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PSI

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FERMI-PSI collaboration on nano-fabricated wire-scanners with sub-μm resolution: developments and measurements

IBIC2019 Conference, Malmoe, Sweden

September 10, 2019

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Overview

- *Wire-scanners (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*
- *Conclusions and Outlook*

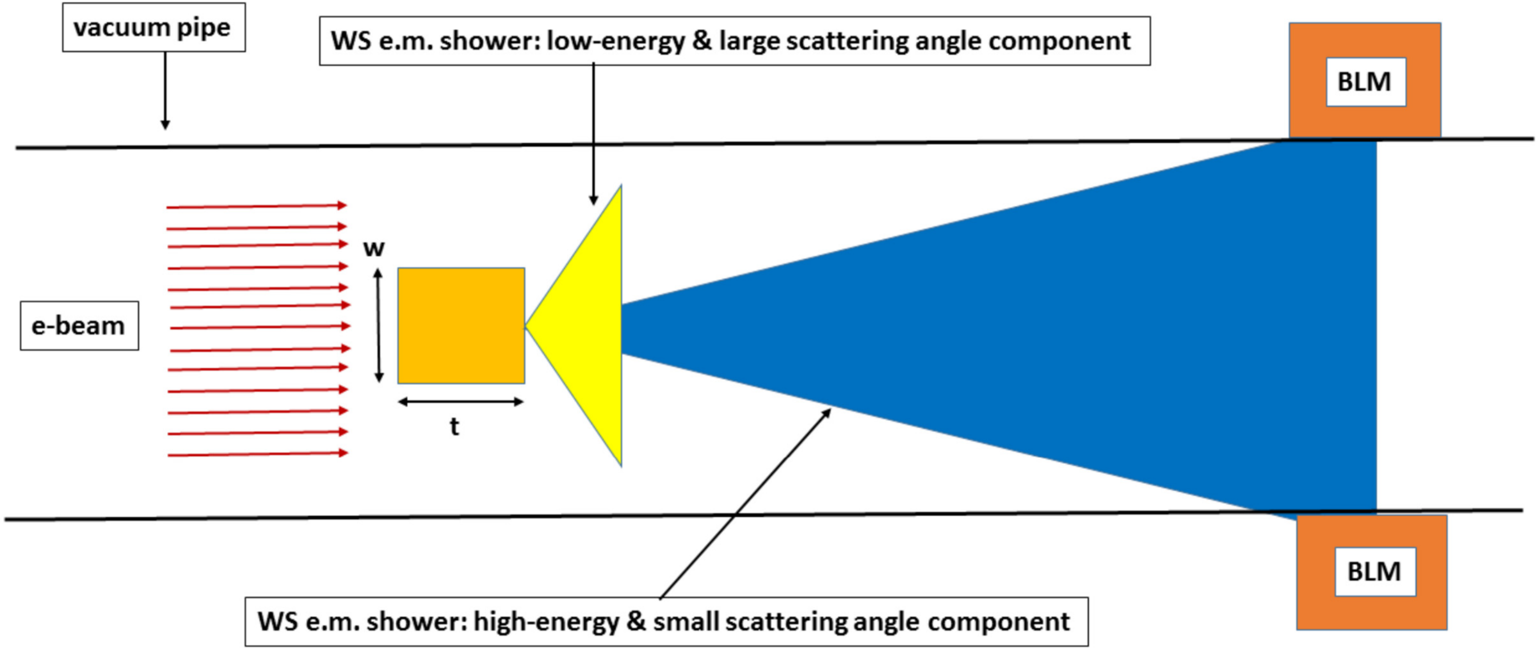
Wire-Scanners (WS) in a FEL: brief introduction (1/3)

WS in a linac driven free electron laser (FEL):

- Diagnostics of the beam transverse profile
- Beam-probe: metallic wire intercepting different portions of 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

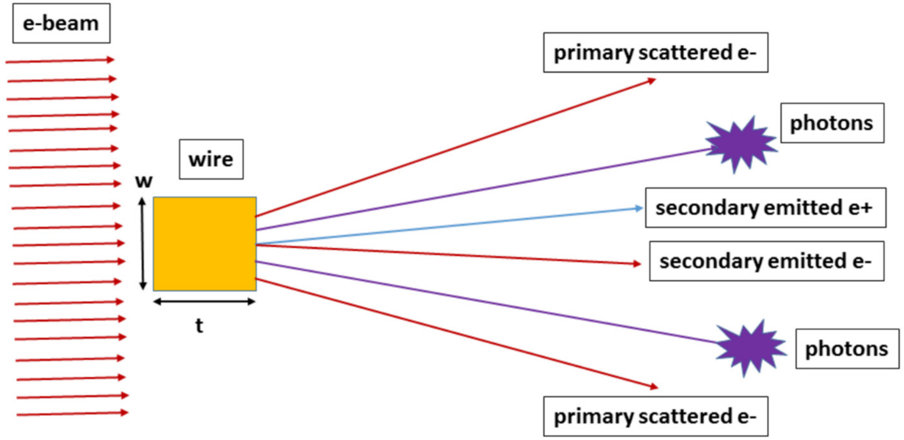
Wire-Scanners (WS) in a FEL: brief introduction (3/3)

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



Wire-Scanners (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

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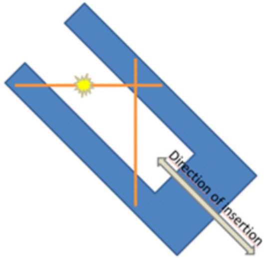
Motivations and Goals of "WS nano-fabrication"

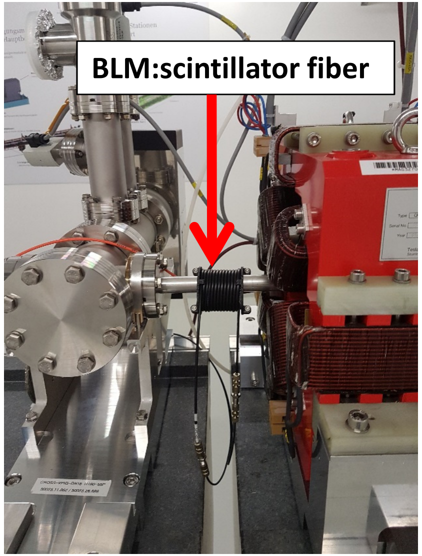


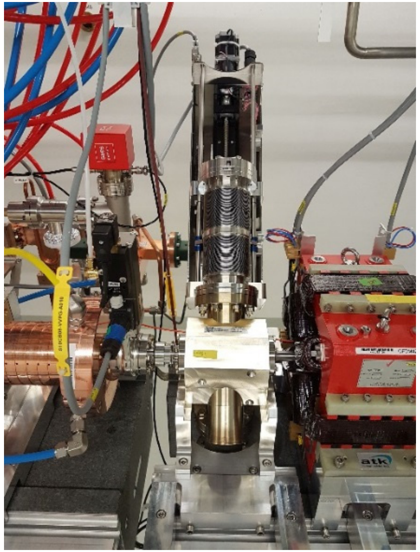
- <u>Diagnostics with sub-μm resolution</u> needed for:
  - Low-charge and low emittance FEL operations
  - Novel laser and plasma driven accelerator
- <u>WS top ranked diagnostics ➔ high spatial resolution and minimal invasivity</u>
- <u>Conventional WS</u> (cylindrical metallic wires stretched onto a fork): <u>spatial resolution limit ~1μm</u> (rms)
- <u>Higher WS spatial resolution</u> ⇔ thinner wire ⇔ smaller number of perturbed electrons ⇔ minimal beam invasivity and higher lasing transparency
- <u>New techniques to fabricate WS with resolution beyond the 1 μm</u> (rms) limit
  ➔ Nano-lithography (integration wire+fork in unique structure)
- <u>Nowadays</u>, free-standing WS independently nano-fabricated at PSI and FERMI and tested at SwissFEL:
  - sub-μm spatial resolution (~250 nm)
  - beam clearance ~2mm
- <u>Near future</u>, nano-fabricated free-standing WS with sub-μm resolution and beam clearance ~10mm
- <u>Final goal</u>, free-standing sub-um wires (X,Y scan) integrated into a fork as standard WS solution for a FEL.

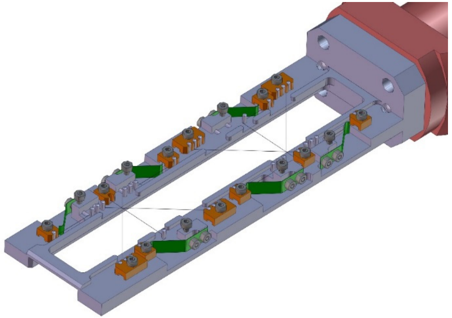
Conventional WS: resolution and invasivity constraints (1/3)

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



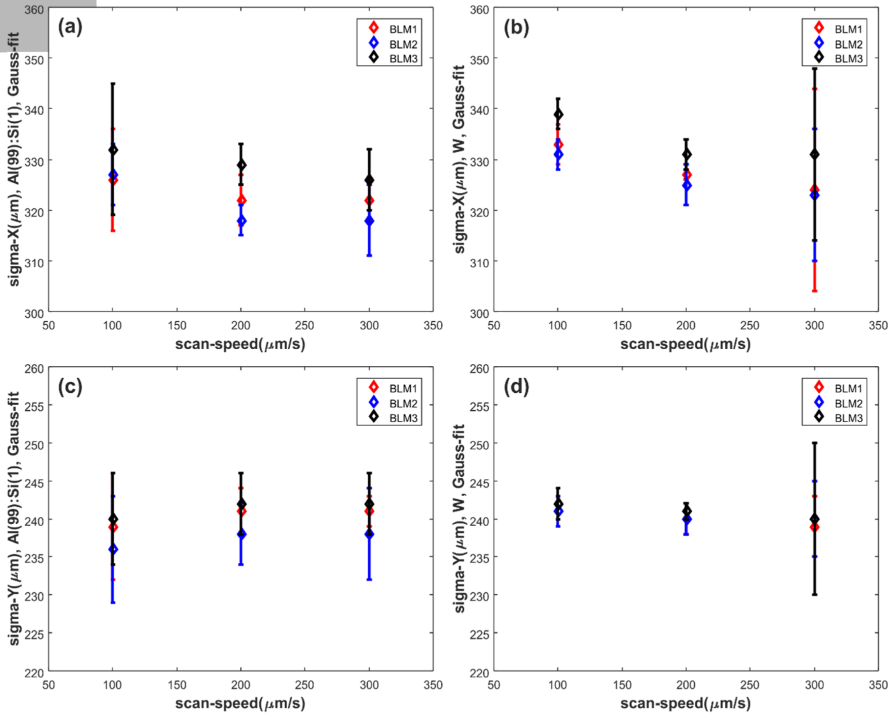




Conventional WS: resolution and invasivity constraints (2/3)

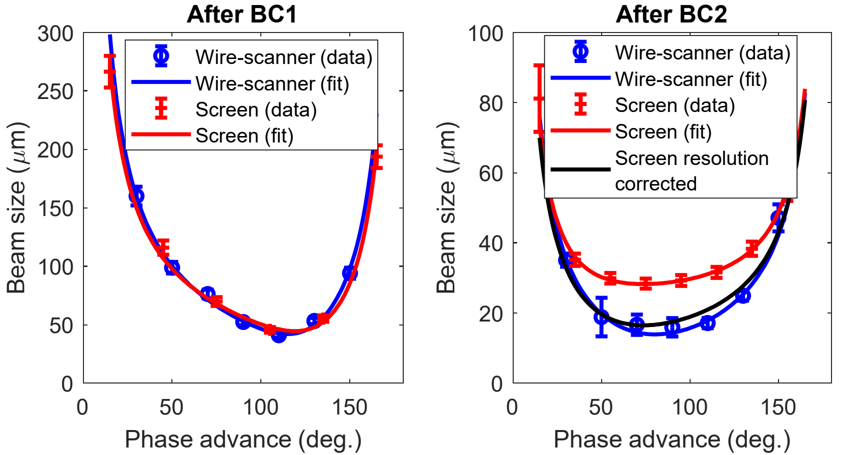
Beam profile measurements at SwissFEL

- **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)**



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

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



Emittance measurements at SwissFEL: WS vs YAG screen,

Ph. Dijkstal talk at FEL2019 conference, Hamburg, Germany

THB03 *Emittance Measurements and Minimization at SwissFEL*

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

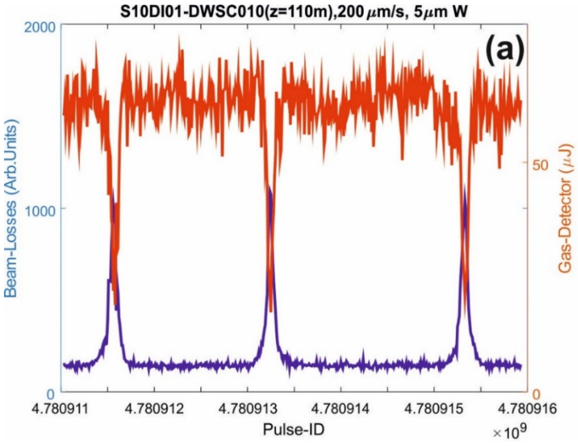
Simultaneous WS and laser pulse energy measurements with gas detector (*):

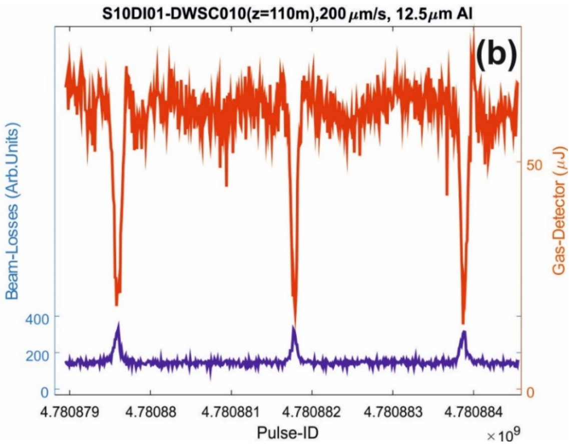
Scan electron beam with 5μm W wire and 12.5μm Al(99):Si(1) wire and, in parallel, measure laser pulse energy

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





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

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

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

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

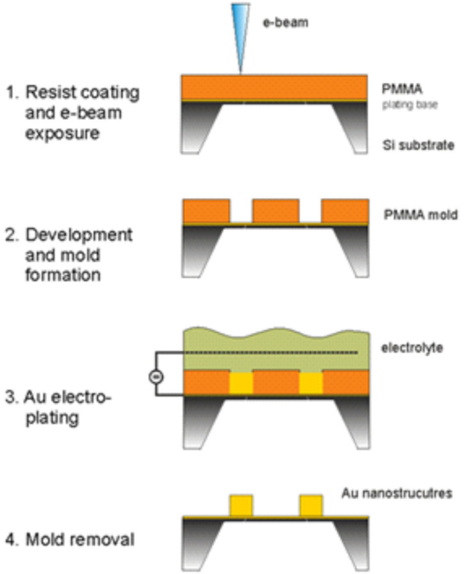
$$L_{Al} = 8.9 \text{ cm}$$

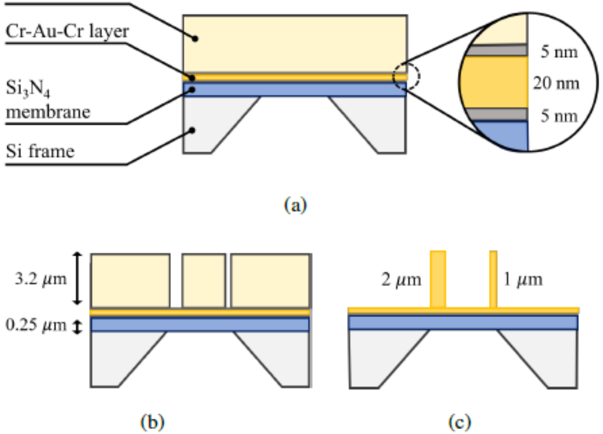
$$L_W = 0.35 \text{ cm}$$

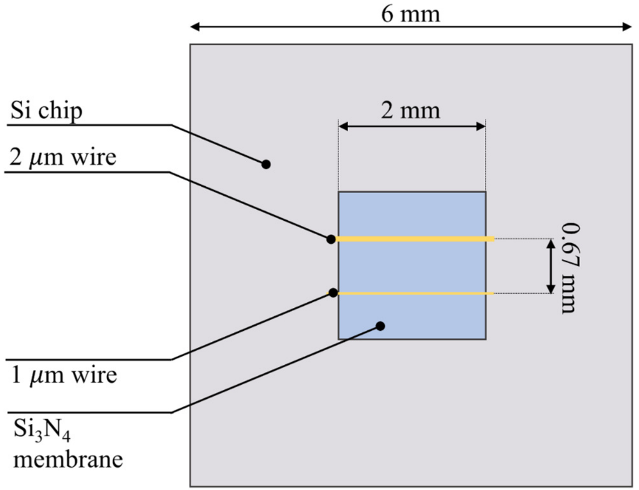
Beam-synchronous measurements of laser pulse energy (Gas-Detector) and e-beam profile (WS):
(a) 5 μm W wire;
(b) 12.5 μm Al(99):Si(1) wire.
Bunch charge ~200 pC, beam energy ~300 MeV at the WS location, 2.6 GeV at the undulator beamline, photon energy 2.488 keV (wavelength=4.983A) .

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

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



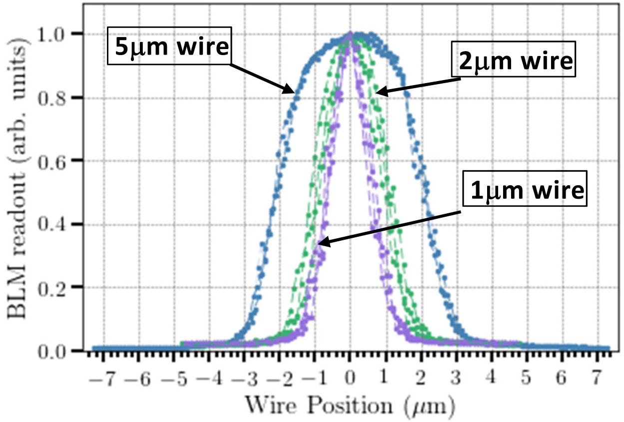


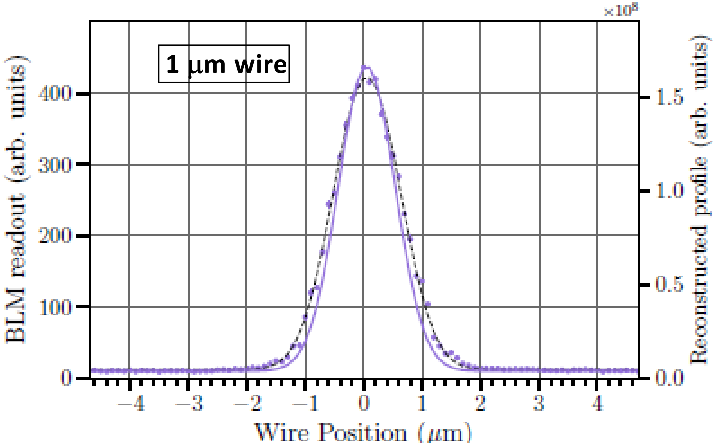


WS nano-fabrication at Laboratory for Micro- and Nanotechnology (LMN, PSI):
(a) Si3N4 membrane + Cr-Au-Cr coating + PMMA resist spin-coating
(b) e-beam lithography of PMMA to write parallel stripes (isopropanol+water treatment to develop exposed resist)
(c) Developed membrane trenches filled with Au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

(*) 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).

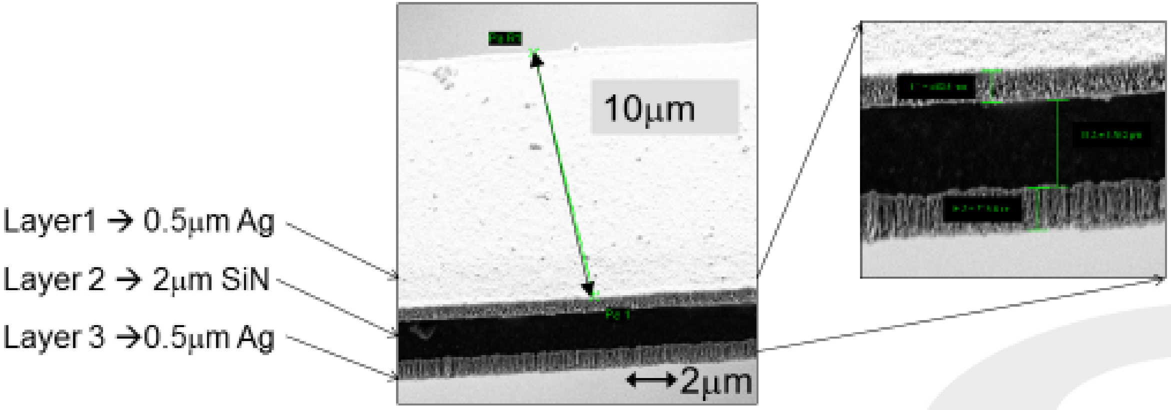
Elettra Sincrotrone Trieste

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.

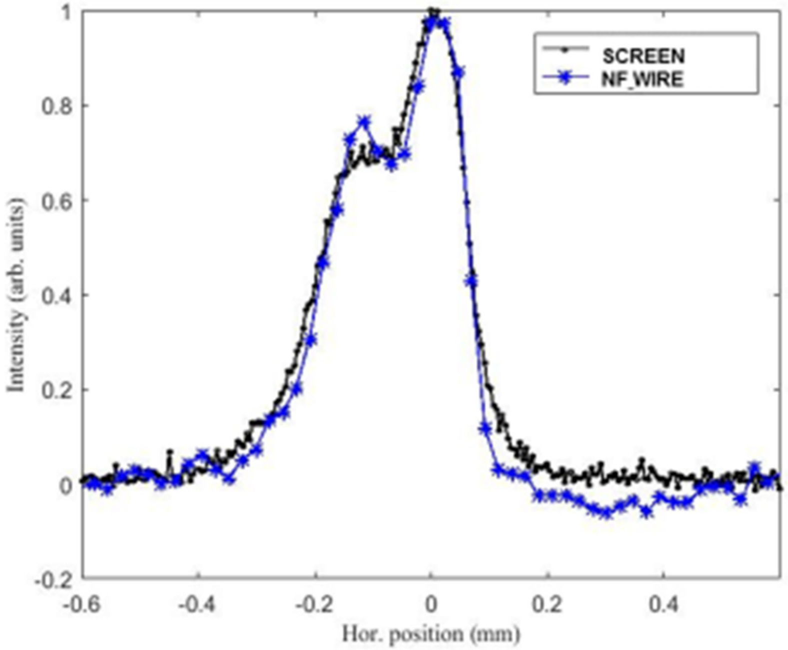


M.Veronese IBIC17 Grand Rapids, USA, 23 August 2017 9

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

Elettra Sincrotrone Trieste

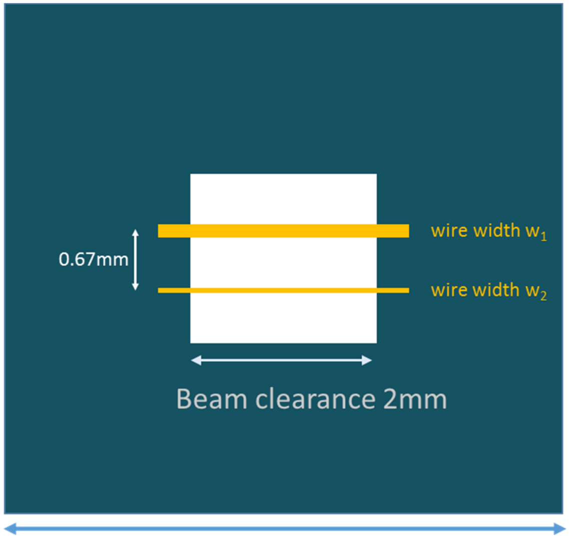
NF WIRE VS HIGH RESOLUTION SCREEN



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

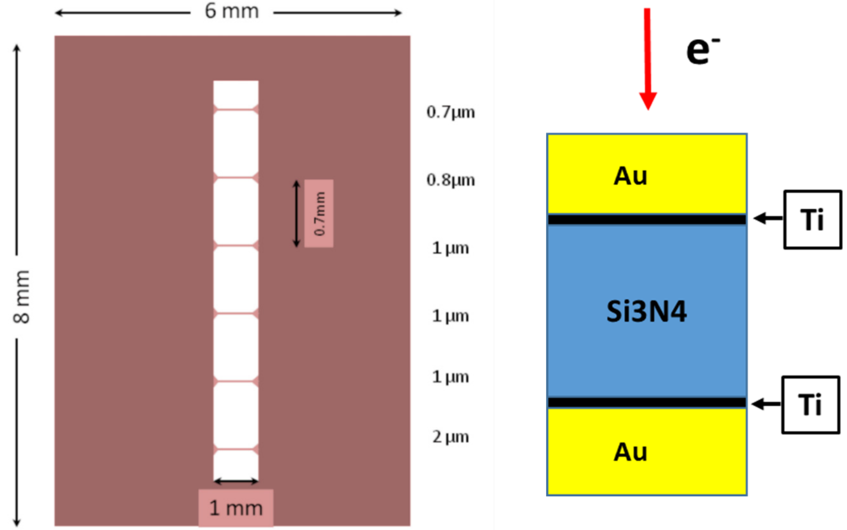
PSI and FERMI nano-fabricated free-standing WS

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



6mm

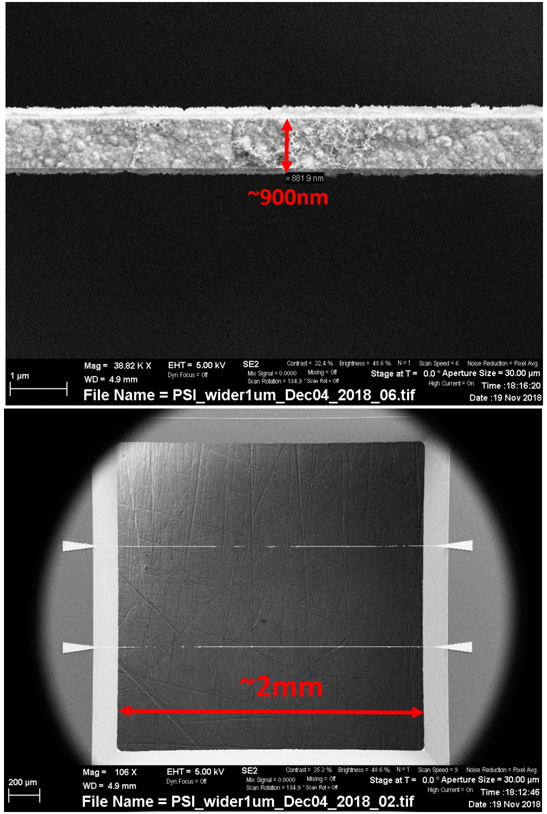
FERMI WS chip: sandwich Au/Si3N4/Au; thickness ~3μm [Au(1μm),Si3N4(2μm),Ti(20nm)]



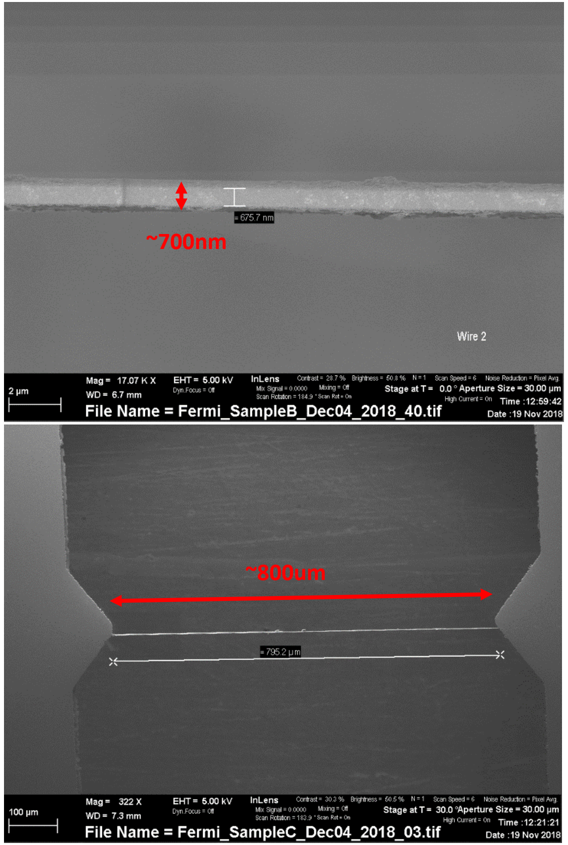
Bulk Au vs sandwich Au/Si3N4/Au:

- 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

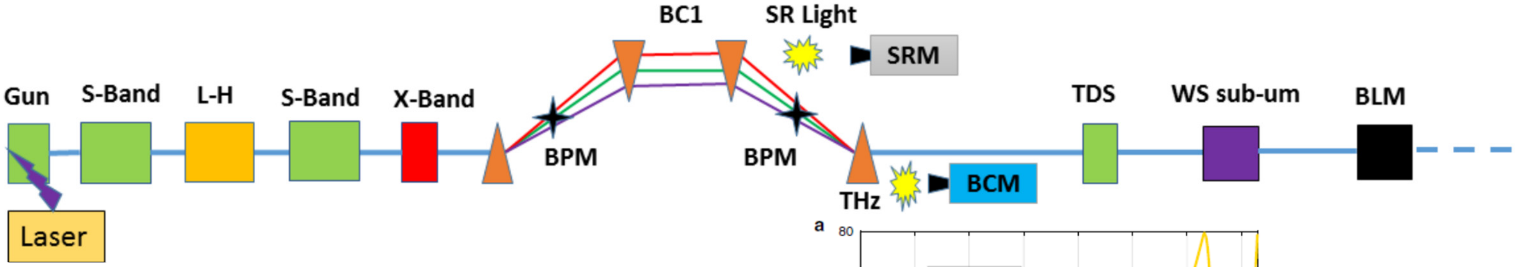


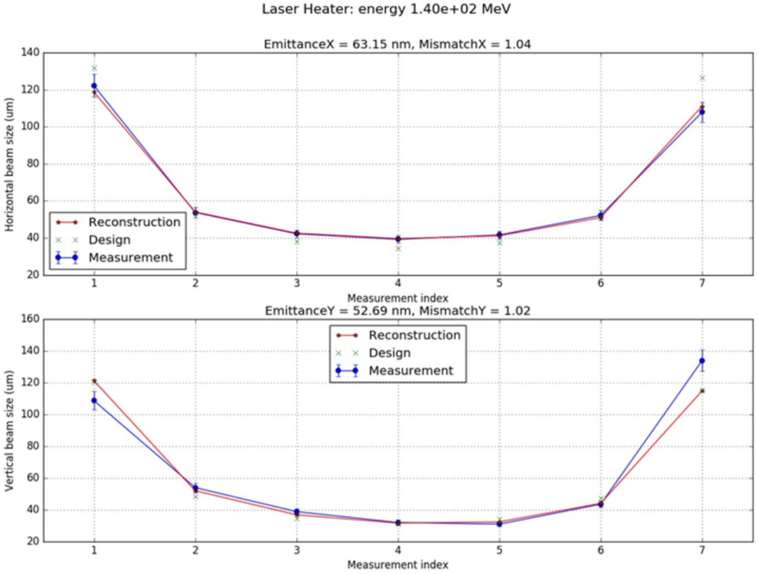
PSI WS nano-fabrication,
Laboratory for Micro- and Nanotechnology, LMN, PSI

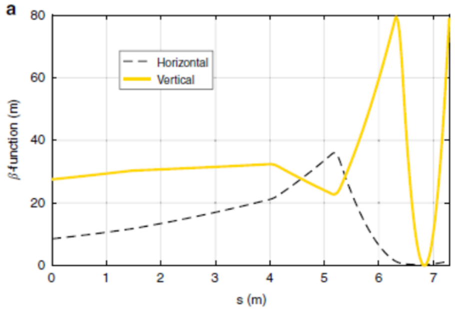


FERMI WSC nano-fabrication,
IOM-CNR, Trieste, Italy

Experimental set-up at SwissFEL







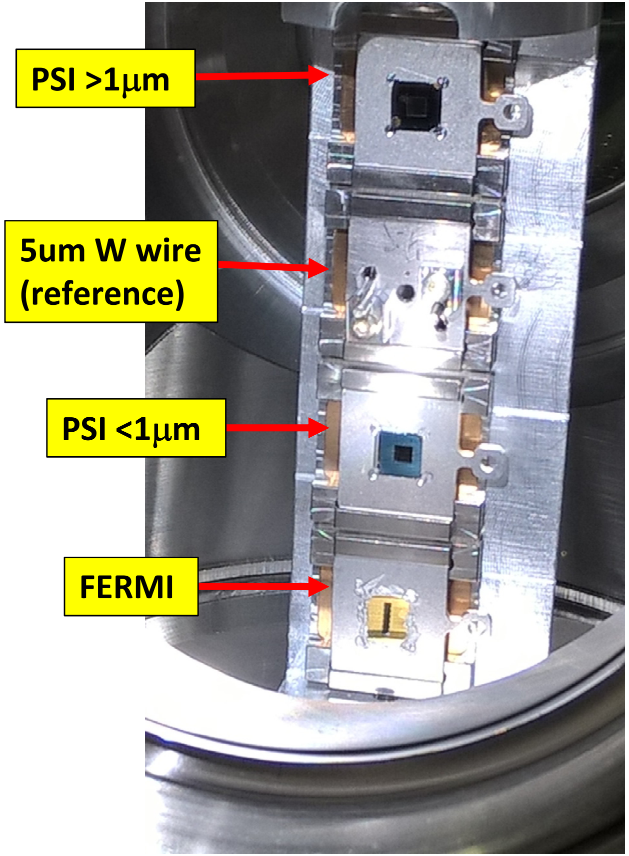
beam vertical size at the WS position: ~500nm

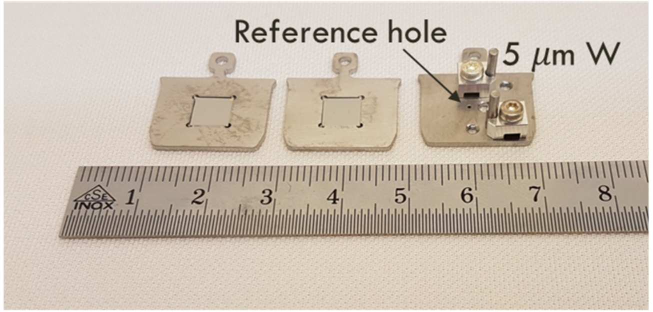
βx, βy evolution between BC1 and WS sub-μm

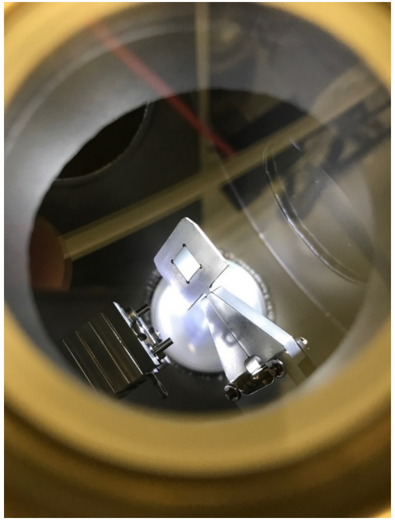
Table 2 Beam parameters

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







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)**

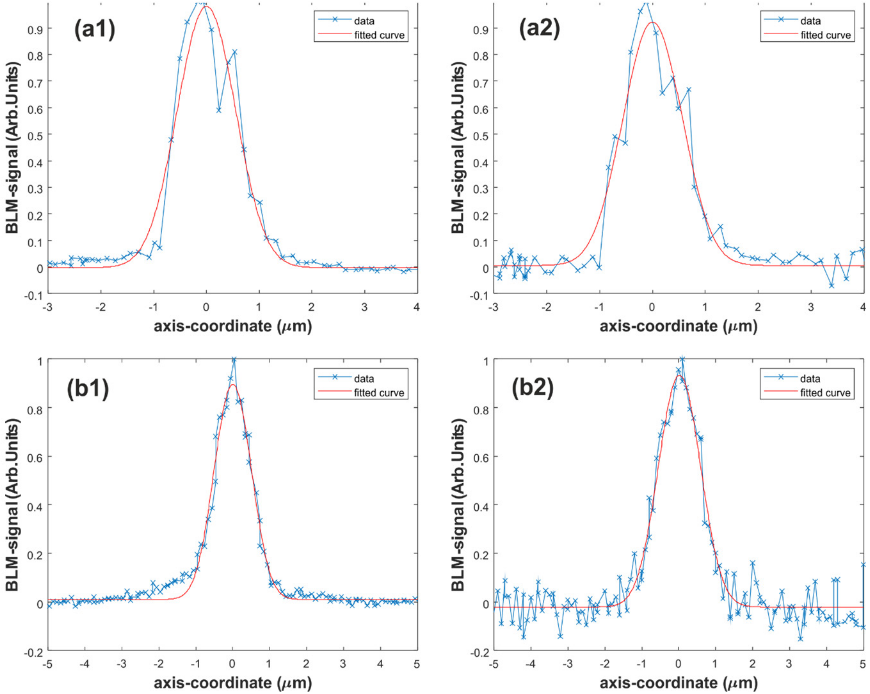
<u>Only vertical WS measurements are possible!</u>

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) ➔ beam size~500nm**
- **beam energy ~300 MeV**



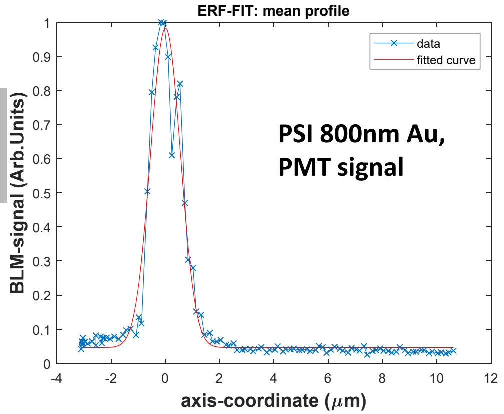
Error-function-fit: convolution of Gaussian distribution with rectangular shaped distribution with a width w:

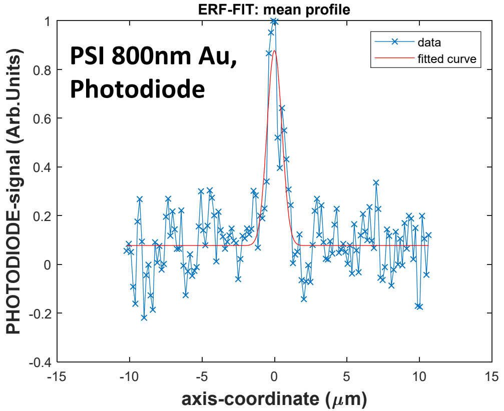
$$erf - fit(x) = \quad a \times [erf([x - c + w/2]/\sqrt{2}/\sigma) + \\ -erf([x - c - w/2]/\sqrt{2}/\sigma)] + b,$$

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

(*) G.L. Orlandi et al., *Nanofabricated free-standing wire scanners with sub-micrometer resolution*, submitted for publication

Satellite measurements: PMT vs photo-diode WS profile reconstruction

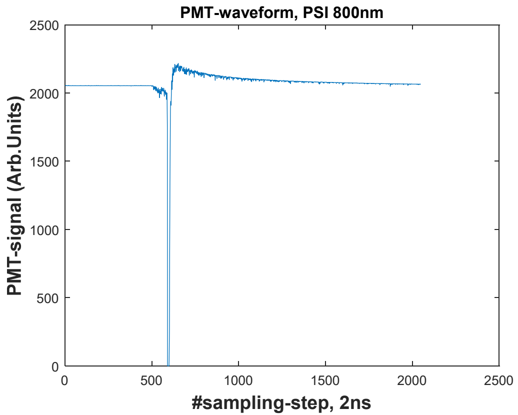


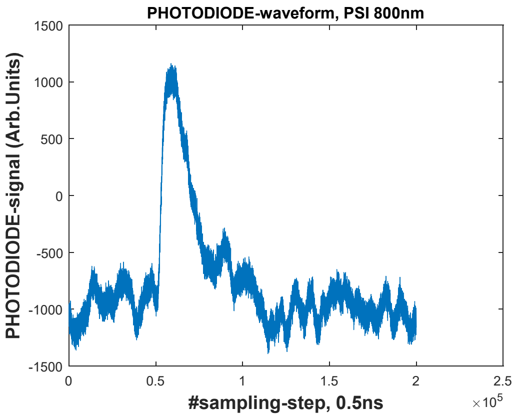


Tests of new detection solutions of the beam-loss signal: photo-diode vs PMT

WIRE	FIT	SIGMA (nm)	BEAM-LOSS-DETECTOR
PSI 800nm	ERF fit	488+/-20	PMT
FERMI 900nm	ERF fit	477+/-70	PMT
PSI 800nm	ERF fit	498+/-134	Photodiode

[S/N_Ratio(PMT)]/[S/N_Ratio(PHOTODIODE)]~10





Conclusions and Outlook

- Innovative free-standing WS structure - nano-fabricated at PSI and FERMI-IOM-CNR - with unprecedented sub-micrometer geometrical resolution (~250nm)

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

- Fruitful collaboration between FERMI-IOM-CNR and PSI: possible synergy in nano-fabrication and joint experimental activities

- Long terms goal:
  - Make nano-fabricated WS with sub-micrometer resolution a standard diagnostics solution for a FEL:
    - Increase the WS beam clearance from the present 2mm up to 10mm, at least.
    - Nano-fabricated WS fork with integrated free-standing stripe pair for X,Y scanning
    - Mechanical stability studies: bulk metal or metal-silicon-nitride sandwich stripe?
    - Beam-loss signal-to-noise ratio: optimize ratio thickness-to-width of the stripe (from 1 up)

Thank you for your attention