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EuPRAXIA
Preparatory Phase

Progress on Wire Scanners Manufactured by Photolithography

Minimal invasive Nano-fabricated Wire-Scanners (WS) with sub-micrometer spatial resolution

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Eupraxia_pp annual meeting, September 25th, Biodola - Italy

PSI

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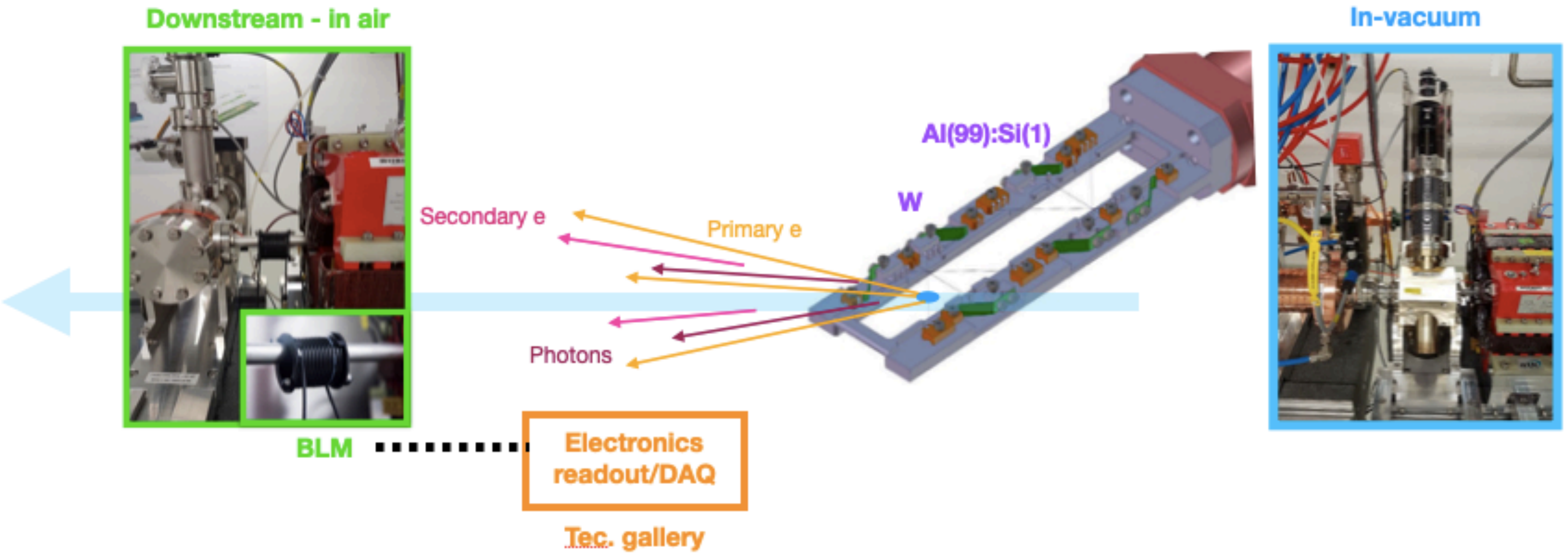
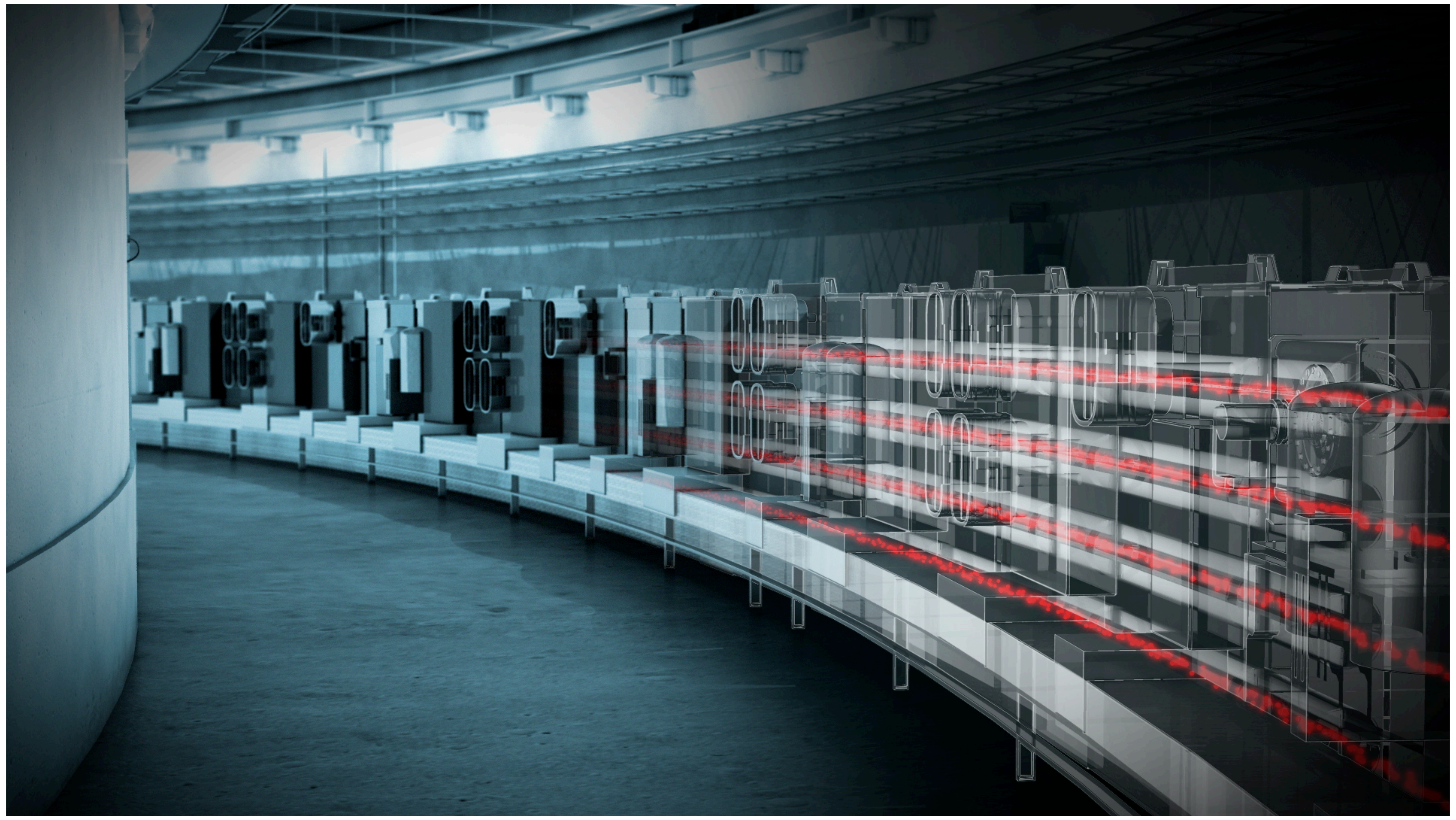
Outline

- Wire scanners in a nutshell
- From conventional to nano-fabricated wire scanners: first prototypes
- On-going R&D
- On beam tests at SwissFEL
- Conclusion and Outlook

Wire Scanner beam diagnostic in a nutshell

- Multi-shot and mono-dimensional reconstruction of the beam transverse profile in linear and in circular accelerators.
- Providing for high spatial resolution along with minimal invasiveness to beam operations (factor of 10 better resolution wrt view screens).
- Traditional design: metallic wire (beam probe) fixed and stretched onto a metallic fork. Ultimate spatial resolution limit set at the micrometer level by the minimum achievable wire width.
- Beam profile from beam synchronous correlation of BLM (Beam Loss Monitor) signal and wire position.





Wire Scanner keywords

Depending on the beam and machine features and operational condition, different design choice

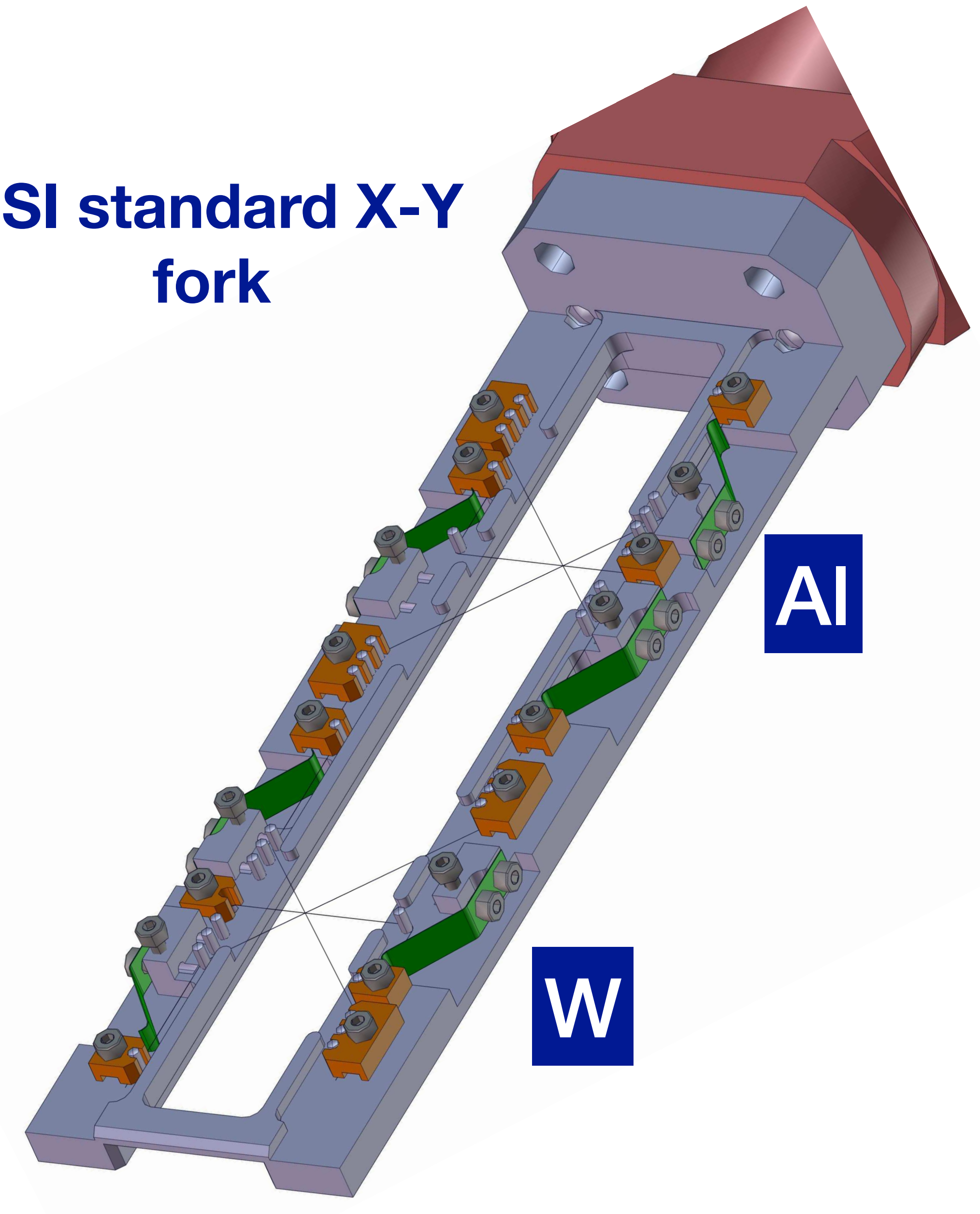
- **Spatial resolution** - wire width/diameter —> typical beam size
- **Scan speed** - movement mechanism (linear, rotational) —> machine type (linear, circular), repetition rate, beam intensity etc
- **Invasiveness** - wire material, width, thickness —> machine technology (superconductive RF or magnets), standard or dedicated operation

- **30 um carbon wire** - beam size from 300 um (SPS) to 1,5 mm (PS)
- **Scan speed 20-24 m/s** - High repetition rate and beam intensity (10^11 p/ bunch, Rep rate> MHz) - wire heating, sublimation
- **No constraints** on invasiveness, no superconductive magnets, monitoring of the beam in the inj. chain


CERN LHC Inj.

- **5 um Tungsten and 12um Al wire** - beam size from 5um to 500um
- **Scan speed 20 um/s** - Low repetition rate (100Hz) and beam intensity (10^9 e/ bunch)
- **Constraints** on invasiveness, used to monitor the beam before lasing. WS Operation incompatible with lasing

PSI standard X-Y fork



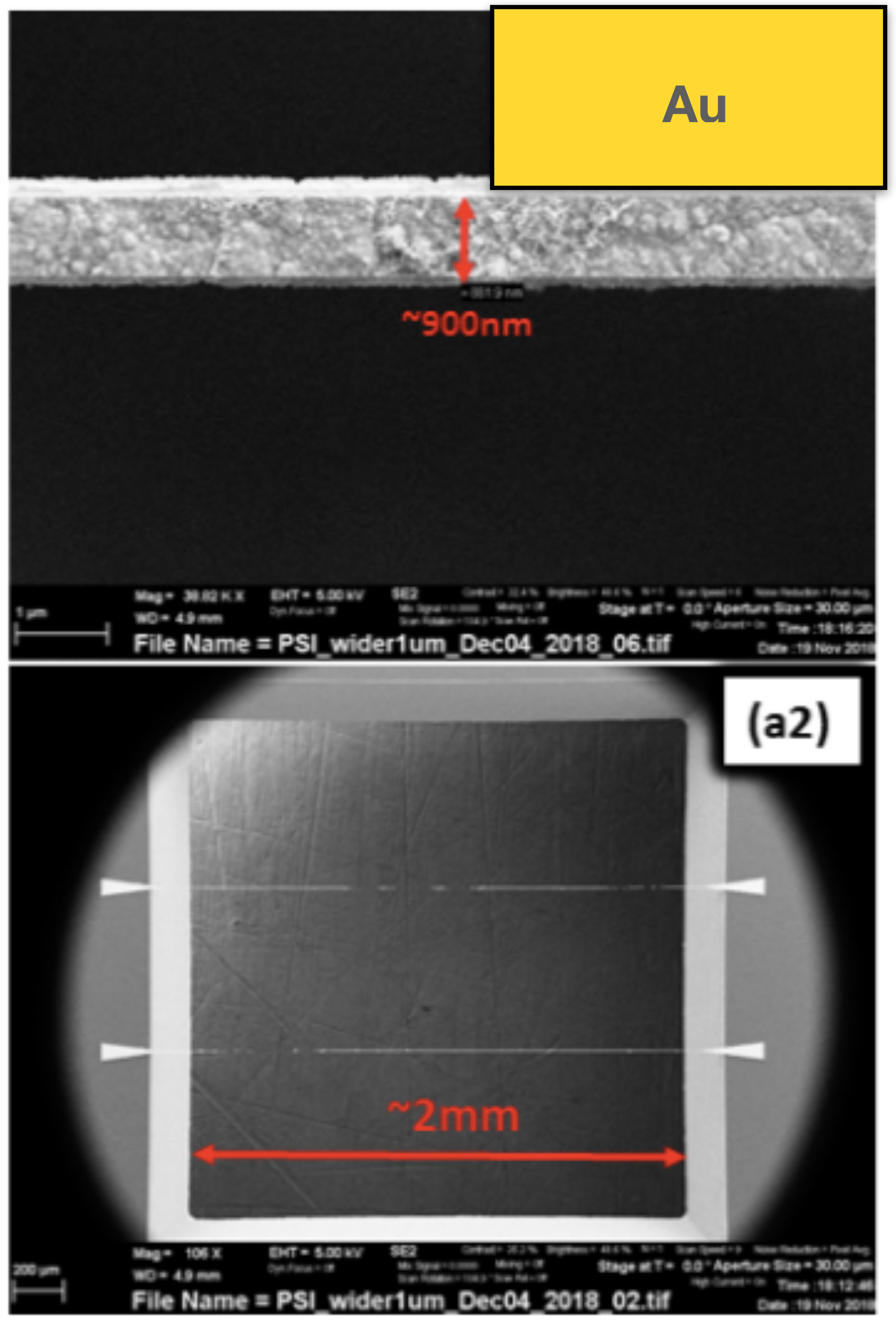
From conventional to sub-micrometer spatial resolution and minimal invasive Wire Scanner: Why?

- characterizing and monitoring low and ultralow-emittance and sub-micrometer transverse size electron beams highly demanded by Free Electron Laser (FEL) developments and advanced acceleration concepts
    - FELs: reducing beam emittance down to the nanometer scale allows for a more compact design with lower beam energy and shorter undulators.
    - Dielectric Laser Accelerators (DLAs): sub-micrometer transverse size beams needed to match the size of the dielectric accelerating microstructures.
    - Plasma wake field accelerators: reducing beam emittance down to the nanometer scale paves the way towards applications such as colliders and light sources.
- high resolution transverse beam profile monitoring during standard operations in FELs minimizing machine protection issues, particularly important in FELs with superconductive RF structures (European X-FEL, LCLS-II).
- on-line emittance monitoring in SwissFEL (FODO WS station).

From conventional to sub-micrometer spatial resolution and minimal invasive Wire Scanner: How? Phase I

Intrinsic limitation of WS traditional manufacturing > Nano-lithography has been identified as the most promising technique. First step taken with electron-beam nano-lithography

Free standing wire



DOI: 10.1103/PhysRevAccelBeams.23.042802

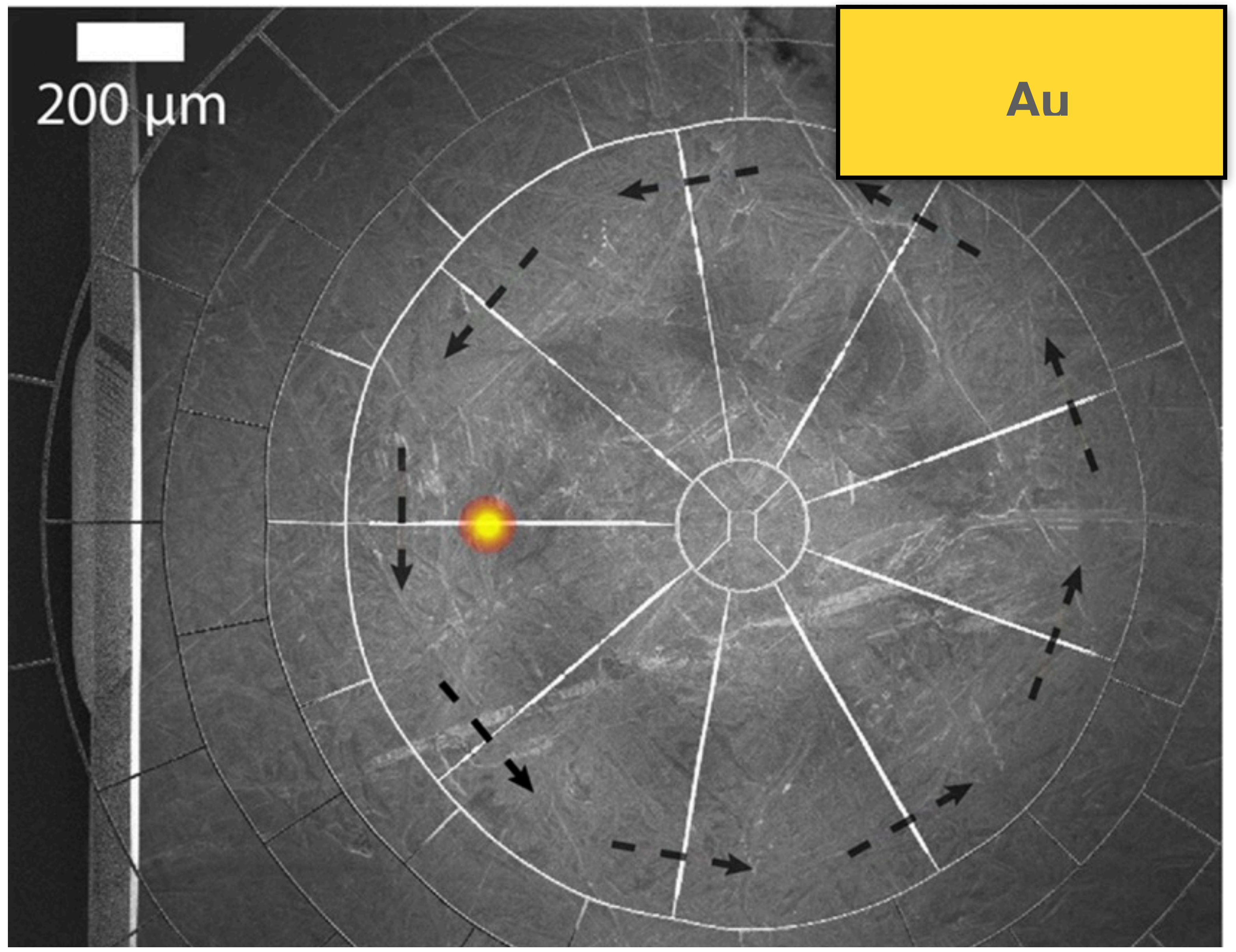
Sub-micrometer Au bulk scanning stripe free-standing over a silicon frame

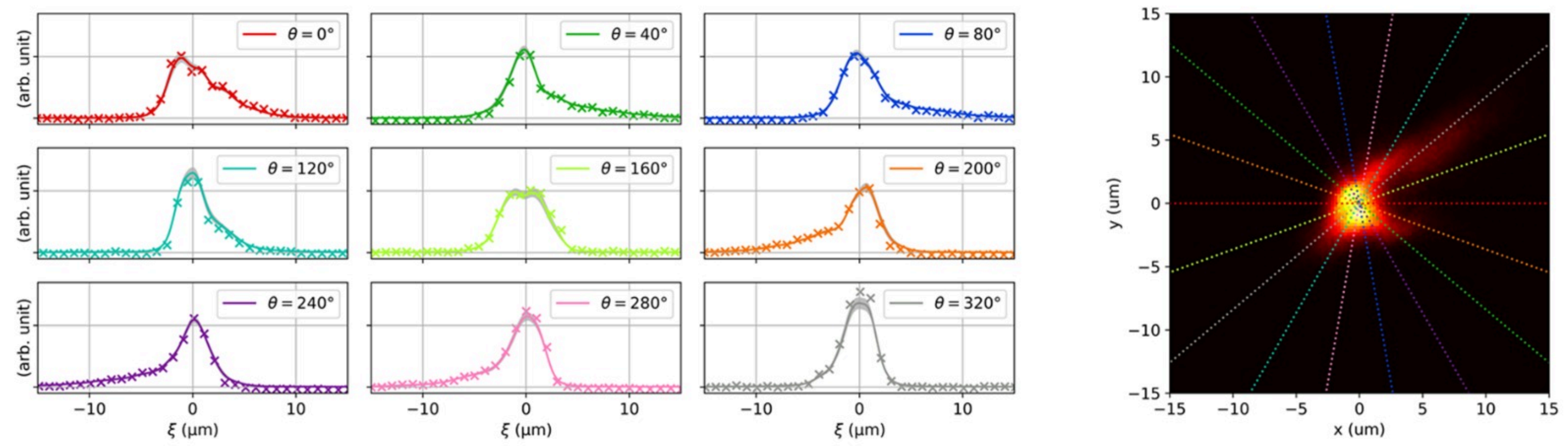
- electron-beam lithography to define the wire footprint over Si
- electroplating to nanofabricate the Au wire

Best achievement:
width= 900 nm
thickness = 2um
length= 2mm
Geometrical resolution~ 260 nm

Goal 8-10mm

Spider web - 9 free standing wires



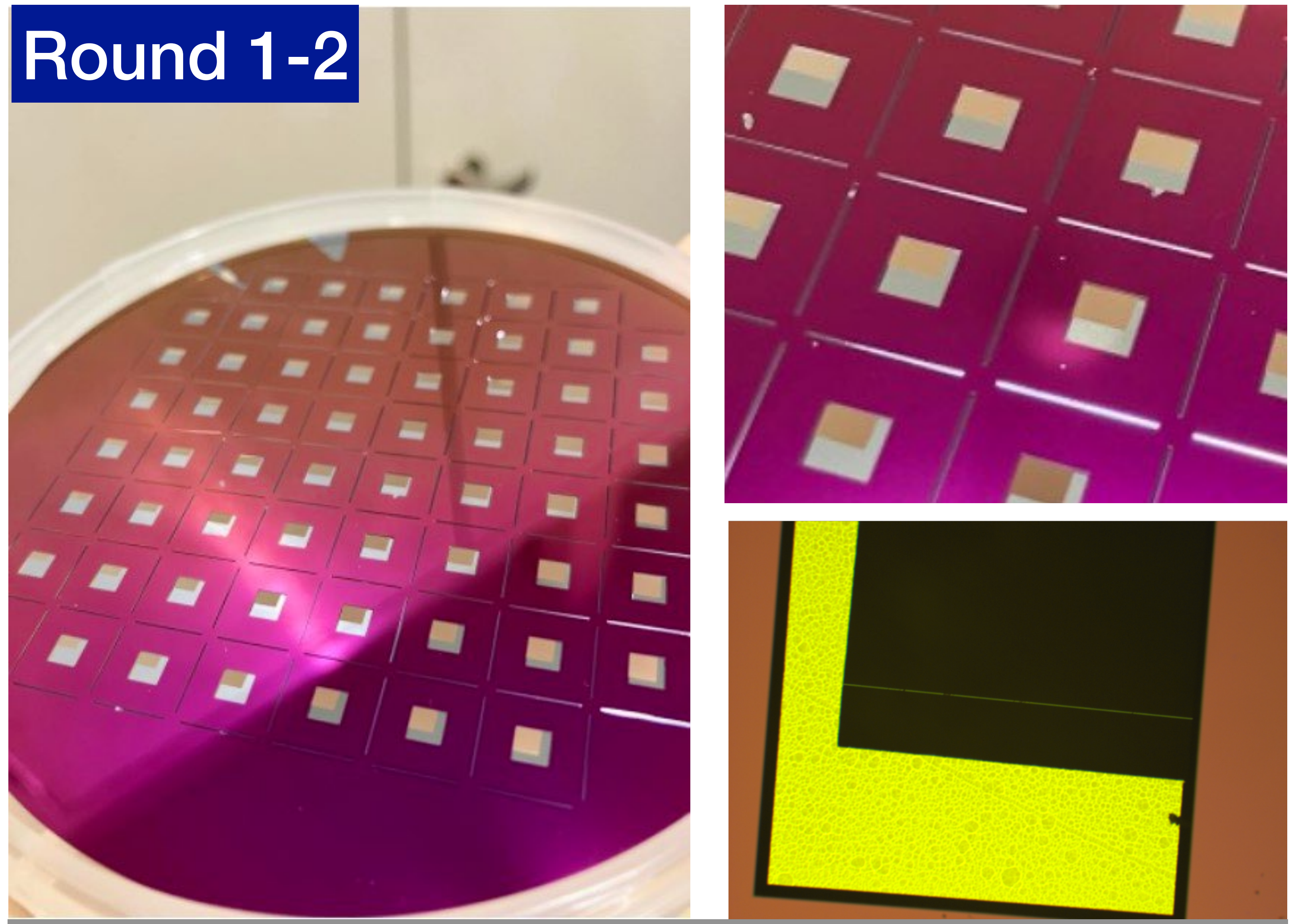


DOI: 10.1103/PhysRevAccelBeams.24.022802

From conventional to sub-micrometer spatial resolution and minimal invasive Wire Scanner: How? Phase II

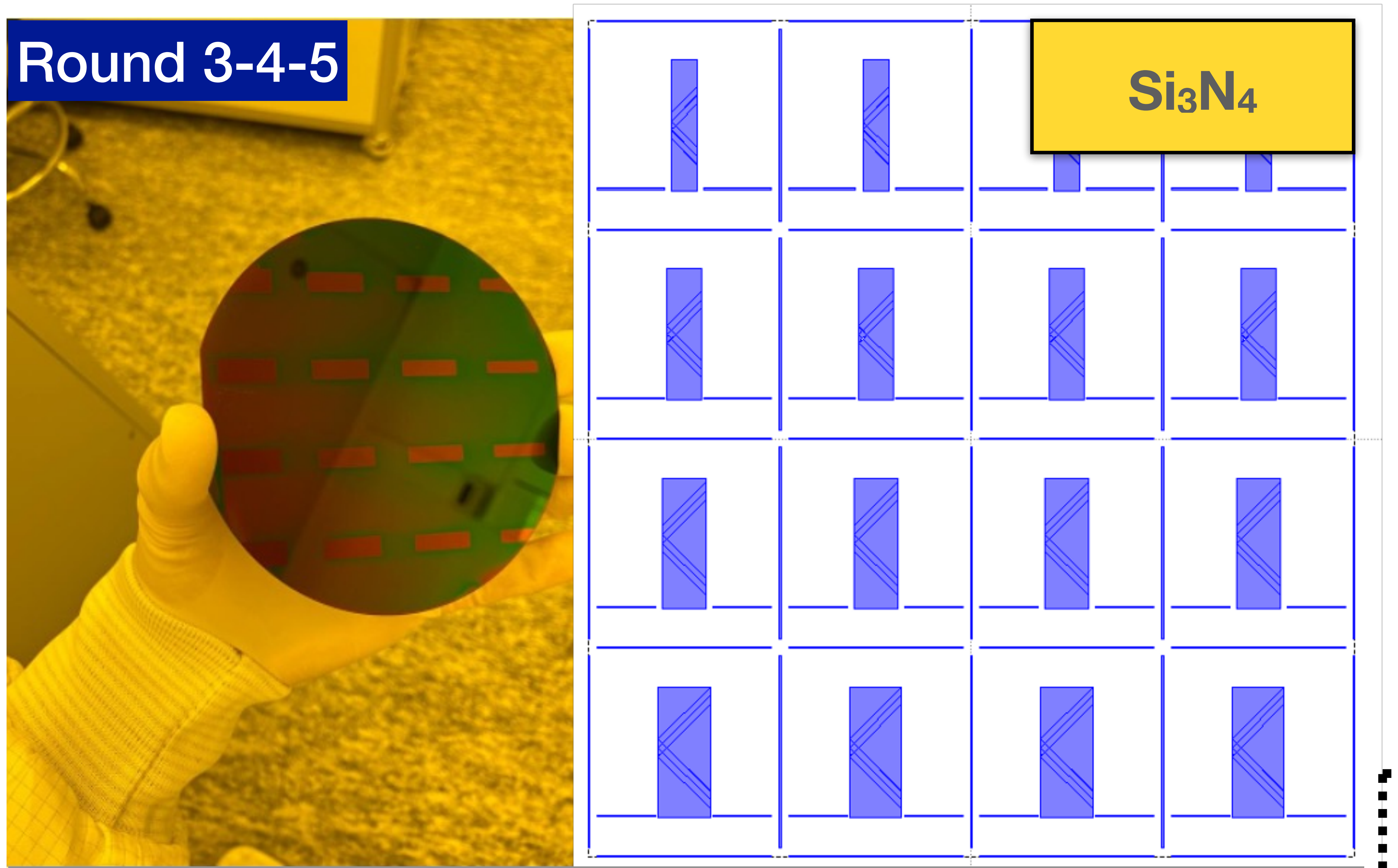
New prototyping round on-going with the aim to improve **SPATIAL RESOLUTION, TRANSPARENCY, BEAM CLEARANCE.**

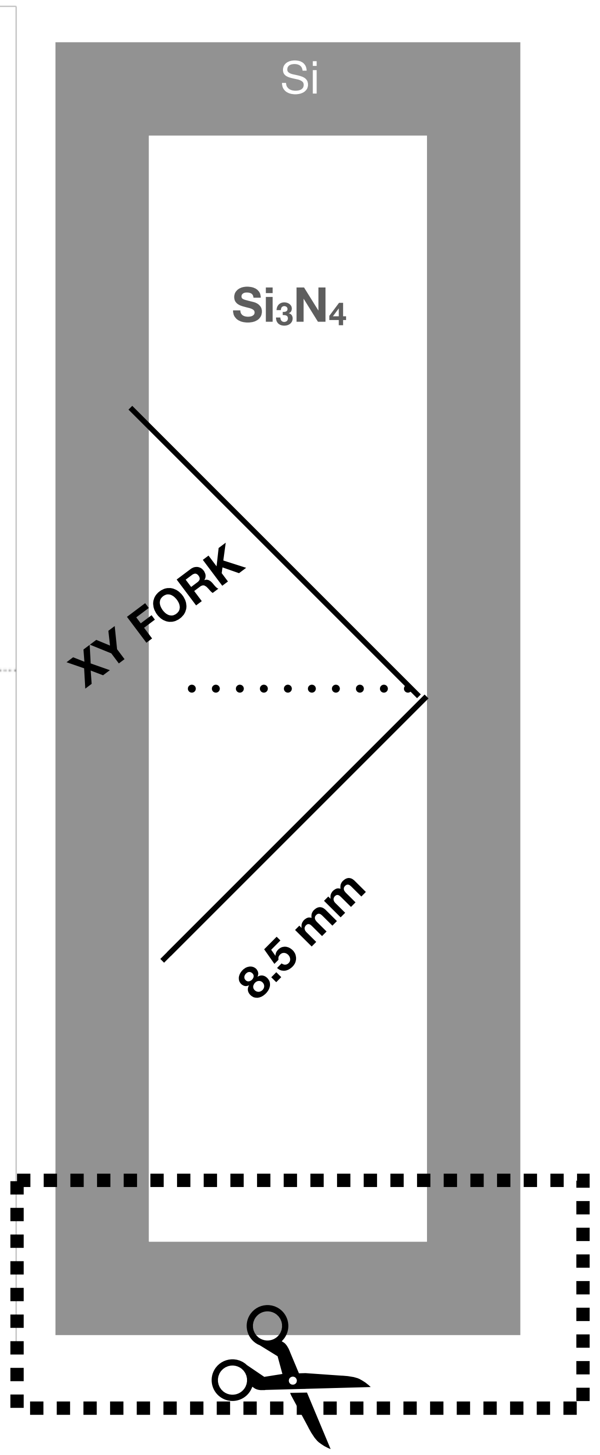
Standard Photolithography



MANUFACTURING ROUND 1-2: 200 nm tick LPCVD Si_3N_4 single wire free standing over a 3x3 mm silicon frame. Width: 1-2-3-5 um

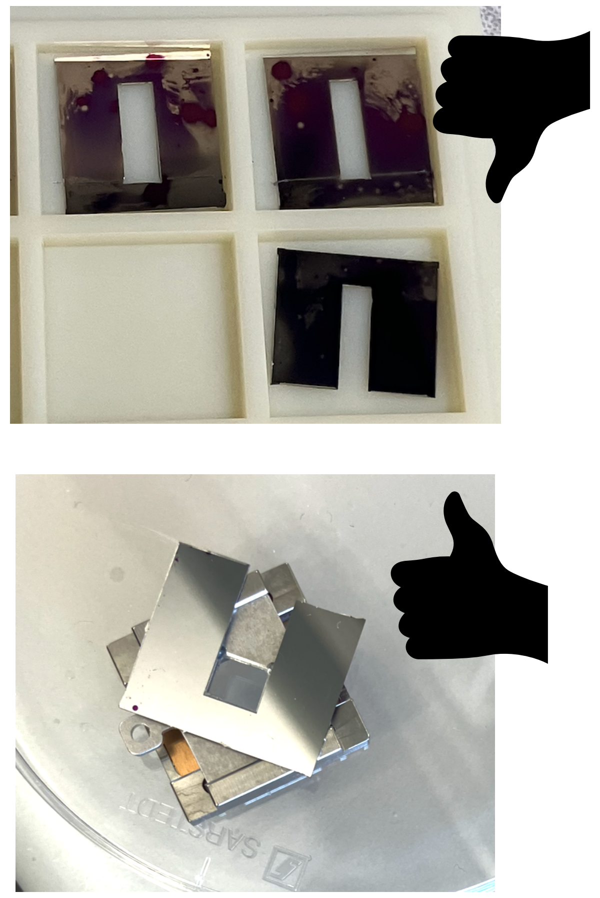
Direct Laser writing





MANUFACTURING ROUND 3-4-5: 200 nm tick LPCVD Si_3N_4 X-Y wire free standing over up to 6 mm wide silicon frame. Width: 1-3-4-5-6 um. Cleaving lines.

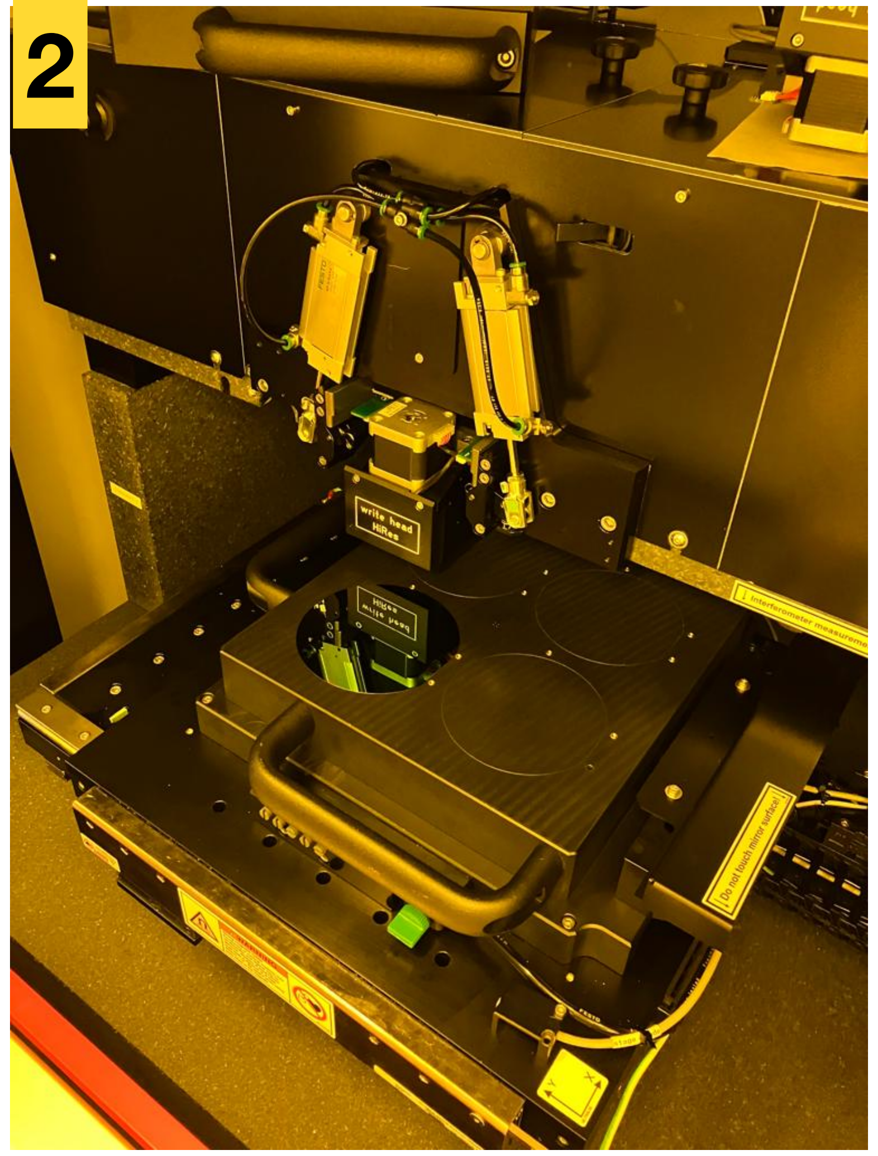
IRIDIUM COATING



Almost 200 times less invasive than previous prototypes, 4 times longer!

Technical insight: Lab for nano and Quantum tech. @PSI


1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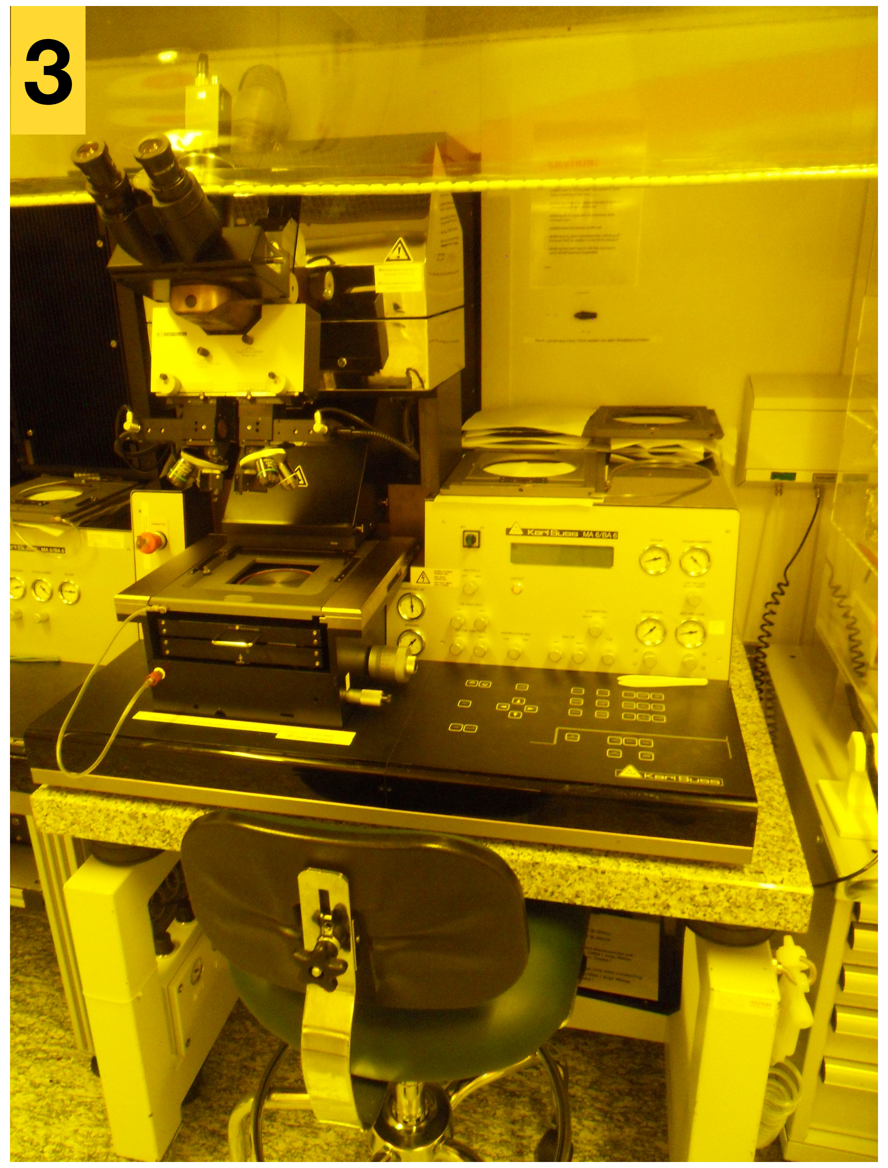
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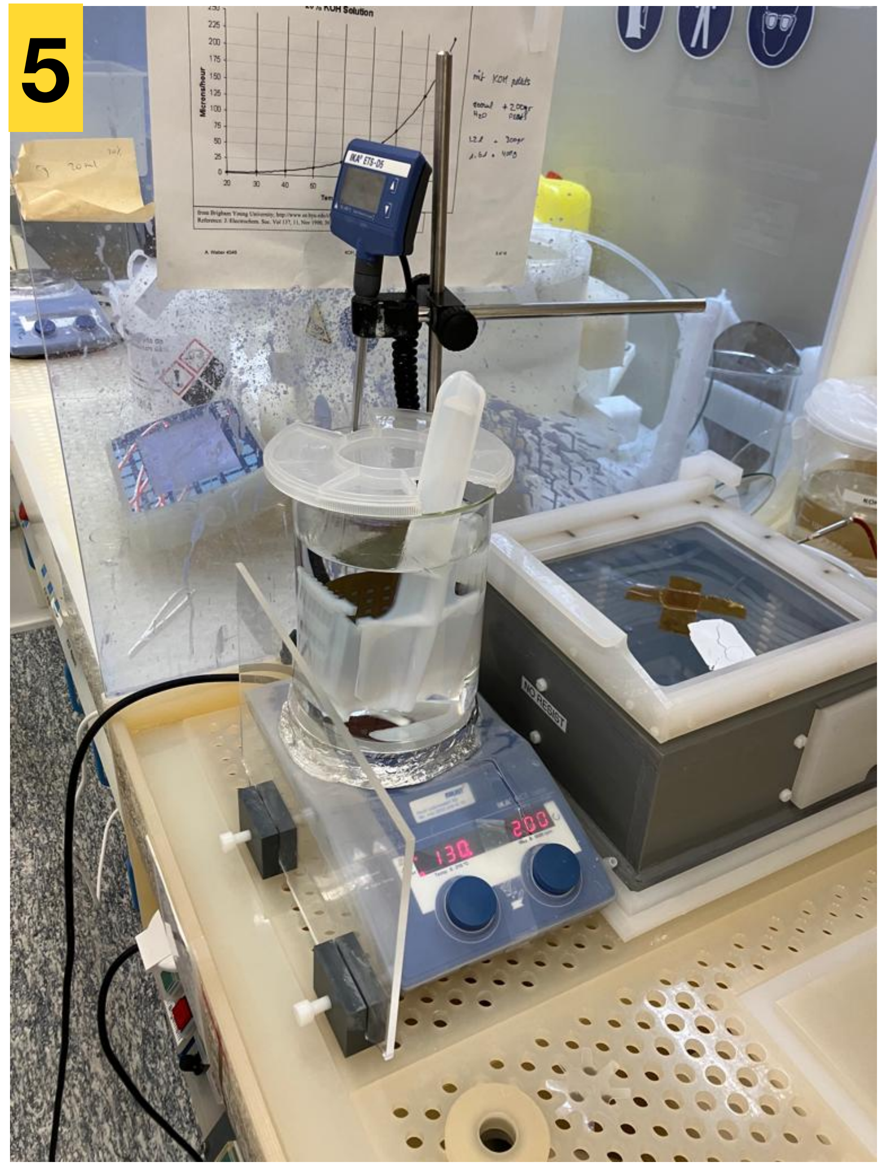
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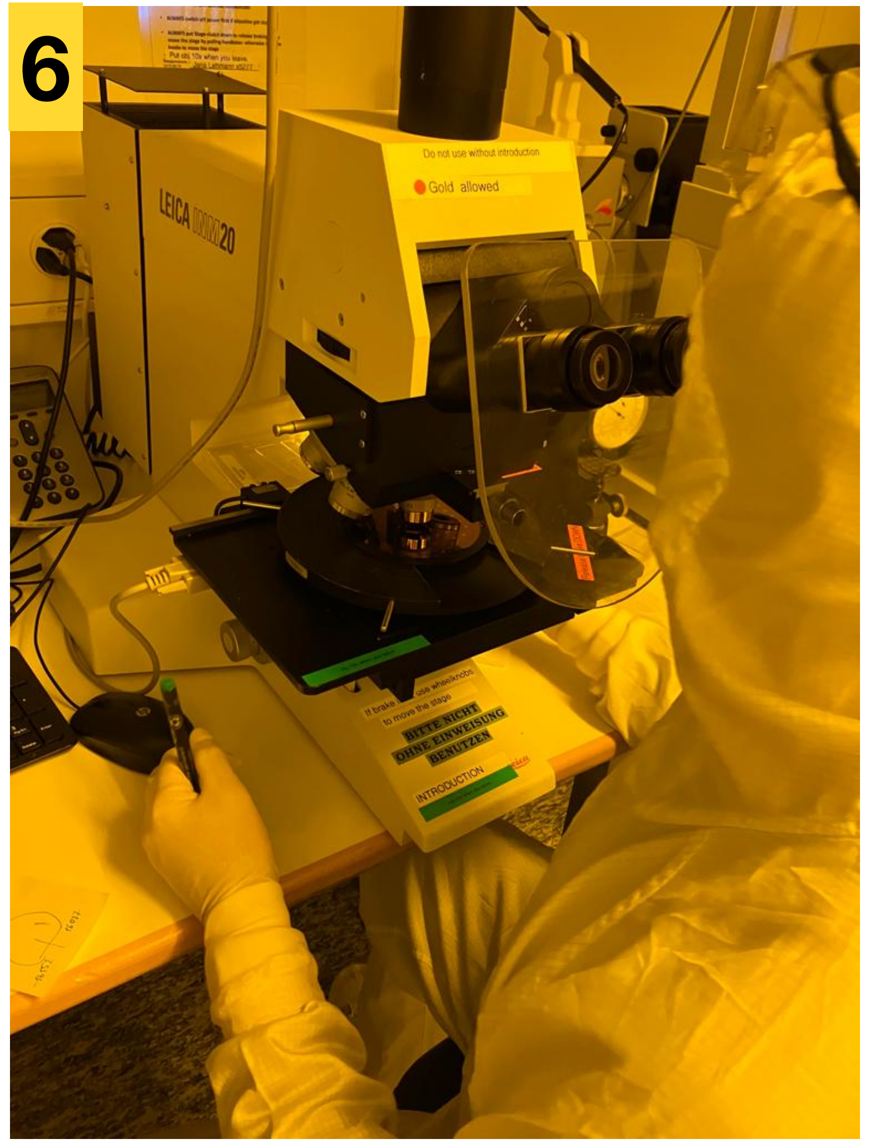

6

1. Spin coating. Applying the photoresist on the wafer

2. Direct Laser Writing (Heidelberg DWL66+). Design the structures on the Wafer (Wire, wire frame, cleaving lines)

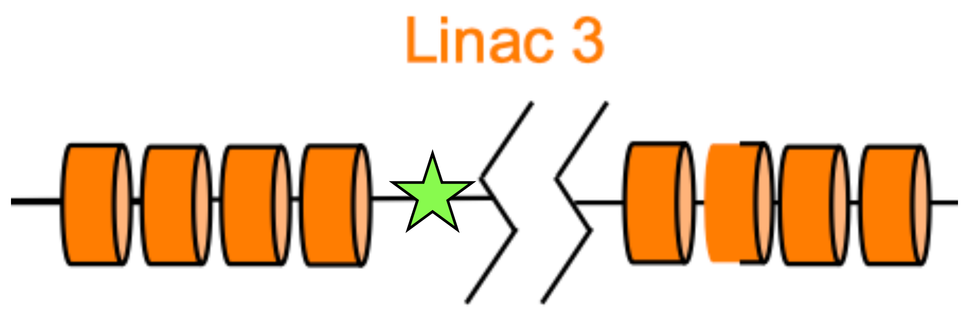
3. Mask Aligner (SUSS MA6-BA6). Design the structures on the Wafer (wire frame, cleaving lines)

4. Reactive Ion Etching (Oxford RIE 100). Removing SiN inside the wire frame

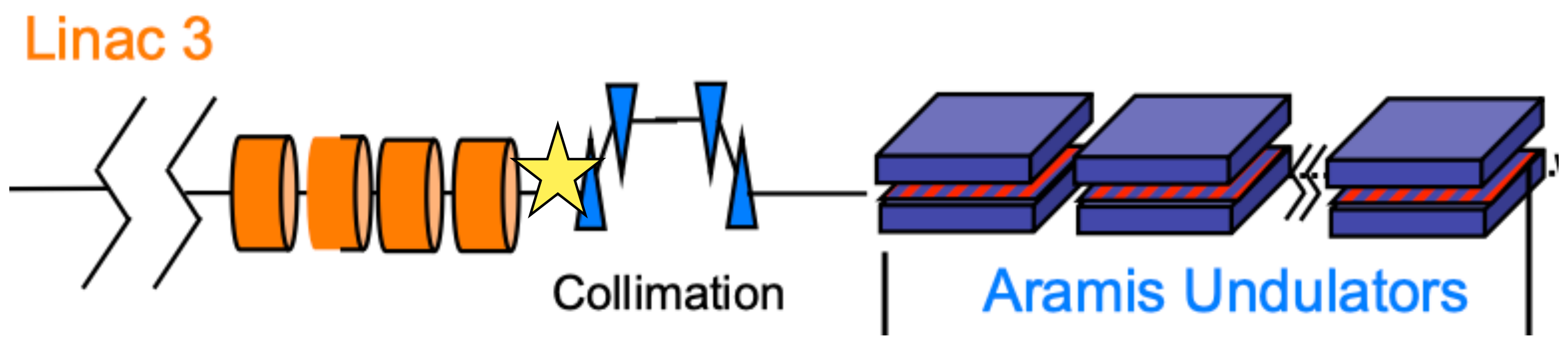
5. Chemical Etching (KOH). Removing Si inside the wire frame

6. Optical Microscope (Leica INM20). Checking the structure on the wafer after photoresist development

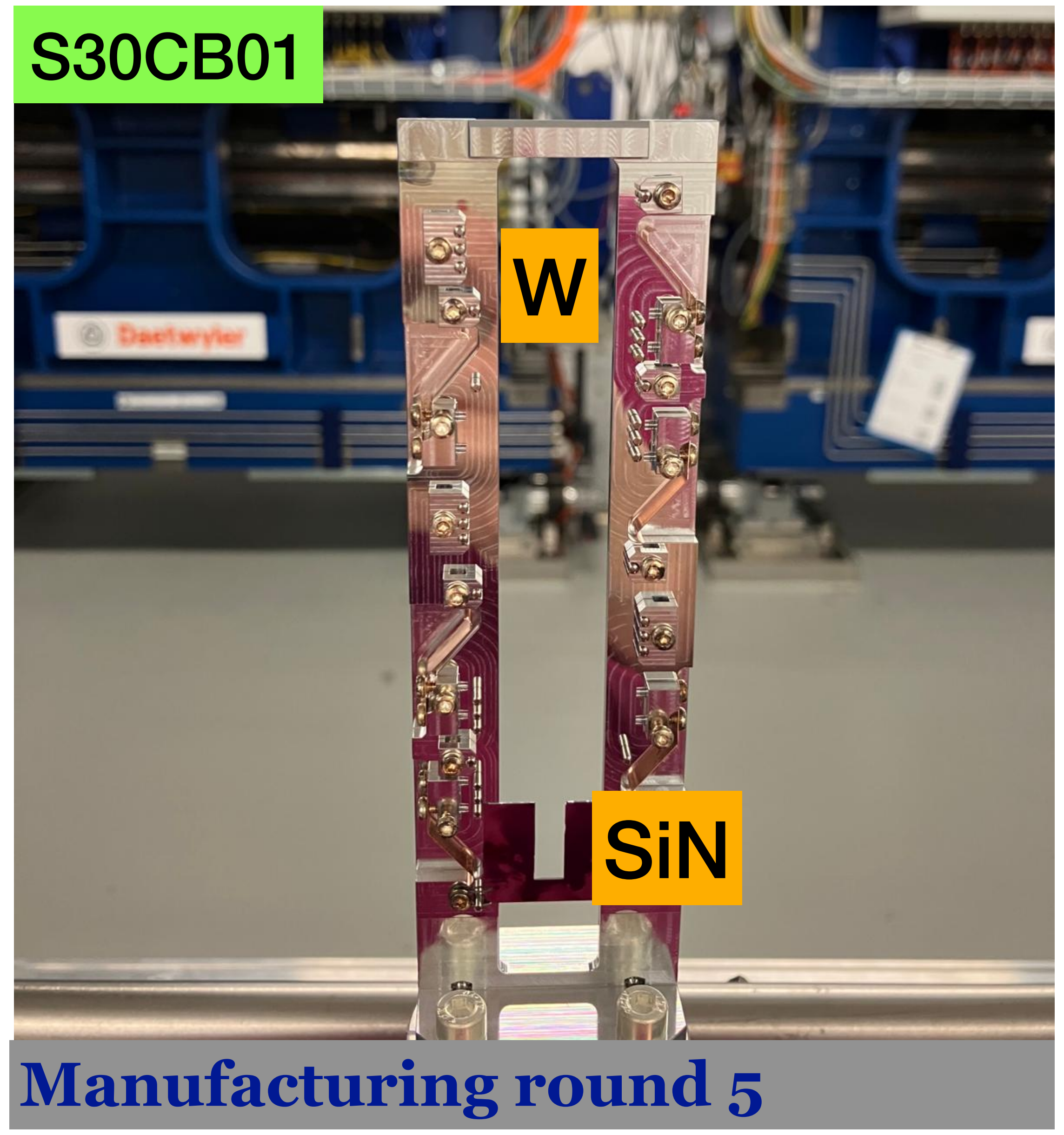
Installations and First Experimental Tests @SwissFEL - May 24



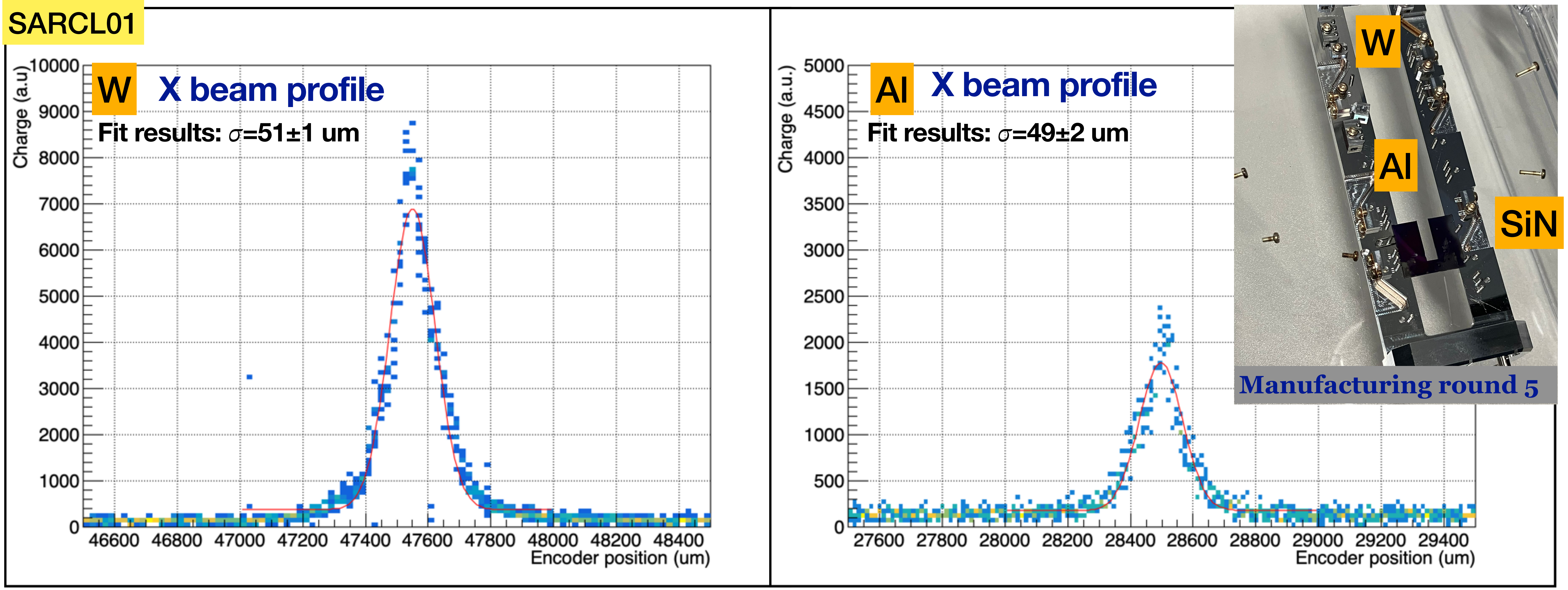
Energy tuning
C band (52 x 2 m)
max 28.5 MV/m, 0 °



Bunch charge 200 pC, repetition rate 10 Hz, beam Energy @WS position 5.8 GeV



Both W and SiN wires broken during operation due to the RF coupling (heating up - sublimation?)



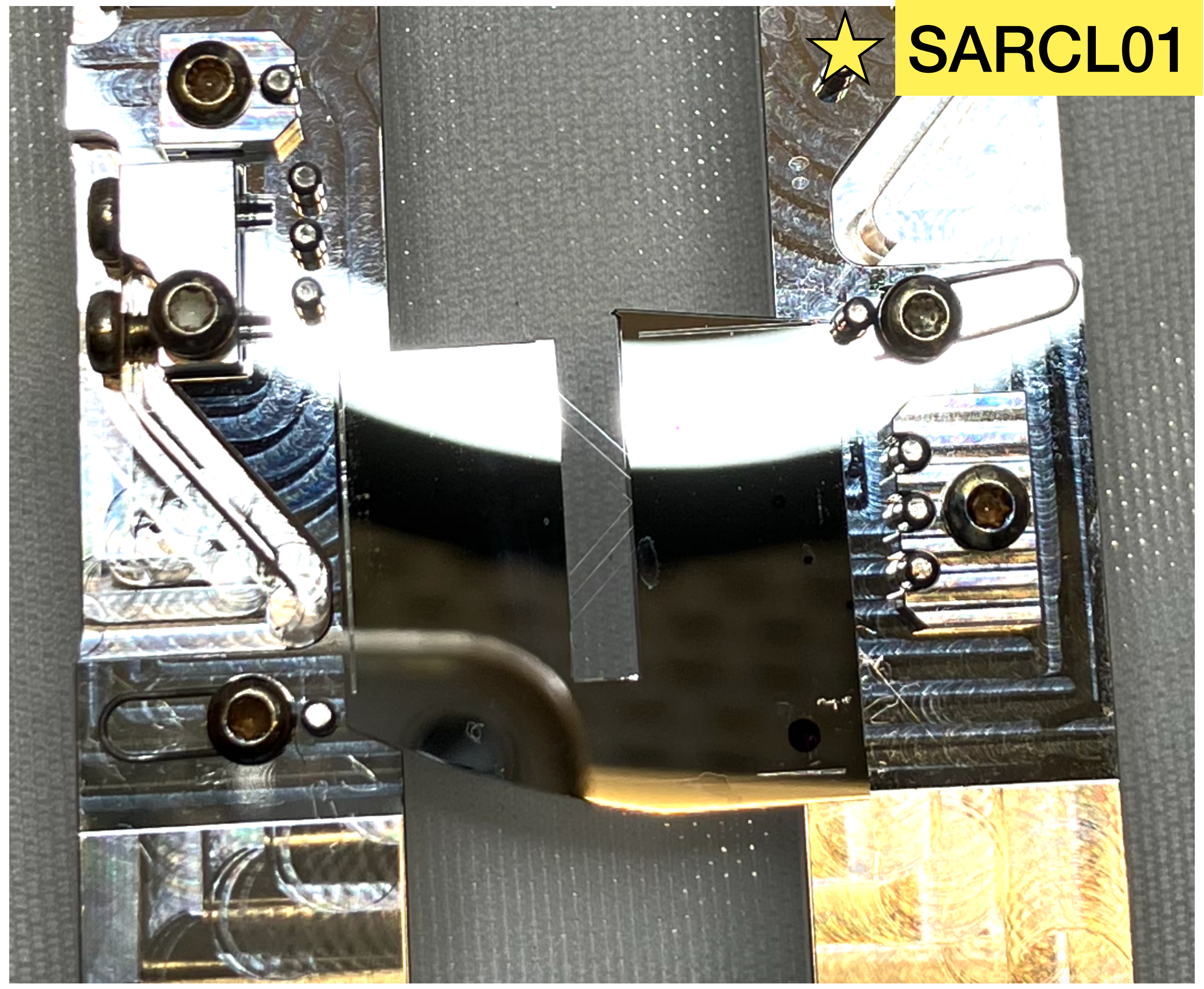
- **Wires successfully transparent to the beam (too transparent) > Beam loss monitor not sensitive enough > build a new one more sensitive (in vacuum?)**

SiN ?

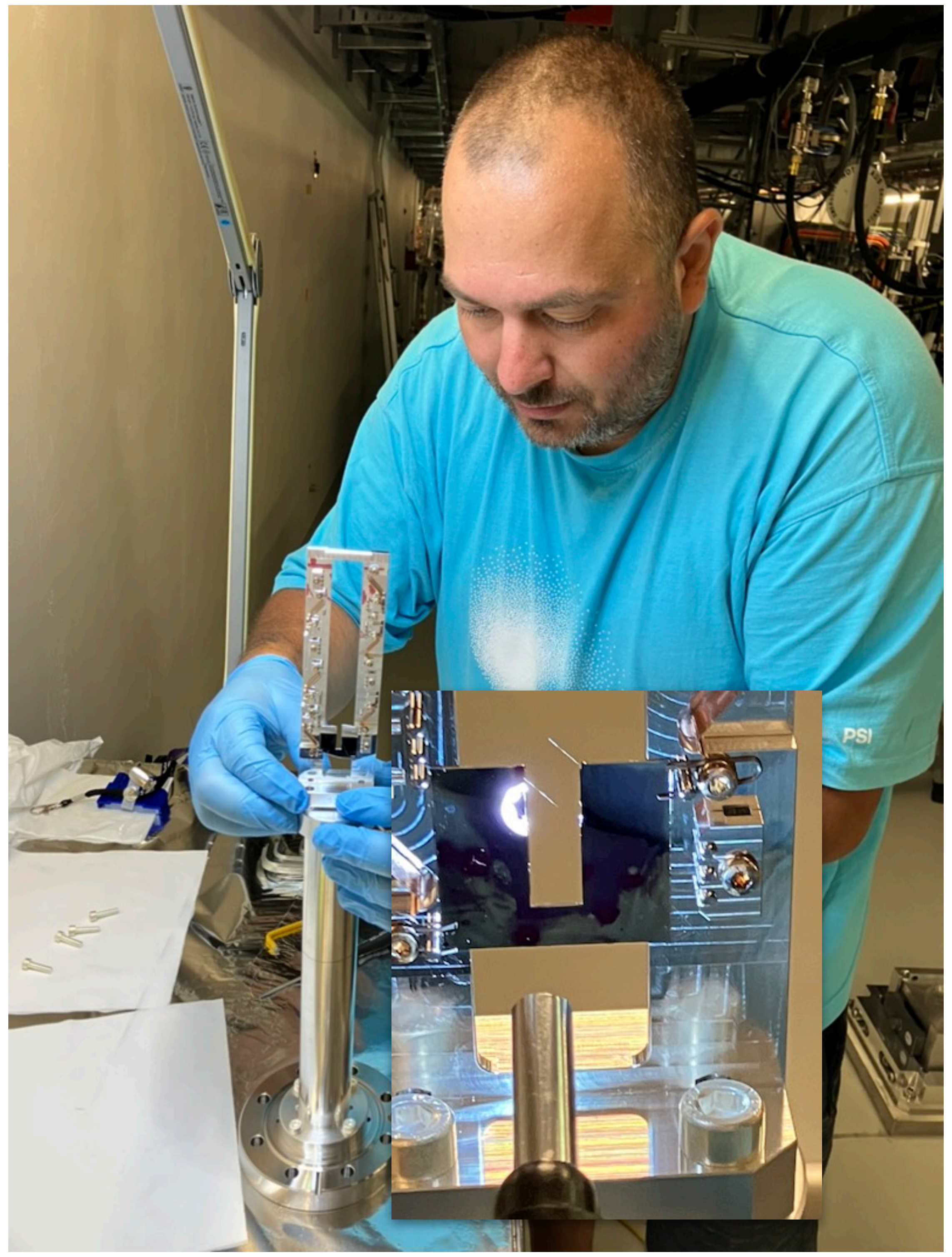
- **Wires heating up and breaking**

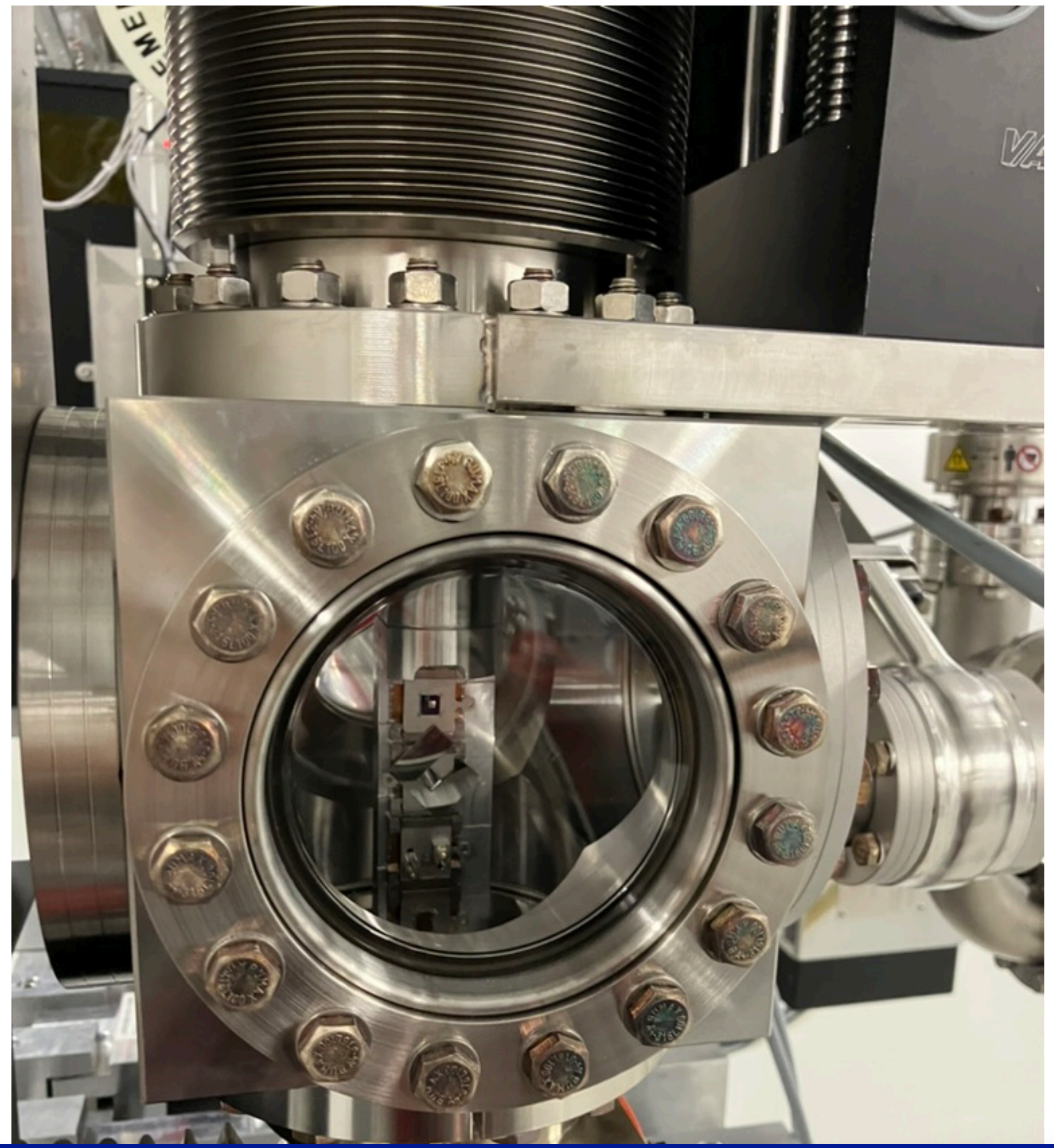
(Opportunity to open the vacuum and check only 2-3 times/year ….)

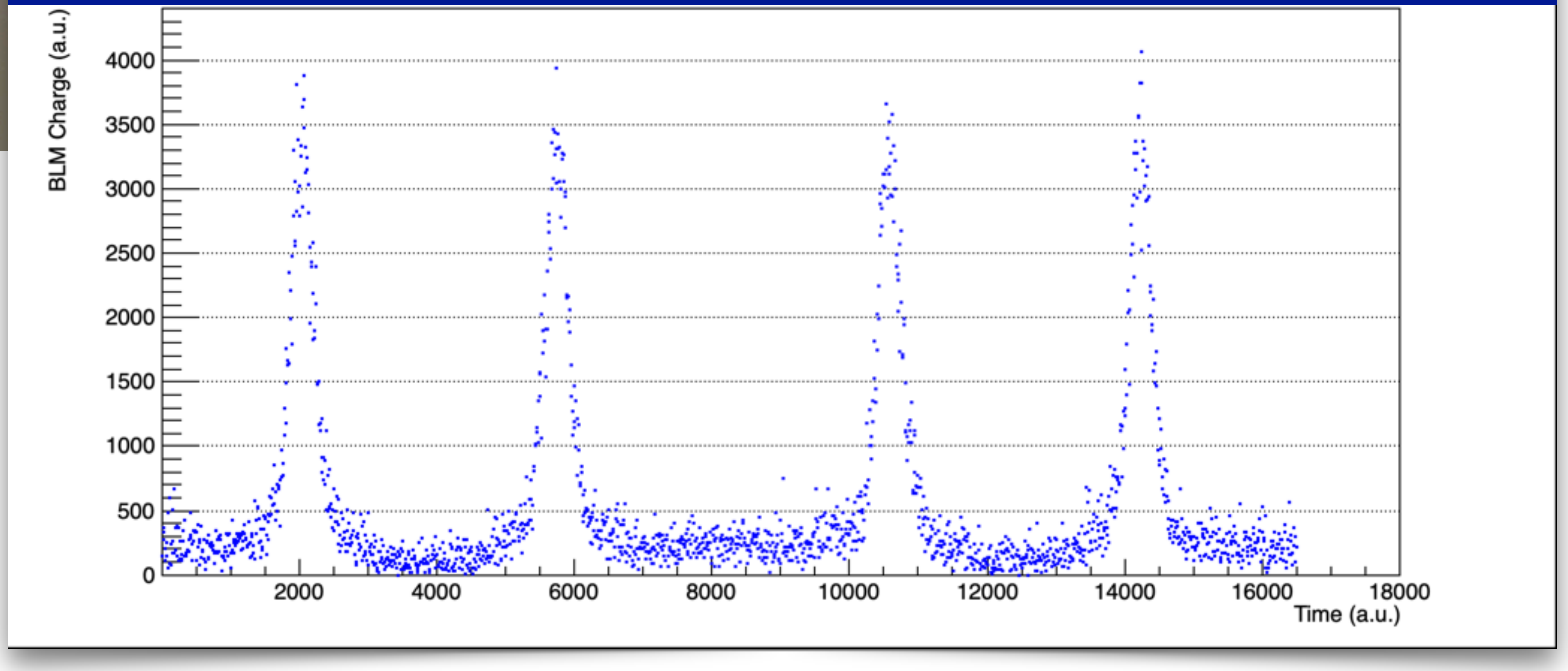
Installations and Experimental Tests @SwissFEL - Sept 24



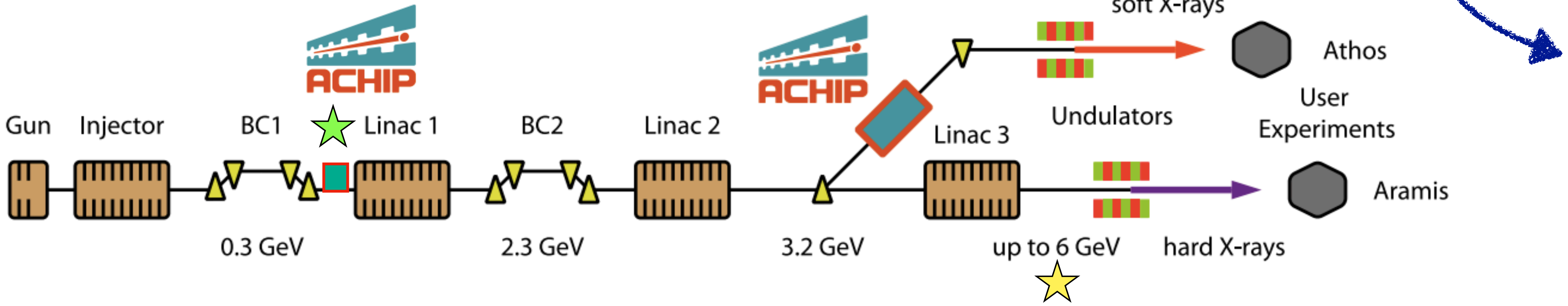
MANUFACTURING ROUND 5: 200 nm tick LPCVD Si_3N_4 X-Y wire free standing over up to 6 mm wide silicon frame. Width: 3-4-6 um. Cleaving lines.







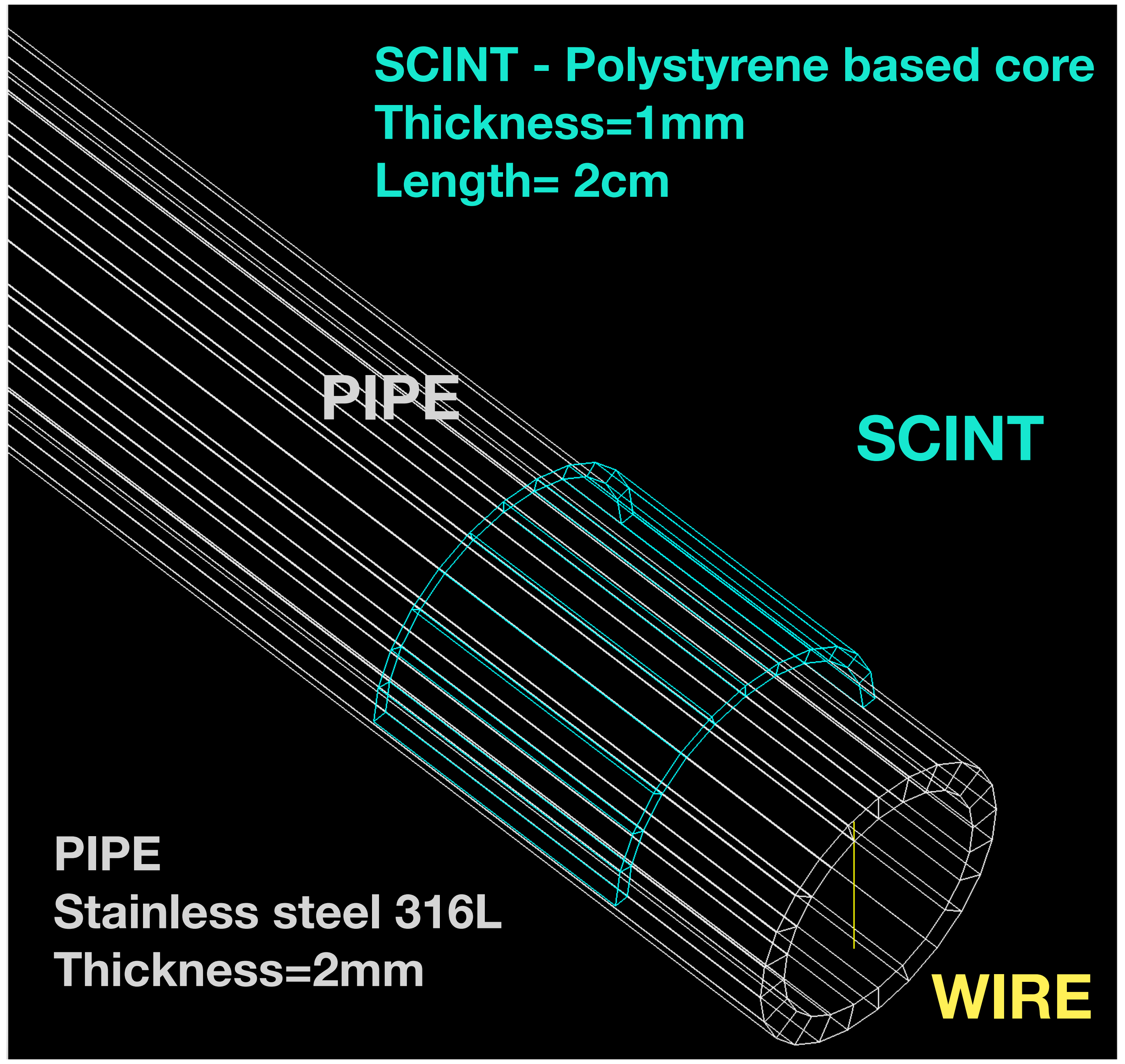
First observation of scattered particles from the SiN prototype



Bunch charge 10 and 200 pC, repetition rate 10 Hz, beam dumped before undulators. Beam energy @WS position 157 MeV

Simulations & BLMs R&D

Experimental tests highlighted the importance to efficiently collect scattered particles to optimise the signal to noise ratio of the BLMs especially in the case of the minimal invasive wire scanners.



Calculation for the losses ratio

$\frac{dE}{dx} \cong \frac{E}{X}$ This approx hold if $E \gg e_{\text{critical}}$ $e_{\text{critical}} = \frac{610\text{MeV}}{Z + 1.24}$ Rossi formulation

$X = 716.4 * A/(Z * (Z + 1) * \ln\left(\frac{287}{287/\sqrt{Z})}\right))$

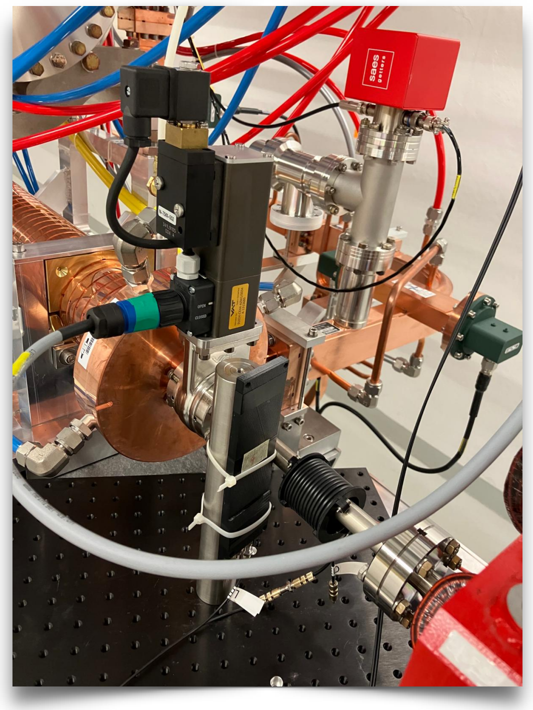
Wire	type	Width um	Tickness um	Length mm	X cm	DeltaE*/E
W	cilindrical	5	5	12	0.3504	$7.0\text{x}10^{-3}$ um
Al(99)Si	cilindrical	12	12	12	8.897	$1.62\text{x}10^{-3}$ um
Au (PSI nano)	rectangular	0.9	2	2	0.3334	$0.55\text{x}10^{-3}$ um
Au/SiN/Au	rectangular	0.8	3 (1Au, 2Si)	1	0.3334/8.310	$0.26\text{x}10^{-3}$ um
SiN	rectangular	1	0.25	4.2	8.31	$0.003\text{x}10^{-3}$ um

Simulations can help identifying the optimal position of the standard BLM system and/or to develop a more sensitive one in terms of geometry and material

- **TOPAS** (Tool for Particle Simulations, GEANT4 embedded) to simulate the interaction beam-wire and scattered particles-scintillator
  - Simulations correctly reproduce the experimental Tungsten/Alu loss ratio.
  - Good agreement with the theoretical calculations for the other wire materials while considering the energy deposition inside the wire.

- **Need for particles tracking software - Elegant (ELEctron Generation ANd Tracking)** to transport the scattered particles and collect them more efficiently

Beside simulations, new BLMs featuring different geometries and materials are already under test for the SiN WS stations.



Conclusion and Outlook

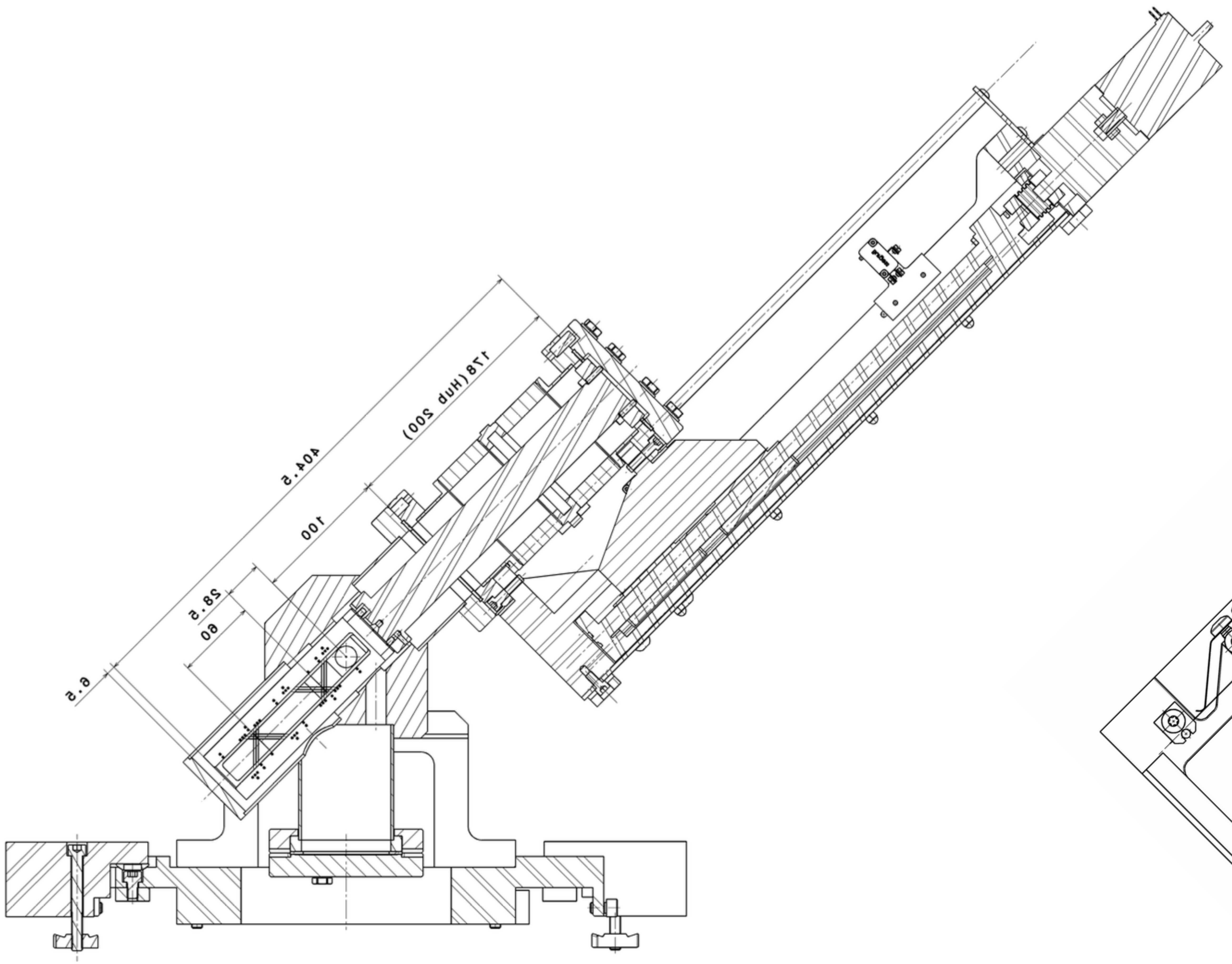
- Nano-lithography allows for the fabrication of a new generation of sub-micrometer and minimal invasive wire scanners, customisable in terms of width, thickness, length and material wrt the beam characteristics.
- New pure Si_3N_4 wires free standing on a silicon frame with a C shape have been developed to increase beam clearance and decrease invasiveness.
- 2 SiN prototypes currently installed in SF. First successful on beam test in Sept 24, at low energy.
- Further on beam testing expected in fall at high energy and to evaluate the impact of the wire scanner operation on lasing performance. Comparative tests with the old nano-fabricated prototypes also foreseen.
- Minimal invasive SiN wire scanners performance could be limited by existing BLMs sensitivity. Simulations and tracking of scattered particles are fundamental to optimise the signal to noise ratio of the BLM.
- SiN spiderweb with a non total-interceptive frame (C shape concept)

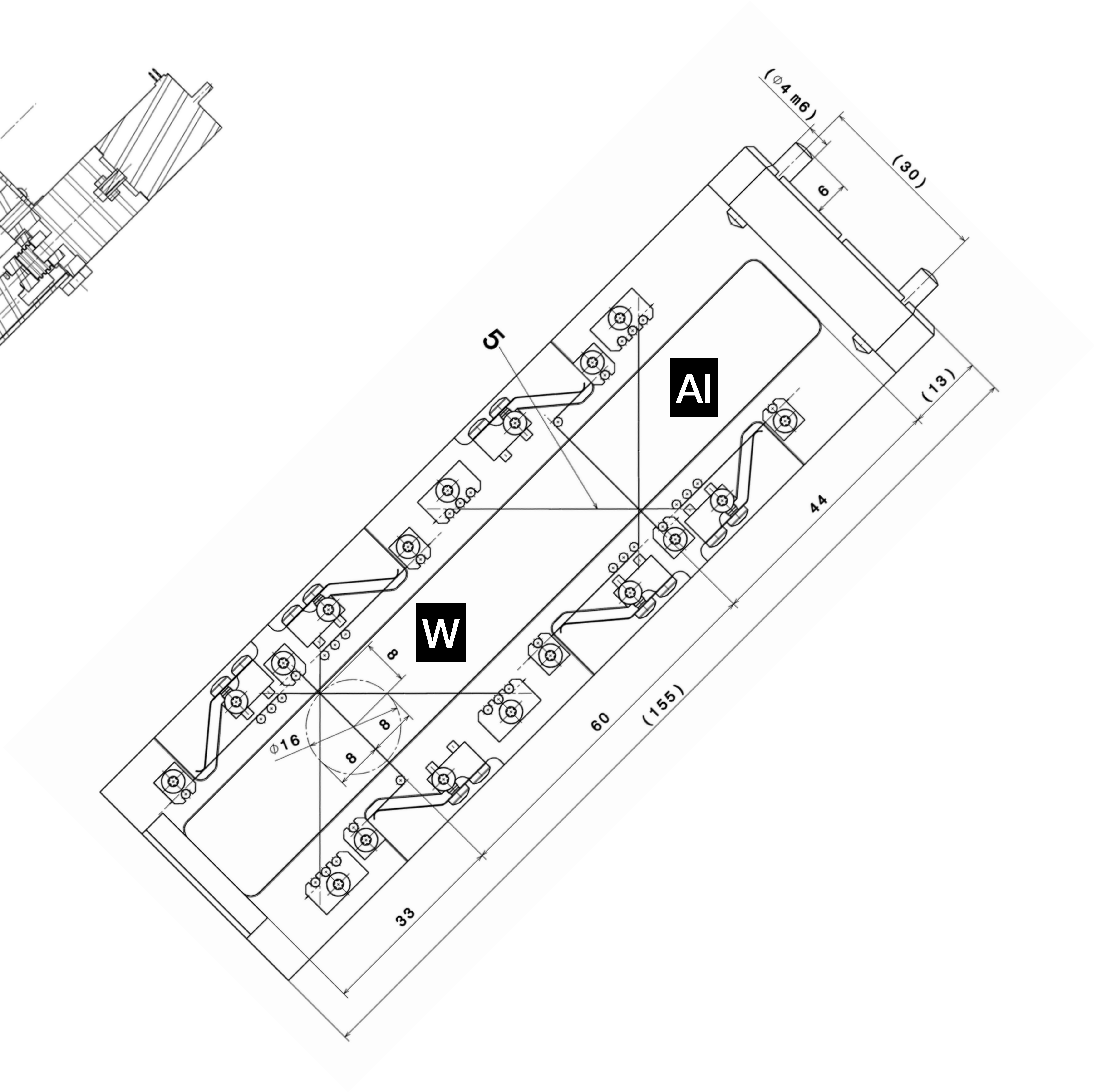
Many thanks to A. Fazan, A. Foskolos, C. Ozkan-Loch, P. Juranic, S. Bettoni, SF operators, PSI vacuum team!

Thank you for your attention.

BACK UP

WS Standard Fork Design

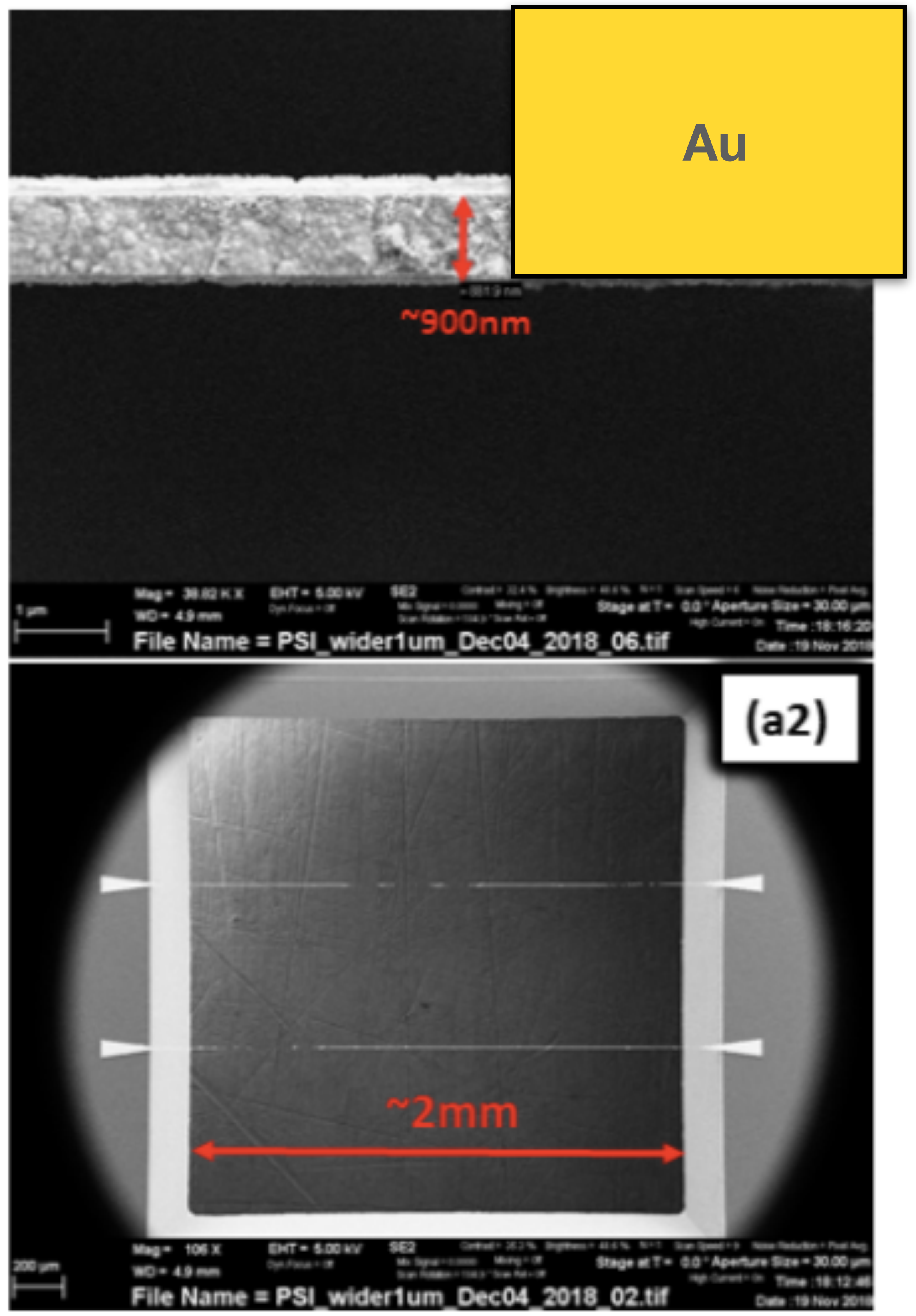




From conventional to sub-micrometer spatial resolution and minimal invasive Wire Scanner: How?

Intrinsic limitation of WS traditional manufacturing > Electron beam nano-lithography has been identified as the most promising technique. R&D independently pursued at PSI (Laboratory for Micro and Nano-technology) and FERMI-IOM-CNR.

PSI



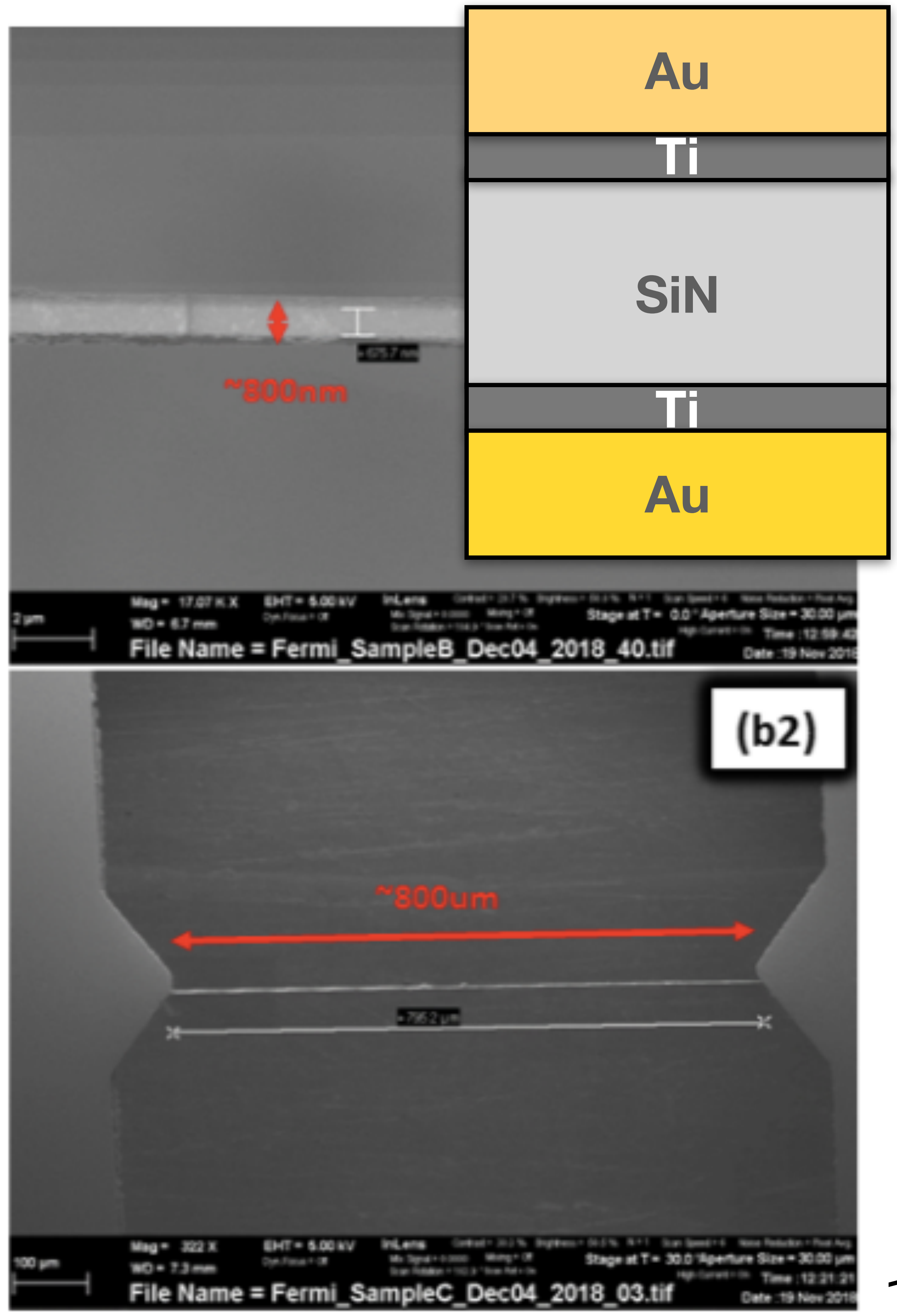
Sub-micrometer Au bulk scanning stripe free-standing over a silicon frame

- electron-beam lithography to define the wire footprint over Si
- electroplating to nanofabricate the Au wire

Best achievement:
width= 900 nm
thickness = 2um
length= 2mm
Geometrical resolution~ 260 nm

Goal 8-10mm

FERMI



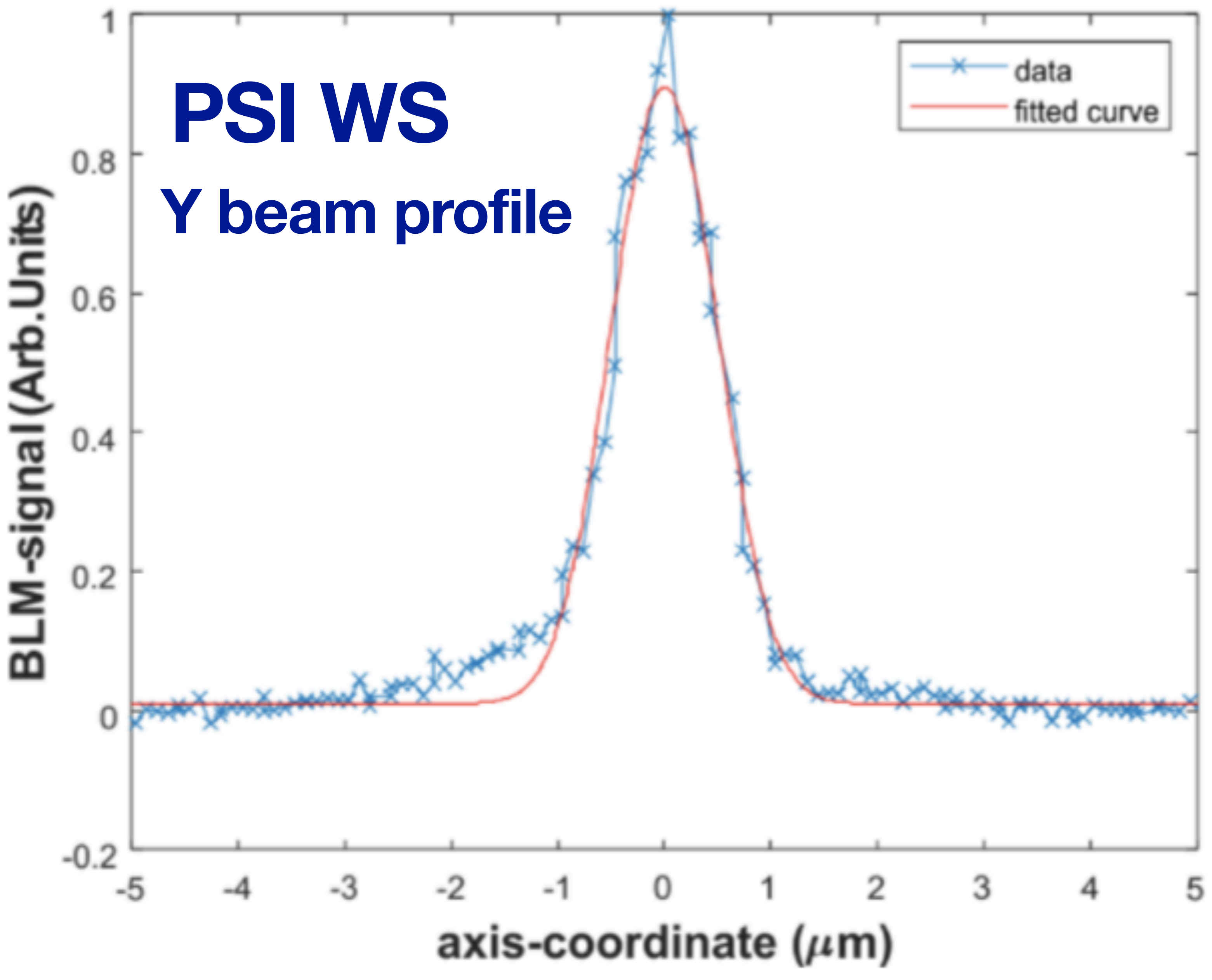
Sub-micrometer Au/Si_3Ni_4/Au scanning stripe free-standing over a silicon frame

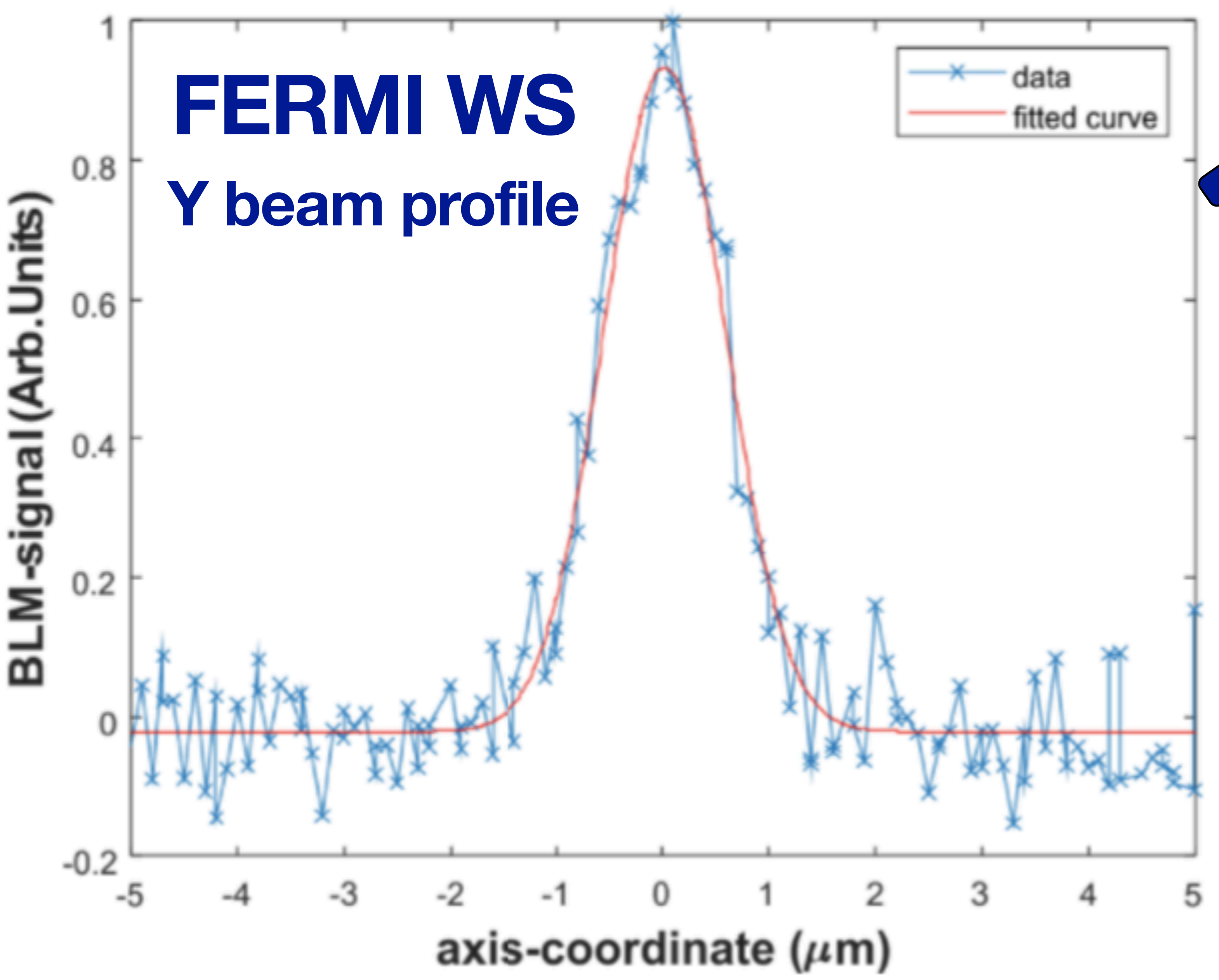
- electron-beam lithography to define the wire footprint over Si_3Ni_4
- e-gun evaporation to deposit the Au layer of wire

Best achievement:
width= 800 nm
thickness= ~3um (1um Au, 2um SiN)
length= 1mm
Geometrical resolution~ 230 nm

On beam performance validation of nano-fabricated WS

PSI and FERMI nano-fabricated WSs successfully tested at SwissFEL with a low charge (<1pc) and low emittance (ε_y~55 nm) electron beam (beam energy ~300 MeV). Vertical beam size expected at the WS station ~450 nm (from beta function).





FERMI WS characterized by a noisier signal (lower signal to noise ratio resulting in higher statistical error)

FERMI WS less invasive, featuring a radiation length ~ two times longer than the PSI one

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

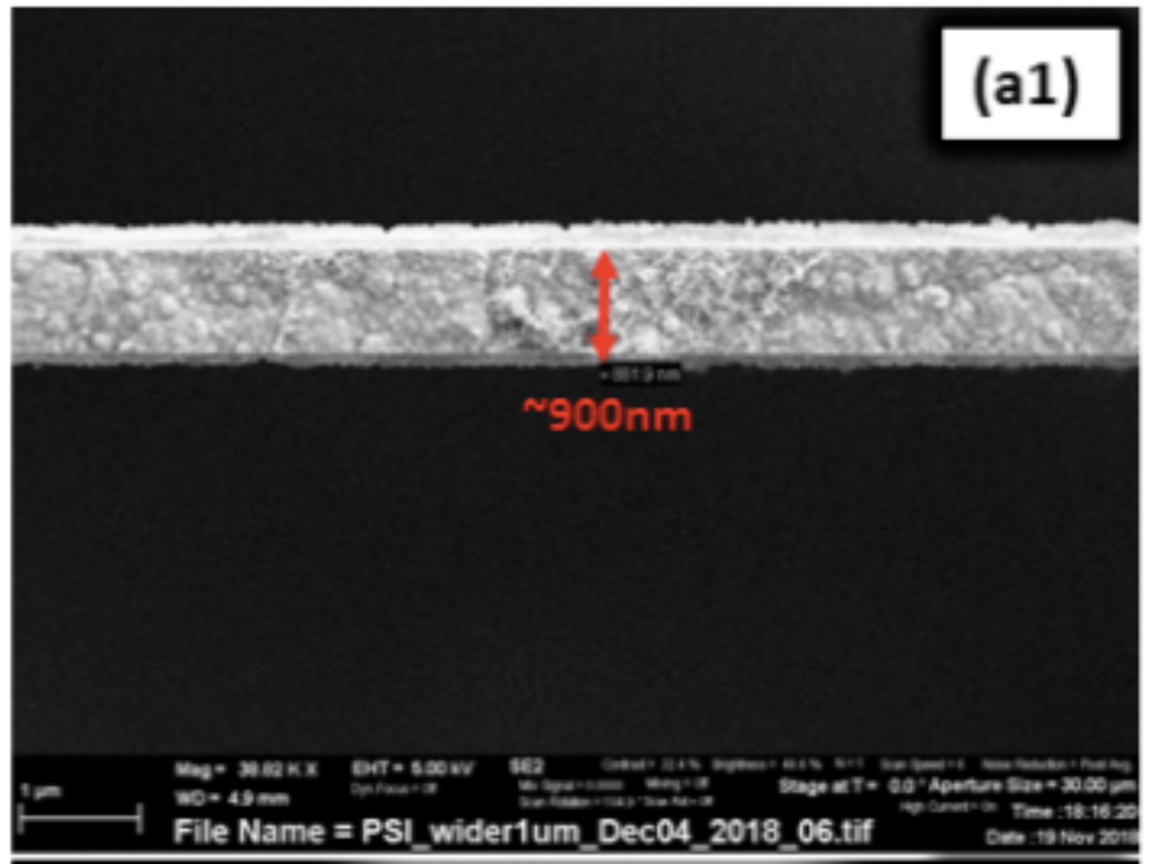
Heat-loading resilience test (200 pC, 1 Hz) successfully passed by both

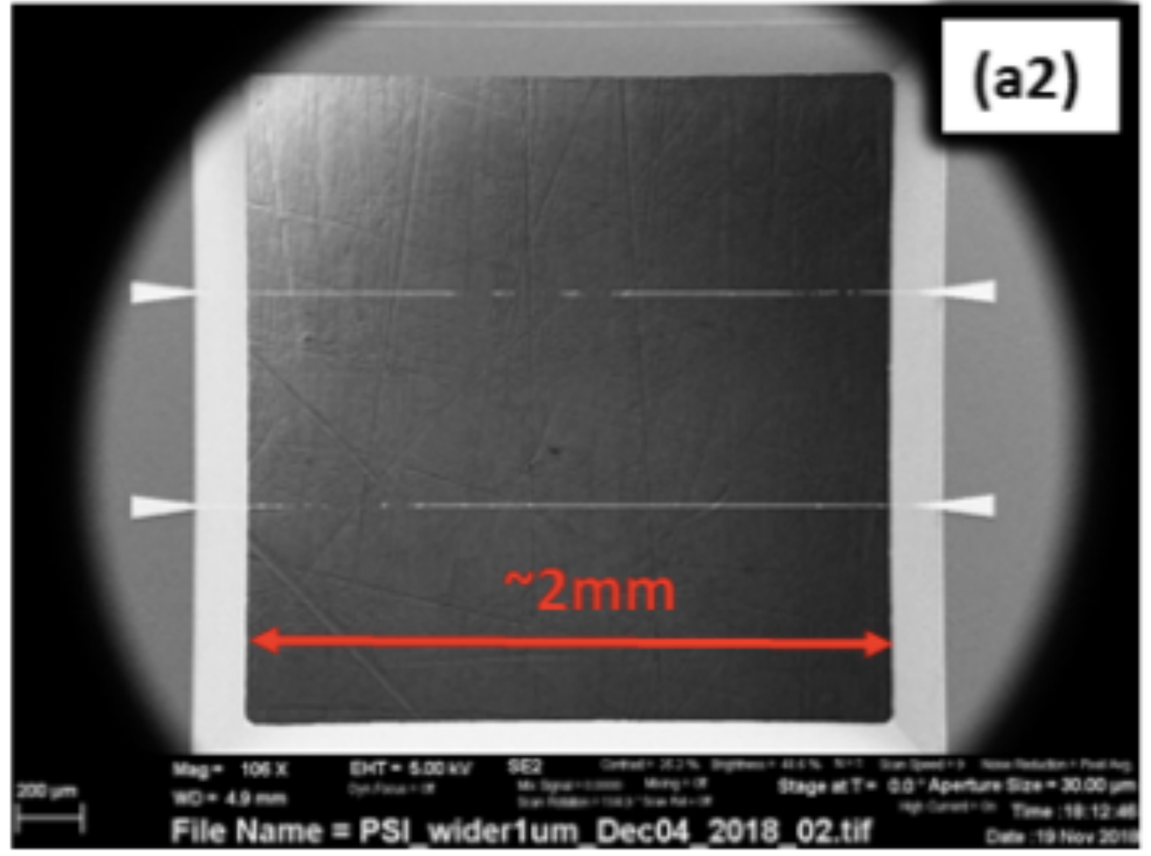
G.L. Orlandi et al., *Nanofabricated free-standing wire scanners for beam diagnostics with submicrometer resolution*, PHYSICAL REVIEW ACCELERATORS AND BEAMS 23, 042802 (2020)

Beam size measured by PSI and FERMI WSs within expectations and consistent within statistical errors.

From conventional to sub-micrometer spatial resolution and minimal invasive WS: How? @ PSI

Intrinsic limitation of WS traditional manufacturing -> Electron beam nano-lithography has been identified as the most promising technique. R&D independently pursued at PSI and FERMI-IOM-CNR.





Sub-micrometer Au bulk scanning stripe free standing over a silicon frame

- Si wafer coated with a thin layer (250 nm) LPCVD silicon nitride (Si_3Ni_4)
- Back-side aligned optical lithography to define the silicon frame, Si_3Ni_4 plasma etching
- Top side of the wafer evaporated with a stack of Ti(5nm)/Au(15nm)/Ti(5nm) to create the seed layer for gold electro-deposition
- E-beam lithography to define the footprint of the line spanning across the Silicon frame
- Electroplating of the gold nano-wire in its footprint
- Removal of the the e-beam resist and Si bulk and the metal seed layer
- Removal of the Si inside the frame

Best achievement: 900 nm wide and 2mm long scanning stripe. Spatial res: 260 nm