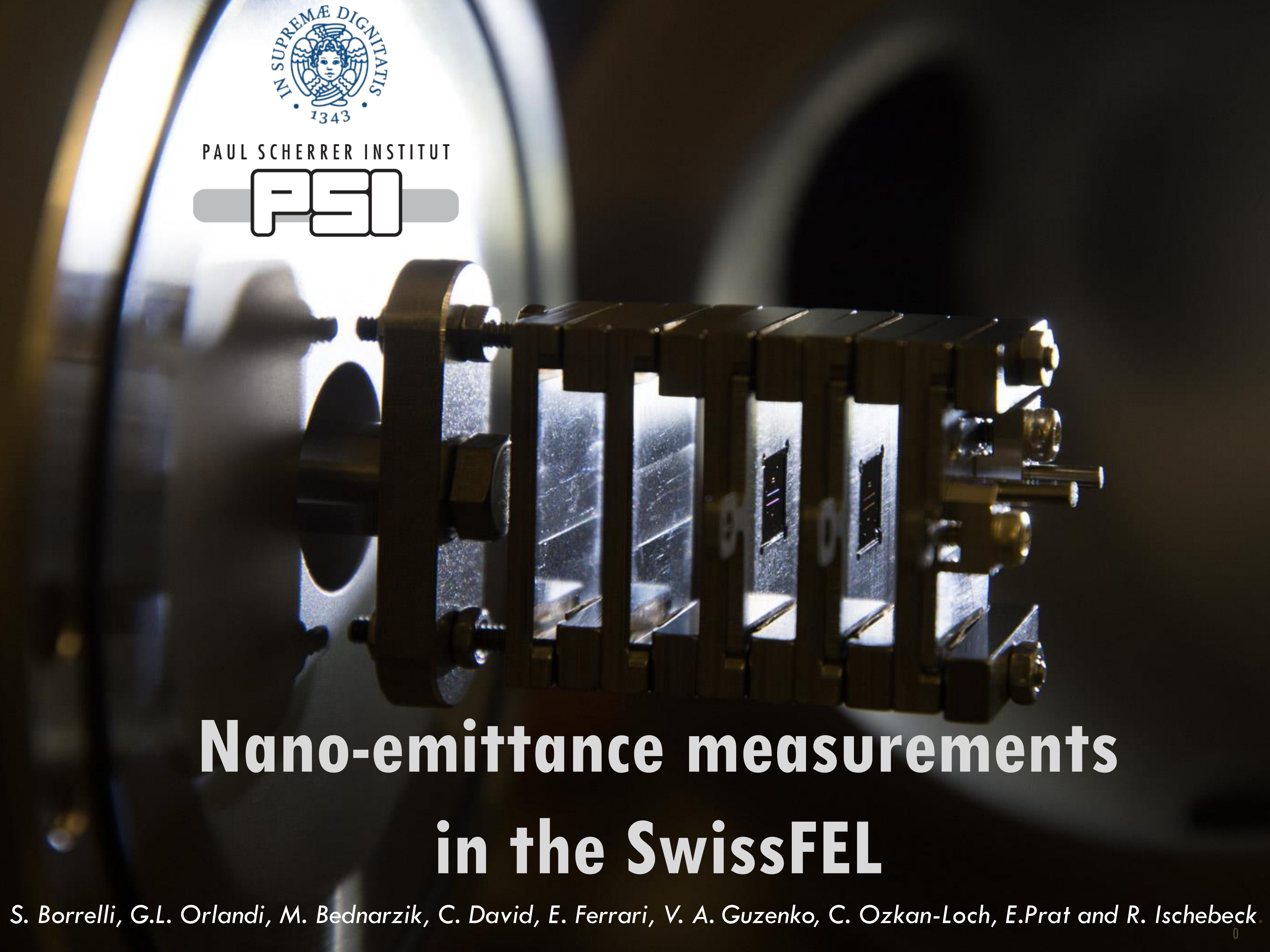

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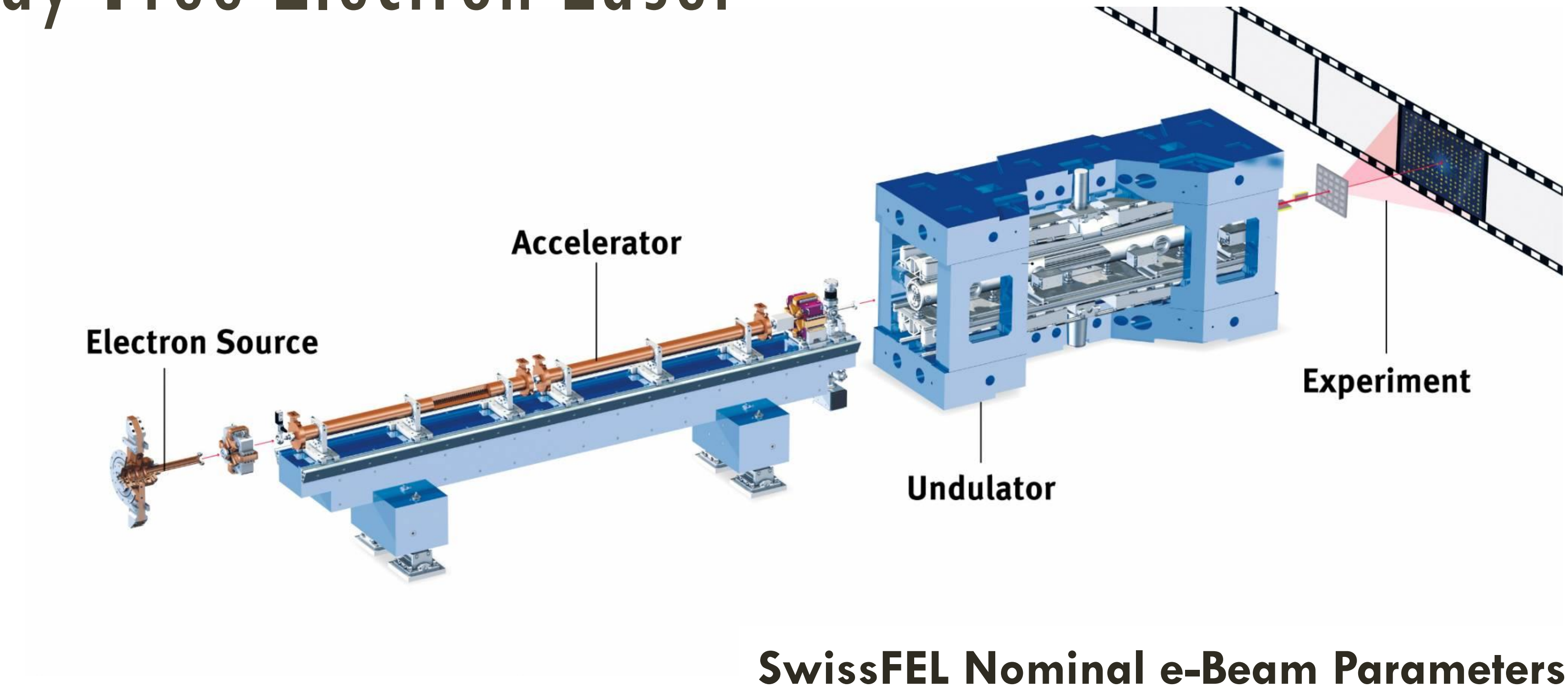
Nano-emittance measurements in the SwissFEL

S. Borrelli, G.L. Orlandi, M. Bednarzik, C. David, E. Ferrari, V. A. Guzenko, C. Ozkan-Loch, E.Prat and R. Ischebeck

X-ray Free Electron Laser



SwissFEL Nominal e-Beam Parameters

E	5.8 GeV
Q	200-10 (pC)
ε_N	0.4-0.2 *(mm mrad)*
σ_{min} (@10 pC)	8 μm (rms)

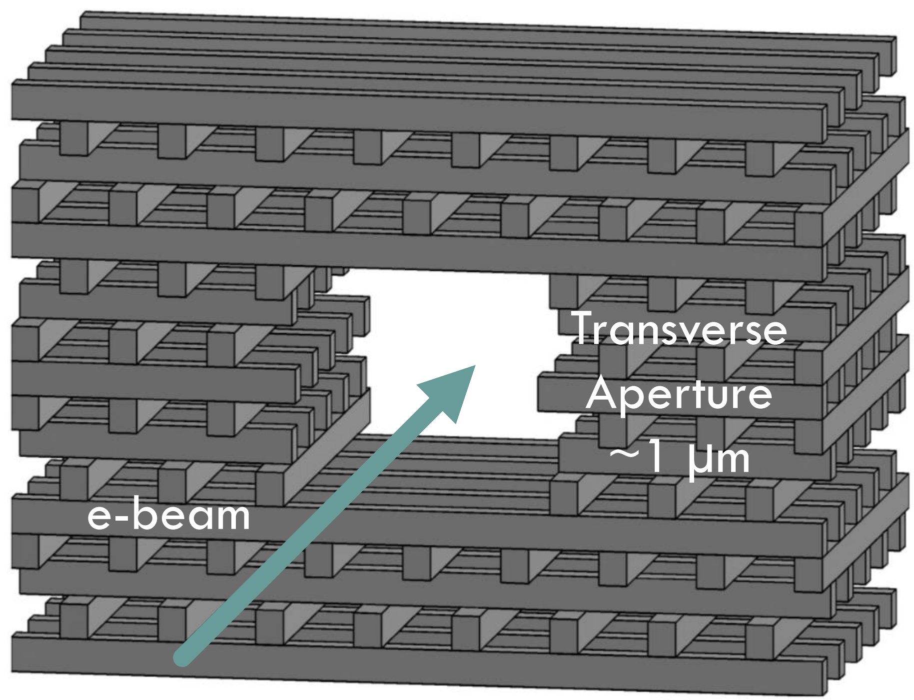
In a XFEL it is important to generate e-beam with low normalized emittance and preserve it in order to produce laser pulses of the desired small wavelength.

→ High resolution emittance measurements are necessary.

Dielectric Laser Accelerator

Compact electron accelerator in which the accelerating structure is a dielectric microstructure excited by femtosecond laser pulses.

Sub-micrometer e-beam transverse diemensions and low emittance are necessary.



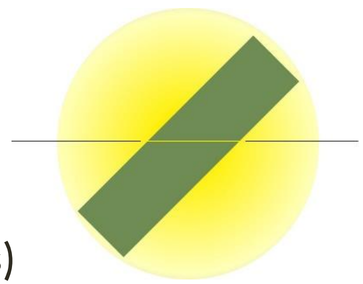
B. M. Cowan, Phys. Rev. ST Accel. Beams 11, 011301 (2008)

Beam Transverse Profile Monitors

2-D Screens

Scintillating crystal

YAG:Ce Screen



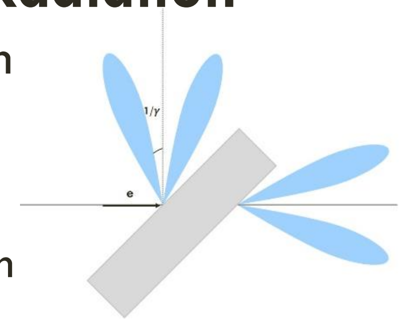
- High dynamic range but not linear
- Possible saturation
- Resolution is 8 μm (rms)

(*SwissFEL*)

Ischebeck, R., et al. "Transverse profile imager for ultrabright electron beams." PRST-AB 18.8 (2015): 082802.

Optical Transition Radiation

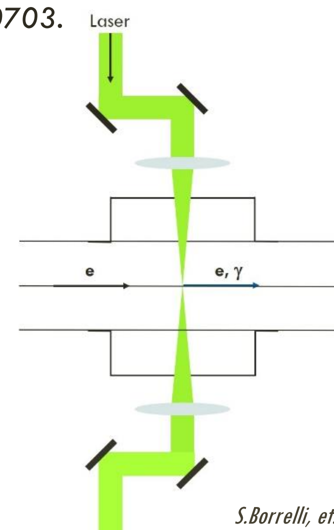
OTR Screen



- Linear
- Coherent OTR emission from compressed bunch

Akre, R., et al. "Commissioning the linac coherent light source injector." PRST-AB 11.3 (2008): 030703.

Laser Wire Scanners



- 1-D monitor
- Minimum laser waist limited by the laser wavelength
- Measured beam size 70 nm

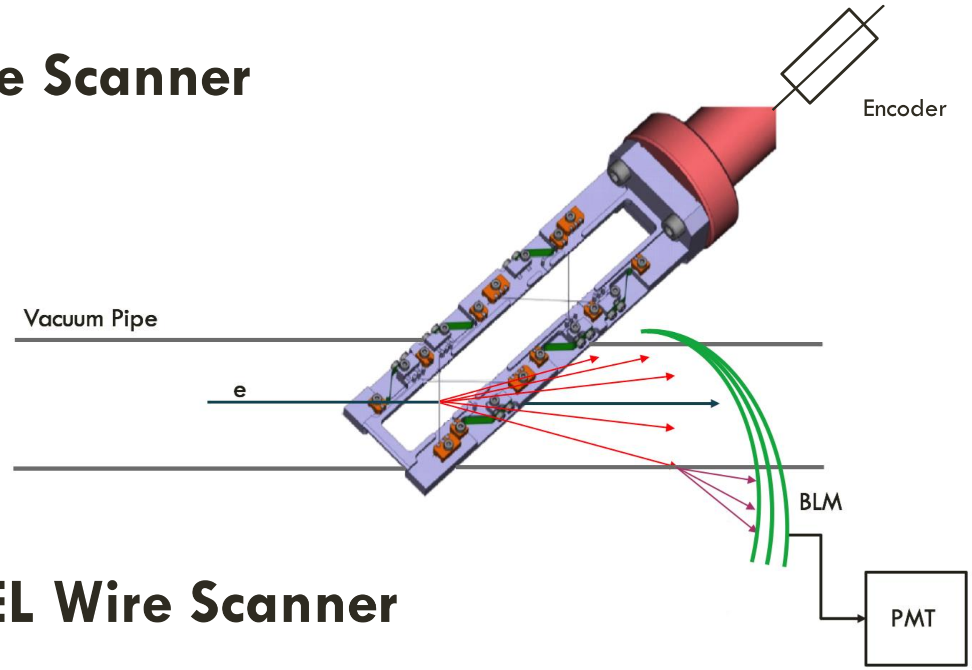
(*SLC-FFTB*)

Balakin, V., et al. "Focusing of Submicron Beam for TeV-scale e+-e- Linear Colliders." PRL 74.13 (1995): 2479.

Beam Transverse Profile Monitors

Wire Scanner

- 1-D monitor
- Multi shot measurement
- Resolution limited by
  - Wire diameter
  - Wire vibration
  - Encoder resolution
  - Beam jitter



SwissFEL Wire Scanner

- Geometrical rms resolution (5 μm W wire) 1.25 μm
- Wire vibration below the geometrical resolution
- Encoder resolution 0.1 μm

Orlandi, G. L., et al. "Design and experimental tests of free electron laser wire scanners." *PR-AB.*,19.9 (2016): 092802.

→ Reduce wire diameter to improve resolution

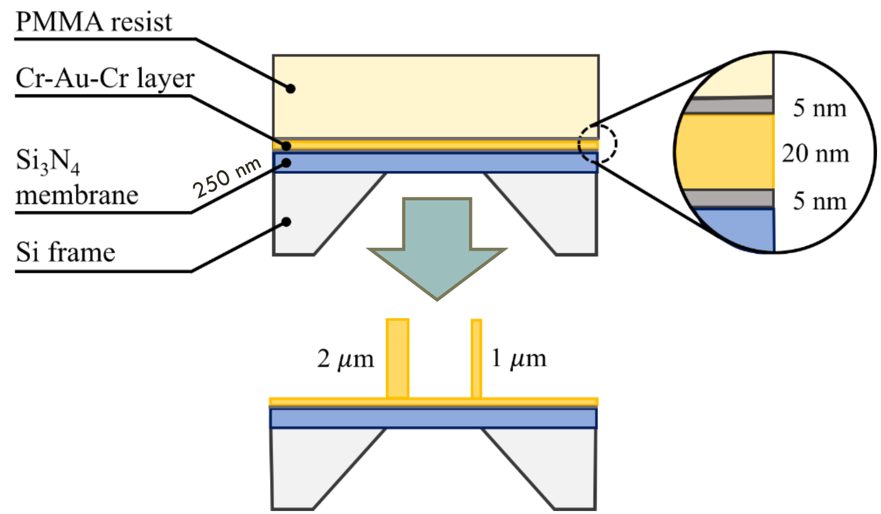
IDEA

Nanofabrication techniques to produce a 1 μm stripe on a membrane via e-beam lithography and electroplating.

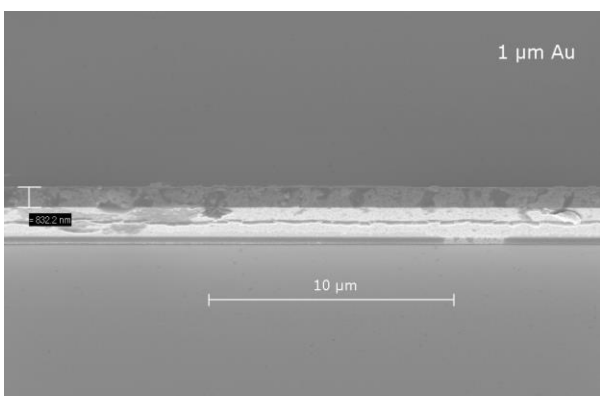
Wire Scanner on-a-chip with Sub-μm Resolution

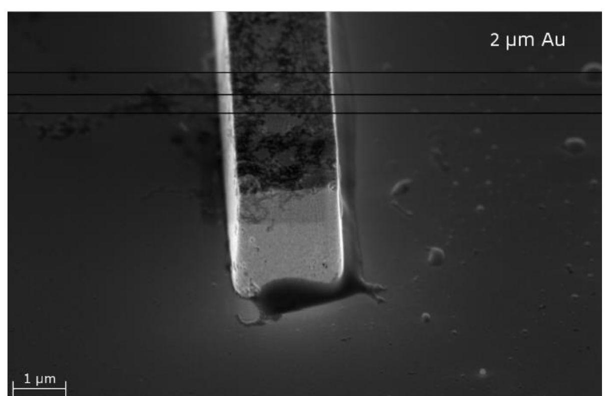
Fabrication Technique

- Electron Beam Lithography on the Resist
- Resist development
- Top Cr layer removal
- Electroplating of two Au wires of different widths (*1 μm-2 μm*)
- Resist removal



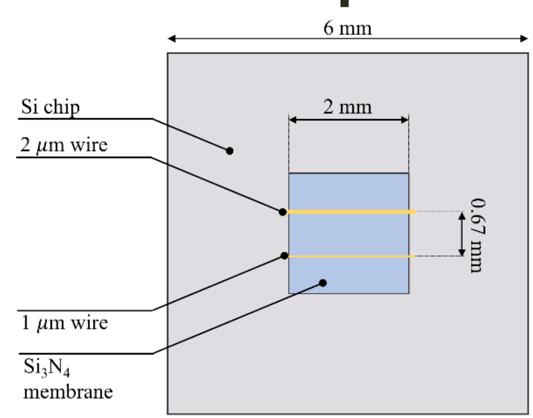
Scanning Electron Microscope characterization





Vitaliy Guzenko

Wire Scanner on-a-chip Sketch



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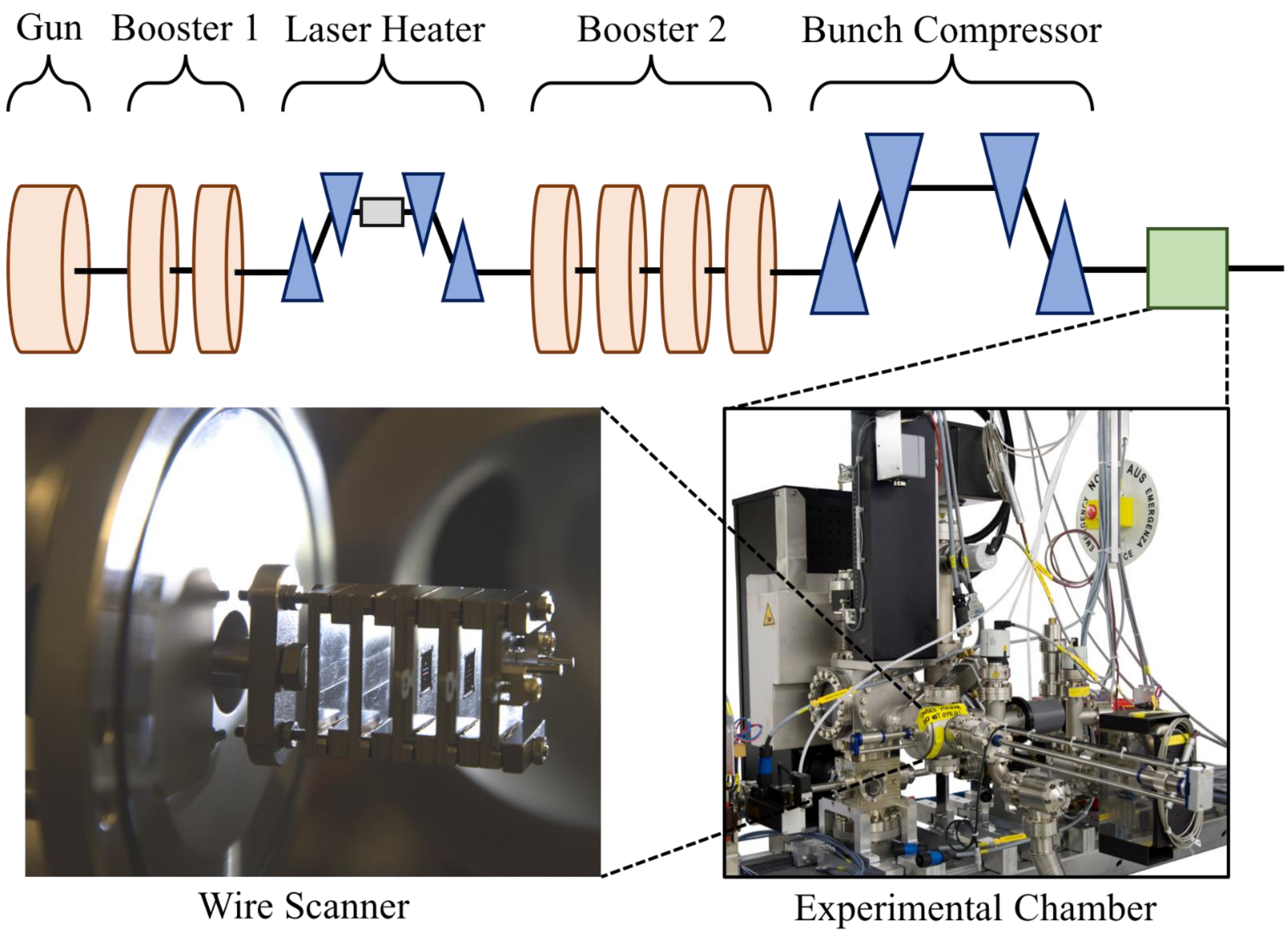
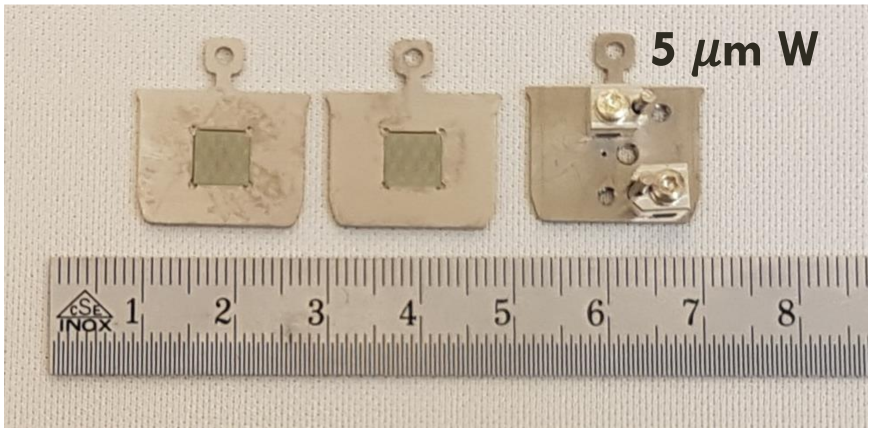
Generation & Measurement of Sub-μm e-beams

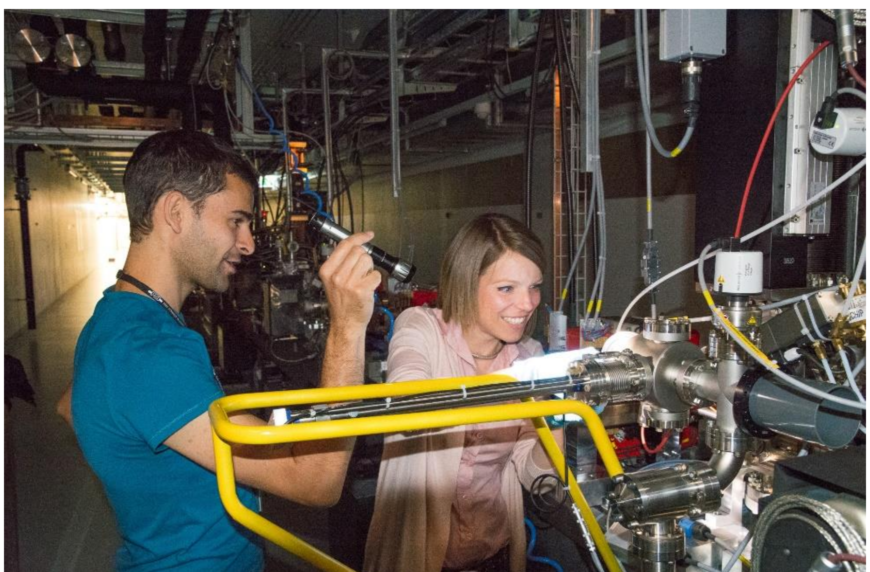
SwissFEL Injector

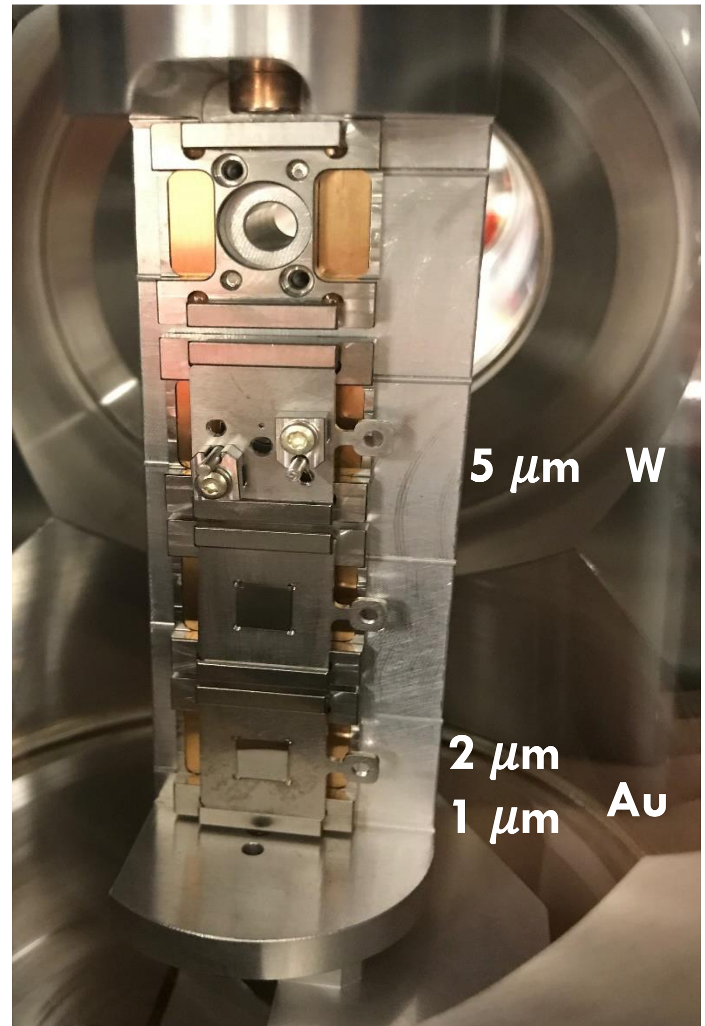


Generation & Measurement of Sub-μm e-beams

Wire Scanners Installation



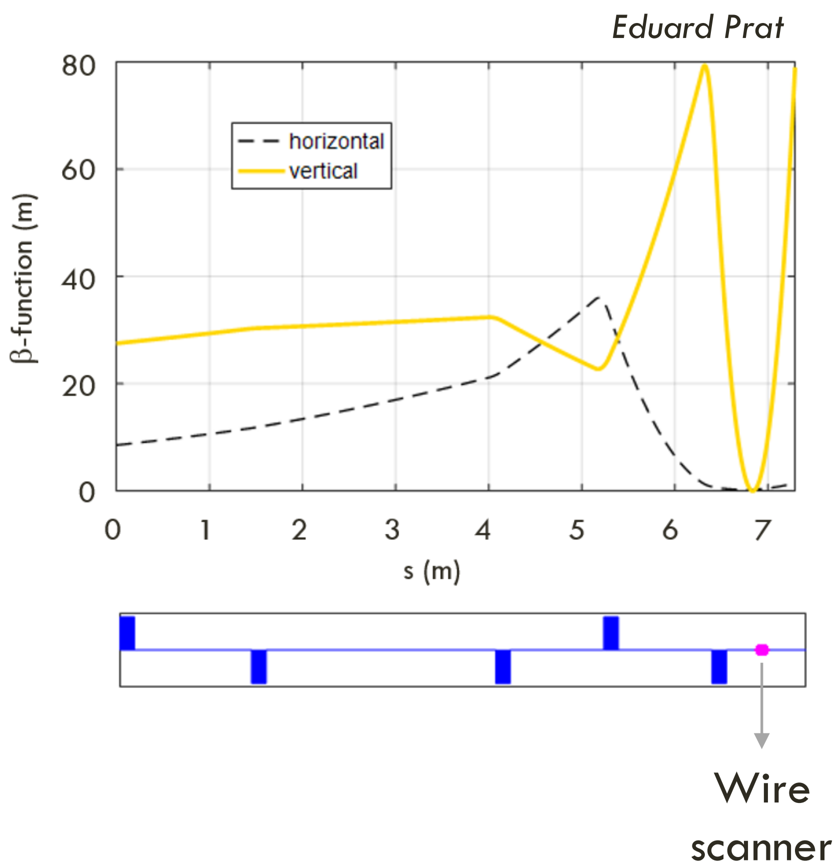




Generation & Measurement of Sub-μm e-beams

Generation of Sub-μm Relativistic e-Beams

E	330 MeV
Q	< 1 pC
$\varepsilon_{N,y}$	53 nm
β_y	2.61 mm

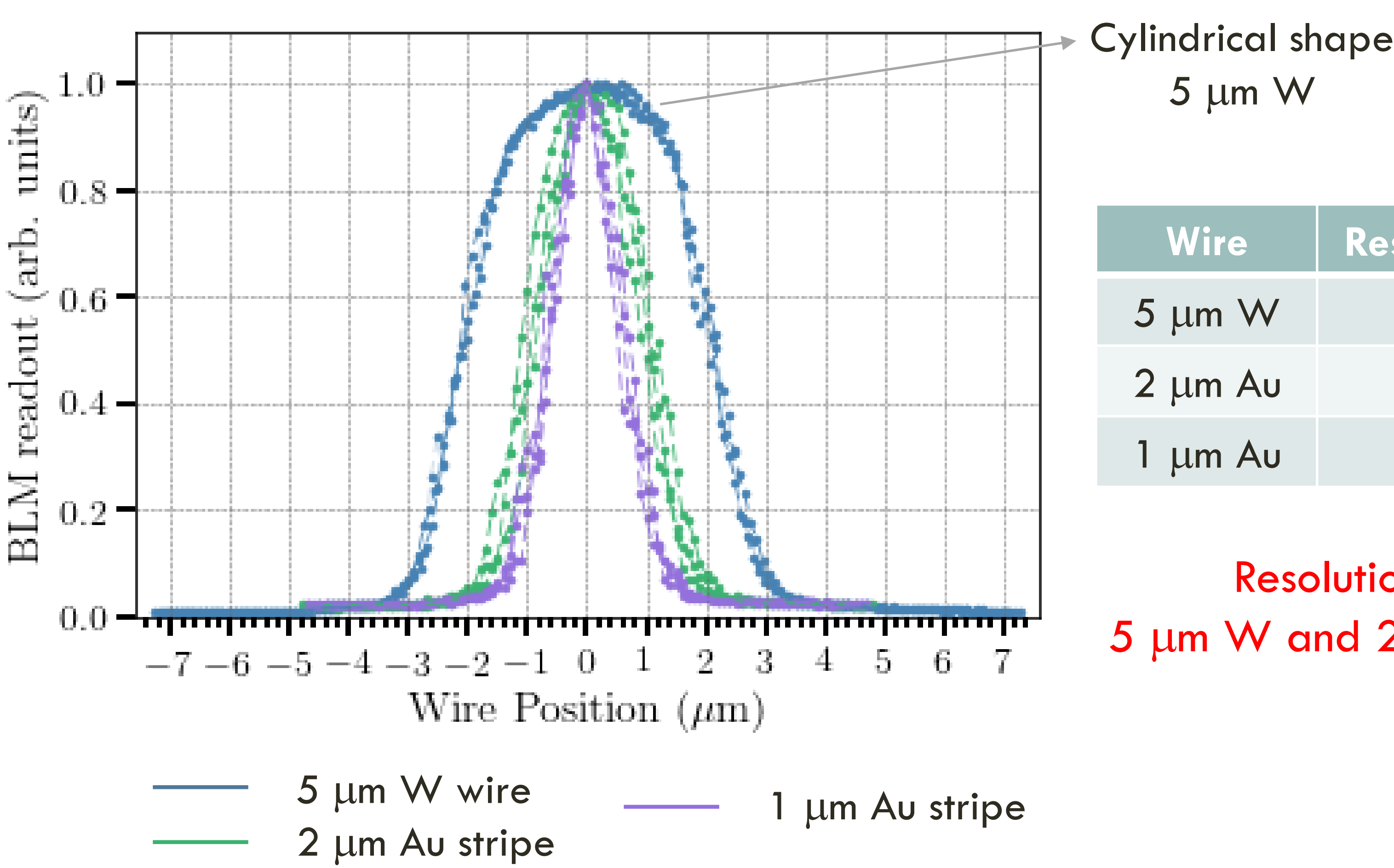


Beam Size at wire scanner location

σ_y = 463 nm (rms)

Generation & Measurement of Sub-μm e-beams

Beam Profile Measurements



Three sequential measurements for each wire

Wire	Resolution (μm)
5 μm W	1.25
2 μm Au	0.58
1 μm Au	0.29

Resolution limit:
5 μm W and 2 μm Au wires

Generation & Measurement of Sub-μm e-beams

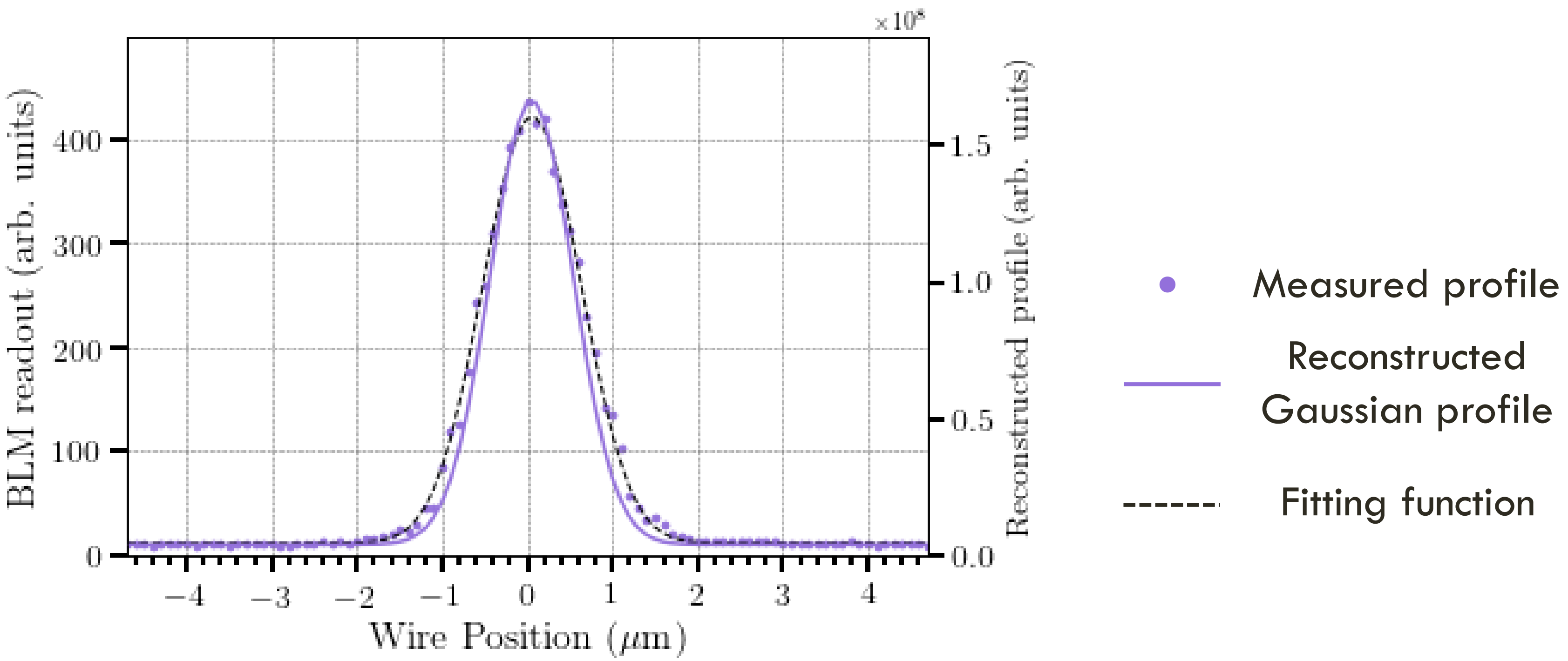
Convolution Fit

Fitting function

$$f(y;\Delta,\alpha,\sigma,\gamma) = \int t(u)\left[\Delta + \alpha e^{\frac{-(u-y-\gamma)^2}{2\sigma^2}}\right]du$$

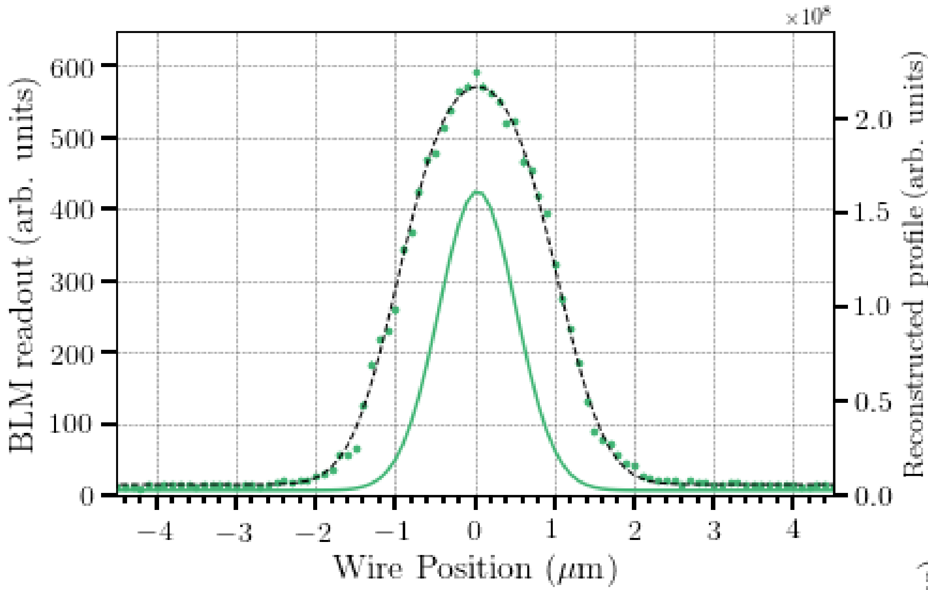
Wire shape

hyp: Gaussian Beam profile



Generation & Measurement of Sub-μm e-beams

Convolution Fit

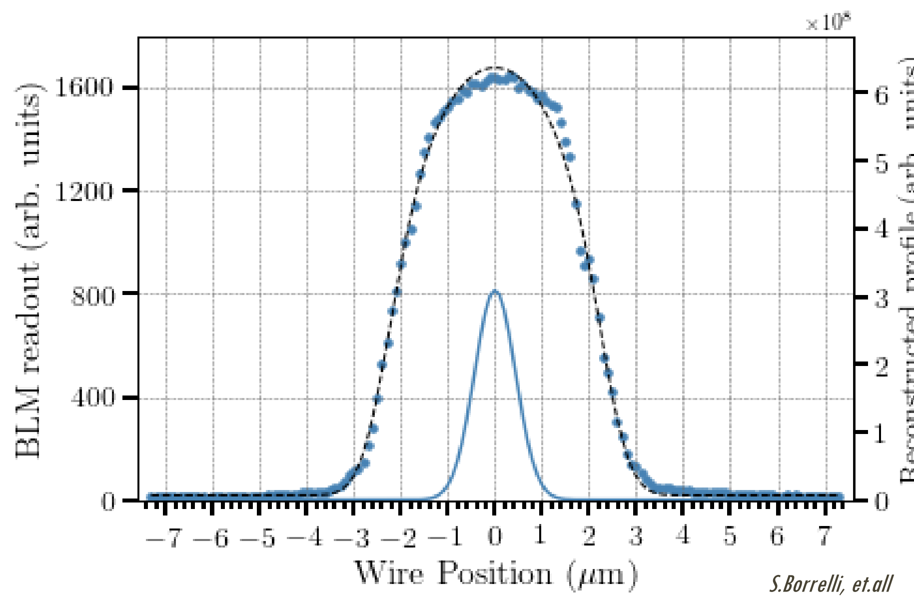


Measured profiles

Reconstructed
Gaussian profiles

Fitting function

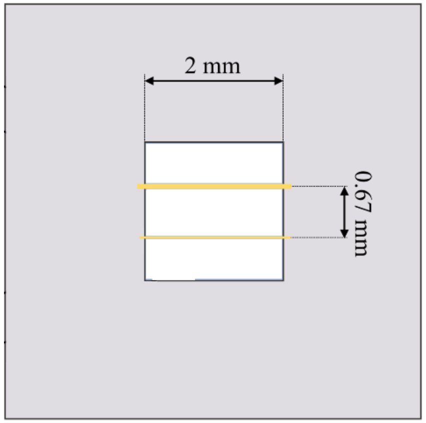
Wire	σ_y (nm)
5 μm W	*462 ± 11*
2 μm Au	*491 ± 4*
1 μm Au	*491 ± 5*

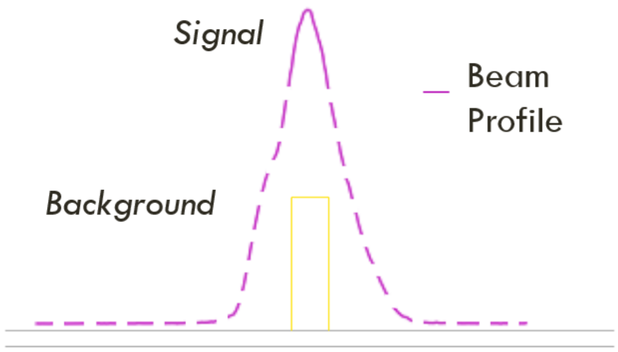


σ_y : Average fit sigma over 3 sequential beam profile measurement with its standard deviation

Outlook

- Membrane removal to improve the signal-to-noise ratio.





Only a small fraction of the beam traverse the membrane and the wire producing the signal of interest.

- Generate a smaller beam in the SwissFEL high energy region and test wire scanner on-a-chip prototypes with 0.3 µm and 0.5 µm wide stripes

- Beam jitter correction

Thanks so much!

Gian Luca Orlandi
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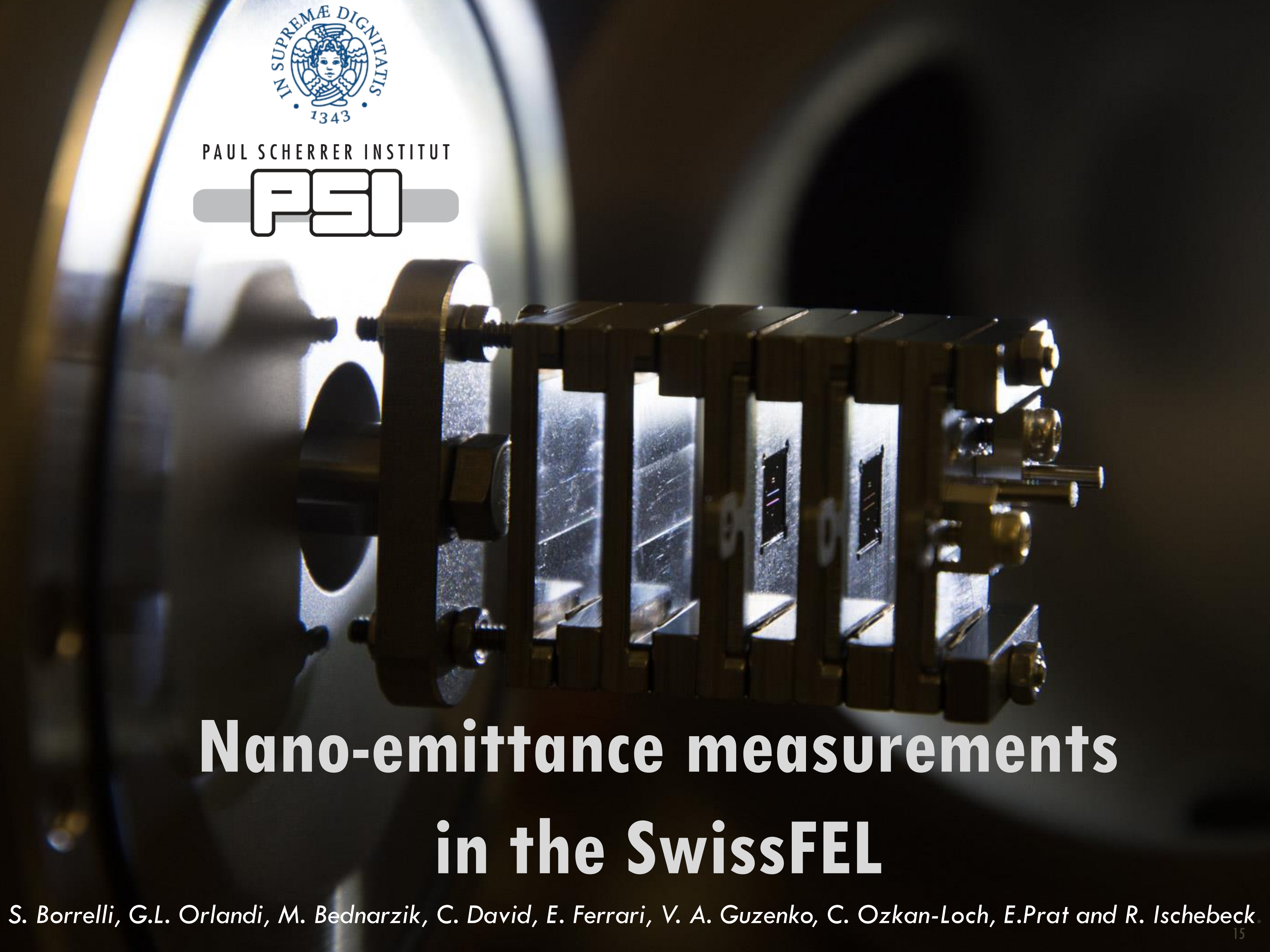
Cigdem Ozkan-Loch
Volker Schlott
Nicole Hiller
PSI Vacuum Group
Christian David
Martin Bednazik
Beat Rippstein
Alexandre Gobbo
Arturo Daniel Alarcon



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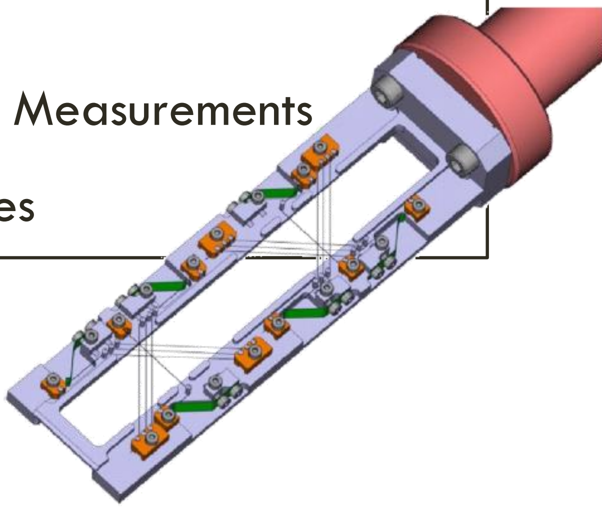
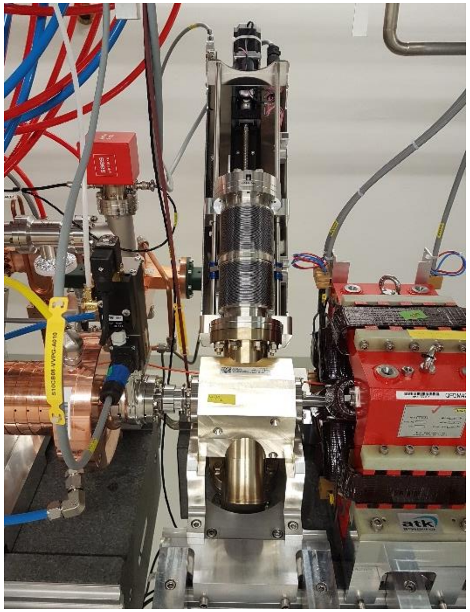
BACKUP SLIDES

SwissFEL WIRE SCANNER

SwissFEL Wire Scanners (WSCs) consist of a wire fork equipped with two couples of wires:

- 5 µm W wires — High Resolution Measurements
- 12.5 µm Al(99):Si(1) wires — Low Beam Losses





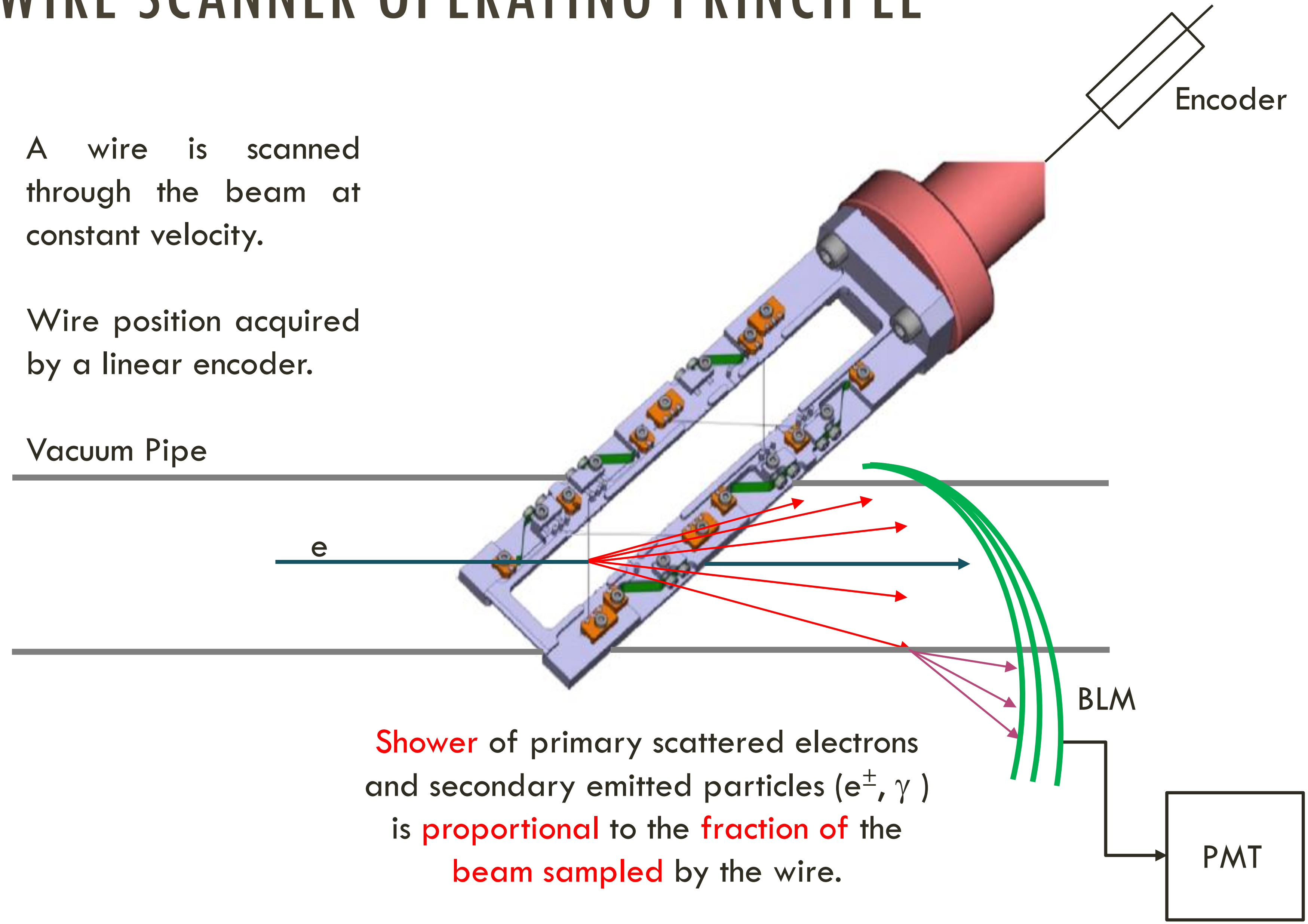
Fork inserted in the vacuum by means of an Ultra-High Vacuum linear-stage driven by a two phase stepper motor.

Fork inserted at 45°w.r.t. the vertical direction so that for each couple, one wire scans the beam vertically and the other horizontally.

WIRE SCANNER OPERATING PRINCIPLE

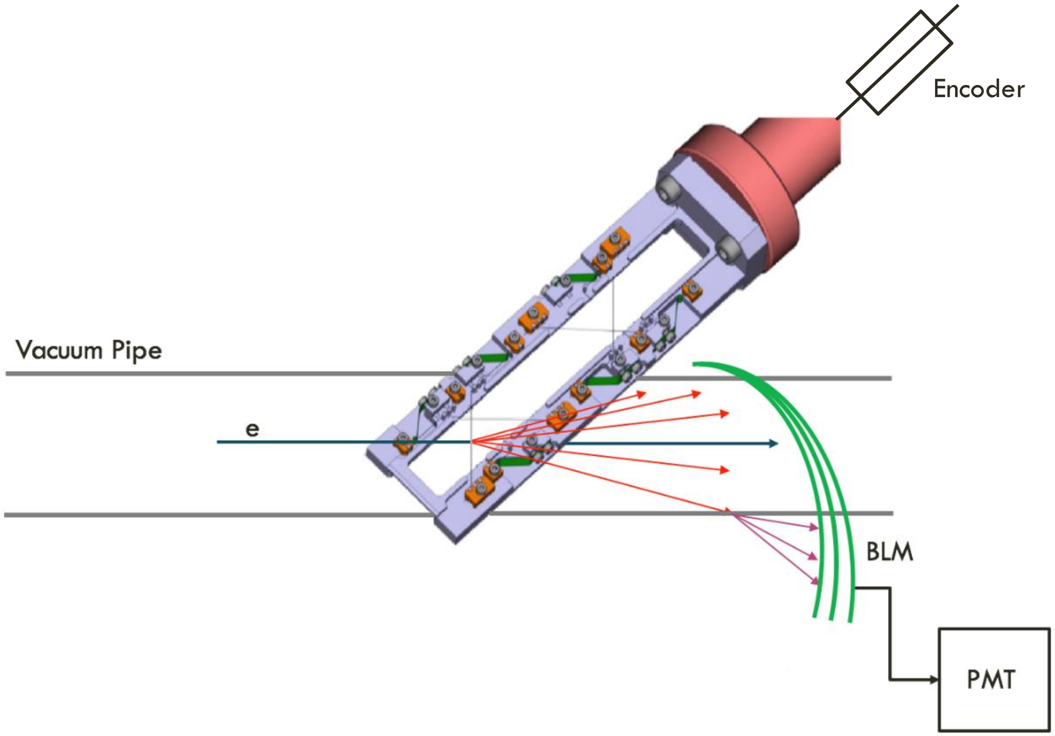
A wire is scanned through the beam at constant velocity.

Wire position acquired by a linear encoder.



Shower of primary scattered electrons and secondary emitted particles ($e^{\pm}$, γ) is proportional to the fraction of the beam sampled by the wire.

WIRE SCANNER OPERATING PRINCIPLE

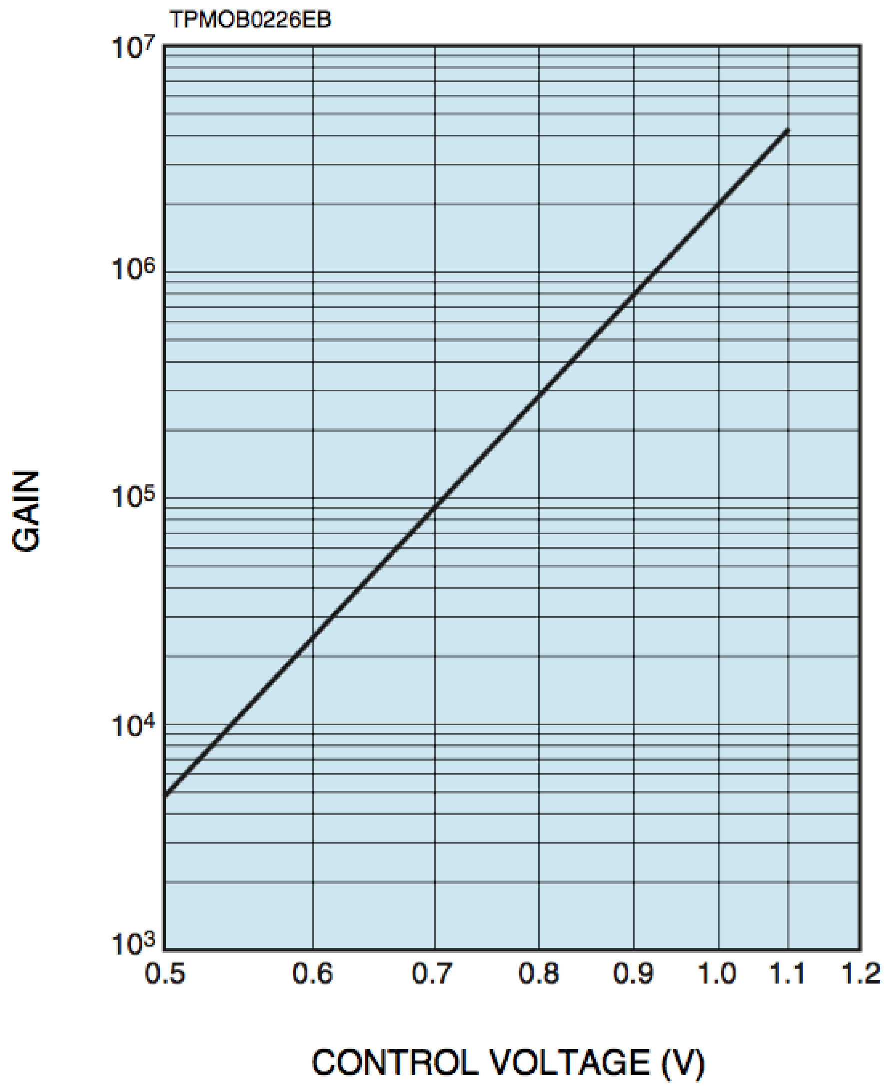


Out-of-vacuum detection of the shower's forward component through scintillator fiber.

Scintillator light sent to a PMT with an adjustable gain in the range [$5 * 10^3, 4 * 10^6$].

The beam's horizontal / vertical profile can be reconstructed acquiring in beam synchronous way the wire position and BLM signal.

BLM GAIN CURVE



SUB-MICROMETER RESOLUTION WIRE SCANNER

WIRE HEATING BY E-BEAM EXPOSURE

Rough estimation

Energy transferred by the beam particles to the wire material

$$E_{loss} = \frac{dE}{dt} * t * \rho_{Au} \underbrace{* Ne * R}$$

Collisional stopping power in Au for E = 320 MeV

$\frac{dE}{dt}$ = 1.5 MeV cm²/g

N° of particles intercepted by the wire

$E_{loss} = 5.3 * 10^{-11}$ J

SUB-MICROMETER RESOLUTION WIRE SCANNER

WIRE HEATING BY E-BEAM EXPOSURE

Rough estimation

Increase of temperature

$$\Delta T = \frac{E_{loss}}{c_s * m_{eff}}$$

Gold specific heat

Wire effective mass

$$m_{eff} = \rho_{Au} * \sigma_b * t * \frac{w}{\sqrt{12}}$$

For each RF-shot

$\Delta T = 14$ K

Wire Scanner on-a-chip with Sub-μm Resolution

STRIPE HEATING BY E-BEAM EXPOSURE

2 μm Au stripe

Irradiated power

$$P_{irr} = \sigma A T^4 \epsilon$$

Area of stripe involved

$$A = (3.2\ \mu\text{m} * 2\ \mu\text{m}) * 4$$

Gold emissivity

$$\epsilon = 0.47$$

$$T = 300\ \text{K} + \Delta T = 314\ \text{K}$$

P_{irr} = 1.106 * 10-9 W

Wire Scanner on-a-chip with Sub-μm Resolution

STRIPE HEATING BY E-BEAM EXPOSURE

2 μm Au stripe

Absorbed power $P_{in} = E * 10\ \mathrm{Hz} = 5.3 * 10^{-10}$ W

Absorbed energy

$$\Delta P = 1.106 * 10^{-9}\ \mathrm{W} > P_{in}$$

SUB-MICROMETER RESOLUTION WIRE SCANNER

WIRE HEATING BY E-BEAM EXPOSURE

12.5 µm Al & 5 µm W wires comparison

Rough estimation

	ΔT (°C)	Melting Point (°C)
GOLD	3.7	1064
ALUMINUM	0.7	660
TUNGSTEN	3.7	3695

BACKGROUND FROM THE MEMBRANE

Beam Parameters

E_e	=	320 MeV
Q_b	=	1 pC
$\sigma_{x/y}$	=	3.2 μm

Wire & membrane parameters

Wire Width	$w_{Au} = 2\ \mu m$
Wire Thickness	$t_{Au} = 2\ \mu m$
Membrane Thickness	$t_{Si_3N_4} = 0.250\ \mu m$

Radiative energy loss of the beam intercepted by the wire in the Si_3N_4 +Au thickness

$$\Delta E\Big|_{rad}^{Si_3N_4+Au} = \frac{E_e}{L_R^{Si_3N_4+Au}} * t_{Si_3N_4+Au} * \Delta N_e$$

Si_3N_4 +Au radiation length $L_R^{Si_3N_4+Au} = 0.3$ cm

Fraction of e^- intercepted by the wire.

BACKGROUND FROM THE MEMBRANE

Radiative energy loss of remaining part of the beam in Si_3N_4 thickness

$$\Delta E\Big|_{rad}^{Si_3N_4} = \frac{E_e}{L_R^{Si_3N_4}} * t_{Si_3N_4} * (N_e - \Delta N_e)$$

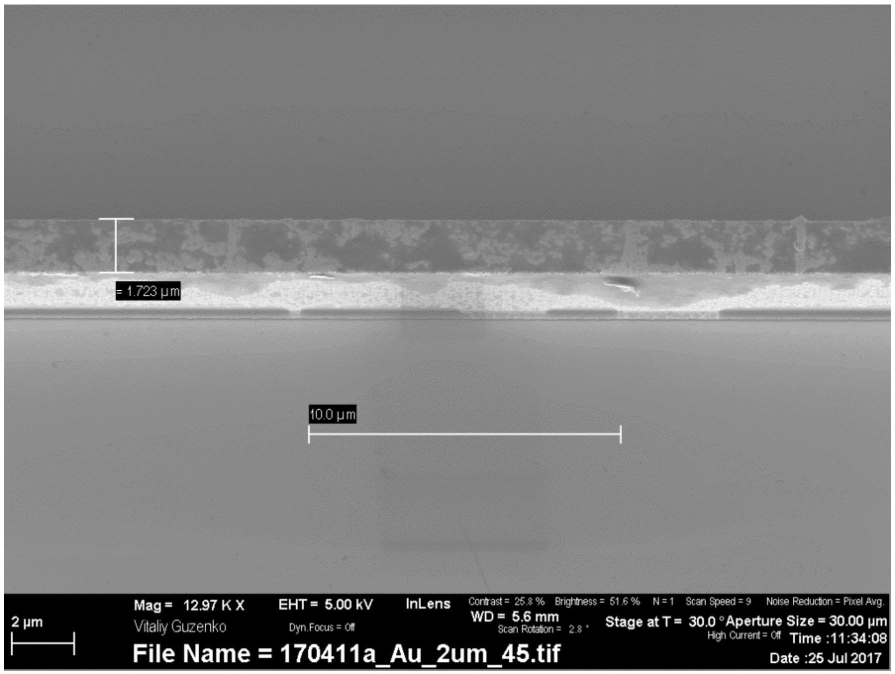
Si_3N_4 radiation length
$L_R^{Si_3N_4+Au} = 8.3$ cm

Fraction of e^- passing only the membrane

Background to signal ratio

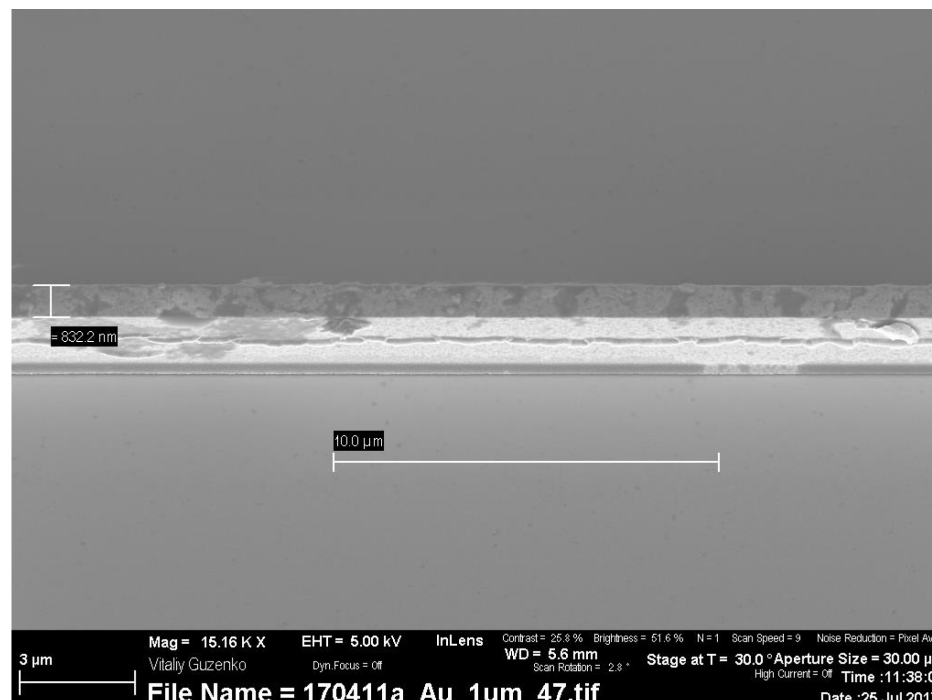
$$\frac{\Delta E|_{rad}^{Si_3N_4}}{\Delta E|_{rad}^{Si_3N_4+Au}} = \mathbf{18}$$

WIRES AFTER THE BEAM EXPOSURE



2 µm Au wire

$\sigma_w = 0.6$ µm



1 µm Au wire

$\sigma_w = 0.3$ µm

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NICKEL WIRES

Beam losses estimation

Beam loss $\propto Z^2$ → $\frac{Au}{Ni} = 8$ 8 times lower signal

Background from the membrane

Background to signal ratio

$$\frac{\Delta E|_{rad}^{Si_3N_4}}{\Delta E|_{rad}^{Si_3N_4+Ni}} = \mathbf{9}$$

SKETCHES

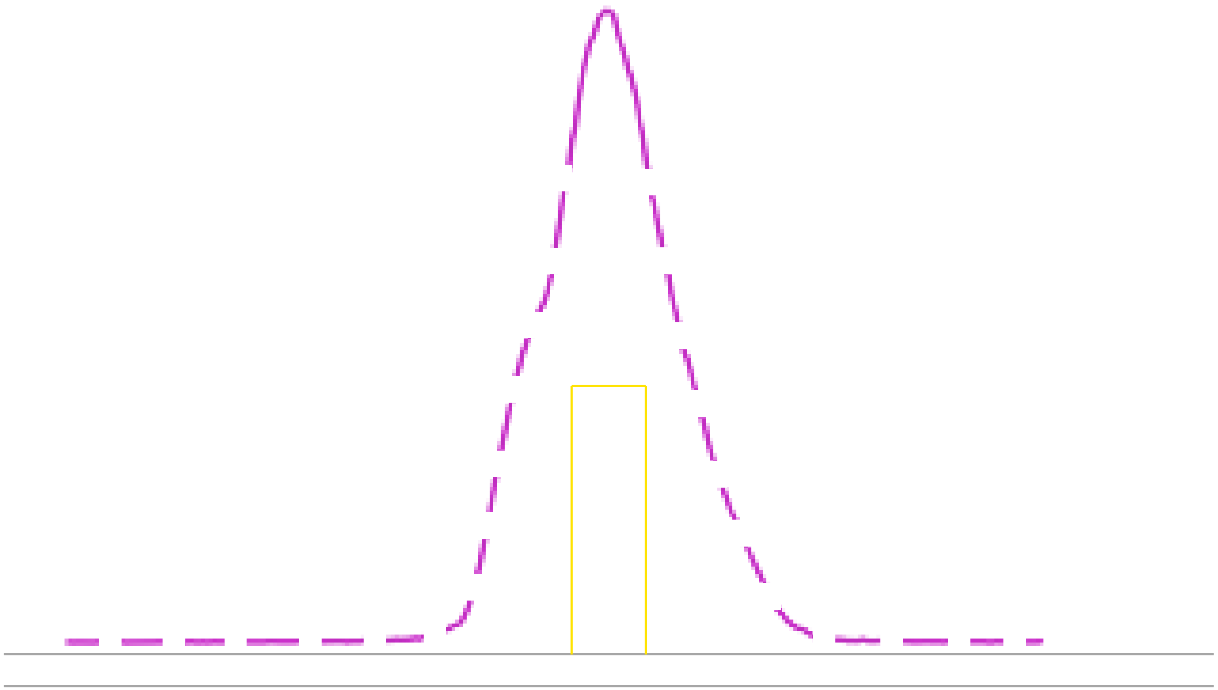
SwissFEL

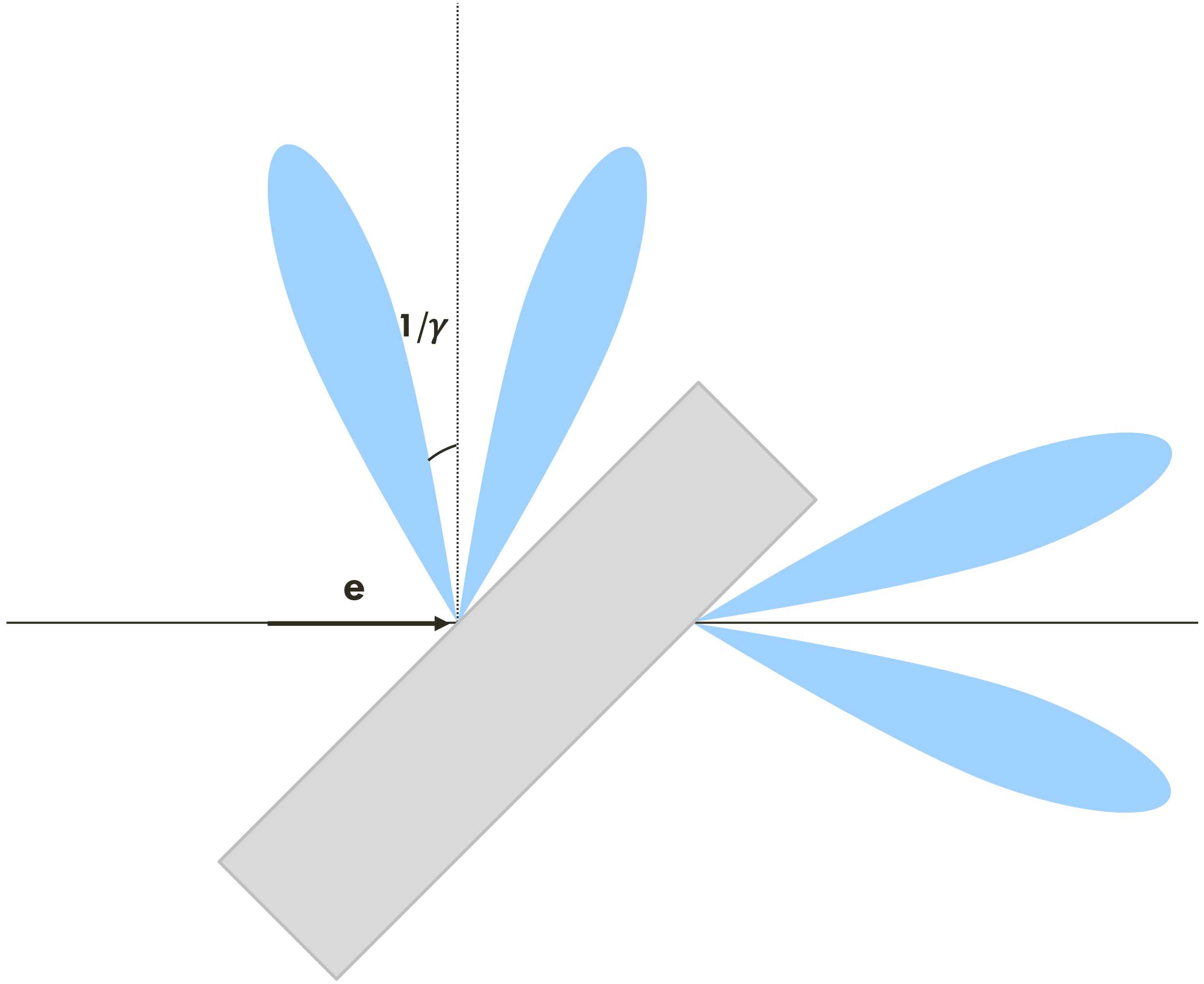
Design parameters		
Design parameters for the electron beam	Operation Mode	
	Long Pulses	Short Pulses
Charge per bunch (pC)	200	10
Core slice emittance (mm.mrad)	0.43	0.18
Projected emittance (mm.mrad)	0.65	0.25
Slice energy spread (keV, rms)	350	250
Relative energy spread (%)	0.006	0.004
Peak current at undulator (kA)	2.7	0.7
Bunch length (fs, rms)	25	6
Bunch compression factor	125	240

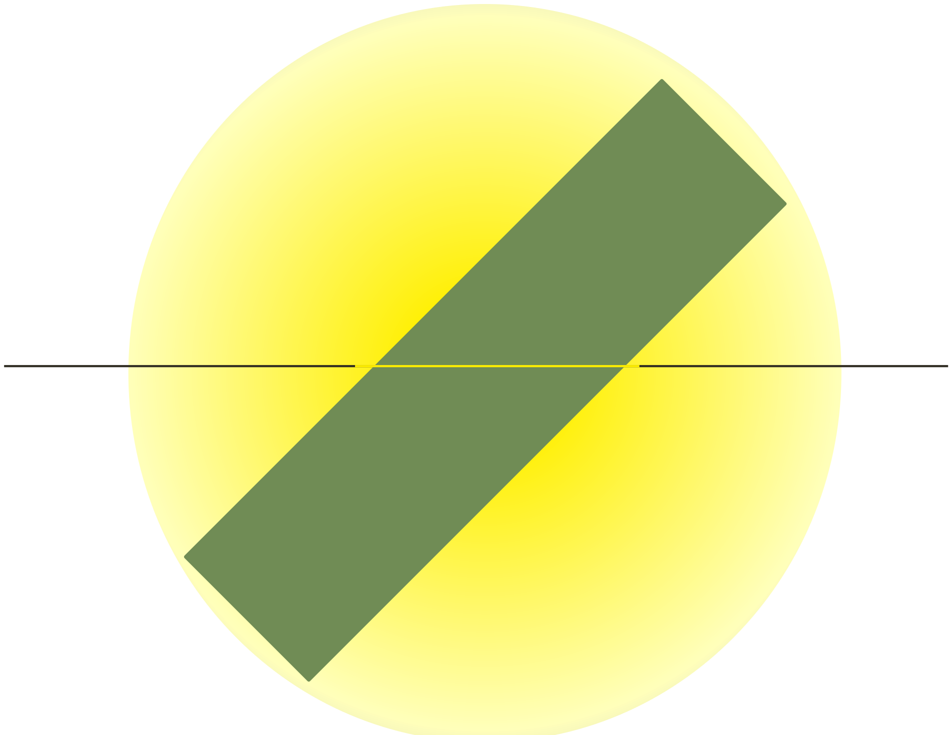
Performance of Aramis		
Performance of Aramis for 5.8 GeV electron energy and 1Å lasing wavelength	Long Pulses	short Pulses
Maximum saturation length (m)	47	50
Saturation pulse energy (μJ)	150(*)	3
Effective saturation power (GW)	2.8	0.6
Photon pulse length at 1 Å (fs, rms)	21	2.1
Number of photons at 1 Å (×10e9)	73	1.7
Bandwidth, rms (%)	0.05	0.04
Peak brightness (# photons.mm-2.mrad-2.s-1/0.1% bandwidth)	7.e32	1.e32
Average Brightness (# photons.mm-2.mrad-2.s-1/0.1% bandwidth)	2.3e21	5.7e18

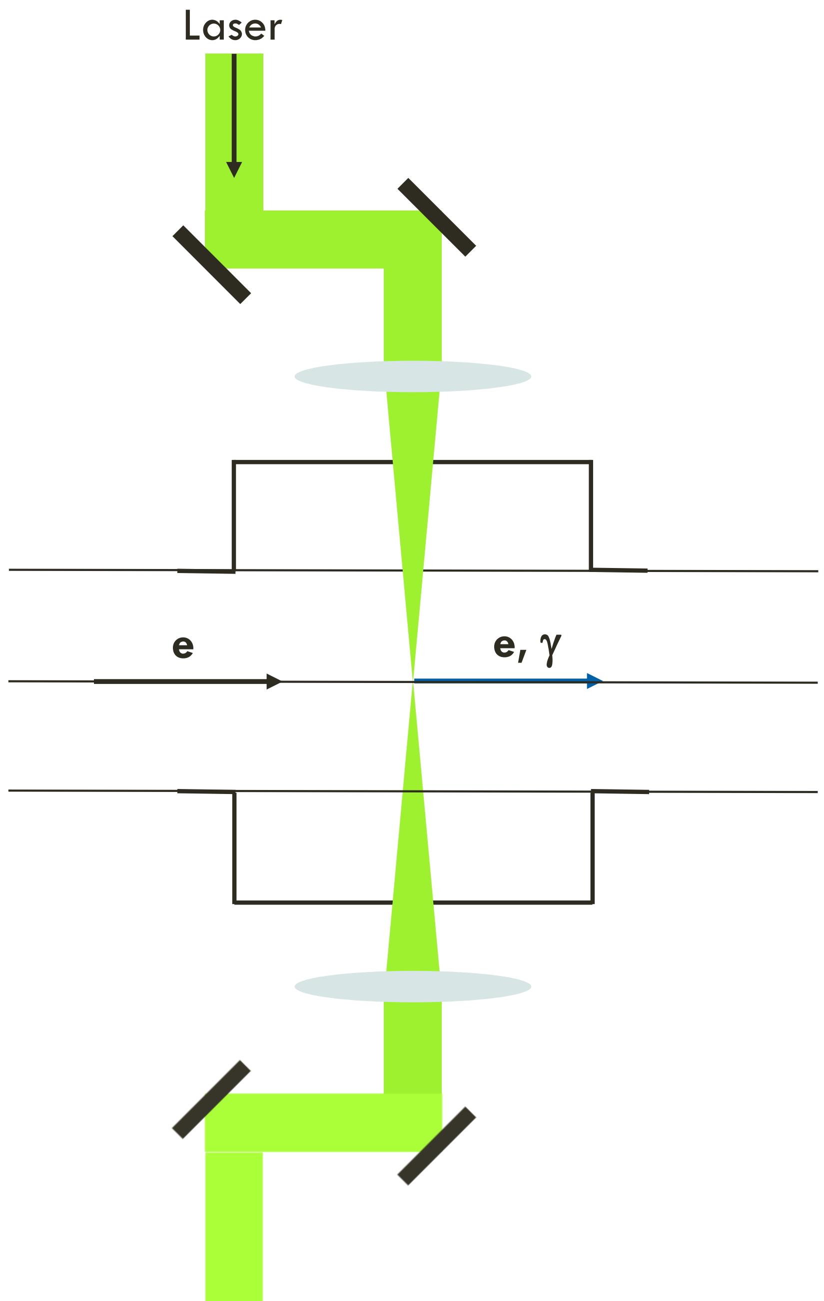
SwissFEL

Performance of Athos (SASE)	
Performance of Athos (SASE), for example at 3.4 GeV electron energy and 2.8 nm lasing wavelength	Long Pulses
Maximum saturation length (m)	22 m
Saturation pulse energy (μJ)	360
Effective saturation power (GW)	11.2
Photon pulse length at 2.8 nm (fs, rms)	13
Number of photons at 2.8 nm (×10e9)	5000
Bandwidth (%)	0.19
Peak brightness (# photons.mm-2.mrad-2.s-1/0.1% bandwidth)	6.e35
Average Brightness (# photons.mm-2.mrad-2.s-1/0.1% bandwidth)	8.e23

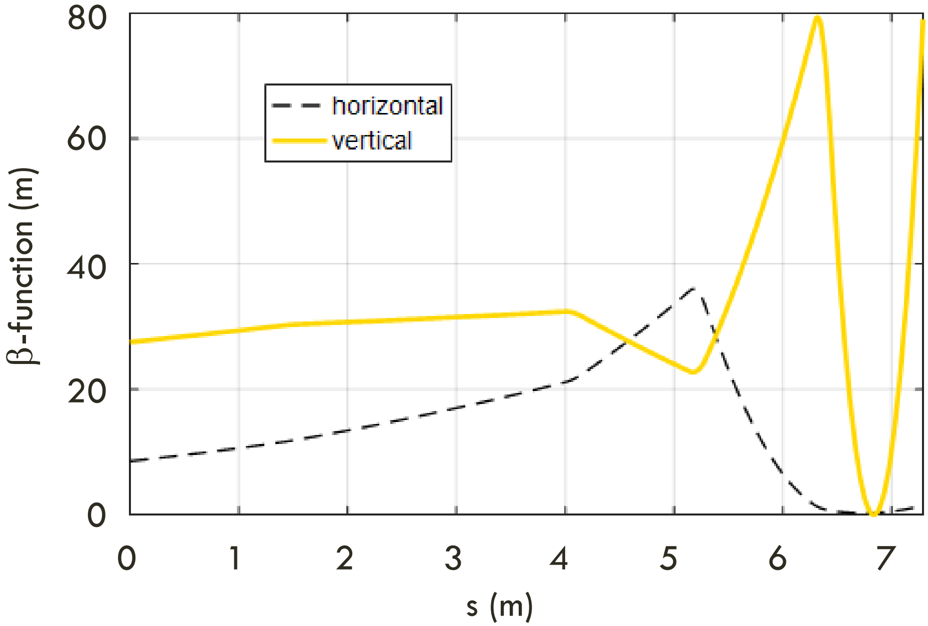



1/γ
e





Laser
e
e, γ


80
60
40
20
0
β-function (m)
0
1
2
3
4
5
6
7
s (m)
horizontal
vertical