OVERVIEW AND STATUS OF SWISSFEL DIAGNOSTICS

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Abstract

SwissFEL is an X-ray free electron laser user facility presently under construction at the Paul Scherrer Institut (PSI) in Villigen, Switzerland. All diagnostics systems have been developed and successfully tested within the baseline SwissFEL parameters, including a low charge, ultra-short pulse operation mode. The monitor designs have been finished, production is ongoing and most of the components are ready for installation. The paper will give an overview of the SwissFEL diagnostics systems, highlight some of the instrumentation developments, summarize the latest results and report on the installation and commissioning schedule.

SWISSFEL

SwissFEL is a compact free electron laser user facility presently under construction at the Paul Scherrer Institut in Villigen, Switzerland [1]. In its first project stage, which lasts from 2012 – 2017, it will provide hard X-rays with photon energies ranging from 4 to 12 keV to the three ARAMIS user end-stations [2]. In a second project stage, which is scheduled for 2018 – 2020 soft X-ray users will be served by an additional FEL line, called ATHOS [3].

Most of the SwissFEL key accelerator components (e.g. solid state modulators, C-band accelerator structures, in-vacuum undulators, as well as the optical synchronization system and also the beam instrumentation devices) have been developed and successfully tested at the SwissFEL Injector Test Facility (SITF) during the past years. The SwissFEL building is almost ready for occupation and the technical infrastructure is presently being built up, so that installation of accelerator components can start by the end of 2015 and commissioning of the accelerator complex has been scheduled for spring 2016.

The SwissFEL electron beam is generated in a 2½ cell S-band photo-injector RF gun, which provides a 7 MeV, low emittance beam with bunch charges of 10 to 200 pC at a bunch repetition rate of 100 Hz. The S-band injector LINAC, which boosts the beam energy up to 450 MeV, contains a laser heater and two X-band RF structures, located in front of the first magnetic bunch compression stage (BC-1) for linearizing the longitudinal phase space. Further acceleration to 2.1 GeV is achieved by the C-band LINAC-1, before the electron bunches are fully compressed in the second bunch compressor (BC-2) to 2.5 fs (at 10 pC) respectively 20 fs (at 200 pC). The C-band LINAC-2 and LINAC-3 are ramping the beam energy up to its final value of 5.8 GeV before the electron bunches are transferred to the hard X-ray ARAMIS FEL line. For the future ATHOS soft X-ray FEL line, a second bunch will be accelerated at a distance of 28 ns and extracted in a magnetic switchyard at beam energies of 2.4 GeV. All diagnostics components have accounted for this two-bunch option already during their design stage and beam tests have been executed at the SITF [5, 6] in

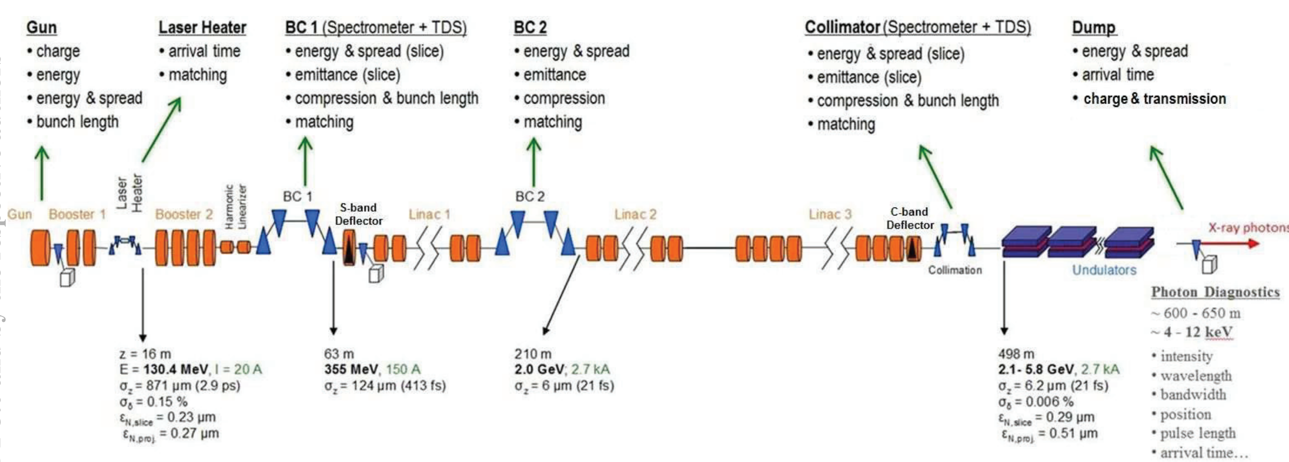

Figure 1: Schematic overview of the SwissFEL hard X-ray ARAMIS line, which will be set-up in the first project phase. Locations are indicated, where the most important beam parameters will be measured during set-up and commissioning and monitored during operation. In addition (not shown here), beam position monitors, loss and charge monitors as well as wire scanners and screens are distributed along the machine to measure transverse beam positions and profiles as well as transmission and losses. Photon diagnostics is set-up in the ARAMIS front end.

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order to resolve the SwissFEL beam parameters as listed in table 1.

Table 1: SwissFEL Key Parameters

SwissFEL Key Parameters	Operation Modes	
	Long Bunch	Short Bunch
photon energy	0.2 – 12 keV	0.2 – 12 keV
power / energy	60 µJ / 2 GW	3 µJ / 0.6 GW
electron energy	5.8 GeV (1 Å)	5.8 GeV (1 Å)
bunch charge	200 pC	10 pC
rep. rate	100 Hz	100 Hz
bunch distance	28 ns	28 ns
bunch length	20 fs (rms)	2.5 fs (rms)
comp. factors	125	240
norm. emittances	430 nmrad	180 nmrad
timing stability	jitter	drift
sync. system	< 10 fs (rms)	< 20 fs_{pp} / day
bunch arrival time	< 10 fs (rms)	< 10 fs_{pp} / day

Figure 1 provides a schematic overview of the SwissFEL facility, indicating the different locations along the accelerator where a full phase-space characterization can be performed (sliced and projected transverse emittances and energy spreads) and the longitudinal beam parameters can be measured (compression, bunch length and bunch arrival time). In addition to these dedicated measurement stations, a large number of beam position (BPM), profile (screens and wire scanners), beam loss (BPM) and charge monitors (BCM) are distributed along the accelerator to observe and control the orbit, transmission and matching. The hard X-ray ARAMIS FEL line will also be equipped with a full suite of photon beam diagnostic monitors, which provide intensity, wavelength and bandwidth, position, length and arrival time of the hard X-ray (4 - 12 keV) pulses.

DIAGNOSTICS REQUIREMENTS

Table 2 summarizes the type and number of electron beam diagnostics devices for the first stage (ARAMIS) of the SwissFEL project.

Table 2: SwissFEL Electron Beam Diagnostics Devices

Diagnostics Device	Type	Number
beam position	cavity BPMs	145
transverse profile monitors	scintillator screens	24
	wire scanners	23
	SR-monitors	3
charge monitors	Turbo ICT	4
loss monitors	scintillating (local)	38
	Cerenkov (dist.)	8
dose rate monitors	Rad-FET	32
beam arrival time	electro-optical	4
compression	THz / FIR-vis	1 / 2
laser arrival time	electro-optical	1
transverse deflector	S-band / C-band	1 / 1

The main challenges for the SwissFEL beam instrumentation are posed by the “low charge (10 pC) / short bunch” operation mode, where the diagnostics systems have to cope with low signal levels, small beam sizes, high compression factors, short bunches and stringent temporal jitter and drift tolerances. In addition, fast detection schemes and high bandwidth data acquisition systems are required for the future “two-bunch option”, which is realized in the 2nd project stage, where two bunches at a distance of 28 ns will be accelerated in a single RF pulse allowing the operation of both, the ARAMIS hard X-ray and ATHOS soft X-ray FEL lines at the full repetition rate of 100 Hz. The specific demands to the particular diagnostics systems are described below. In some cases the selected solution is shorty described and more detailed information and results are referenced, while in other cases, the latest achievements are presented in more detail in the following paragraph on diagnostics performance.

- For controlling the beam orbit and thus preserving the low emittance of the SwissFEL electron beam, the beam position monitors (BPM) should provide rms position noise of < 5 µm along the whole SwissFEL accelerator. In the undulators < 1 µm rms position noise is required in order to ensure sufficient overlap between electron and photon beam for stable SASE operation. In addition, the BPMs should provide a beam charge related signal with sufficient resolution (< 1% of the bunch charge) to monitor the overall transmission through the accelerator, serving as an input for the SwissFEL machine protection system.
- Transverse profile monitors have to provide high spatial resolution (< 10 µm rms) to allow the determination of projected and sliced emittances, the measurement of beam optics and the matching of the highly brilliant SwissFEL electron beam. Coherent optical transition radiation has to be supressed for the preferred solution of two-dimensional profile imaging with screen monitors (SCM), while one-dimensional profile information is obtained by wire scanners (WSC), which serve as a “SCM back-up solution” and which will be used for online and quasi non-destructive monitoring of transverse beam profiles and emittances (with four WSCs at 90° betatron phase advance) in the C-band LINACs. In addition, synchrotron radiation monitors (SRM) are installed in the centre of the bunch compressor chicanes to measure the transverse beam profile and thus to monitor the energy spread (and chirp) of the electron beam during compression.
- Bunch charge and transmission through the SwissFEL accelerator has to be determined with < 5% absolute accuracy and 1% resolution. Thus, one Turbo-ICT [7] per accelerator section (injector, LINAC-1, LINAC-2 and undulator region) has been installed to allow the calibration of the high(er) resolution BPM charge measurement.

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- As an input to the machine protection system, beam loss needs to be monitored along the SwissFEL accelerator, which is achieved by installing Cerenkov fibres parallel to the accelerator. In addition, local hot-spots will be surveyed with scintillating fibres, which are wrapped around the accelerator beam pipe. These very sensitive scintillating fibres are also serving as detectors for the WSC profile measurements [8]. A set of dose rate monitors (rad-FET types) [9] are installed in the undulator sections to monitor the absolute acquired dose and to make sure that radiation-induced demagnetization of insertion devices is avoided.
- Beam arrival time (BAM) information with < 10 fs rms accuracy in reference to the SwissFEL optical synchronization system is required at the bunch compressors to determine the longitudinal stability of the accelerator and to provide an input signal for a possible beam-based feedback of the previous RF stations. Behind the ARAMIS undulator, the BAM information will be given to the users for monitoring the longitudinal stability of the electron beam and for possible sorting of their experimental data. Since the temporal stability of the photo-injector (gun) laser is important to retain the injector beam parameters for stable SASE operation, an additional arrival time monitor for the gun laser (LAM) following the principle of the electro-optical BAM is presently under development. The LAM output signal will be used to monitor and improve the gun laser to accelerator RF temporal stability by providing active common mode jitter and drift suppression.
- In addition to the beam arrival time, the bunch compression needs to be monitored (preferably non-invasively) in BC-1 and BC-2 as well as in the ARAMIS collimator section, which can also be operated as an additional bunch compressor in case of the SwissFEL ultra-short pulse (sub-fs) operation mode. Different types of compression monitors (BCM) have been developed, covering the spectral ranges of coherently emitted edge (or diffraction) radiation, ranging from THz (BC-1) to NIR (BC-2 and collimator). In a possible compression feedback, the BCM outputs are used as input signals for the phase regulation of the previous RF stations to adjust and stabilize the energy chirp of the electron bunches.
- Bunch length respectively the longitudinal distribution of the SwissFEL electron bunches and the sliced beam parameters such as transverse emittance and energy spread will be measured with two different transverse deflectors (TDS). Behind BC-1, a S-band standing wave deflector will be used at beam energies of 450 MeV to control the SwissFEL injector set-up, while two C-band deflecting structures (of the SACLA RAIDEN [10, 11] type) will be installed behind LINAC-3 at full energy and compression to provide time-resolved phase space information before transporting the electron beam to the ARAMIS undulator. With an anticipated deflecting voltage of 70 MV, a temporal resolution of 2.5 fs (rms) should be achievable at full SwissFEl energy of 5.8 GeV. This is adequate to set-up the SwissFEL electron beam in the 200 pC operation mode, but may not be sufficient for the low charge / short bunch operation mode at 10 pC.

All SwissFEL diagnostics devices will be pre-calibrated such that they are able to support accelerator commissioning with slightly reduced resolution, accuracy and dynamic ranges. Beam-based alignment (e.g. of BPMs) and cross-calibration of monitors (e.g. relative charge measurement of BPMs against absolutely calibrated Turbo-ICTs or compression monitors against TDS bunch length measurements) will lead to the ultimate performance level of the diagnostics systems. For active stabilization of the SwissFEL accelerator, all monitors will finally provide signals, which will be / can be used in beam-based real-time feedbacks.

DIAGNOSTICS PERFORMANCE

The SwissFEL diagnostics systems follow a modular topology, which is divided in three blocks: optimized pick-up and detector types followed by customized and well matched (RF) front ends and a generic digital back end. Figure 2 illustrates this approach for some selected monitors.

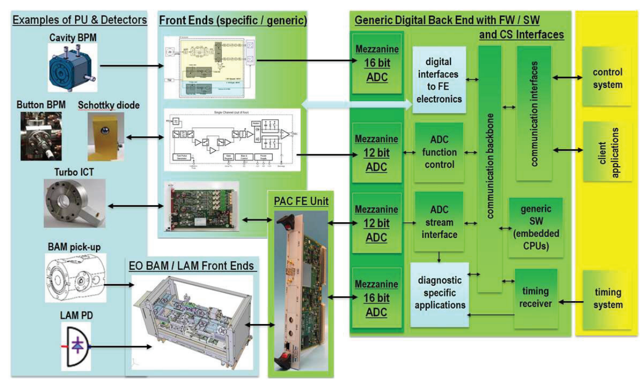

Figure 2: Schematic illustration of the modular topology of the SwissFEL diagnostics systems with specific pick-ups, detectors and customized front ends (blue) and the generic digitization and signal processing part.

The selected measurement method (e.g. electrical or optical) defines the pick-up or detector type, which is optimized to the required sensitivity and dynamic range of the detection system. The (RF) front ends provide signal conditioning for best signal-to-noise performance and adjustment of dynamic ranges. They are customized to the pick-up / detector signal type, allow (online) calibration and adjust the output levels to the optimum input of the digitizing and signal processing part of the detection system. The control of (RF) front end parameters is usually achieved by a single, generic interface (electronics board and firmware). For some of the SwissFEL diagnostics monitors with similar signal types (e.g. BAM and LAM, compression monitor and (button-type) BPMs), it was possible to make use of the same front end electronics. All SwissFEL diagnostics

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components are connected to the generic FPGA-based electronics platform (GPAC) with its fast (12 bit, 500 MS/s) and high resolution (16 bit, 160 MS/s) digitizers as well as its generic communication interfaces to the timing, control and feedback systems. In this way most of the (generic) firmware and software of the GPAC platform is re-used by every diagnostics system, while only the monitor-specific interfaces and applications have to be adapted to the particular pick-up / detector and (RF) front end combination. A more detailed overview of this signal processing concept for SwissFEL diagnostics is given in [12] and a specific example for the loss and charge monitors is introduced in [8].

A more detailed description of the design approach and the latest results and achievements of some SwissFEL diagnostics systems are given in the following sections.

Beam Position Monitors

In order to satisfy the high demands on orbit stability at low bunch charges, cavity-type BPM pick-ups have been selected for the entire SwissFEL accelerator. The pick-ups have three different apertures: 38 mm diameter behind the gun, in the bunch compressors and the beam switchyard to the soft X-ray FEL line (ATHOS), 16 mm diameter in the injector, LINACs and transfer lines and 8 mm in the ARAMIS and (future) ATHOS undulators. While the BPM-38 and BPM16 pick-ups are a low-Q (40) stainless steel design with a resonant frequency of 3.3 GHz to accommodate for the SwissFEL "two-bunch operation mode", the undulator BPM-8 pick-ups have been designed in a special stainless steel / copper sandwich structure to provide a high quality factor (1000) at 4.9 GHz. This design approach has been chosen to achieve the best performance for single bunches in the SwissFEL FEL lines. The rms position resolution of the BPM-38 has been measured to be < 10 µm over a measurement range of ± 10 mm. The BPM-16 provides < 5 µm rms position noise over a measurement range of ± 5 mm and the first (not yet optimized) prototypes of the undulator BPMs (BPM-8) have achieved < 1 µm rms position noise over a limited measurement range of ± 500 µm. All BPMs provide excellent charge noise of about 10 fC, which is extracted from the monopole cavity signal. The BPM electronics is based on the PSI design for the European XFEL using the latest FPGA technology (Kintex-7/Artix-7). While the LINAC BPM electronics makes an IQ down-conversion of the BPM pick-up signal to base-band followed by digital post-processing and local oscillator (LO) feedback, the higher frequency undulator BPM signals are first down-converted to an intermediate frequency (IF) followed by a digital down-conversion stage to base-band. A more detailed description of the SwissFEL BPM system with its latest achievements can be taken from [13].

Transverse Profile Monitors

Scintillating screen monitors and wire scanners are used for transverse profile measurements along the SwissFEL accelerator. While the SCMs provide two-dimensional profile information in a single-shot, the WSCs can be used during accelerator (possibly also SASE) operation to monitor one-dimensional profiles and transverse beam emittances in the background. Both monitor types can be used at low charges (10 pC) and have achieved < 10 µm spatial resolution. The SCM design follows the Scheimpflug imaging principle so that a large region of interest (RoI) can be observed without depth-of-field issues. The tilted CMOS sensor (15°) of the camera provides 1:1 imaging and avoids astigmatism. YAG (or LuAG) scintillator crystals are used instead of optical transition radiators (e.g. Al or metallized Si) and the beam profiles are observed according to Snell's law of refraction so that electron beam sizes can be imaged, which are much smaller than the scintillator thickness. A more detailed description of the SwissFEL SCM design and results of test measurements from LCLS proofing their COTR immunity have been presented in [14].

The SwissFEL wire scanners have been tested and optimized in a series of measurements at the FERMI FEL facility in Trieste. Profile measurements with the required spatial resolution and sufficient sensitivity have recently been made by using Al:Si wires of 12.5 µm thickness. It is planned to move the wires continuously through the beam while applying a beam-synchronized readout of the wire position (encoder) to retrieve the profiles. The WSC detection system is identical to the SwissFEL beam loss monitors and described in more detail in [8].

Compression Monitors

Coherent edge radiation (CER) from the 4th bending magnet of both bunch compressors BC-1 and BC-2 will be used to obtain a signal, which is related to the compression of the electron bunches. For nominal bunch lengths of a few hundred femto-seconds in BC-1 (250 to 500 fs rms), the detected CER spectrum falls into the THz range. Two signal paths are equipped with THz high-pass filters and broadband Schottky diodes to obtain the best sensitivity for the different bunch lengths and to allow for the SwissFEL "two bunch operation" at bunch distances of 28 ns. The signals from the highly sensitive Schottky detectors are processed in a button-type BPM electronics (as also used for the European XFEL button BPMs), which provides sufficient signal-to-noise (in the order of 0.5%) for bunch charges as low as 10 pC, thus fulfilling the stability requirement for a phase feedback of the upstream S-band or X-band RF stations. The CER emission in the bunch length range behind BC-2 (2 to 20 fs rms) falls in the FIR to NIR spectral range (30 to 1µm) so that liquid nitrogen cooled MCT detectors have to be used. For the SwissFEL BC-2 compression monitor, a KBr prism spectrometer with a 32-channel MCT detector array is presently under design. It will be set-up in the technical gallery, where the CER will be transported through an optical transfer line.

Beam and Laser Arrival Time Monitors

SwissFEL is following the design of an electro-optical beam arrival time monitor, which was originally

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developed at DESY [15]. It correlates the signal of a high bandwidth pick-up with the laser pulses of the highly stable optical reference distribution (< 10 fs jitter and drift) in an electro-optical modulator. In order to accommodate for the low charge SwissFEL beam (10 pC) a high-bandwidth (40 GHz) pick-up has been developed in collaboration with DESY and TU-Darmstadt. In addition, further improvements and optimizations on several critical BAM components such as EO modulator, RF cables etc. as well as in the BAM front end box and data acquisition system (using the GPAC-based digital back end) could be implemented in the latest SwissFEL BAM design, so that the required time resolution of < 10 fs over the whole dynamic range (200 to 20 pC) can be expected for SwissFEL (7 to 13 fs resolution have already been shown at the SwissFEL Test injector Facility from bunch charges between 30 and 200 pC) [16].

A laser arrival time monitor (LAM) for the SwissFEL gun laser following the BAM principle is presently under design. It uses a high speed UV photo-diode, which has been optimized for minimal AM/PM conversion to detect the UV gun laser pulses. Its signal is then correlated with the pulses from the highly stable optical reference distribution system in an electro-optical modulator. This approach has been selected, since it is expected to be much more robust than a spectrally resolved auto- or cross-correlator but promises to provide the required high resolution (10 fs) and covers at the same time a large measurement range of several tens of pico-seconds. All LAM components have been tested, a demonstrator is expected by the end of 2015 and a first operational prototype will be installed in Q2/2016 to support the SwissFEL injector commissioning.

STATUS AND OUTLOOK

All SwissFEL diagnostics monitors have achieved the performance requirements and will be ready for commissioning of the first project stage (ARAMIS) starting in spring 2016. Full integration in the new SwissFEL control system is still ongoing and integration of the monitor signals in beam-based feedbacks will be realized in the first stage of the SwissFEL user operation. Presently, new ideas for measurement of ultra-short electron bunches are under considerations, such as THz streaking of the X-ray pulses [17] and electron bunches [18] as well as the development of a “plasma peak current” monitor [19].

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