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WIRE-SCANNERS WITH SUB-MICROMETER RESOLUTION: DEVELOPMENTS AND MEASUREMENTS

G.L. Orlandi*, S. Borrelli, C. David, E. Ferrari, V. Guzenko,
B. Hermann, O. Huerzeler, R. Ischebeck, C. Lombosi, C. Ozkan-Loch, E. Prat,
Paul Scherrer Institut, Villigen PSI, Switzerland
M. Ferianis, G. Penco, M. Veronese,
Elettra-Sincrotrone Trieste S.C.p.A, Basovizza, Trieste Italy
N. Cefarin, S. Dal Zilio, M. Lazzarino,
IOM-CNR Laboratorio TASC, c/o Area Science Park - Basovizza, Trieste, Italy

Abstract

Monitors of the beam transverse profile with ever more demanding spatial resolution and minimal invasivity are required by the FEL community. In order to improve the spatial resolution towards the sub-micrometer limit as well as to decrease the impact on the lasing process, nano-fabricated wire-scanners have been manufactured independently at PSI and FERMI by means of a lithographic technique. Experimental tests carried out at SwissFEL at a low emittance demonstrated the capability of such innovative wire-scanner solutions to resolve beam transverse profiles with a size of 400-500 nm without being affected by any resolution limit. Status and outlook of nano-fabricated wire-scanners (WS) will be presented.

PREMISE

The present proceeding briefly reports on the recent experimental results obtained in the nano-fabrication and electron beam characterization of free-standing WS with sub-micrometer resolution. The free-standing WS prototypes - independently nano-fabricated at PSI and FERMI by means of lithographic techniques - can measure the transverse profile of an electron beam with a rms geometrical resolution of about 250 nm. The experimental test of the PSI and FERMI WS prototype have been performed at SwissFEL, where electron beams with a vertical size smaller than 500 nm have been successfully and consistently resolved. All information and technical details on the nano-fabrication and experimental tests - carried out at SwissFEL - of the PSI and FERMI free-standing WS with sub-micrometer resolution are reported in a manuscript submitted to a peer-reviewed journal for a publication. For more details on the WS nano-fabrication and characterization, the reader is hence addressed to the archived version of the manuscript, to the paper submitted to the journal and to the slides of the conference talk [1, 2]. In the present proceeding, the authors will summarize the main highlights, achievements and perspectives of the experimental work on free-standing WS with sub-micrometer resolution. In addition, the authors will briefly summarize the background experience of PSI and FERMI on nano-fabrication and test of WS. Results of satellite tests carried out at SwissFEL in parallel with the characterization of the free-standing WS will be reported as well. The introduction and the conclusion sections are directly derived from [1, 2].

INTRODUCTION

Wire-scanners (WS) constitutes a precious complement to view-screens for monitoring the transverse profile of the electron beam in a linac [3–12]. Because of the multi-shot and mono-dimensional reconstruction of the beam transverse profile, WS are not timewise competitive with view-screens for beam finding and for matching the magnetic optics in an electron linac. WS are inappropriate for slice emittance measurements as well. Nevertheless, WS are a unique and essential diagnostics whenever the beam characterization requires a high spatial resolution along with a minimal invasivity to the beam operation. The spatial resolution of a WS depends on the measurement resolution of the wire positioning, on the possible wire vibrations and, finally, on the geometry of the wire. The geometrical resolution of a WS is inversely proportional to the wire width. This also determines the surface of impact of the wire with the electron beam and hence the wire transparency to the beam (also depending on the wire thickness for non-cylindrical wires). Conventional WS solutions - as normally in operation in several free-electron lasers (FELs) - are realized according to the standard technique to fix and stretch a metallic wire (beam-probe) onto a metallic frame (fork). They are able to attain a spatial resolution at the micrometer scale [12] which is at least an order of magnitude higher than the spatial resolution of a typical view-screen operating in a FEL [13, 14]. Low charge and low emitance machine operation modes - presently under investigation in several FEL facilities - requires the characterization of ever smaller beam profiles. This triggers the community of the electron-beam diagnostics to push forward the resolution limit of the conventional WS beyond the micrometer limit. In order to improve the WS spatial resolution, new fabrication techniques are under investigation at PSI and FERMI. At PSI, a WS prototype with a sub-micrometer resolution nano-fabricated on-a-membrane (250 nm thick Silicon Nitride membrane) was successfully tested [15]; while at FERMI a free-standing nanofabricated WS with a resolution of about 2.9 μm has been successfully tested [16]. These experiences paved the way to use the

* gianluca.orlandi@psi.ch

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nano-litography technique to fabricate free-standing WS with sub-micrometer resolution, a goal that PSI and FERMI have independently pursued. The PSI and FERMI nano-fabricated WS consist of a free-standing Au stripe fully integrated in a Silicon frame. With a stripe width (w) of 800 nm and 900 nm, respectively, the PSI and FERMI WS attain a geometrical resolution ($\frac{w}{\sqrt{12}}$) of about 250 nm. They have been experimentally tested at SwissFEL at nominal and low bunch charge regime (200 pC and below 1 pC, respectively). The experimental tests carried out at SwissFEL demonstrated the capability of these novel WS solutions to resolve beam profiles with a size of 400 – 500 nm as well as the necessary resilience to the heat-loading at nominal machine operations (200 pC).

NANO-FABRICATED WIRE-SCANNERS AND EXPERIMENTAL TESTS

The research and development on diagnostics of the transverse profile of the electron beam in a Free-Electron-Laser (FEL) is presently aiming at improving the spatial resolution beyond the micrometer scale in order to meet the constraints of low-emittance and low-charge FEL operations. Moreover, in order to preserve radiation sensitive devices as well as the lasing process when monitoring the beam profile, minimally invasive diagnostics of the electron beam is required. In terms of spatial resolution and minimally invasivity, WS are the top-ranked diagnostics. Spatial resolution, beam invasivity and lasing transparency are strictly related features of a WS: the higher the geometrical resolution - i.e., the thinner the wire diameter - the smaller is the surface of impact of the wire with the beam as well as the number of electrons perturbed during a scan. Conventional WS - designed according to the traditional technique to fix and stretch a metallic wire onto a fork - can provide a rms spatial resolution at the micrometer scale, at best. Hence, the necessity to investigate new fabrication techniques. PSI and FERMI independently pursued the way of the nano-lithography to produce WS structures with a sub-micrometer resolution.

At PSI, the first attempt of WS nano-fabrication consisted in a prototype structure made of a 1 μm wide Au stripe electroplated onto a thin Silicon Nitride membrane (so called *WS on-a-membrane*). After the successful experimental test of this prototype [15], a further progress was achieved at PSI with the nano-fabrication of a WS consisting of a 2 mm long and 800 nm wide Au stripe free-standing over a rigid Silicon frame [1, 2].

FERMI adopted a different approach to the WS nano-fabrication. A first WS prototype consisting of a 10 μm wide $Ag/Si_3N_4/Ag$ stripe free-standing onto a Silicon frame was initially nano-fabricated and tested at FERMI [16]. Finally, an upgrade of the previous free-standing WS solution consisting of a 0.8 mm long and 900 nm wide $Au/Si_3N_4/Au$ stripe has been produced at FERMI [1, 2].

The aforementioned free-standing WS structures with a 800 nm and 900 nm wide scanning stripe - nano-fabricated at PSI by LMN and by IOM-CNR for FERMI, respectively - have been experimental tested at SwissFEL. SwissFEL is a X-ray FEL facility [17–19] in operation at Paul Scherrer Institut. Driven by a rf linac - a S-band injector and a C-band accelerator - in the beam energy range 2.1 – 5.8 GeV, SwissFEL is presently producing tunable and coherent hard X-ray pulses in the wavelength region 0.7 – 0.1 nm (ARAMIS undulator line) and, by 2021, will also generate soft x-ray radiation in the wavelength region 7 – 0.7 nm (ATHOS undulator line).

The PSI and FERMI free-standing WS were in parallel tested on the electron beam of SwissFEL in two different days at a beam energy of about 300 MeV. In both measurement sessions, SwissFEL was operated according to a low-emittance and low-beta setting [1, 2, 15]. Low-emittance operations at SwissFEL are possible thanks to a low-charge setup (below 1 pC) of the rf gun photo-cathode which allows for a normalized vertical emittance ($\varepsilon_{n,y}$) of about 55 nm. Thanks to a suitable magnetic optics (low-beta), at the wire interaction point the beta functions (β_x, β_y) are $(0.27, 2.61 \times 10^{-3})$m. At the WS position, the vertical beam size ($\sigma_y = \sqrt{\beta_y \varepsilon_{n,y}/\gamma}$) is hence about 400 – 500 nm - where γ is the relativistic Lorentz factor at a beam energy of 300 MeV - while the beam horizontal size is about 10 times larger.

The experimental results of the measurements carried out at SwissFEL of the PSI and FERMI free-standing WS with sub-micrometer resolution are summarized in Table 1 where the measured beam size has been obtained by fitting the acquired WS profile by means of a an error-function-fit (erf-fit) resulting from the convolution of a Gaussian profile and a rectangular shaped distribution modelling the transverse section of the scanning wire. As reported in Table 1, the two different WS solutions consistently measured a beam profile of about 500 nm which is in agreement with the theoretical prediction.

A beam test of the two WS solutions at the nominal SwissFEL opeation mode (200 pC) was also performed in order to check the resilience of the two WS structure to the heat-loading. No damage was observed in the WS structures at 200 pC.

During the experimental test of the free-standing WS a satellite measurement was also performed. This consisted in reconstructing the beam transverse profile from the readout of the beam-loss signal simultaneously detected by a photomultiplier-tube (PMT, standard solution at SwissFEL) and a photodiode during a scan with the free-standing WS. Goal of this test was to verify the signal-to-noise ratio of the photodiode compared to the PMT. The comparative experimental test of the two detectors showed statistically consistent results of the measured beam size. About the quality of the detected signal by the two detectors, the signal-to-noise response of the photodiode was about 10 times worse than the PMT one.

In conclusion, to the best of the authors' knowledge, the experimental results reported in the manuscripts and presented in the FEL2019 conference talk [1, 2] constitute a

Table 1: Results of the erf-fit estimate of the vertical size of the SwissFEL electron beam scanned by the PSI and FERMI free-standing WS in the measurement sessions of December 4, 2018 and March 31, 2019. Beam profile measurements performed at a beam charge less than 1 pC and at a beam energy of 300 MeV. Vertical emittance about 55 nm expected vertical beam size of about 480 nm for a beta function value $\beta_y = 2.61 \times 10^{-3}$ m at the WS position.

WS type	**stripe width**(nm)	**geom. res.**(nm)	**beam size** (nm, **Dec 2018**)	**beam size** (nm, **Mar 2019**)
PSI-WS	800	230	488±20	434±7
FERMI-WS	900	260	477±70	443±33

world record in terms of spatial resolution ever reached by a WS solution made of a free-standing metallic wire. The lithographic nano-fabrication - developed at PSI and FERMI - and the experimental tests carried out at SwissFEL of the free-standing WS with a sub-micrometer resolution paved the way to the development of innovative WS solutions with sub-micrometer resolution to be used as a standard electron beam diagnostics in a FEL.

CONCLUSIONS AND OUTLOOK

PSI and FERMI are independently pursuing a research and development program aiming at improving the spatial resolution of wire-scanners (WS) beyond the standard limit of the micrometer scale as well as the WS transparency to the lasing operations in a FEL. Nano-lithography permits to overcome the bottleneck of the micrometer resolution limit which characterizes the conventional WS design consisting of a metallic wire stretched over a metallic fork. It is indeed possible to nano-fabricate free-standing Au bulk or sandwich $Au/Si_3N_4/Au$ WS stripes with a sub-micrometer width which are fully integrated into a silicon frame. In the present work, the production details and the experimental characterization of two different prototype solutions of nano-fabricated free-standing WS with a geometrical resolution of about 250 nm has been presented. The two free-standing WS prototypes with a stripe width of 800 and 900 nm have been nano-fabricated at PSI and FERMI, respectively. The PSI WS prototype consists of a 2 mm long bulk Au stripe, while the FERMI prototype consists of a 0.8 mm long stripe made of a sandwich of $Au/Si_3N_4/Au$. Both nano-fabricated WS prototypes have been in parallel tested at SwissFEL under a low-charge and low-emittance setting of the machine where a beam size of 400 – 500 nm has been consistently - and without any resolution limit issue - measured by the two WS solutions in two different experimental sessions. Moreover, an experimental test - still performed at SwissFEL under the nominal high charge mode of the machine (200 pC) - demonstrated the resilience to heat-loading of the nano-fabricated WS. The presently nano-fabricated free-standing WS solutions can ensure a beam clearance of about 2 mm. In order to extend the applicability of them as a standard WS solution in a linac driven FEL, the present beam clearance should be increased by a factor 4 – 5, at least. This improvement issue is in the to-do list of the further development program of design and nano-fabrication of free-standing sub-micrometer WS at PSI and FERMI. The hereby experimental campaign of measurement carried out at SwissFEL demonstrated the excellent performance of the PSI and FERMI free-standing WS in resolving electron beam profile with a sub-micrometer size and the reliability of two independent and different techniques of nano-fabrication. The way to the implementation of nano-fabricated WS with sub-micrometer resolution as a standard WS solution in a FEL is paved.

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