ups were used there

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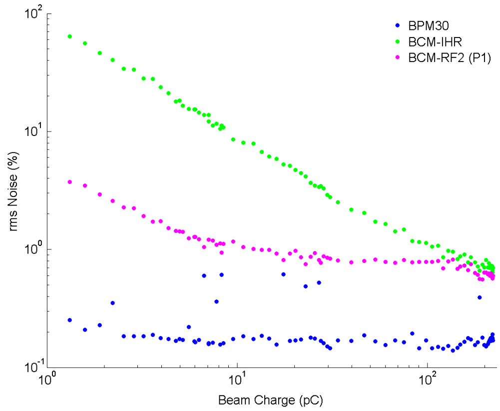

Figure 1: Signal-to-noise ratio measurement as a function of bunch charge, comparing resonant strip line sum signals (BPM30) with charge monitors BCM-IHR and BCM-RF2.

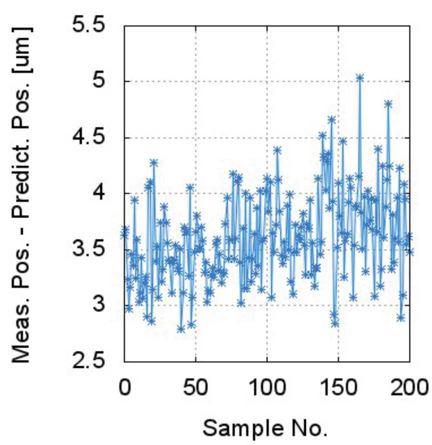

Figure 2: Beam position monitor resolution, measured by comparing several BPMs installed in series.

– a button with 80 GHz intrinsic bandwidth (vacuum side) and a Ridge Waveguide (RWG) with 16 GHz bandwidth and potentially stronger response at low charge. The bandwidth of both pick-up types was limited to 20 GHz by the vacuum feedthroughs, the highest bandwidth feedthroughs available on the market. In addition, the EOMs in the tunnel front-end had a bandwidth of 10 GHz and the acquisition ADC card was 12 bit, AC coupled. With this BAM, the best resolution achieved with the button pick-up was 18 fs in the range 60 to 200 pC and 30 to 170 fs in the range 10 to 60 pC. Several improvements were made in the second BAM commissioned in 2014 downstream the bunch compressor. Installed were button pick-ups equipped with 40 GHz vacuum feedthroughs. Used were EOMs with 33 GHz bandwidth (40 Gs/s) and small half-wave voltage (4.6 V). A DC-offset DAC allowed utilization of the full ADC dynamic range. The improved photoreceiver design allowed higher input optical powers and adjustable RF-amplification. Thus even with a 12 bit ADC a resolution of 10 fs to 13 fs was demonstrated in the range of 90 to 200 pC and 13 to 40 fs in the range of 20 to 90 pC. This measurement satisfies the specification for SwissFEL at high charge (Fig. 3). Two further improvements are due to be

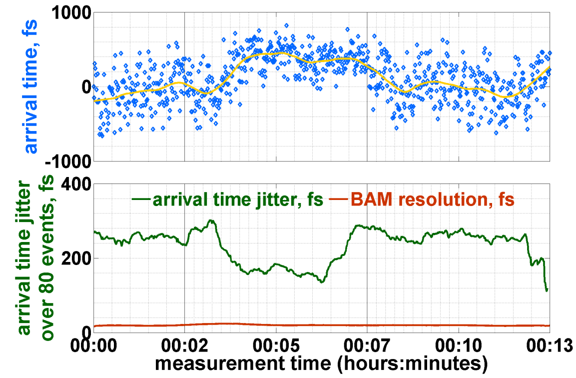

Figure 3: The bunch arrival time monitor has been used to measure arrival time jitter and drift in the SwissFEL Injector Test Facility.

tested in September 2014 before decommissionig of SITF: use of a 16 bit ADC card and a button pick-up mounted on a vacuum chamber with 16 mm inner diameter. With the utilization of the full dynamic range of the 16 bit ADC and the stronger signals of the 16 mm beampipe pick-up, at least factor 4 improvement in the resolution is expected, thus meeting the requirements for SwissFEL also for small charge.

BUNCH COMPRESSION MONITORS

Bunch Compression Monitor BC1

At the first bunch compressor of SwissFEL, the electron bunches will be compressed to a bunch duration of 250 to 500 fs. Dependent on the bunch shape and length, this implies coherent edge as well as coherent diffraction radiation up to the few THz spectral range. A bunch compression monitor (BCM) detecting relative bunch length changes is based on measuring two different spectral bands (0.26 to 2 THz and 0.6 to 2 THz) by using "thick grid" high pass THz filters and fast Schottky diodes.

The response of these detectors on accelerator parameters has been measured, applying small variations around the operating point [6]. The radiation detected behind the two filters shows a slightly different dependency on S-band and X-band phase (Fig. 4). Further investigations will aim at increasing the ratio between the two detectors, in order to achieve a linearly independent measurement of the relevant parameters.

Bunch Compression Monitor BC2

In a second magnetic chicane, the electron bunches will be further compressed to 3…75 fs. Therewith, the coherent radiation emitted by the electron bunch is extending up to the infrared spectral region. To cover the wide spectral range required, the design of a prism based spectrometer, using a mercury cadmium telluride (MCT) array as detector, is currently under investigation.

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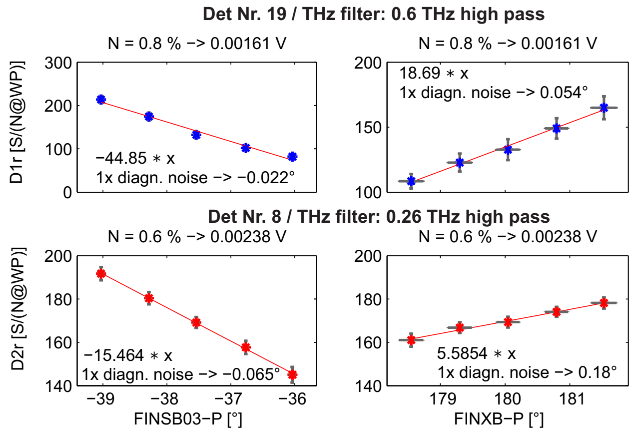

Figure 4: Measurement of the dependency of terahertz radiation in two spectral bands, as a function of S-band and X-band phases.

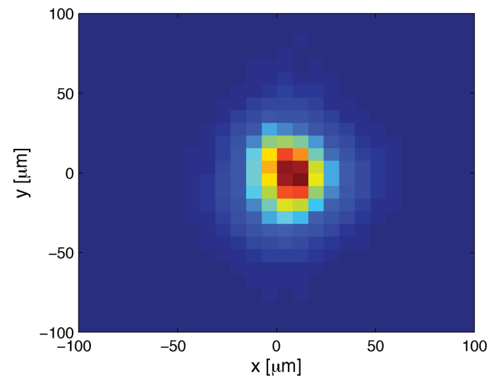

Figure 5: Measurement of a beam with 15 μm rms size.

ELECTRO-OPTICAL MONITORS

We have developed a non-invasive, compact and cost effective longitudinal profile monitor based upon the electro-optic effect. A chirped laser pulse propagates through a GaP crystal parallel to the electron beam in the beam pipe. Electric field of the electron bunch induces birefringence in the crystal. The laser light polarization is rotated proportionally to the electric field in the part of the laser pulse that temporally overlaps with the electron bunch. Polarizers convert the polarization angle into an intensity modulation, measured with a spectrometer. This modulation can be mapped into time by measuring the laser pulse chirp. Electron bunch longitudinal profiles as short as 300 fs were measured at SITF using this technique.

TRANSVERSE PROFILE IMAGERS

The transverse profile is measured by three diagnostics: screen monitors using a fluorescent crystal, synchrotron radiation monitors, and wire scanners.

The screen monitors consist of a cerium doped yttrium aluminum garnet (Ce:YAG) crystal that can be inserted into the vacuum chamber. It is imaged through an in-vacuum mirror onto a CCD or CMOS detector. The imaging is be set up with different magnifications, accounting for the change in beam size along the accelerator. In each case, the imaging is set up according to Snell's law of refraction to achieve a resolution that is not affected by the thickness of the crystal (Fig. 5), and observing the Scheimpflug imaging condition, such that a large field of view can be obtained [7].

A system to read out the cameras at the beam rate of 100 Hz has been set up [8]. It allows for a bunch-synchronous data acquisition and processing.

SYNCHROTRON RADIATION IMAGERS

In SwissFEL four synchrotron radiation monitors will be used to measure the transverse profile of the electron beam in the charge range 10. . . 200 pC. Two of them – installed in BC1 and BC2 – will monitor at 100 Hz the beam energy at 350 MeV and 2.1 GeV, respectively, and the related energy spread. The SR monitors installed in BC1 and BC2 will image in the visible the SR light emitted by the 3rd dipole of the magnetic chicane by means of CMOS cameras equipped with an f = 300 mm lens. The projected pixel size corresponds to a relative energy spread resolution of $1.13 \cdot 10^{-4}$ for BC1 and $1.54 \cdot 10^{-4}$ for BC2. In a second phase, the two SR-monitors of BC1 and BC2 will be equipped with a two-bunches camera system, to resolve the 28ns time structure of the 100Hz two-bunches train of SwissFEL. This will be accomplished with a beam splitter, internal optics and two fast switchable micro channel plate image intensifiers.

Two SR monitors will be also installed in the Aramis High-Energy Collimator and in the ATHOS switchyard to monitor the beam transverse size in the UV radiation or X-ray. The conceptual design of the SR monitors in the Aramis High-Energy Collimator and the ATHOS switchyard is under development.

WIRE SCANNERS AND LOSS MONITORS

In SwissFEL, YAG screens and wire scanners will be used to monitor the electron beam in the charge range 10. . . 200 pC and in the energy range 0.340. . . 5.8 GeV. In particular, wire-scanner will be used to resolve the 28 ns time structure of a 100 Hz two-bunches train. Design criteria of the SwissFEL wire-scanner are: use a single UHV linear stage to scan beam profile in the X,Y and X-Y directions; use Tungsten wire with different diameters 5-13 μm to ensure a resolution in the range 1.5-3.5 μm; equip each wire-scanner with spare/different-resolution wires; detect the wire-losses with scintillator fiber downstream the wire; Beam-Synchronized-Acquisition (BS-ACQ) of the read-out of both the encoder wire position and the loss-monitor; wire-fork designed for routine beam scanning during FEL operations (no beam interception with the wire-fork); wire-fork equipped with different pin-slots (distance of wire-vertex from vacuum-chamber axis: 8, 5.5, 3 mm) in order to reduce the scanning time as a function of the position of the wire-scanner along the machine. Bench and beam tests of prototypes of wire-scanner have been carried out. The results of the

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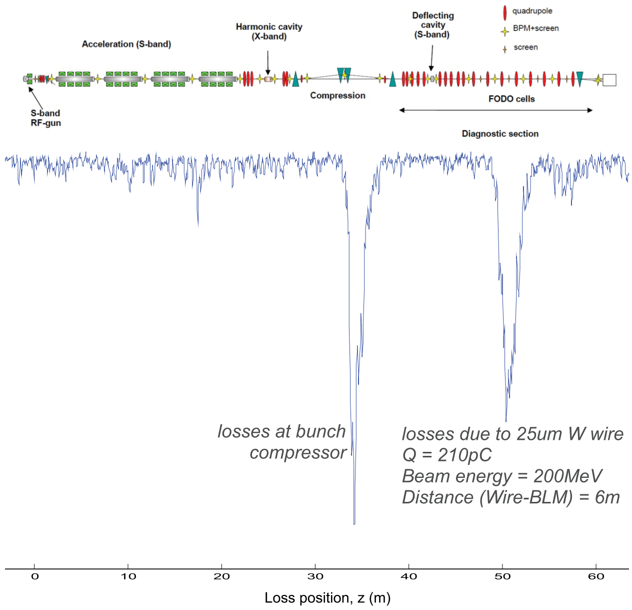

Figure 6: The longitudinal loss monitor uses the arrival time of the Cherenkov photons at the detector to infer the location of the losses.

wire vibration tests indicate that, in the wire velocity range 0.2…2 mm/s, the measured vibration of the wire is below the intrinsic resolution limit which is expected for a wire scanning the transverse profile of a beam [9]. Beam tests of wire-scanners confirmed the reliability of the wire-scanning technique in comparison with OTR screen measurements.

The interaction of the electron beam with the wire causes a scattering of the initial beam - scattered primary electrons and secondary particles which is proportional to the number of the electrons sampled by the wire. The scattered secondary particles and photons reach the Beam loss monitor mounted at a certain distance to the wire-scanner. A Beam Loss Monitor (BLM) is composed of 1mm diameter polystyrene scintillator fibers. The scintillation light is carried away from the tunnel to be detected by photomultiplier tubes (PMTs), located in the electronics racks outside, via plastic waveguide fibers. Due to the fast decay time (2 ns) of the scintillators and the fast PMTs (Hamamatsu H10720), the BLMs are able to discriminate the 28 ns time structure of the two bunches.Tests carried out at SITF show that the BLMs can detect the wire losses down to an input bunch charge of 1 pC and resolve the 28 ns time structure of the electron beam. A second system is composed of a fiber installed along the accelerator. Lost particles generate Cherenkov radiation, which is detected by a PMT at the upstream end of the fiber (Fig. 6). Measurements have also shown that beam size measured with OTR screens versus WSC scans show an excellent linearity (less than 2% deviation) and the comparison of the WSC-BLM and OTR measurements show an agreement within 8% (Fig. 7) [10].

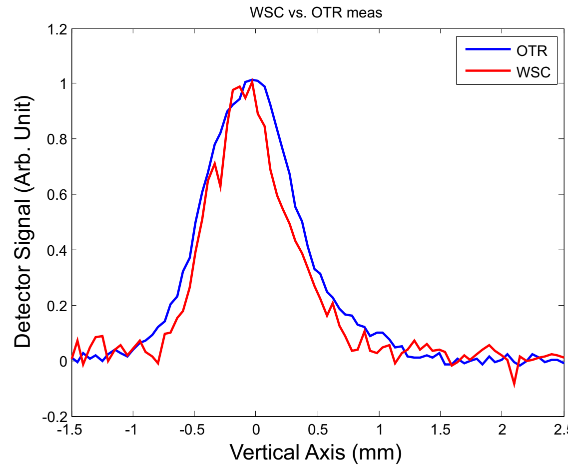

Figure 7: A measurement of beam size with a wire scanner. For comparison, the beam size measured by optical transition radiation is shown.

DOSE RATE MONITORS

The SwissFEL requires monitoring of radiation doses to prevent radiation-induced demagnetization of its in-vacuum Undulators. To this purpose, integrating dosimeters called the Radiation-sensing field-effect transistors (RADFET, RFT-300-CC10 RADFET, REM Oxford Ltd) will be placed on each Undulator flange, close to the beam pipe. Regular readings from 30 RADFETs over the years of operation of the accelerator will track and locate periods of high and low dose. A dosimetry system DOSFET-L02, developed at Elettra, allows reading out 4 RADFETs at a time [11]. The system has performed well at the SITF during the U15 test measurements, acquiring one dose reading per 20 seconds. The REM RFT-300 sensors were set in 25V bias mode, as the application of a positive bias to the sensors vastly increases their response at the expense of limiting the measurable dose range [12]. This choice of mode allows the measurement of integrated doses up to 110 Gy. The readings from the RADFET system were found to be in good agreement with Gafchromic XR-RV3 film dosimeters which were also mounted on the undulator flanges, behind the RADFETs. A measurement performed during the undulator experiment is shown in Figure 8.

X-RAY PULSE ARRIVAL TIME AND LENGTH MONITORS

The X-ray pulse arrival time and length will be measured by terahertz streak cameras in the SwissFEL end stations [13]. This device has only a small absorption, and can be placed in front of the user experiments.

The terahertz streak camera is based on the ionization of Xenon clusters that are injected into the beamline through a pulsed piezo valve. The energy of the photoelectrons is modulated by a terahertz potential generated by the experimental laser, and measured by two time of flight spectrometers, oriented at opposite sides of the chamber. Due to the time-

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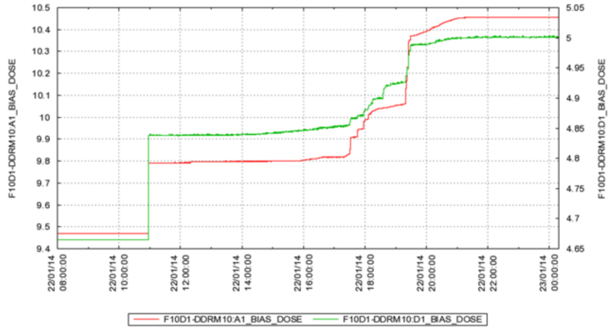

Figure 8: Measurement of dose rate at the undulator installed in Summer 2014. About half of the dose accumulated in this particular day has been deposited during two short time periods, demonstrating the need for a fast interlock system.

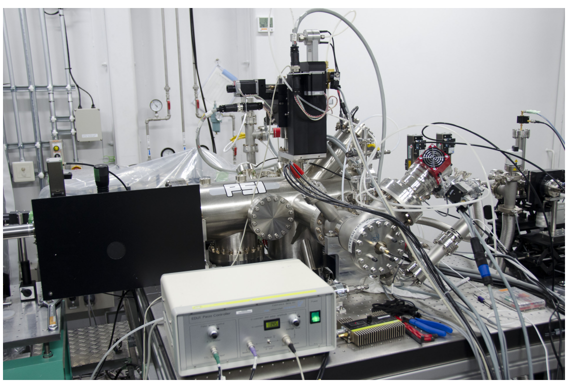

Figure 9: Installation of the terahertz streak camera at SACLA.

dependent nature of the terahertz field, an arrival time shift then manifests itself as a relative change of the electron energy in the two spectrometers. The X-ray pulse length can be measured by the width of the spectra. We have tested the prototype of the terahertz streak camera at SACLA (Fig. 9), and measured arrival time and pulse length at photon energies up to 10 keV.

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