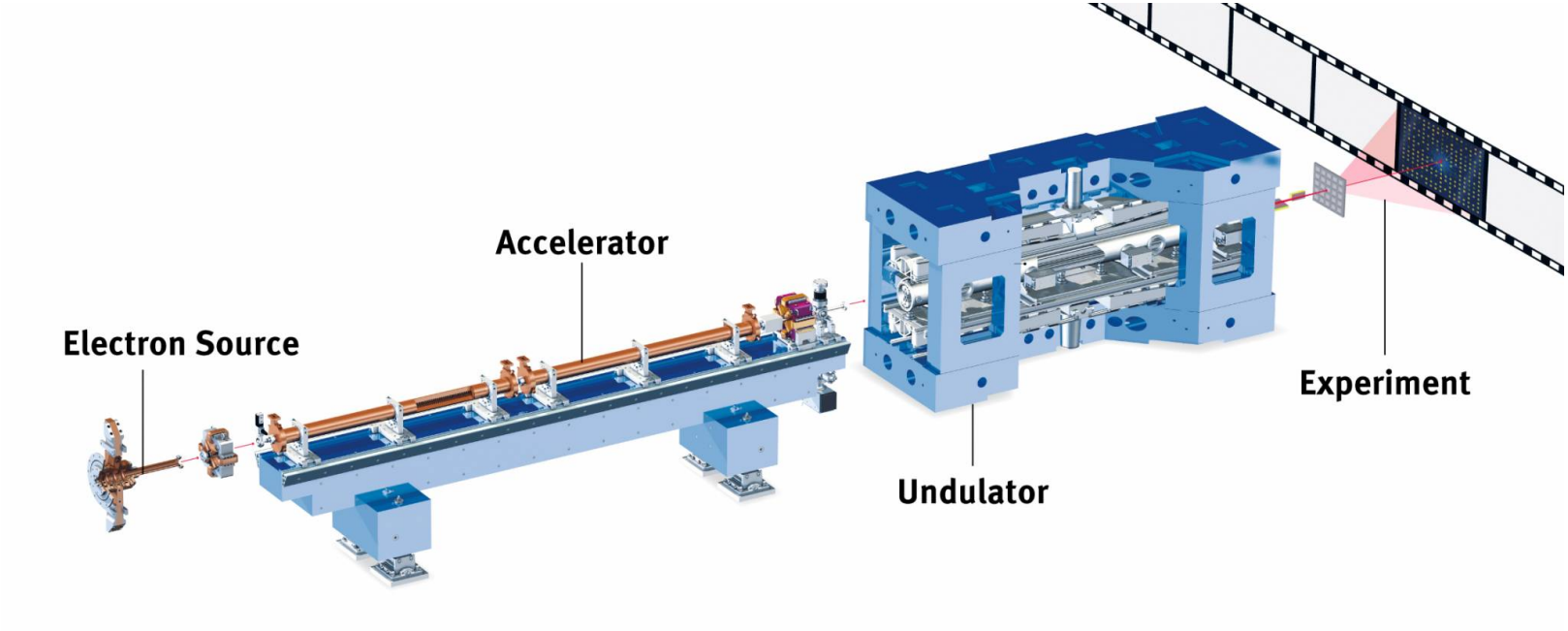
Wire Scanner on a Chip

S. Borrelli, M. Bednarzik, C. David, E. Ferrari, A. Gobbo, V. A. Guzenko, N. Hiller, R. Ischebeck, G.L. Orlandi, C. Ozkan-Loch, B. Rippstein and V. Schlott

Free Electron Laser



In a FEL machine it is important to preserve the e-beam normalized emittance in order to produce laser pulses of the desired wavelength.

SwissFEL Nominal e-Beam Parameters

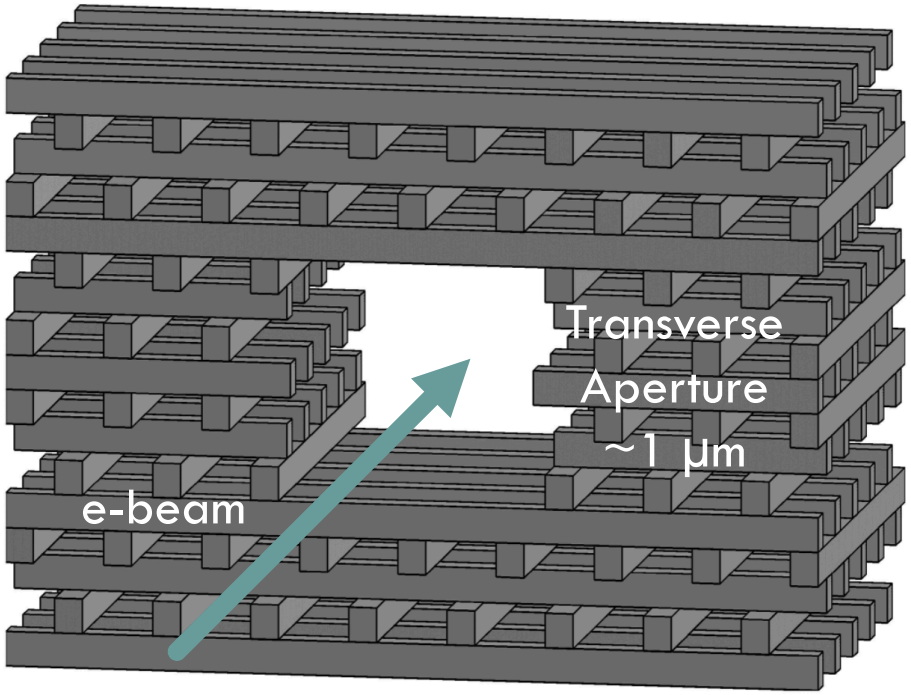
E	5.8 GeV
Q	200-10 (pC)
ε_N	0.4-0.2 *(mm mrad)*
σ_{min} (@10 pC)	8 μm (rms)

→ High resolution emittance measurements necessary.

The ACHIP Project

Compact electron accelerator in which the accelerator structure is a dielectric microstructure excited by femtosecond laser pulses.
(**D**ielectric **L**aser **A**ccelerator)

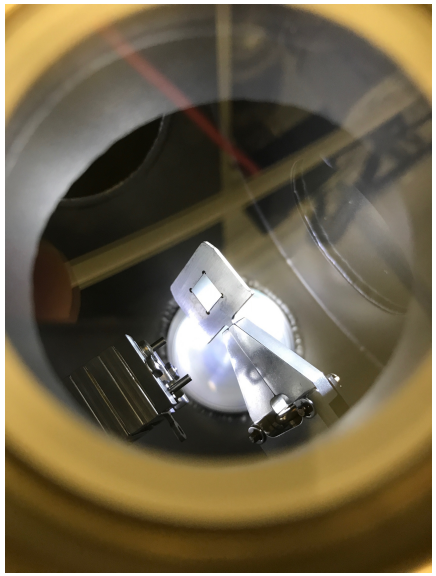
Sub-micrometric beam size and low emittance is necessary.



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

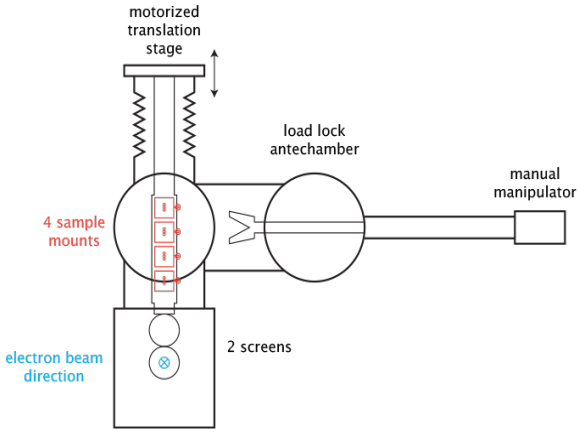
The ACHIP Project at SwissFEL

Proof-of-principle demonstration of the acceleration of a highly relativistic beam at SwissFEL.



SwissFEL Injector ACHIP chamber

Load-lock chamber to install four different samples without breaking beamline vacuum.



SwissFEL ATHOS ACHIP chamber

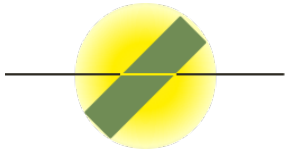
A second ACHIP chamber will be installed in the SwissFEL ATHOS line.
Expected spot size $< 1\mu m$

Beam Transverse Profile Monitors

2-D Monitors

Scintillating crystals

YAG:Ce Screen

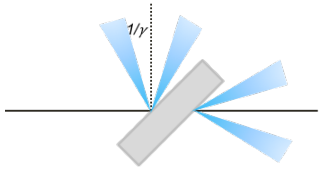


- High dynamic range but not linear
- Possible saturation
- Resolution is 8 μm (rms) (SwissFEL)

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.

Synchrotron Radiation Monitor

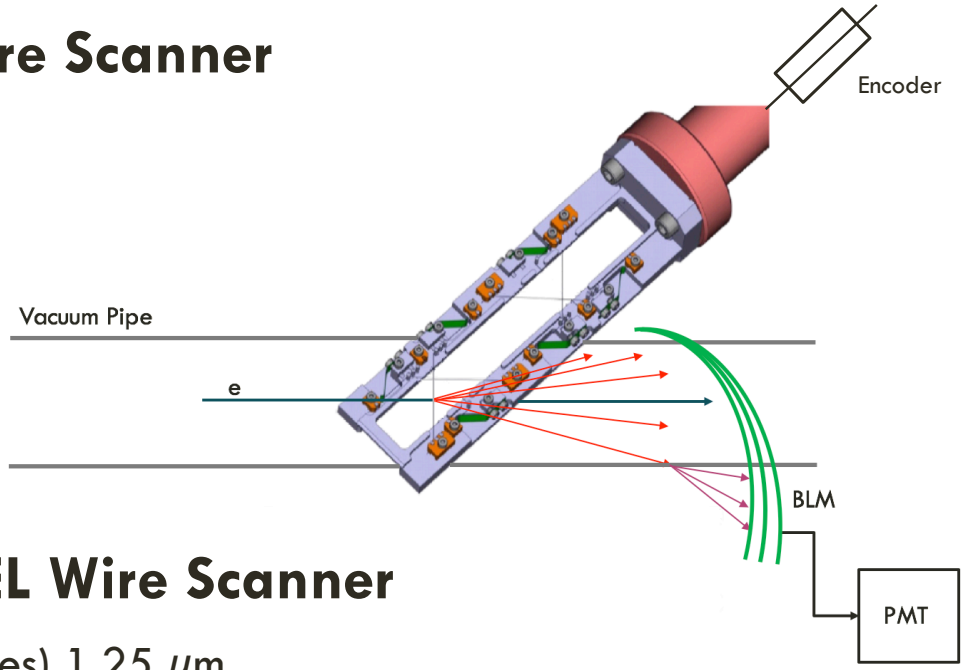
- Linear in case of no coherent radiation emission
- Not affected by saturation
- Resolution 6 μm (rms) SLS
  ~50 μm SwissFEL

Andersson, Å., et al. "Determination of a small vertical electron beam profile and emittance at the Swiss Light Source." *Nuc.Instr. and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 591.3 (2008): 437-446.

Beam Transverse Profile Monitors

Wire Scanner

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



SwissFEL Wire Scanner

- Geometrical resolution (5 μm W wires) 1.25 μm
- Wire vibration within the geometrical resolution limit
- Encoder resolution 0.1 μm

Orlandi, G. L., et al. "Design and experimental tests of free electron laser wire scanners." *PRA.*,19.9 (2016): 092802.
Wire scanner commissioning >>> WEPCC16 Poster by G.L.Orlandi

→ Reduce wire diameter to improve resolution

🤔

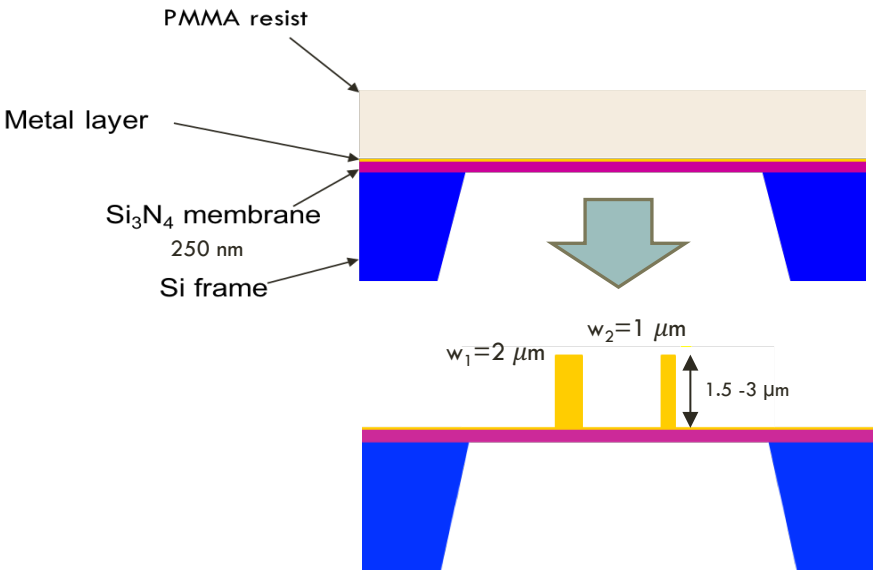
IDEA

Use the nanofabrication of sub-micrometer metallic stripes on a membrane via e-beam lithography.

Sub-micrometer Resolution Wire Scanner

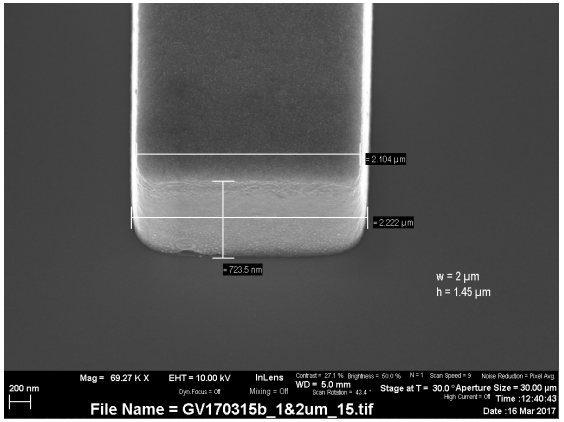
Fabrication Technique

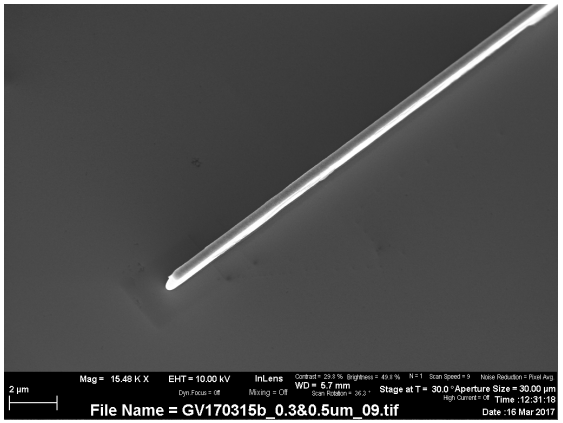
- Electron Beam Lithography on the Resist
- Resist development
- Top Cr layer removal
- Electroplating of two Au wires of different widths (w_1, w_2)
- Resist removal



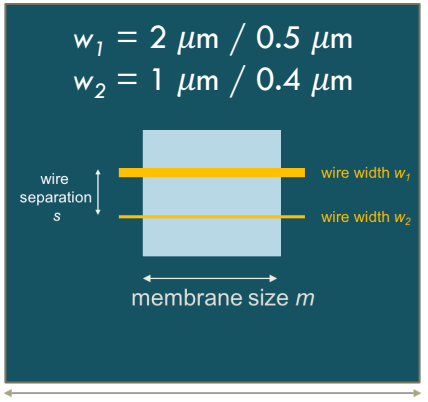
Scanning Electron Microscope characterization

Vitaliy Guzenko





Prototype Sketch



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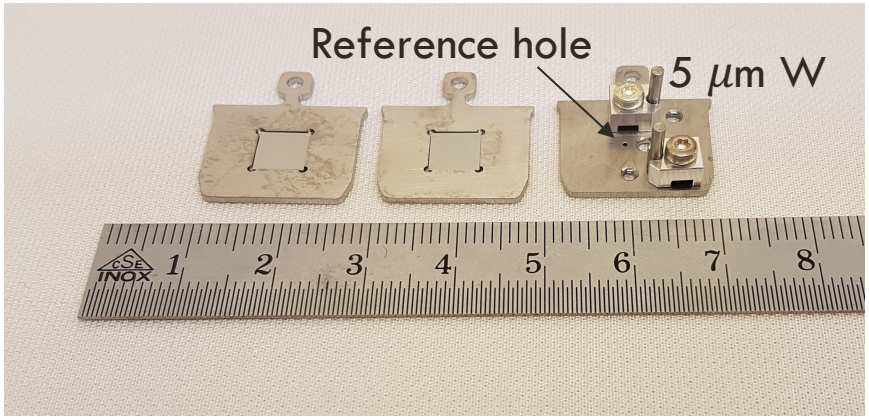
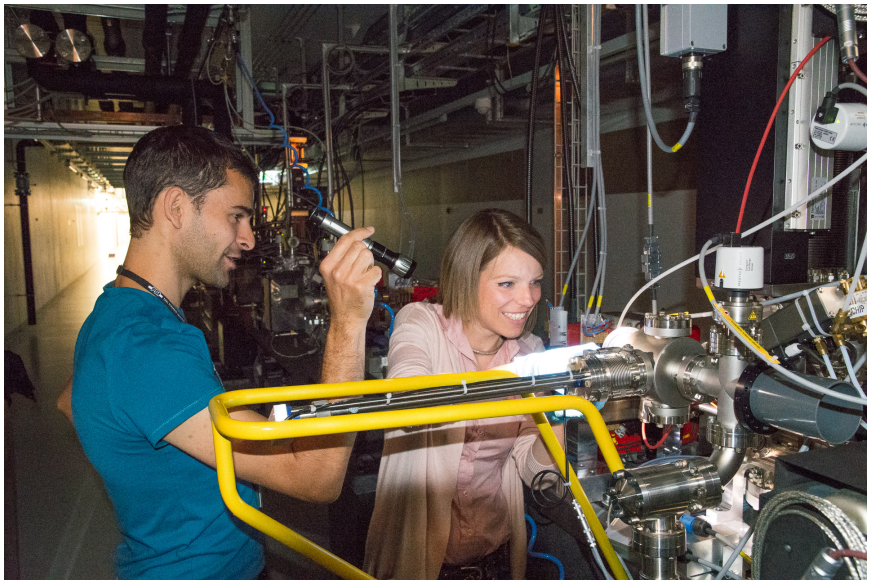
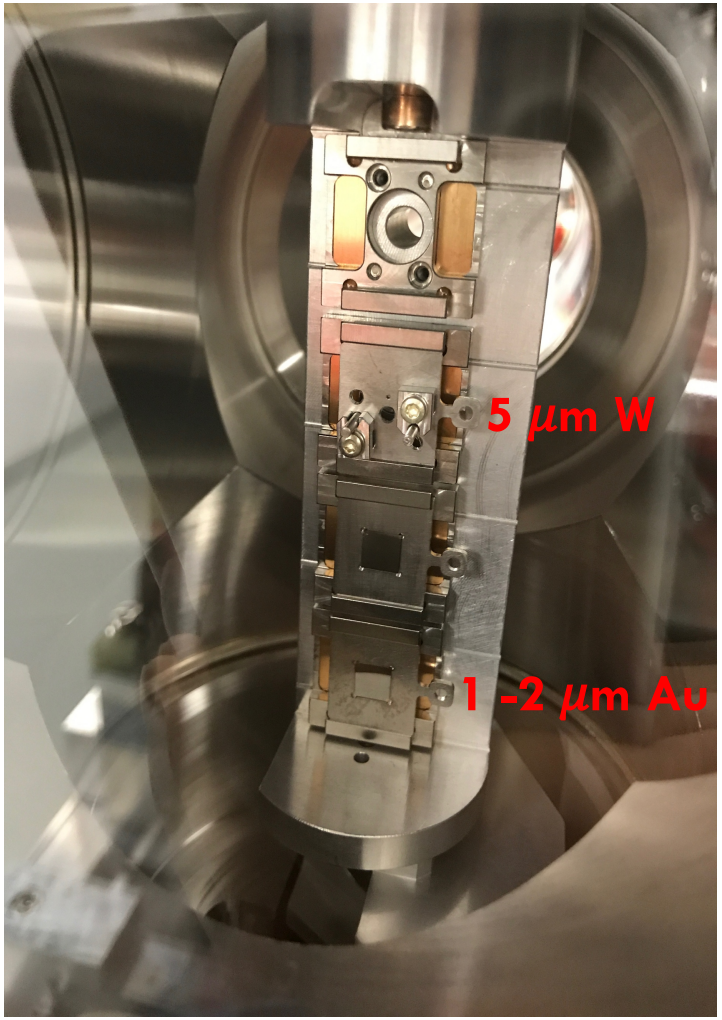
Sub-micrometer Resolution Wire Scanner

Prototype Installation

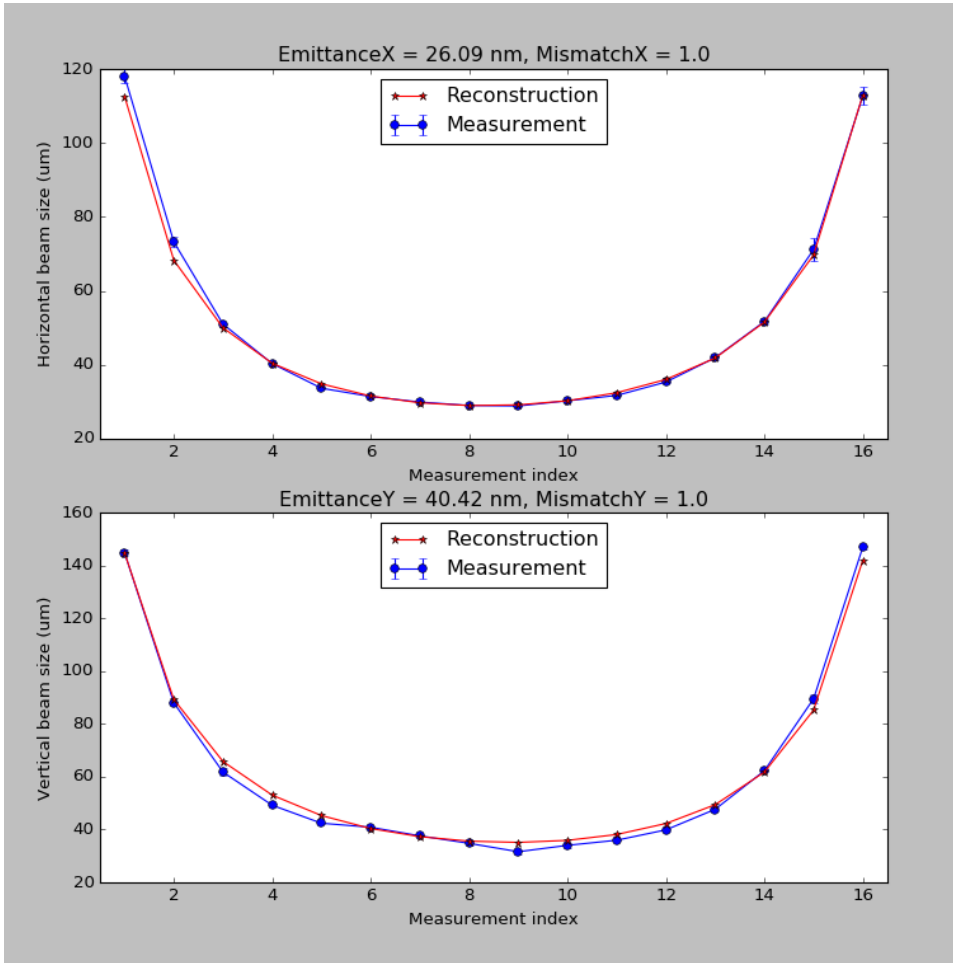






First Experimental Results

Optics Settings



Beam Parameters

Energy	=	330 MeV
Charge	=	200 fC
ε_x, ε_y	=	30, 40 nm

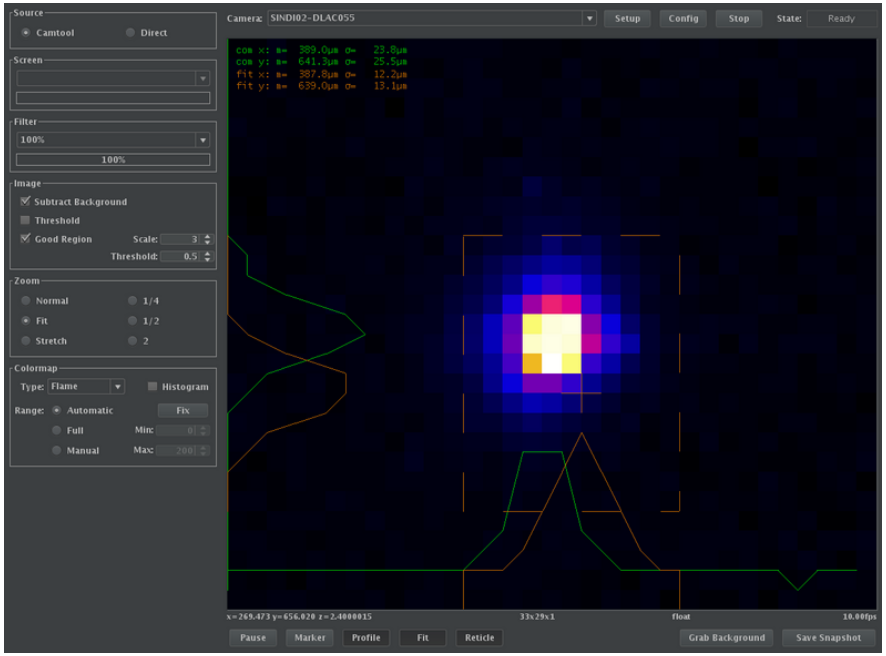
Optics

Expected Beam Size

σ_x = 2.7 μm
σ_y = 3.2 μm

First Experimental Results

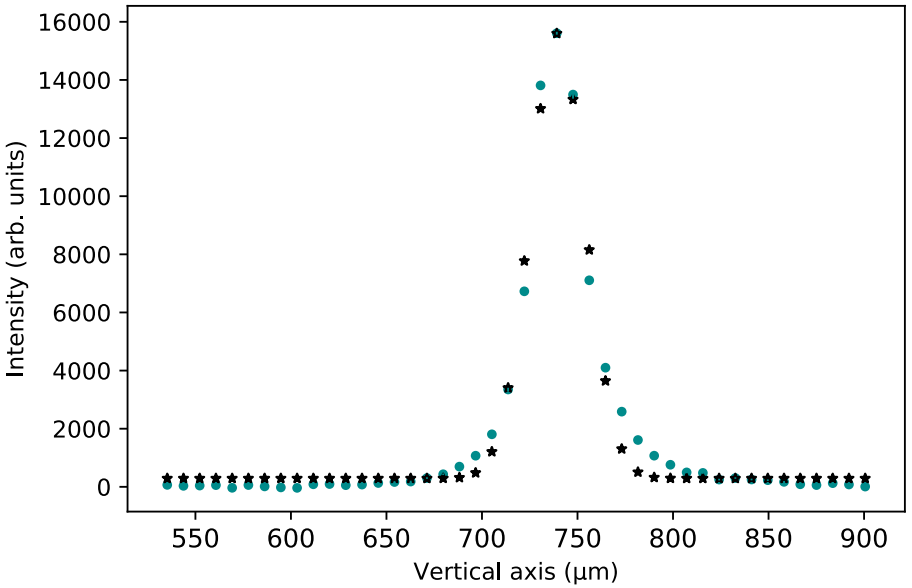
Screen Beam Profile Measurement



Gauss Fit

$$\bar{\sigma}_y = 14.4\ (\mu\text{m})^{*}$$

Mean over 100 images



*YAG:Ce screen beam size measurement is limited by a resolution of ~ 14 μm.

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First Experimental Results

5 µm W WSC Beam Profile Measurement

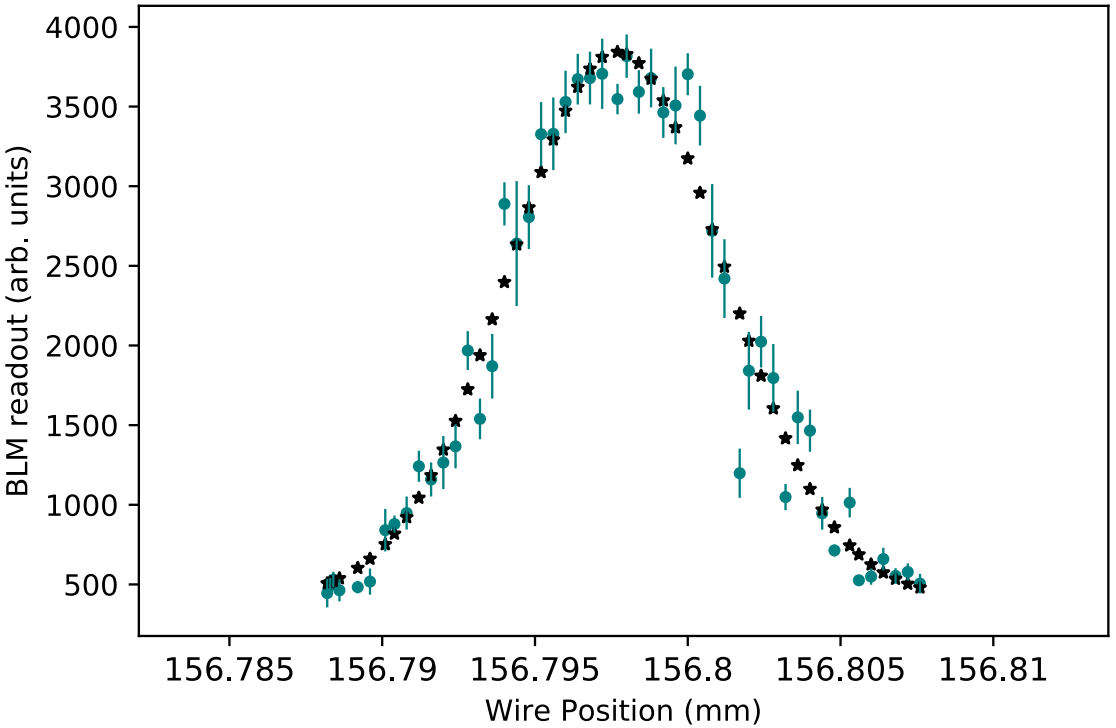
Gauss Fit

$$\bar{\sigma}_y = 3.52 \pm 0.02\ (\mu\mathrm{m})$$

Mean over 10 scan cycles

Signal to noise ratio

SNR = 13



Mean Profile

First Experimental Results

2 µm Au WSC Beam Profile Measurement

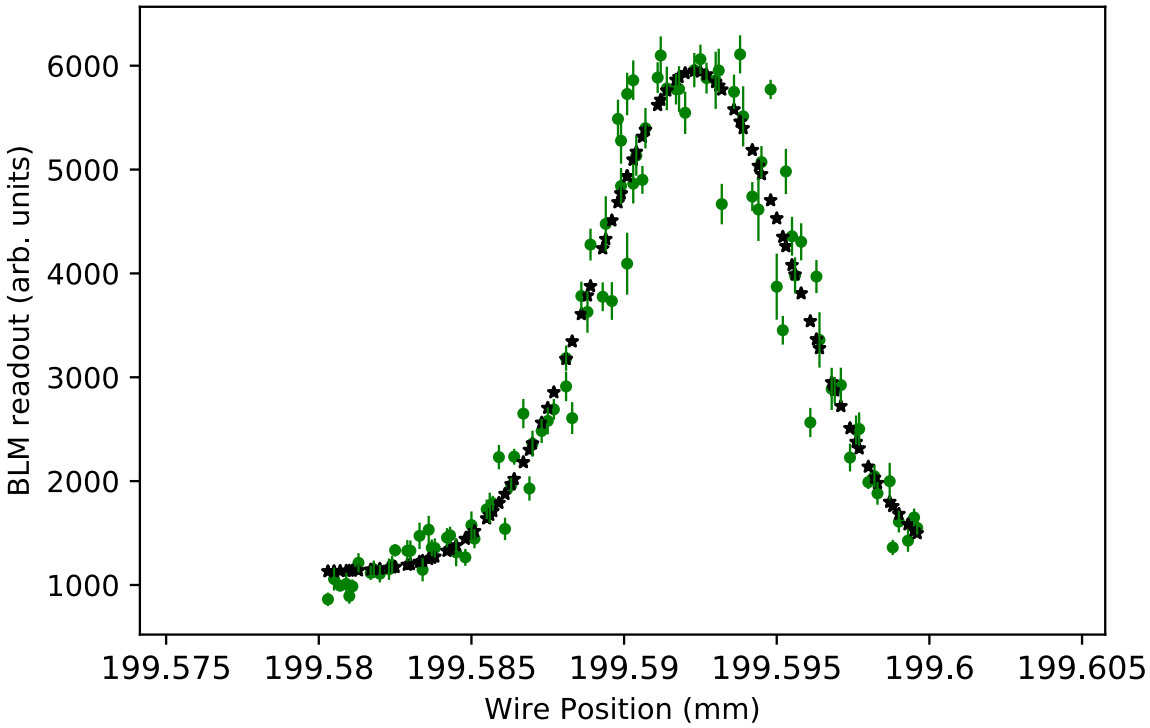
Gauss Fit

$$\bar{\sigma}_y = 3.21 \pm 0.04\ (\mu\mathrm{m})$$

Mean over 10 scan cycles

Signal to noise ratio

SNR = 7



Mean Profile

First Experimental Results

1 µm Au WSC Beam Profile Measurement

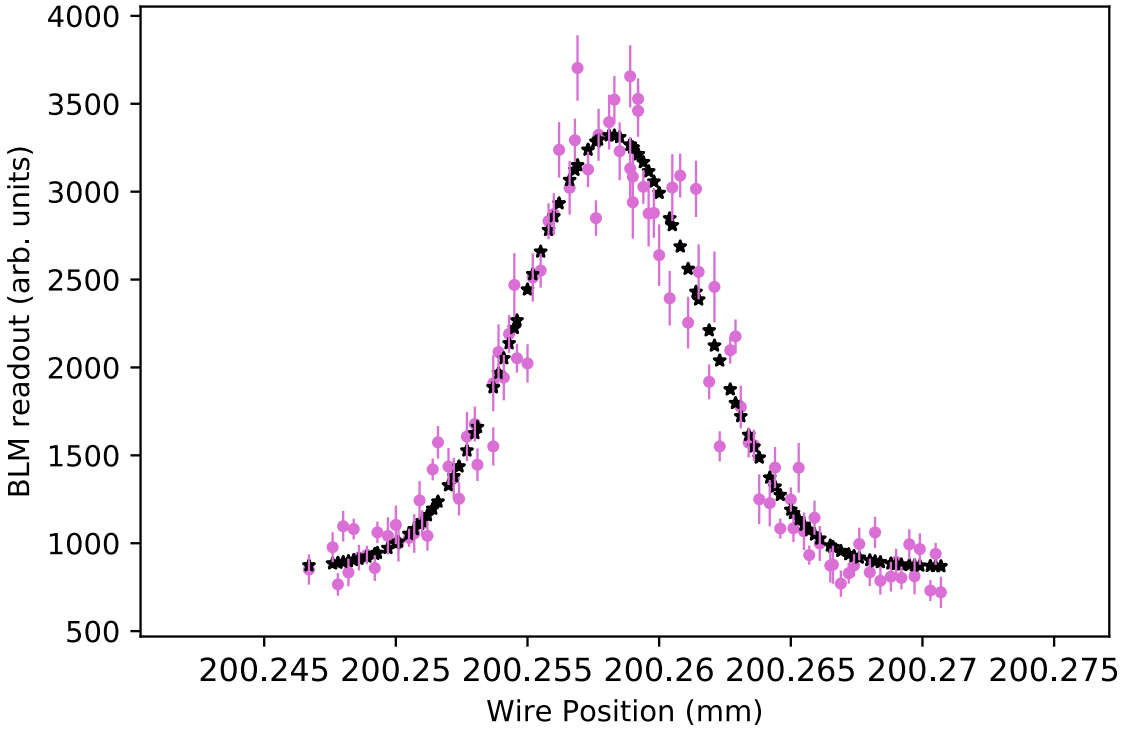
Gauss Fit

$$\bar{\sigma}_y = 3.37 \pm 0.06\ (\mu\mathrm{m})$$

Mean over 10 scan cycles

Signal to noise ratio

SNR = 5



Mean Profile

Background From The Membrane

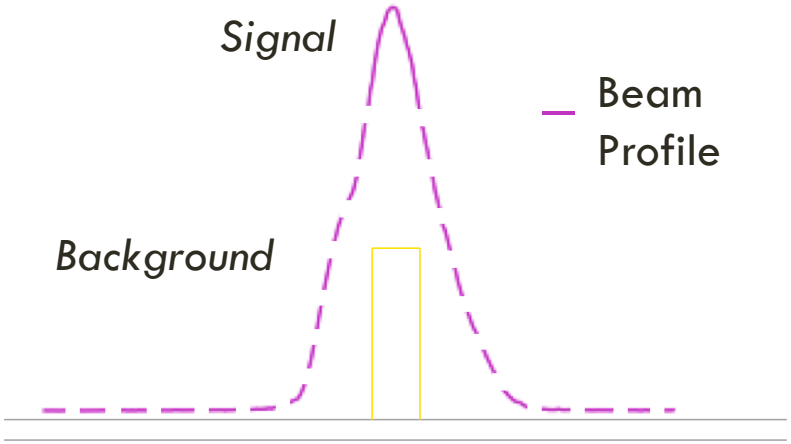
Measured Values	5 µm W	2 µm Au	1 µm Au
SNR	13	7	5

Signal to Noise ratio degraded by the membrane.

Background to signal ratio

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

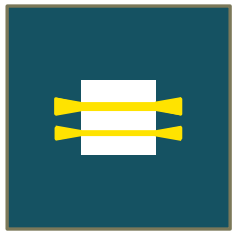
From the radiative energy loss in the membrane + wire thickness and in the membrane thickness.



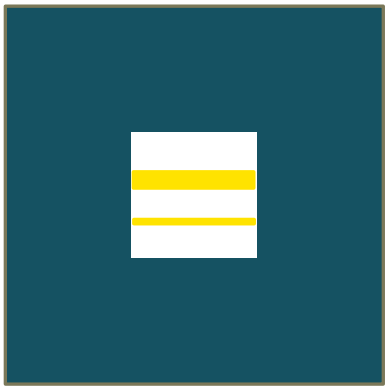
Only a small fraction of the beam cross the membrane and the wire producing the signal of interest.

Outlook

Signal to Noise Ratio Improvement



Reshape the wires



Remove the membrane

Remove a central hole in the membrane

Measure Resolution Limit

Measure a sub-micrometric beam profile focusing the beam in the ATHOS ACHIP chamber via in vacuum quadrupoles.

Thanks so much!

Gian Luca Orlandi
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Vitaliy Guzenko
Cigdem Ozkan
Eugenio Ferrari
Volker Schlott
Nicole Hiller
Eduard Prat
Josh McNeur
Simona Bettoni
PSI Vacuum Group
Christian David
Martin Bednazik
Beat Rippstein
Alexandre Gobbo
Arturo Daniel Alarcon

Wire Scanner on a Chip

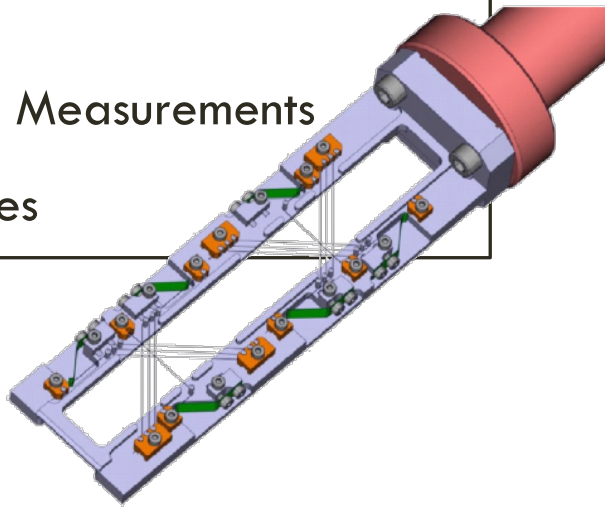
S. Borrelli, M. Bednarzik, C. David, E. Ferrari, A. Gobbo, V. A. Guzenko, N. Hiller, R. Ischebeck, G.L. Orlandi, C. Ozkan-Loch, B. Rippstein and V. Schlott

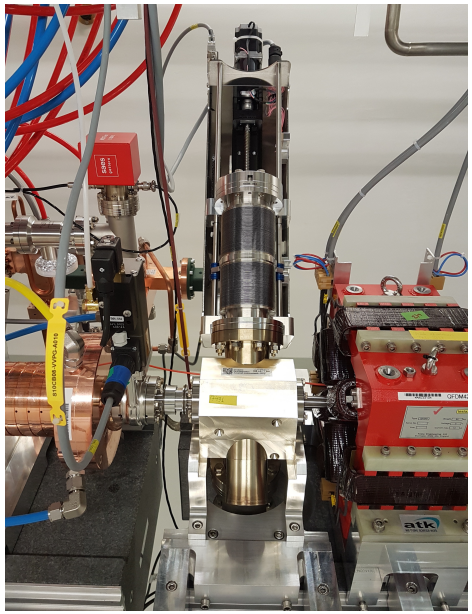
BACKUP SLIDES

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





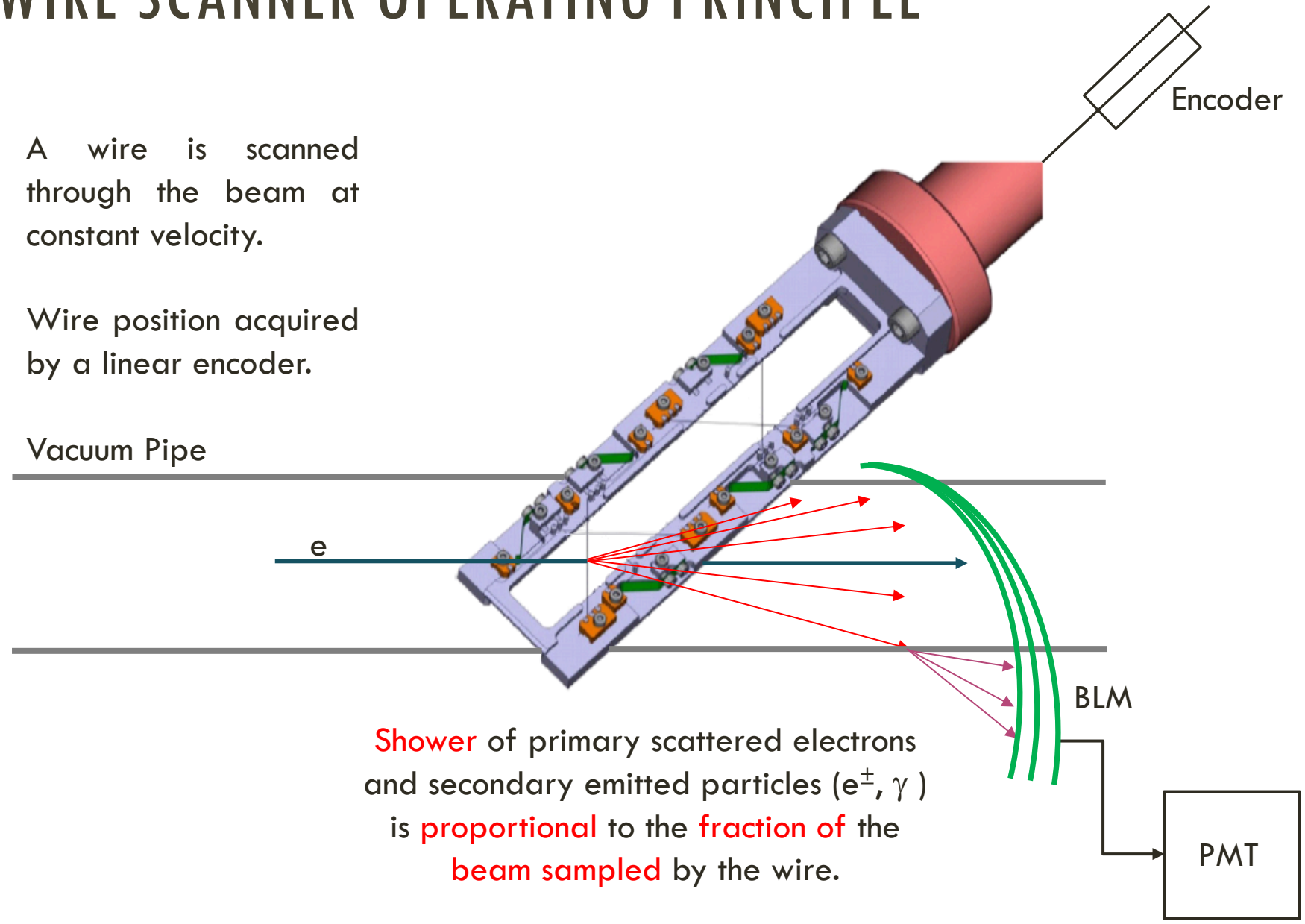
Fork inserted in the vacuum by means of an Ultra-High Vacuum linear-stage driven by a two phase stepper motor.

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

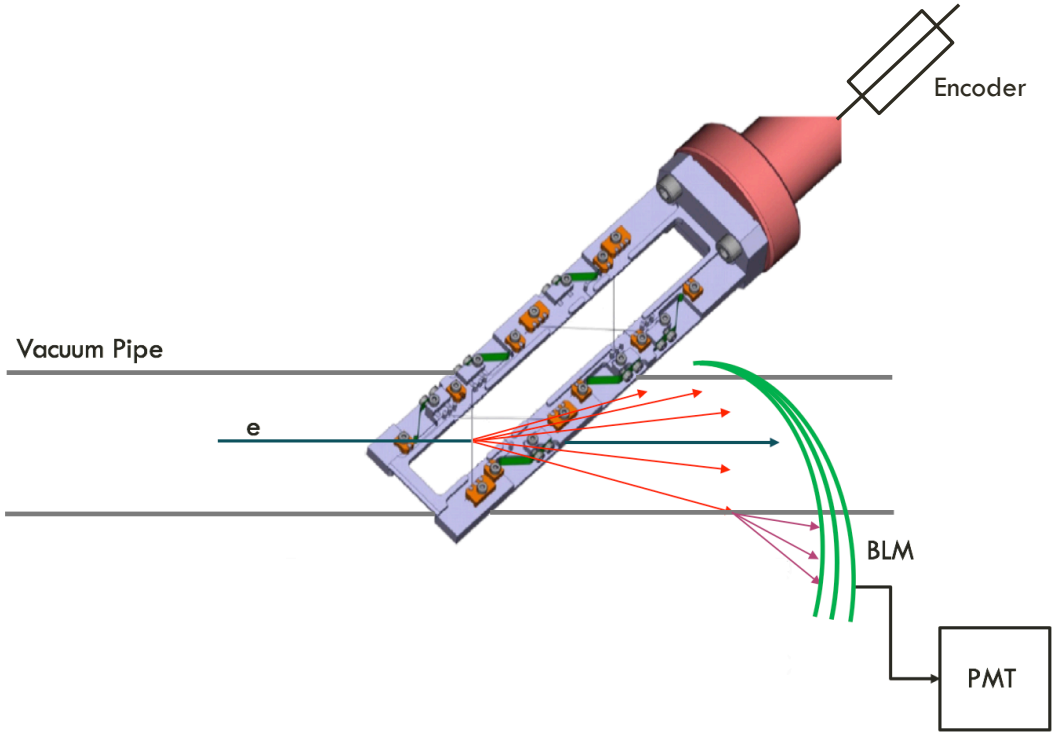
A wire is scanned through the beam at constant velocity.

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

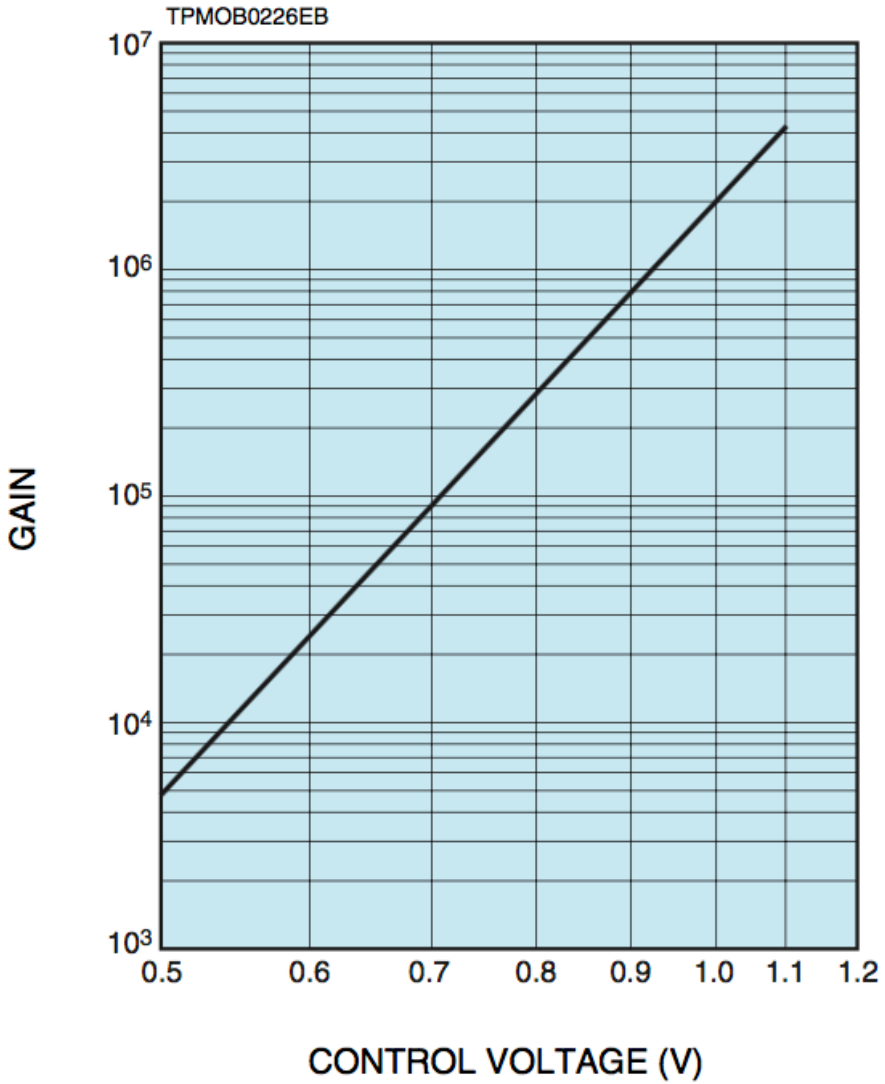


Out-of-vacuum detection of the shower's forward component through scintillator fiber.

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

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

Collisional stopping power in Au for E = 320 MeV

$\frac{dE}{dt}$ = 1.5 MeV cm^2/g

N° of particles intercepted by the wire

$$R = \frac{w}{\sqrt{12}} * \frac{1}{\sigma_b}$$

$E_{loss} = 9.6 * 10^{-11}$ 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

$\Delta T = 3.8$ K

N.B. The computation not include any heat dissipation effect

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

SUB-MICROMETER RESOLUTION WIRE SCANNER

WIRE HEATING BY E-BEAM EXPOSURE

EGS simulation

Q = 1 fC

Energy into the wire for $\mathbf{E_e = 350\ MeV}$

$E_{in} = 2.19 * 10^{10}$ keV

Energy emitted as secondary particles

$E_{out} = E_e + E_\gamma + E_{e+}$

Fraction of energy deposited in the wire

$$Loss = \frac{E_{in} - Eout}{E_{in}}$$

Loss= 0.0015

E_{loss} = 0.525 MeV for single e of 1 fC

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

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

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

ΔN_e: 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

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

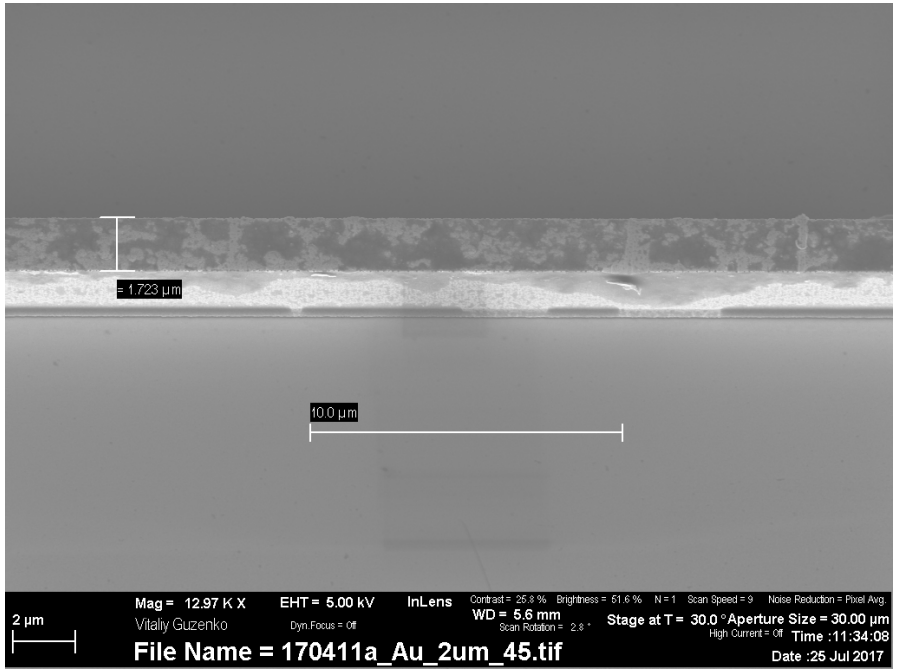
Si_3N_4 radiation length $L_R^{Si_3N_4+Au}$ = 8.3 cm

Fraction of e^- passing only the membrane

Background to signal ratio

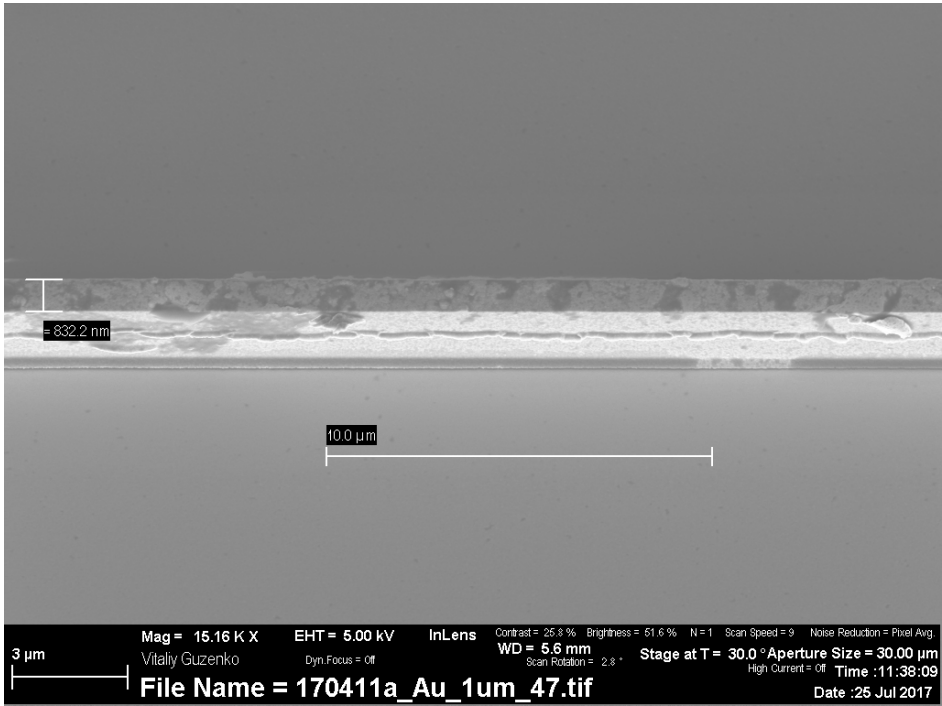
$$\frac{\Delta E|_{rad}^{Si_3N_4}}{\Delta E|_{rad}^{Si_3N_4+Au}} = 18$$

WIRES AFTER THE BEAM EXPOSURE



2 µm Au wire

σ_w = 0.6 µm



1 µm Au wire

σ_w = 0.3 µm

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BEAM JITTER

From the 100 YAG screen images

Jitter rms = 0.57 μm

Rms of the gauss fit centroids from the 100 YAG screen images.

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

ACHIP EXPERIMENT

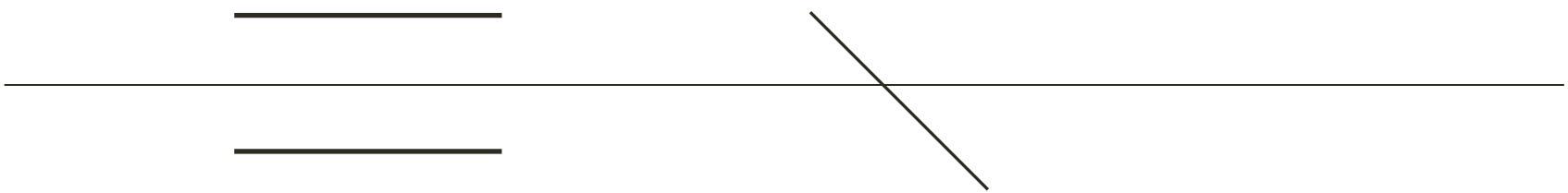
Dielectric Laser Accelerators (DLAs) are electron
linear accelerators composed of dielectric
microstructures powered by pulsed infrared las

One aspect of DLAs that is significantly different from radiofrequency (rf) accelerator structures is that the transverse aperture of the accelerating structure is on the order of ~1 μm

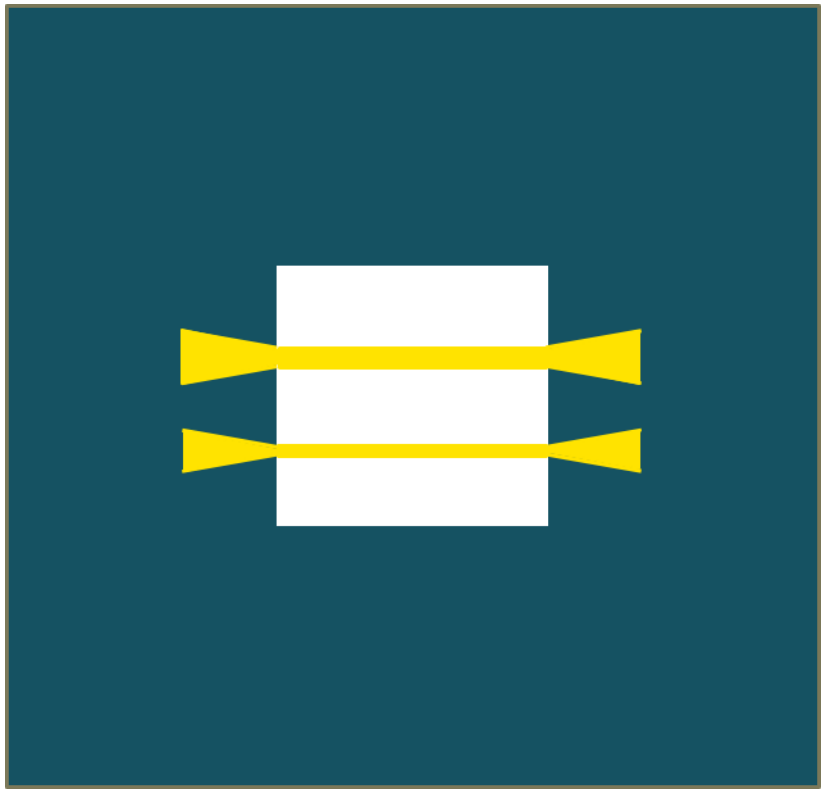
In the case of the planar grating structure and even in more general terms, DLAs operate via laser-induced excitation of an electromagnetic field mode with a nonzero electric component parallel to the velocity of electrons traversing the mode .. the phase velocity of the excited mode must match the electron velocity.

Various geometry optimizations of accelerating structures have been experimentally demonstrated

PHOTONIC BANDGAP structures



SUB-MICROMETER RESOLUTION WIRE SCANNER



SwissFEL

Key parameters and features of SwissFEL	
Overall length (incl. experimental hall)	720 m
Total electrical power consumption	5.2 MW
Maximum electron beam energy	5.8 GeV
Height of beamline above tunnel floor	1.2 m
Electron gun	3 GHz RF gun with 2.5 cells
Cathode type	Cu photocathode driven by a frequency-tripled TiSa laser
Injector booster	Normal-conducting travelling wave structures (copper) with f=3 GHz
RF source main linac	Klystron with solid-state modulator and RF pulse compression
Accelerating structures, main linac	Normal conducting travelling wave structures (copper) with f=5.7 GHz and G=26 -28 MV/m
Linac repetition rate	100 Hz
Bunch compression	Two 4-magnet chicane bunch compressors at 0.35 GeV and 2.0 GeV, with X-band harmonic cavity at 1st bunch compressor
Number of FEL lines	2 (Aramis and Athos)
Undulator type, Aramis	In-vacuum permanent magnet with period =15 mm
Wavelength range, Aramis FEL	1Å-7Å (SASE)
Polarization, Aramis	Linear
Undulator type, Athos	Apple II permanent magnet with period=40 mm
Wavelength range, Athos FEL	7Å-70Å; seeded and SASE
Polarization, Athos	Variable (circular, elliptical and linear)

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

SCREEN MONITORS

Two types of Screen Monitors, both for electrons and photon beams:

- Scintillating crystals: observation of fluorescence in the crystal
  - ✓ YAG
  - ✓ LuAG (factor two more visible photons)
- Optical transition radiation* screens (OTRs): observation of the optical transition radiation on a metallic surface
  - Aluminum-coated silicon mirror to generate OTR

The visible light emitted is imaged onto area detectors like CCD or CMOOS sensors.

Due to their interceptive nature, the screens will not be inserted during routine operation.

Resolution limit:

- Finite thickness of the scintillator (seen under an angle of 45°)
- Angular distribution if the OTR light

* radiation emitted when a when charged particles with relativistic velocities pass a metallic foil.

GAUSS FIT

Gaussian fit to Beam Profile in the vertical as well in the horizontal plane.

Fitting function

$$y = off + A\, e^{-\frac{(x-c)^2}{2\sigma^2}}$$

Wire Position

BLM loss signal

Initial guess for the fitting parameters

Offset: off = background signal mean value

Amplitude: A = BLM signal – off

Centroid: c = wire position value corresponding to the BLM signal maximum

Sigma: σ = Integrated signal$/A\sqrt{2\pi}$

Measure of the beam dimension