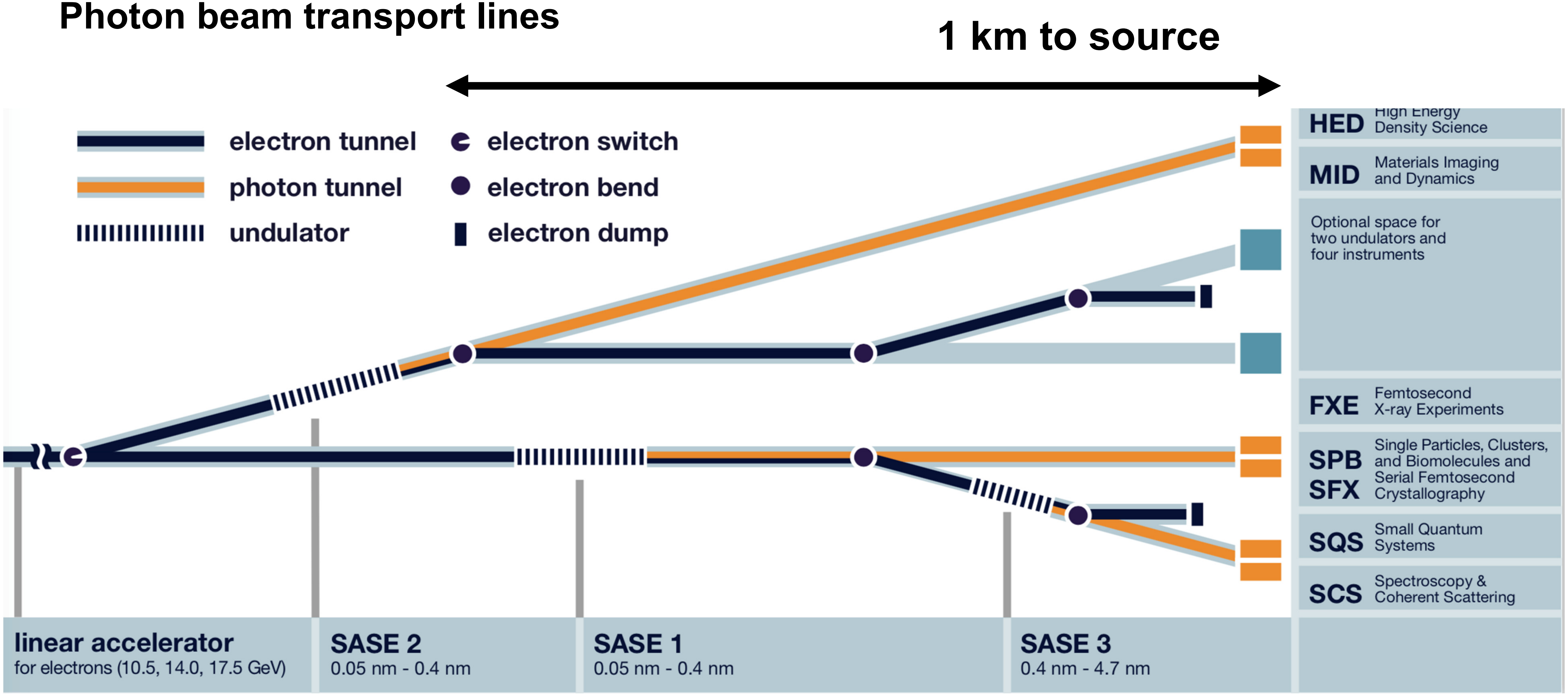
Tutorial WET01:
Photon Transport Beamline Design

FEL19
August 28, 2019

Harald Sinn
European XFEL

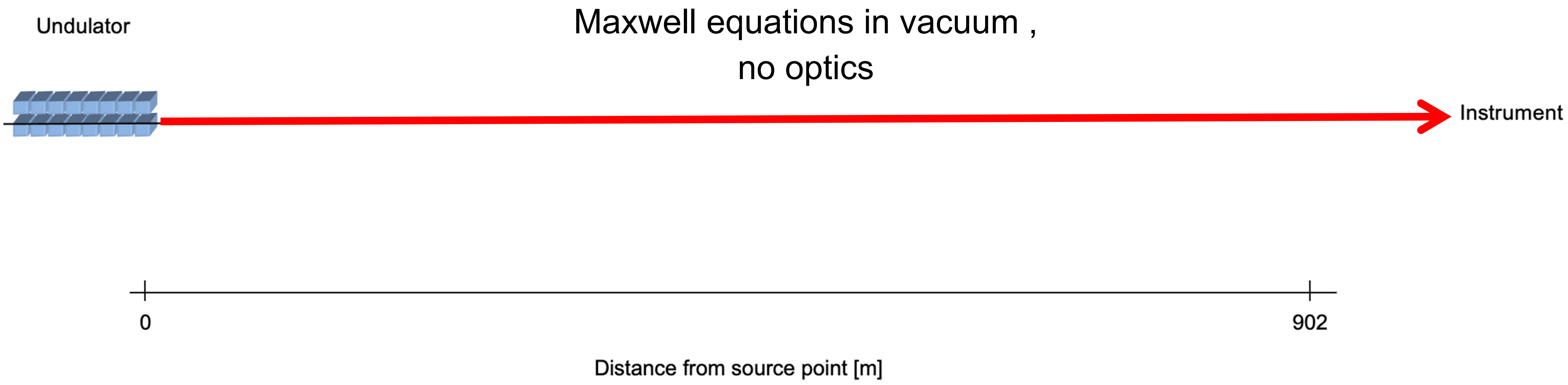
Contents

Photon beam transport lines



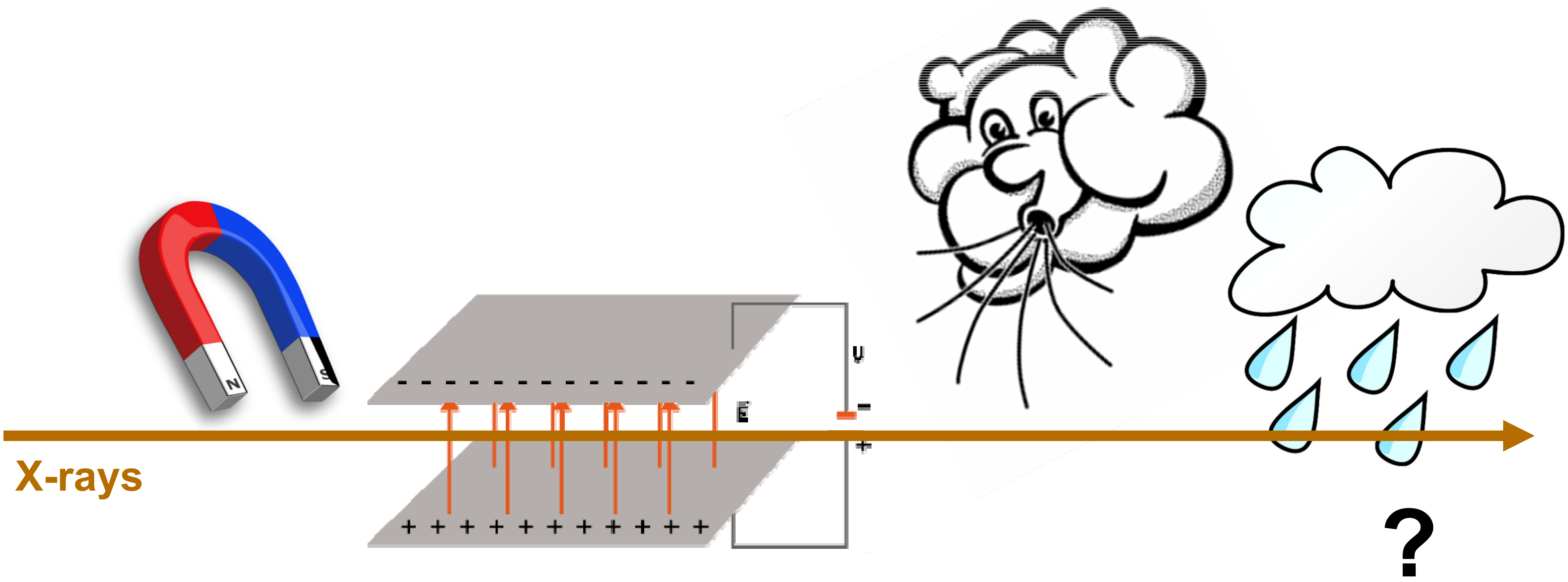
How to transport a photon beam?

Ideal FEL photon beam transport

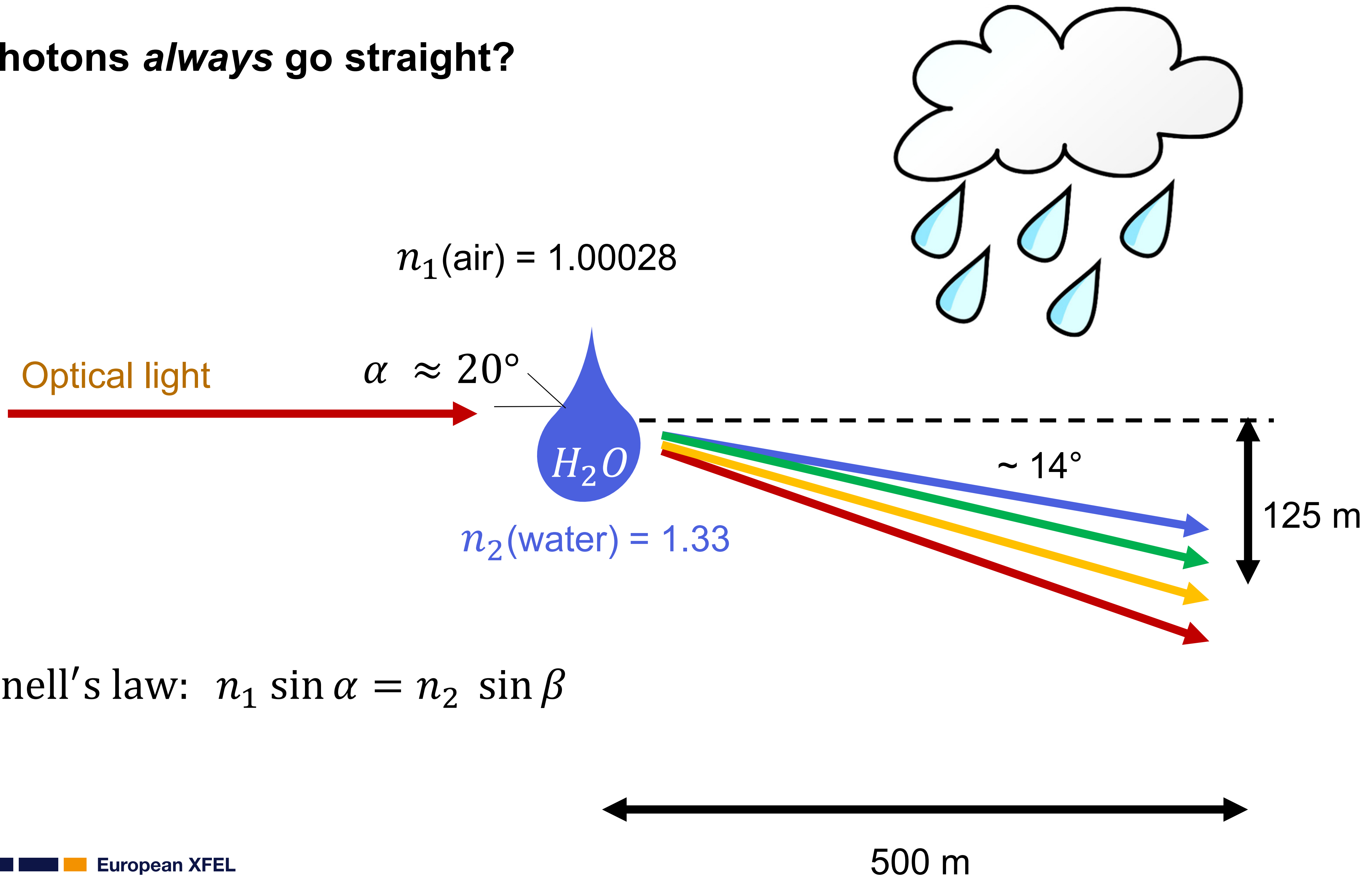


Beam propagation in photon tunnel XTD9

X-ray Photons Go Straight!



Do photons *always* go straight?

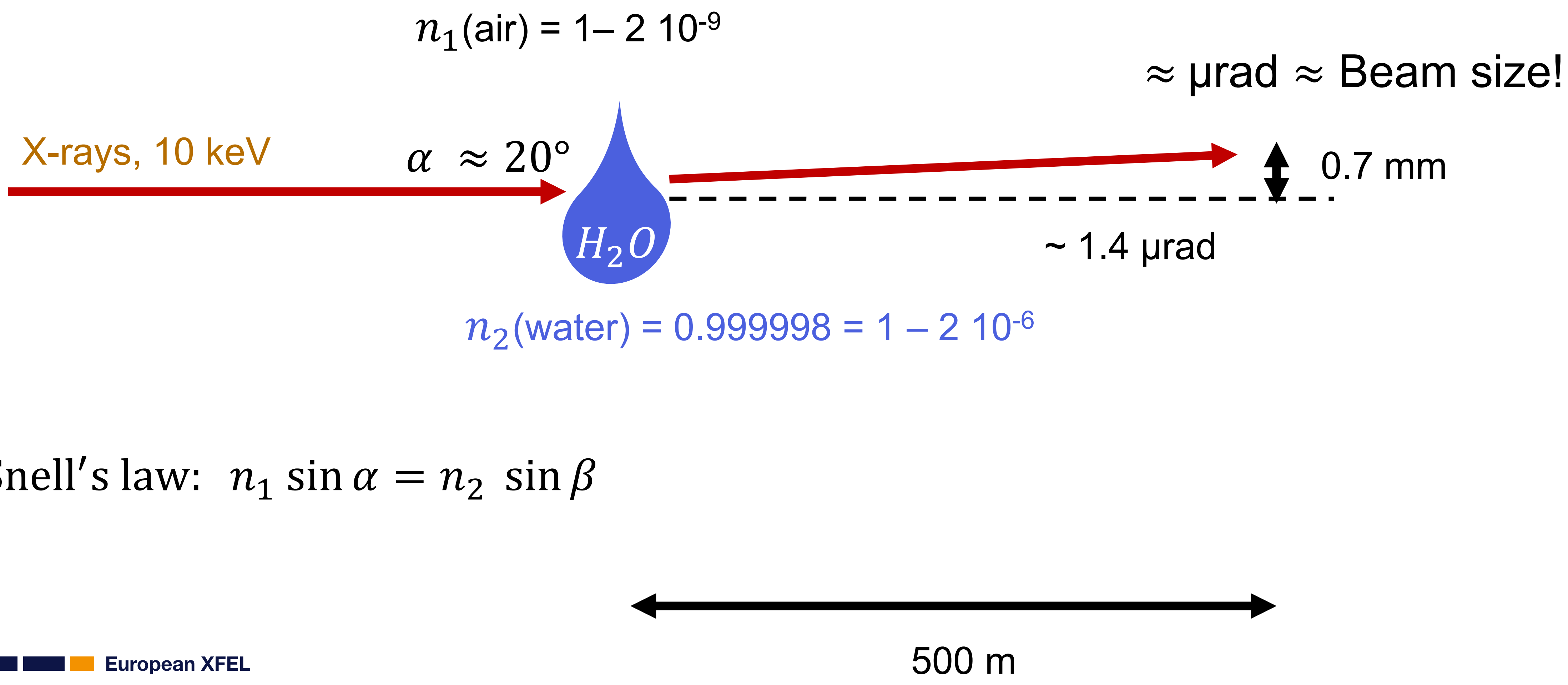


Snell's law: $n_1 \sin\alpha = n_2 \sin\beta$

Optical light can be diffracted and reflected by large angles!

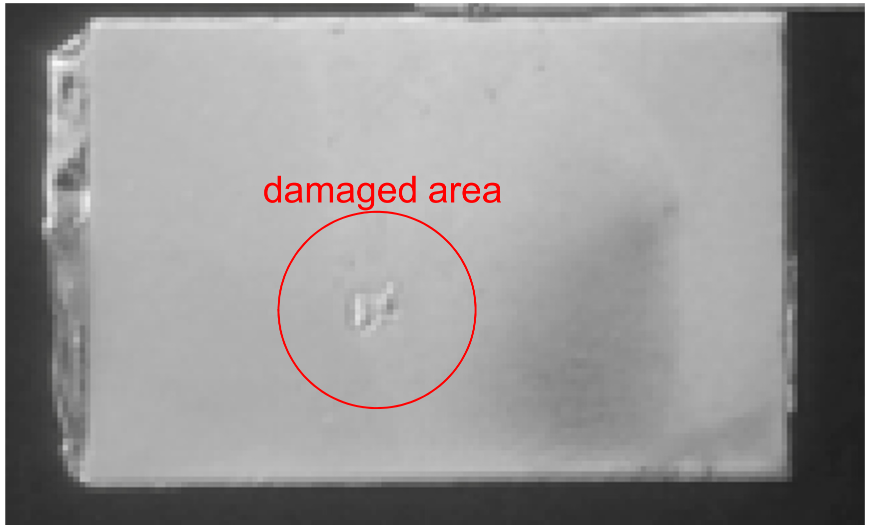
30.7.2019, Emberger Alm, Austria

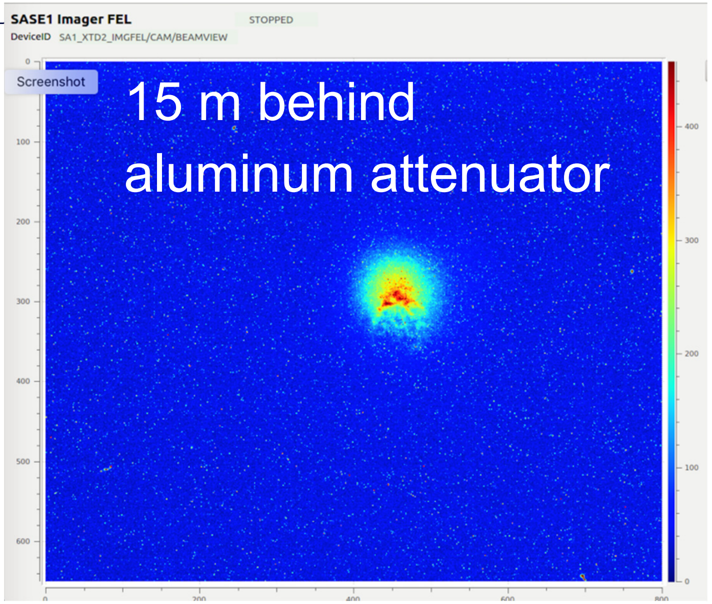
Do X-ray photons go straight?

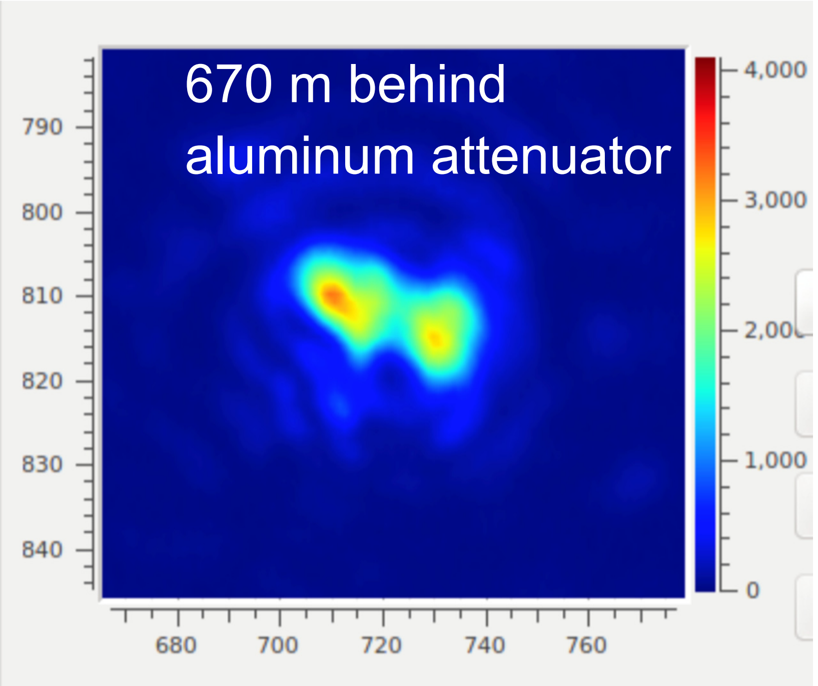


Snell's law: $n_1 \sin\alpha = n_2 \sin\beta$

A droplet of aluminum:
0.5 mm thick aluminum attenuator in FEL beam (9.3 keV)

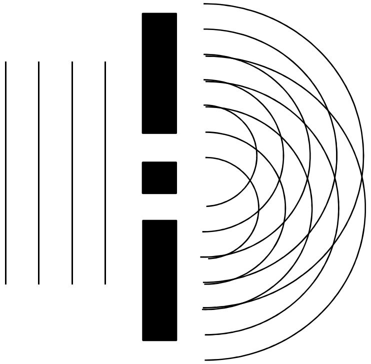




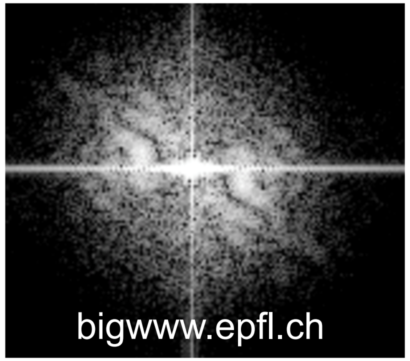


Refraction + diffraction + interference effects

<u>Huygens Principle</u>



Fourier Transform of damaged area

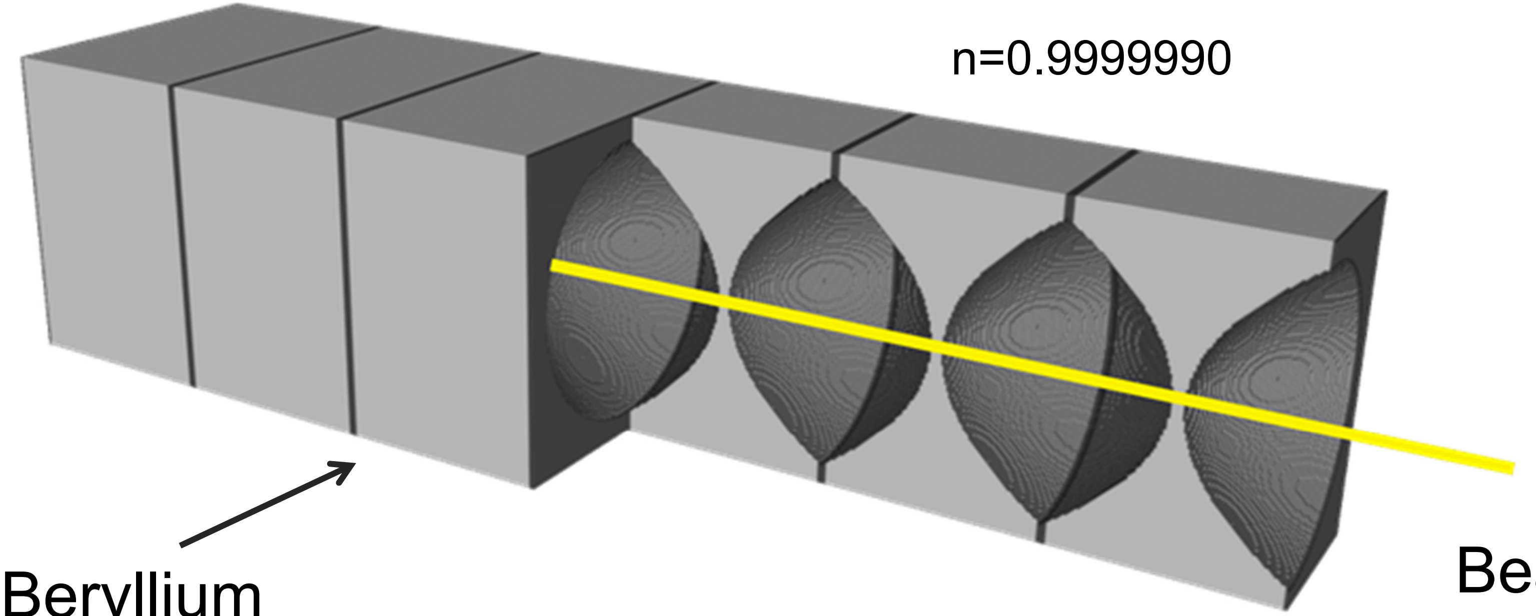


Sept 7, 2017, Photon commissioning team

Can we take advantage of this? Compound refractive lenses (CRLs)!

Convex lenses!

n=0.9999990



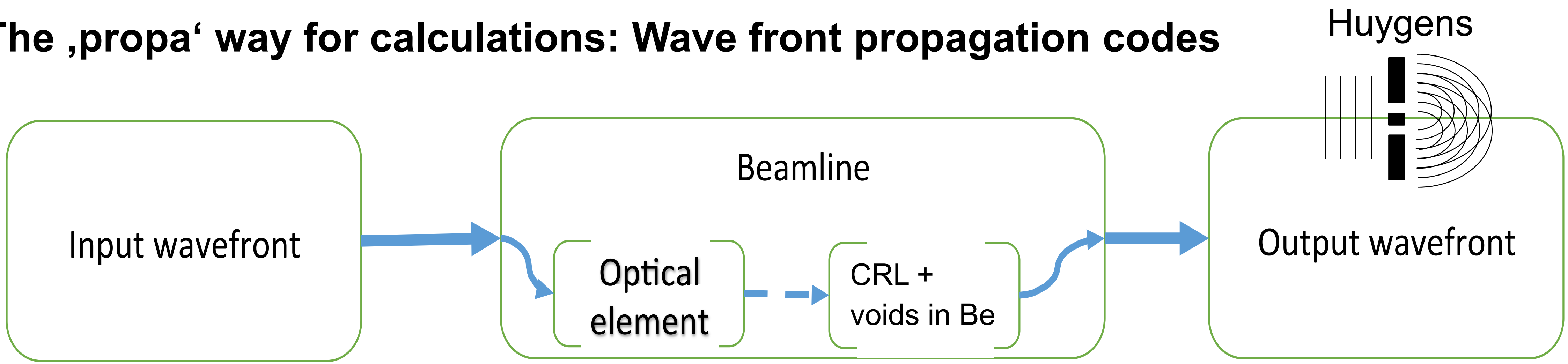
Beryllium
(water cooled)

Beam stays on axis

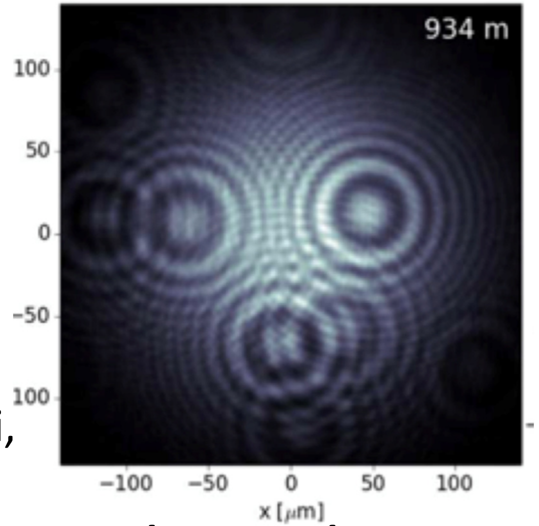
Collimation + focussing

Problem: chromatic!

The ‚propa‘ way for calculations: Wave front propagation codes



- **WavePropaGator**: interactive framework for X-ray free-electron laser optics design and simulations, L. Samoylova et al., J. Appl. Cryst., Vol. 49, no. 4 (2016), WPG sources *https:/github.com/samoylv/WPG*
  and documentation *http://wpg.readthedocs.org/en/latest/index.html*
- **FAST-XPD**: XFEL photon pulses database for modeling XFEL experiments, M. Manetti, .., M. Yurkov, AIP Conference Proceedings (2054), 030019 (2019), *in.xfel.eu/xp*
- **SIMEX**: Simulations of experiments *https://eucall-software.github.io/simex_platform/*



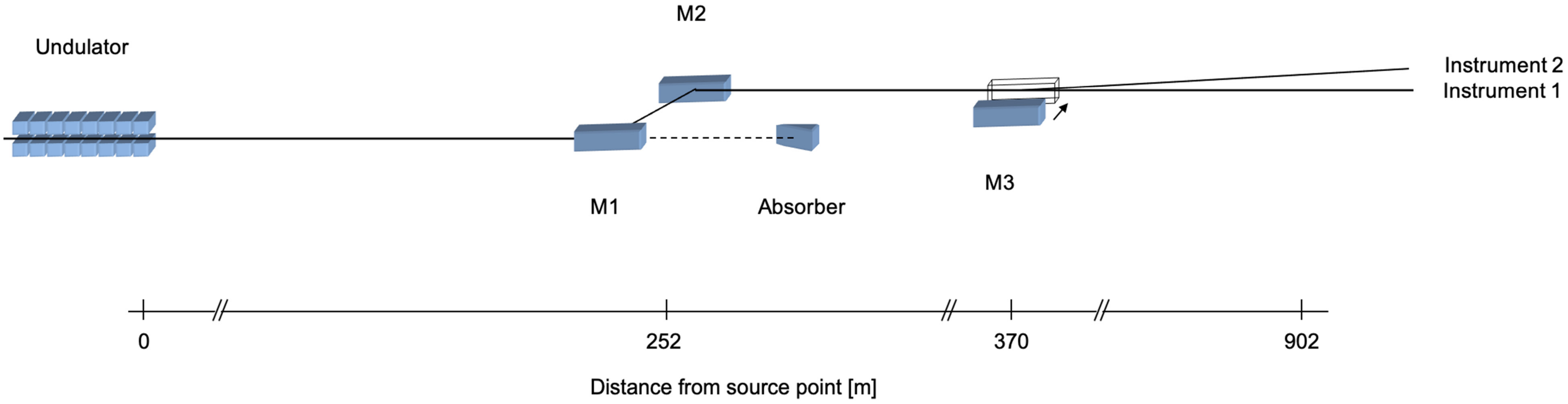
Roth, T., et al.
Proc. SPIE (2014). 9207

How to deflect the beam?

Generic FEL photon beam transport design at European XFEL

25 mm photon beam offset
for safety reasons
(hard background radiation)

Side-deflection by 1.4 m
to second instrument



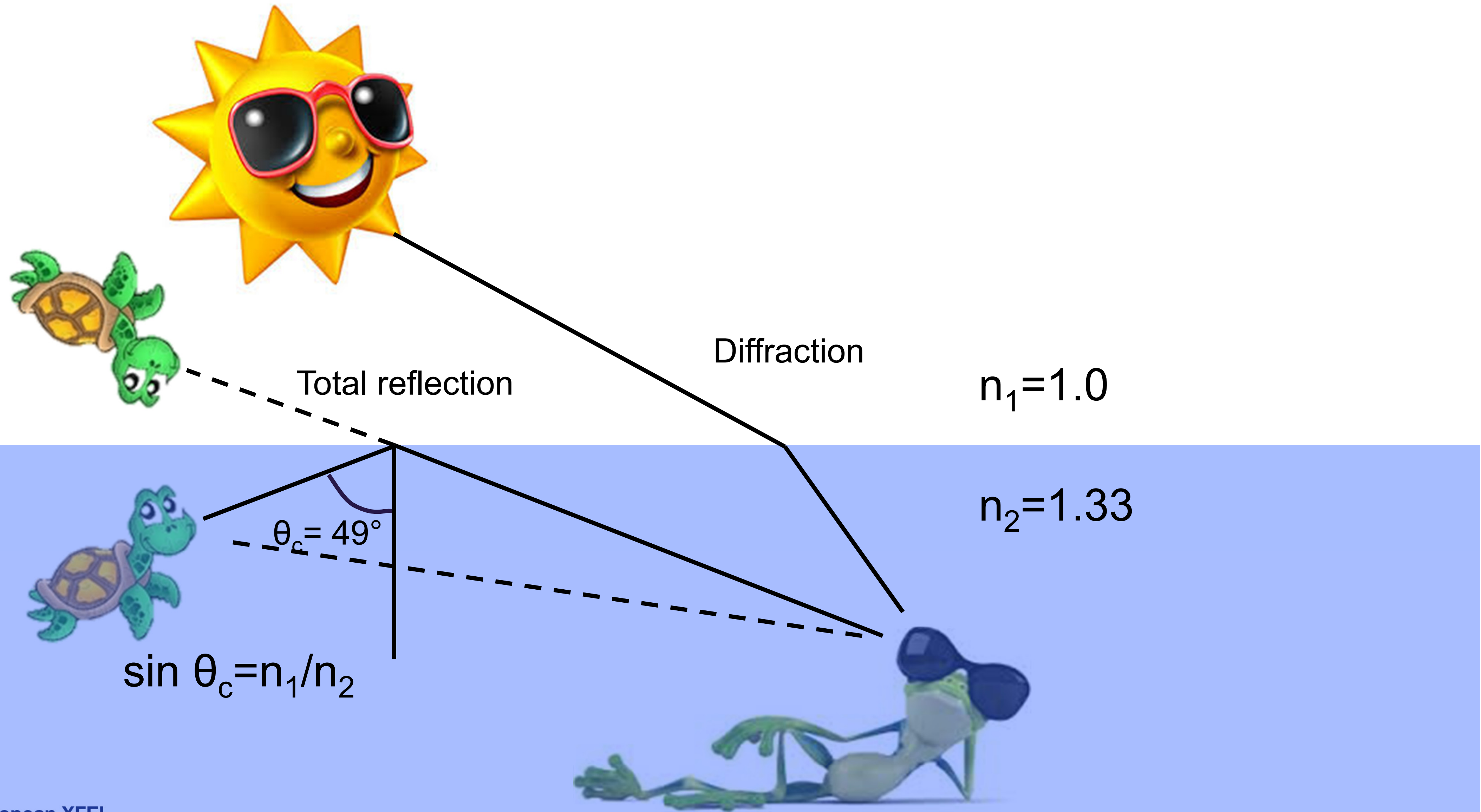
Total reflection on mirrors

Total reflection of light on interface to optical thinner medium

Wavy surface gives image distortions

(and the turtle doesn‘t care)

Diffraction and total reflection of optical light

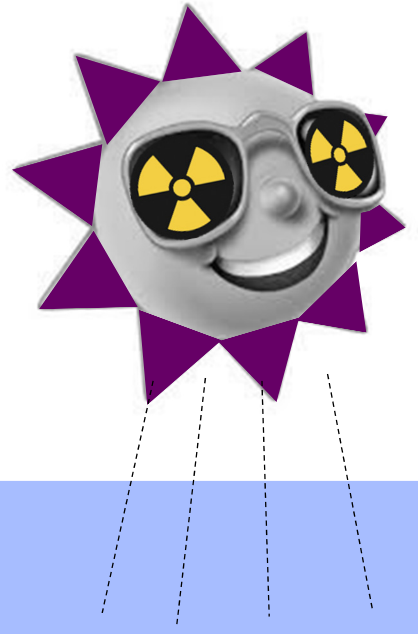


Basics: Total reflection of X-rays on (any) surface

$\alpha_c \sim \lambda \sqrt{\rho_{electron}}$

α_c Gold > Diamond

α_c soft > hard X-ray



10 keV

$\theta_c = 89.9°$

$\alpha_c = 0.1° \approx$ mrad!

$n_1 = 1.0$

Total reflection on water

$n_2 = 0.999998$
$= 1 - 2 \times 10^{-6}$

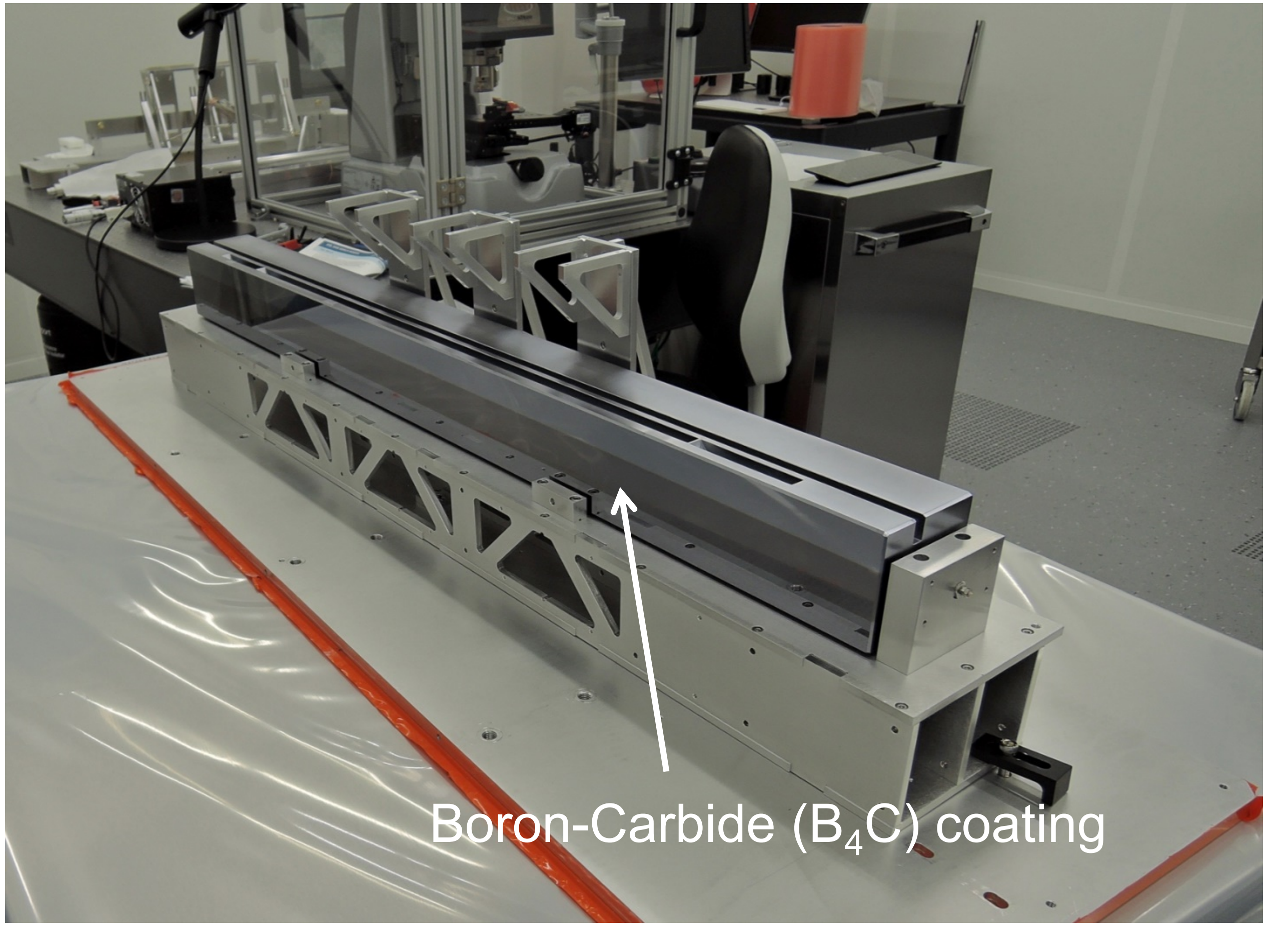
critical angle: $\theta_{water} = 90°$

$\sin \theta_c = n_2/n_1$

No X-ray rainbow possible!

30.7.2019, Emberger Alm, Austria

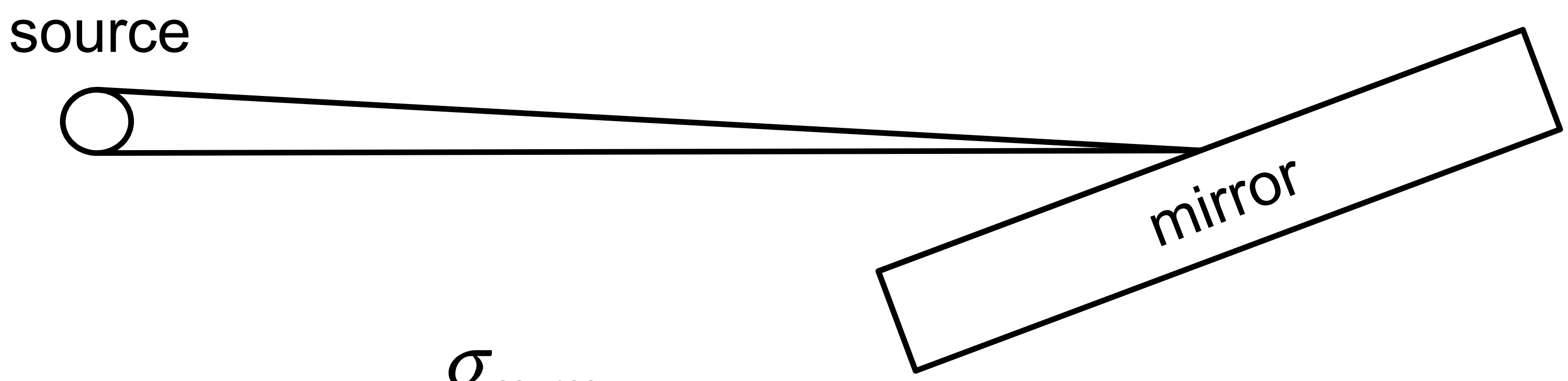
Reflection on silicon does also work: X-ray mirror (75x75x900mm) on its mount



Only one side is polished!

How good does the polishing need to be?

Specs on slope error



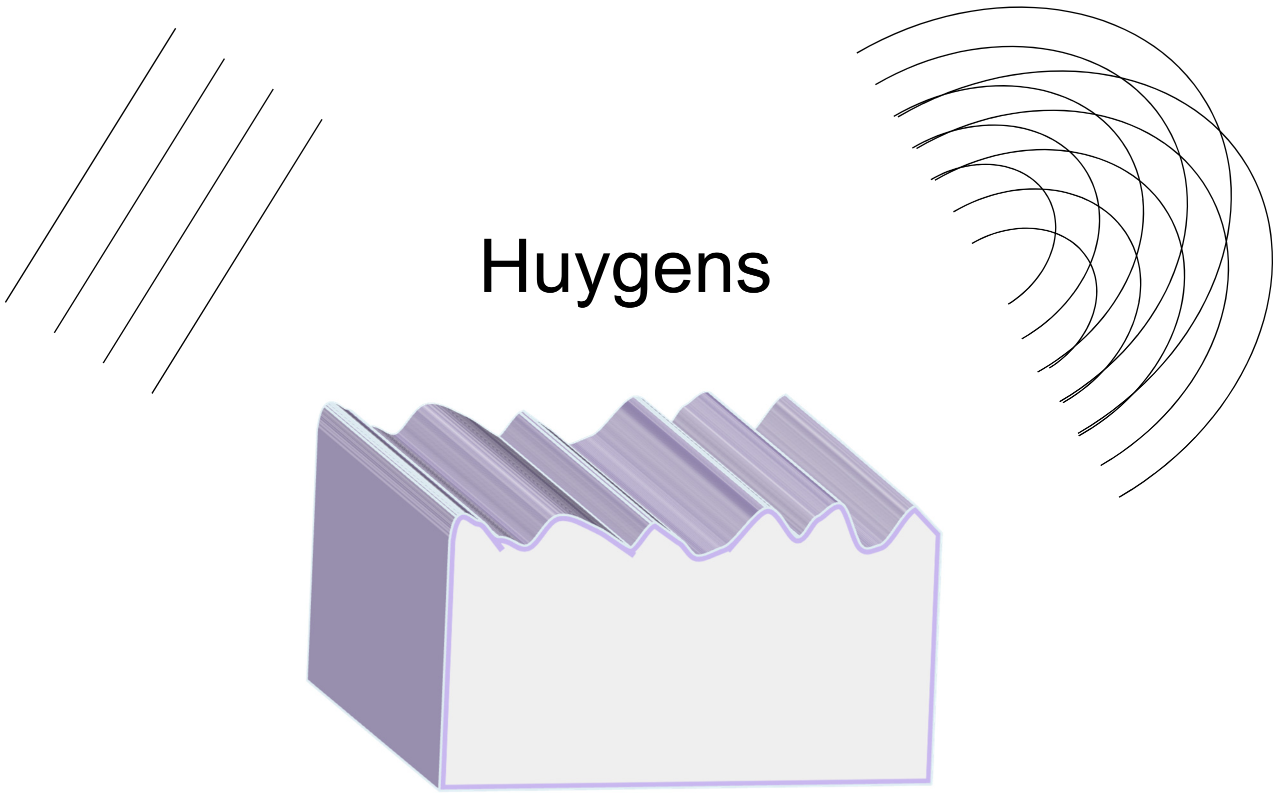
$$\sigma_{slope} = \frac{\sigma_{source}}{L}$$

$$\frac{20\ \mu m}{500\ m} = 40\ nrad\ (rms)$$

at storage rings typically 500-1000 nrad

but: Alpha Centauri: 1.2 R_s/ 4.3 LY = 17 nrad

Diffraction limited optics: *Interference from different parts of mirror*



Diffraction limited optics: Strehl ratio *(Interference from different parts of mirror)*

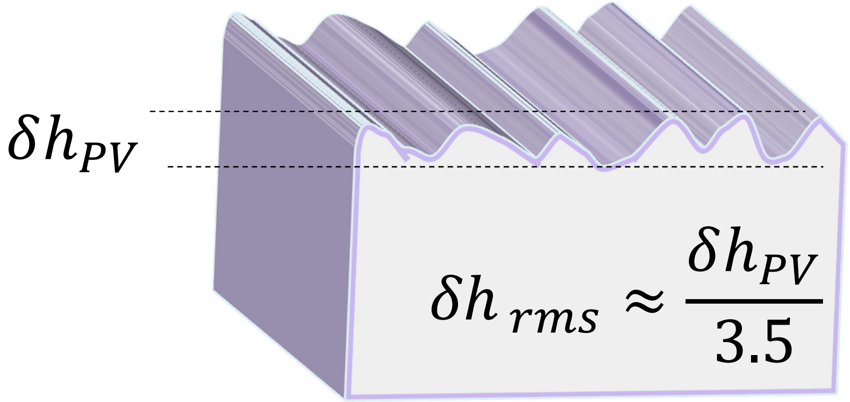
$$S = \frac{obtained\ peak\ intensity}{theoretical\ max.peak\ intensity} > 0.82$$

(Marechal criterion, diffraction limited optics)

$$S \approx e^{-(2\pi\phi_{rms})^2} \qquad \phi_{rms} \leq \frac{1}{14}$$

Wave front error introduced by *N* mirrors:

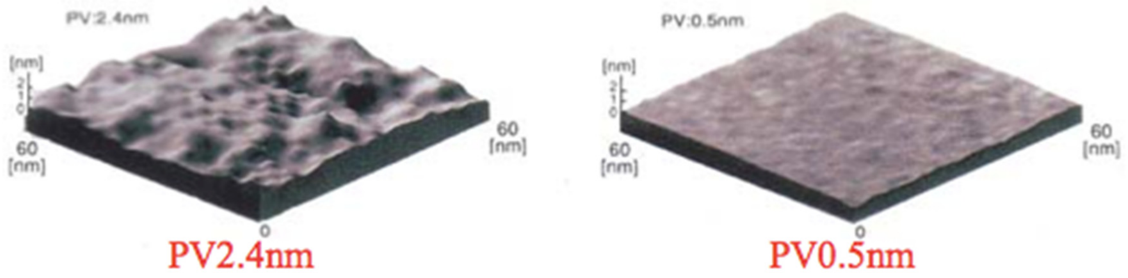
$$\lambda\,\phi_{rms} = \sqrt{N}\ 2\ \sin\alpha\ \ \delta h_{rms}$$



Example: $1\ \text{Å}, N = 6,\ \alpha = 2mrad\ \rightarrow \delta h_{PV} \leq 2.5\ \text{nm}$

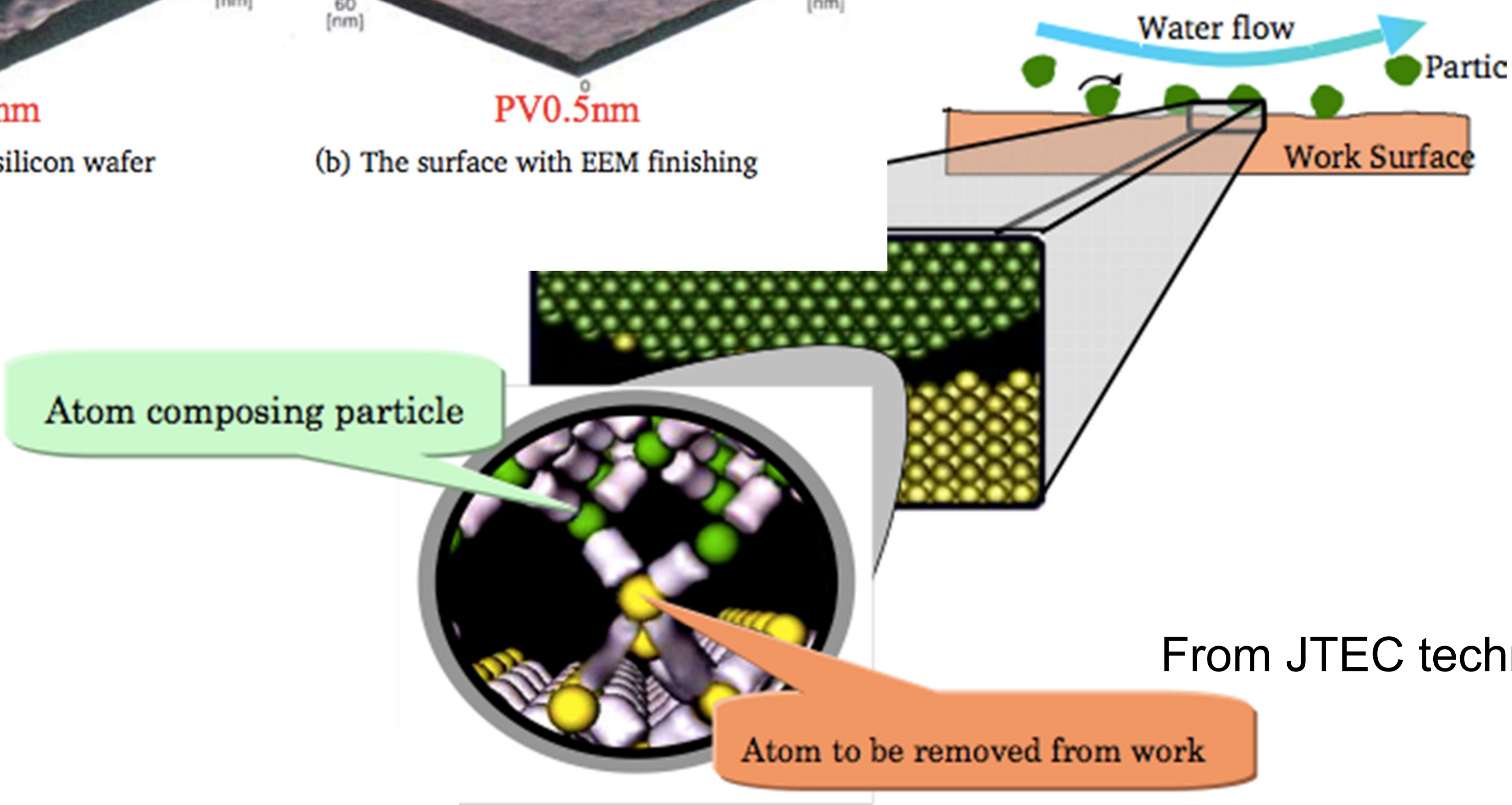
Polishing mirrors to the extreme: Elastic Emission Machining (EEM) polishing process (Osaka University, JTEC, Japan)

Selective polishing according to precise metrology map (6 month)



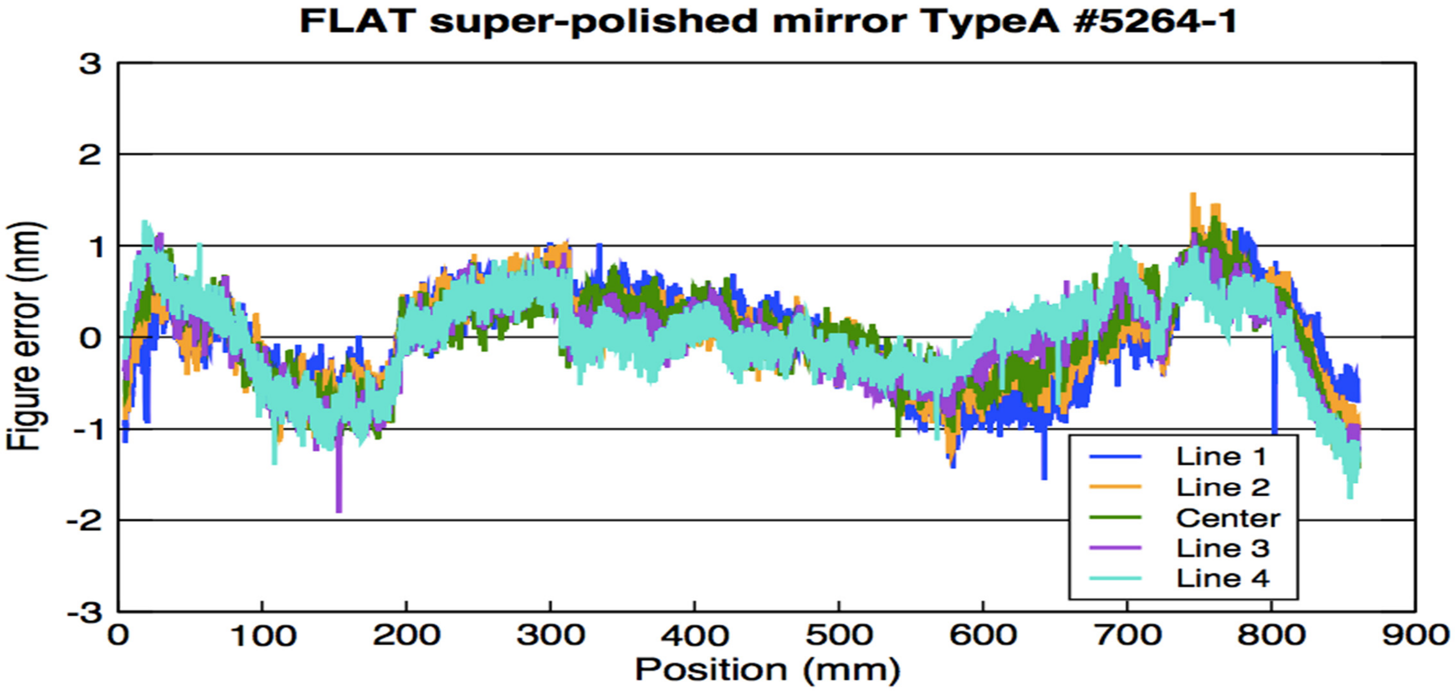
(a) A surface of silicon wafer for Ultra LSI

(b) The surface with EEM finishing



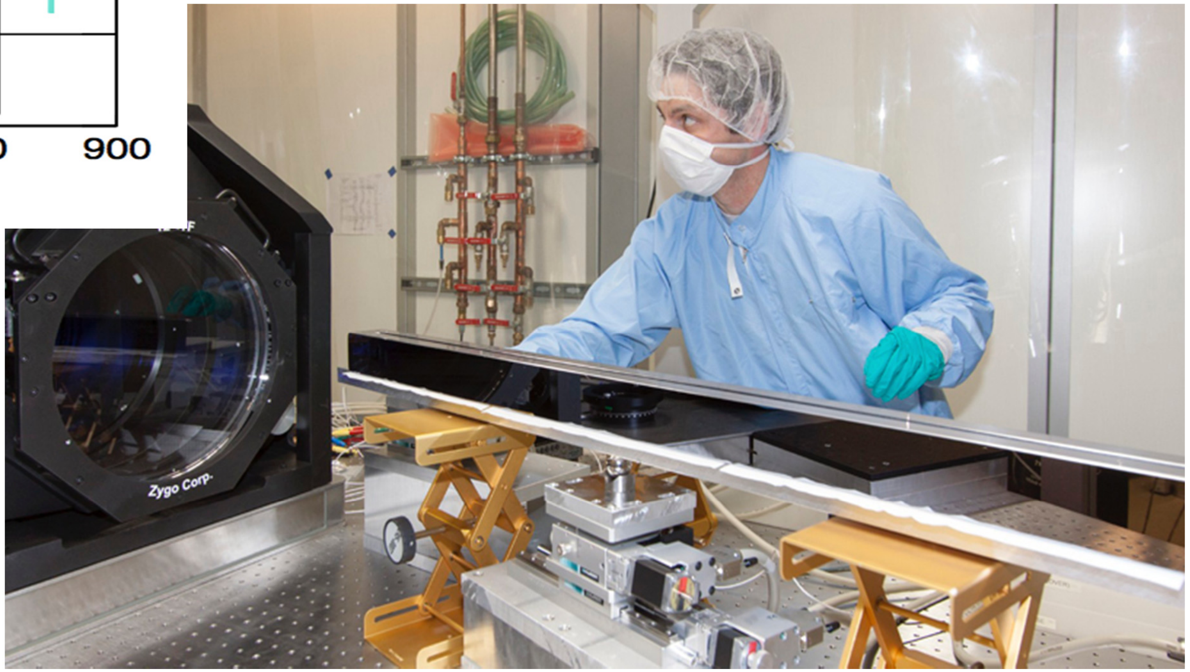
From JTEC technical data sheet

March 2016: First 950 mm long mirror received from JTEC in Hamburg



TEC CORPRATION

Maurizio Vannoni



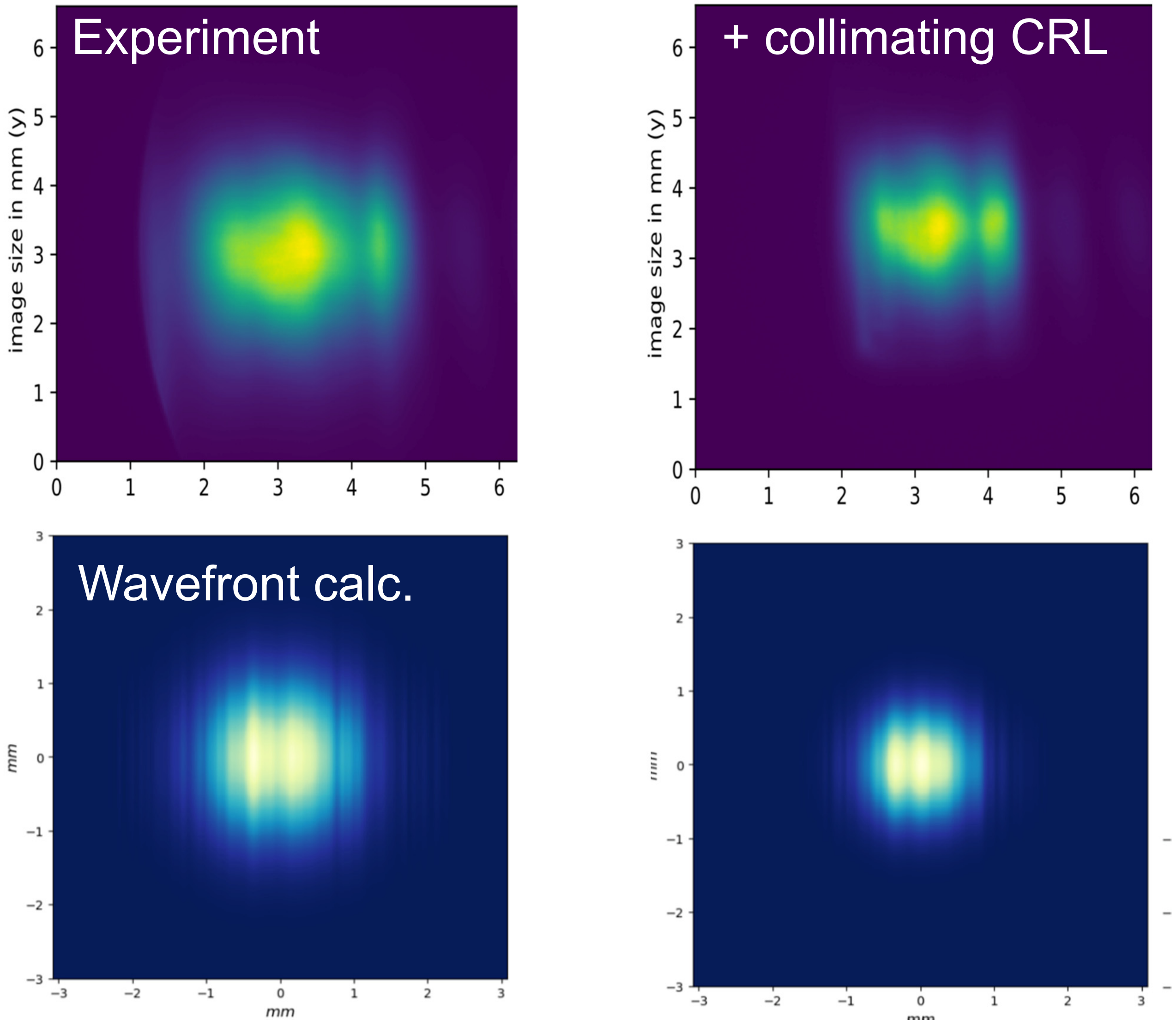
Wavefront calculations of FEL beam over two mirrors (600 m downstream)

Stripes come from polishing errors

'Collimatiing' CRL just 'shrinks' the beam

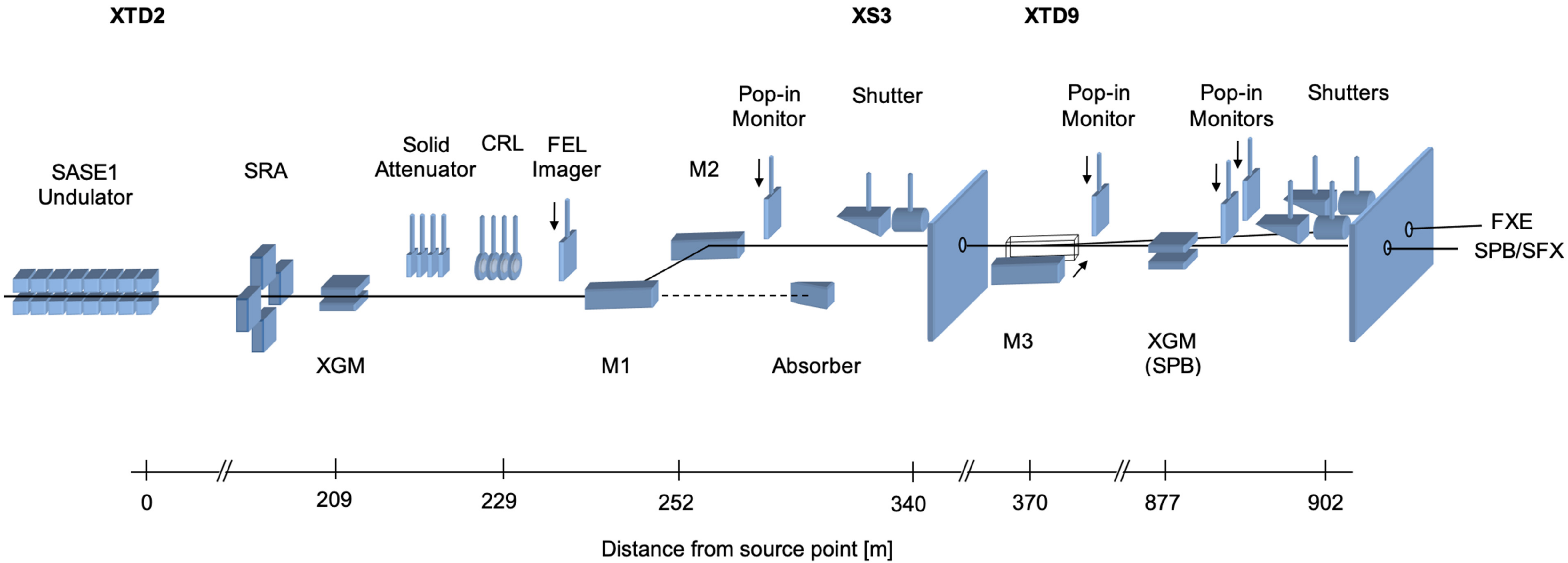
Some uncertainties come from mirror mounting ..

Valerija Music, Master thesis, University Hamburg & European XFEL, 2018



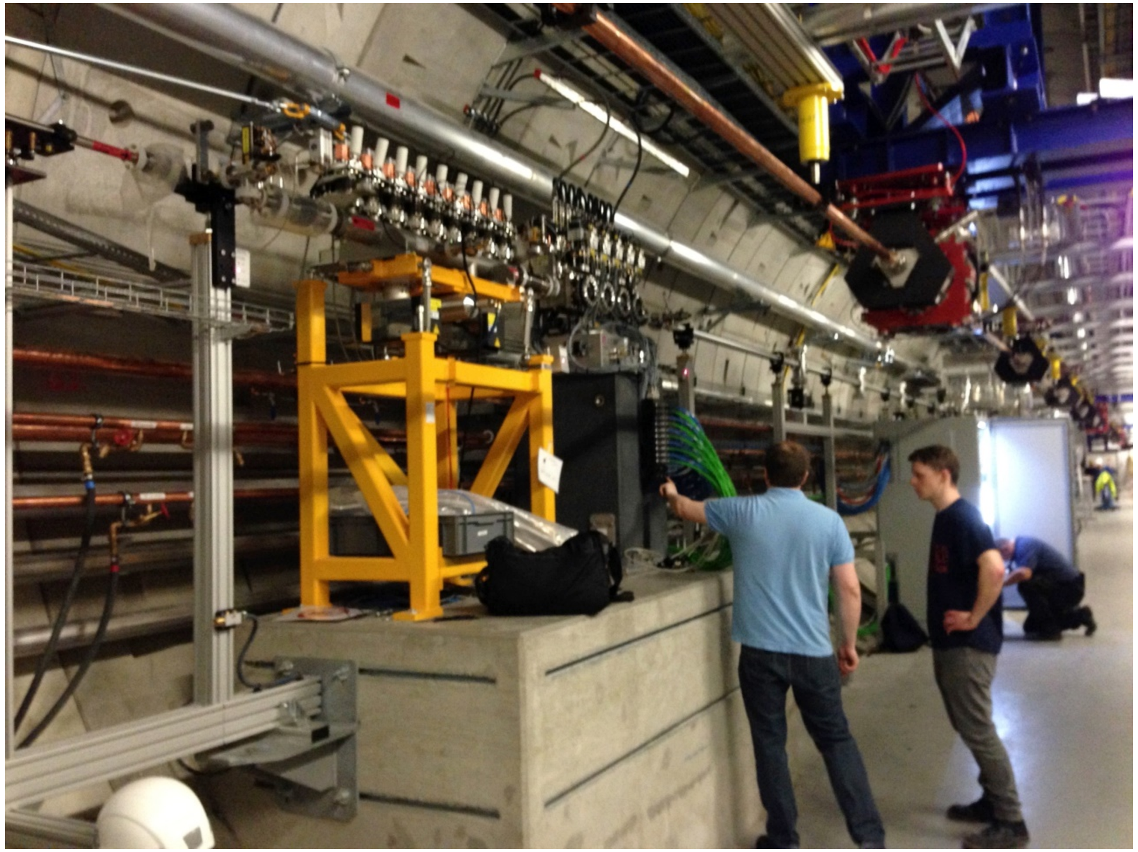
Photon Beam Transport
SASE1

SASE1 photon beam transport design



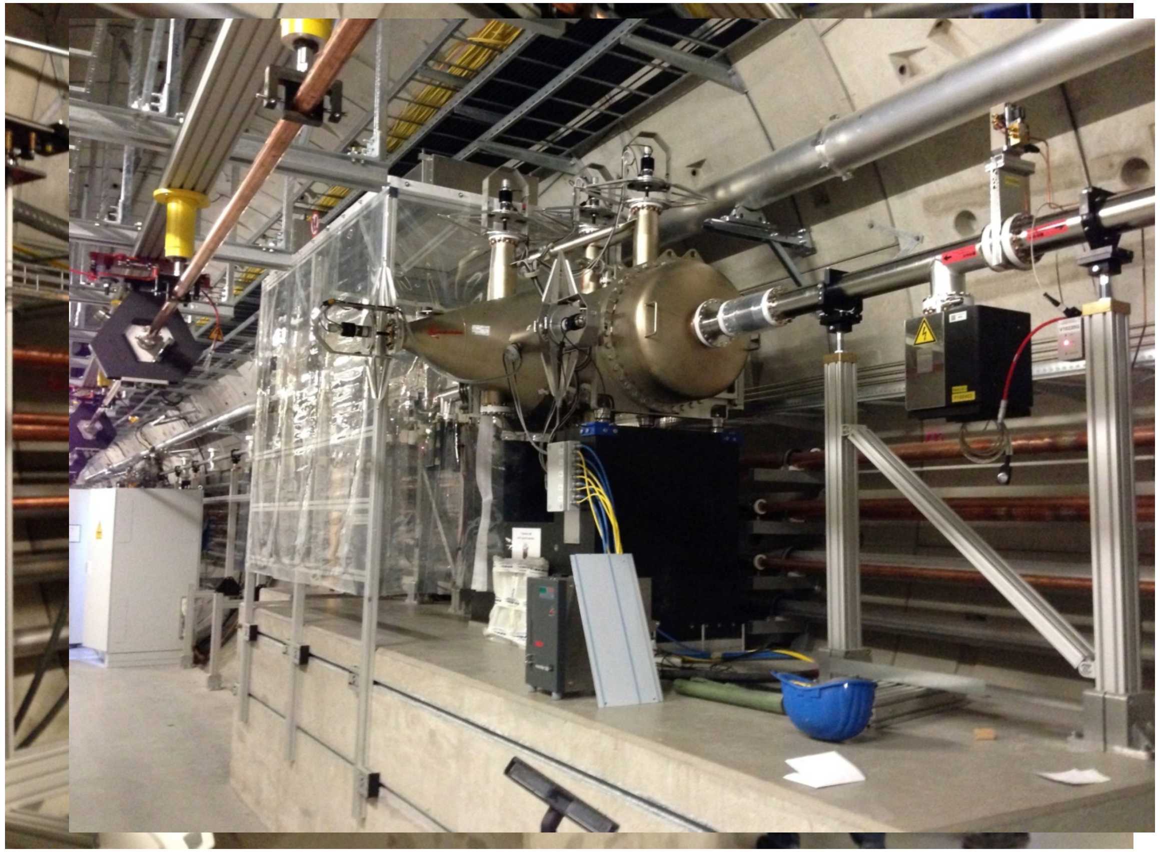
SASE1 photon beam line

XTD2, Attenuator, CRL



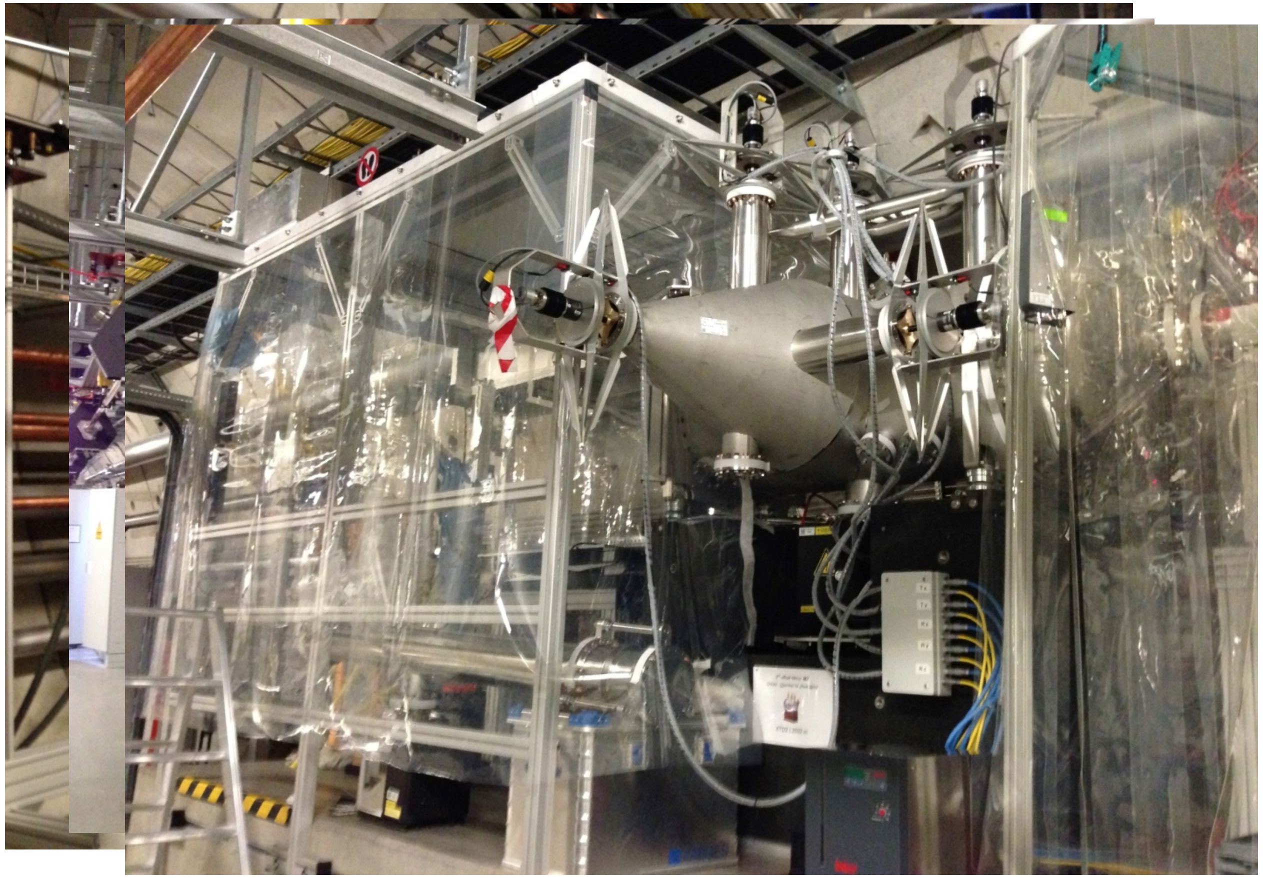
SASE1 photon beam line

XTD2, Mirror M1



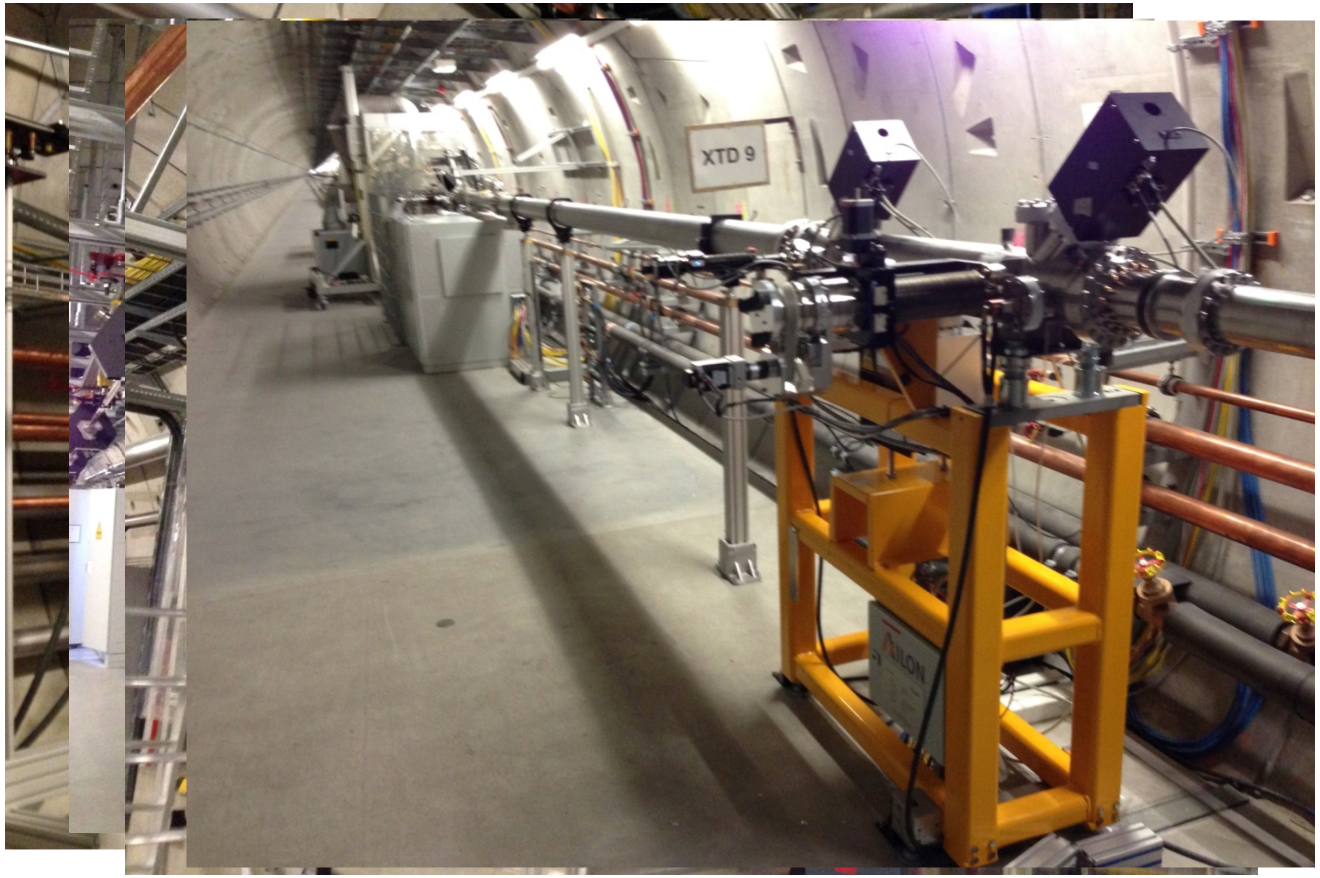
SASE1 photon beam line

XTD2, Mirror M2



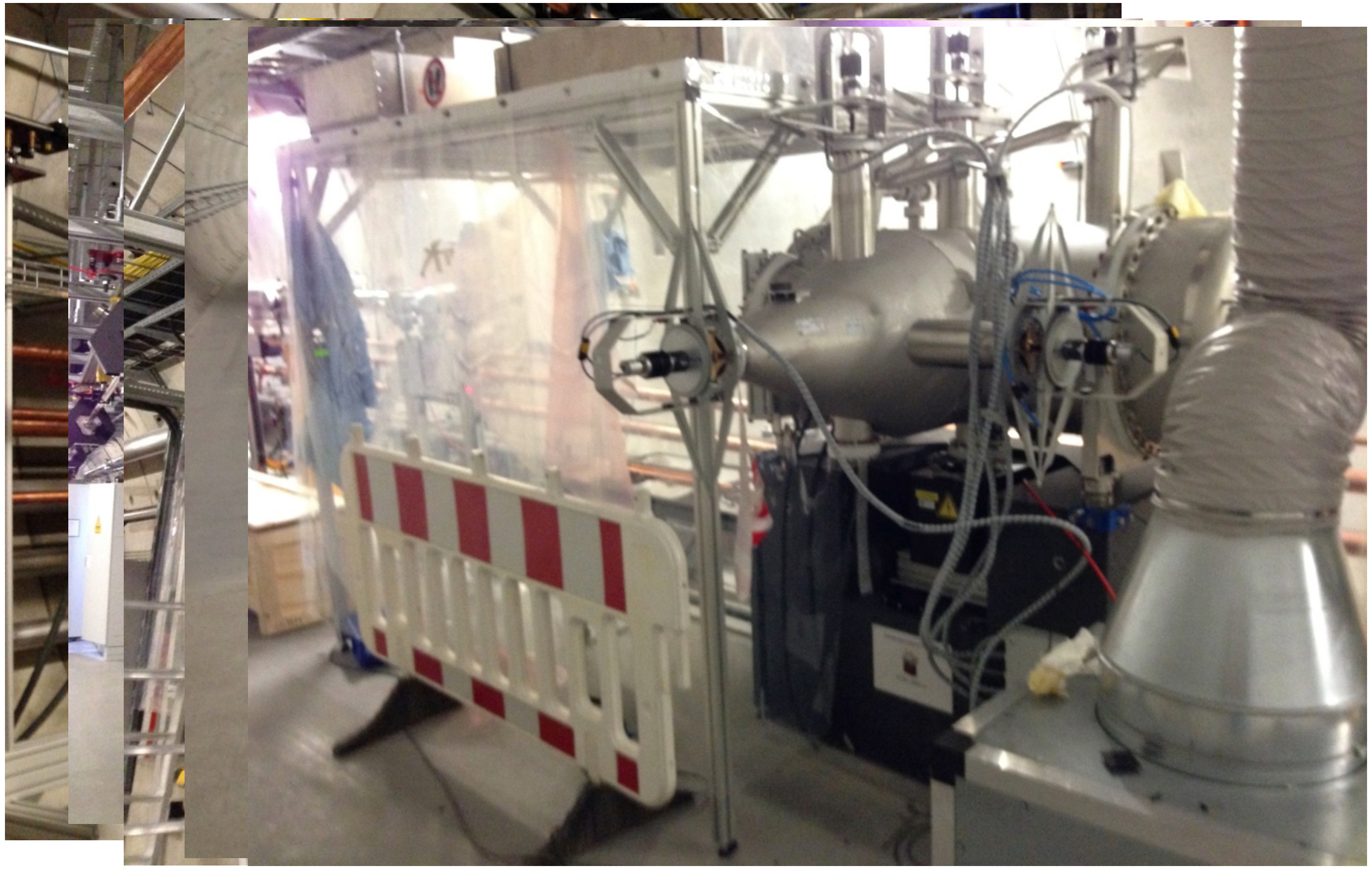
SASE1 photon beam line

XTD9, Hirex



SASE1 photon beam line

XTD9, M3



SASE1 photon beam line

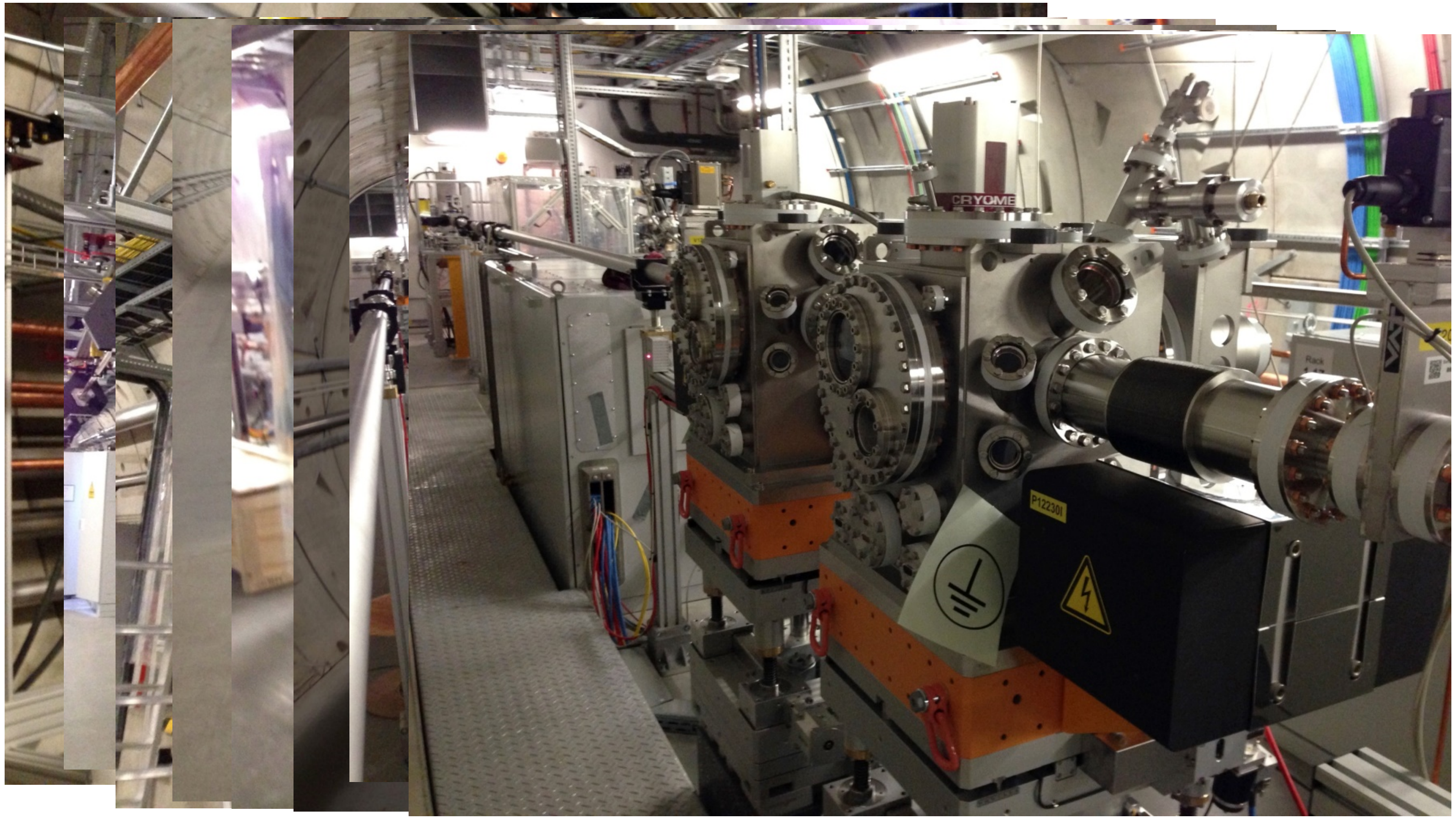
XTD9, 500 m pipes

SASE1 photon beam line

XTD9, XGM

SASE1 photon beam line

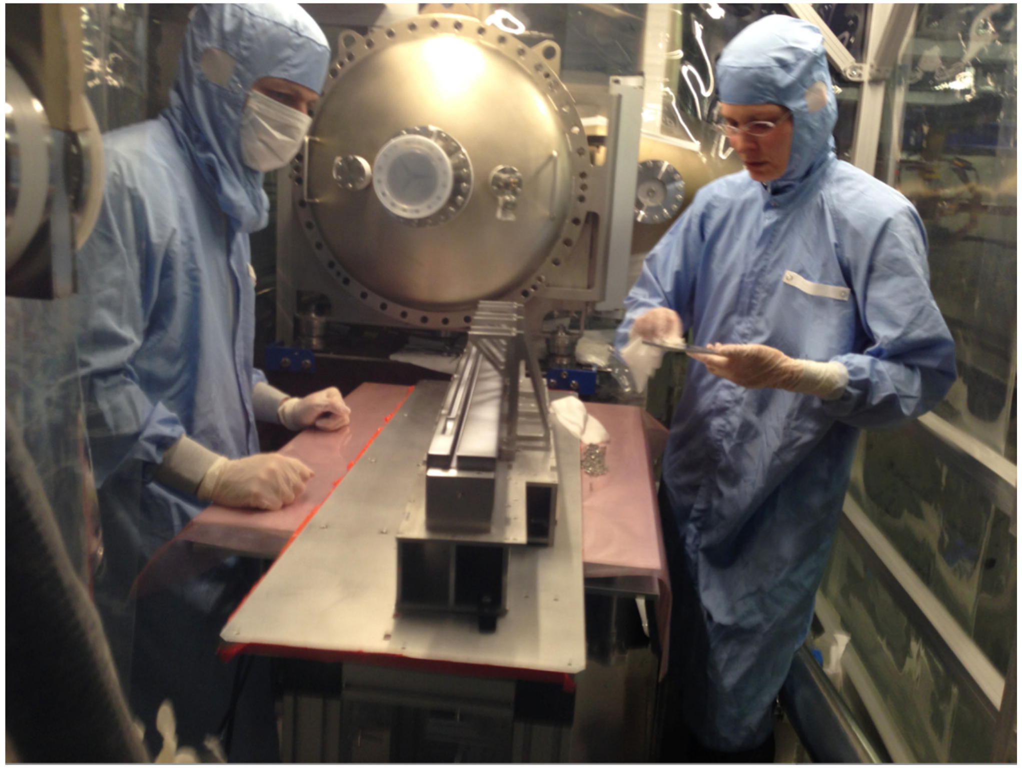
XTD9, 4 bounce mono



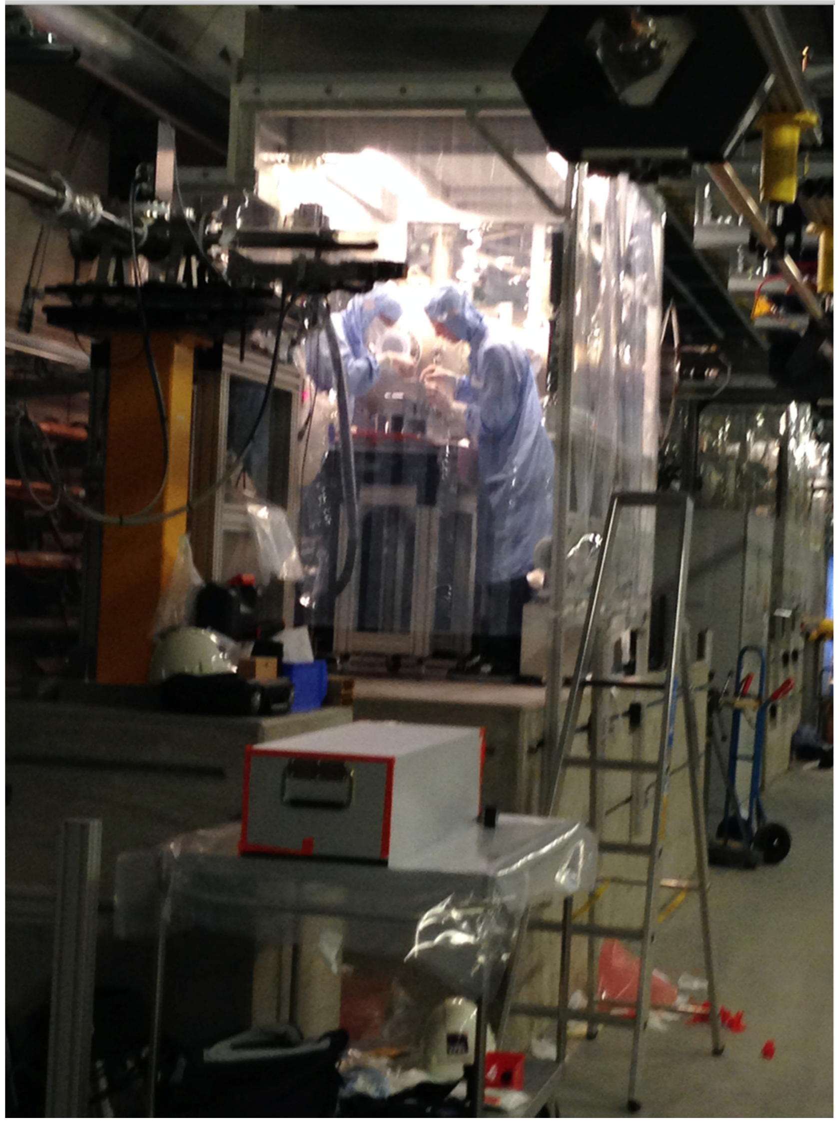
SASE1 photon beam line

XTD9, CRL, Shutters

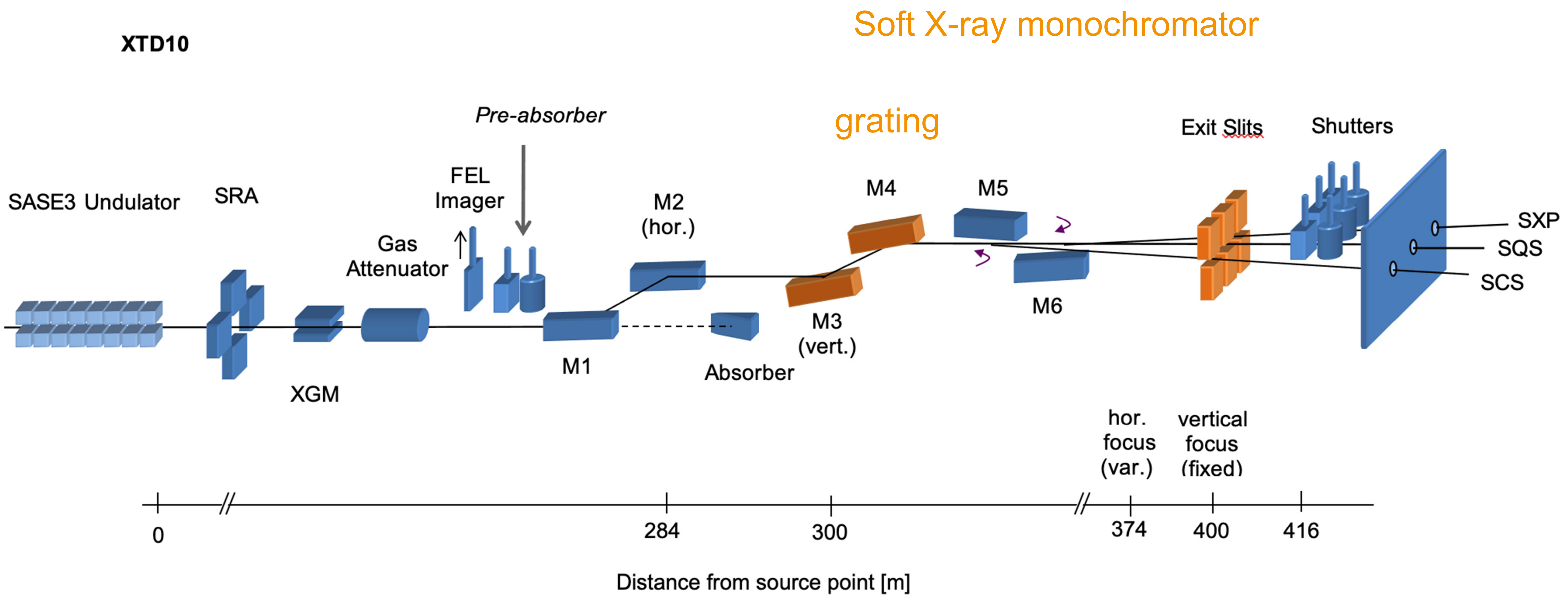
Installation of mirror



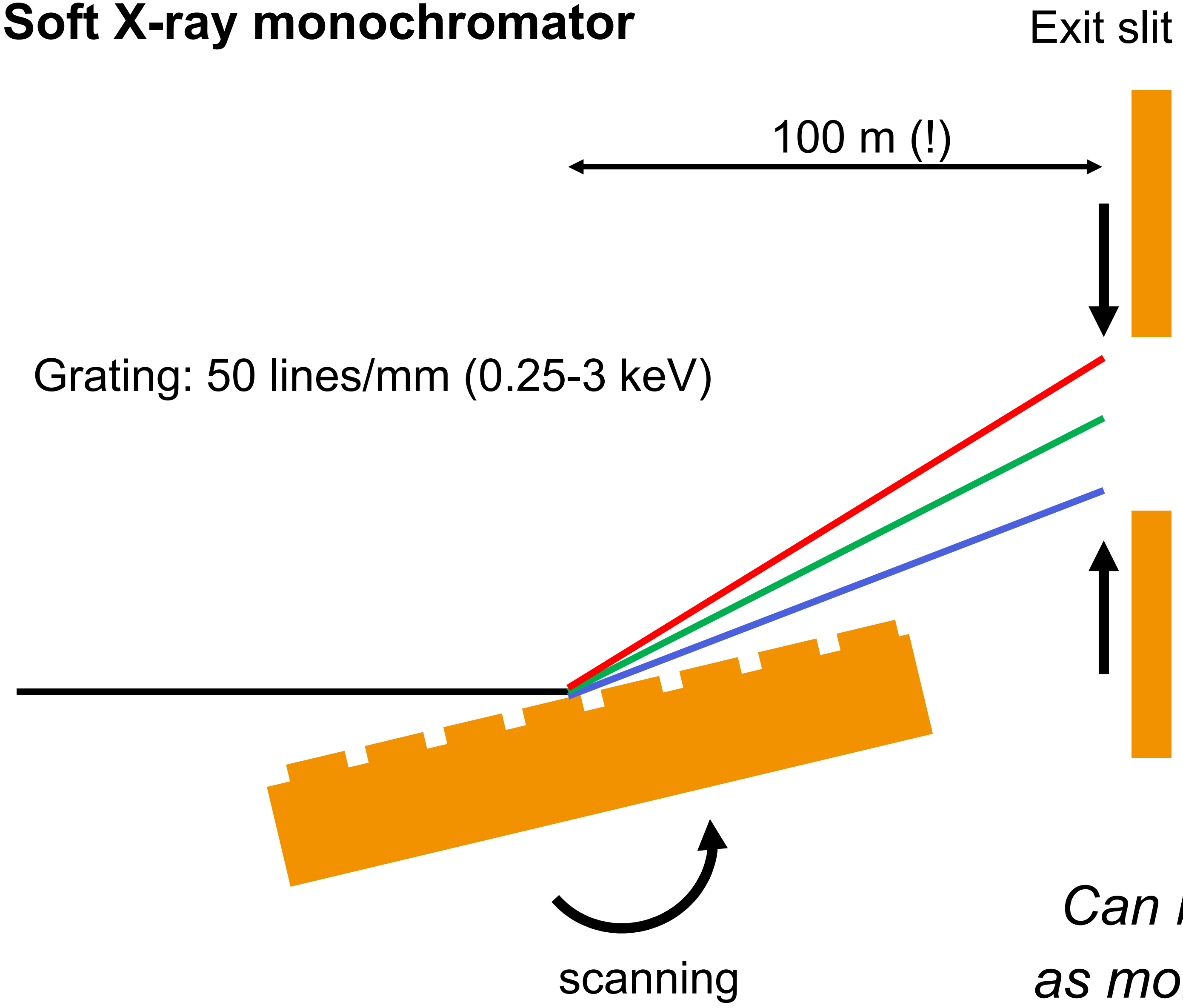
Maurizio Vannoni & Antje Trapp



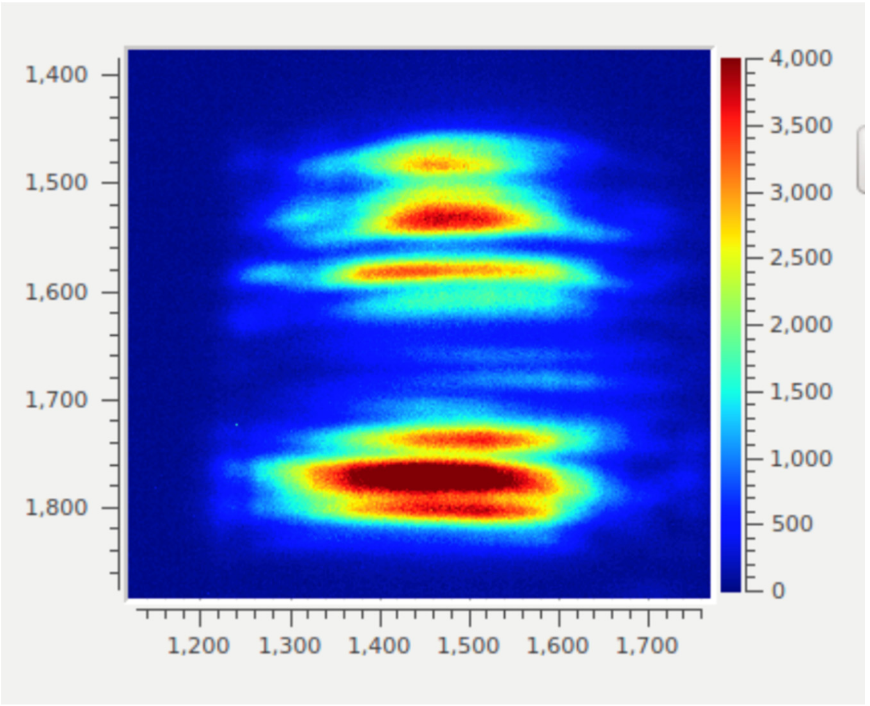
Photon beam transport design SASE3



Soft X-ray monochromator

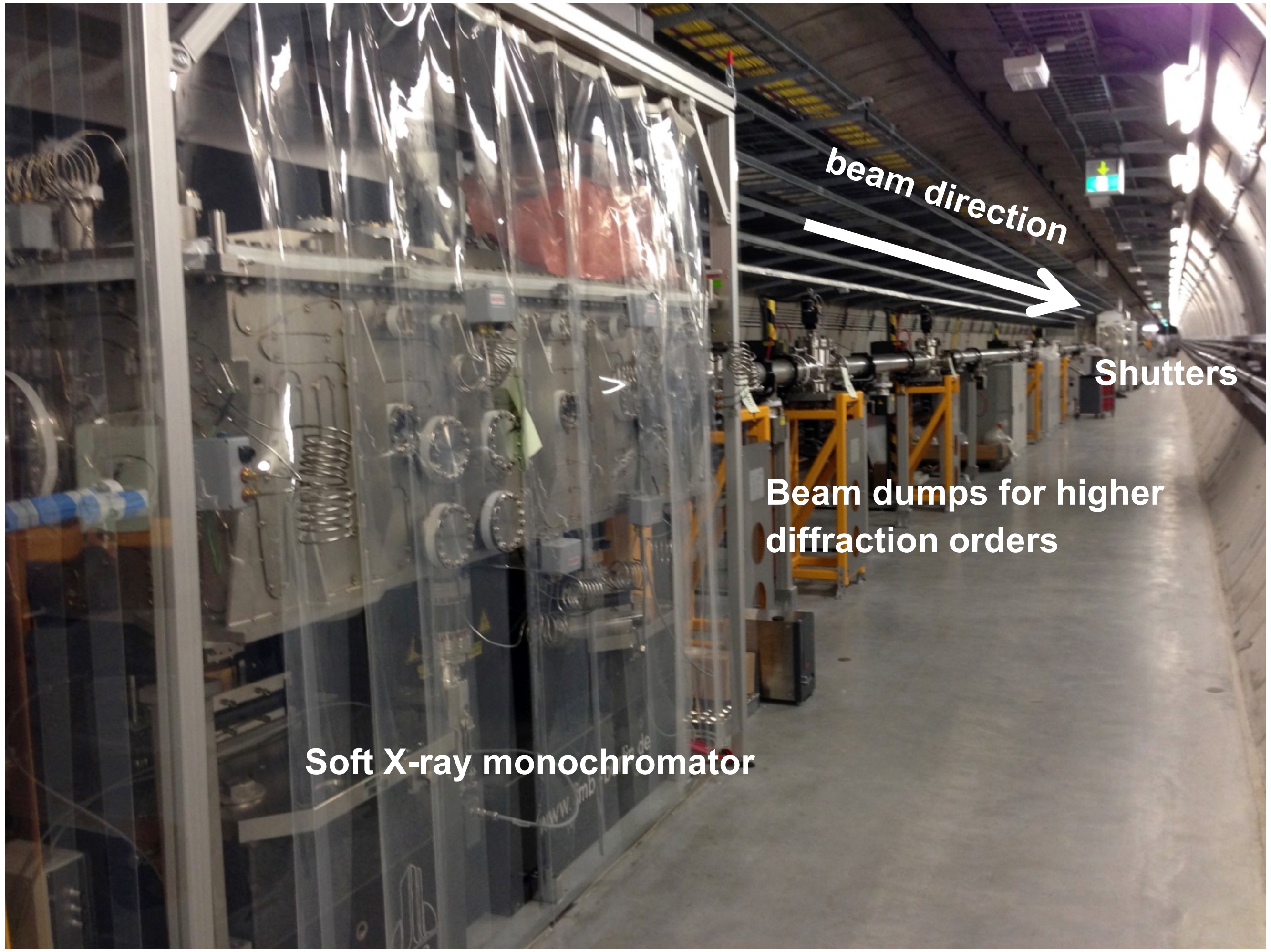


24.2.2018 SASE3 commissioning team



Can be used for to see SASE spikes & as monochromator, when slits are closed

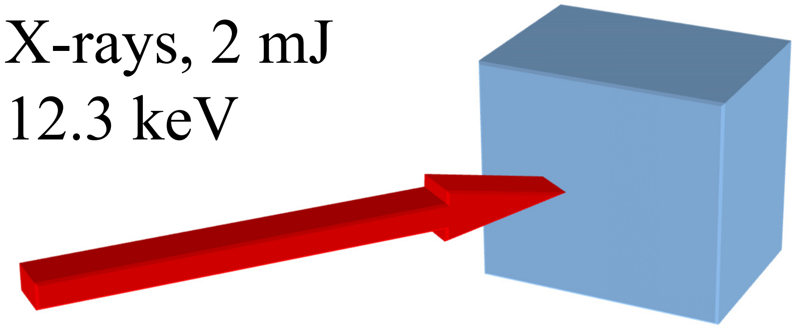
View into SASE3 XTD10 tunnel



How to stop the beam?

Temperature rise after a single pulse

X-rays, 2 mJ
12.3 keV



$$Q = c_p \rho V \Delta T$$

$$V = fwhm^2 \times l_{abs} \times 1.133, \; fwhm = 0.5\ mm$$

$$\Delta T \sim 1/(l_{abs} \times fwhm^2)$$

Gold > Diamond

soft > hard X-ray

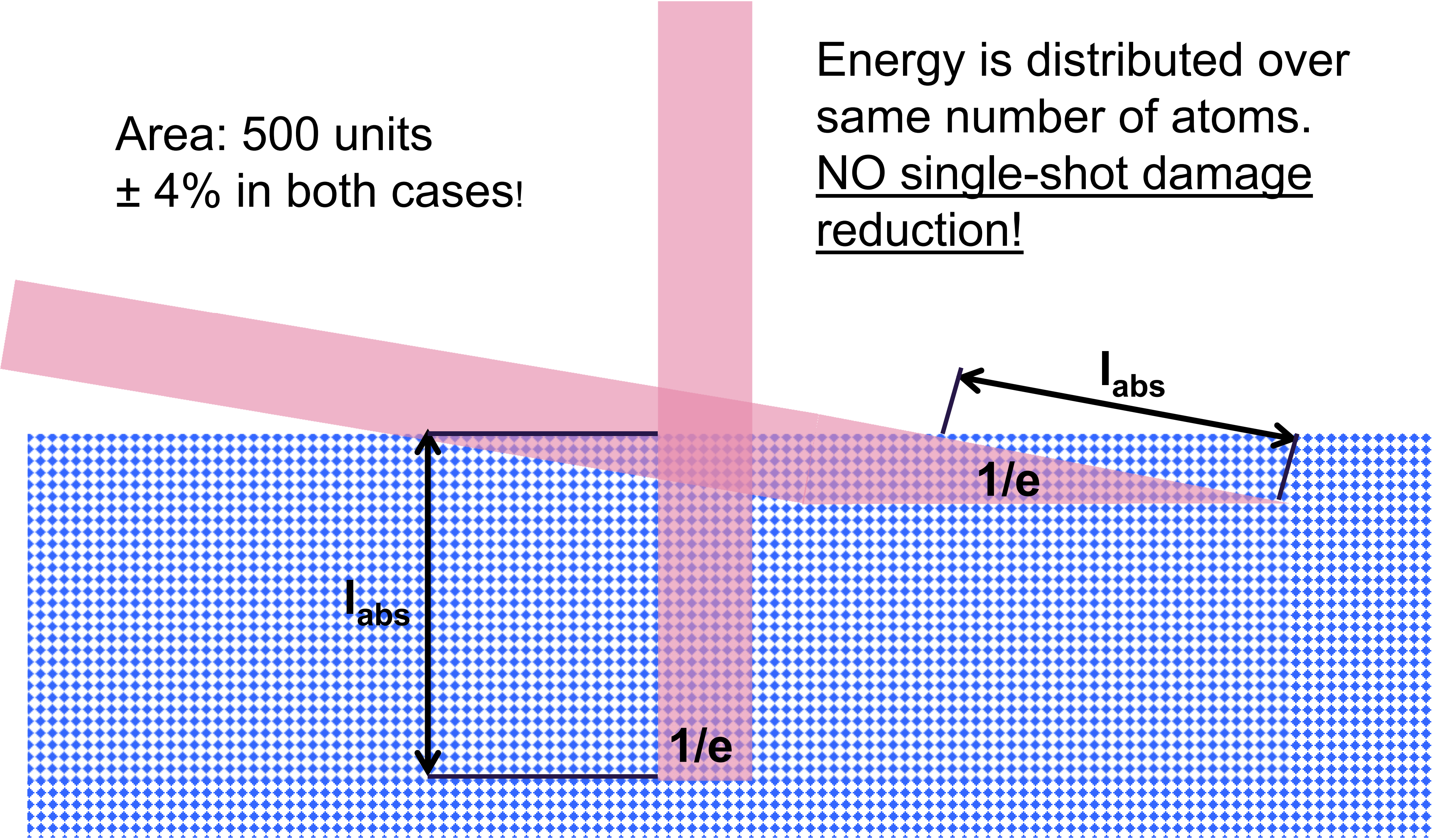
small >> large beam

	ρ, g/cm^3	c_p, J/gK	l_{abs}, (μm)	ΔT_{shot} (K)
LiF	2.639	1.562	1172	1.46
Be	1.848	1.82	13400	0.16
B	2.34	1.02	5958	0.50
BN	2.2	1.4	3377	1.0
B_4C	2.51	0.95	4730	0.62
C_{diam}	3.52	0.51	2200	1.78
C_{glass}	2.262	0.71	3420	1.28
Al	2.70	0.90	265	10.96
Al 2014	2.70	0.90	265	10.96
Al_2O_3	3.97	0.419	283	15.0
AlN	3.33	0.80	303	8.74
Si	2.33	0.703	237	18.18
SiC	3.15	0.67	242	13.82
SiO_2	2.649	0.75	371	9.57
Ti	4.50	0.52	35.5	85.0
Copper	8.92	0.385	8.88	231.5

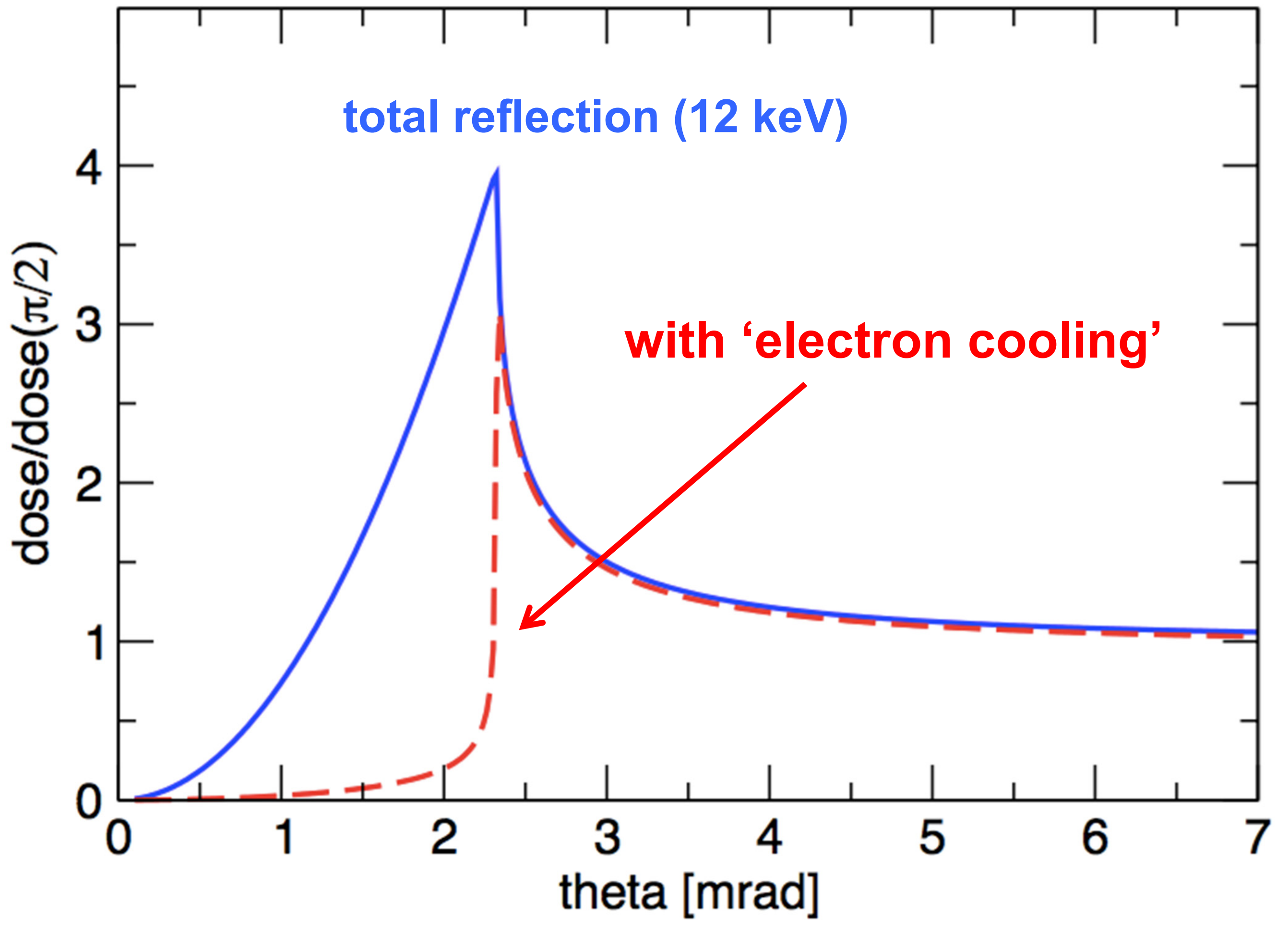
Can grazing incidence geometry prevent single shot damage? (α > α_crit)

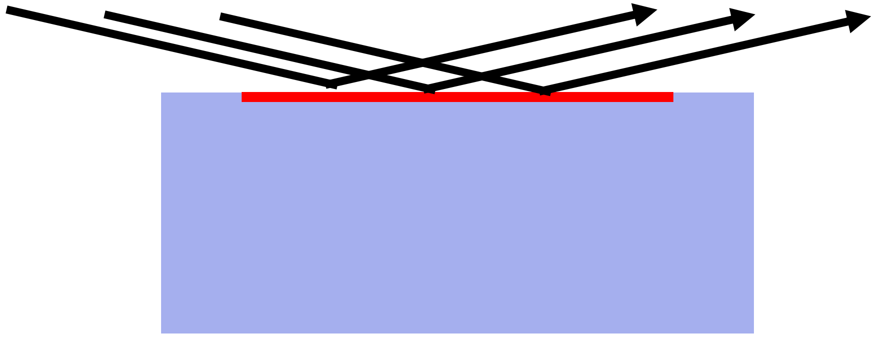
Area: 500 units
± 4% in both cases!

Energy is distributed over same number of atoms.
<u>NO single-shot damage reduction!</u>



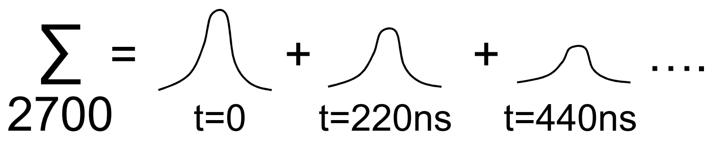
Dose per atom around critical angle





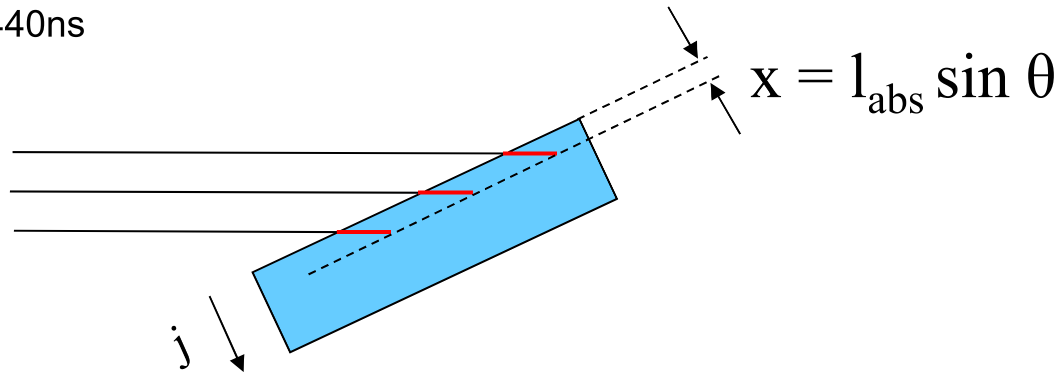
Only ~20 nm penetration into bulk at total reflection!

Cooling during pulse train (time > 0)



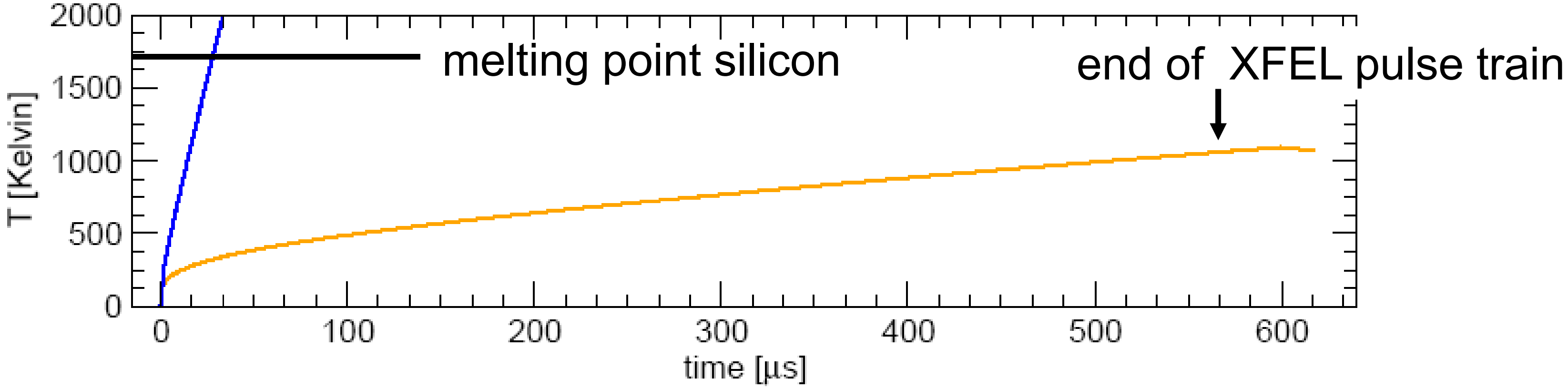
heat flow:

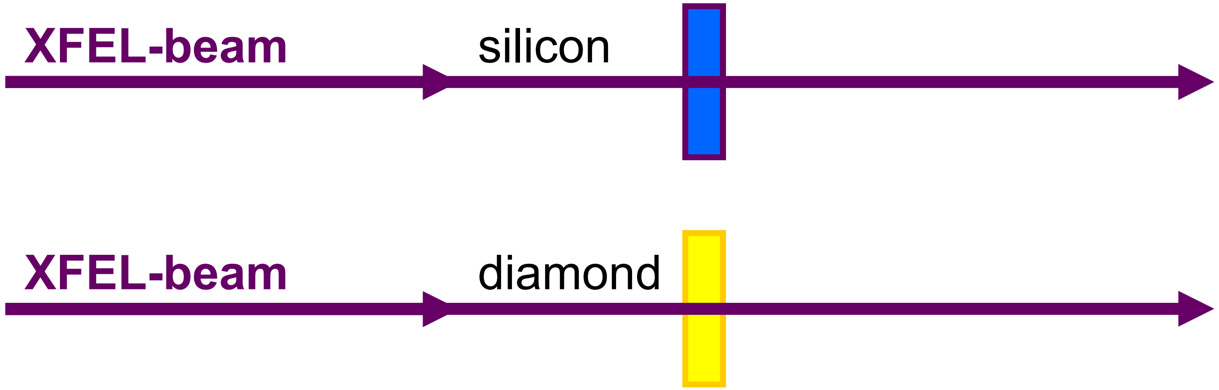
$\Delta Q/\Delta t = \lambda\, \Delta T/\Delta x$



Angular dependence (for $\alpha > \alpha_c$) becomes relevant when thermal transport is happening!

Heat up during pulse train (~marco pulse)



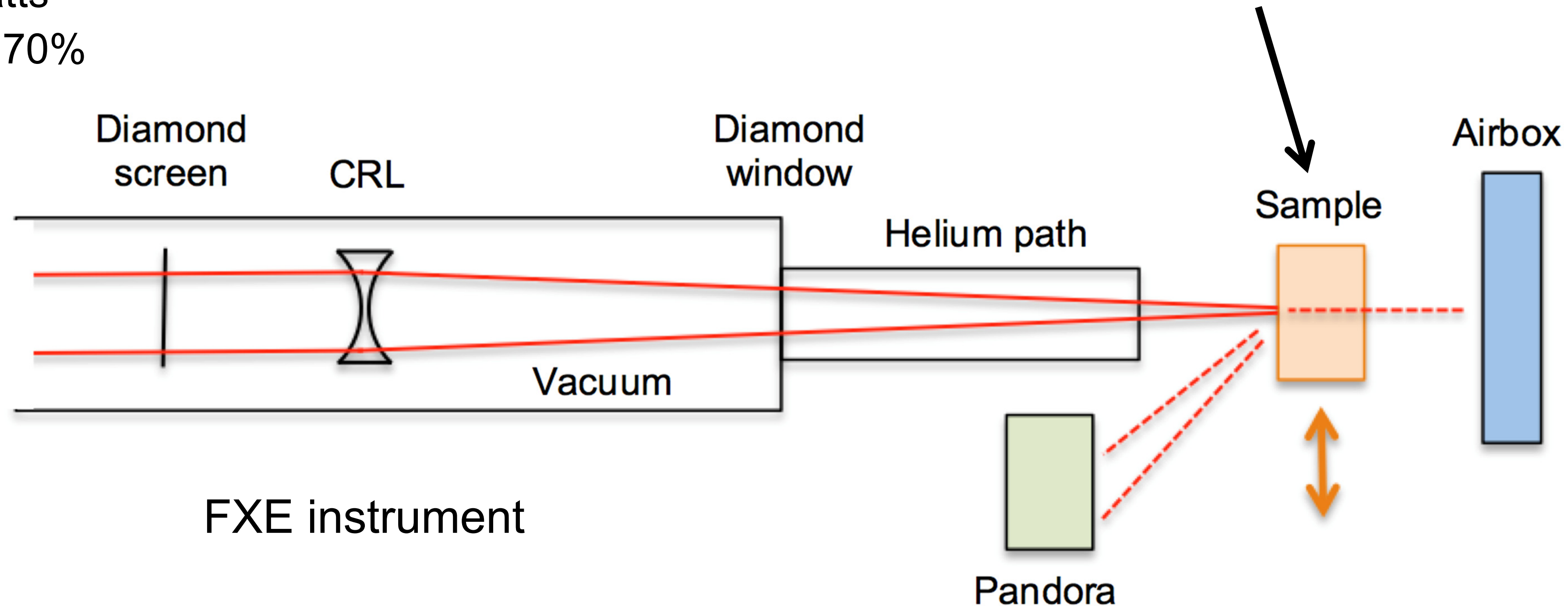


Depends strongly on material on beam size!

Radiation safety material tests (started April 2018 at FXE instrument)

9.2 keV X-rays, 25 µm focus
6 10^{11} phts/pulse x 1580 pulses /sec
(rep rate: 1.1 MHz, 10 Hz pulse trains)
Average power: 1.5 Watts
Beamline transmission 70%

Sample thickness: 0.5 mm… 50 mm
Materials relevant for shutter design:
B4C, copper, steel, tungsten

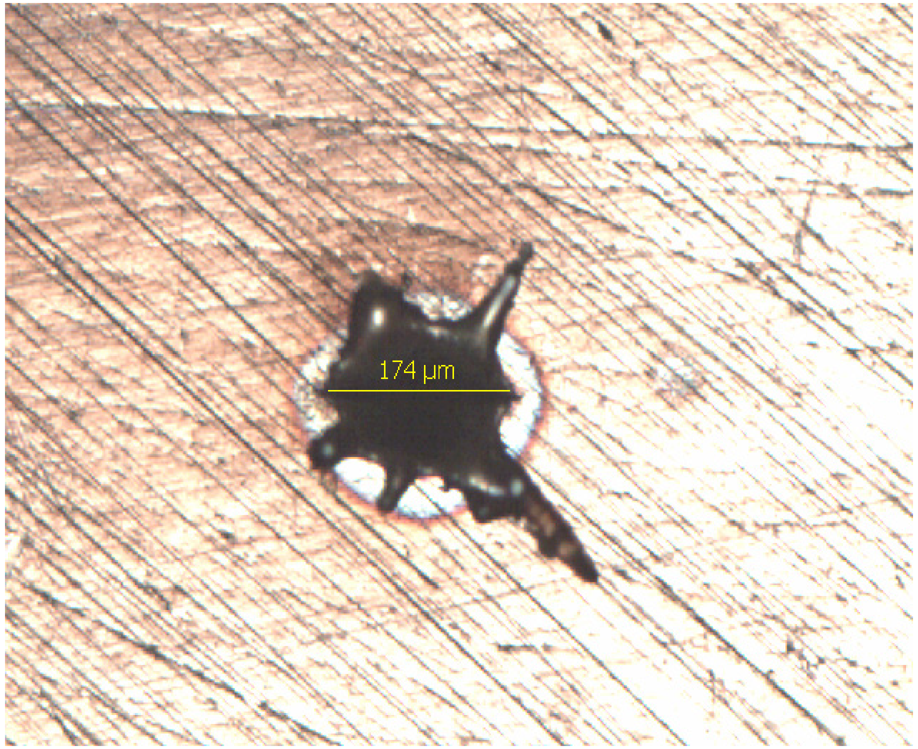


FXE instrument

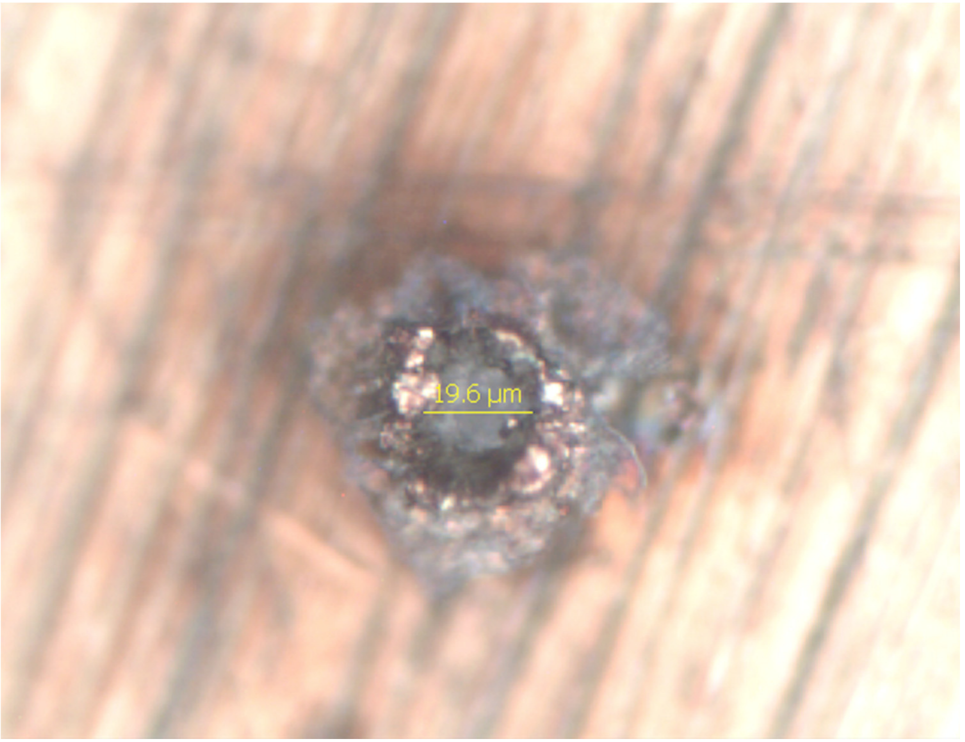
Experiments were done by DESY D3 Strahlensschutz, **FXE** team, X-ray Optics team and DESY accelerator team

Drilling through 0.5 mm Copper

Front side: 180 µm hole



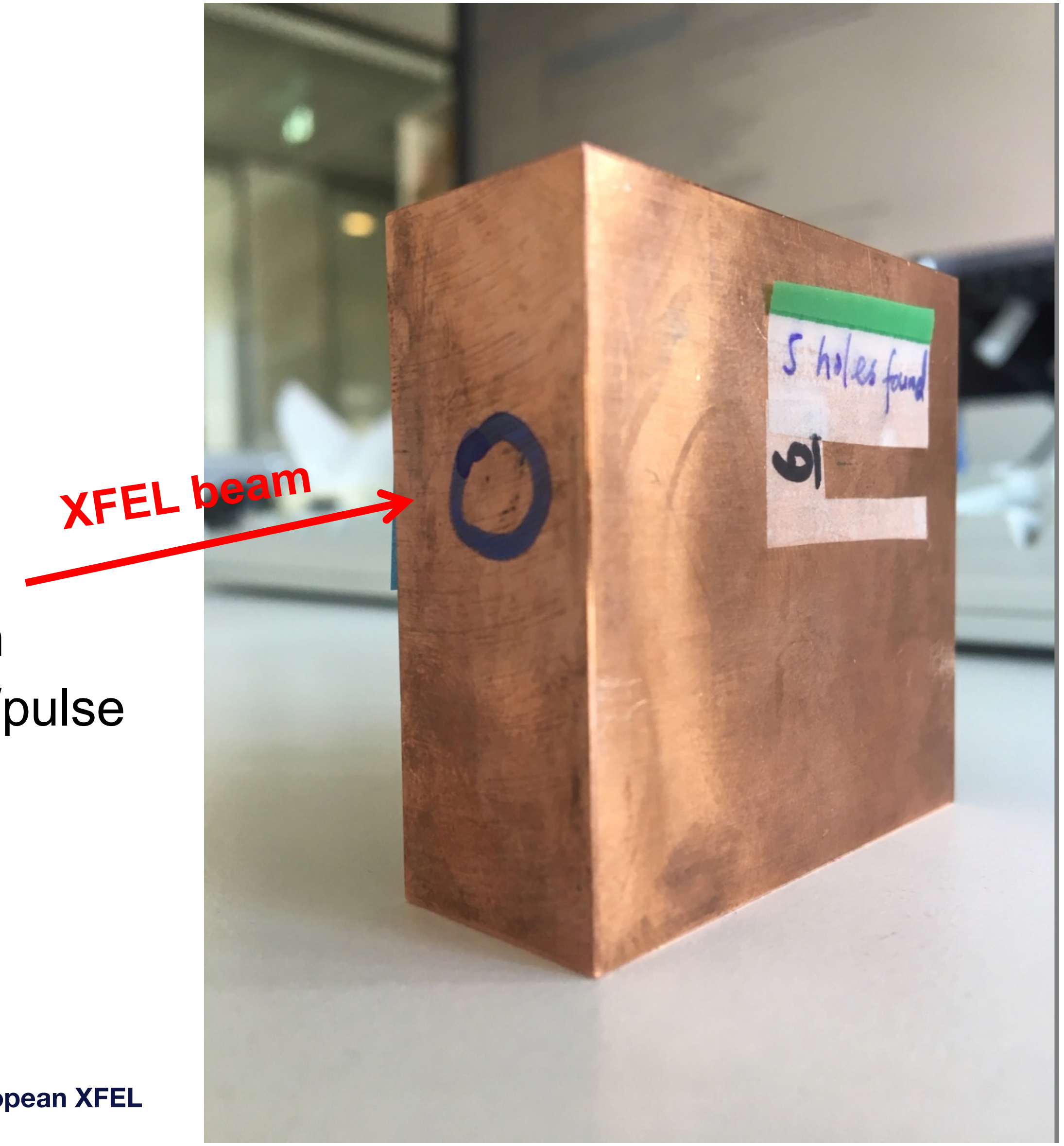
Back side: 20 µm hole



Drill through time: very short! (1 second or less)

All microscopic pictures were done by Fan Yang & X-ray optics group

Material test April 2018: Drill through 50 mm copper: 3 seconds!



Focus: 20 µm
9.3 keV, 1mJ/pulse

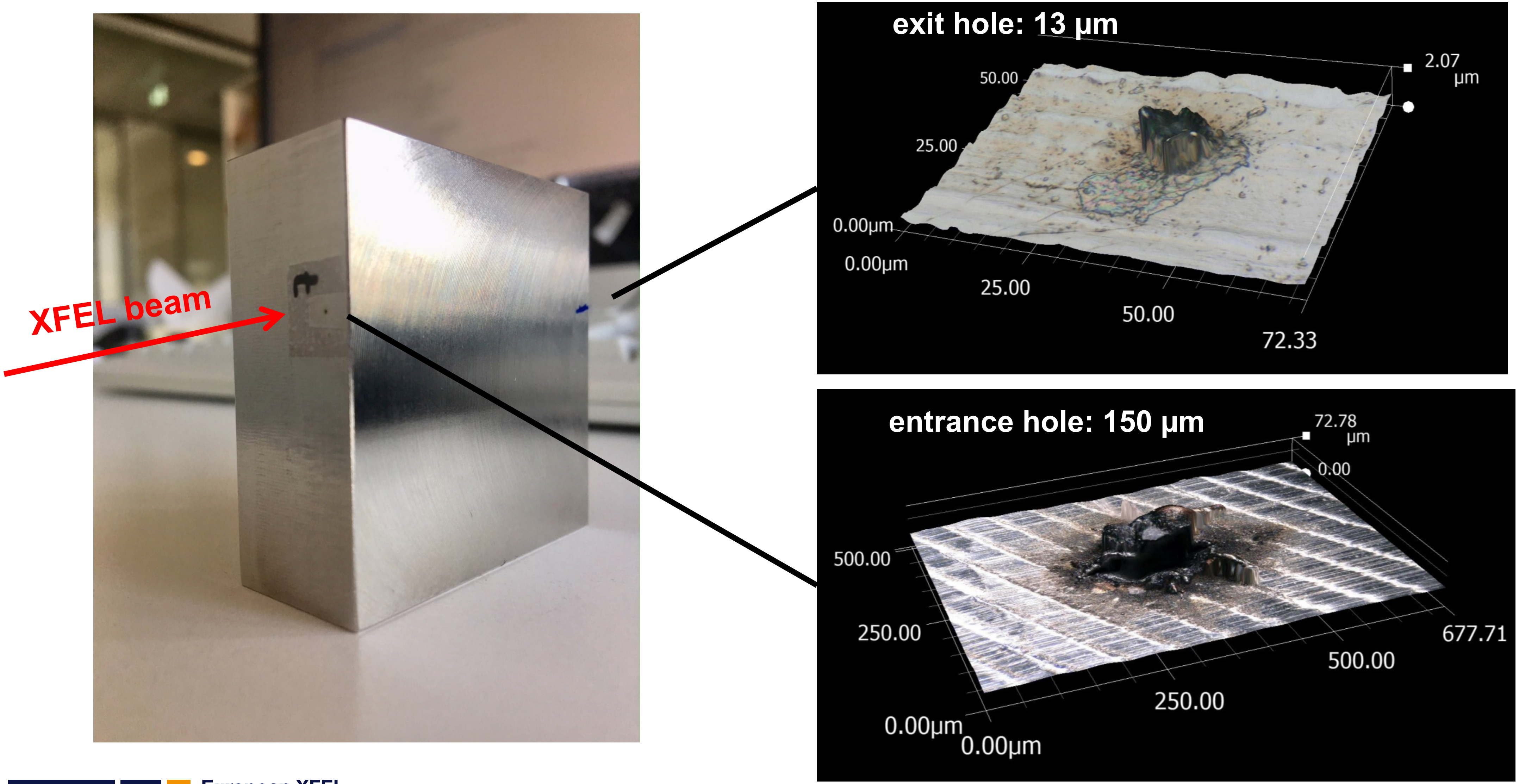
5cm/3sec = 16 mm/sec

max. ablation rate: 10-15 µm/pulse

Propagation speed
during pulse train:
15 µm/1µs= 15 m/s = 54 km/h

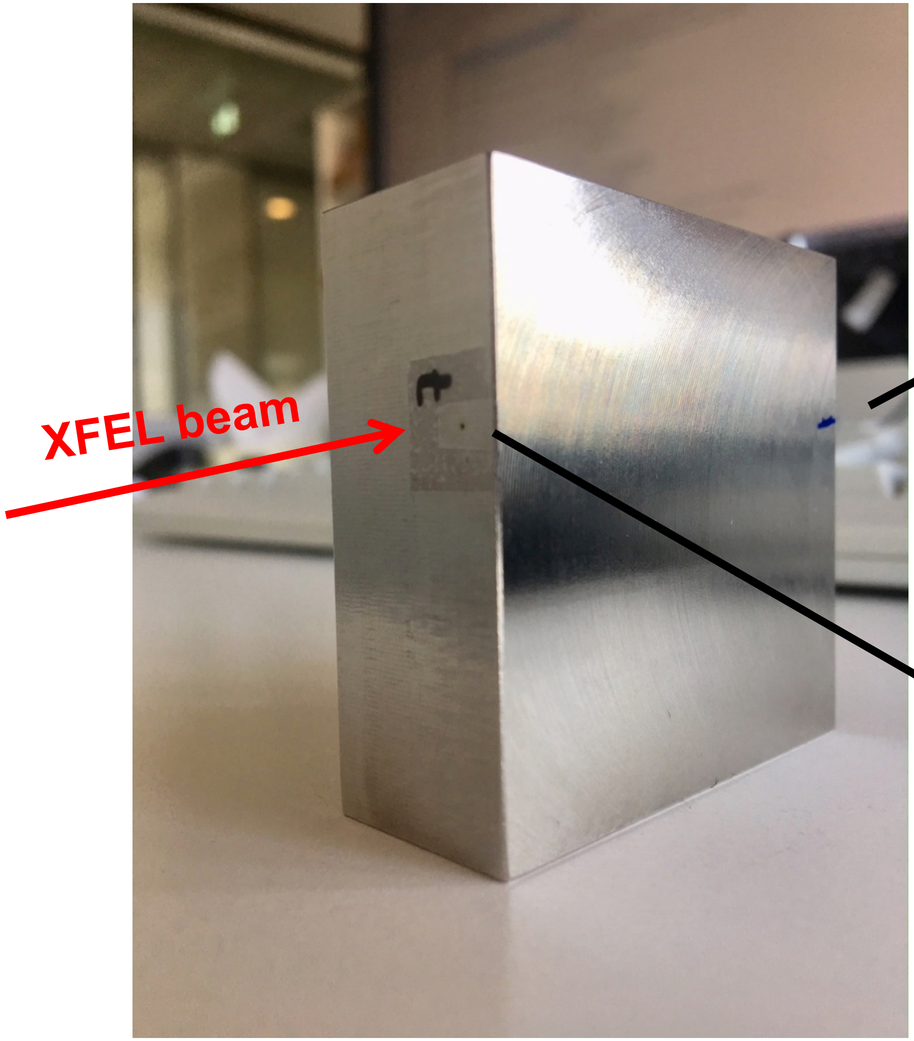
Up to 150 mm drill-through copper slab was observed
200 mm thickness with reduced transmission

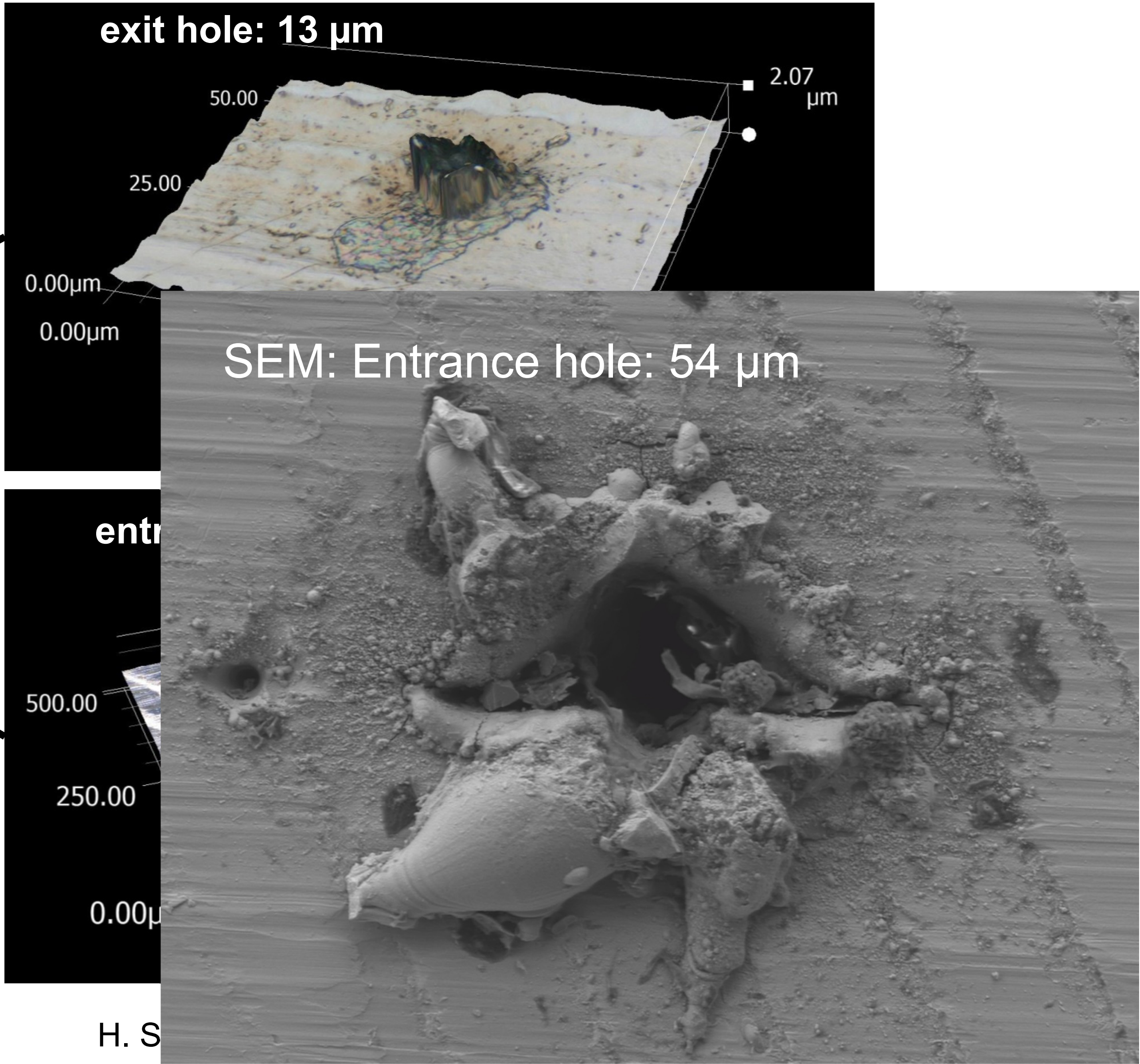
Drilling with XFEL beam through 50 mm of steel in 26 seconds



H. Sinn, A. Leuschner, F. Yang et al., European XFEL & DESY 2018

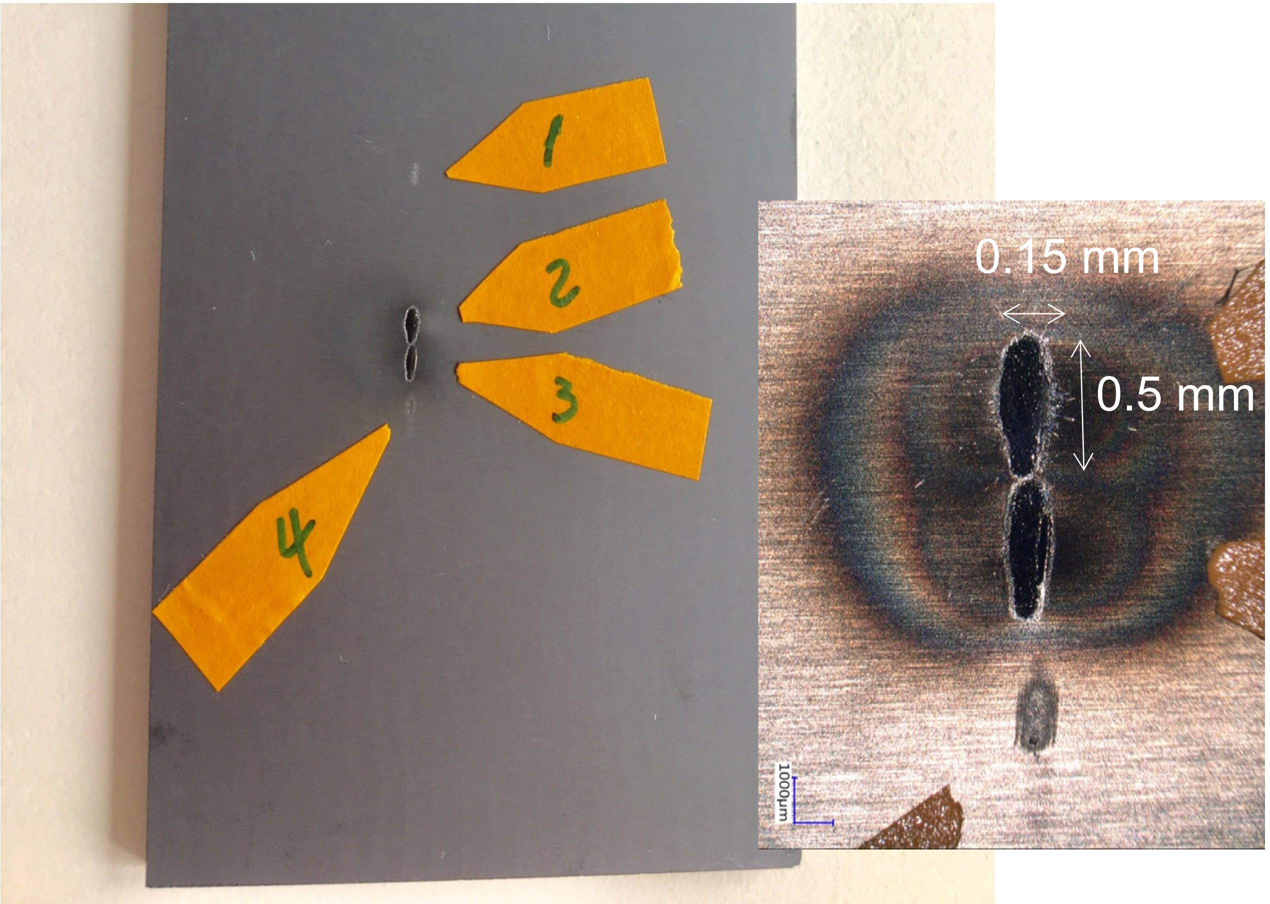
Drilling with XFEL beam through 50 mm of steel in 26 seconds



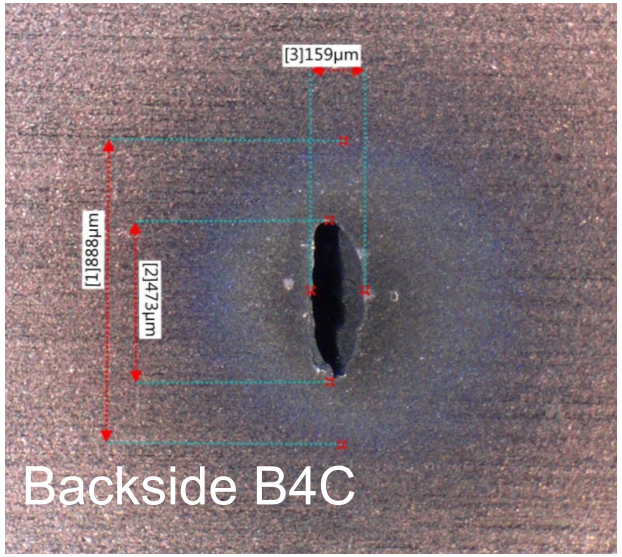


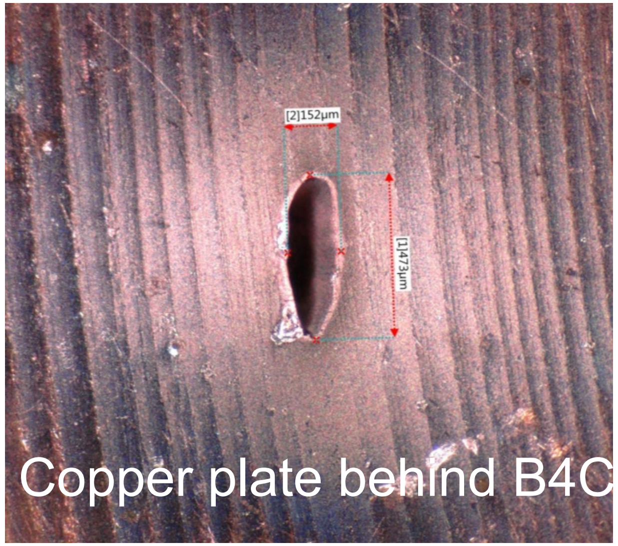
H. S

August 2018: Drilling tests at SASE3 (700 eV, 300 x 4 mJx 10 Hz = 12 W, $Q_{max} \geq Q_{abl}$)

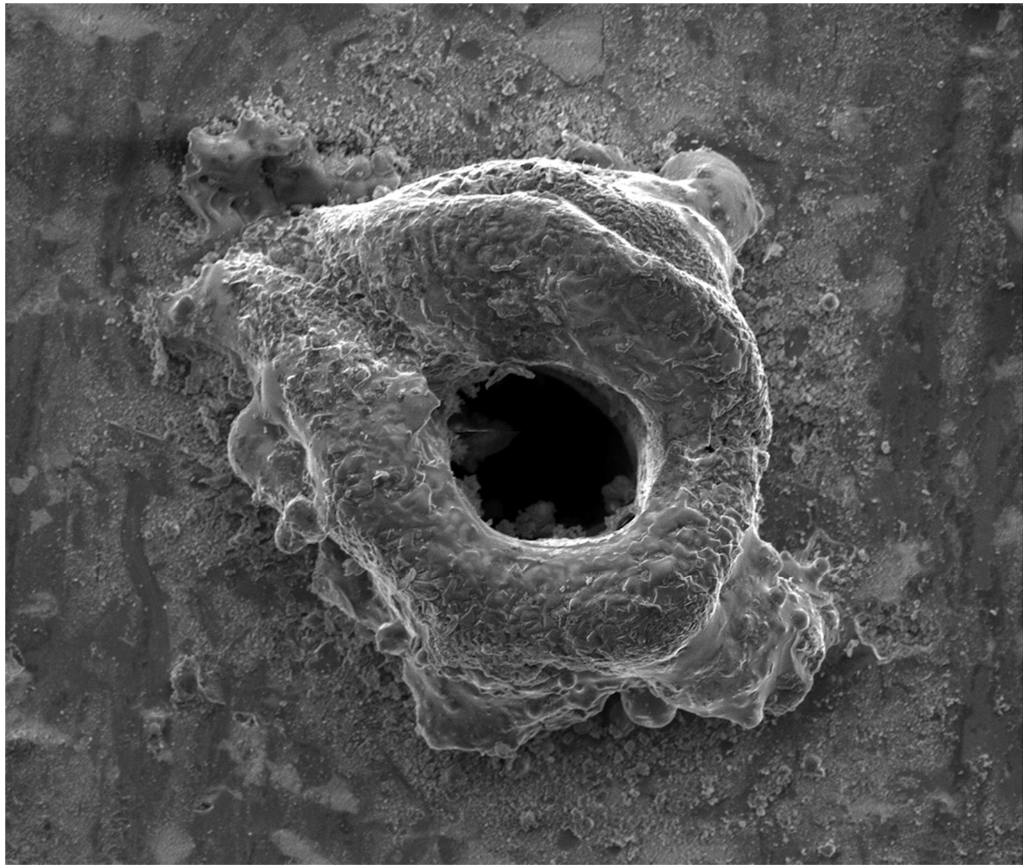


Frontside of 4 mm thick B4C, 10-20 min exposure



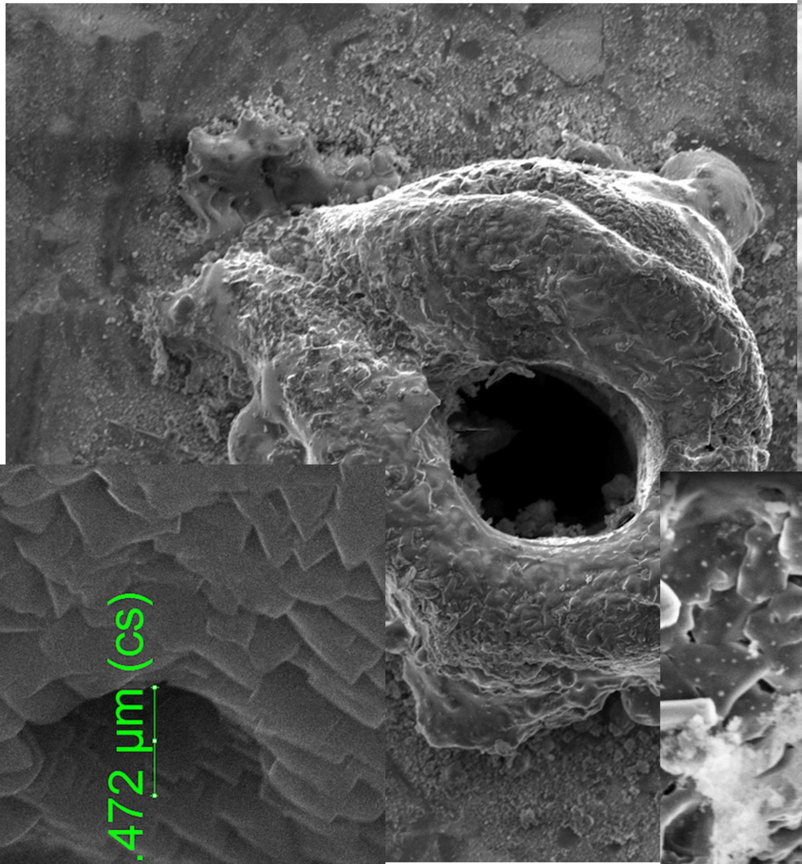


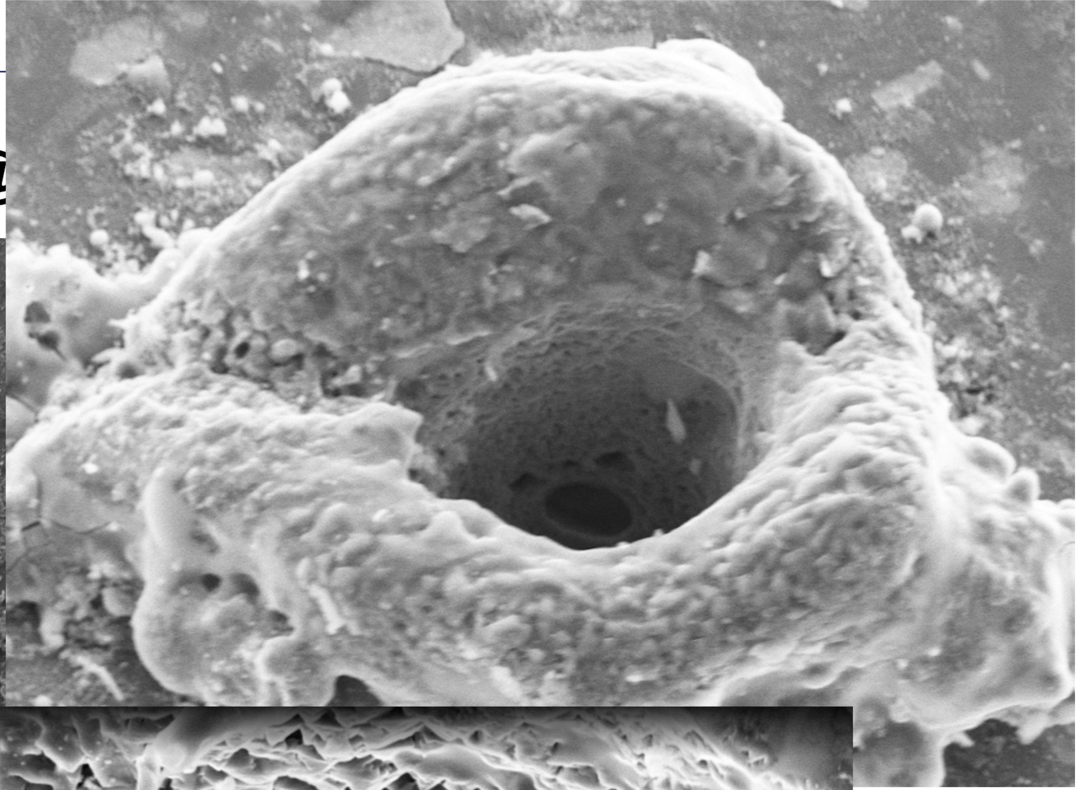
SEM pictures of B4C hole with 20 µm beam @ 9 keV

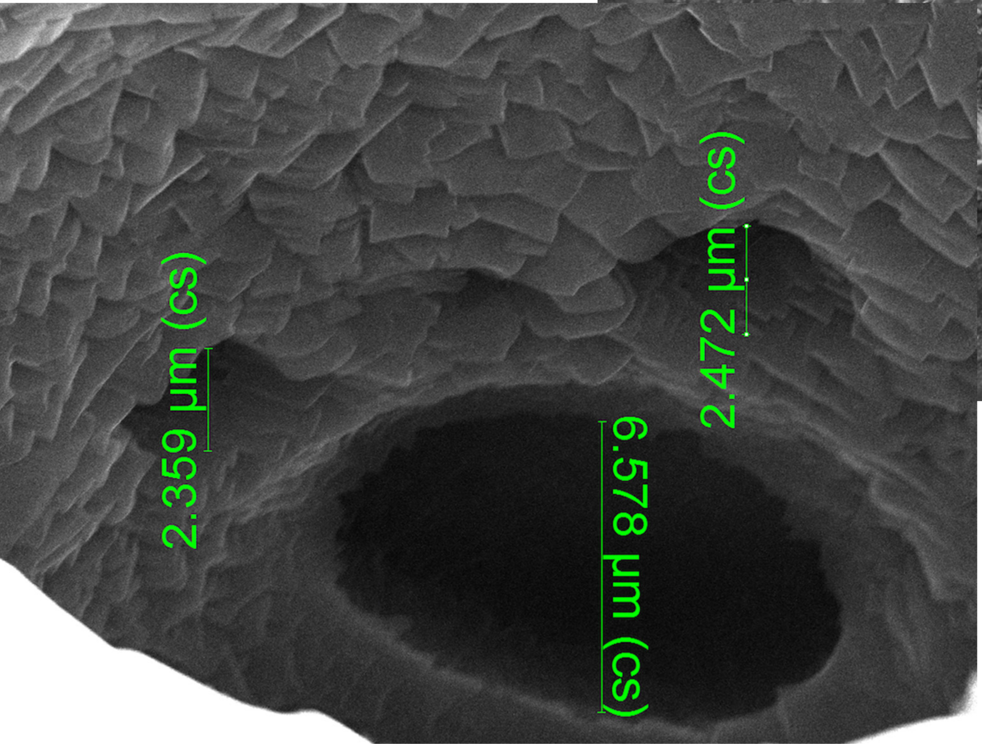


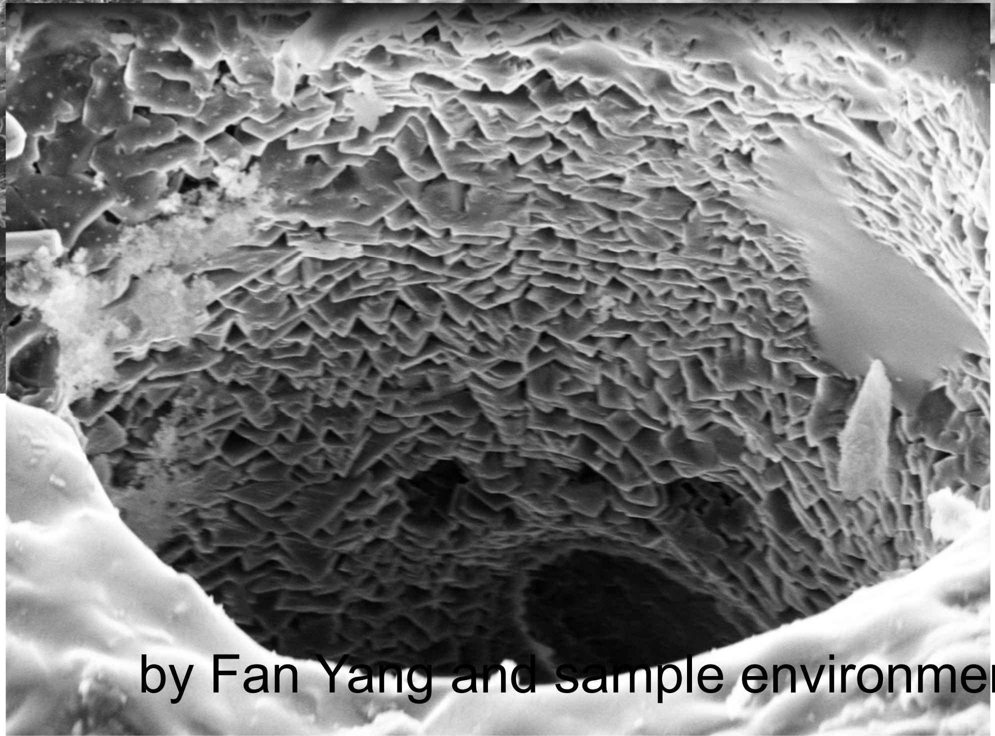
by Fan Yang and sample environment group

SEM pictures of B4C hole with 20 μm beam @



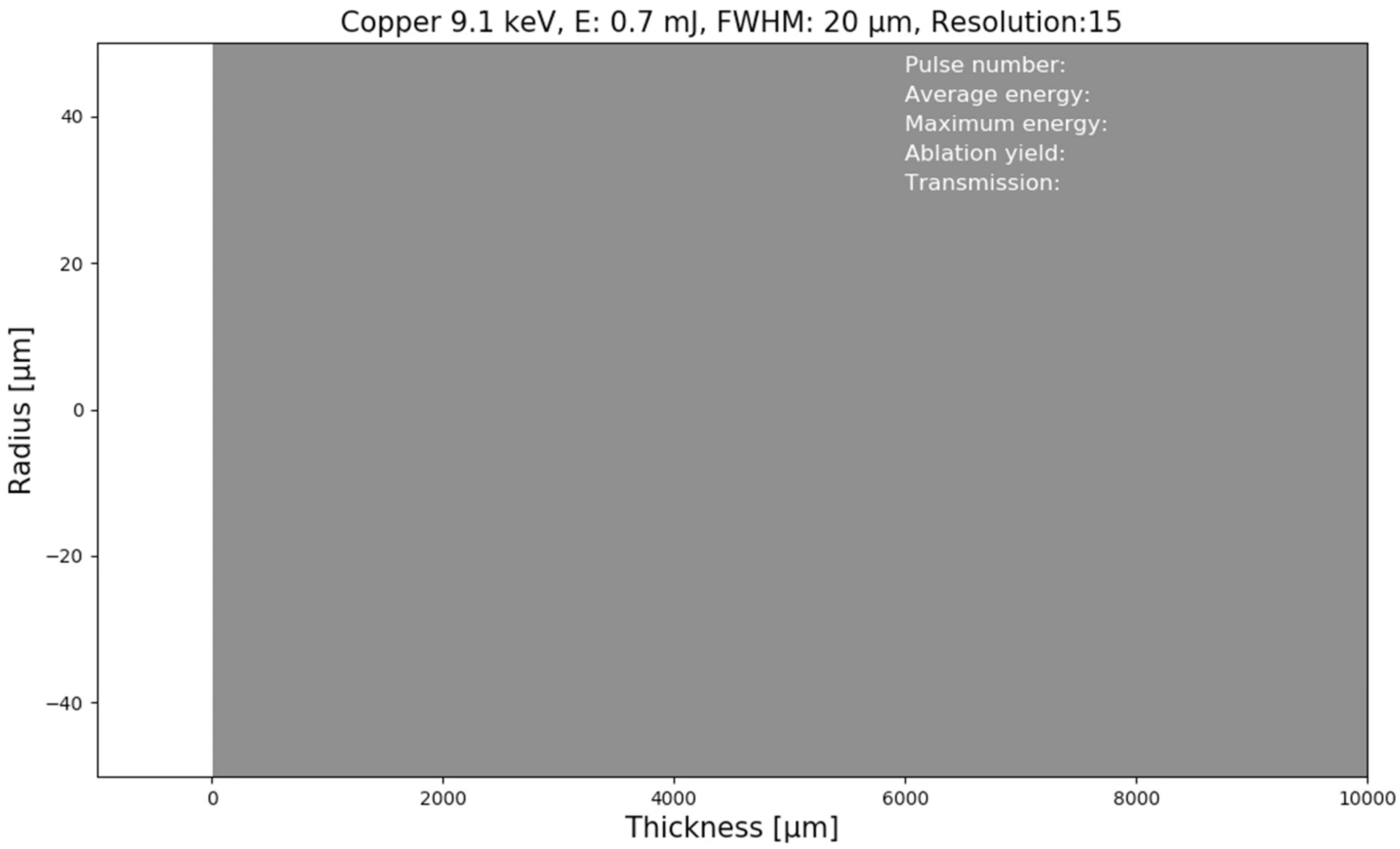






by Fan Yang and sample environment group

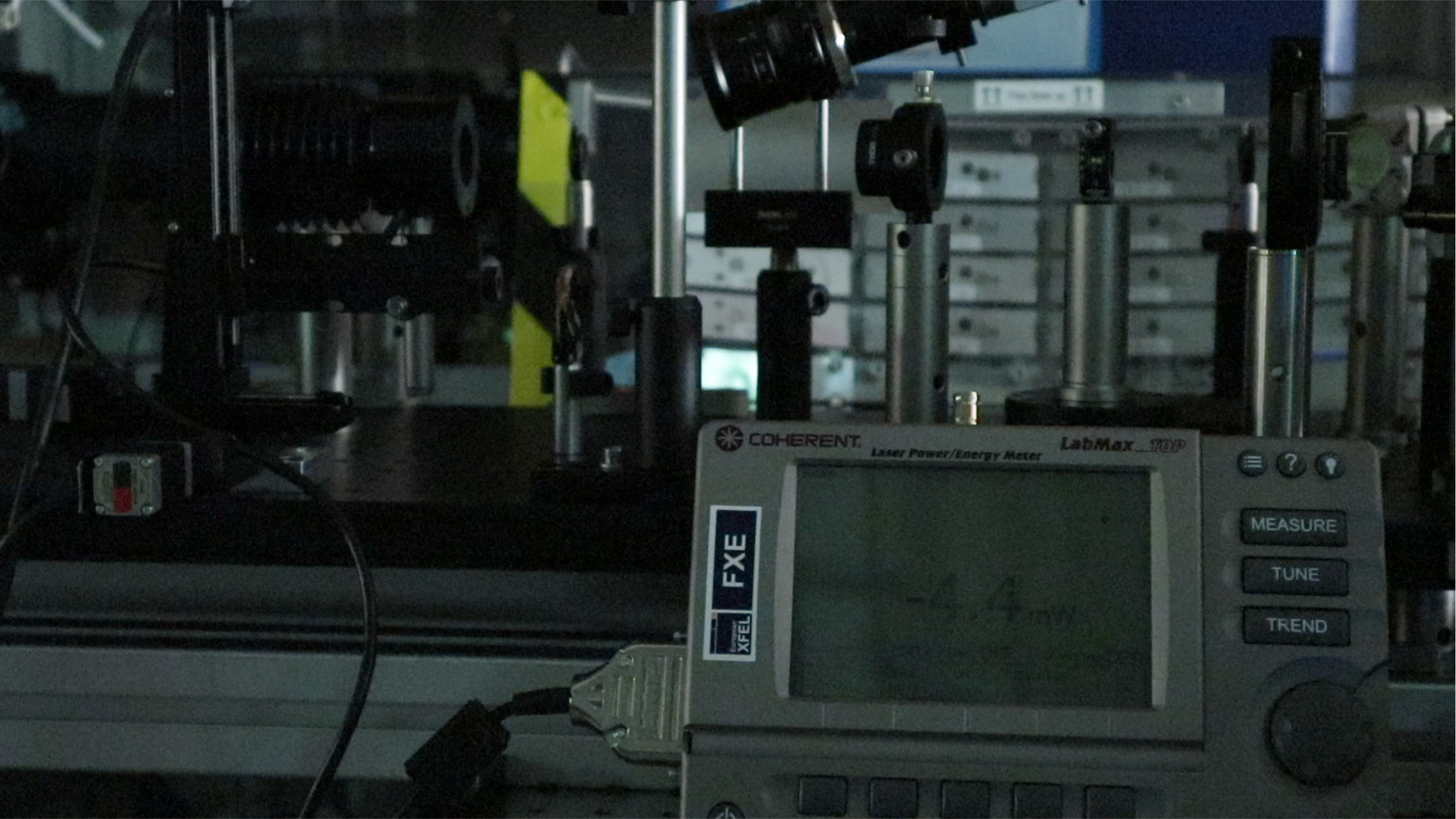
Movie of drilling process



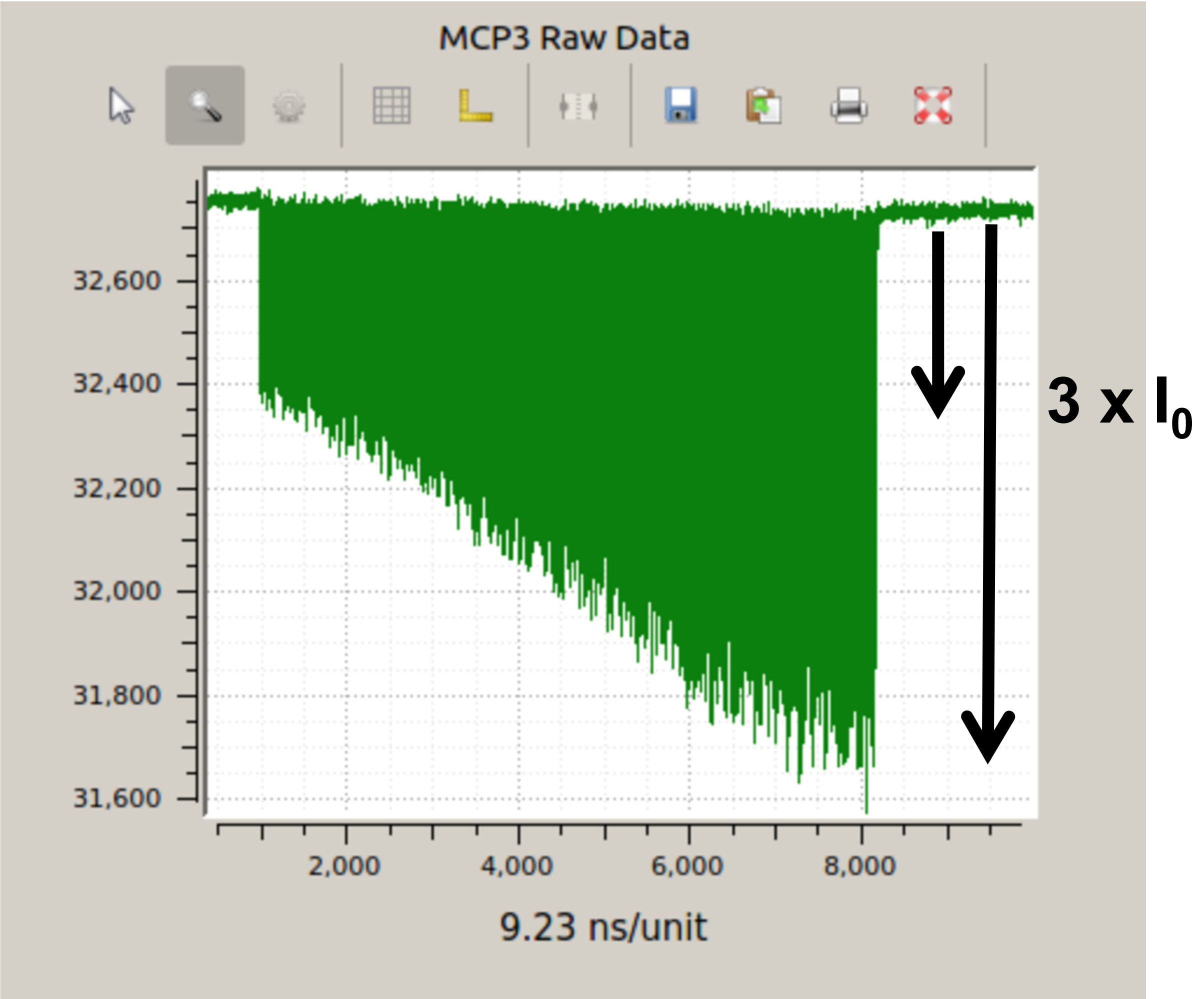
Some more drilling measurements

Material	Steel		Copper			Lead	B4C		Concrete	Graphite	Tungsten
Pulse energy *(mJ)*	1.0	0.7	0.7	0.7	1.0	1.0	0.7	1.0	1.0	1.0	1.0
Repetition rate *(MHz)*	10 Hz	1.1	10 Hz	1.1	4.5	4.5	1.1	4.5	4.5	4.5	4.5
Pulses/train	1	156	1	158	60	300	158	300	300	300	300
Sample thickness *(mm)*	9	50	10	50	10	2	12	12	38	20	2.5
Drill-through time *(seconds)*	54	26	56	3	11	<1	--	214	>800	>925	260
Empirical ablation per pulse (*μm*)	17	1.2	15	10	1.5	>0.6	--	0.02	< 0.01	< 0.007	0.003
Maximum ablation per pulse from eq. 6	21	19	15	15	16	28	0	0	200	0	15
Maximum deposited energy (eV/atom)	28	20	28	28	40	77	0.04	0.05	3.6	0.07	51
Ablation threshold (eV/atom)	0.73	0.73	0.75	0.75	0.75	0.44	0.43	0.43	0.44	0.44	1.4

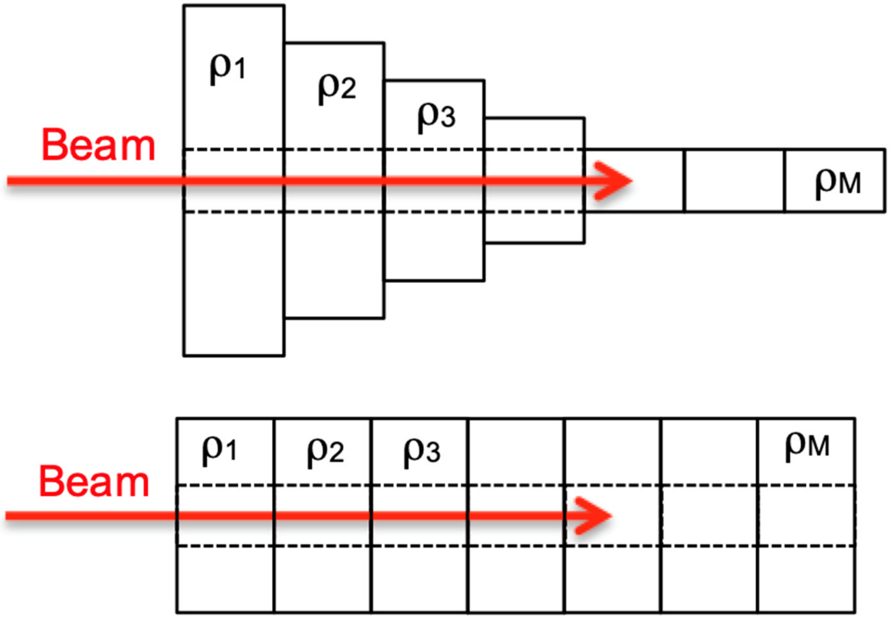
Transmission of hard X-ray through air


COHERENT
Laser Power/Energy Meter
FXE
European XFEL
MEASURE
TUNE
TREND

Can gas stop the beam? Burn through test at gas attenuator (SASE3)



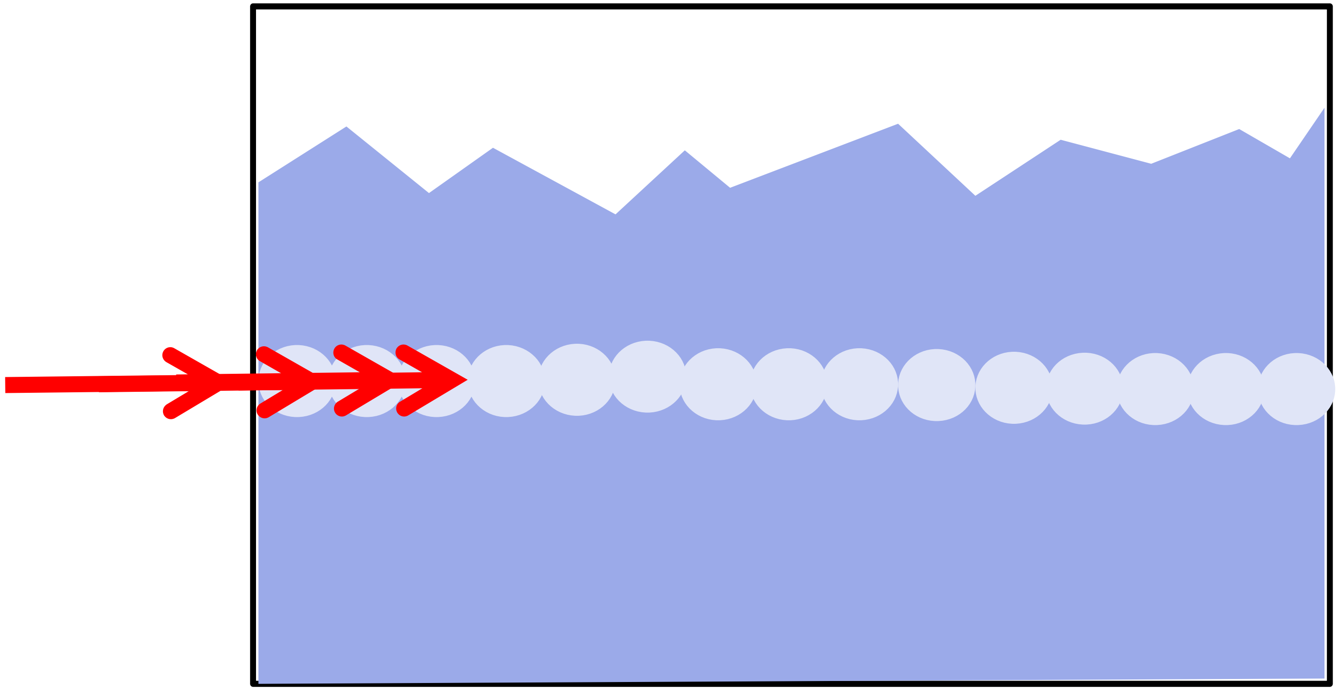
300 pulses of 4 mJ
0.5 mbar N2, 700 eV



Calculated effect for above situation: 15 x higher transmission at end of pulse train

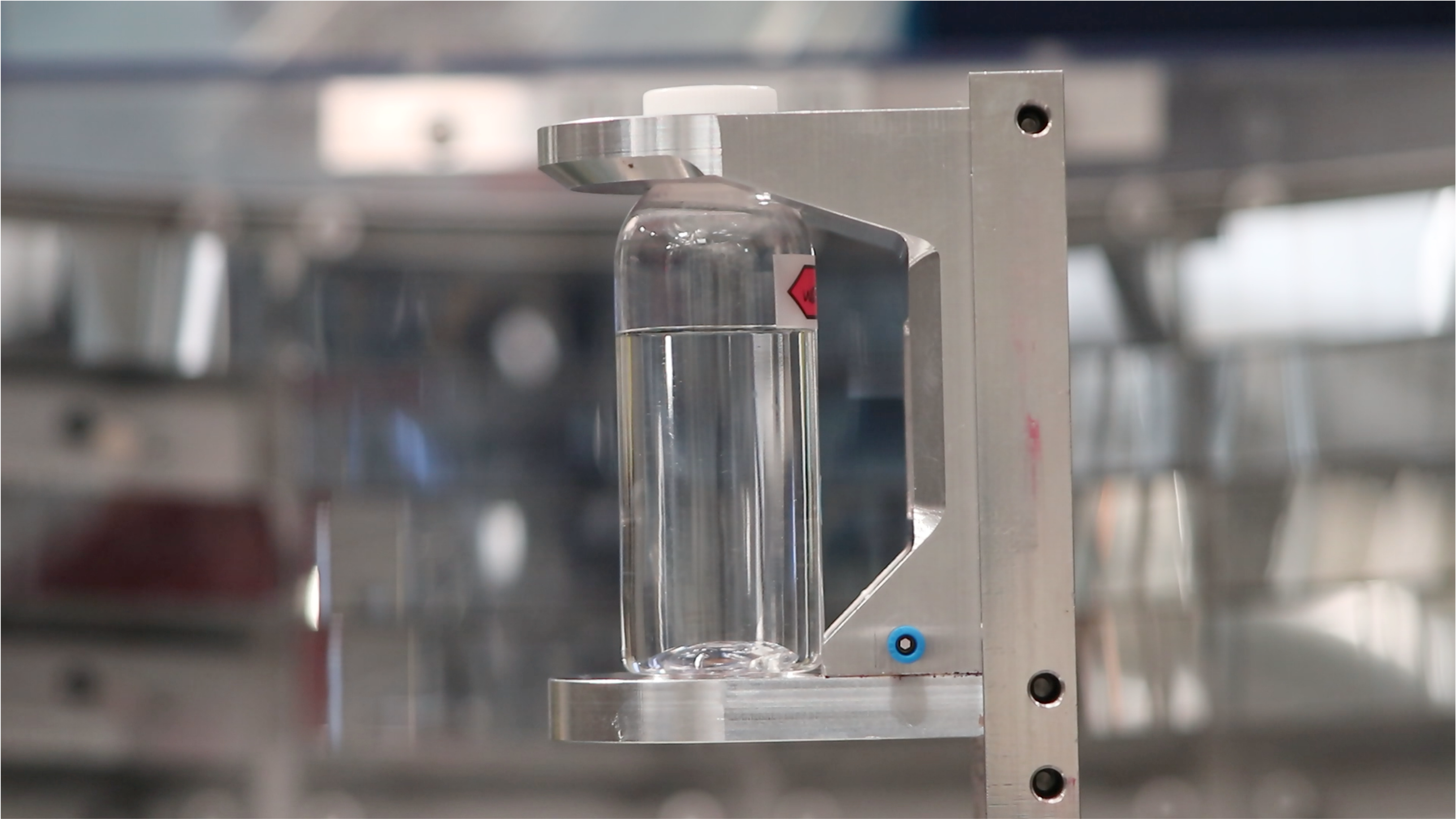
data by Jan Grünert

Can liquid stop the beam?



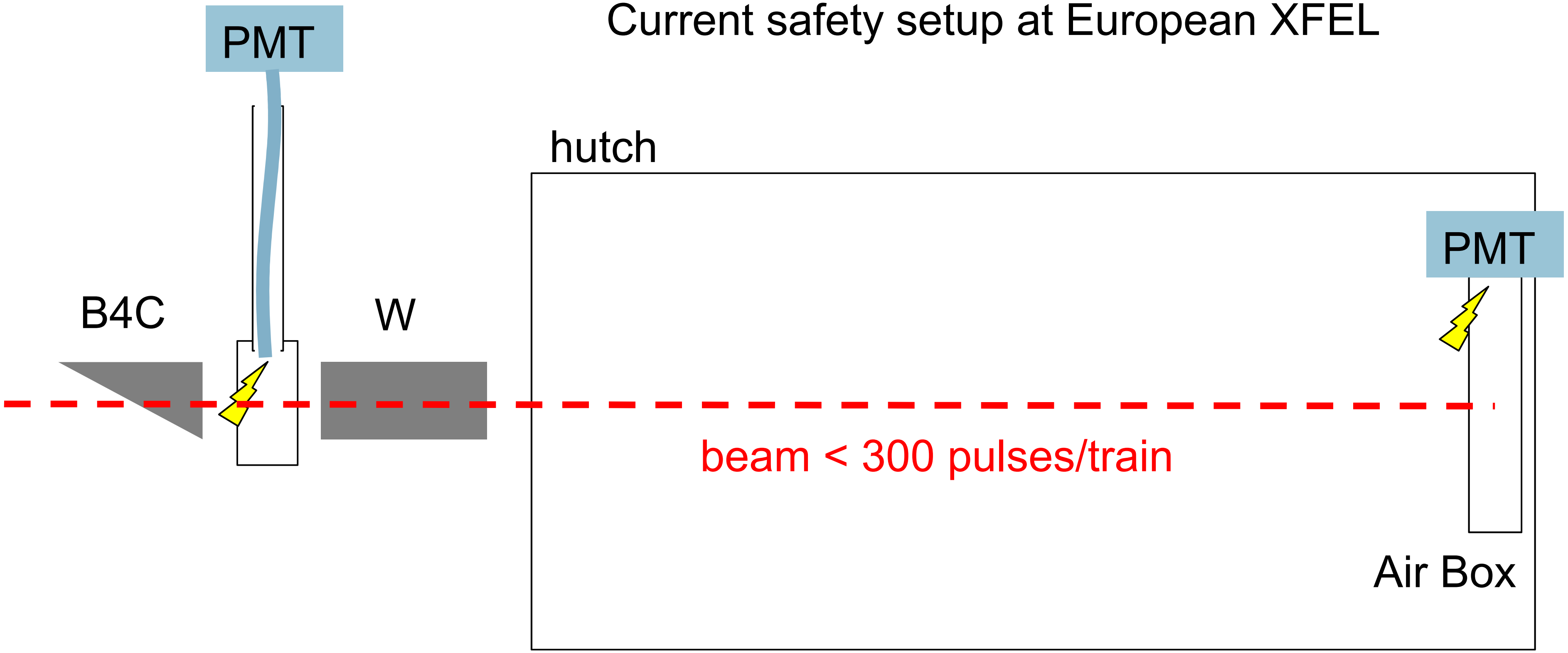
‘Bubble train’

Absorption length water: 1.5 mm at 9 keV



Conclusion for safety: Beam < 20 µm cannot be stopped at EuXFEL

Current safety setup at European XFEL



Upgrade to diamond shutters in WS 19/20 will be able to stop beams > 40 µm

Take home messages

- The photon beam goes (mostly) straight
- X-ray reflection angles are < 1°
- Therefore mirrors are typically long (1 m)
- Stopping a beam of < 40 µm size (at EUXFEL) is a challenge!
  (active components in beam shutters + beam stops required)

Thank you for your attention!