ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-MOPWC03

COMMISSIONING RESULTS AND FIRST OPERATIONAL EXPERIENCE WITH SwissFEL DIAGNOSTICS

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Abstract

SwissFEL is a free electron laser user facility at the Paul Scherrer Institute in Villigen, Switzerland designed to provide FEL radiation at photon energies ranging from 0.2 to 12 keV. Beam commissioning of the hard x-ray line ARAMIS has started in October 2016 and first lasing at 300 eV was achieved in May 2017. First pilot user experiments at photon energies ≥ 2 keV are foreseen for the end of 2017. This contribution comprehends commissioning results and first operational experience of various SwissFEL diagnostics systems, such as beam position monitors, charge and loss monitors as well as transverse profile measurements with screens and wire scanners. It also provides first results from the BC-1 compression monitor and summarizes the status of the electron and laser bunch arrival time monitors.

STATUS OF THE SWISSFEL PROJECT

The compact free electron laser user facility SwissFEL is presently under commissioning at the Paul Scherrer Institute (PSI) in Villigen, Switzerland. In its first project stage, the installation of the hard X-ray branch ARAMIS, which is designed to provide linearly polarized SASE radiation at photon energies between 2 and 12 keV to three user end stations, has been completed and the accelerator has been equipped with all required beam diagnostics systems. The soft X-ray branch ATHOS, which will deliver variably polarized radiation at photon energies between 0.2 and 2 keV, will be realized during a second construction phase during 2018 and 2020. All diagnostics systems for the ATHOS bypass line have been designed and successfully tested and most of the components are already ordered.

Since the delivery schedule for the solid-state modulators of the C-band LINACs drives the SwissFEL commissioning schedule, a staged commissioning approach has been chosen.

- In August 2016 first electrons at beam energies of 7.9 MeV have been generated by the 2 ½ cell S-band photo-injector RF gun and transported to the injector beam dump, including the first successful acceleration through one of the LINAC-1 C-band accelerator modules.
- In November 2016 first beam has been transported through the ARAMIS undulators with achievement of first lasing at 24 nm with moderate beam energies of 345 MeV, just in time for the SwissFEL inauguration ceremony on December 5th 2016.
- After a two months winter shut down, where some final installation and consolidation work was done, first SASE lasing in the nominal SwissFEL wavelength range (0.1 – 5 nm) could be achieved at 4.1 nm mid of May 2017. The electron beam energy was set to 910 MeV at bunch charges of 145 pC and bunch length of 400 fs (rms).

The accelerator set-up for lasing included careful optimization of the RF gun and photo-cathode laser operating points, transverse beam optics measurements and matching in the injector, tuning of the first bunch compressor (BC-1) with the S-band deflecting cavity, implementation of the computed beam optics in the LINACs and undulators and steering of the beam according to the BPM centres. Figure 1 shows the FEL gain curve at 4.1 nm, which was measured with a Neon gas photon intensity monitor.

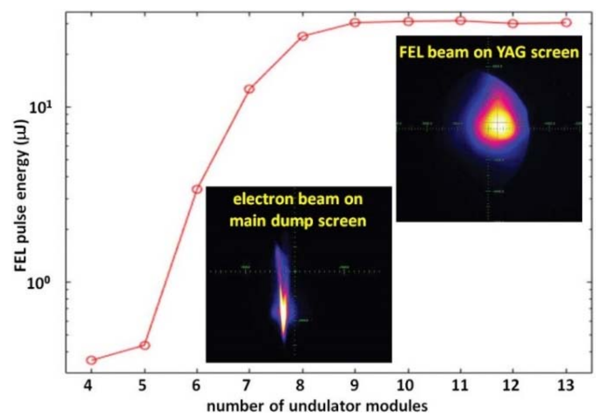

Figure 1: Gain curve for first lasing at SwissFEL at 4.1 nm. The inlets show the FEL beam on an ARAMIS front end YAG screen and the electron beam on the main dump screen monitor (LYSO screen).

After the first lasing attempts, which demonstrated the operability of most of the SwissFEL sub-systems, the commissioning is ongoing, presently focusing on the set-up of the bunch compression stages, beam optics matching and further characterization and calibration of diagnostics systems with beam. With further increase in beam energy by consecutively adding more C-band accelerator stations, a first pilot ("friendly user") experiment at photon energies ≥ 2 keV is envisaged for the end of 2017.

DIAGNOSTICS COMMISSIONING

Although the performance of the diagnostics monitors could be successfully demonstrated at the SwissFEL Injector Test Facility [1] and the front end, data acquisition and

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data processing parts of the measurement systems has been implemented on generic electronics platforms [2, 3], the control system interfaces (e.g. motion control and bunch synchronous data reading) had to be adapted to the newly developed SwissFEL control system standards [4].

Table 1: Beam Diagnostics Devices for ARAMIS

Diagnostics Device	Type	Number
beam position	cavity BPMs	119
transverse profile monitors	scintillator screens	21
	wire scanners	22
	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

Prior to their timely installation in the SwissFEL technical gallery, the final hardware and firmware configurations of the diagnostics systems were calibrated in the laboratory, so that the beam commissioning activities could be supported from the beginning. A list of the ARAMIS beam diagnostics devices is given in table 1.

Beam Position Monitors

A total of 119 cavity beam position monitors (CBPM) with apertures of 38 mm (7), 16 mm (88) and 8 mm (24) have been installed in the SwissFEL ARAMIS branch. All LINAC and transfer line pick-ups, which have to measure two (or more) bunches with 28 ns bunch spacing, are made of stainless steel with a low quality factor ($Q_L \sim 40$) at a working mode frequency of 3.3 GHz, while the undulator pick-ups, which will only be operated in single bunch mode, have been designed with a massive copper core brazed into an outer frame of stainless steel, resulting in a high quality factor ($Q_L \sim 1000$) at a frequency of 4.9 GHz. The BPM electronics uses the same modular digital back end for all BPMs in combination with customized RF front ends, applying IQ down-conversion to baseband for the low-Q CBPM-38 and CBPM-16 and mixing to an IF frequency of 133 MHz for the high-Q CBPM-8. Both, pick-up and electronics designs have been described in more detail in [5, 6, 7, 8, 9, 10].

The laboratory pre-calibration of the BPMs was sufficiently good to provide beam position and charge readings for threading the beam through the accelerator and the ARAMIS undulator into the main beam dump including orbit corrections to a 10 μm level. Beam-based calibration and further optimization by elimination of systematic effects is presently ongoing. The position resolution has been determined to 8 μm * pC for the 3.3 GHz low-Q BPMs and 5 μm * pC for the high-Q 4.9 GHz BPMs, which results to sub-μm resolution at 10 pC bunch charge and a few 100 nm at higher charges. The noise for the charge readings is at 0.07% for the low-Q BPMs and at 0.04% for the high-Q BPMs, which corresponds to 5 fC and 2 fC respectively.

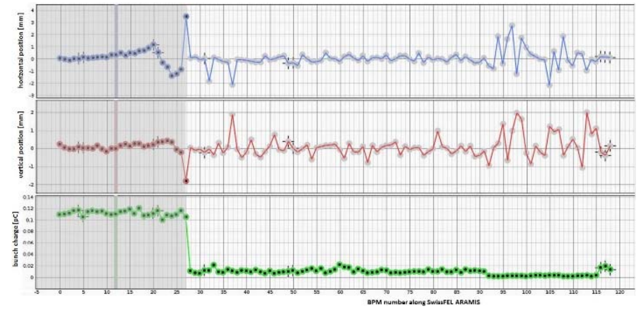

Figure 2: Display of BPM readings along SwissFEL ARAMIS. The beam is transported in the injector beam dump (grey area). Note that the bunch charge is 120 fC. The downstream BPM charge readings (white area) indicate the offset and noise levels of the low-Q CBPM-16 (no. 28 to 91 / 116 to 118) and the high-Q CBPM-8 (no. 92 to 115).

More detailed and elaborated status reports on the SwissFEL BPM commissioning are given in [11, 12]. Figure 2 shows a screen shot of the control room display of the beam position and charge readings for beam transport to the injector beam dump for very low bunch charges of 120 fC.

Charge and Loss Monitors

The charge and loss measurements provided crucial information on beam transmission during the early SwissFEL commissioning phase, where the different accelerator sections were progressively set-up. For the ARAMIS accelerator lines, a total of four Turbo-ICTs with BCM-RF electronics [13] are installed behind locations, where beam loss can occur. The Turbo-ICTs have been absolutely calibrated at the company to a 4 % level [14] and thus used for cross-calibration of the BPM charge readings, which are providing an accurate transmission mapping through the SwissFEL accelerator (lower part of Fig. 2). The Turbo-ICTs single-shot and integrated charge readings (e.g. over one hour) are also used for controlling pre-defined accelerator commissioning modes, where pre-set charge threshold values in the ICT firmware generate interlock signals for the SwissFEL machine protection system (MPS).

The longitudinal beam loss monitors (LBLM), which are based on glass fibres pulled along the accelerator and photo-multiplier read out [15], are also fully integrated in the SwissFEL MPS, providing interlocks and alarms (to the control room), when the beam loss exceeds the pre-defined threshold values. The MPS is then adjusting the bunch repetition rate such that the overall beam loss is kept below an acceptable level.

Screen Monitors

The SwissFEL screen monitors (SCR) have been designed to provide high spatial resolution (≤ 10 μm) for low bunch charges (≤ 10 pC) without being affected by coherent optical transition radiation [16], which is emitted by micro-bunched structures in highly brilliant electron beams. All 21 SCRs in the SwissFEL ARAMIS branch

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have been equipped with YAG:Ce (Cer-doped Yttrium-Aluminium-Granat) and LYSO (Lutetium-Yttrium –Oxyorthosilicate) scintillators. They have been calibrated and successfully commissioned with the "*CamTool*" application, which provides SCM control and beam synchronous display of beam images. Although, linearity and saturation studies are still ongoing, the SCMs have been integrated in automated emittance measurements, which allow beam optics matching and optimization of different SwissFEL operation modes.

Wire Scanners

The SwissFEL wire scanners (WSC) are equipped with two pairs of wires of different thickness and material: 5 µm tungsten (W) wires for high resolution measurements and 12.5 µm Al(99):Si(1) wires for routine monitoring [17]. During WSC measurements, the wire-fork is continuously moved through the beam by means of a motorized UHV linear-stage, while the wire position is beam synchronously read out with an incremental optical encoder (0.1 µm resolution). Correlation of the encoder read out (wire position by presence of beam) with the signal from a nearby beam loss monitor (BLM) allows the reconstruction of the beam profile. In addition, the position and charge readings of two adjacent BPMs, located upstream and downstream of the WSCs, permits correction of the beam profile measurement by possible error due to charge and position jitter.

Beam commissioning of the overall 22 SwissFEL ARAMIS wire scanners is presently ongoing. Apart from a basic functionality check of all sub-systems, it includes the selection of the most suitable BLM and its PMT gain settings for the different SwissFEL operation modes with 10 pC up to 200 pC bunch charges [18].

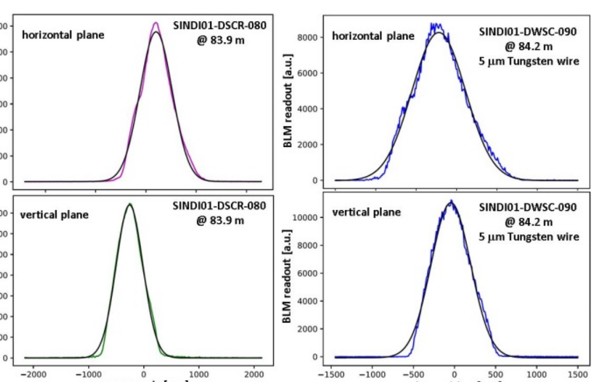

Figure 3: Comparison of transverse beam profile measurements with a LYSO screen monitor (left side) and an adjacent wire scanner (right side) in the SwissFEL injector at a bunch charge of 20 pC.

Comparative beam profile measurements with a wire scanner (5 µm tungsten) and a near-by screen monitor (LYSO scintillator) at bunch charges of 20 pC are shown in Fig. 3. After considering the differences in the β-functions at the locations of the screen and the wire scanners and correcting for the transverse beam jitter of ~ 4 µm (rms) during the WSC measurements by including the adjacent BPM readings in the profile analysis (charge variations were negligible), a horizontal rms beam size of 327 µm ± 3 µm and a vertical rms beam size of 238 µm ± 2 µm could be obtained with the wire scanner, which is in good agreement with the rms profiles measured with near-by SCM of σ_h = 319 µm ± 3 µm and σ_v = 240 µm ± 2 µm.

BC-1 Compression Monitor

The proper set-up of the first SwissFEL bunch compression stage (BC-1), which has been designed to provide nominal rms bunch lengths of a few hundred femto-seconds (223 fs at 10 pC bunch charge and 290 fs for 200 pC), is observed by a compression monitor (BCM), which uses coherent edge radiation (CER) from the 4th BC-1 bending magnet. The THz intensity is split into two signal paths, which are equipped with two different high-pass filters at 0.3 and 0.6 THz and broadband Schottky diodes, covering the whole spectral range of interest (0.3 - 2 THz). Relative CER intensity variations, which correspond to bunch length or bunch profile changes, are related to the amplitude and phase settings of the off-crest operated S-band (SINSB-03, SINSB-04) RF stations and the X-band (SINXB-01) linearizer at the end of the SwissFEL injector (upstream of BC-1).

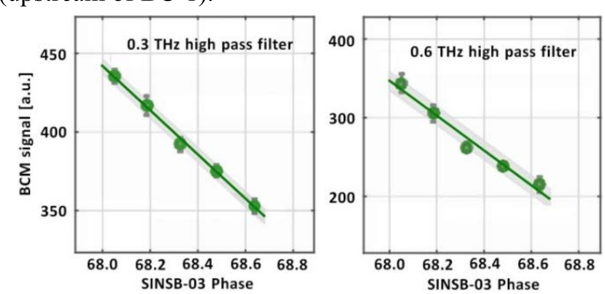

Figure 4: BCM output signals with respect to the phase settings of the off-crest operated S-band structure SINSB-03. Left side: CER signal path equipped with a 0.3 THz high-pass filter, right side: 0.6 THz high-pass filter.

In preparation of the first systematic bunching studies, the BCM signals were optimized by aligning the CER optical paths to the selected BC-1 compression angle and by eliminating initial ringing of the Schottky diode signals with THz absorption material in the BCM chamber. For determination of the BCM sensitivity on electron bunch length changes, the BC-1 compression factors were scanned between 4 and 4.4 (the nominal BC-1 compression factor for SwissFEL user operation will be set to 10) by using an automated "compression scan tool" [19]. It varies the off-crest phases of the last two S-band structures in the injector (SINSB-03 and SINSB04) simultaneously, while keeping the beam energy constant through readjustment of the SINSB03 and SINSB04 RF amplitudes. For this BCM commissioning run, the X-band linearizer phase was kept constant. During the compression factor scans the electron bunch length was measured with the S-band deflecting cavity, which is located directly behind BC-1. It varied between 560 and 610 fs (rms). In parallel, the BCM outputs

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from both CER signal paths were recorded for different phase settings of the off-crest operated S-band structures around 68° (90° corresponds to on-crest acceleration). The BCM signals with respect to the SINSB-03 phase settings are shown in Fig. 4.

From the first commissioning shifts, it can be concluded, that the BCM sensitivity with respect to the SINSB-03 phase settings is already close to the resolution, which will be required to monitor and stabilize the off-crest S-band phases in case of the nominal operation of the first SwissFEL compression stage. The grey areas around the measurement points of the SINSB-03 phase scan in Figure 2 indicate a BCM phase sensitivity of 0.03° for the CER optical path with the 0.3 THz high-pass filter and 0.05° for the optical path equipped with the 0.6 THz high-pass filter. Further BCM studies are foreseen after the SwissFEL summer shut-down to optimize the THz filters to the nominal compression factors of BC-1 such that bunch length changes caused by S-band phase fluctuations as well as bunch shape variations caused by phase jitter of the X-band linearizer can be detected.

Electron Bunch Arrival Time Monitor

Key components of the bunch arrival time monitor (BAM), which was already successfully tested at the SwissFEL Injector Test Facility [20, 21], were subject to improvements, aiming for sub-10 fs resolution at low (10 pC) bunch charges. In addition, adaptations of the original design, accounting for space limitations and newly developed controls hardware for SwissFEL were made and the BAM user interface and data readout, including automated stabilization and control applications was improved for more user-friendly operation form the control room. Details on the latest SwissFEL BAM design are reported in [22]. For the first phase of the ARAMIS commissioning, two BAM stations have been installed so far. Beam commissioning is foreseen for September 2017 in view of the first "pilot user experiments", where the electron beam arrival time information will be taken into account for improving the overall time resolution.

Gun Laser Arrival Time Monitor

A balanced optical cross correlator (BOXC) based on two LBO crystals in type II phase matching and in collinear arrangement (single colour of 1040 nm, orthogonal polarization) is employed to measure the arrival time of laser pulses at the gun laser amplifier output against the oscillator pulses, which act as a local time reference. The resulting error signal gives the single shot variation in arrival time and in closed loop operation feeds back to a continuously variable optical delay stage to compensate for drift in the amplifier and in free space path caused by changes of environmental parameters like e.g. temperature and humidity (controlled to 24°C ± 0.1°C and 42.5% ± 2.5%) as well as air pressure (unregulated). With laser arrival time feedback on, the amplifier output is stabilized to below 10 fs rms (or < 50 fs peak-peak) over 1000 shots as shown in Fig 5. Without the arrival time feedback running, drifts in excess of 12 ps over 24h have been observed.

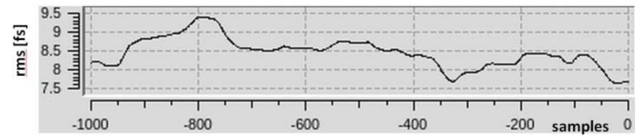

Figure 5: Display of SwissFEL gun laser stability behind its amplifier (1000 shots) with running IR/IR LAM feedback based on a BOXC.

This laser arrival time feedback loop includes the regenerative optical amplifier with an integrated optical path length of 1.3 km that is significantly longer than the combined remaining optical path for the UV generation and transfer line from the laser output to the photo-injector gun in the accelerator tunnel. Thus, the most significant sources of drift are already compensated with this BOXC-based IR/IR LAM feedback.

As in the current configuration the IR to UV conversion stage, the pulse-stacking scheme and the transfer line to the gun cathode are still out of loop, a UV/IR laser arrival time monitor (LAM) located next to the gun photocathode will be set-up in a next step to measure the UV pulses (260 nm) from the gun laser directly against the optical reference (1560 nm), which is delivered to the LAM location via a stabilized optical link. This LAM upgrade will include the entire gun laser chain (oscillator locked against the optical master oscillator, amplifier, UV conversion, pulse stacking and optical transfer line to gun photo cathode). The feedback will then provide the required SwissFEL gun laser stability of 40 fs (rms) for stable user operation.

SUMMARY AND OUTLOOK

Timely installation, pre-beam commissioning and precise laboratory calibration have made the SwissFEL ARAMIS diagnostics monitors valuable systems for beam property measurements since the first day of operation and supported beam optics commissioning as well as the first successful lasing attempts at SwissFEL. So far, all diagnostics systems fulfil or exceed the SwissFEL requirements, although improvements of absolute charge readings in case of the Turbo-ICTs and saturation studies of screen monitors are still pending but foreseen for the near future. More elaborate studies of systematic effects and limitations of the diagnostics monitors will be carried out side by side with the ongoing beam commissioning of all SwissFEL operation modes, so that the implementation of beam-based feedbacks should be possible in time for the start of the nominal user operation.

ACKNOWLEDGEMENTS

The timely provision and successful commissioning of the SwissFEL diagnostics systems has of course been a collaborative effort of the Diagnostics Section together with many other groups at PSI. Without explicitly naming individual people, we would like to thank many of our colleagues in the divisions of mechanical engineering, vacuum, electrical infrastructure, planning and installation, controls, beam dynamics and operations.

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