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New precision wire scanners at PSI

G.L. Orlandi
Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

ARIES Workshop on ‘Materials and Engineering Technologies for Particle Accelerator Beam Diagnostic Instruments’

Remote, June 21, 2021

gianluca.orlandi@psi.ch

Co-authors Acknowledgment

The present work is the result of a team achievement to which many experts contributed:

S. Borrelli, C. David, E. Ferrari, A. Gobbo, V. Guzenko, P. Heimgartner, B. Hermann, O. Huerzeler, R. Ischebeck, C. Lombosi, C. Ozkan-Loch, E. Prat, V. Schlott

Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

M. Ferianis, G. Penco, M. Veronese,

Elettra-Sincrotrone Trieste S.C.p.A, 34149 Basovizza, Trieste Italy

N. Cefarin, S. Dal Zilio, M. Lazzarino,

IOM-CNR Laboratorio TASC, c/o Area Science Park - Basovizza, Trieste, Italy

Milestones of WS development at PSI

- SwissFEL wire-scanners (WS) with micrometer resolution:
  innovative design on a footprint of a standard technique

- Nano-fabricated WS with sub-micrometer resolution “on a membrane”
  Simona Borrelli, Master thesis,Universita’ degli Studi di Pisa

- “Free-standing” nano-fabricated WS with sub-micrometer resolution

- Beam profile tomography with nano-fabricated WS,
  Benedikt Hermann, PhD candidate, PSI and University of Bern

- Nanofabricated WS at FERMI: similar development path pursued independently.

- Fruitful collaboration between FERMI and PSI in the nano-fabricated WS project

Presentation overview

- ➢ *WS in a FEL: brief introduction*
- ➢ *Motivations and Goals of “WS nano-fabrication”*
- ➢ *Nano-fabricated WS at PSI and FERMI: first developments*
- ➢ *Nano-fabrication of free-standing sub-μm WS at PSI and FERMI*
- ➢ *Free-standing sub-μm WS: experimental test at SwissFEL*
- ➢ *Beam profile tomography with nano-fabricated WS*
- ➢ *Conclusions and Outlook*

WS in a FEL: brief introduction (1/3)

- Diagnostics of the beam transverse profile

- Beam-probe: travelling wire (typically metal) sampling the beam transverse profile at every RF shot

- Probe-signal ("wire-signal"):
  - e.m. shower (e-,e+,photons…) produced by the wire partially detected by a beam-loss-monitor (BLM)
  - BLM signal proportional to the number of particles sampled by the wire at every RF shot

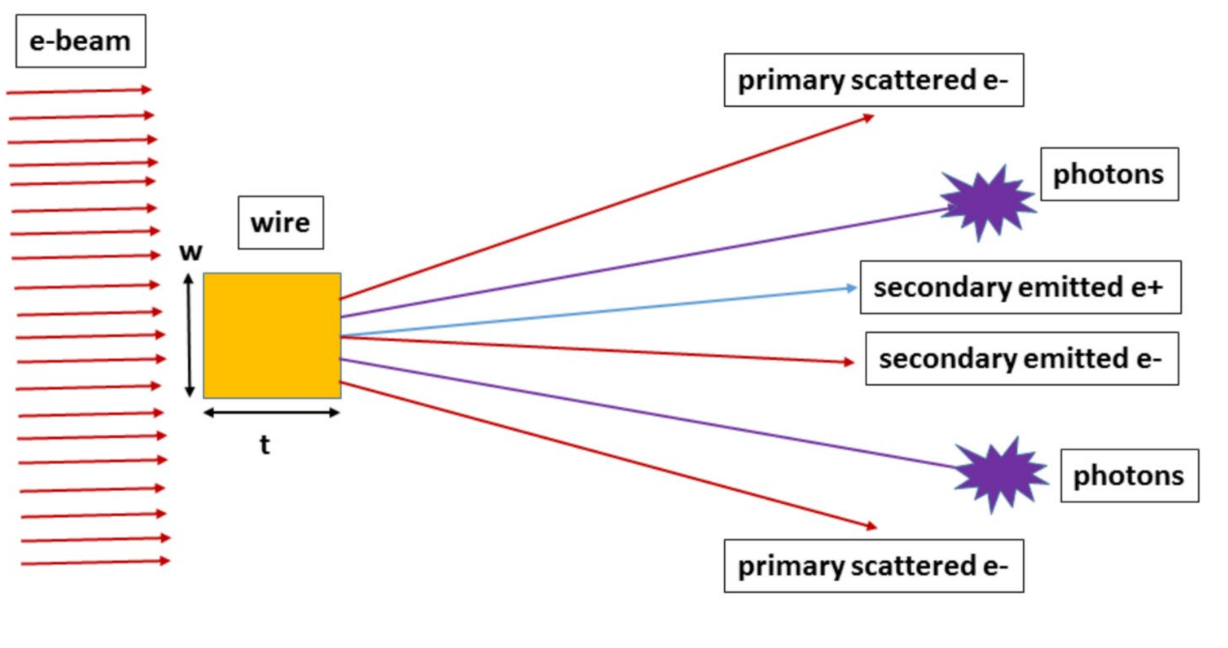
- Profile reconstruction: beam synchronous correlation of BLM signal and encoder readout of wire position

- Spatial resolution:
  - Beam charge and transverse position jitter (corrected by BPM readouts and magnetics optics in between)
  - Encoder resolution
  - Mechanical vibration of the wire
  - Geometrical resolution (normally dominating): rms size of the wire width

- Performance:
  - Multi-shot and 1-dimensional reconstruction of the beam profile
  - High resolution and minimally invasive diagnostics

WS in a FEL: brief introduction (2/3)

- **e.m. shower (WS signal):**
  - **mainly composed by primary scattered e- and secondary emitted particles (e+,e-,photons)**
- **energy loss depending on:**
  - **Density and atomic number of the material**
  - **Wire width (w) determine wire impact surface ←→ number of primary scattered electrons**
  - **Wire thickness (t) determine:**
    - **Amount energy loss (bremsstrahlung) per scattered electron**
    - **Mean angular spreading per electron by multiple Coulomb scattering**
    - **Minimize t←→ improve matching of scattered beam with machine energy and angular acceptance**



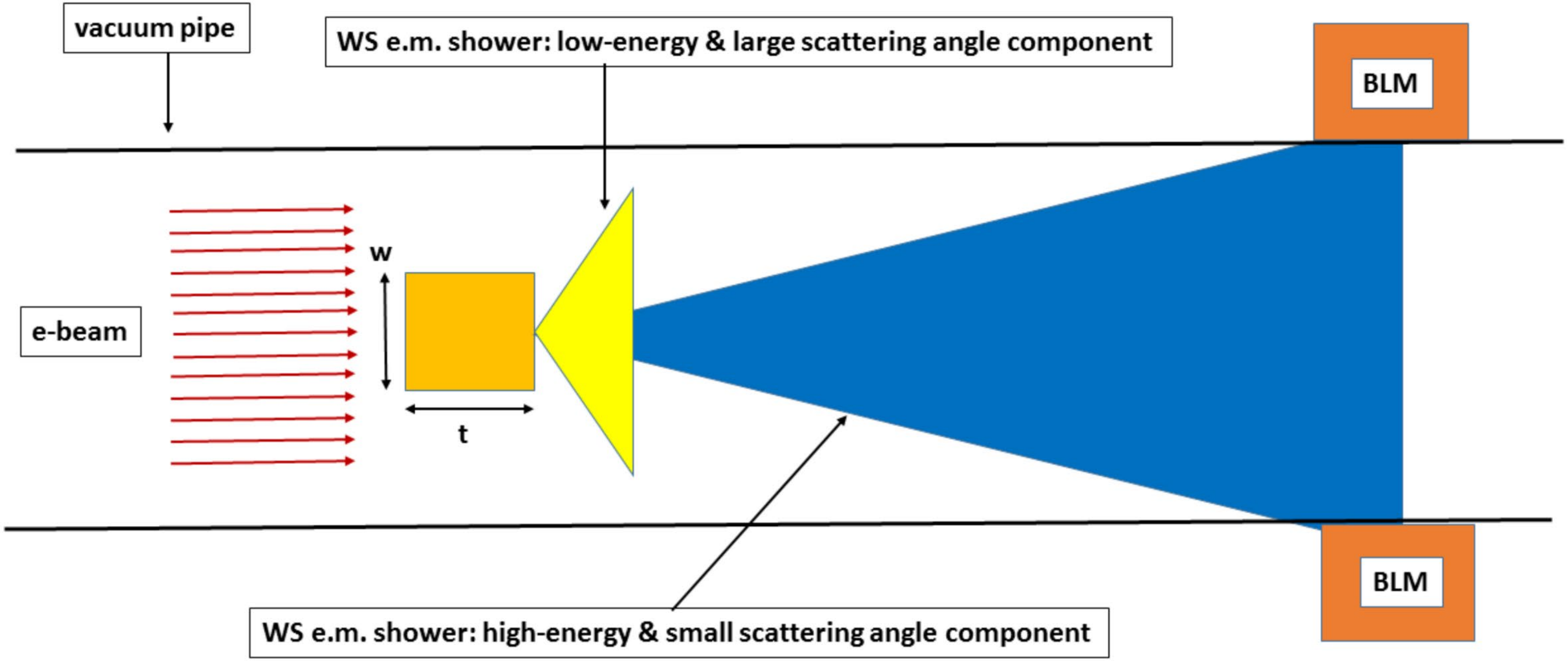
Design goal of WS in a FEL:

- **Minimize w and t→w:**
  - **High geometrical resolution**
  - **Minimal invasiveness to the beam (machine protection)**
  - **High transparency to the lasing**
- **wire material with low density and atomic number…**

…but adequate signal-to-noise ratio of BLM needed…
…then optimize thickness (t) to possibly compensate

WS in a FEL: brief introduction (3/3)

WS signal in a FEL (e.g., SwissFEL): energy loss detected by BLM



vacuum pipe

WS e.m. shower: low-energy & large scattering angle component

BLM

e-beam

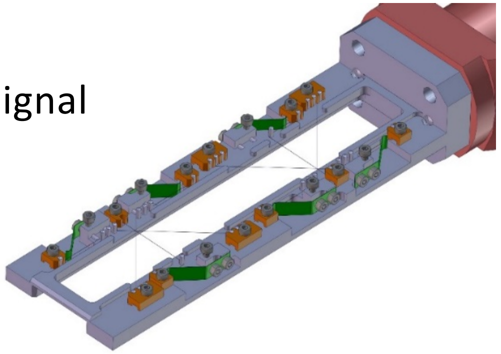
BLM

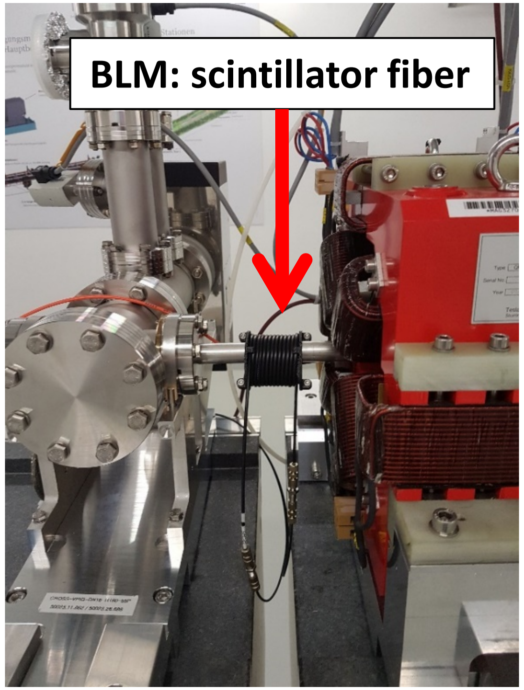
WS e.m. shower: high-energy & small scattering angle component

Conventional WS: resolution and invasiveness constraints (1/3)

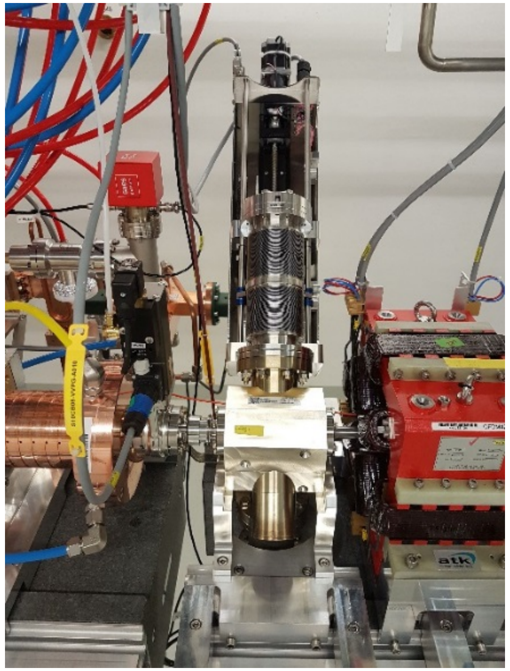
SwissFEL WS:

- ➢ Conventional WS design (metallic wire stretched onto a fork)
- ➢ ~20 WS installed all along the machine for beam profile monitoring and emittance measurements
- ➢ Fork equipped with 2 pairs of wires (5 μm W and 12.5 μm Al(99):Si(1) wires)
- ➢ SwissFEL, WS-relevant parameters: 200/10 pC, 0.300-5.8 GeV, beam-size 5-500 μm (rms)
- ➢ Geometrical resolution (5 μm W wire): 1.25 μm
- ➢ Beam profile reconstruction: beam synchronous acquisition of encoder position and BLM signal
- ➢ BLM: scintillator fiber+POF+PMT





BLM: scintillator fiber



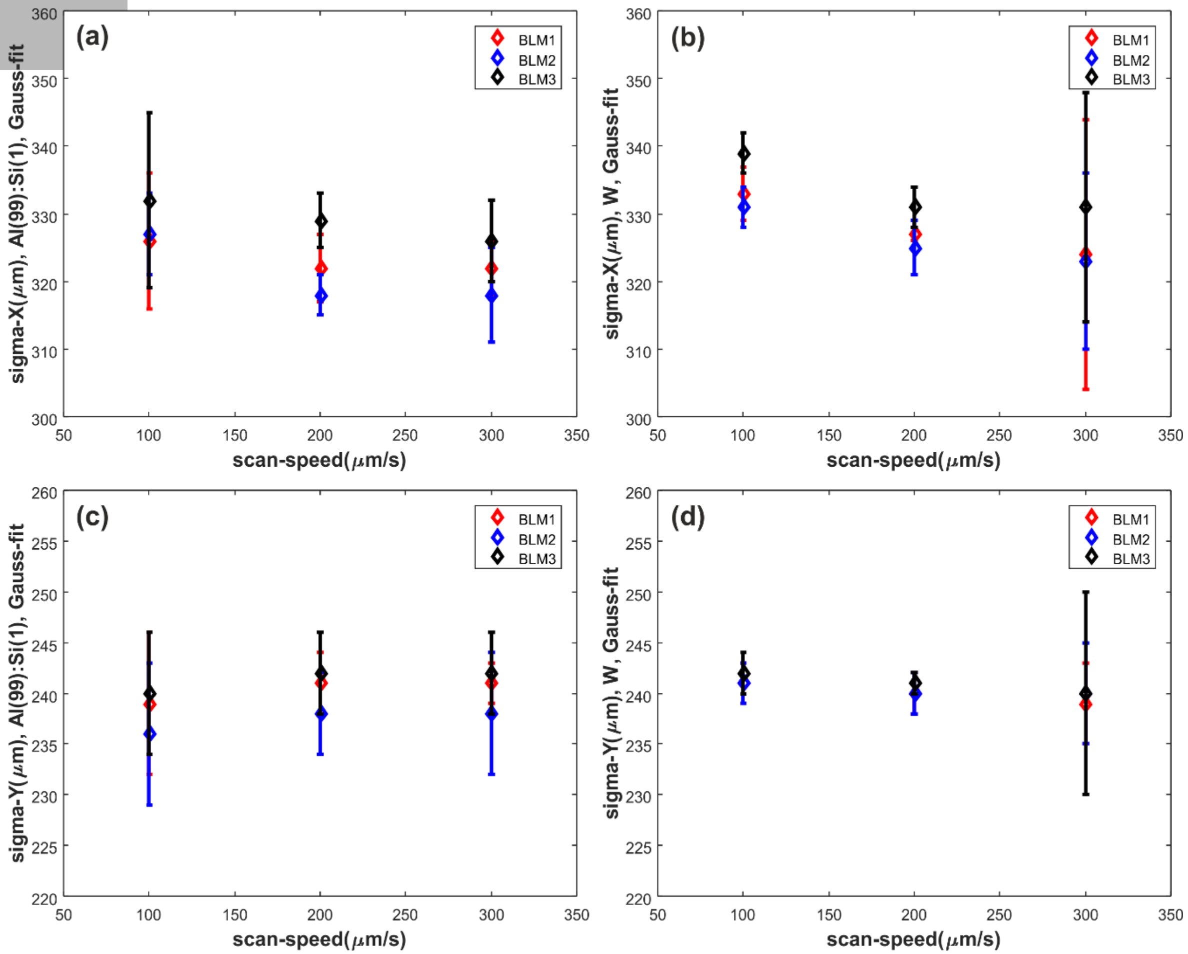
- License Agreement between PSI and UHV-Design Ltd. for the commercialization of the vacuum chamber+wire fork.

- Motorized feedthrough produced by UHV-Design

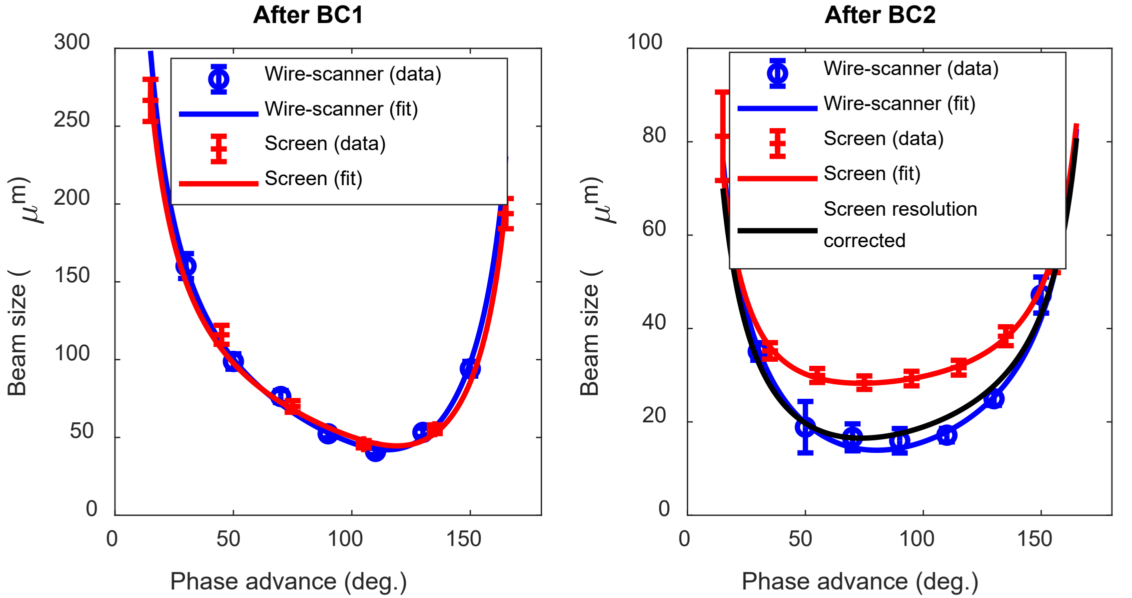
Conventional WS: resolution and invasiveness constraints (2/3)

Beam profile measurements at SwissFEL

- **Beam energy 300 MeV, charge 20 pC, rep.rate 10Hz**
- **5 μm W wire: scan_X (b) ; scan_Y (d)**
- **12.5 μm Al(99):Si(1) wire: scan_X (a) ; scan_Y (c)**



Beam charge 10 pC, beam energy after BC1 ~300MeV, BC2~5.8 GeV



Emittance measurements at SwissFEL: WS vs YAG screen,
E.Prat et al., *Generation and Characterization of Intense Ultralow-Emittance Electron Beams for Compact X-Ray Free-Electron Lasers, PHYSICAL REVIEW LETTERS 123, 234801 (2019),*

G.L. Orlandi et al, *First experimental results of the commissioning of the SwissFEL wire-scanners*, IBIC2017, Grand Rapids. Mi, USA

Conventional WS: resolution and invasiveness constraints (3/3)

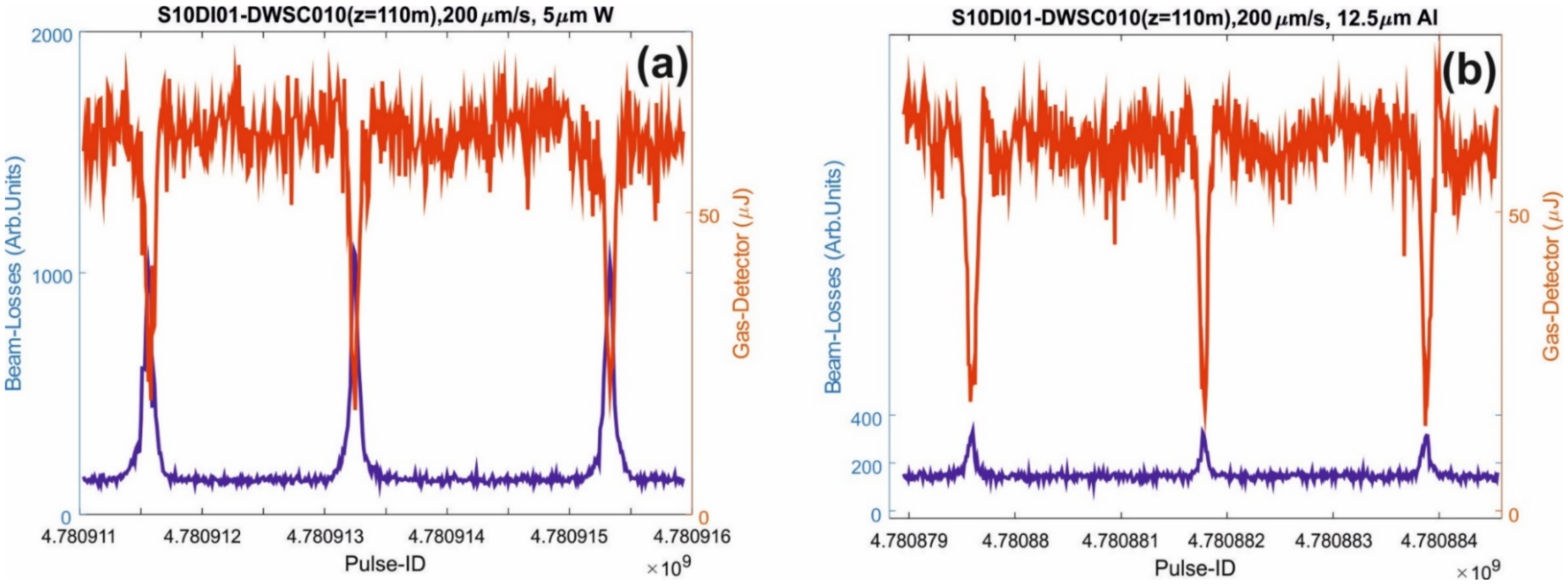
Simultaneous WS and laser pulse energy measurements with gas detector (*):

Scan electron beam with 5µm W wire and 12.5µm Al(99):Si(1) wire and, in parallel, measure laser pulse energy

Al(99):Si(1) vs W wire➔ beam-loss reduction by a factor 3-4 (beneficial to machine protection)

Al(99):Si(1) vs W wire ➔ despite lower density and atomic number, larger impact surface detrimental to lasing transparency

Higher WS geometrical resolution of the wire ➔ better wire transparency to the lasing



Beam-synchronous measurements of laser pulse energy (Gas-Detector) and e-beam profile (WS):
(a) 5 µm W wire;
(b) 12.5 µm Al(99):Si(1) wire.
Bunch charge ~200 pC, beam energy ~300 MeV at the WS location, 2.6 GeV at the undulator beamline, photon energy 2.488 keV (wavelength=4.983A) .

Energy (dE) radiated by single electron with energy E in a thickness dX of matter with radiation length L_R

$$\frac{dE}{E} = \frac{dX}{L_R}$$

$$\frac{\Delta E_W}{\Delta E_{Al}} = R_{W/Al} \frac{X_W}{L_W} \frac{L_{Al}}{X_{Al}} = 4.1$$

$$R_{W/Al} = 0.4$$

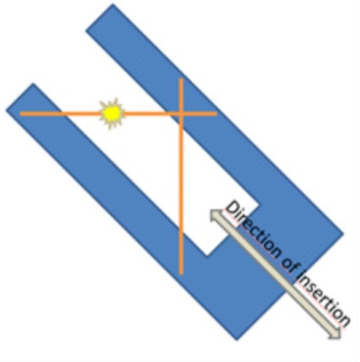
$$L_{Al} = 8.9 \text{ cm}$$

$$L_W = 0.35 \text{ cm}$$

(*) P. Juranic, et al., *SwissFEL Aramis beamline photon diagnostics*,J. Synchrotron Rad. (2018). 25, 1238-1248.

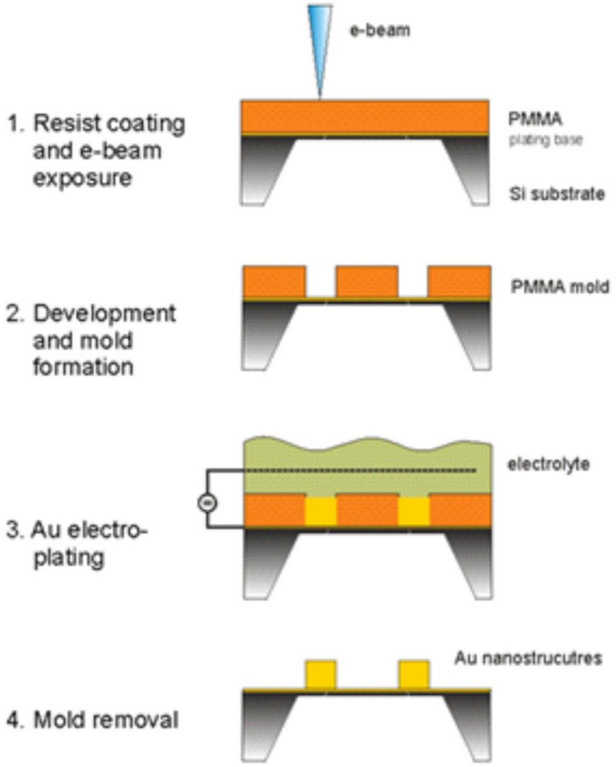
invasiveness

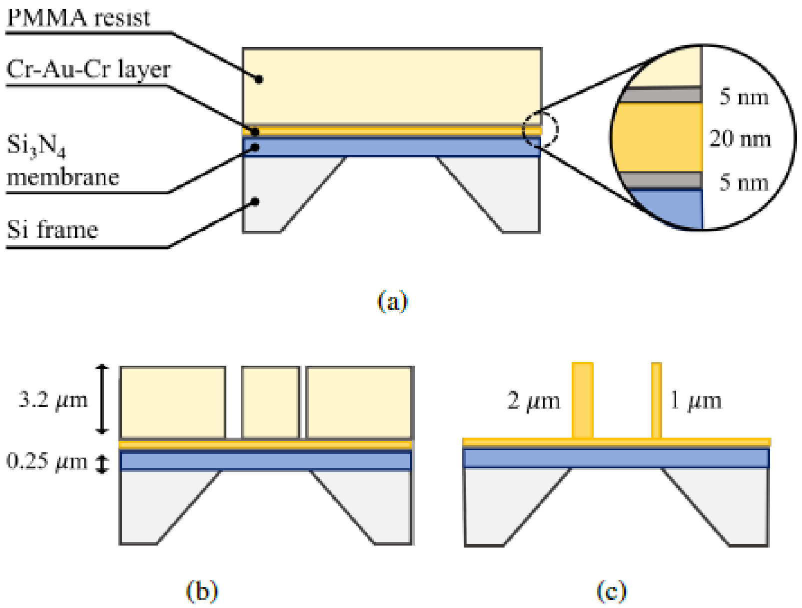
Motivations and Goals of “WS nano-fabrication”



- Diagnostics with sub-μm resolution and minimally invasiveness needed for:
    - Low-charge and low emittance beam and monitoring FEL operations
    - Novel laser and plasma driven accelerator
- Conventional WS (cylindrical metallic wires stretched onto a fork): spatial resolution limit ~1μm (rms)
- Improve WS spatial resolution ←→ thinner wire ←→ smaller number of perturbed electrons ←→ minimal beam invasiveness and higher transparency to lasing
- New techniques to fabricate WS with resolution beyond the 1 μm (rms) limit
  → Nano-lithography (integration wire+fork in a unique structure)
- Present status, free-standing WS independently nano-fabricated at PSI and FERMI and tested at SwissFEL:
    - sub-μm spatial resolution (~250 nm)
    - beam clearance ~2mm
- Future plans:
    - nano-fabricated free-standing WS with sub-μm resolution and beam clearance ~10mm
    - free-standing sub-um wires (X,Y scan) integrated into a fork as a standard WS solution for a FEL.

First nano-fabricated WS at PSI: WS on-a-membrane with sub-µm resolution

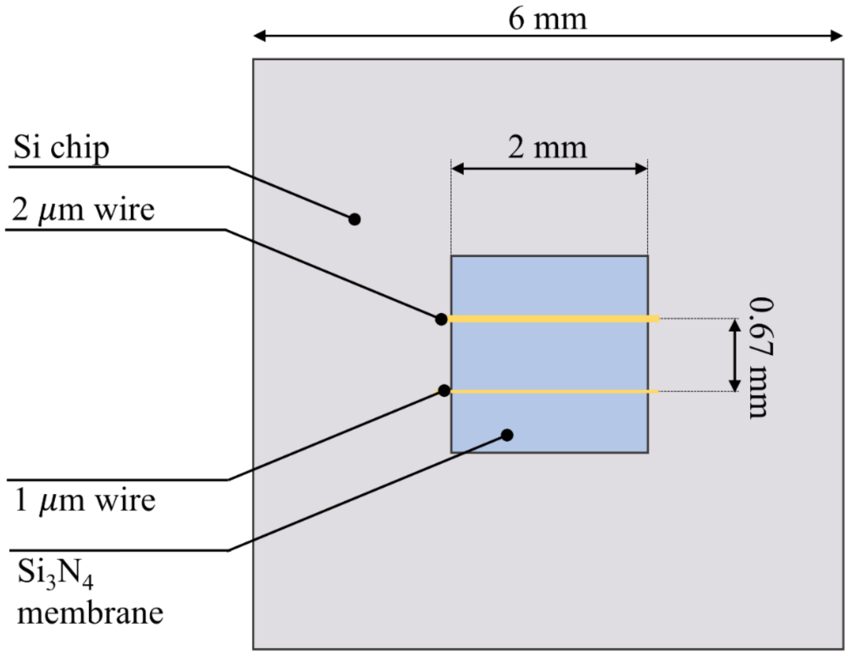




(a)

(b)

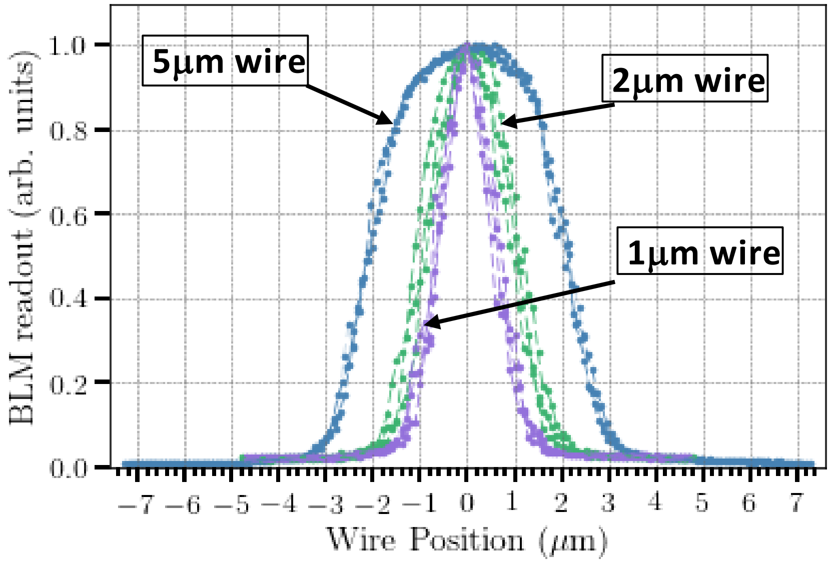
(c)

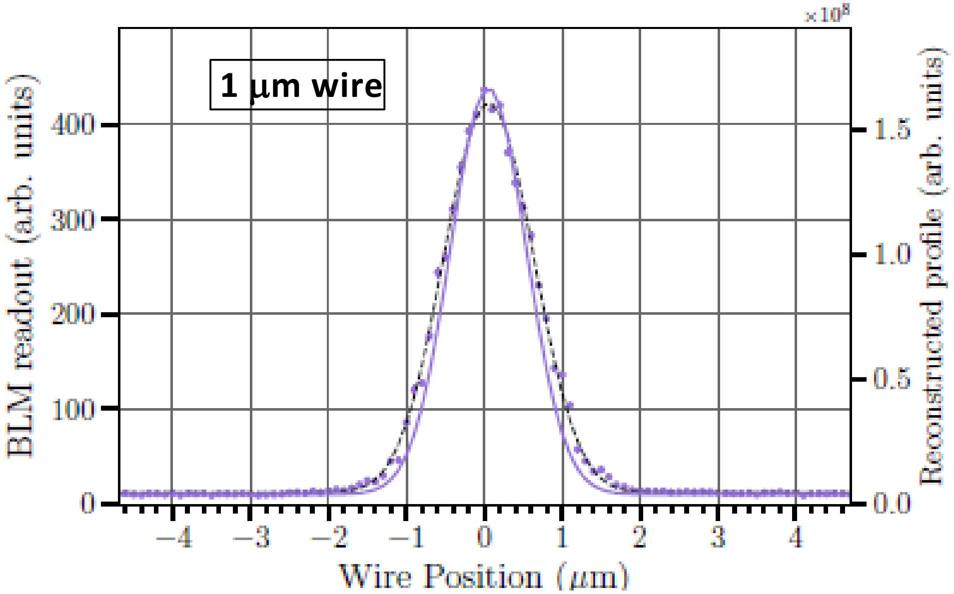


WS nano-fabrication at Laboratory for Micro- and Nanotechnology (LMN, PSI):
(a) Si3N4 membrane + Cr-Au-Cr coating + PMMA resist spin-coating
(b) e-beam lithography of PMMA to write parallel stripes (isopropanol+water treatment to develop exposed resist)
(c) Developed membrane trenches filled with Au by electroplating (PMMA resist removed by oxygen-plasma)

Sub-µm WS on-a-membrane: e-beam test at SwissFEL (*)

- Low charge and emittance machine setting: 330MeV, <1pC, emittance ~50 nm, vertical beam size ~500 nm
- Beam profile analysis: fit with a Gaussian profile convoluted with a rectangular shaped distribution function



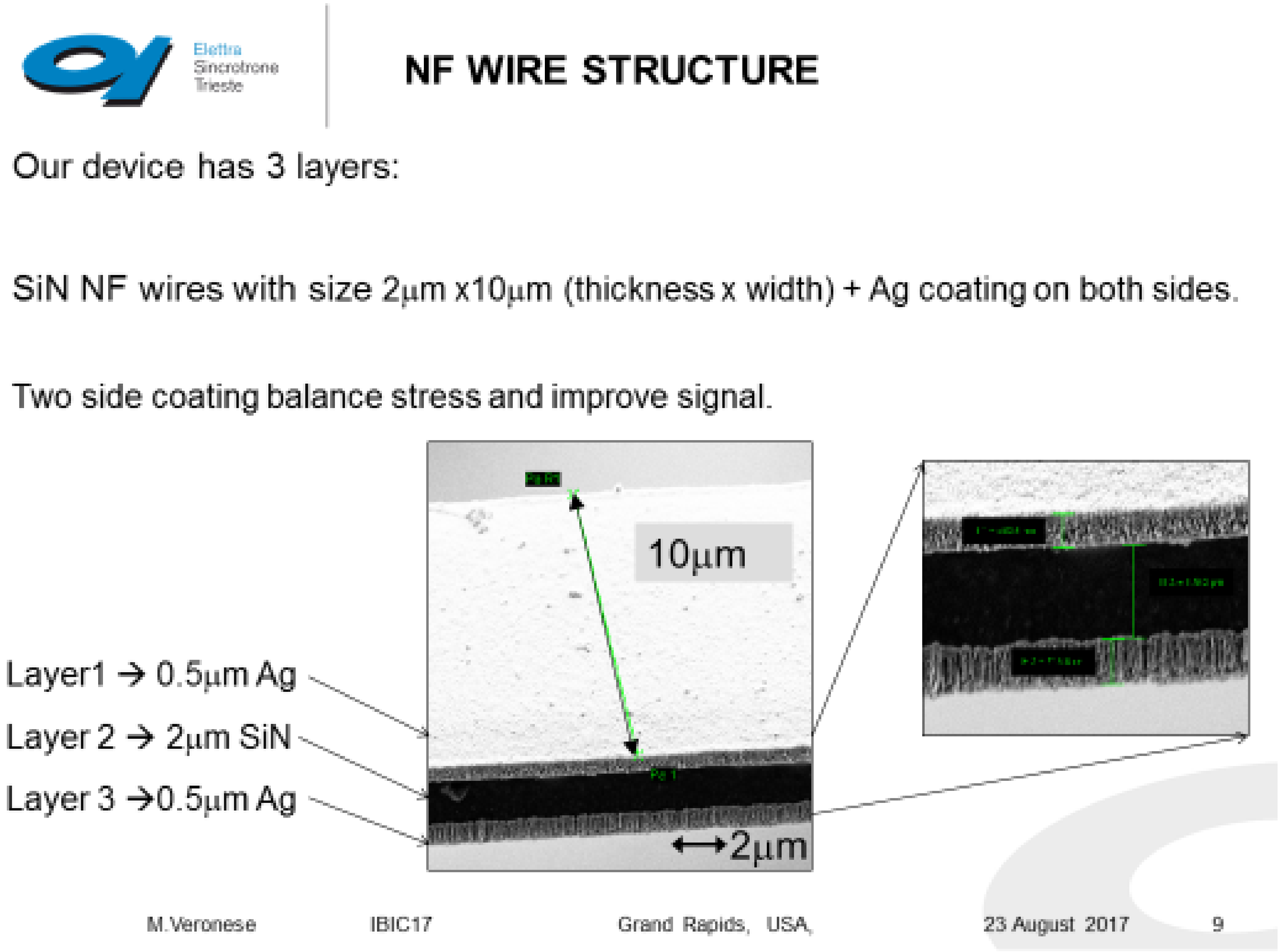


	5 μm W	2 μm Au	1 μm Au
Resolution (nm)	1250	600	300
σ_{rms} (nm)	1967 ± 16	890 ± 2	449 ± 32
σ_y (nm)	462 ± 11	491 ± 4	491 ± 5

(*) S. Borrelli, G. L. Orlandi, M. Bednarzik, C. David, E. Ferrari, V. A. Guzenko, C. Ozkan-Loch, E. Prat, R. Ischebeck, *Generation and Measurement of Sub-Micrometer Relativistic Electron Beams*, Communications Physics-Nature, 1, 52 (2018).

First nano-fabricated WS at FERMI-IOM-CNR: free-standing WS (*)

Free-standing WS nano-fabricated by IOM-CNR and tested at FERMI: geometrical resolution 2.9 µm



Elettra Sincrotrone Trieste

NF WIRE STRUCTURE

Our device has 3 layers:

SiN NF wires with size 2µm x10µm (thickness x width) + Ag coating on both sides.

Two side coating balance stress and improve signal.

Layer1 → 0.5µm Ag

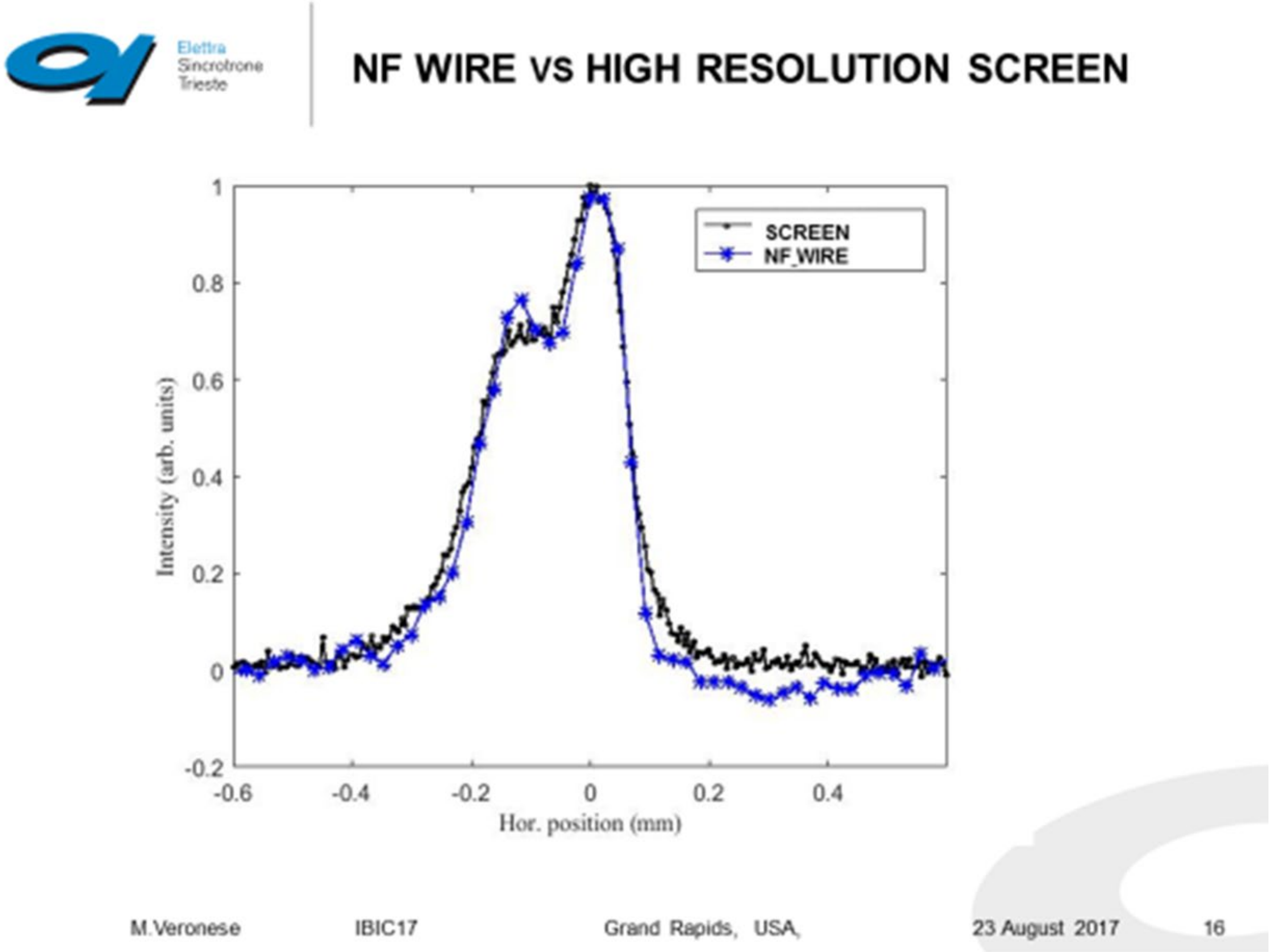
Layer 2 → 2µm SiN

Layer 3 →0.5µm Ag

M.Veronese IBIC17 Grand Rapids, USA, 23 August 2017 9

(*) M. Veronese, S. Grulja, G. Penco, M. Ferianis, L. Froehlich, S. Dal Zilio, S. Greco, M. Lazzarino, *A nanofabricated wirescanner with free standing wires: Design, fabrication and experimental results*, NIM A, 891, 32-36 (2018).

Free-standing nano-fabricated WS (IOM-CNR): e-beam test at FERMI



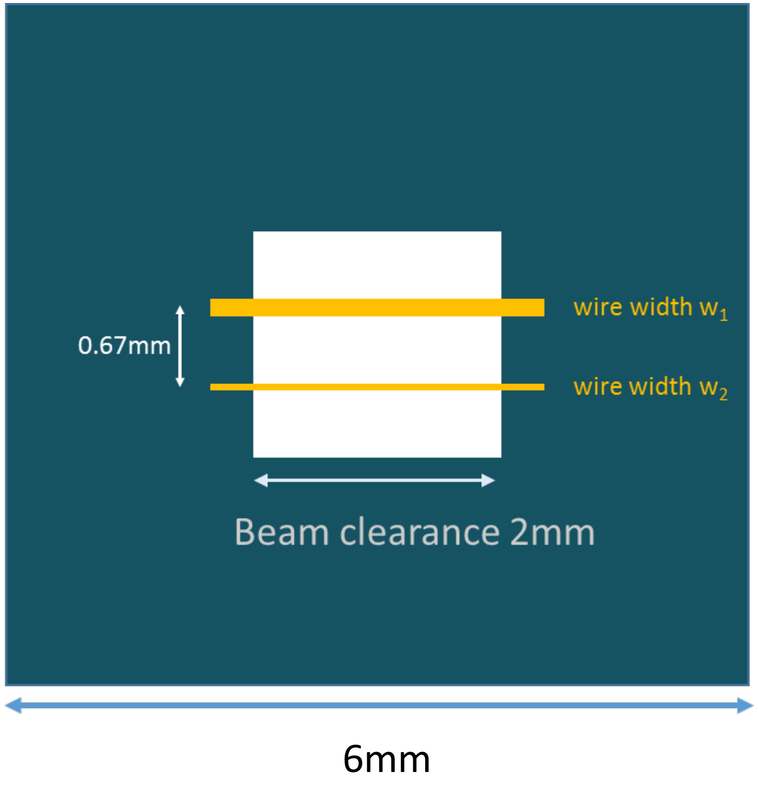
Elettra Sincrotrone Trieste

NF WIRE vs HIGH RESOLUTION SCREEN

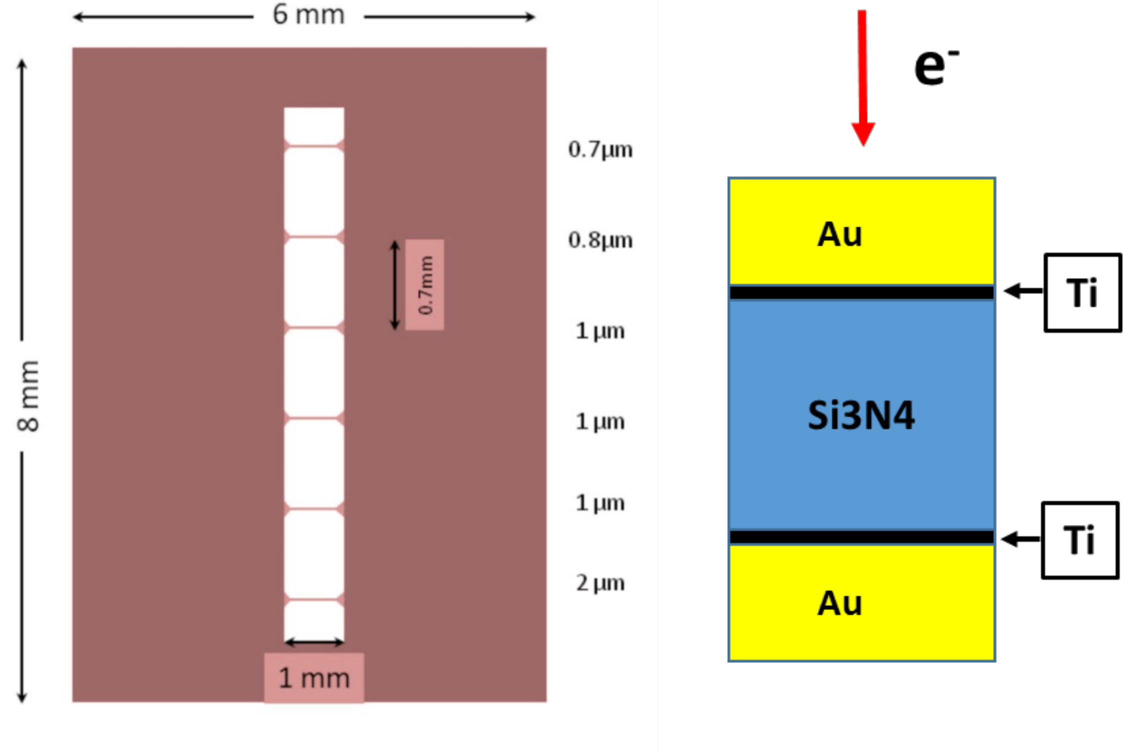
M.Veronese IBIC17 Grand Rapids, USA, 23 August 2017 16

PSI and FERMI nano-fabricated free-standing WS

PSI WS chip: bulk Au stripe; width 800nm and 500nm; thickness ~2μm



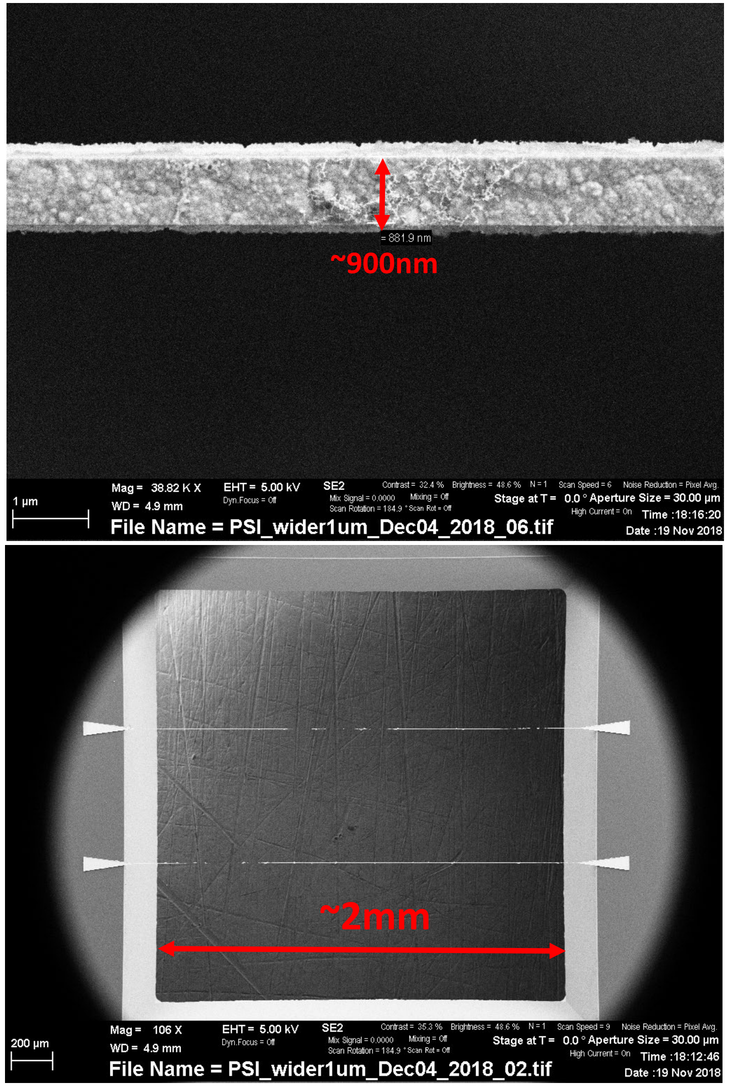
FERMI WS chip: sandwich Au/Si3N4/Au; thickness ~3μm [Au(1μm),Si3N4(2μm),Ti(20nm)]



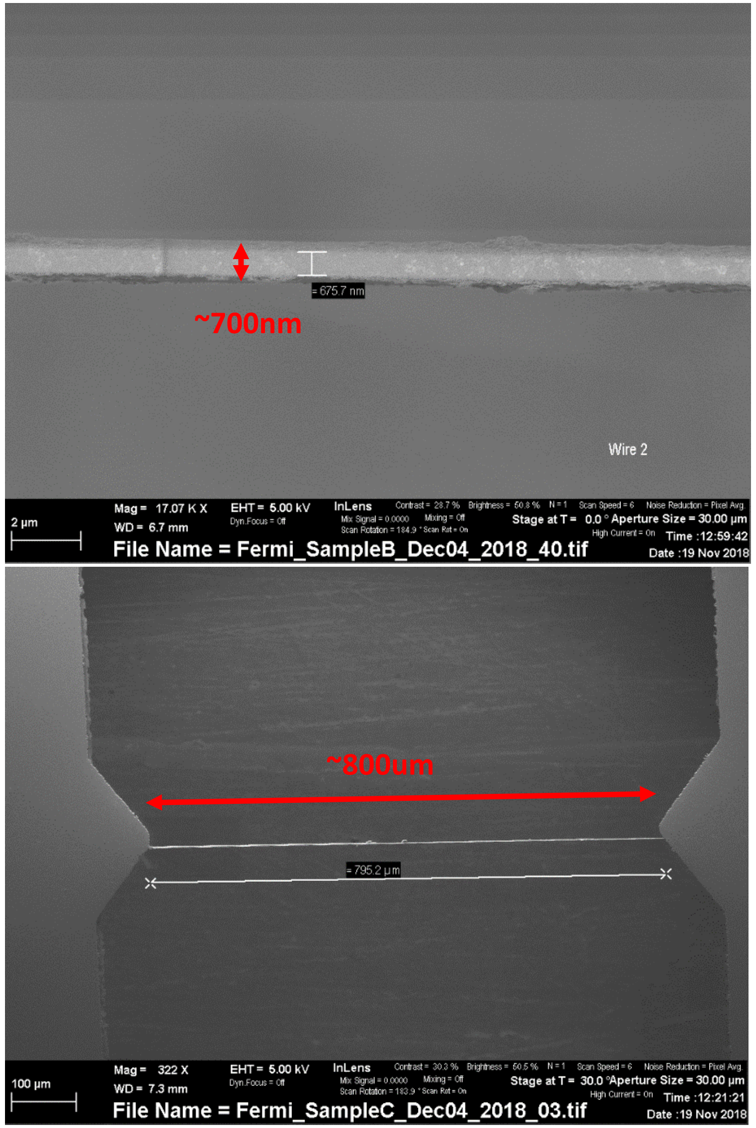
Bulk Au vs sandwich Au/Si3N4/Au:

- Higher signal-to-noise ratio (see WS measurement slide)
- Possible minor mechanical stability when increasing the beam clearance

SEM images of the nano-fabricated WS structures

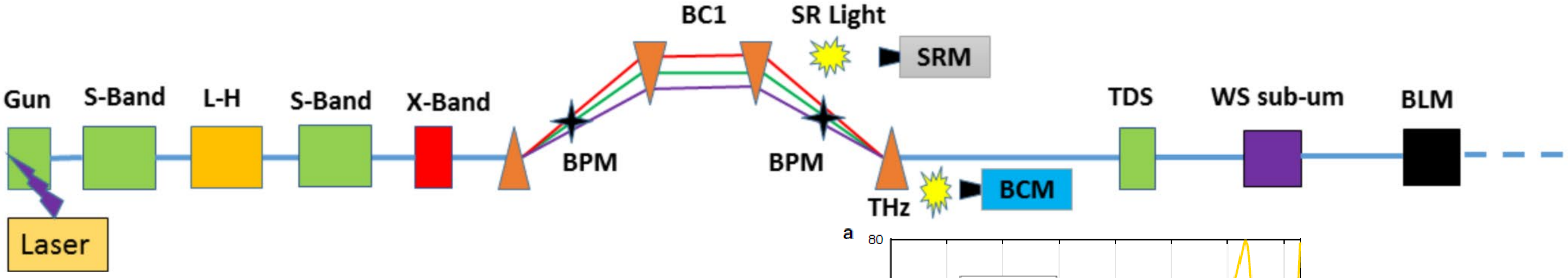


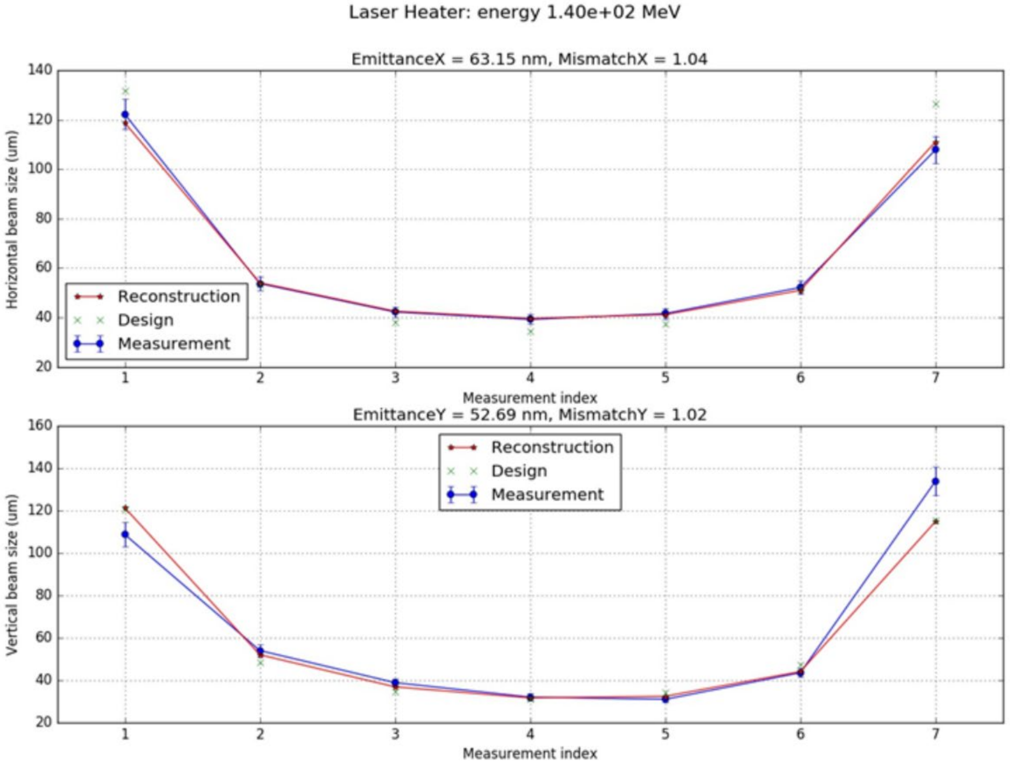
PSI WS nano-fabrication,
Laboratory for Micro- and Nanotechnology, LMN, PSI

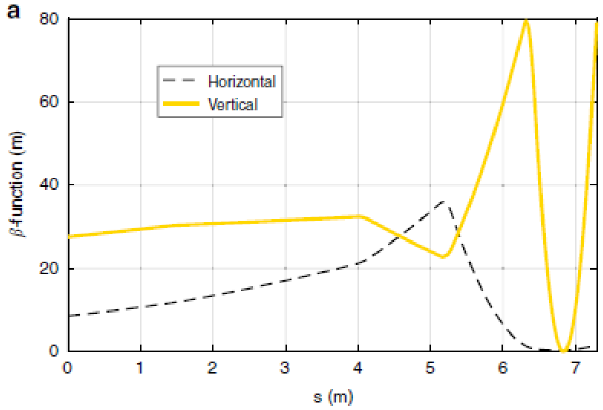


FERMI WSC nano-fabrication,
IOM-CNR, Trieste, Italy

Experimental set-up at SwissFEL







βx, βy evolution between BC1 and WS sub-μm

beam vertical size at the WS position: ~500nm

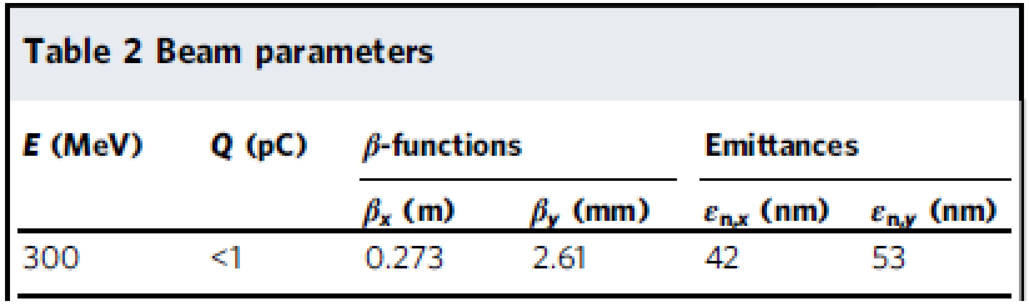
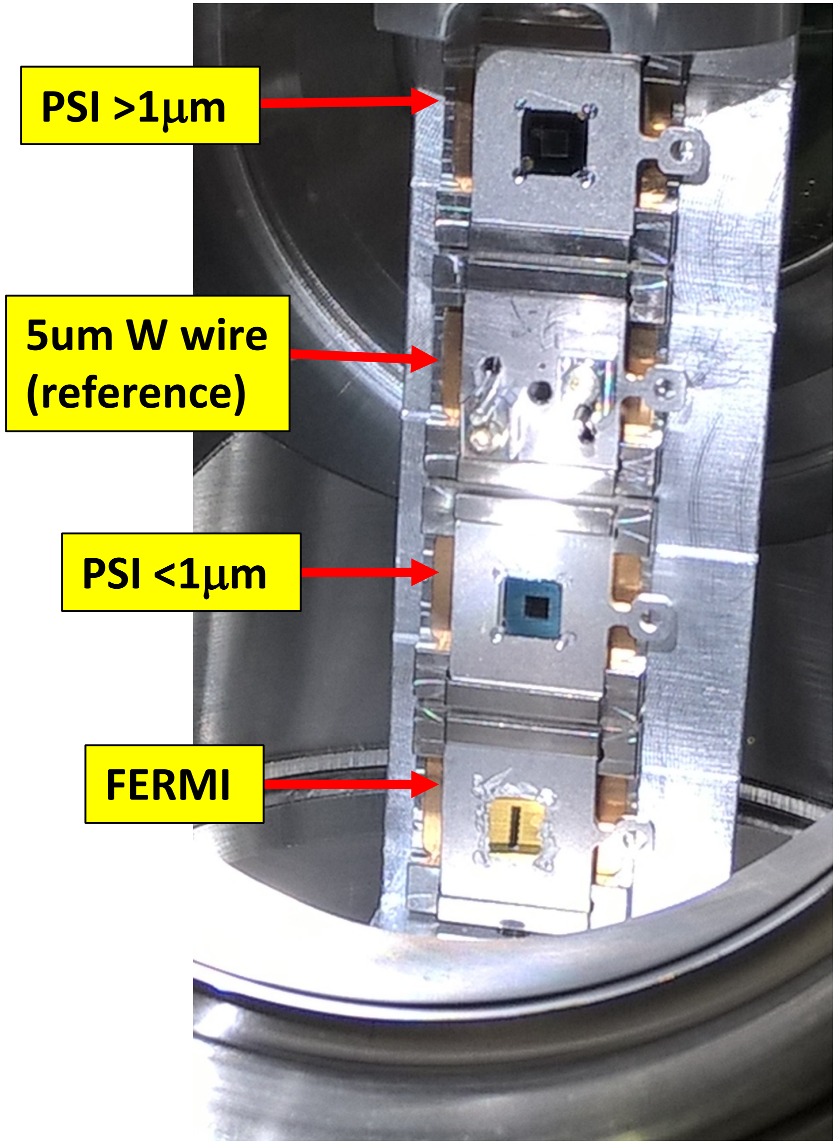


Table 2 Beam parameters

E (MeV)	*Q* (pC)	*β*-functions		Emittances	
		β_x (m)	β_y (mm)	$\varepsilon_{n,x}$ (nm)	$\varepsilon_{n,y}$ (nm)
300	<1	0.273	2.61	42	53

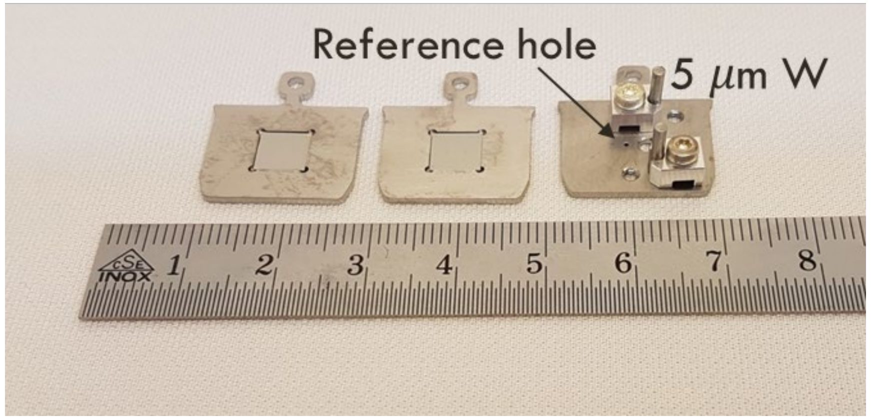
Sub-um WS set-up in the sample holder of the “ACHIP” vacuum-chamber

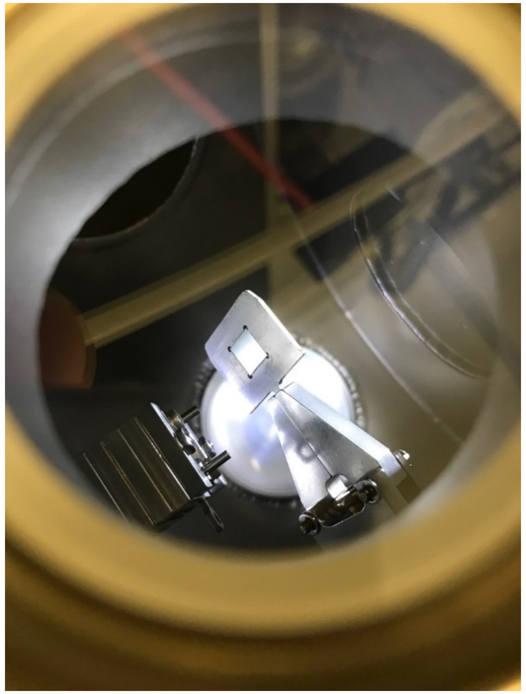

PSI >1μm

5um W wire (reference)

PSI <1μm

FERMI





WS chips mounted on a 4-slot sample holder.

ACHIP vacuum chamber equipped with:

- **Load-lock pre-vacuum chamber**
- **UHV feed-through**
- **Stepper motor**
- **Encoder (0.1 μm resolution)**

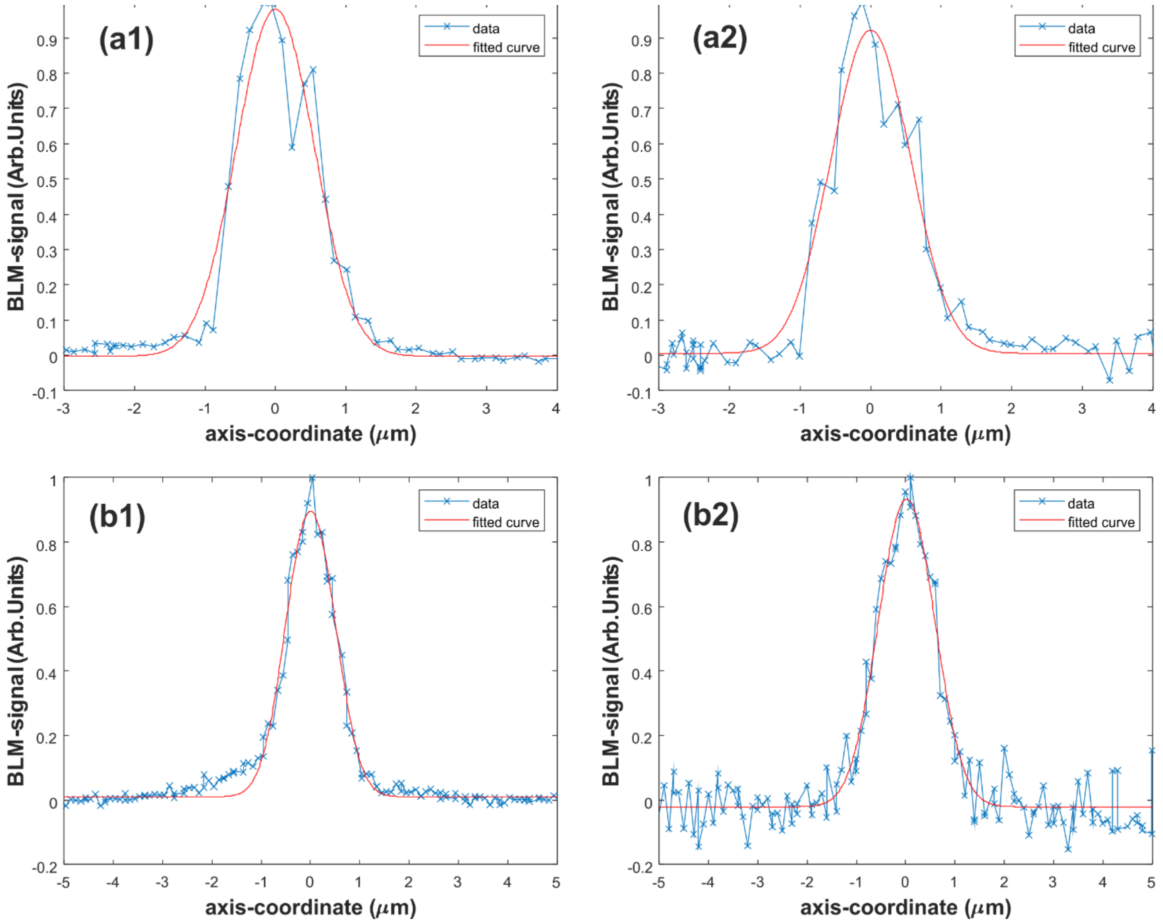
<u>Only vertical WS measurements are possible!</u>

Free-standing sub-μm WS: experimental test at SwissFEL (*)

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

Beam profiles acquired with PSI (1) and FERMI (2) WS in two different measurement sessions (a, b):

- **low-charge (<1pC)**
- **low emittance (ε_y~55 nm) ➔ <u>beam size~500nm</u>**
- **beam energy ~300 MeV**



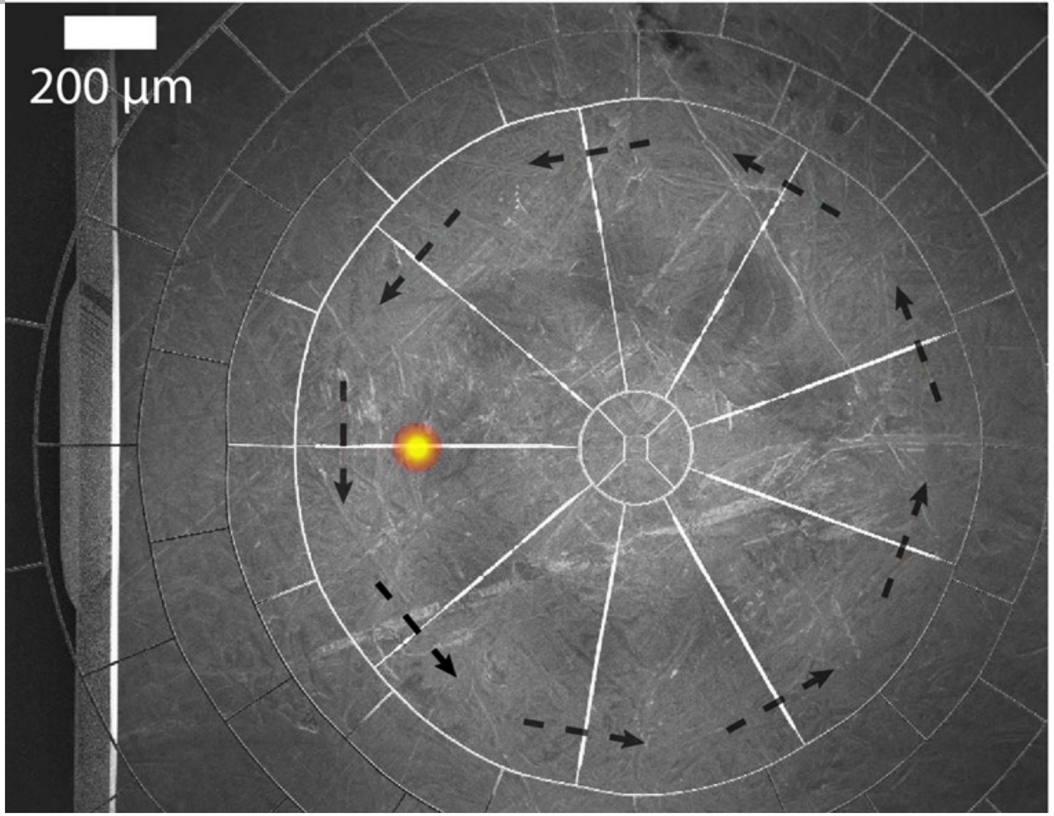
<u>Error-function-fit</u>: convolution of Gaussian distribution with rectangular shaped distribution with a width w:

$$
\begin{aligned}
erf-fit(x) = \quad & a \times [erf([x-c+w/2]/\sqrt{2}/\sigma)+ \\
& -erf([x-c-w/2]/\sqrt{2}/\sigma)]+b,
\end{aligned}
$$

<u>Heat-loading resilience</u> test (200 pC, 1Hz): <u>no damage observed</u> in WS structures

(*) G.L. Orlandi et al., *Nanofabricated free-standing wire scanners for beam diagnostics with submicrometer resolution*, PHYSICAL REVIEW ACCELERATORS AND BEAMS 23, 042802 (2020)

Beam Profile Diagnostics with Nanofabricated Wire Scanner - Tomography

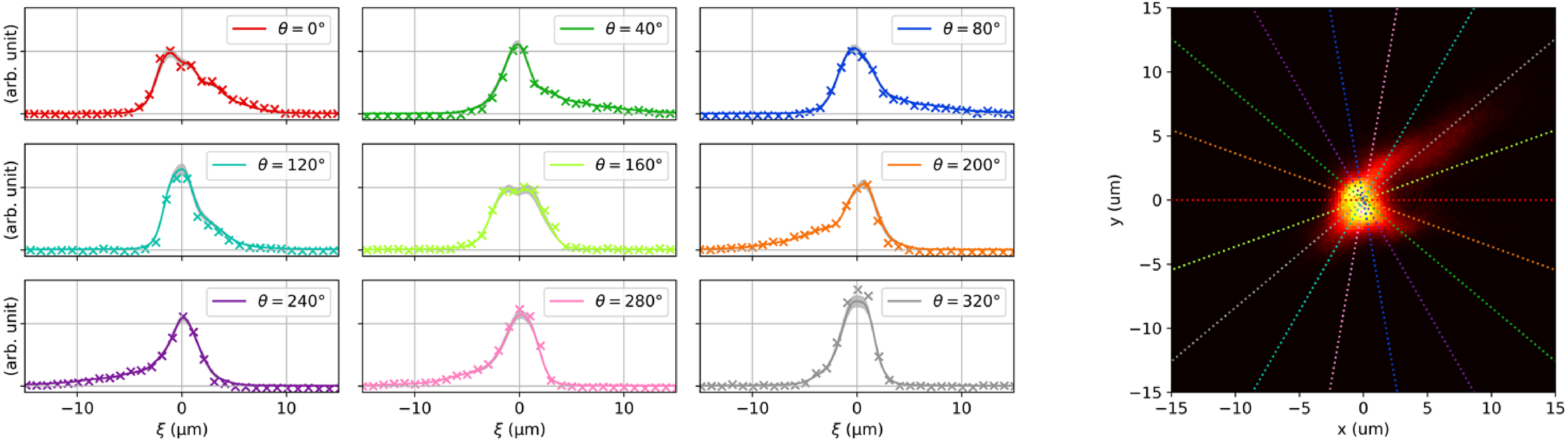


- 9 Gold wires oriented at different angles
- Wire width: 1 µm
- Free-standing spider web
- Fabricated at PSI by Laboratory for Micro- and Nanotechnology with e-Beam lithography
- Measure 1D beam projections with downstream loss monitor
- 4D Beam tomography:

  B. Hermann et al, 2021, PRAB
  https://doi.org/10.1103/PhysRevAccelBeams.24.022802

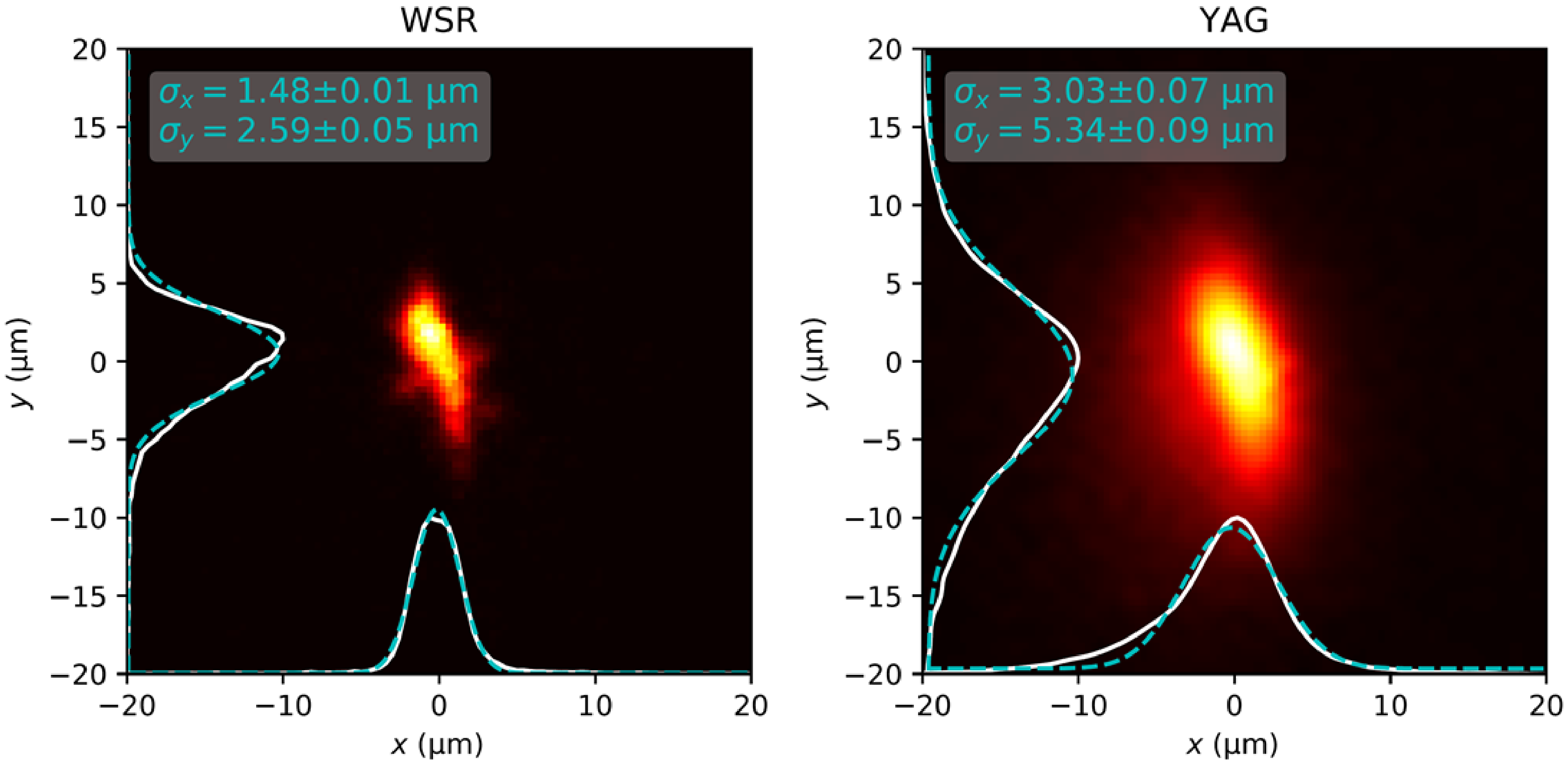
Beam Profile Diagnostics with Nanofabricated Wire Scanner - Tomography

Charge: 10 pC, Energy: 3 GeV



B. Hermann et al, 2021, PRAB
https://doi.org/10.1103/PhysRevAccelBeams.24.022802

Wire Scanner Reconstruction vs. 50 µm Thick YAG Screen + Microscope



Same machine settings for WSR and YAG measurement, charge: 1 pC.

Conclusions and Outlook

- Innovative free-standing WS structure with unprecedented sub-micrometer geometrical resolution (~250nm). Nano-fabrication by LMN at PSI and byIOM-CNR for FERMI.

- Successful experimental tests at SwissFEL of FERMI and PSI free-standing WS at low charge (<1pC, σ~500nm, 300MeV) and high charge (200 pC, heat-loading resilience test)

- Beam profile reconstruction by tomography with nano-fabricated WS

- Long terms goal:
  - Make nano-fabricated WS with sub-micrometer resolution a standard diagnostics solution for a FEL:
    - Increase the WS beam clearance from 2mm up to 10mm (metal-silicon-nitride sandwich stripe probably more promising than bulk metal strips for such a goal).
    - Nano-fabricated WS fork with integrated free-standing stripe pair for X,Y scanning and, possibly, new wire geometry for tomographic reconstruction of the beam transverse profile
    - Minimal invasive nano-fabricated WS with sub-micrometer resolution ideal tool in a FODO section of a FEL for routine measurement of the beam emittance during lasing operation

Thank you for your attention