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FIRST EXPERIMENTAL RESULTS OF THE COMMISSIONING OF THE SwissFEL WIRE-SCANNERS

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Abstract

Several wire-scanners - 19 out of 22 - are presently installed in SwissFEL, the hard X-ray FEL facility under commissioning at Paul Scherrer Institut (www.psi.ch). Thanks to a wire-fork designed to be equipped with two different pairs of scanning wires (5 μm tungsten and 12.5 μm Al(99):Si(1)), high resolution measurements of the beam profile - and emittance - and, alternatively, a minimally-invasive beam monitoring during FEL operations can be performed. First experimental results of the SwissFEL wire-scanner commissioning will be presented as well as a summary of the prototyping design and characterization.

INTRODUCTION

SwissFEL is a Free Electron Laser (FEL) facility [1] presently under commissioning at Paul Scherrer Institut (www.psi.ch). Two undulator lines - so called ATHOS and ARAMIS - will provide X-rays pulses at a repetition rate of 100 Hz in the wavelength region $7-0.7$ nm and $0.7-0.1$ nm, respectively. The SwissFEL linear accelerator is a compact machine - the length of the entire facility including photon transfer lines and experimental hall is about 720 m - with a relatively moderate beam energy: 5.8 GeV being the maximum energy required to reach the saturation regime of coherent radiation emission in the given wavelength range. In order to meet such constraints of compactness and energy, the beam acceleration is mostly ensured by a C-band RF linac and the compression scheme is optimized to preserve the high brightness quality of the electron beam, which is characterized by a transverse normalized slice emittance of 0.4/0.2 mm.mrad for the two nominal charge operation modes 200/10 pC of the machine. The electron beam - emitted by a photo-cathode with an initial bunch length of 3/1 ps (rms) and with a two-bunch temporal macrostructure of 28 ns - is accelerated by a 2.5 cell S-band gun up to 7.1 MeV at a repetition rate of 100 Hz. The further acceleration of the electron beam is performed by a S-band RF linear booster - up to 330 MeV - and by a C-band linac up to $2.1-5.8$ GeV. During the transition from the S-band to the C-band RF sections, the S-Band induced energy chirp of the electron beam is linearized by a pair of X-band RF cavities and converted to a longitudinal compression of the electron beam - 300/200 fs (rms) - by a magnetic chicane. After a further compression stage in a second magnetic chicane - 20/3 fs (rms) - at a beam energy of about 2.1 GeV, an RF kicker and a magnetic switch-yard deviate the orbit of the second bunch of the two-bunch train from the ARAMIS arm to the ATHOS arm. After a further acceleration stage, the two bunches are separately injected at 100 Hz into the two undulator lines (ARAMIS and ATHOS).

In a FEL driver linac, wire-scanners (WSCs) [2, 3, 4, 5] complement view-screens to monitor the beam profile monitor. Compared to view-screens, WSCs are normally immune to non-linear effects of the signal response and can perform high resolution measurements which ultimately depends on the wire diameter and scanning speed. In SwissFEL, the WSCs are designed to absolve two main tasks [6, 7]: high resolution characterization of the beam profile for high precision measurement of the beam emittance and a routinely and minimally-invasive monitoring of the beam profile under FEL operations. Moreover, because of the afterglow characterizing the YAG:Ce crystals of the view-screens, in SwissFEL only WSCs can discriminate in time the two-bunch temporal macrostructure (28 ns) of the electron beam. The SwissFEL wire-fork is motorized by a stepper motor and equipped with two pairs of metallic wires, see Fig.1: 5 μm tungsten (W) and 12.5 μm Al(99):Si(1). As the wire scans the beam, a shower of primary scattered electrons and secondary emitted particles is produced in proportion to the fraction of the beam sampled by the wire. In SwissFEL, the forward - high energy and small scattering angle - component of the particle shower ("wire-signal") is out-vacuum detected by means of Beam-Loss-Monitors (BLMs) [8]. The beam-synchronous acquisition (BSREAD) [9] of both the encoder and the BLM readouts permits to reconstruct the one-dimensional transverse profile of the electron beam. The beam-loss sensitive material of the BLMs is a scintillator fiber (Saint Gobain BCF-20, decay time 2.7 ns) wrapped around the vacuum pipe. The scintillator fiber is matched by means of a Plastic Optical Fiber (POF) to a photomultiplier (PMT) having a remotely adjustable gain in the range $5 \times 10^3 - 4 \times 10^6$. The PMT signal is finally digitized and integrated in time by an ADC unit. In a WSC measurement, together with the signals from the encoder and the BLM, also the charge and position signals from Beam Position Monitors (BPMs) upstream and downstream the WSC are BSREAD acquired at every RF shot in order to correct the reconstructed beam

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profile by possible errors due to a charge and transverse jitter of the electron beam.

A total of 22 wire-scanners (WSCs) will be operated in SwissFEL: 19 of them belong to the ARAMIS section of the machine which is presently under commissioning. In the present proceeding, first results of the commissioning of the SwissFEL WSCs will be presented as well as details about the prototyping work.

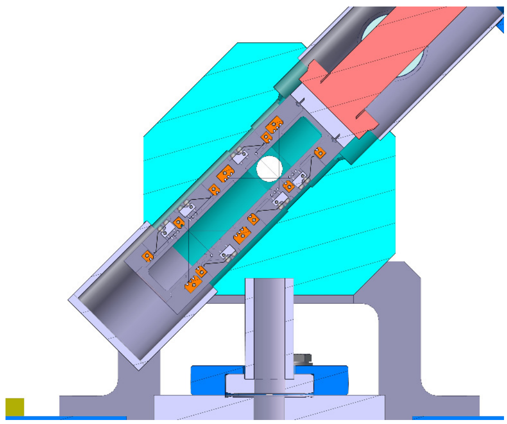

Figure 1: Section view of the SwissFEL WSC fork in the vacuum chamber.

MEASUREMENT SET-UP

The measurement set-up of the SwissFEL WSC composes of an in-vacuum beam-probe and an out-vacuum pick-up of the "wire signal".

About the wire-signal detection, this is out-vacuum performed by a BLM - see previous section - which is placed downstream the WSC at an optimum distance in the range from 3 to 6 m according to the indications drawn from the beam tests carried out at the 250 MeV SwissFEL Injector Test Facility (SITF, Paul Scherrer Institut, CH) and at FERMI (Elettra-Sincrotrone Trieste, Italy) [6]. For more details about BLMs, refer to [8].

The WSC in-vacuum system is composed of a planar wire fork motorized by a Ultra-High Vacuum (UHV) linear stage which is equipped with a 2-phase stepper motor (2-phase, 1.8deg/step, 200steps/turn) and an incremental optical encoder (0.1 $\mu\mathrm{m}$ resolution), see Fig.1. The wire-fork axis forms 45^o with respect to the vertical direction. The wire-fork can be equipped with two pairs of wires scanning the beam either along the horizontal direction (X) or the vertical one (Y), each wire being oriented + or - 45^o with respect to the fork axis. The wire holder in the fork is suitably designed for metallic wire. The metallic wire can be indeed fixed between two pins and submitted to a slight mechanical tension thanks to a metallic spring. Thanks to the applied tension, the frequency band of the oscillation eigenmode of the fixed wire can be maintained above the low frequency stepper-motor induced vibrations of the wire-fork. About the choice of the most suitable wire material, this was initially suggested by the consolidated experience of other FEL facilities where tungsten wires are normally used because of the excellent robustness to the thermal loading (melting point, about 3400 ^oC) and to the mechanical stress (tensile strength, about 1900 MPa). Tungsten wires with a diameter of 5 $\mu\mathrm{m}$ (geometrical resolution of about 1.3 $\mu\mathrm{m}$) were finally selected for the wire pair supposed to be employed in high resolution measurements of the beam profile and emittance in SwissFEL. The choice of the second pair of wires - to be possibly used for minimally invasive monitoring of the beam profile under FEL operations - was not straightforward and conventional. The tricky question was to find a metallic material for the wire that could be able to ensure, on the one hand, a sufficiently high beam and mechanical robustness and, on the other hand, to have a sufficiently low density and Atomic number to minimize as much as possible the beam-losses. After a work of investigation and test of possible candidate materials, 12.5 $\mu\mathrm{m}$ Al(99):Si(1) wires were finally selected. Compared to pure aluminium, this alloy shows a similar melting point (about 600 ^oC) but a much higher tensile strength (about 300 MPa) which is beneficial to the mechanical strength and elasticity of the wire. Both wire solutions - 5 $\mu\mathrm{m}$ tungsten and 12.5 $\mu\mathrm{m}$ Al(99):Si(1) wires - were tested at high charge and energy at FERMI [6]. Experimental results of the beam tests confirmed the suitability of the proposed choice as well as a strong reduction of the beam losses when scanning the beam with a 12.5 $\mu\mathrm{m}$ Al(99):Si(1) wire instead of a 5 $\mu\mathrm{m}$ tungsten wire. Compared to a 5 $\mu\mathrm{m}$ tungsten wire, a drastic reduction of a factor 11 was observed in radiation dose-rates measured by the ionization chambers of the FEL1 undulator line at FERMI when scanning the beam (charge of 700 pC and energy of 1.325 GeV) with a 12.5 $\mu\mathrm{m}$ Al(99):Si(1) wire [6]. The ratio of the beam-losses measured at FERMI - when passing from a 5 $\mu\mathrm{m}$ tungsten wire to a 12.5 $\mu\mathrm{m}$ Al(99):Si(1) wire - was observed to scale down linearly with the material density ρ and quadratically with the Atomic number (Z) in agreement with the formula:

$$\frac{\Delta E}{\Delta x} = \frac{E}{L_R}, \tag{1}$$

where E and ΔE are the energy and the energy loss, respectively, and L_R is the radiation length of the material with $1/L_R$ depending quadratically on Z and linearly on ρ [10].

The mechanical stability of the entire in-vacuum set-up of the WSC was the object of a careful investigation as well [6]. Wire-vibration measurements showed that the wire stability stays largely below the geometrical resolution 1.3 $\mu\mathrm{m}$ (rms) of the wire in the motor speed range 0.1-6.0 $\mathrm{mm/s}$ with the exception of the motor speed range 0.5-0.6 $\mathrm{mm/s}$ where an anomalous wire vibration - 2.1-1.6 $\mu\mathrm{m}$ - slightly exceeding the tolerance limit was observed. Narrow resonances are a unavoidable feature in a stepper-motor driven linear-stage but, in the specific case, not-detrimental and also simply to be deselected from the range of the allowed motor-speeds in a scan.

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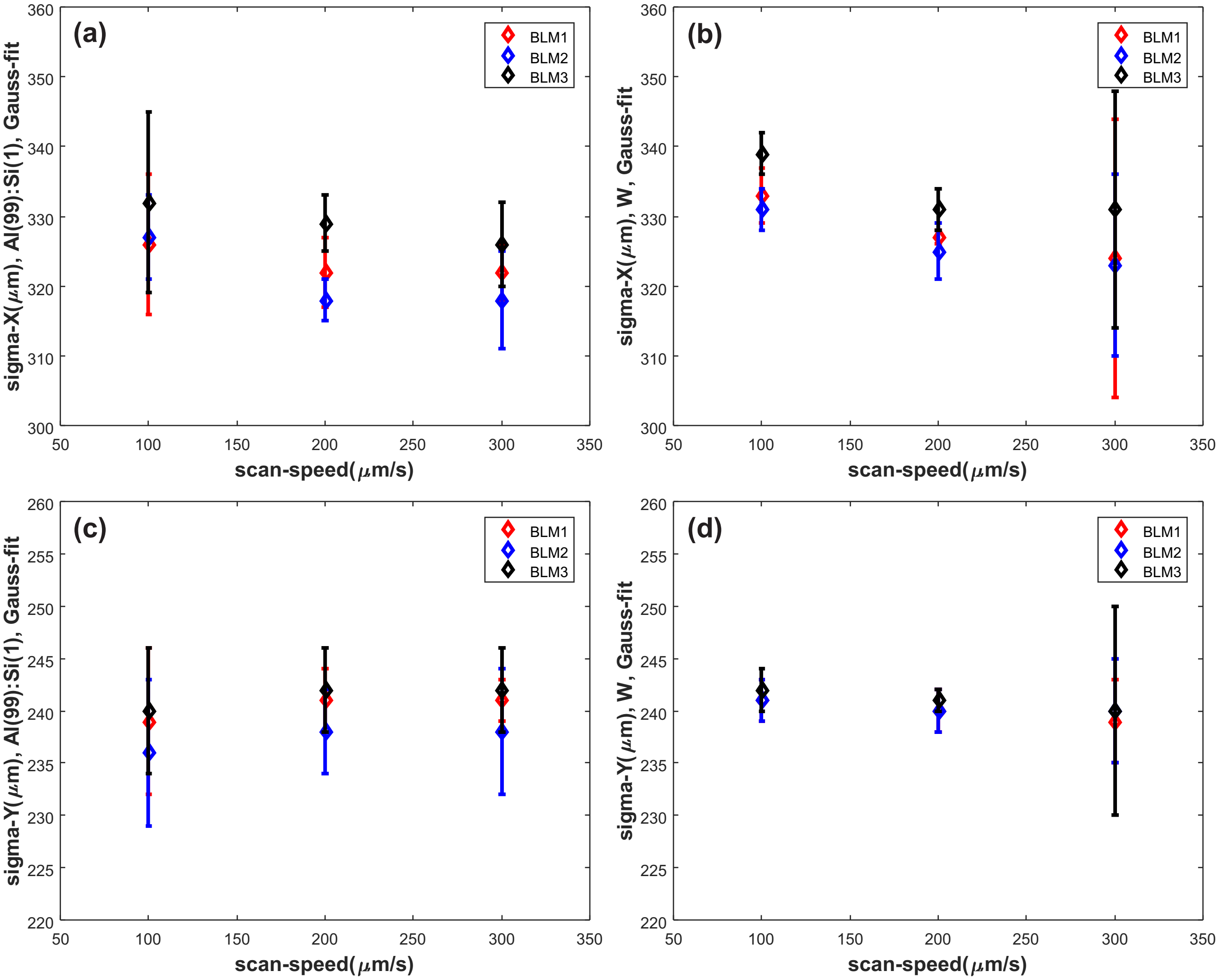

Figure 2: Gauss fit estimates of WSC measured beam size: (a,b) results of horizontal scan with Al(99):Si(1) and W wires, respectively; (c,d) results of vertical scan with Al(99):Si(1) and W wires, respectively. Beam energy 330 MeV, charge 20 pC, repetition rate 10 Hz.

The multi-shot feature of a WSC measurement requires acquiring all the signal of the concerned instruments in a beam synchronous mode at every RF shot (BSREAD) and assigning to each signal an identifying ID global number. The motor controller is provided with a timing card which permits to stream the BSREAD encoder readout to an EPICS channel with a time jitter of about 0.1 ms. Together with BLM signals, signal readouts of BPMs upstream and downstream the WSC are BSREAD acquired as well in order to correct the WSC measurement by possible effects of charge and position jitter. Finally, a high-level application, developed using the PShell workbench [11], provides the user interface and manages the measurement process: setting of the scan parameters (interval of scan, number of cycles, motor speed); acquiring and saving of the BSREAD stream of the instrument signals; preliminary profile analysis and real-time displaying of the scan on-progress.

FIRST COMMISSIONING RESULTS

The commissioning of the SwissFEL WSCs is on-going. First goals of the commissioning are: (1) functionality check of all the sub-systems involved in a WSC measurement (wire integrity, BSREAD of motion and detection signals, data processing and saving); (2) determination of the most suitable BLMs for the WSC under commissioning from the point of view of the signal-to-noise ratio and optimization of the PMT gain; (3) cross-check of the WSC measured size of the electron beam with view-screen measurement; (4) comparative study of the Al(99):Si(1) and 5 μm W wire performance from the point of view of the measurement accuracy and produced beam-losses; (5) evaluation of the effect of the charge and position jitter of the beam on a WSC measurement and implementation of a correction procedure if needed. First WSC to be commissioned in SwissFEL is placed between the first bunch compressor (BC1) and the injector energy spectrometer. In the

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WSC measurement session hereby described, the machine was set at a charge of 20 pC, a repetition rate of 10 Hz and at a maximum beam energy of 330 MeV in the beam line between BC1 and the injector spectrometer. Three different BLMs - BLM1, BLM2, and BLM3 placed respectively at 2.2, 6.5 and 20.5 m from the WSC - were simultaneously acquired together with the readout of the beam charge and position of 2 BPMs placed, respectively, immediately upstream and dowstream the WSC. Several scans were performed with both Al(99):Si(1) and W wires along the X and Y directions (6 cycles per scan). The gain of the PMT was optimized separately for Al(99):Si(1) and W scans in order to have a signal response of each BLM covering the full scale of the 12 bit ADC. The results of the analysis of the measured beam profiles - well fitted by a Gauss function - are shown in Fig.2. The gain of the PMTs is normally higher for an Al(99):Si(1) scan than for a W scan. Moreover, for a given wire material, the PMT gain increases from the closer to the outer BLM. Consequently, the signal-to-noise ratio is different for the 3 BLMs. Nevertheless, the results of the beam profile analysis reported in Fig.2 indicate an excellent agreement - within the statistical errors - of the beam profiles which can be reconstructed by the signal of the 3 BLMs when scanning the beam with both Al(99):Si(1) and W wires. Moreover, the measurement accuracy of the beam size still maintains consistent in the considered range of scan-speeds, 100, 200 and 300 μm/s. According to the signals acquired by BLM2 - which showed the highest signal-to-noise ratio - for a scan speed of 100 μm/s, the beam profile measured at the WSC position is: $(327\pm1\mu\mathrm{m})$ in X and $(240\pm2\mu\mathrm{m})$ in Y with W wire; $(322\pm5\mu\mathrm{m})$ in X and $(241\pm3\mu\mathrm{m})$ in Y with Al(99):Si(1) wire. In order to crosscheck the results of the WSC measurement, the beam profile has been also measured with a view-screen placed 28 cm upstream the WSC. After a suitable re-scaling of the measured beam size at the view-screen according to the ratio of the Twiss beta function at the two positions, the estimate of the beam profile at the WSC is: $(328\pm3\mu\mathrm{m})$ in X and $(240\pm2\mu\mathrm{m})$ in Y. About charge and position jitters, the effects of them on a WSC measurement are negligible in the considered experimental session. Thanks to the BSREAD signals (charge and position) of the two BPMs immediately upstream and downstream the WSC and the knowledge of the magnetic optics in between, it was possible to correct the BLM signal by the shot-to-shot fluctuations of the bunch charge and to estimate the beam jitter at the WSC as a function of the the beam position readouts from the two BPM. The charge jitter correction resulted to be absolutely negligible. The position jitter at the WSC is also negligible with respect to the statistical error. The estimate of the beam jitter at the WSC is 4.0 μm in X and 3.4 μm in Y to be compared with the measured beam jitter at the adjacent view-screen: 3.0 μm and 3.4 μm, respectively. Finally, a preliminary comparative analysis of Al(99):Si(1) vs. W scans indicates that the beam-losses measured by BLM1 and BLM2 show a reduction by about a factor 12 and 6, respectively.

CONCLUSIONS

First results of the on-going commissioning of the SwissFEL wire-scanners (WSCs) are presented. They confirms the reliability of the system as already observed in prototype tests previously carried out in other FEL facilities [6]. In comparison with the 5 W μm wire, the innovative solution of 12.5 Al(99):Si(1) μm wire shows similar performances in terms of beam robustness and measurement accuracy as well as a significative reduction of the beam-losses. This confirms the measurement strategy of SwissFEL to use 5 W μm wire in high precision measurement of the beam profile and emittance under protection conditions of the undulator line and to use 12.5 Al(99):Si(1) μm wires to routinely monitor the beam under FEL operations. For the two different types of wires, the resolution limit still need to be measured as well as the mapping of the distribution of the beam-losses along the machine has to be completed. An extensive work of matching the 22 WSCs installed in SwissFEL with the BLMs which have the best signal-to-noise ratio has to be done as well as the determination of the optimal PMT gain interval for the two charge operation modes (10/200 pC) of SwissFEL. Finally, a procedure of emittance measurement with WSCs has to be tested and settled. The beam-synchronous acquisition of the signals from all the instruments involved in a WSC measurement (motor encoder, beam-loss-monitor, beam-position-monitor) is properly running. The WSC high-level application managing the setting of a measurement parameters, the instrument control, the preliminary processing, displaying and saving of the acquired data is fully operational. Further development step will be the integration of the WSC high-level application with the functionalities required by an emittance measurement.

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