DESIGN AND EXPERIMENTAL TESTS OF THE SwissFEL WIRE-SCANNERS

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Abstract

The SwissFEL wire-scanner (WSC) composes of an in-vacuum beam-probe - motorized by a stepper motor - and an out-vacuum pick-up of the wire-signal. In SwissFEL, WSCs will absolve two main tasks: high precision measurement of the beam profile for determining the beam emittance as a complement to view-screens; routine monitoring of the beam profile under FEL operations. In order to fulfill the aforementioned tasks, the design of the in-vacuum component of the SwissFEL WSCs followed the guidelines to ensure a mechanical stability of the scanning wire at the micrometer level as well as a significative containment of the radiation-dose release along the machine thanks to the choice of metallic wires with low density and Atomic number. Beam-loss monitors have been suitably designed to ensure a sufficient sensitivity and dynamics to detect signals from scanned beams in the charge range 10-200 pC. The design, the prototyping phases, the bench and electron-beam tests - performed at SITF (Paul Scherrer Institut) and FERMI (Elettra, Trieste) - of the entire SwissFEL WSC set-up will be presented.

PREMISE

The proceeding contents are an extract of an article recently accepted for publication in Physical Review Accelerators and Beams [1]. Aim of the present proceeding is to outline the most relevant aspects of the work done for the development of the SwissFEL WSC which the reader can examine in depth in [1]. The introductory and conclusive sections of the proceeding directly descend from [1].

INTRODUCTION

SwissFEL will provide coherent X-rays light in the wavelength region $7 - 0.7\ nm$ and $0.7 - 0.1\ nm$ [2]. Electron bunches with charge of 200/10 pC and transverse normalized slice emittance of 0.4/0.2 $\mathrm{mm.mrad}$ will be emitted by a S-band photocathode gun at a repetition rate of $100\ \mathrm{Hz}$ according to a two-bunches structure with a temporal separation of $28\ \mathrm{ns}$. The electron beam will be then accelerated up to $330\ \mathrm{MeV}$ by a S-band RF booster and, finally, to $5.8\ \mathrm{GeV}$ by a C-band RF linac. Thanks to an off-crest acceleration in the RF Booster, the electron beam will experience a longitudinal compression in two magnetic chicanes from an initial bunch length of $3/1\ \mathrm{ps}$ (rms) down to $20/3\ \mathrm{fs}$ (rms). Two X-band RF cavities will compensate the quadratic distortion of the longitudinal phase space due to the off-crest acceleration of the beam and the non-linear contribution of the magnetic dispersion [3]. In the booster section, a laser-heater will smooth down possible micro-structures affecting the longitudinal profile of the beam [4, 5]. Finally, thanks to a RF kicker - placed after the second bunch-compressor - and a magnetic switch-yard, the second electron bunch of the beam train will be shifted from the main beam line to a secondary one so that the SwissFEL linac, after a further acceleration stage of the two bunches, will supply two distinct undulator chains at a repetition rate of $100\ \mathrm{Hz}$: the hard X-rays line Aramis and the soft X-rays line Athos [2].

In a FEL (Free Electron Laser) driver linac, WSCs are currently used to monitor the transverse profile of the electron beam [6, 7, 8, 9, 10, 11, 12, 13, 14] when the view-screen imaging of the beam is hampered by coherent radiation emission due to microbunching. In SwissFEL, WSCs will be complementary to view-screens for emittance measurements and, thanks to the barely invasive feature, also used for routine monitoring of the transverse profile of the electron beam during FEL operations. Moreover, the beam imaging at SwissFEL being performed by means of YAG:Ce screens [15], only WSCs will be able to discriminate the profile of each single bunch in two-bunches operations. In SwissFEL, the WSC in-vacuum hardware consists of a planar wire fork which can be inserted 45^o with respect to the vertical direction into the vacuum chamber by means of a UHV linear-stage driven by a stepper motor, see Fig.(1). The wire-fork is designed to be equipped with two wire triplets, the spare triplet being possibly composed of wires of different material and/or diameter. Each wire of the triplet will separately scan the beam profile along a given direction: the vertical wire (X-scanning, horizontal-scanning), the horizontal wire (Y-scanning, vertical-scanning) and the diagonal wire (XY-coupling). During a WSC measurement, the single wire scanning the beam at a constant speed produces - at every RF shot - a shower of primary scattered electrons and secondary emitted particles 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) will be out-vacuum detected by means of Beam-Loss-Monitors (BLMs). The beam-loss sensitive material of the SwissFEL BLMs is a scintillator fiber (Saint Gobain BCF-20, decay time 2.7 ns) wrapped

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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. The SwissFEL BLMs are designed to detect the wire-signal from $10 - 200$ pC bunches and to have a sufficient time-response to discriminate the 28 ns time structure of the SwissFEL beam in two-bunches operations [16]. In SwissFEL, the wire-scanned profile of the electron beam will be reconstructed thanks to the beam-synchronous acquisition (BSDAQ) of the encoder read-out of the wire-position and of the signal read-out of the BLM at every RF shot. Furthermore, thanks to the BSDAQ readout of the beam charge and the transverse position of the beam centroid provided by Beam Position Monitors (BPMs) [17] placed immediately downstream and upstream the WSC, possible errors due to the beam jitter can be corrected in the reconstructed beam profile.

In the present work, technical details on the design of the SwissFEL WSCs will be presented as well as the main results of the bench and electron-beam tests of the entire WSC set-up. Laboratory tests aimed at determining the mechanical stability of the in-vacuum hardware of the WSC and, in particular, the stepper-motor induced vibration of the wire in the speed range of interest of SwissFEL were carried out. e-Beam tests of a prototype of the SwissFEL WSC - in-vacuum and out-vacuum components - were performed: (1) at low charge and energy - 10 pC and 250 MeV - at SITF [19] and (2) at high charge and energy - 700 pC and 1.5 GeV - at FERMI [20, 21]. Thanks to the e-beam tests, the issue of the necessary detection sensitivity and dynamics of the SwissFEL BLM in the beam charge range $10 - 200$ pC was clarified as well as the issue of the optimum distance of the BLM from the WSC as a function of the beam energy. The question of the choice of the most suitable wire solution (material and diameter) was also positively defined thanks to the e-beam tests. The robustness of wires of different materials and diameters was tested on electron beams. The relative measurement accuracy and the radiation-dose release along the machine during a WSC measurement was also determined for different wire-solutions. In particular, a comparative study of the scanning performances - relative measurement accuracy and radiation-dose release - of a Al(99):Si(1) wire with a diameter of 12.5 $\mu\mathrm{m}$ and a tungsten (W) wire with a diameter of 5 μm was carried out at FERMI at a beam energy of 1.325 GeV and at a charge of 700 pC.

SWISSFEL WIRE-SCANNER (WSC), MEASUREMENT GOALS

The SwissFEL WSC are requested to absolve the following tasks:
(1a) monitor the transverse profile of beams having a size of 5-500 μm (rms), charge of 10-200 pC and energy of 0.340-5.8 GeV;
(2a) resolve the beam transverse profile of the SwissFEL two-bunches train: time structure, 100Hz repetition rate and 28ns time separation;
(3a) measure the beam transverse profile and emittance as a complement to view screens and as a further option in case the view-screen imaging of the beam will be hampered by possible microbunching induced effects of coherent radiation emission;
(4a) routine monitoring of the beam transverse profile during FEL operations.

SWISSFEL WSC, DESIGN CRITERIA

The design criteria of the SwissFEL wire scanners followed the below indicated guidelines:
(1b) use a single UHV linear stage motorized by a 2-phase stepper motor to scan the beam profile in the vertical plane along the X,Y and X-Y directions, see Figs.(1, 2);
(2b) wire-fork designed to be equipped with two triplets of wires of different material and diameter, see Figs.(1, 2);
(3b) wire-fork equipped with multiple pin-slots to fix the wires of each triplet at different relative distances (wire-vertex from vacuum-chamber axis: 8, 5.5, 3 mm);
(4b) 1^{st} wire-triplet: 5 μm Tungsten wire for high resolution measurement of the beam emittance (1.3 μm geometrical resolution of the wire);
(5b) 2^{nd} wire-triplet: 12.5 μm Al(99):Si(1) wire for routine scanning of the beam profile during FEL operations;
(6b) wire-scanner signal: forward shower of primary scattered electrons and secondary emitted particles in proportion to the fraction of the beam charge sampled by the wire;
(7b) wire-scanner signal (particle shower) detected by beam-loss-monitors (BLMs) composed of a scintillator fiber wrapped around the beam pipe and matched by means of a POF (Plastic Optical Fiber) to a photomultiplier (PMT gain $5 \times 10^3 - 4 \times 10^6$);
(8b) beam transverse profile reconstructed thanks to the Beam-Synchronized-Acquisition (BS-ACQ) of the motor encoder and BLM readouts;
(9b) correction of the beam charge fluctuation and transverse jitter of the beam centroid thanks to the BS-ACQ of the signals (beam charge and position) of the closest beam position monitors (BPMs) placed downstream and upstream the WSC.

SWISSFEL WSC, EXPERIMENTAL RESULTS

The experimental work on the SwissFEL WSC was carried out at the 250MeV SwissFEL Injector Test Facility (SITF, 200MeV, 10-200 pC, 10 Hz) and at FERMI (300-700 pC, 1.3-1.5 GeV, 10 Hz). The work of WSC characterization focused on:
I) determination of the wire stability under motion [wire-vibration measurements on test-bench, see Fig.(3)];
II) e-Beam resistance tests of wires of different material and diameter at high charge (700 pC, 10Hz) and energy (1.3-1.5 GeV);

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III) determination of the optimum distance WSC-BLM as a function of the beam energy (0.200-1.5 GeV);
IV) study of the BLM sensitivity at low charge (10pC);
V) comparative studies WSC vs. OTR: compared to OTR, WSC measurements of emittance at FERMI characterized by a higher resolution and a significative speed-up and improvement of the matching procedure of the magnetic optics to the design lattice;
VI) comparative studies of the WSC performances (5 μm Tungsten wires vs. 12.5 μm Al(99):Si(1) wires): study of the measurement accuracy and determination of the radiation dose release along the machine.

Achievements and expected performances:
(1c) wire-vibration measurements: measured wire-vibration below the tolerance limit of 1.3 μm in the stepper motor velocity range 0.1 - 3.0 mm/s. Anomalous wire-vibration of 2.1-1.6 μm in the velocity range 0.5 - 0.6 mm/s (stepper motor resonance velocity), see Fig.(3);
(2c) spatial resolution and accuracy features: wire-geometrical resolution $\rightarrow$ $1.3 \mu m$ (5 μm Tungsten); motor encoder resolution $\rightarrow 0.1 \mu m$; jitter of the encoder BS-ACQ readout $\rightarrow 0.1 ms$;
(3c) optimum distance WSC-BLM scaling up between 3-6m in the beam energy range 0.200-1.5 GeV;
(4c) BLM sensitivity sufficient to scan 10 pC beam with 5 μm Tungsten wire and detector dynamics sufficient to cover the charge range 10-200 pC;
(5c) FEL operations (FERMI) almost transparent to wire-scanning with Tungsten;
(6c) comparison of the wire-scanning performances 5 μm Tungsten vs. 12.5 μm Al(99):Si(1), experimental results (FERMI):
i) same measurement accuracy in scanning beam profiles with a size of 35 μm;
ii) compared to Tungsten, reduction by a factor 11 of the radiation dose released along the FERMI FEL1 undulator chain when scanning the beam with Al(99):Si(1).

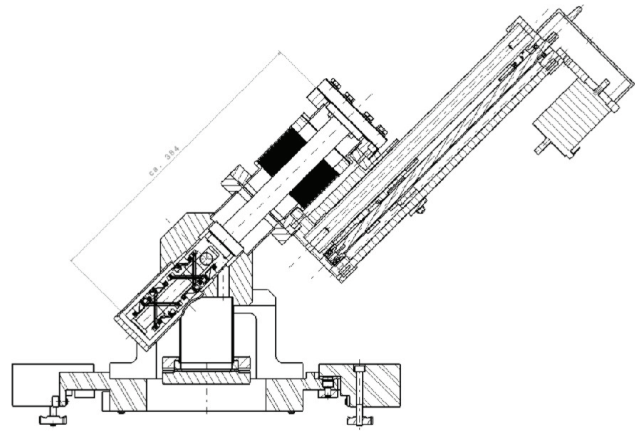

Figure 1: View of the transverse section of the in-vacuum set-up of the SwissFEL WSC: CF16 vacuum chamber, motorized UHV-Linear-Stage and wire fork. The Swiss-FEL wire-fork can be equipped with two triplets of wires. Thanks to a system of multiple pin-slots, the horizontal and the vertical wires of each triplet can be set, respectively, at a distance from the center of the vacuum chamber of either 8 mm or 5.5 mm or 3 mm, see also Fig.(2). In order to outline this feature of the SwissFEL wire-fork - in both Figs.(1,2) - all the three pin-slots are virtually provided with wires. In the real wire-fork of SwissFEL, only one wire is fixed along the horizontal direction by means of one of the three possible pin-slots (the same for the vertical direction).

CONCLUSIONS

The design features and the main prototyping steps of the SwissFEL wire-scanners have been presented as well as the results of bench and electron-beam tests of the entire WSC set-up [1, 22]. Electron beam tests were carried out at SITF and FERMI. The experimental characterization of the mechanical stability of the WSC confirmed that, in the motor-speed range of interest of SwissFEL ($0.1 - 3.0$ $\mathrm{mm/s}$), the wire-vibration stays largely below the tolerance limit of 1.3 μm (rms). According to the results of electron beam tests carried out at SITF, the detection set-up of the wire-signal showed a sufficient sensitivity to reconstruct the beam profile of a 10 pC beam scanned by a 5 μm tungsten wire and, in general, a sufficient large dynamics to cover the beam charge range $10 - 200$ pC. Furthermore, thanks to the electron beam tests carried out at SITF and FERMI, the optimum distance between WSC and wire-signal detector was estimated to scale up between 3 and 6 m in the beam energy range $0.250 - 1.5$ GeV. Several solutions of metallic wires of different material and diameter have been tested on the electron beam at different conditions of charge and energy. In particular, comparative tests of the scanning performance of a 5 μm tungsten wire and of 12.5 μm Al(99):Si(1) wire were carried out at FERMI at a beam energy of 1.325 GeV and charge of 700 pC. The results of this comparative study demonstrated a satisfactory robustness of the Al(99):Si(1) wire to the beam loading as well as a comparable accuracy of the two wire-solutions in measuring an electron beam size of about 35 μm. In addition, the radiation-dose measured at the FEL1 undulator chain of FERMI when scanning the beam with a 12.5 μm Al(99):Si(1) was about a factor 11 smaller than the one measured with a 5 μm tungsten wire. On the basis of the outcome of the electron beam tests, the SwissFEL WSC forks - being designed to be equipped with two distinct triplets of metallic wires - will be provided with 5 μm tungsten wires - for high precision measurements of the beam profile and emittance - and with 12.5 μm Al(99):Si(1) wire for routine monitoring of the transverse profile of the electron beam during FEL operations. The prototyping and experimental characterization phases of the SwissFEL WSC being accomplished, WSC commissioning and operations in SwissFEL are expected to start by Summer 2016.

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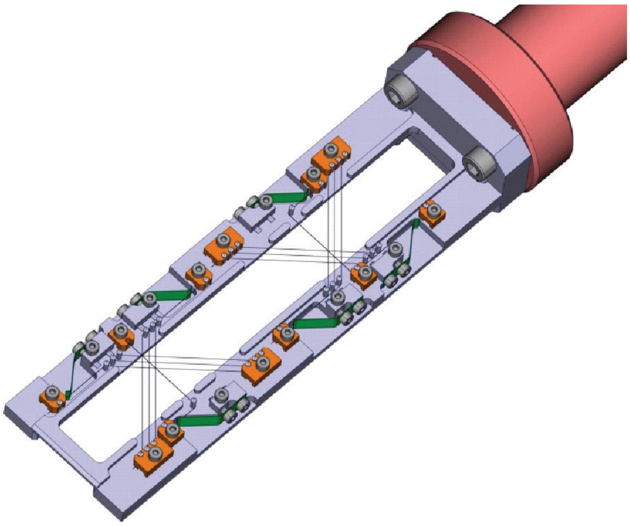

Figure 2: Technical drawing of the SwissFEL wire-fork. Thanks to a system of multiple pin-slots, the vertex of each wire-triplet can be set at three different distances (8, 5.5 and 3 mm) from the center of the vacuum chamber. In order to outline such a flexibility feature of the design of the SwissFEL wire-fork - in the present technical drawing - all the three pin-slots are shown to be provided with horizontal and vertical wires. In reality, only one of the three possible pin-slots will be equipped with a wire so that each of the two wire triplets of the SwissFEL wire-fork will be composed of: one single horizontal wire; one single vertical wire; one single wire for XY coupling.

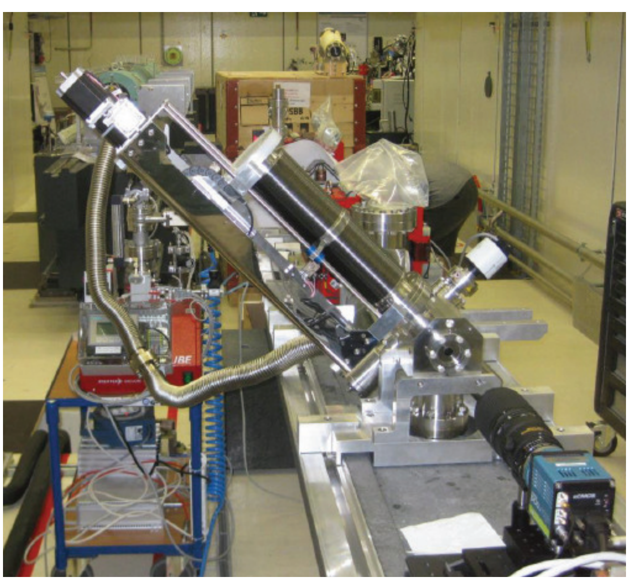

Figure 3: Image of a prototype of the SwissFEL WSC installed onto a girder together with the measurement set-up of the stepper-motor induced vibrations of the wire.

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