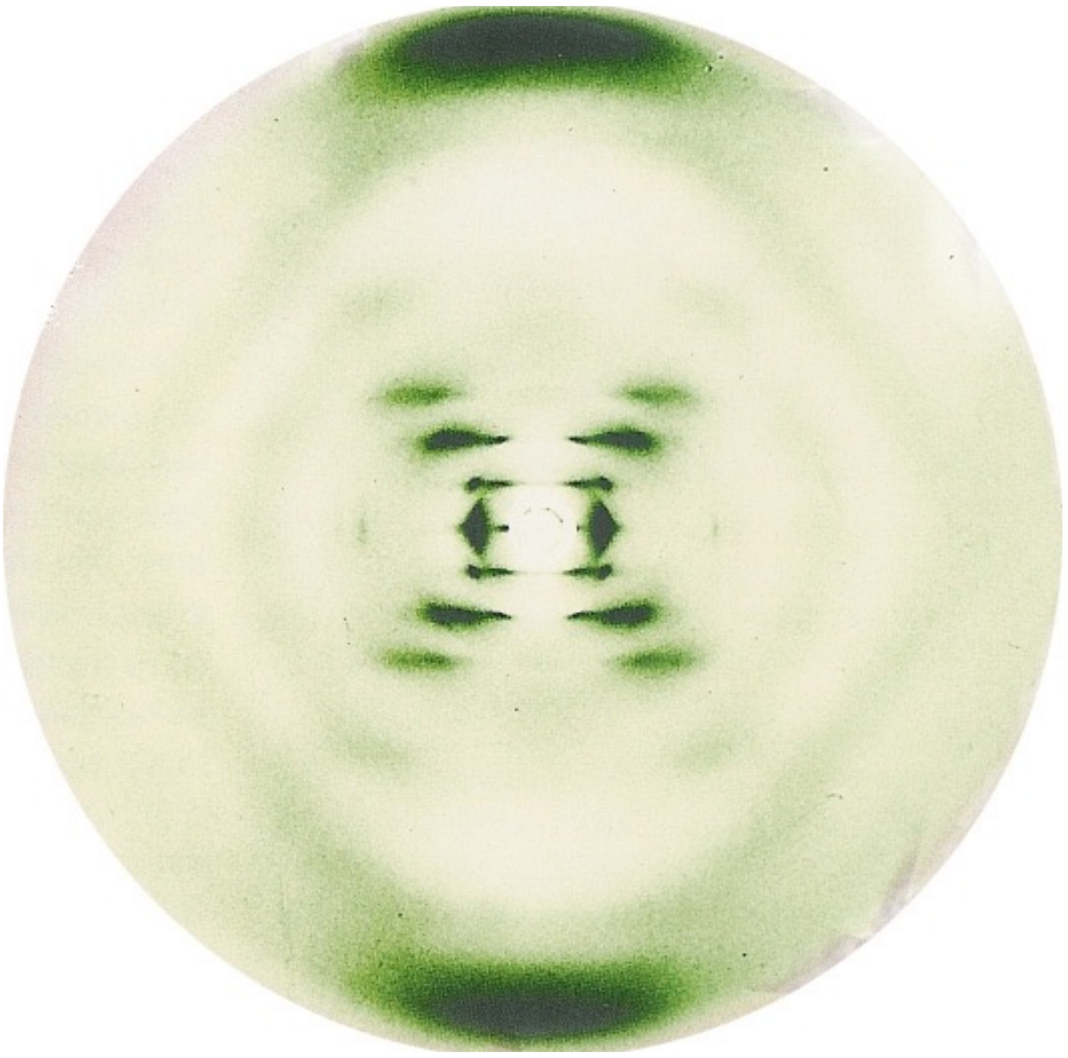
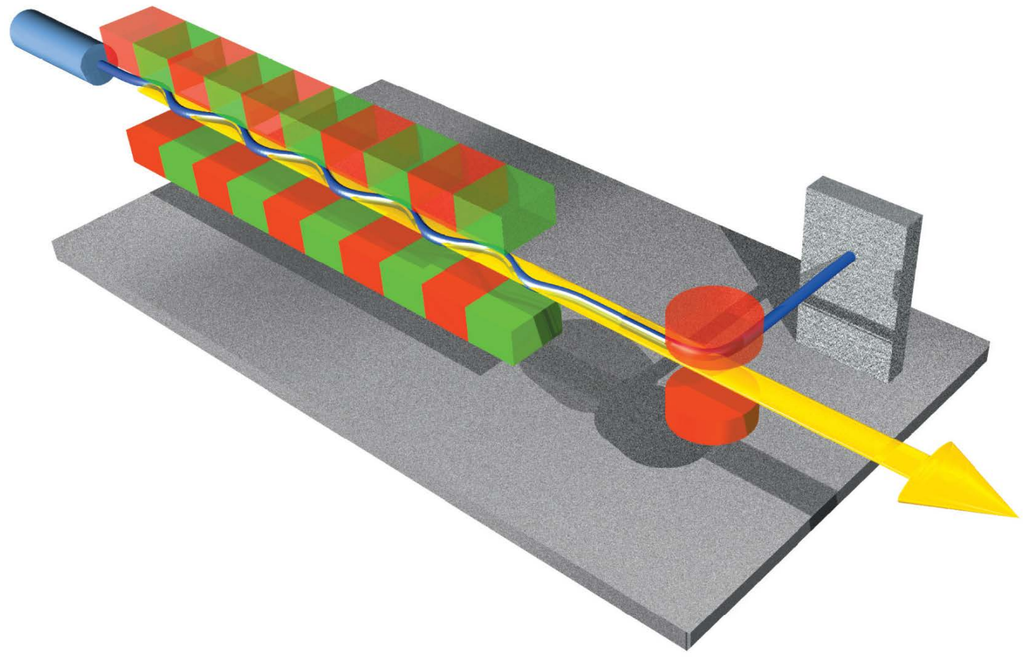
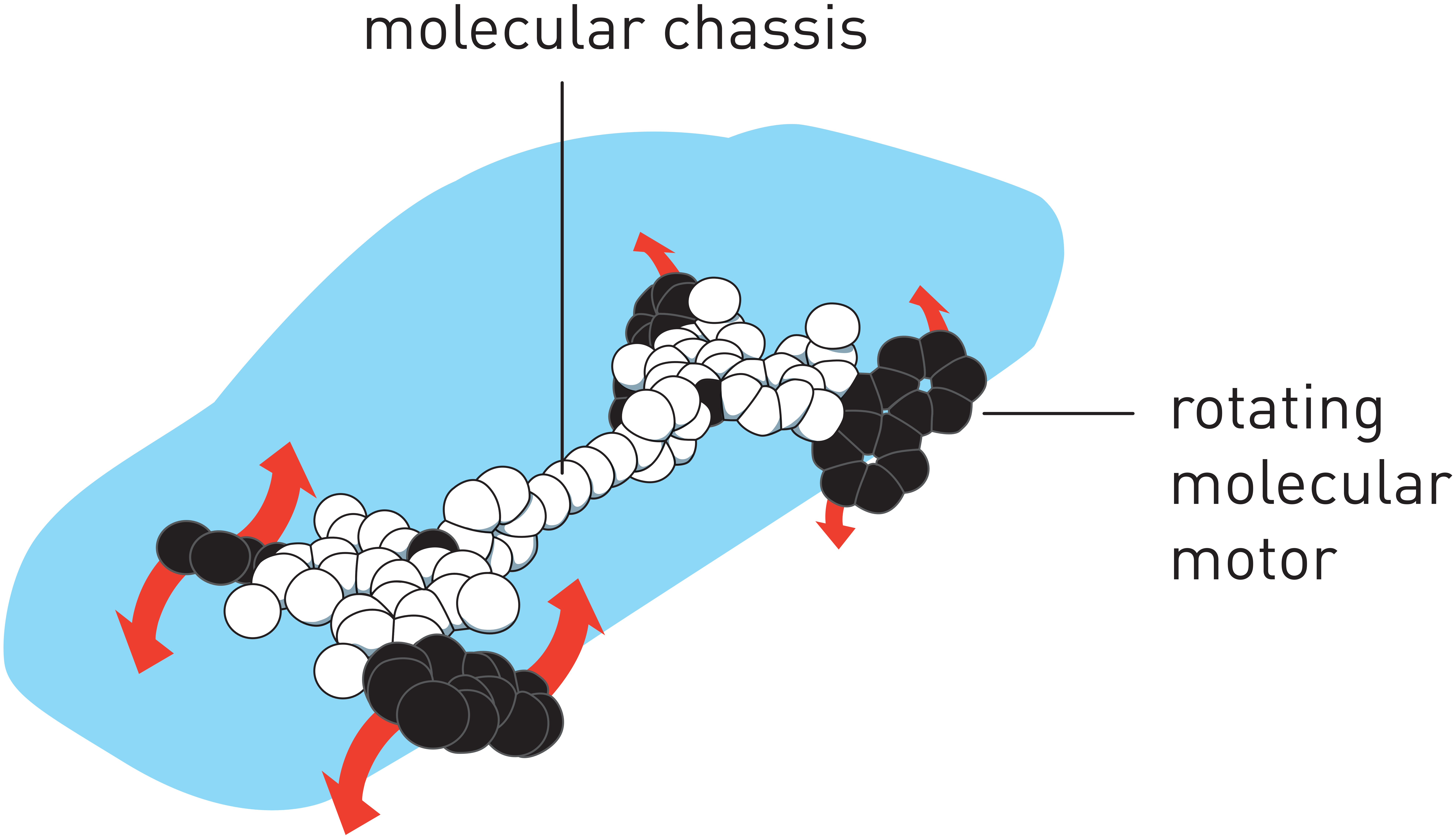
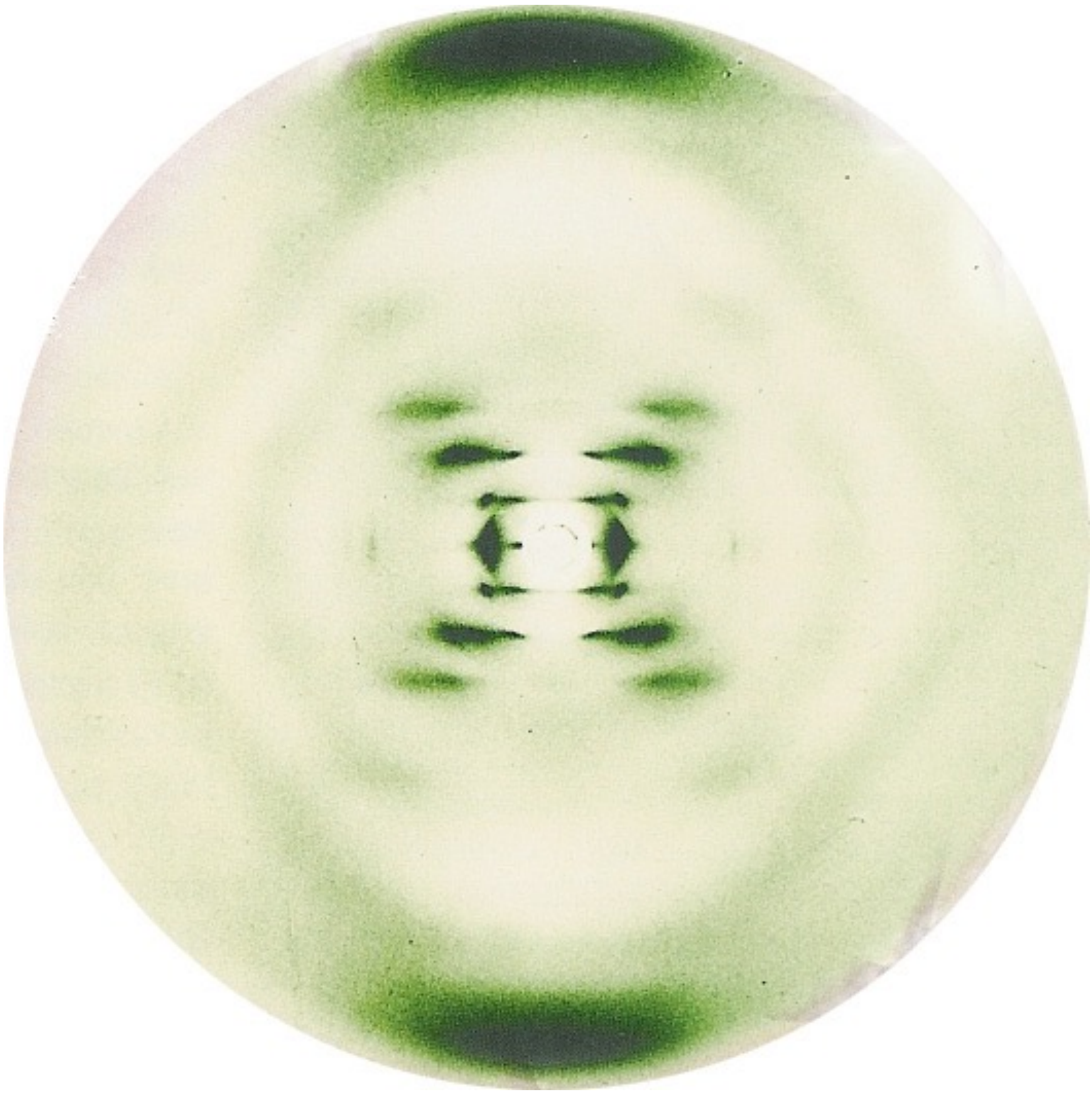


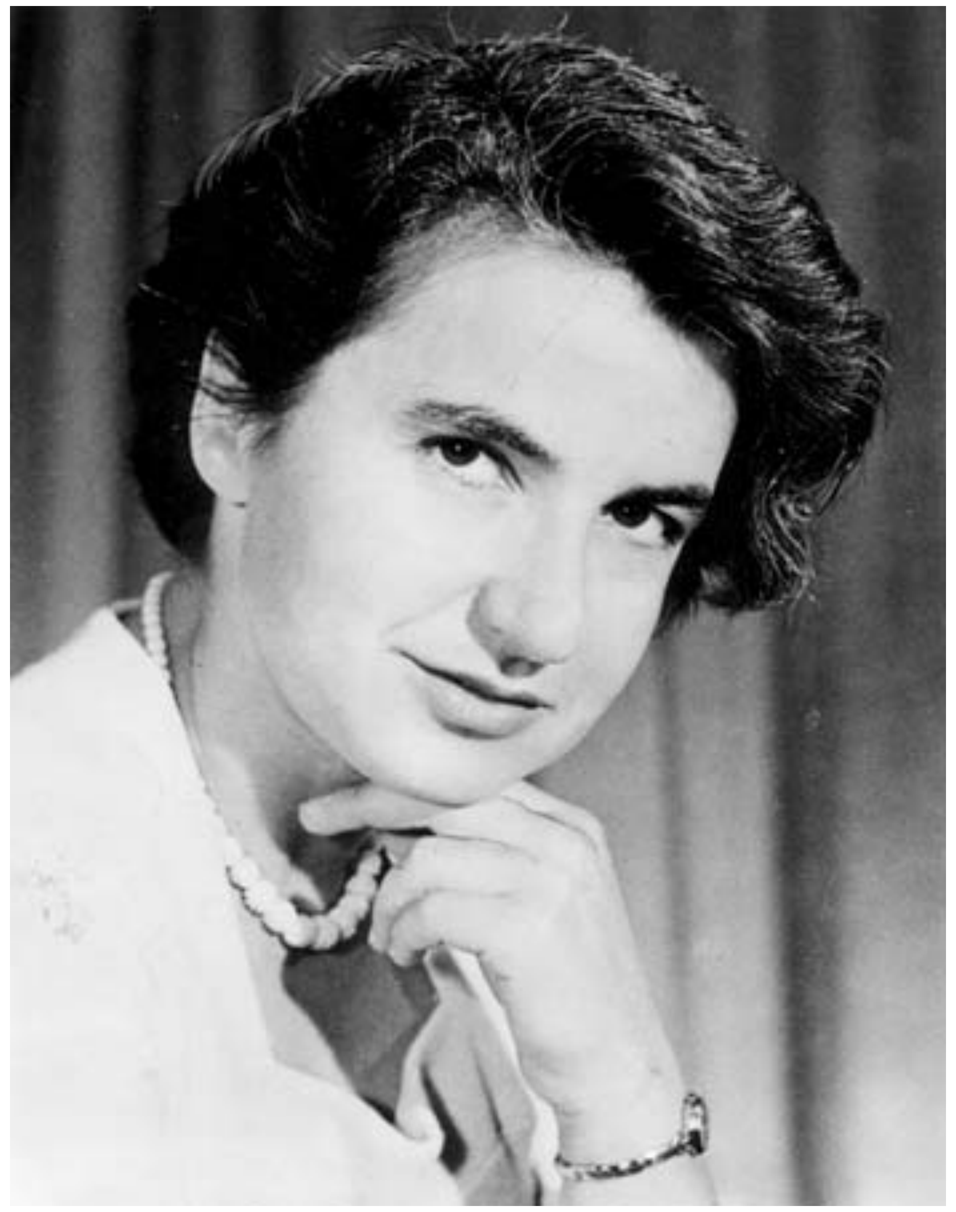


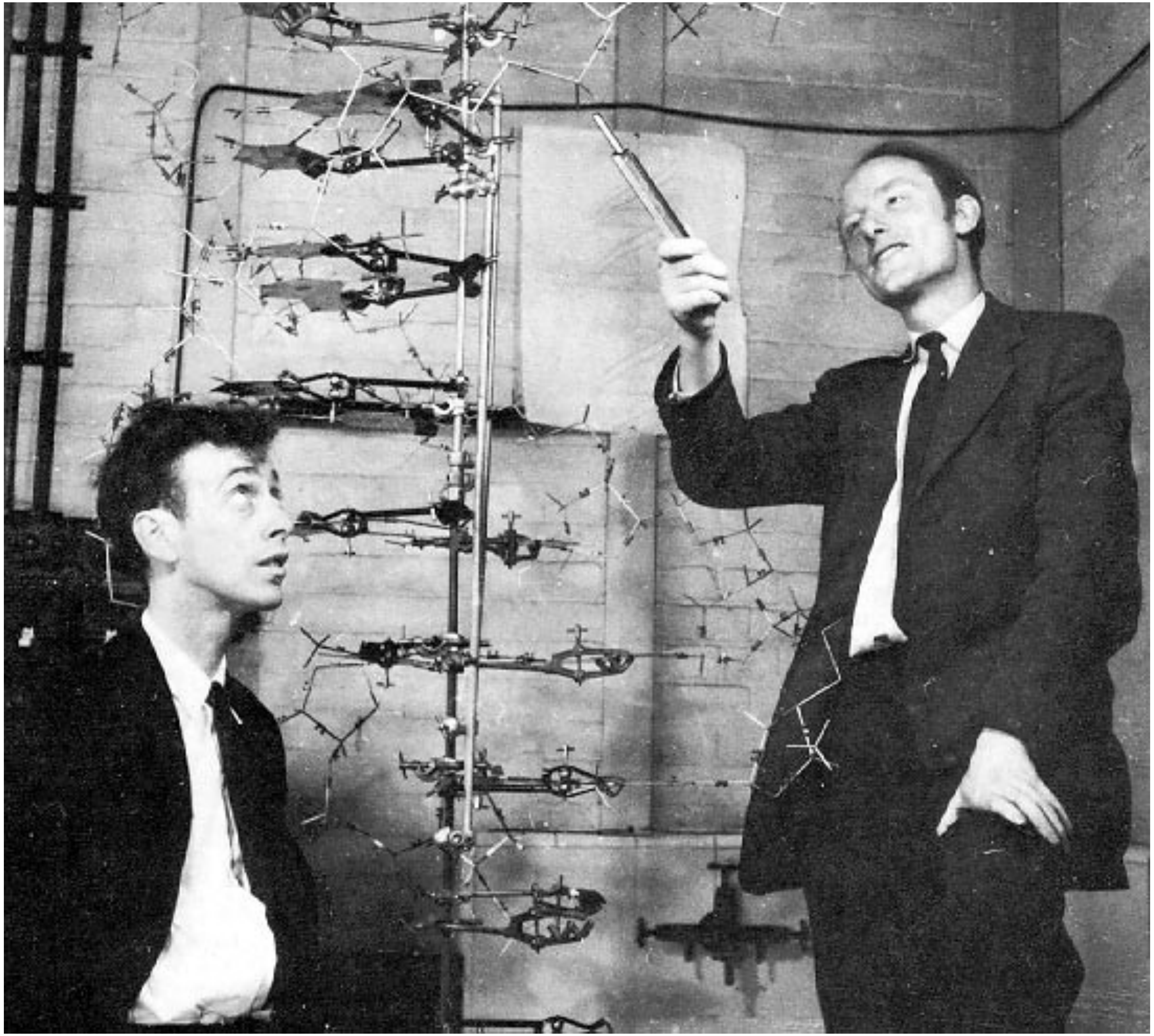
Synchrotron Light Machines and FELs II

Rasmus Ischebeck, Paul Scherrer Institut

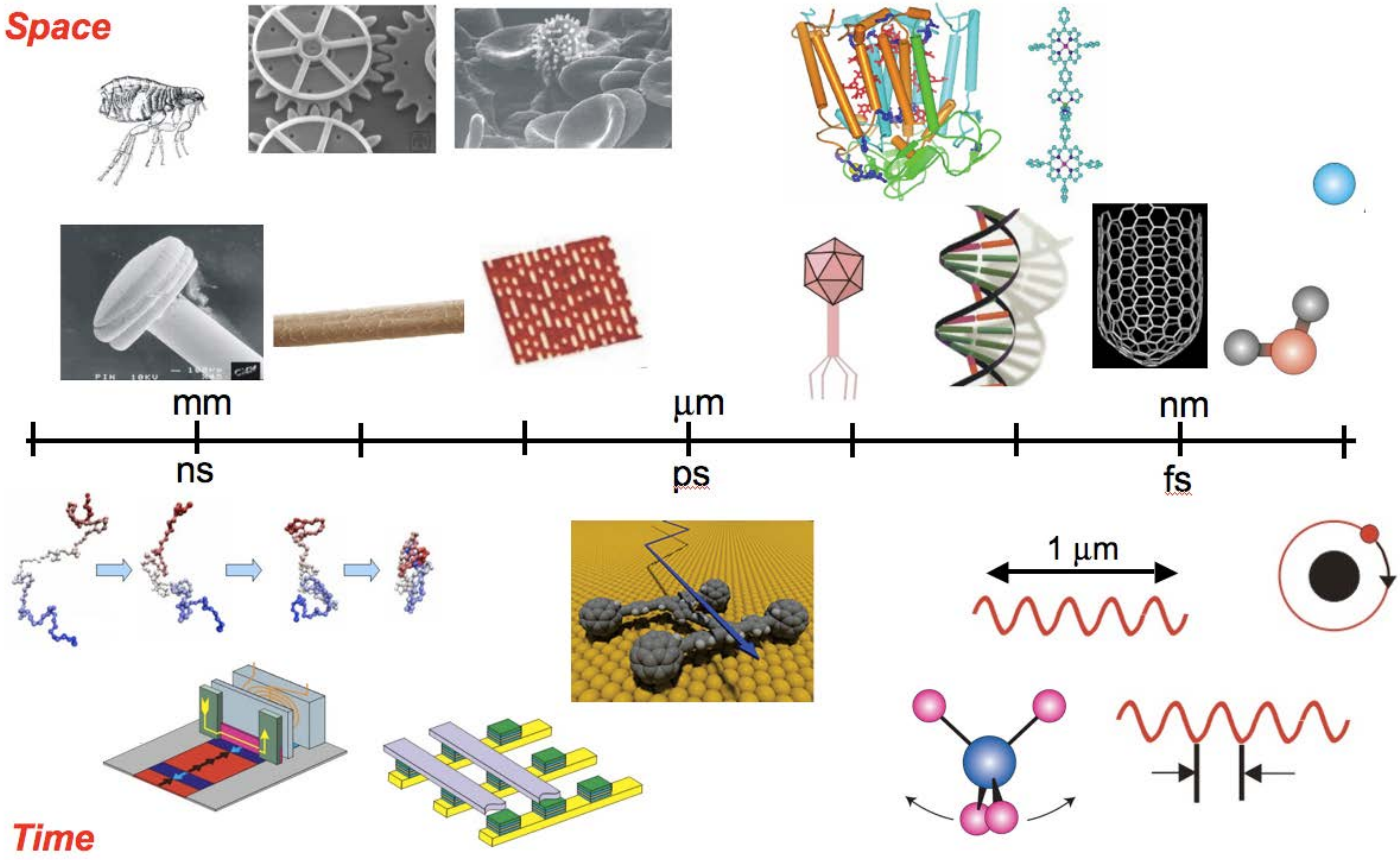

molecular chassis
rotating molecular motor

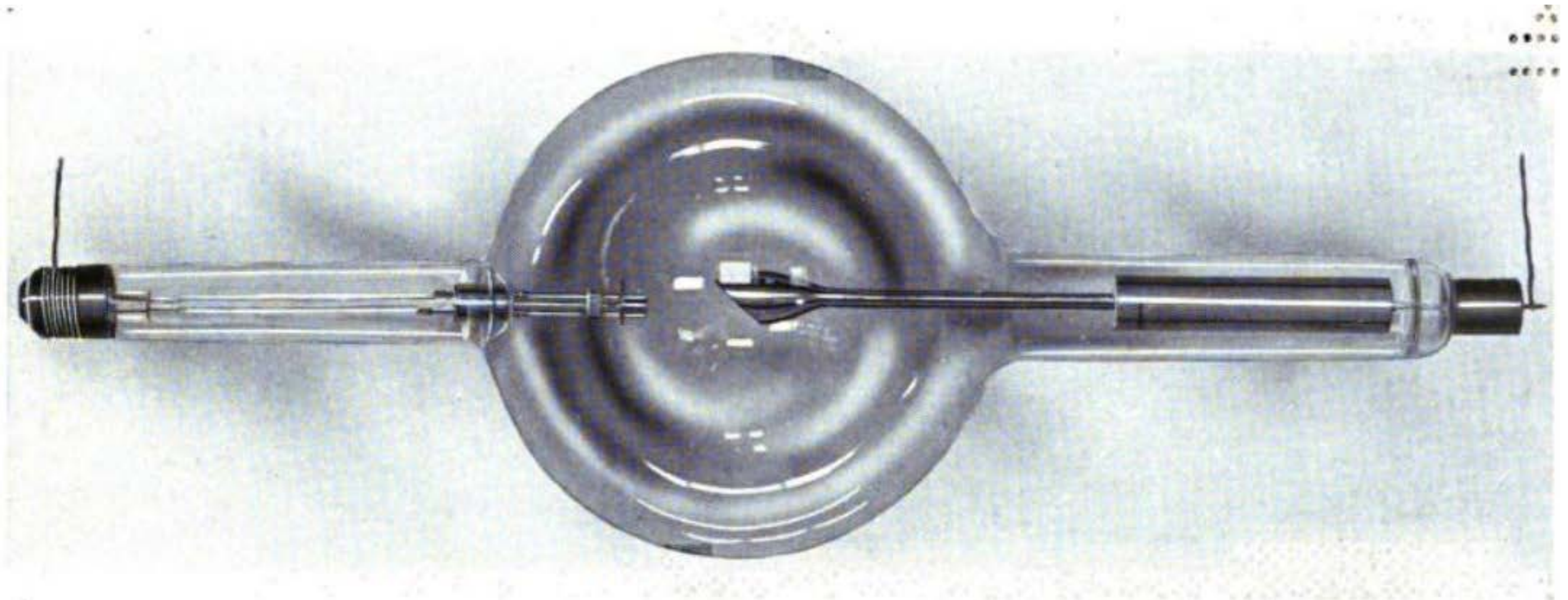


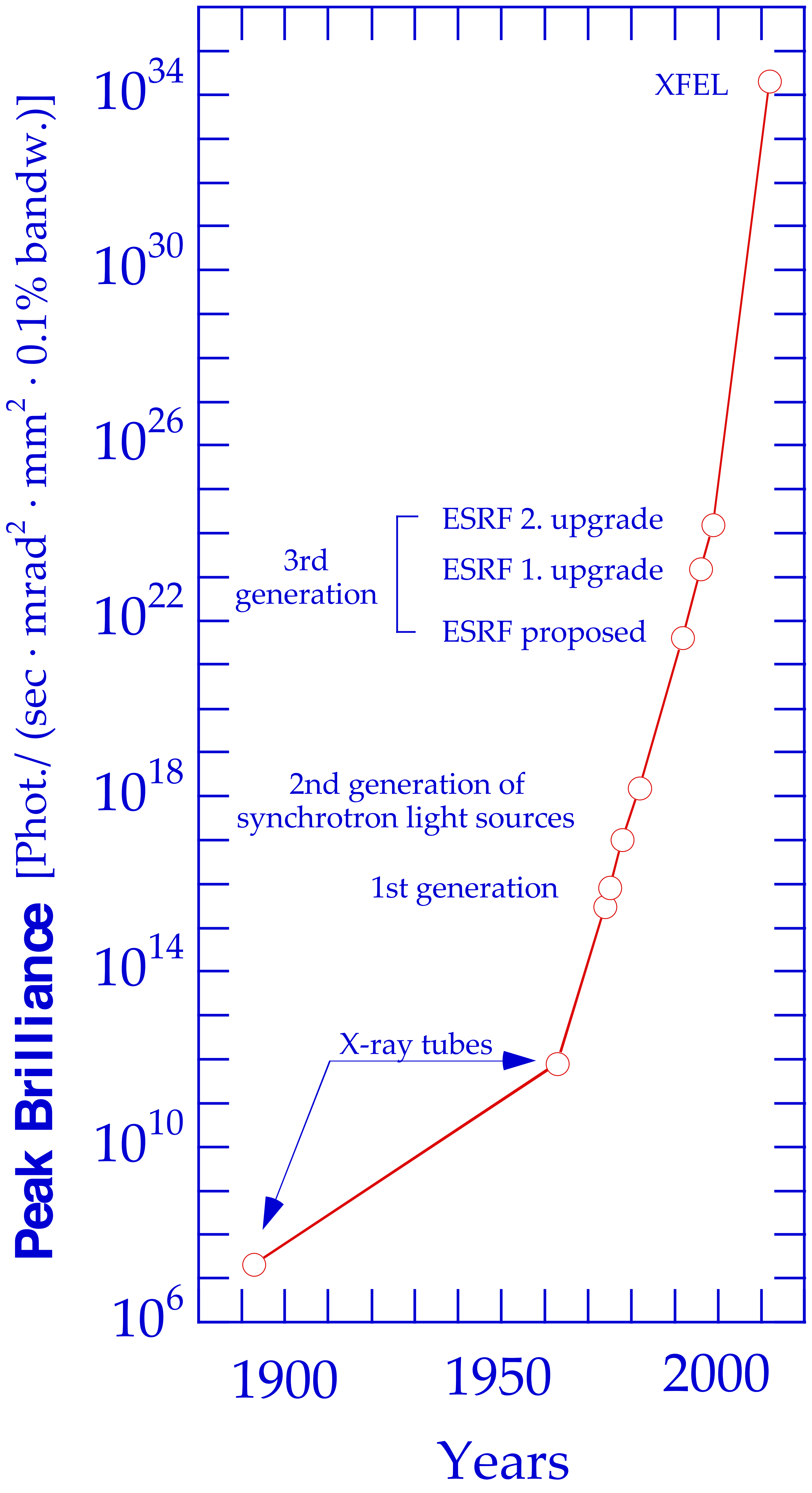




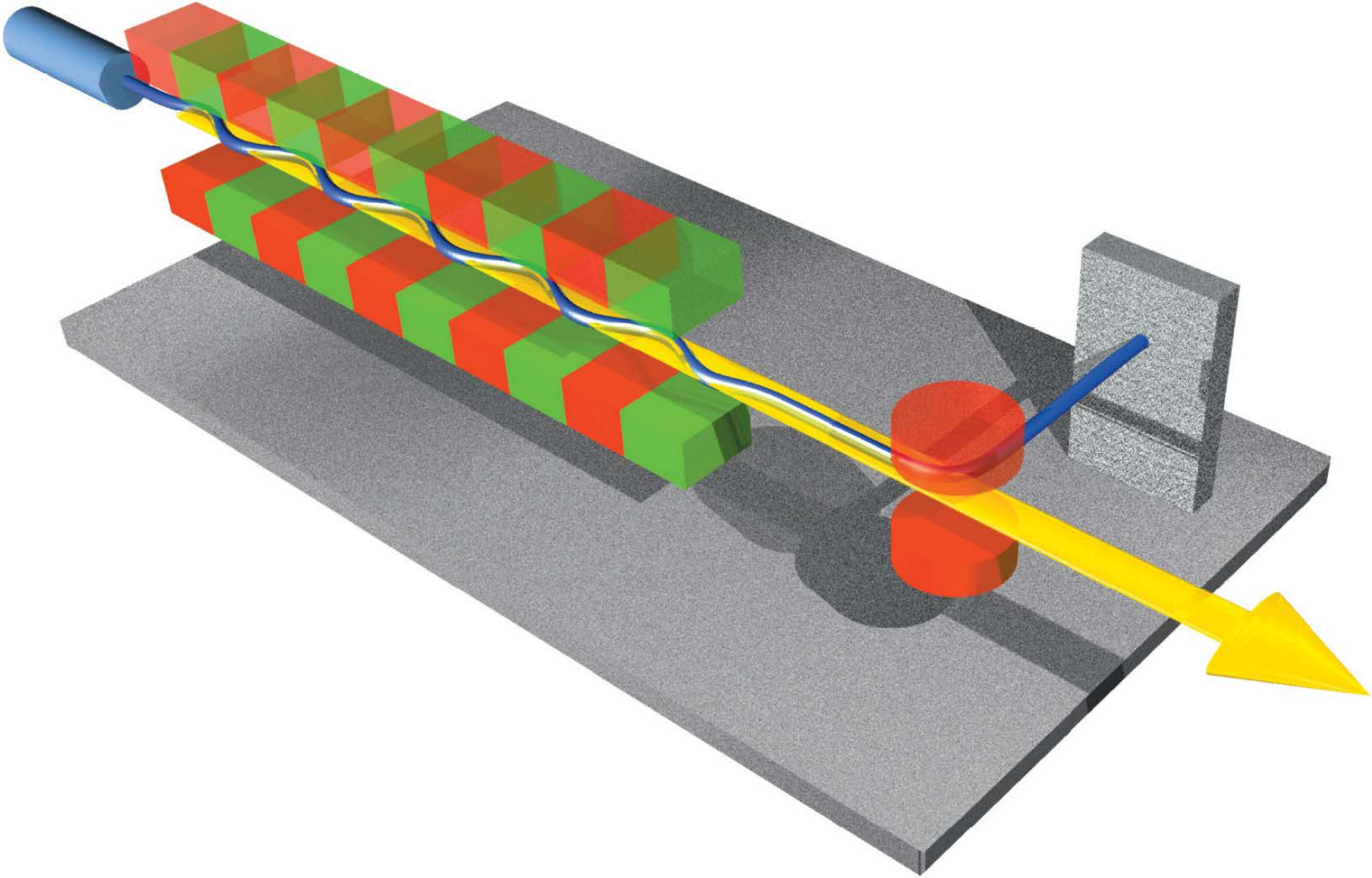
Wikimedia Commons

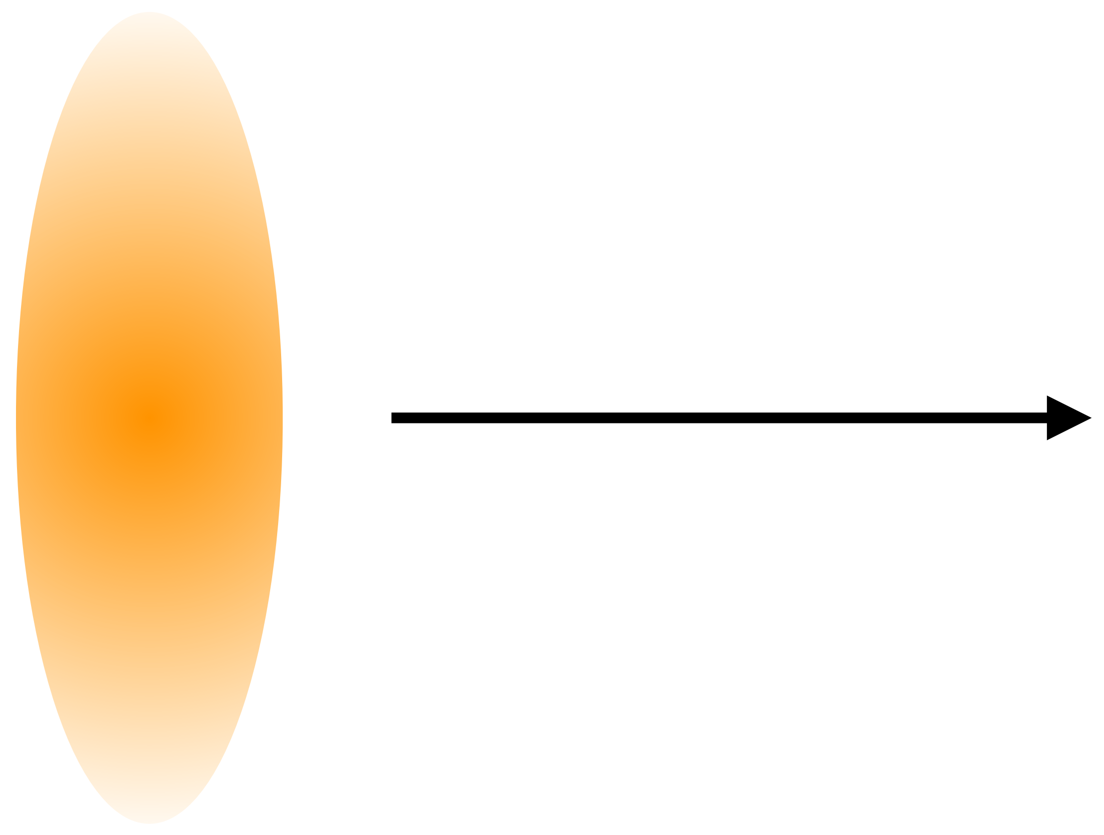

Space
mm
µm
nm
ns
ps
fs
1 µm
Time





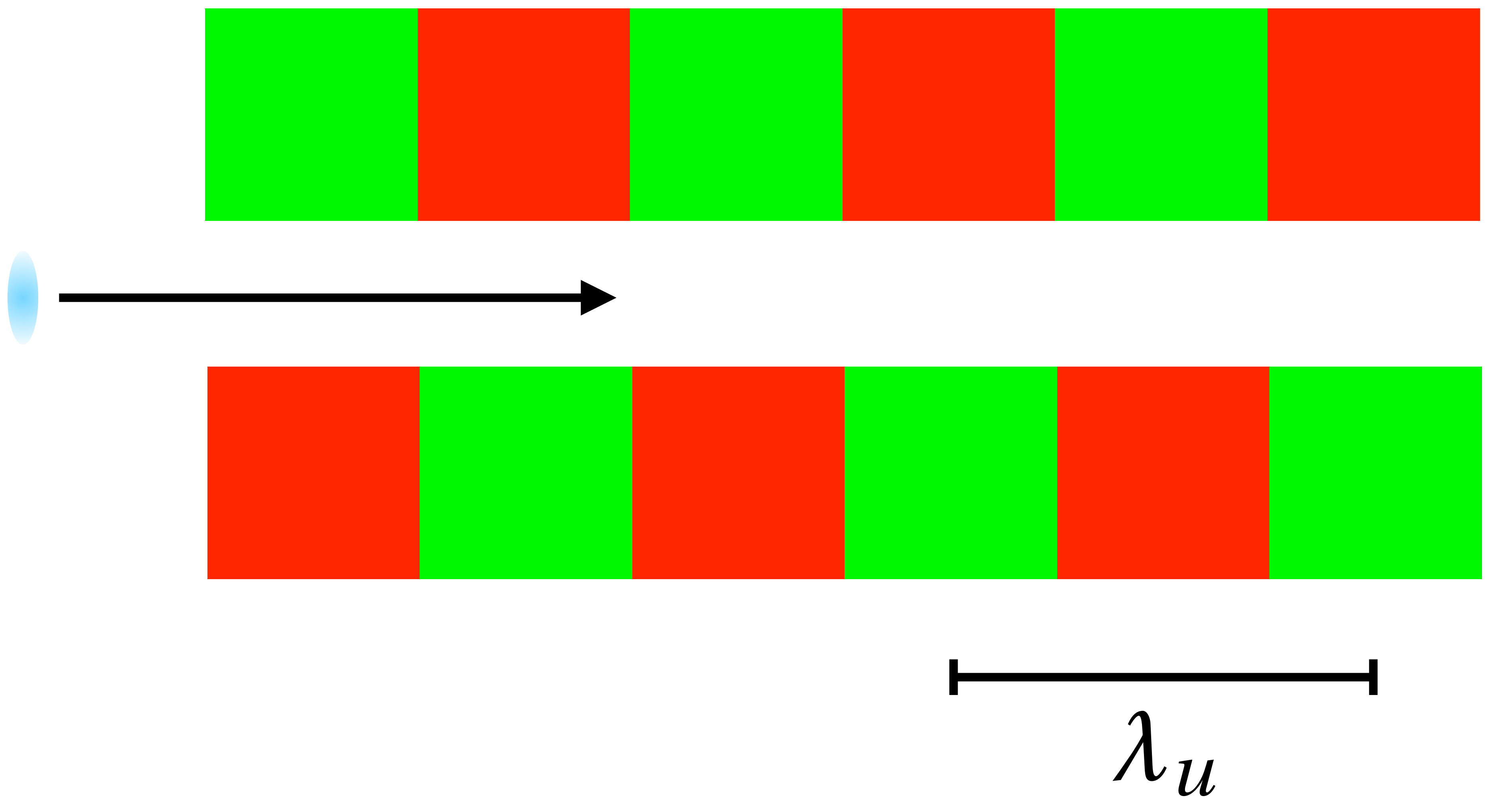
Wikimedia Commons, DESY





Electron bunch

$$\gamma = \frac{1}{\sqrt{1 - v^2 / c^2}} \gg 1$$



Magnetic field in the undulator

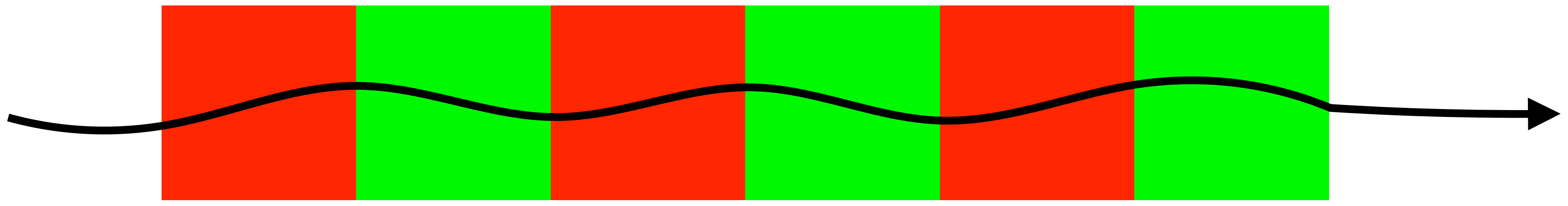
$$B_y(0,0,z) = B_0 \sin(2\pi z/\lambda_u)$$

$$B_x = 0$$

$$B_y = B_0 \cosh(2\pi y/\lambda_u) \sin(2\pi z/\lambda_u)$$

$$B_z = B_0 \sinh(2\pi y/\lambda_u) \cos(2\pi z/\lambda_u)$$

Motion of the electrons in the lab frame



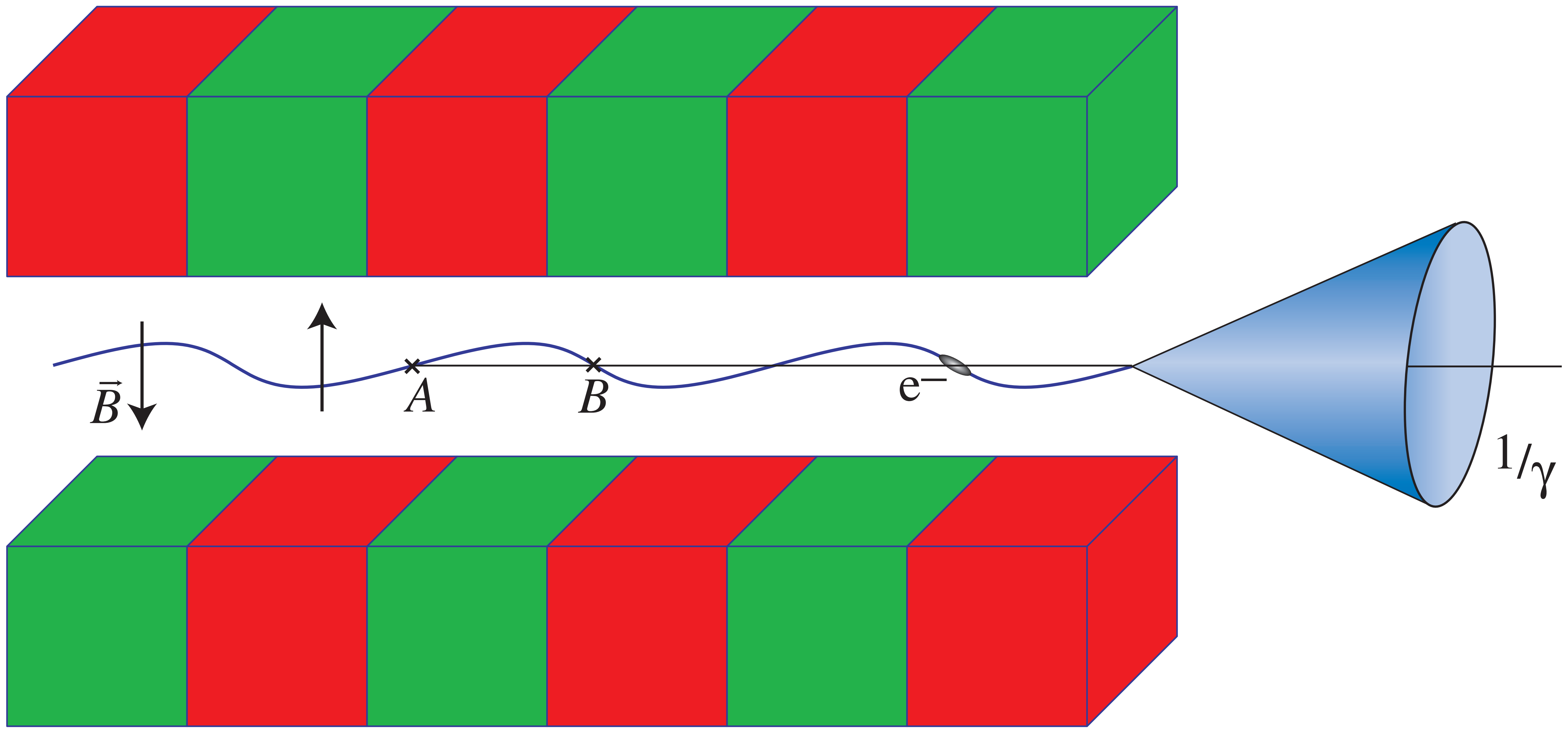
$$m_e \gamma \frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = \vec{F} = -e\vec{v} \times \vec{B}$$

$$m_e \gamma \frac{\mathrm{d}v_x}{\mathrm{d}t} = e v_z B_y = e v_z B_0 \sin(k_u z)$$

$$\Longrightarrow v_x(z) = -\frac{Kc}{\gamma} \cos(k_u z)$$

$$\text{with } K = \frac{eB_0}{m_e c k_u}$$

$$x(z) = -\frac{K}{k_u \gamma \beta_z} \sin(k_u z)$$

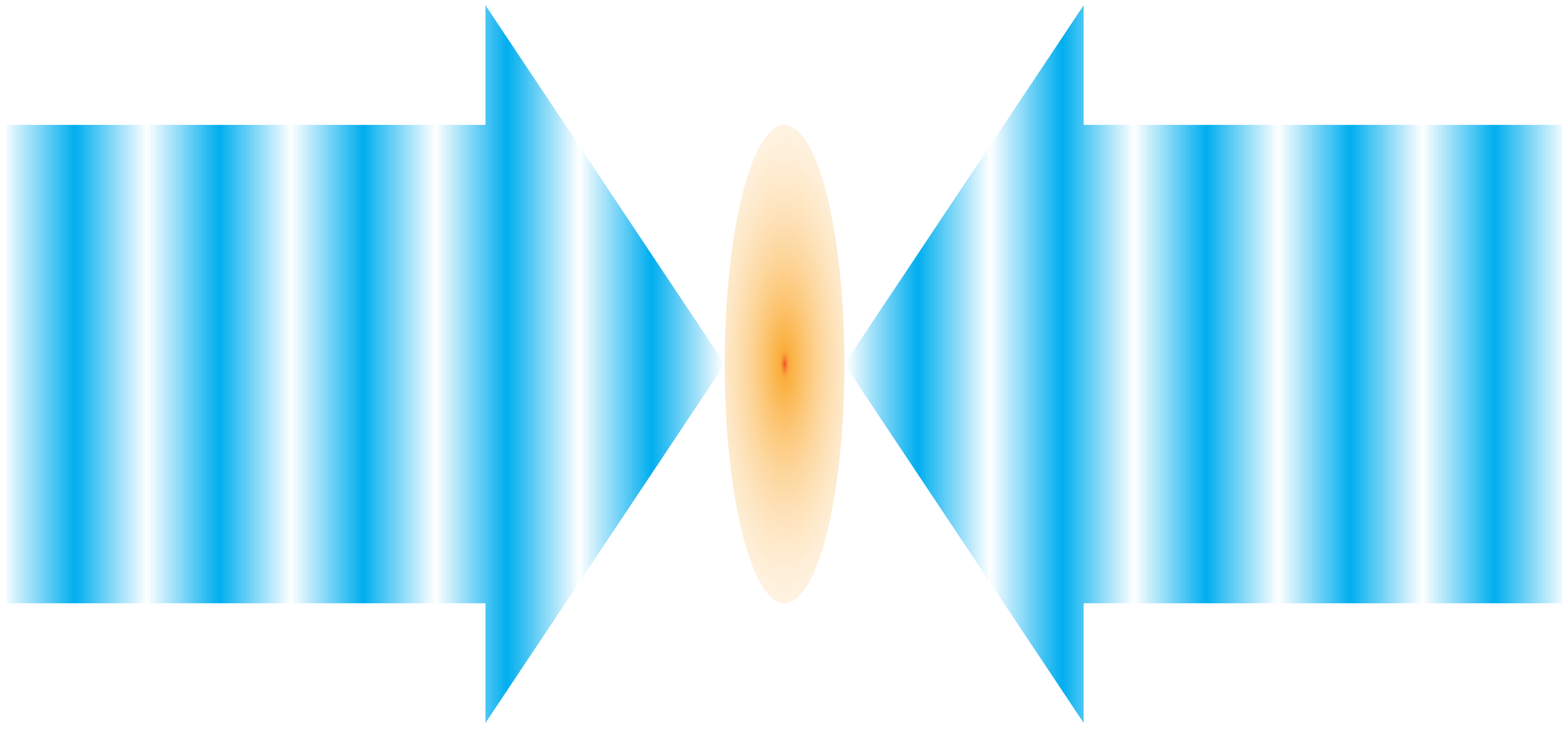


The electrons emit in a narrow cone with opening angle

$$\vartheta = \frac{1}{\gamma}$$

The fundamental harmonic of this radiation is given by:

$$\lambda = \frac{\lambda_u}{\gamma^2} \cdot \frac{(1 + K^2/2)}{2}$$

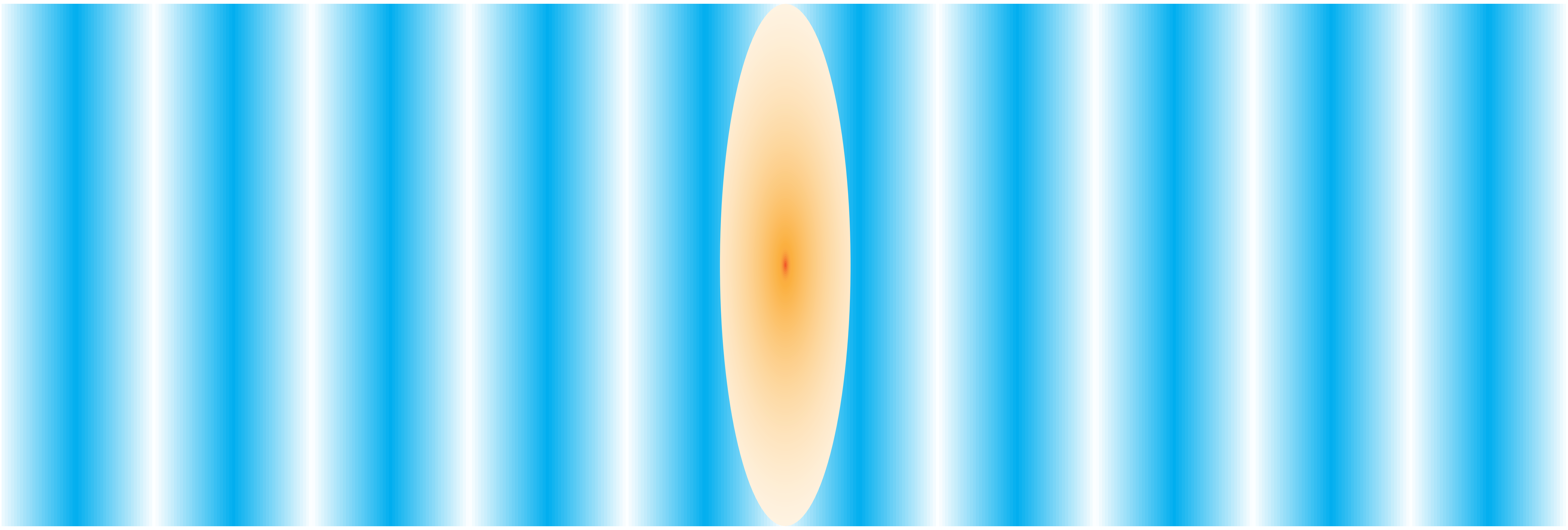


mean speed of
the electrons:

$$\overline{\beta}_z = 1 - \frac{2 + K^2}{4\gamma^2}$$

external
electromagnetic wave:

$$\vec{E} = \vec{u}_x \tilde{E}_x \cos(kz - \omega t + \psi_0)$$

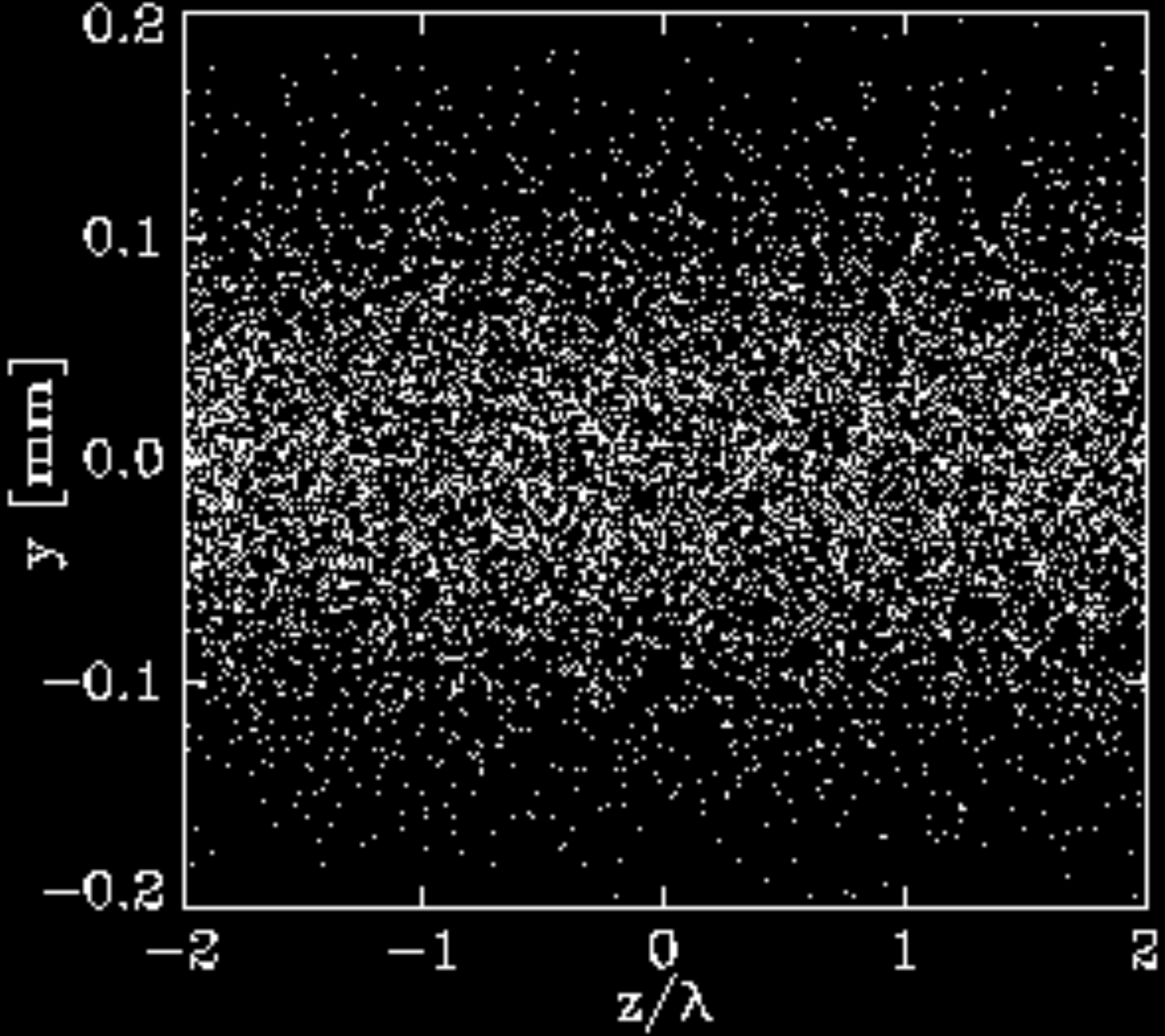


Energy gain:

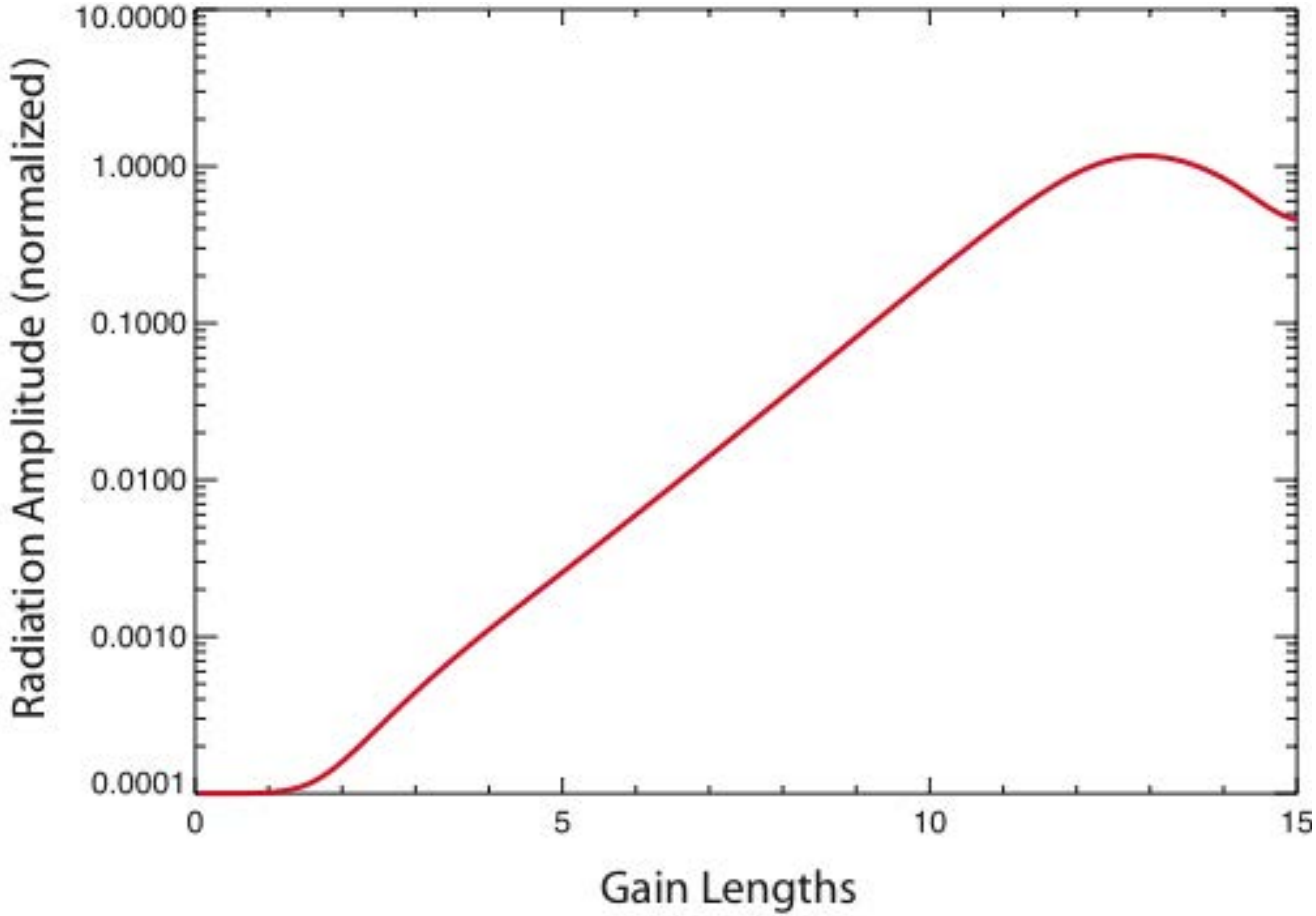
$$\frac{\mathrm{d}W}{\mathrm{d}t} = -e\vec{E}\cdot\vec{v}$$

$$= e\tilde{E}_x \cos(kz - \omega t + \psi_0)\frac{cK}{\gamma}\cos(k_u z)$$

$$= \frac{e\tilde{E}_x cK}{2\gamma}\left[\cos((k+k_u)z - \omega t + \psi_0) + \cos((k-k_u)z - \omega t + \psi_0)\right]$$

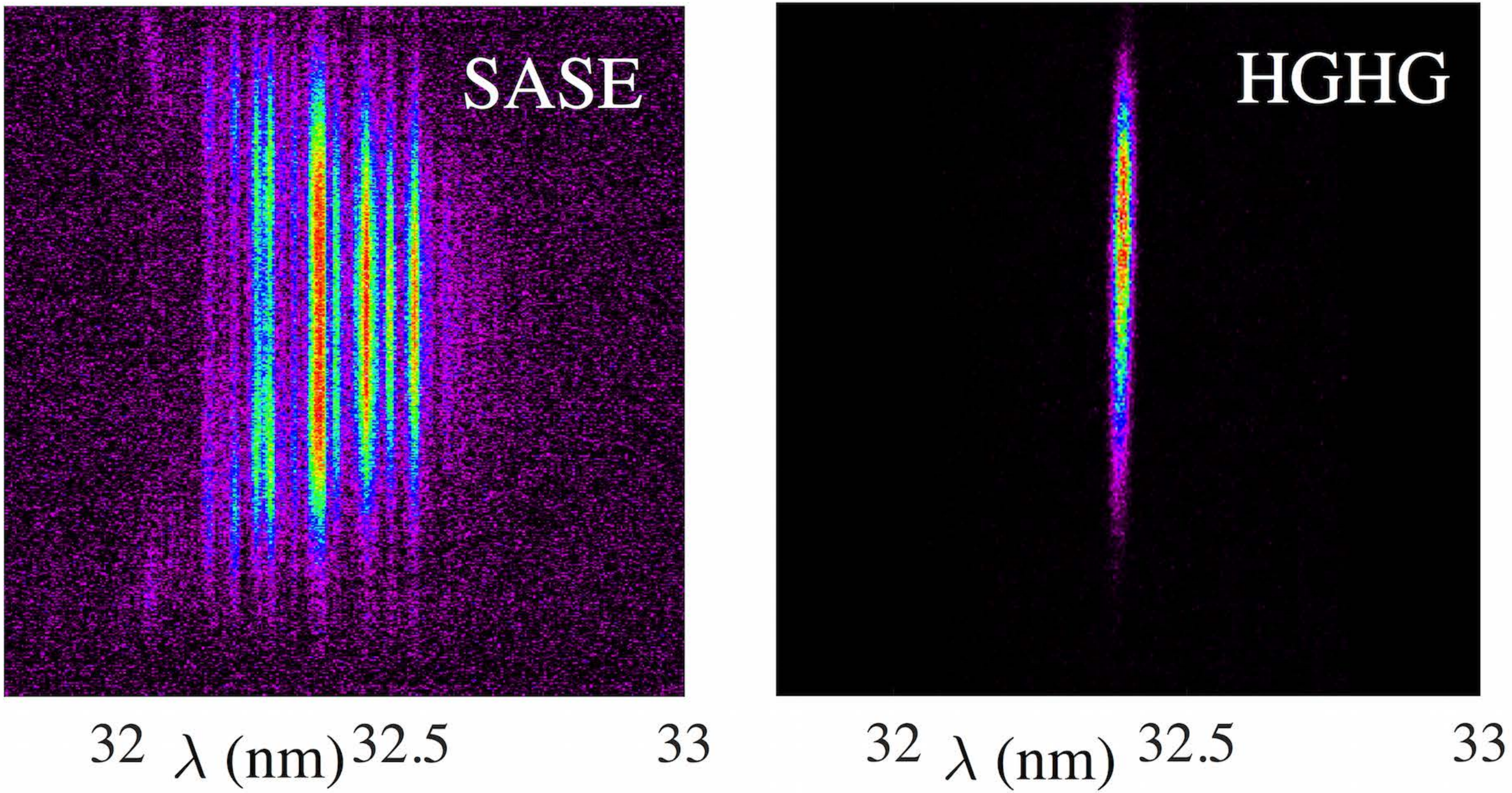


Sven Reiche



10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
Radiation Amplitude (normalized)
0
5
10
15
Gain Lengths

Sven Reiche



SASE
HGHG
32
λ (nm)
32.5
33
32
λ (nm)
32.5
33

The Importance of the FEL Parameter ρ

- FEL parameter ρ. Typical values= $10^{-4} - 10^{-2}$

$$\rho = \frac{1}{\gamma_0}\left[\left(\frac{f_c K}{4 k_u \sigma_x}\right)^2 \frac{I}{2 I_A}\right]^{\frac{1}{3}}$$

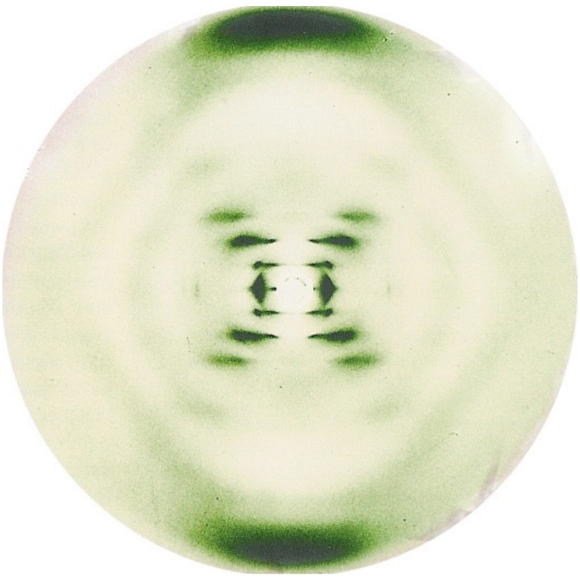
f_c: coupling factor (~0.9 for planar undulator)
I: electron peak current
σ_x: transverse beam size
I_A: Alfven current (~17 kA)

- Scaling of 1D theory

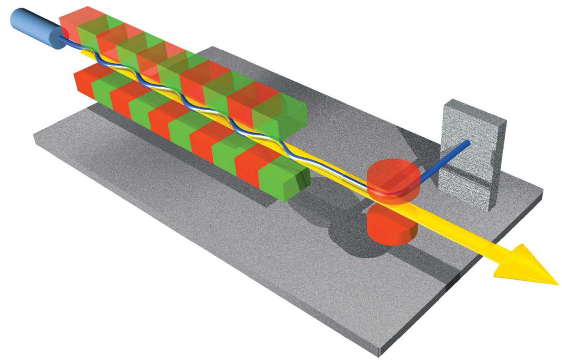
Gain length	Efficiency	SASE Spike Length	Bandwidth
$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\cdot\rho}$	$P_{FEL} \approx \rho P_{beam}$	$L_c = \frac{\lambda}{4\pi\rho}$	$\frac{\Delta\omega}{\omega} = 2\rho$

- Beam Requirements:

Energy Spread	Emittance	Beam Size
$\frac{\sigma_\gamma}{\gamma} << \rho$	$\frac{\varepsilon_n}{\gamma} \approx \frac{\lambda}{4\pi}$	$\beta_{opt} \approx 3\sqrt{\frac{\varepsilon_n}{\gamma}\frac{4\pi}{\lambda}}L_g$



>Motivation



>Physical processes in a free electron laser

>Free electron lasers for XUV and X-Rays

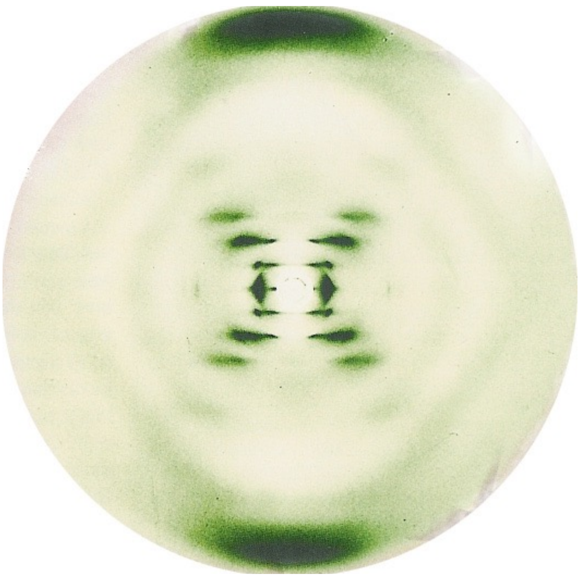
>Components of a free electron laser

SPring-8

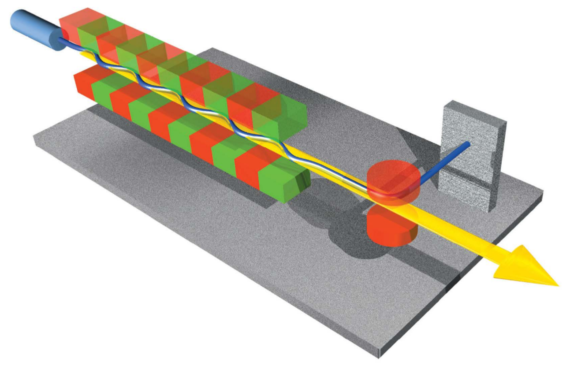
POS TECH

SINAP


Schenefeld
Osdorfer Born
DESY-Bahrenfeld
0
500 m



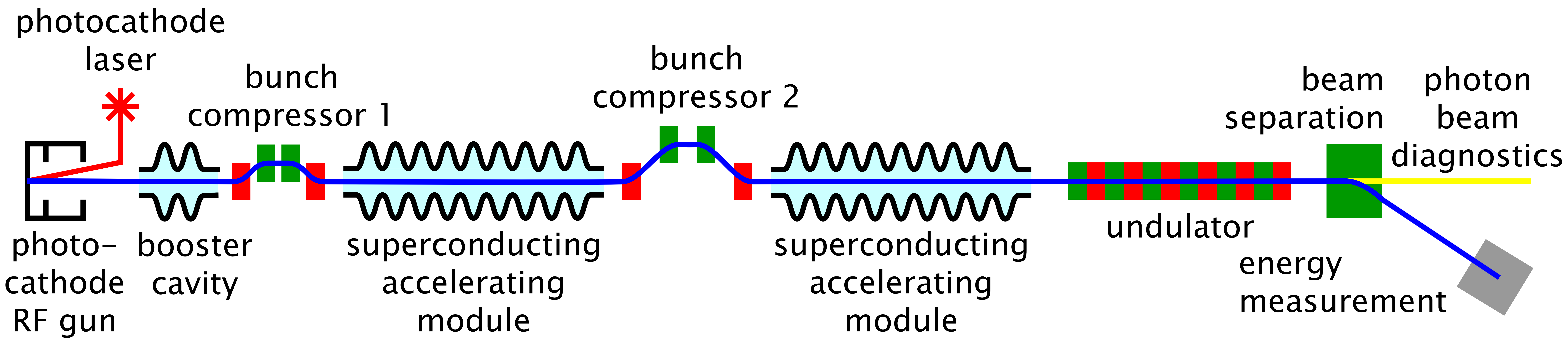
>Motivation

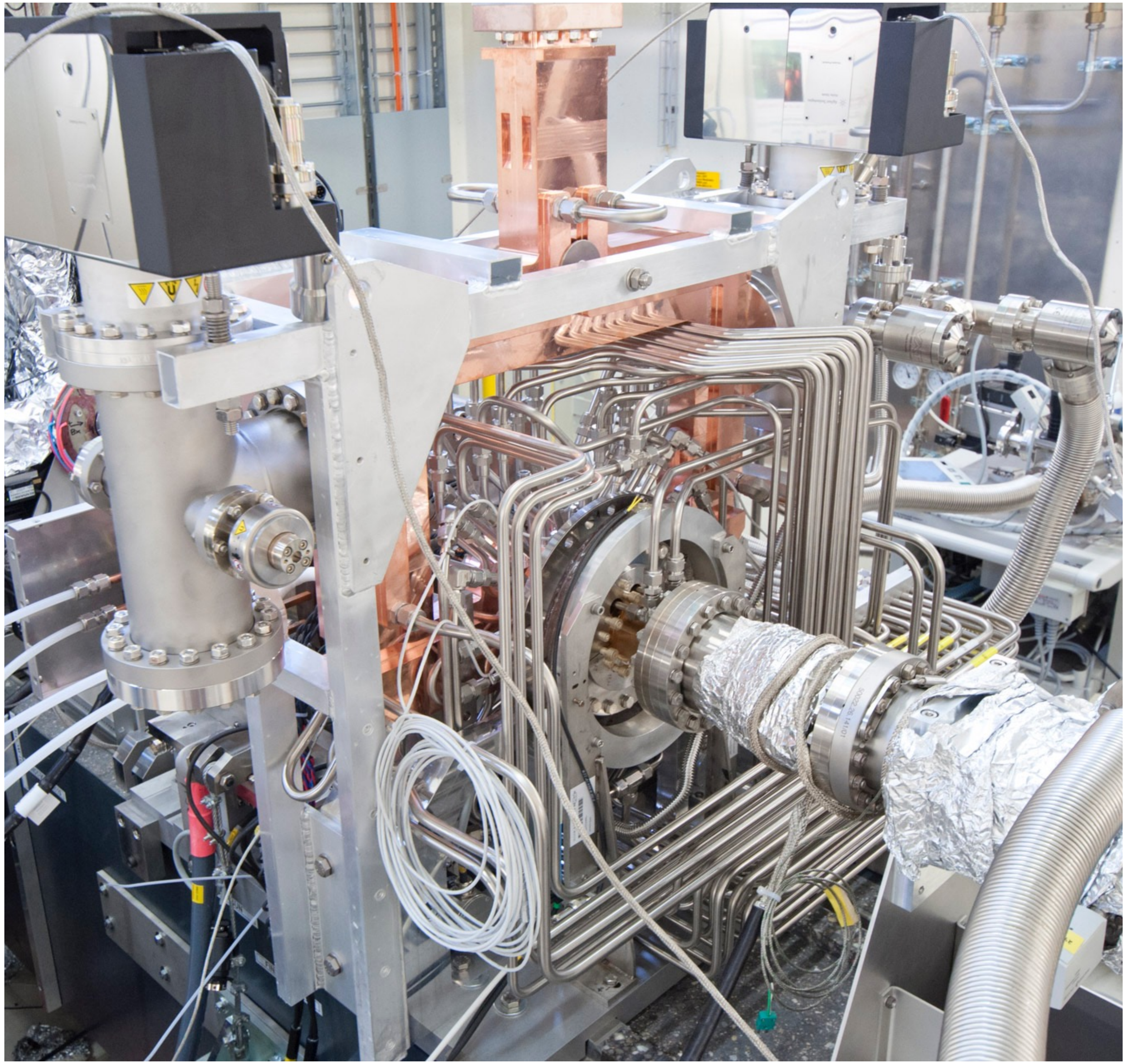


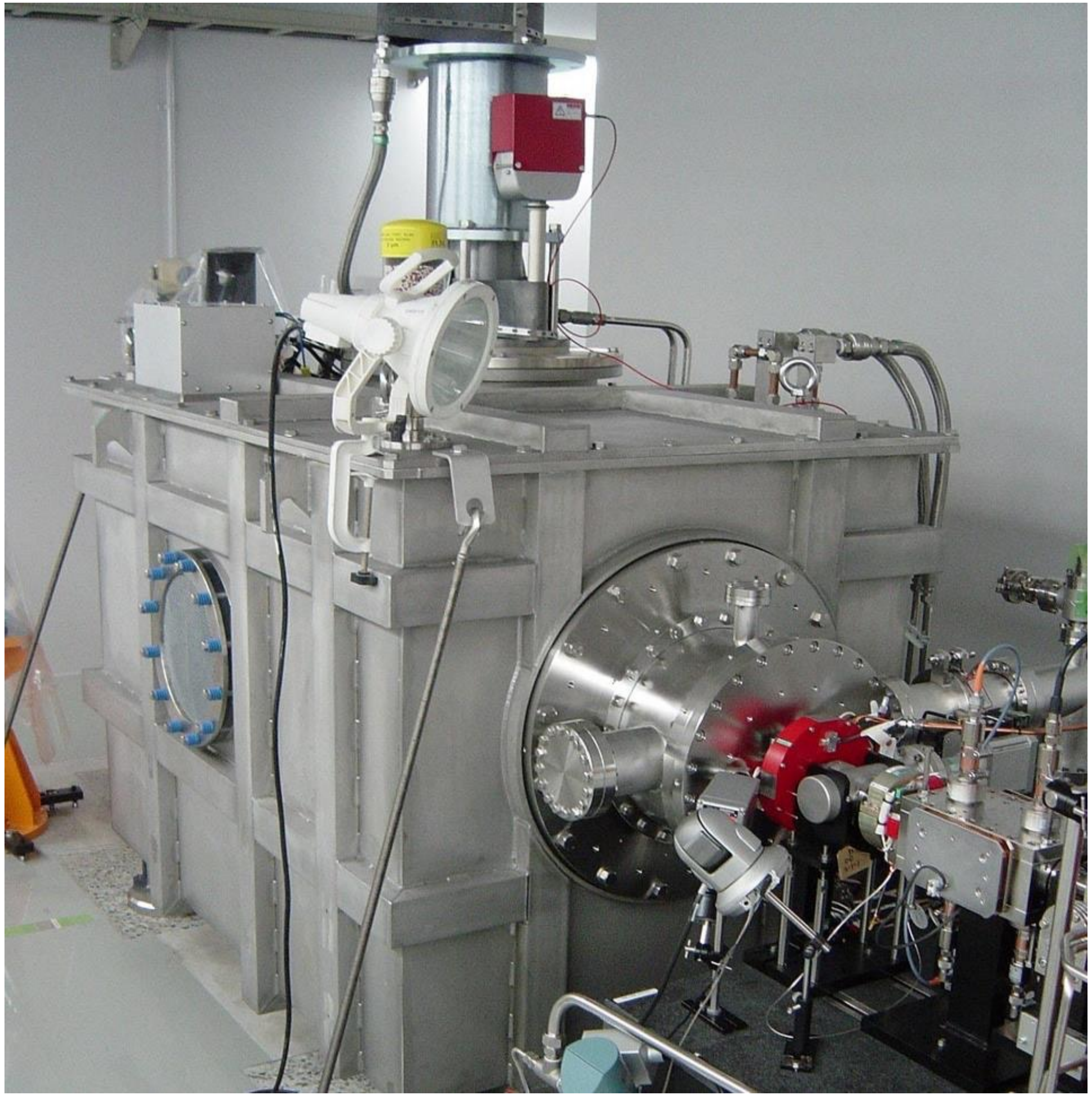
>Physical processes in a free electron laser

>Free electron lasers for XUV and X-Rays

>Components of a free electron laser


photocathode
laser
bunch
compressor 1
bunch
compressor 2
beam
separation
photon
beam
diagnostics
photo-
cathode
RF gun
booster
cavity
superconducting
accelerating
module
superconducting
accelerating
module
undulator
energy
measurement





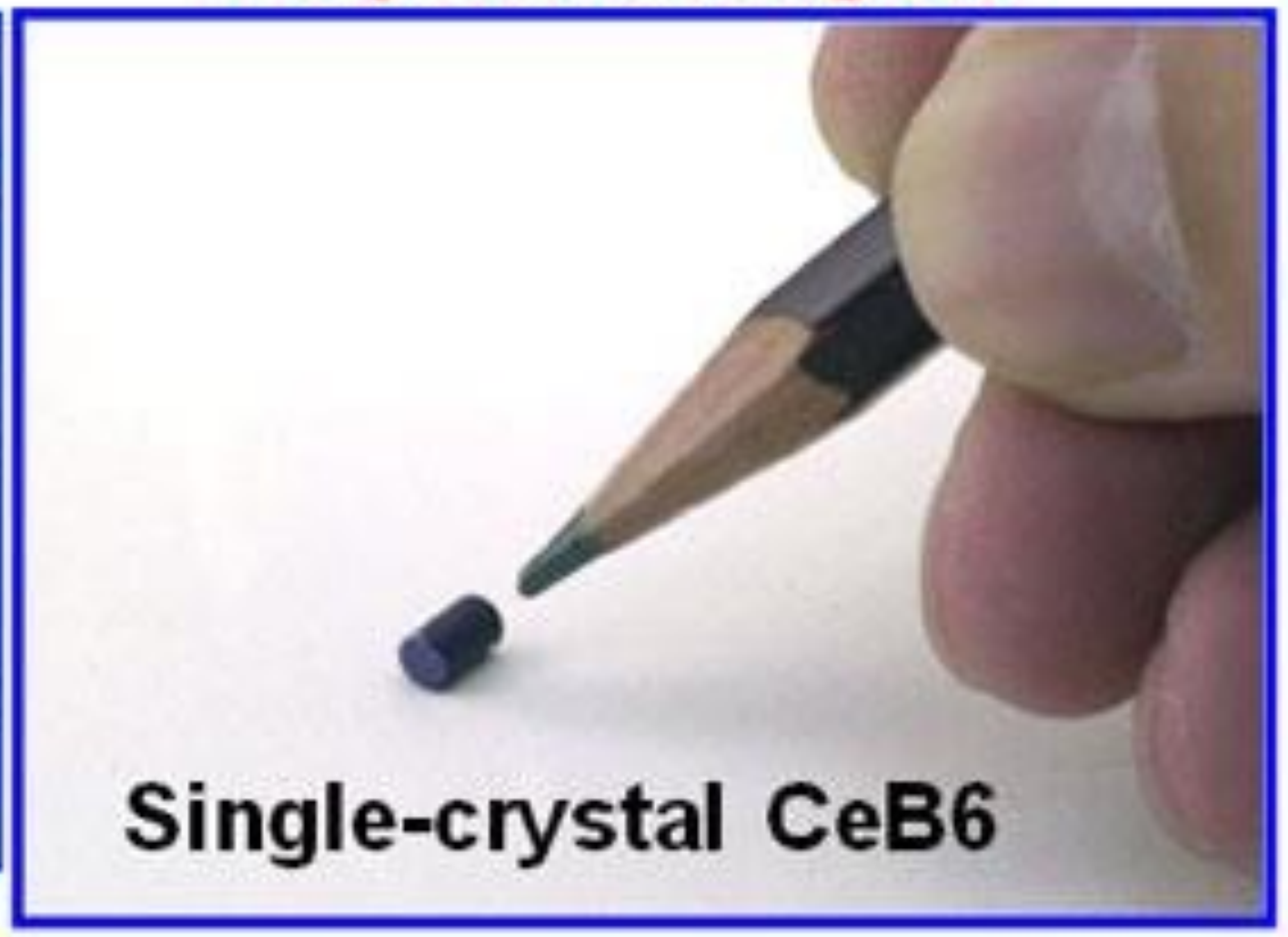
Tsumoro Shintake

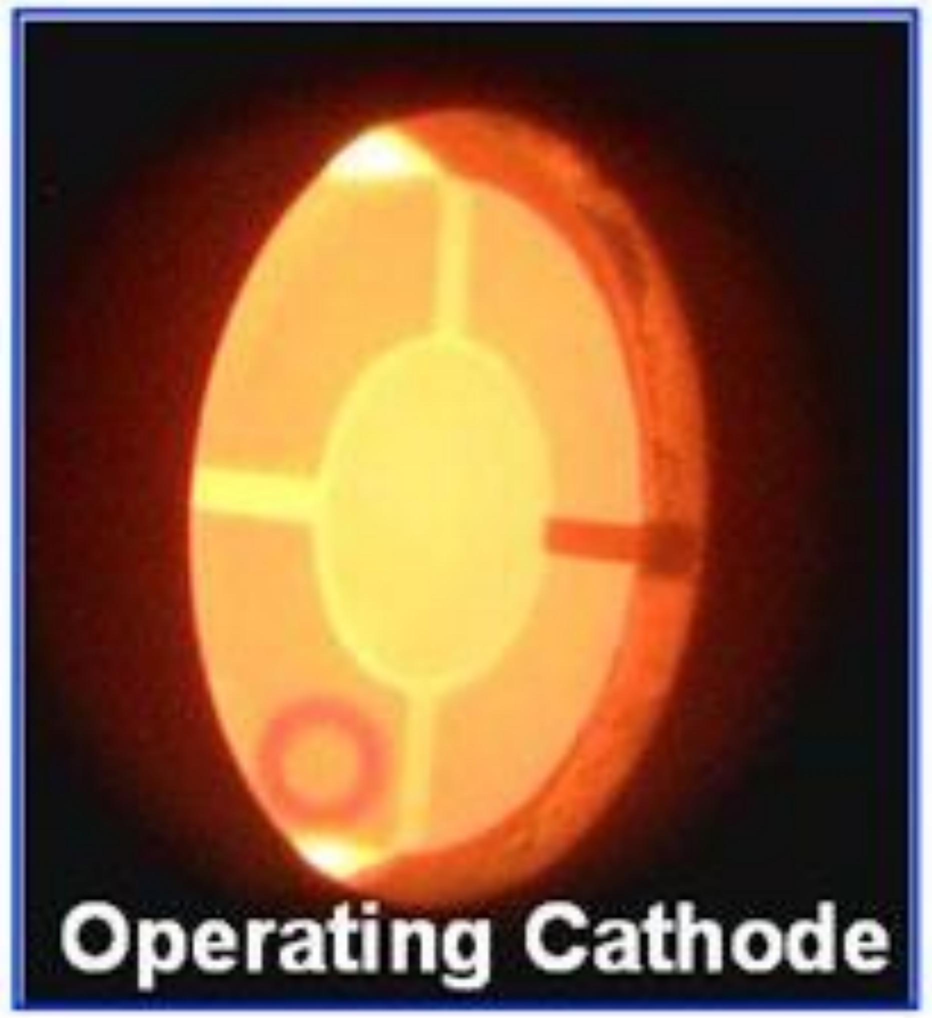

symmetric
RF power
coupler
three cell
RF cavity
electron beam
laserbeam
cooling
channels
Ultra precise machined
photo cathode

Single-crystal CeB_6 Cathode for XFEL/SPring-8 & SCSS Low-emittance Injector

No HV breakdown for 4 years daily operation

After 20,000 hours operation 1 crystal changed.





Diameter : ϕ3 mm
Temperature : ~1500 deg.C
Beam Voltage : 500 kV
Peak Current : 1 A
Pulse Width : ~2 μs
Beam Chopper: 1 nsec

Tsumoro Shintake

The importance of emittance

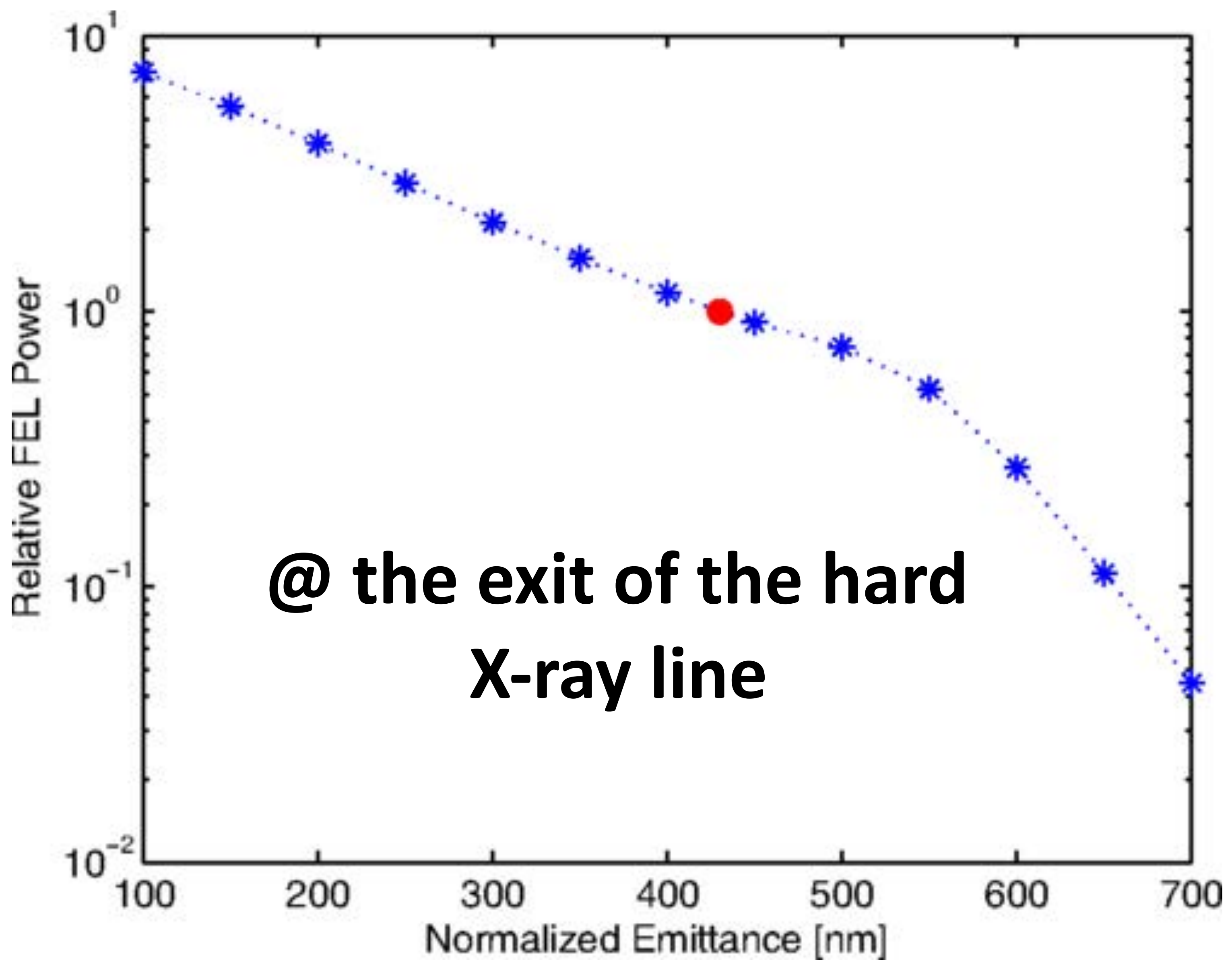
Transversely coherent FEL radiation is generated if:

$$\frac{\varepsilon_N}{\gamma} \sim \frac{\lambda}{4\pi}$$

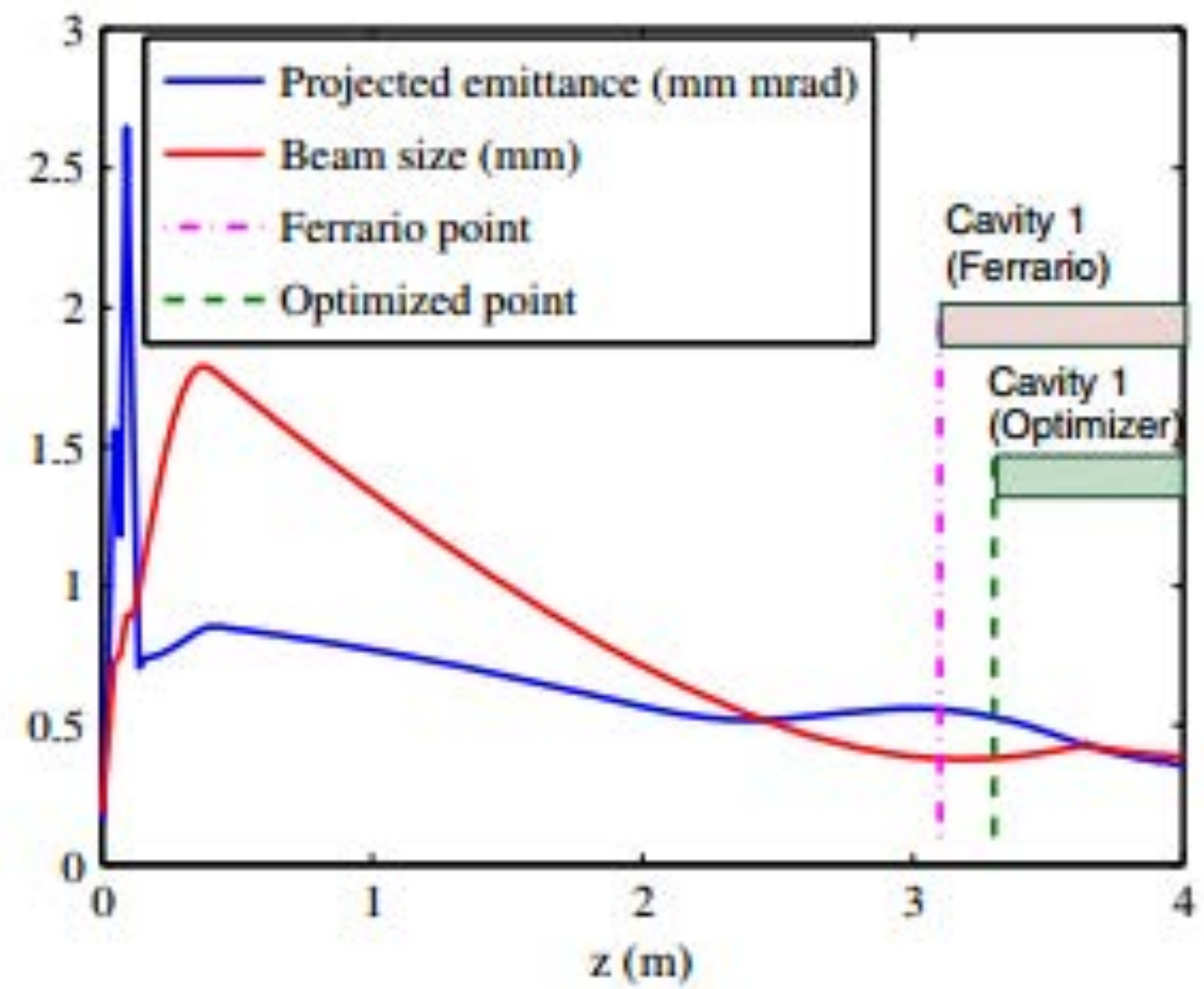
ε_N : normalized emittance
γ : Lorentz factor
λ: FEL radiation wavelength

Smaller ε_N ⇨ smaller e- beam energy ⇨ shorter accelerating section
⇨ larger radiation power ⇨ shorter undulator beam line

In the case of SwissFEL:

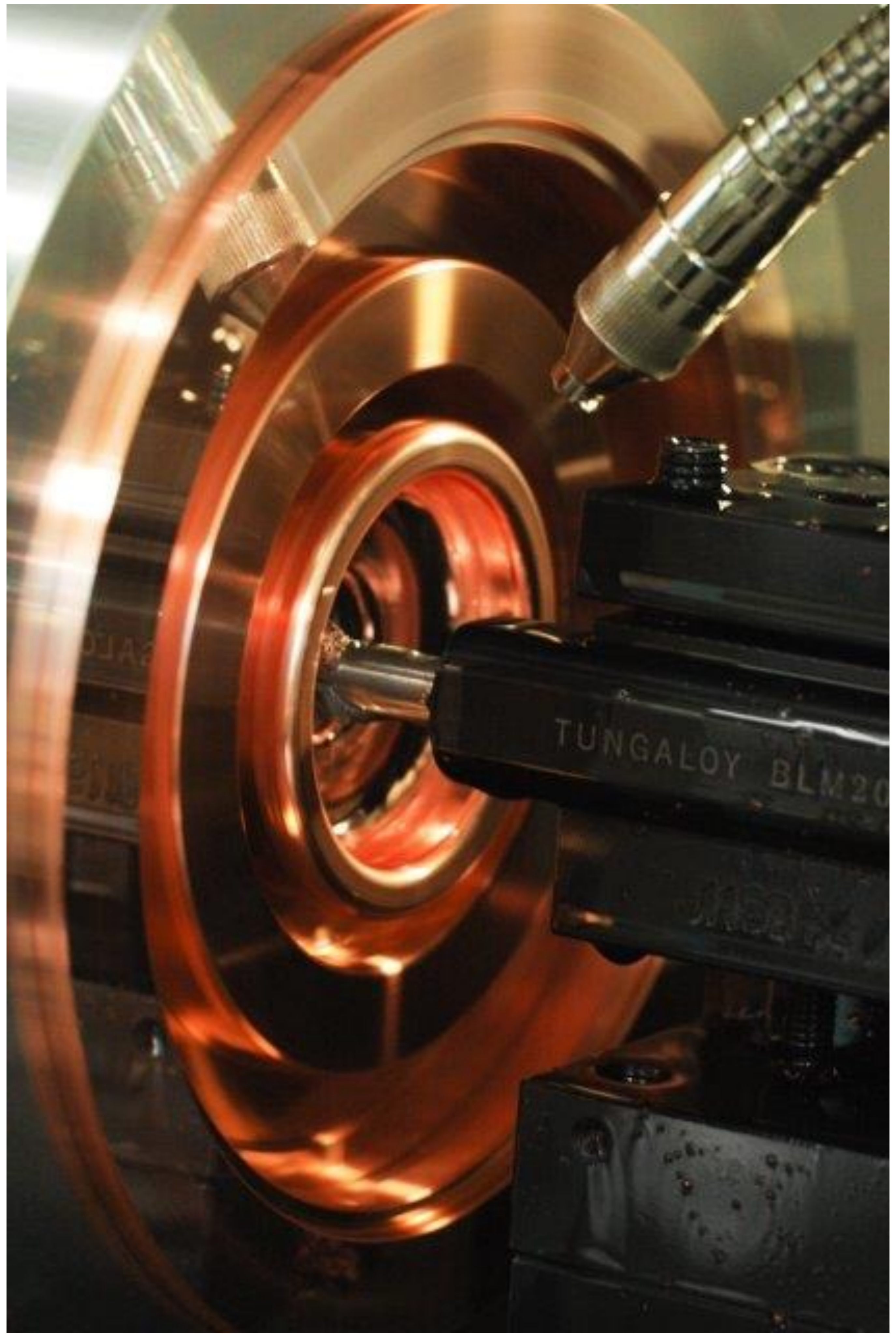


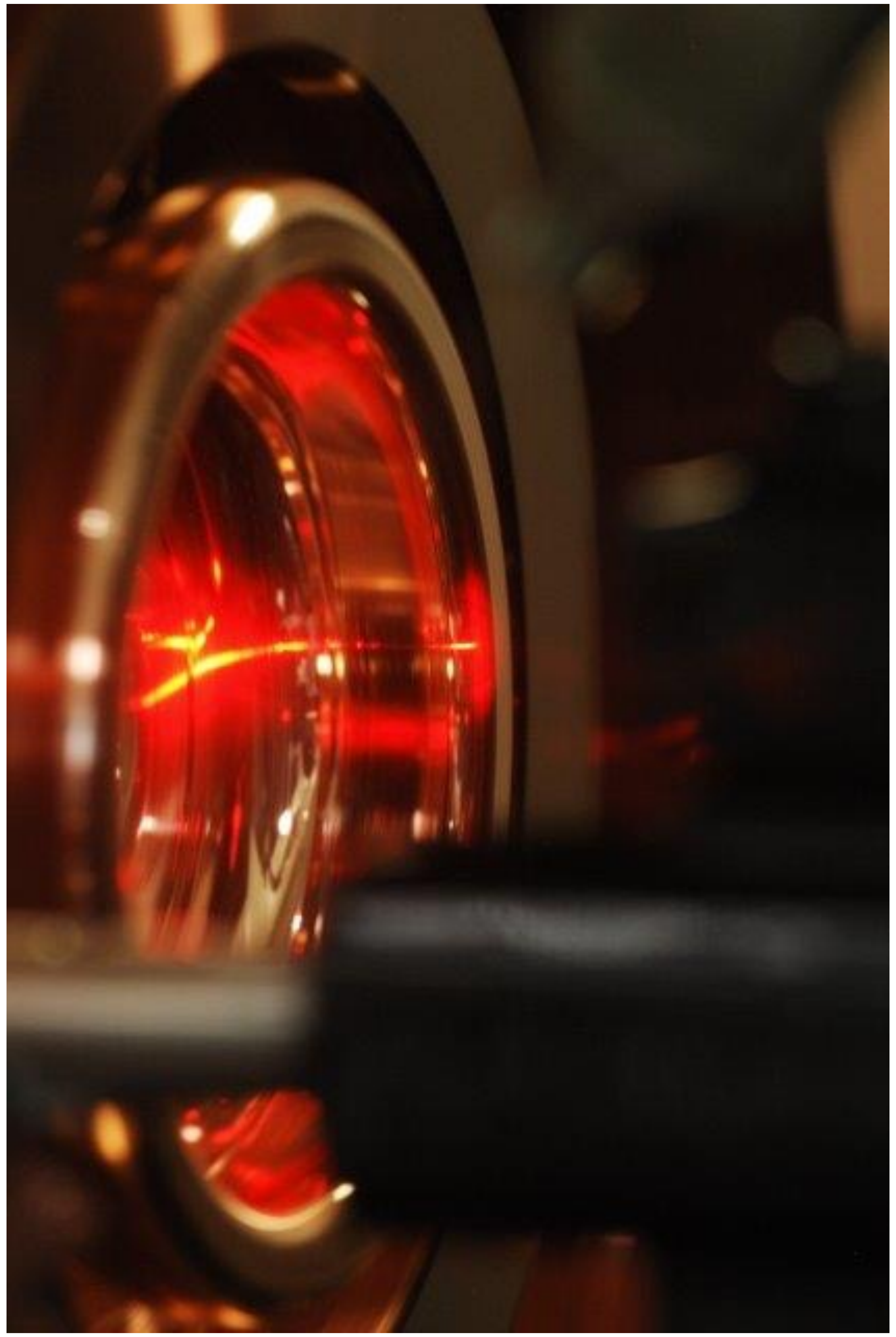
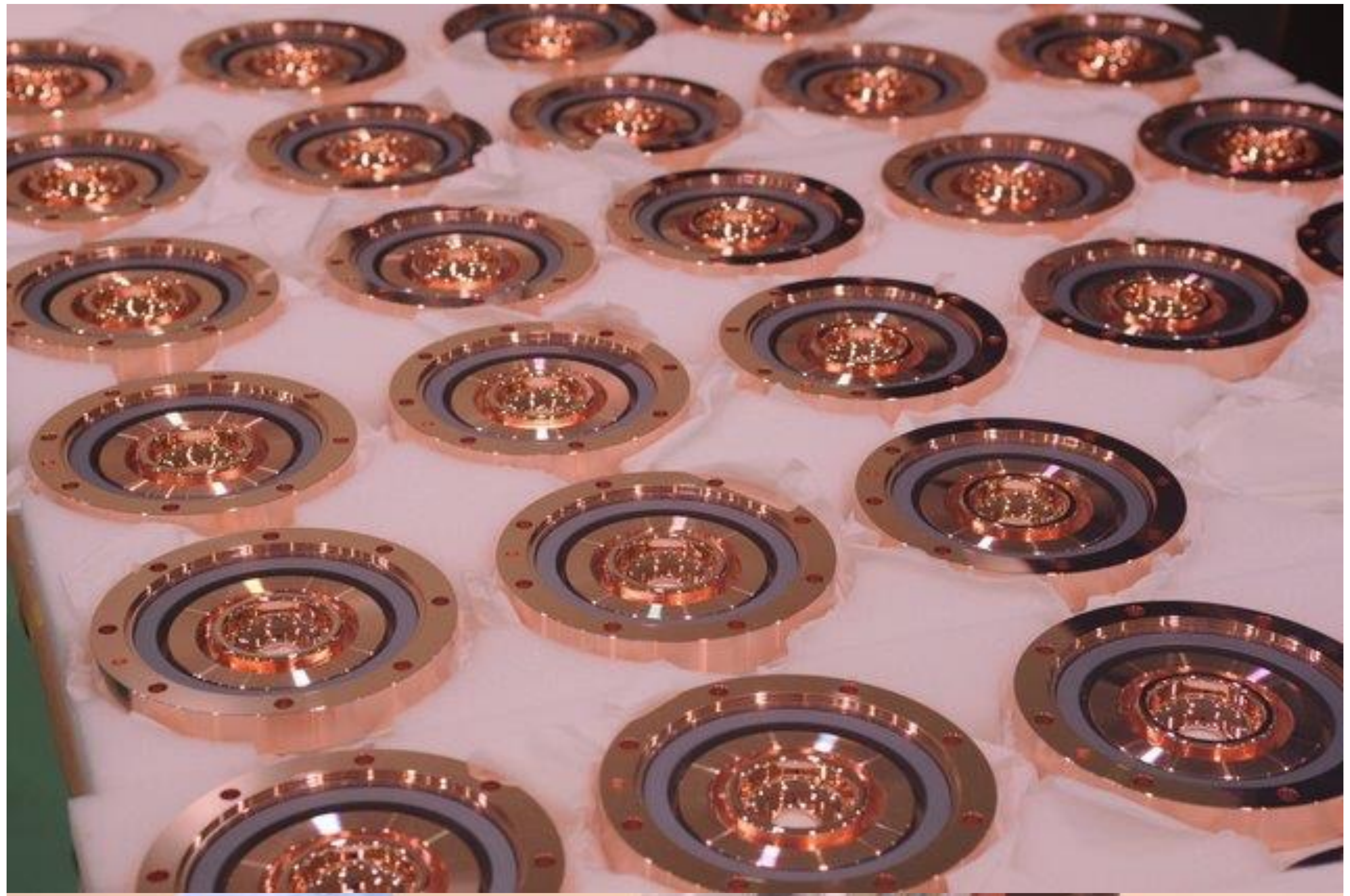
A way to minimize ε_N is to apply a scheme known as "invariant envelope matching" [2,3]:



[1] E. Prat,et al., Phys. Rev. ST-AB 17, 104401 (2014).
[2] L. Serafini and J. B. Rosenzweig, Phys. Rev. E 55, 7565 (1997).
[3] M. Ferrario et al., Report No. SLAC-PUB-8400, 2000.
[4] S. Bettoni et al., Phys. Rev. ST-AB 18, 123403 (2015).

Tsumoro Shintake




Tsumoro Shintake

Florian Löhl


QFDM03
tesla
SINLH01-MQUA020


PAUL SCHERRER INSTITUT
Magnetname : HFA - 01
Baujahr : 2014
Strom / Spannung : 10A / 1.36V
Gewicht : 8.5 kg
MAG3422
HFA01
QFB-07

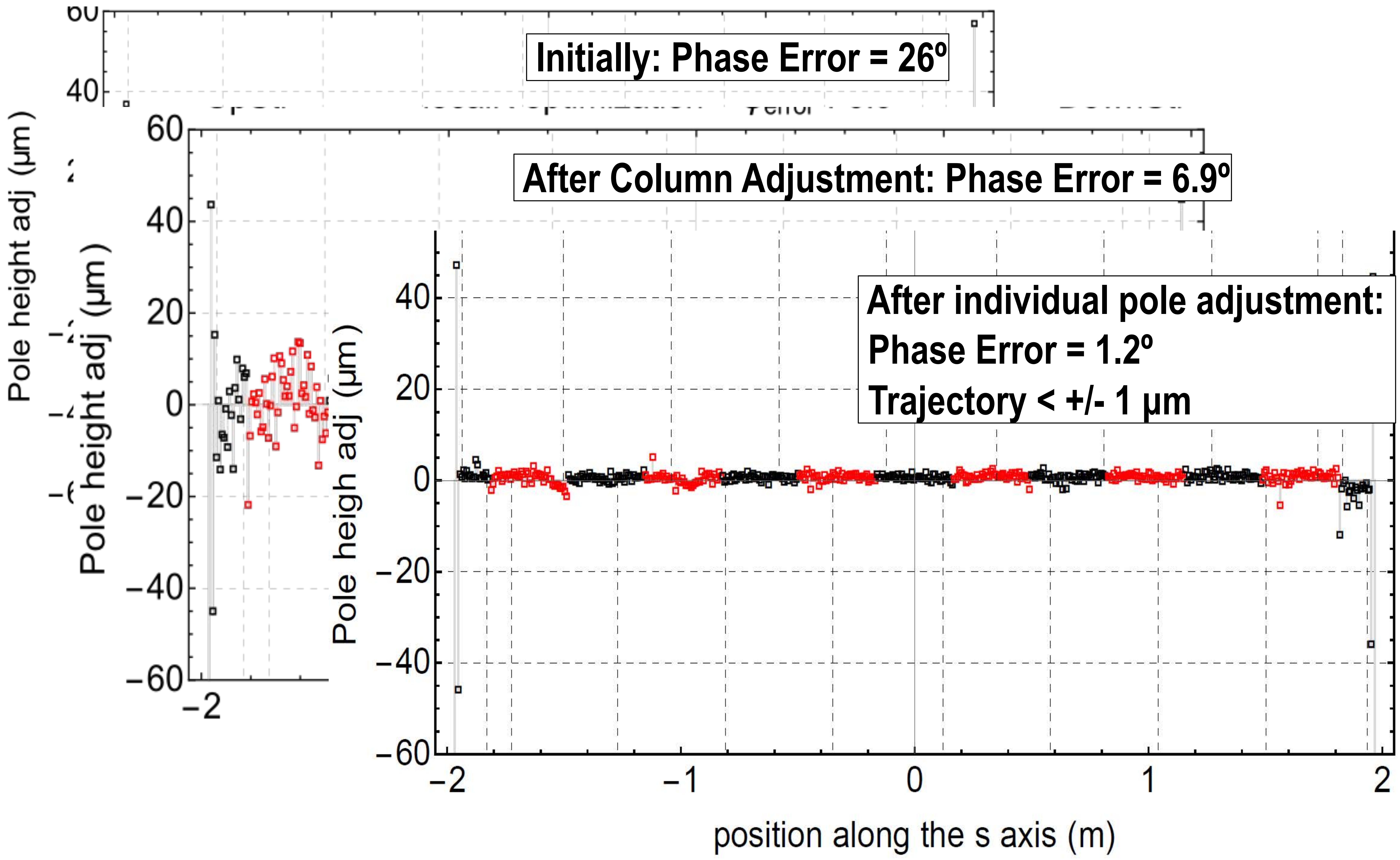

a)
b)
c)
d)
ρ
W
z
–E
off-crest
acceleration
magnetic
chicane
low energy
high energy

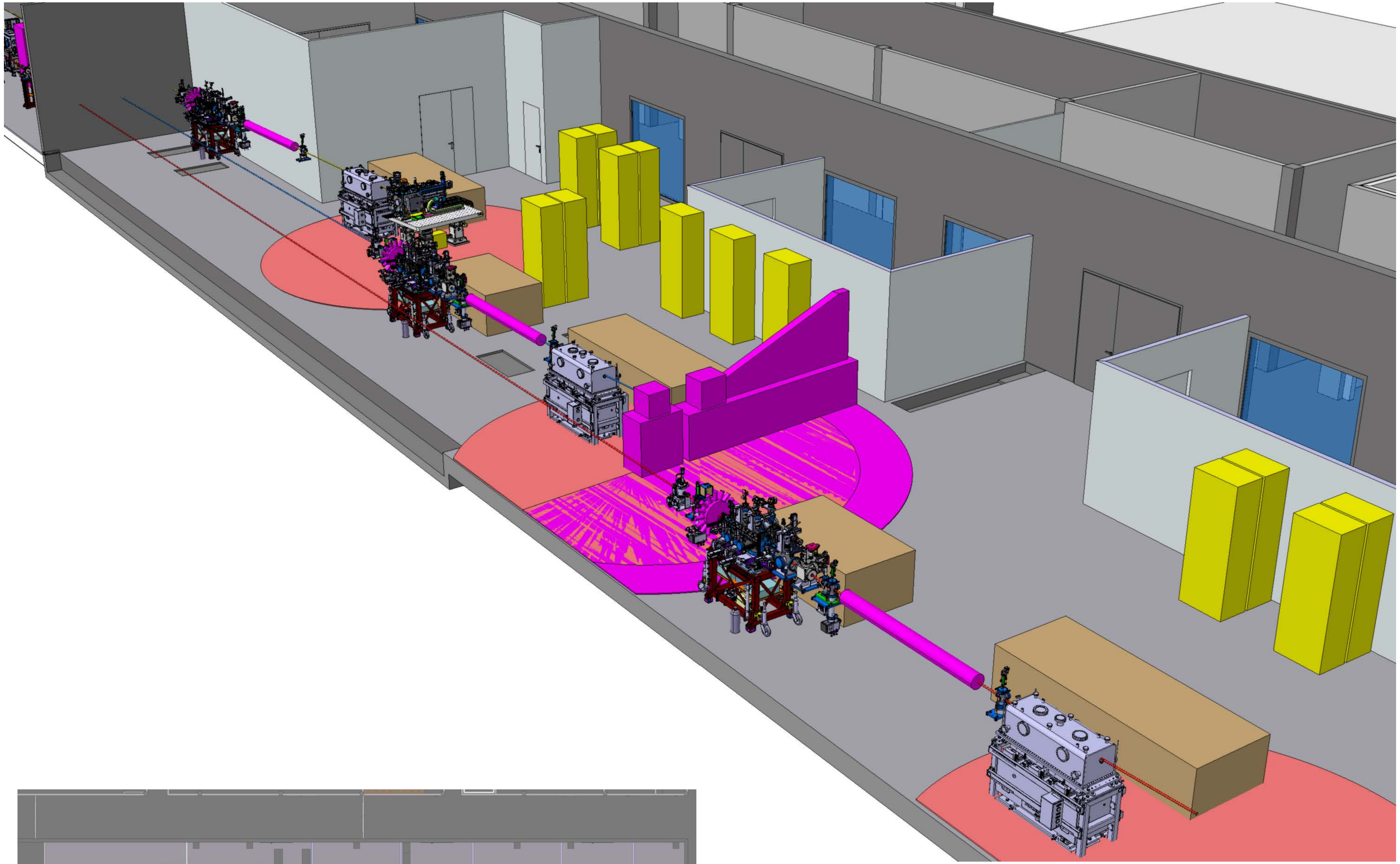

25 000 kg
SWF

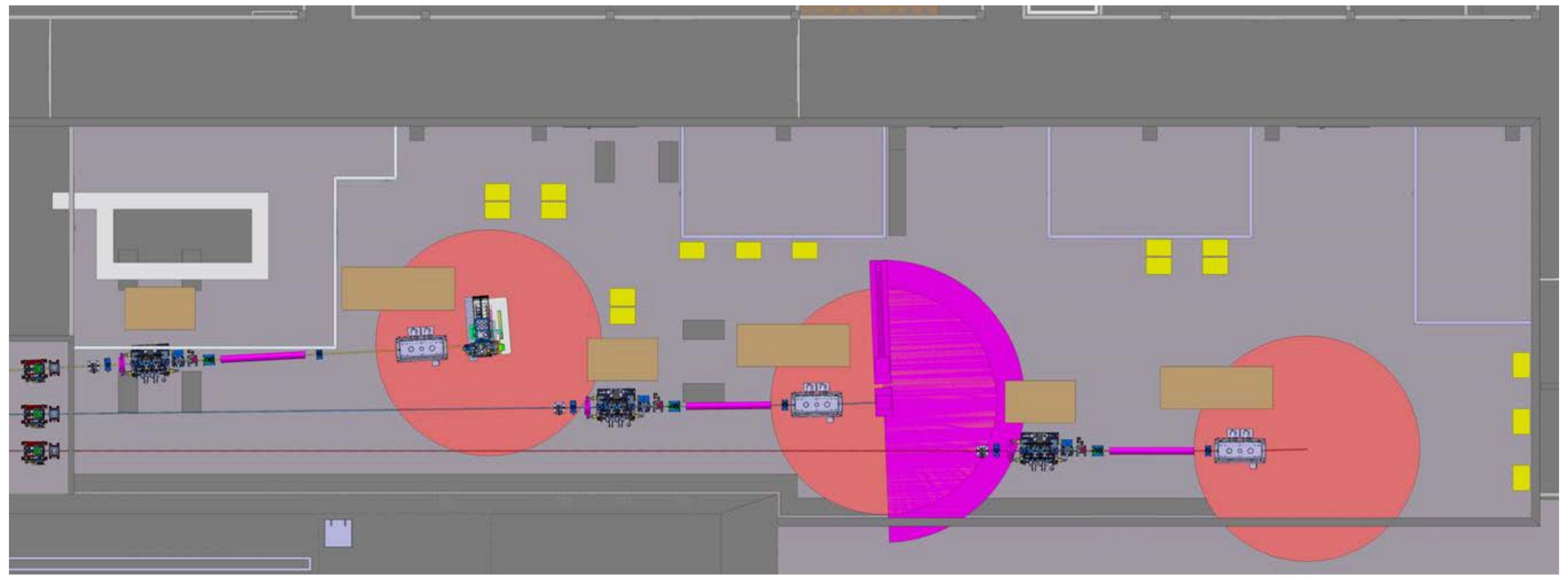
Tsumoro Shintake

Marco Calvi

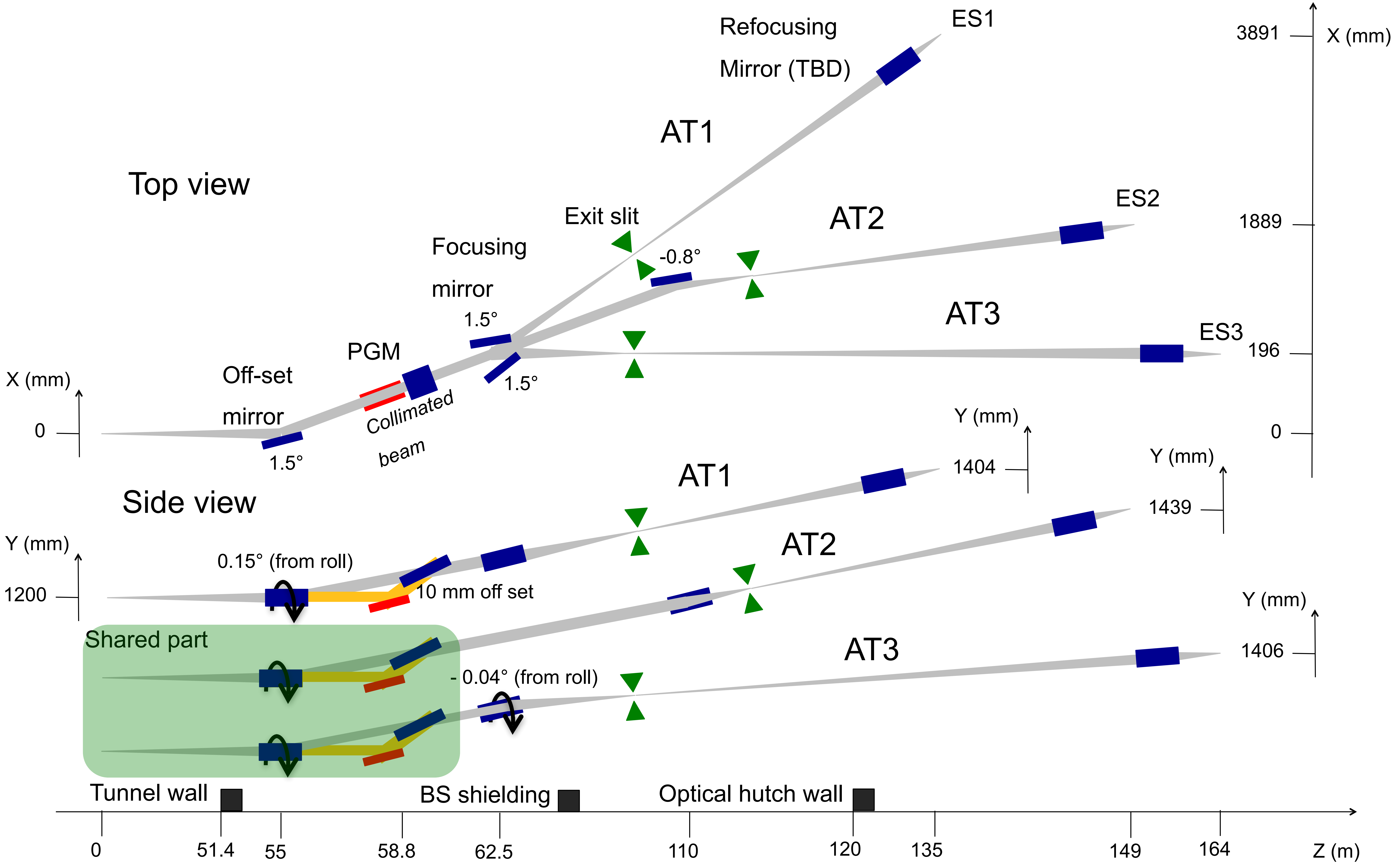
Effect of the adjustements on the field errors



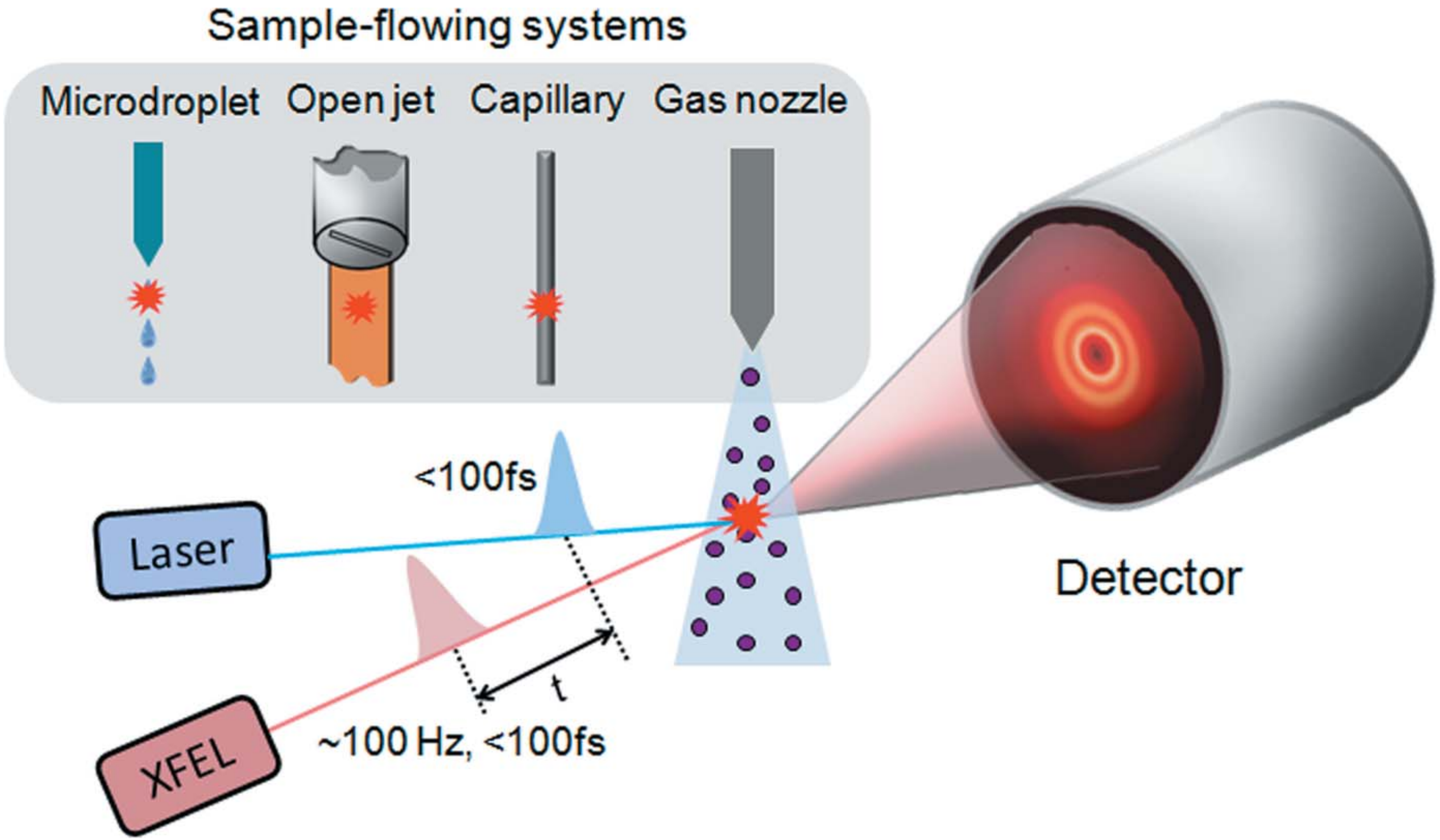


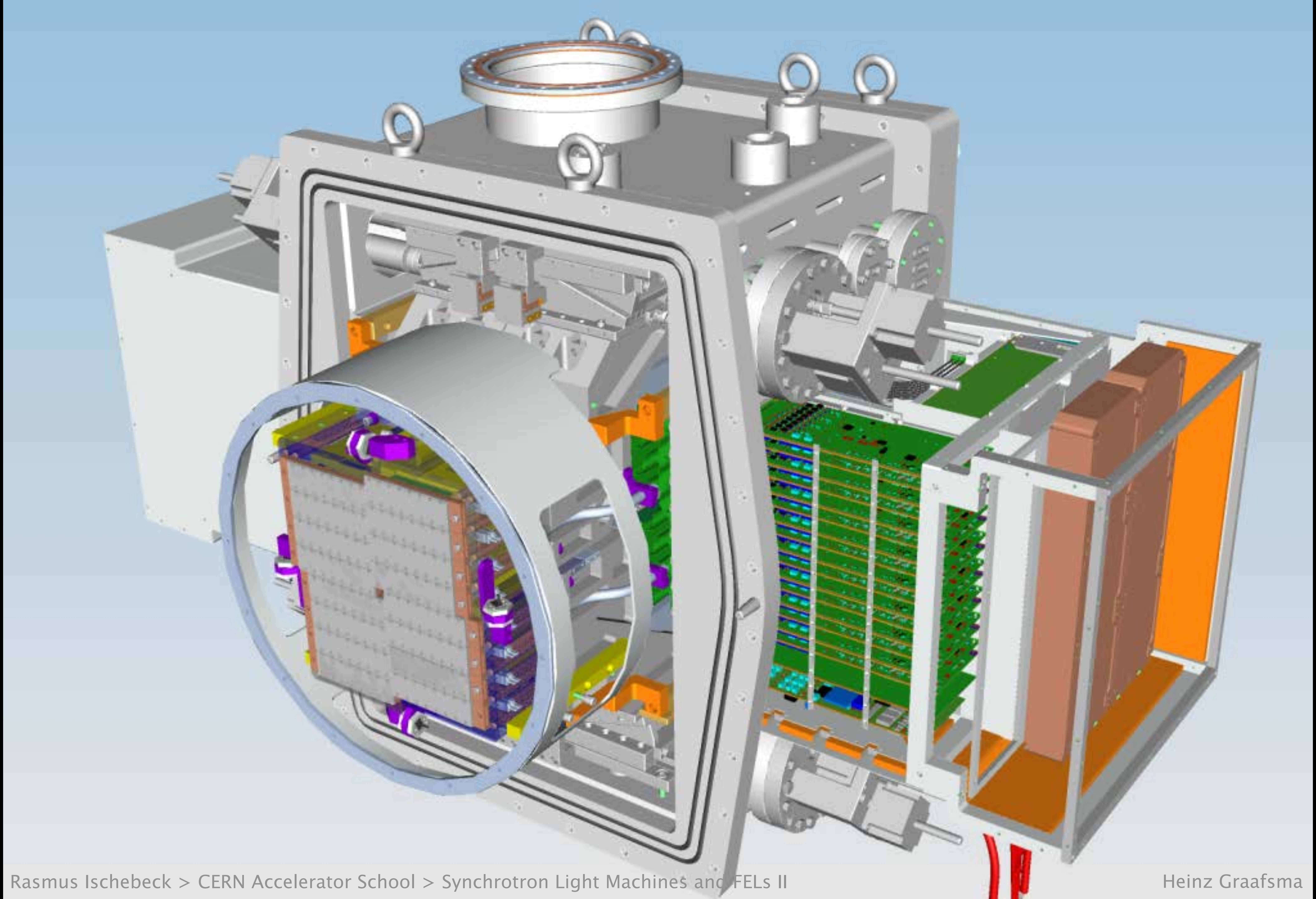


Peter Heimgartner

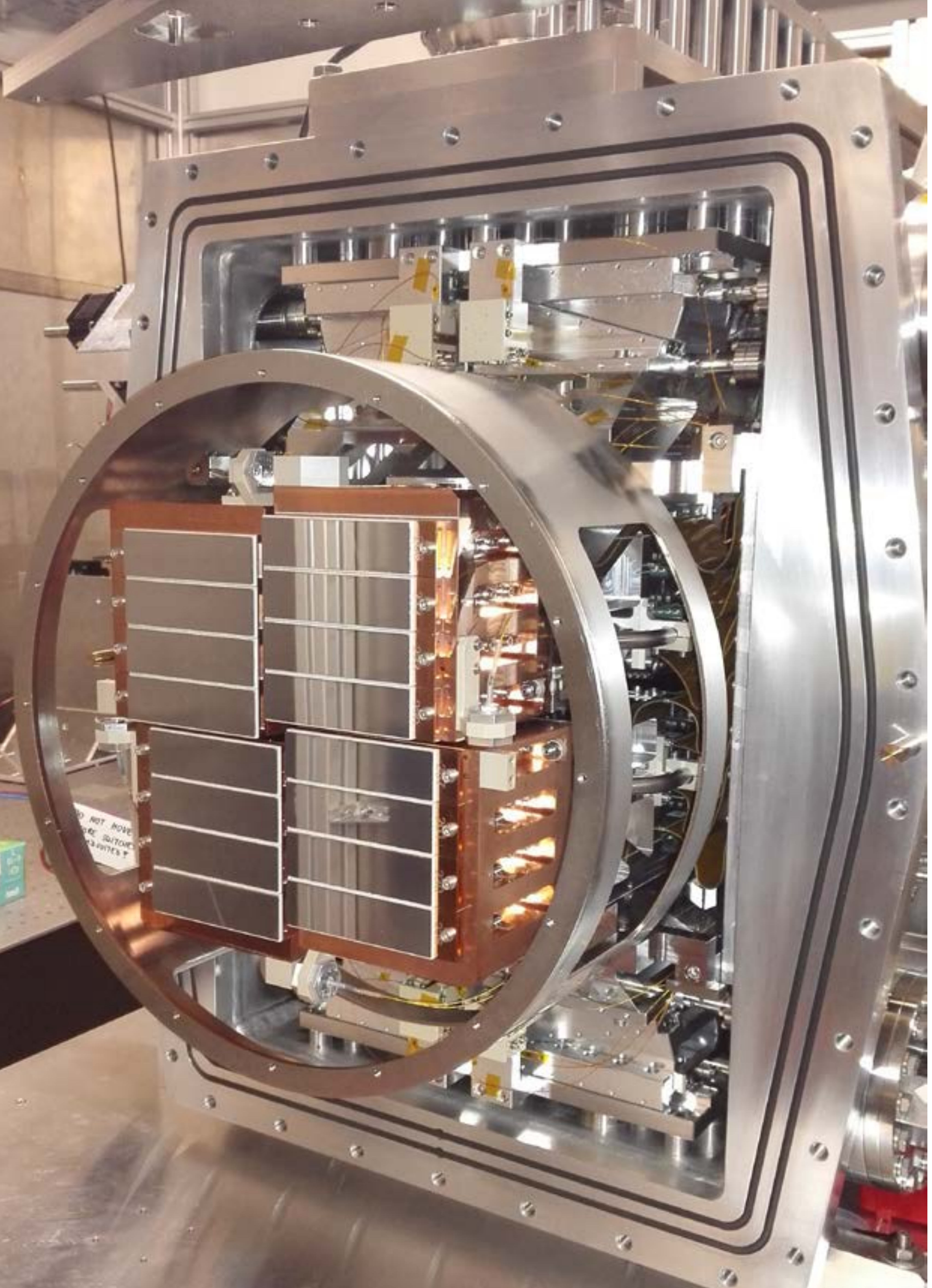


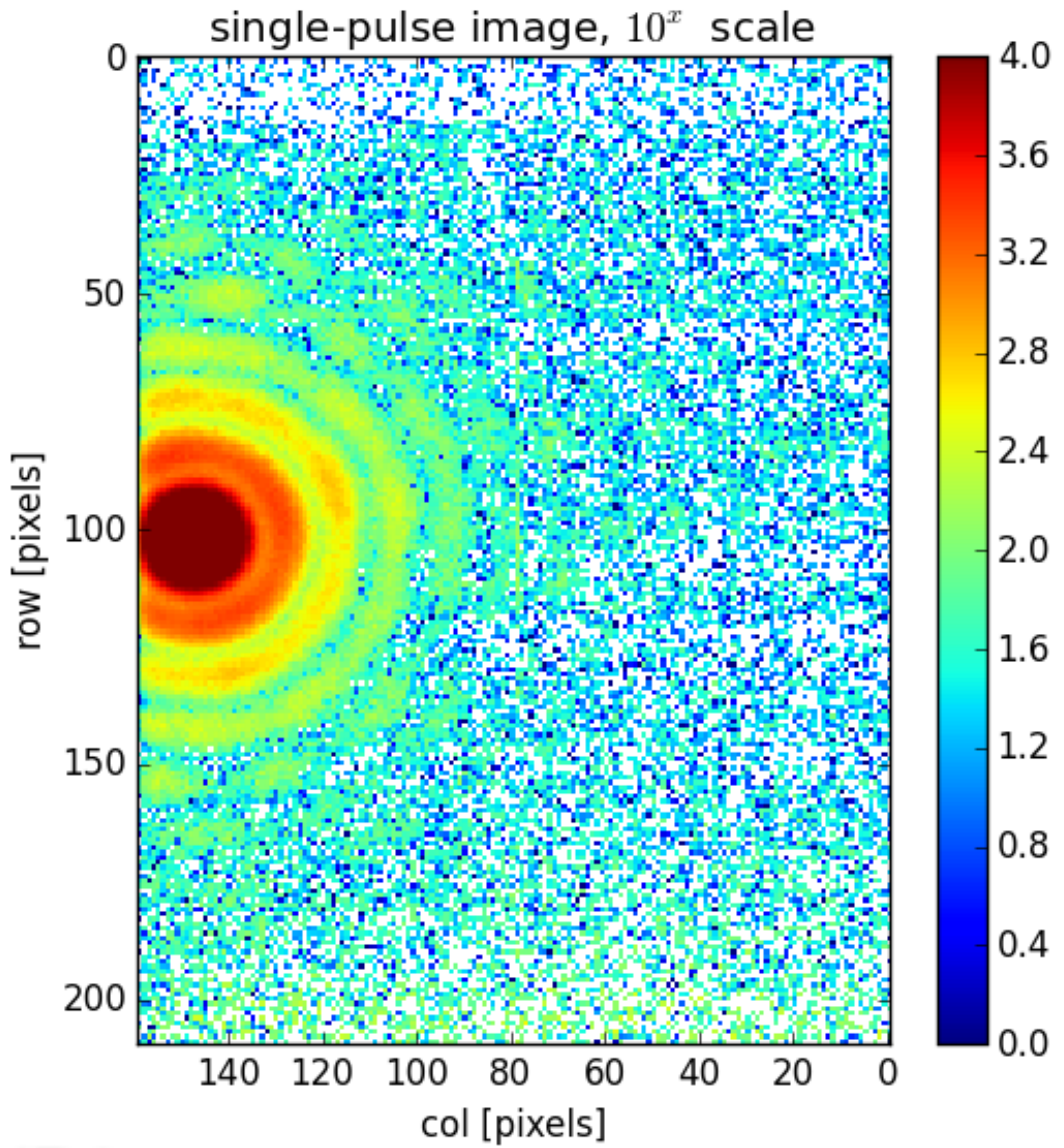
Top view
Refocusing
Mirror (TBD)
ES1
AT1
Exit slit
Focusing
mirror
-0.8°
AT2
ES2
AT3
ES3
1.5°
PGM
1.5°
Off-set
mirror
Collimated
beam
1.5°
X (mm)
0
3891
1889
196
0
X (mm)
Side view
AT1
Y (mm)
1404
Y (mm)
1439
Y (mm)
1200
0.15° (from roll)
10 mm off set
AT2
Shared part
AT3
Y (mm)
1406
- 0.04° (from roll)
Tunnel wall
BS shielding
Optical hutch wall
0
51.4
55
58.8
62.5
110
120
135
149
164
Z (m)


Sample-flowing systems
Microdroplet
Open jet
Capillary
Gas nozzle
<100fs
Laser
Detector
t
XFEL
~100 Hz, <100fs



Heinz Graafsma

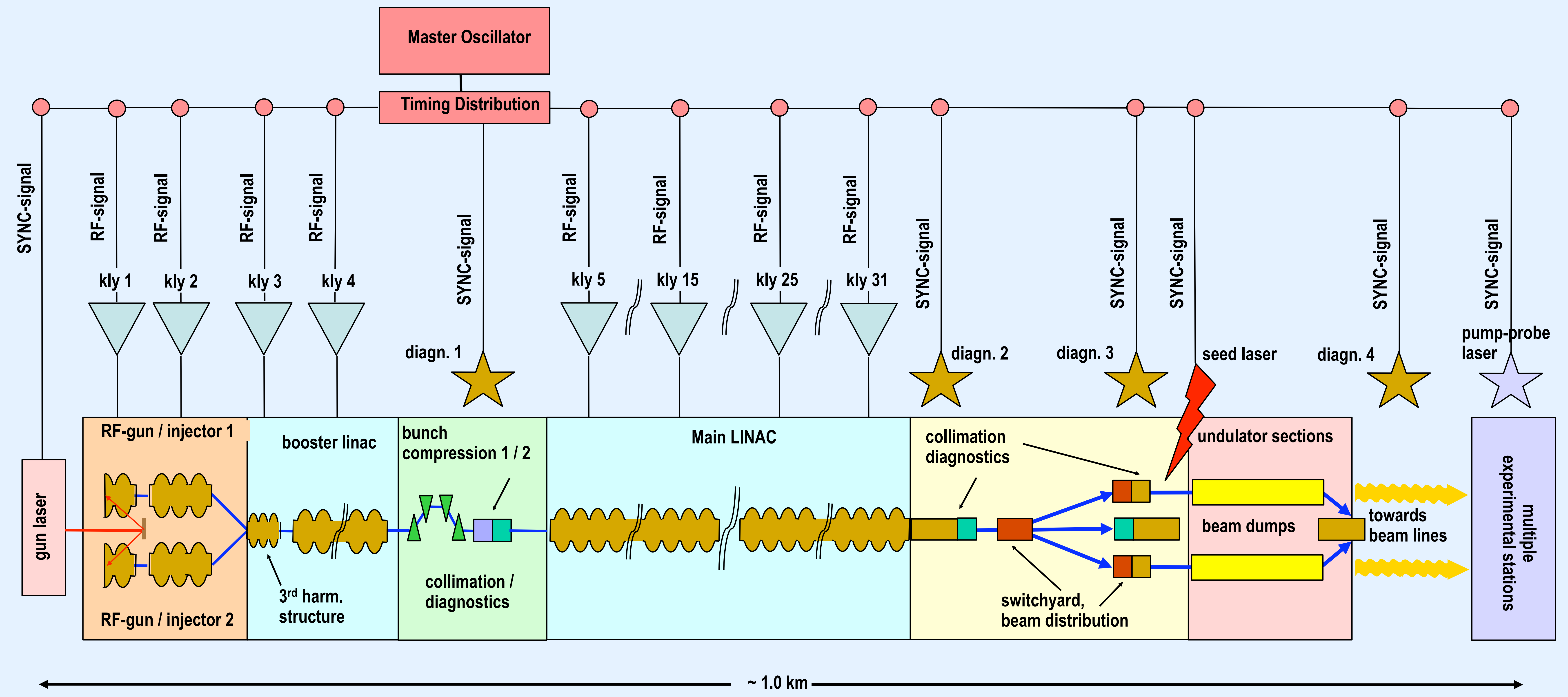


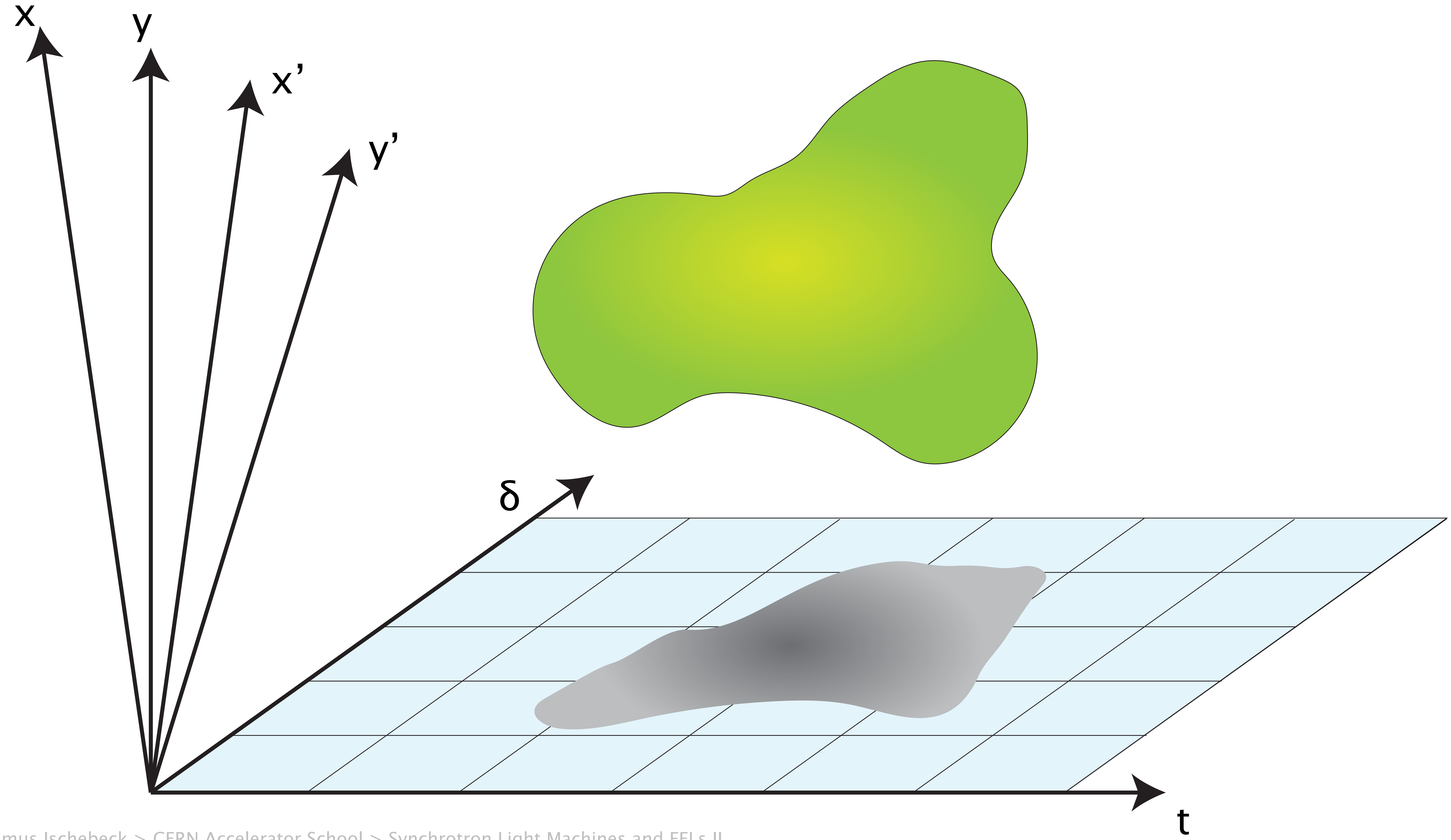


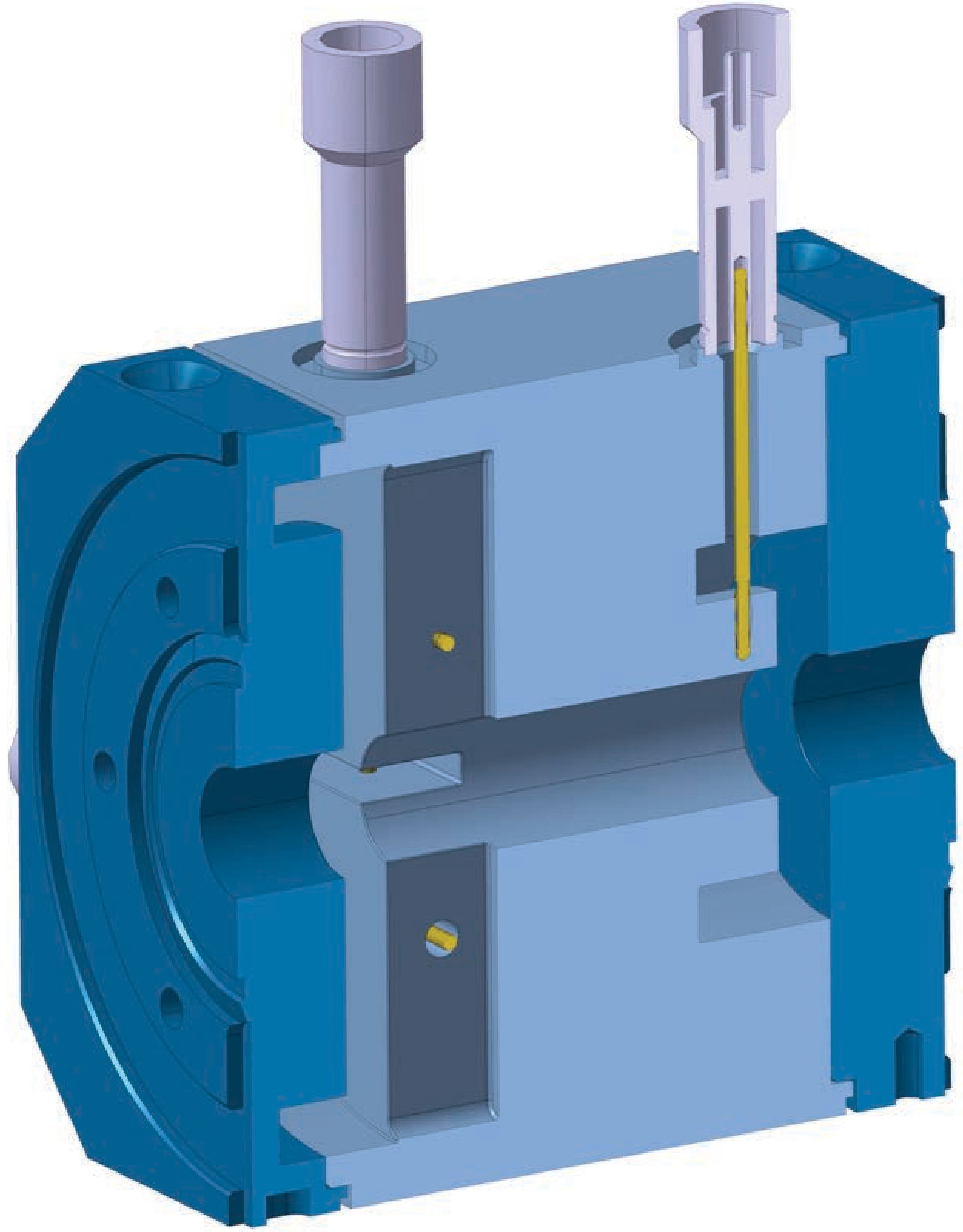
Heinz Graafsma

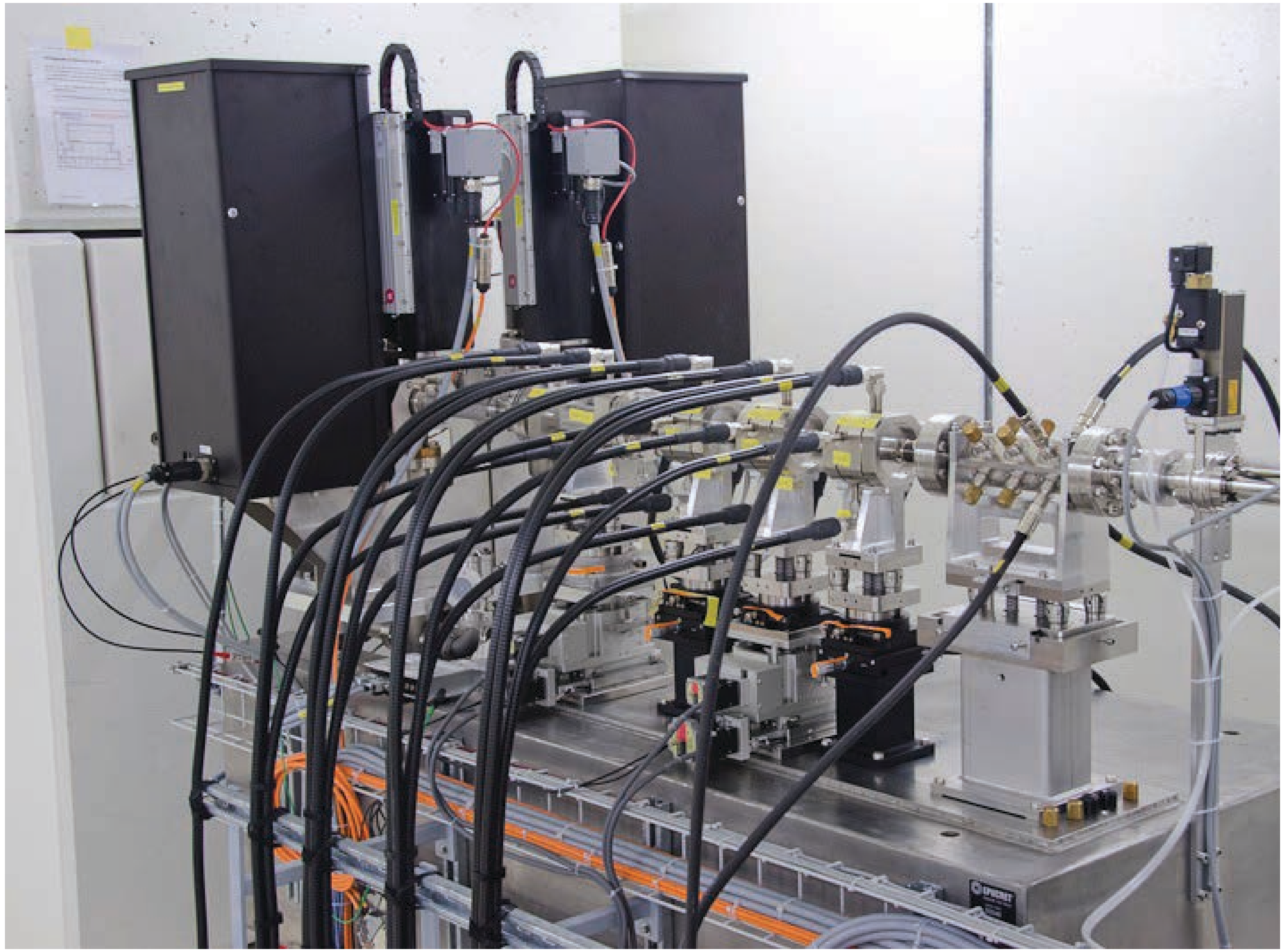
Synchronized Elements

- Photocathode laser
- RF accelerating cavities
- Transverse deflecting structures
- EO bunch length diagnostics
- Seed lasers
- Experiments

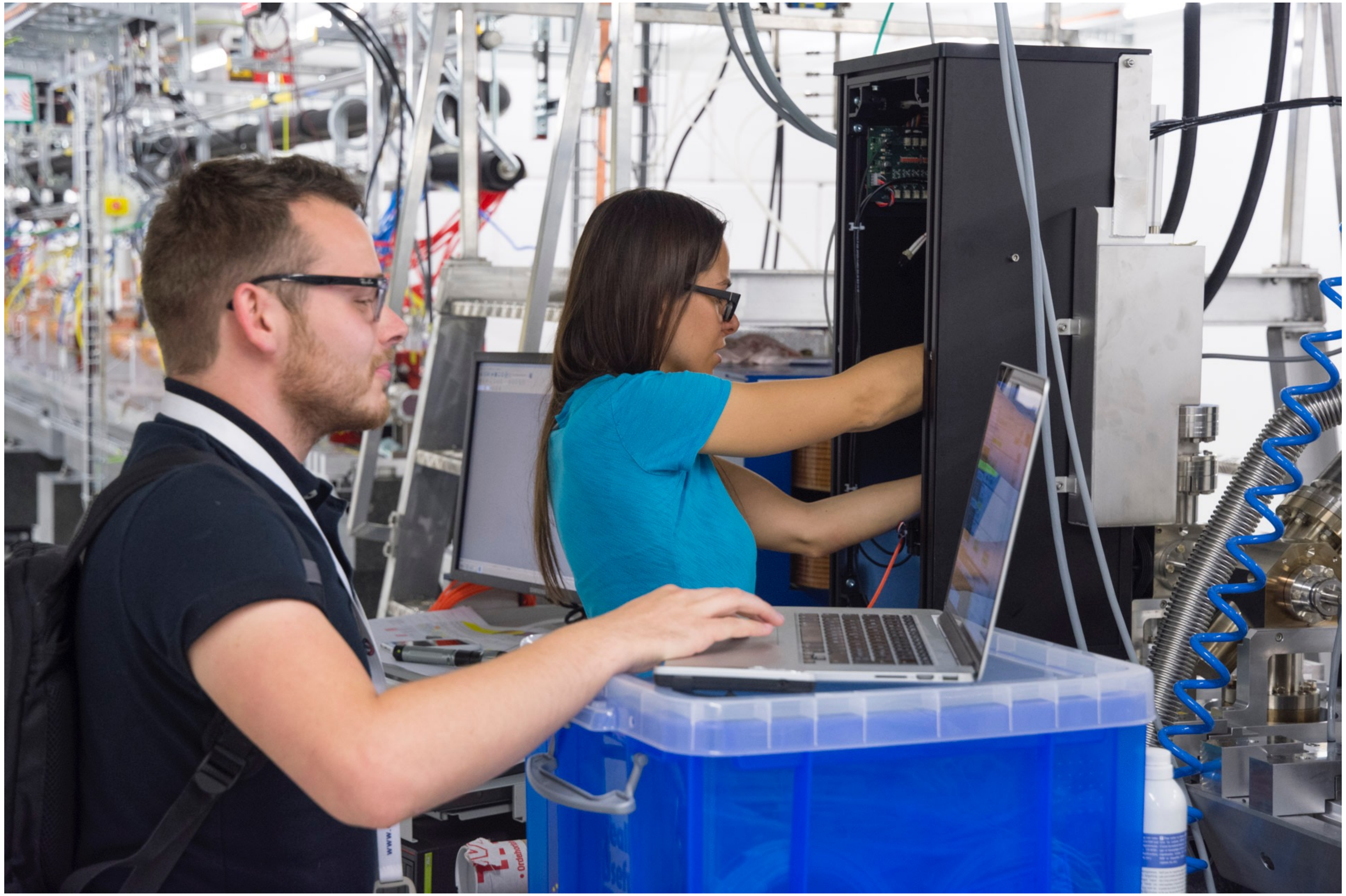


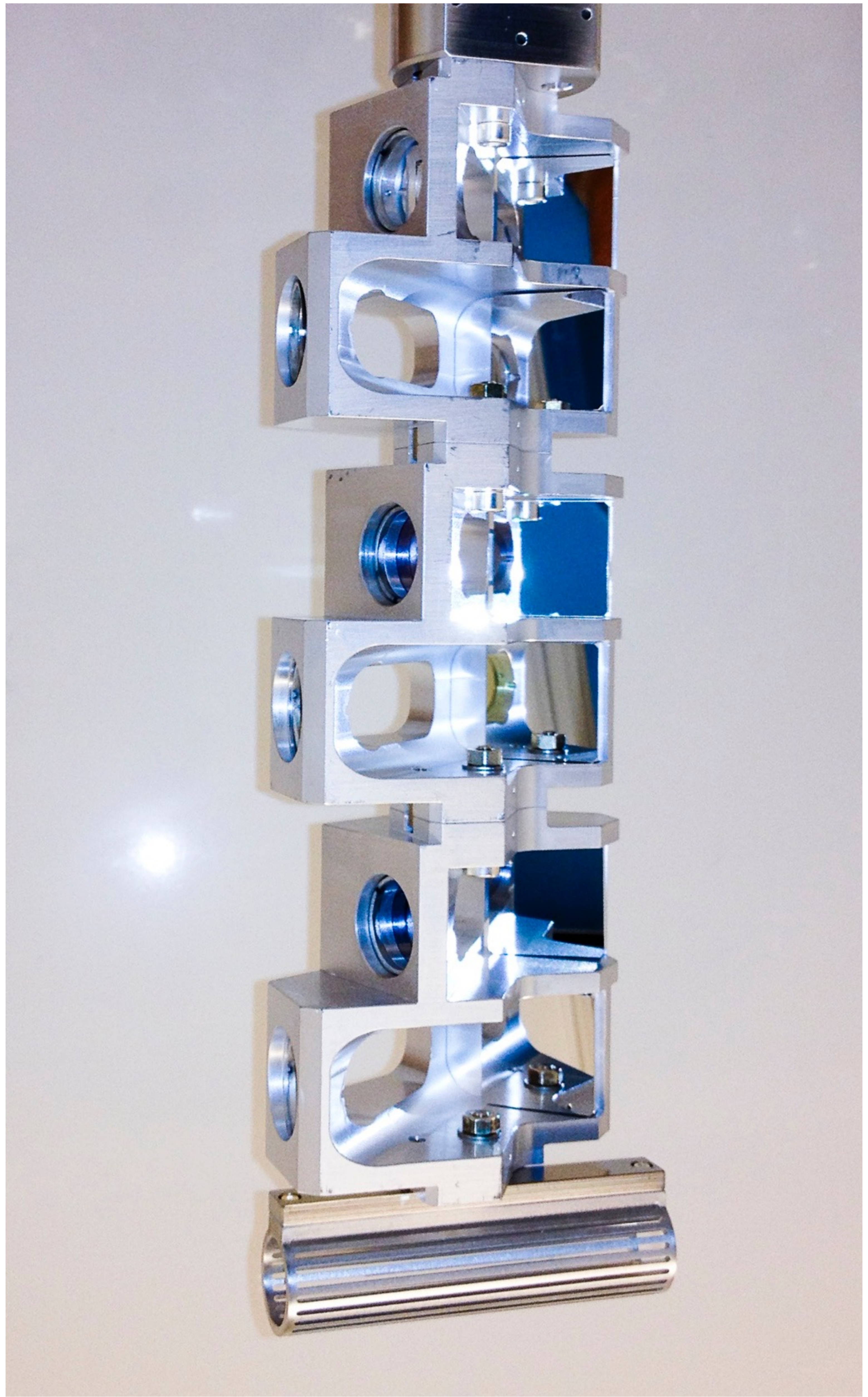

x
y
x'
y'
δ
t





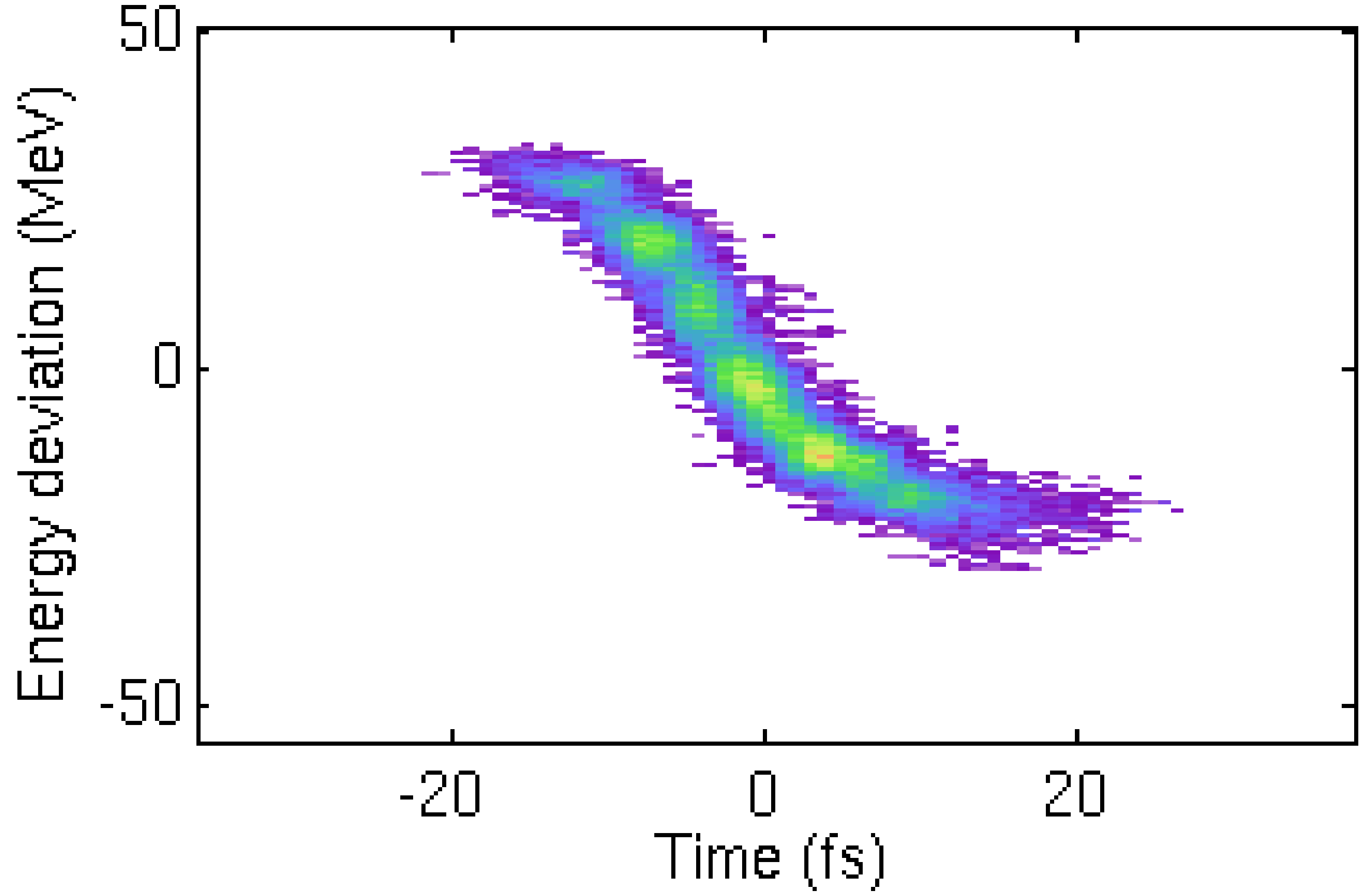
Boris Keil



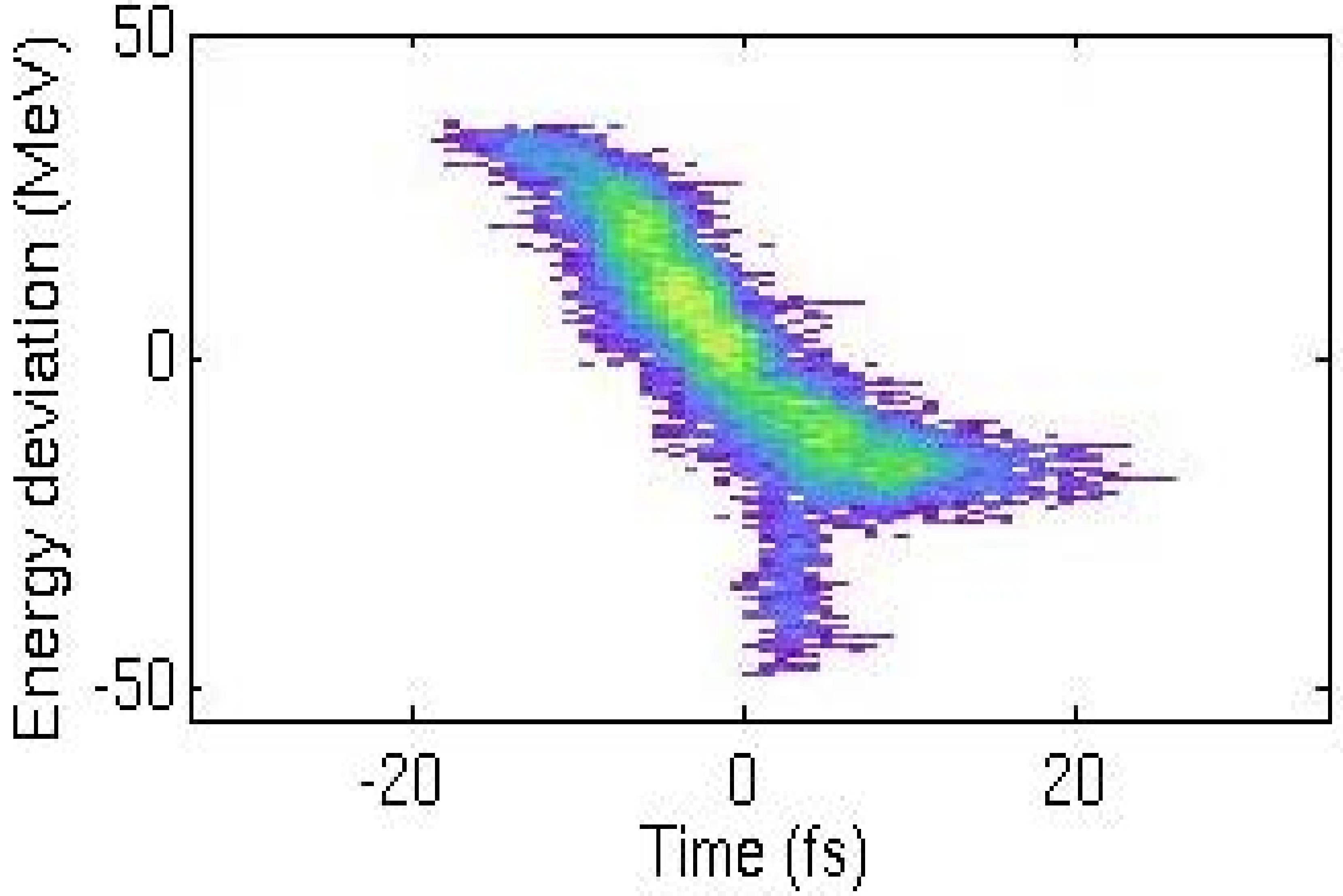


Patrick Krejcik

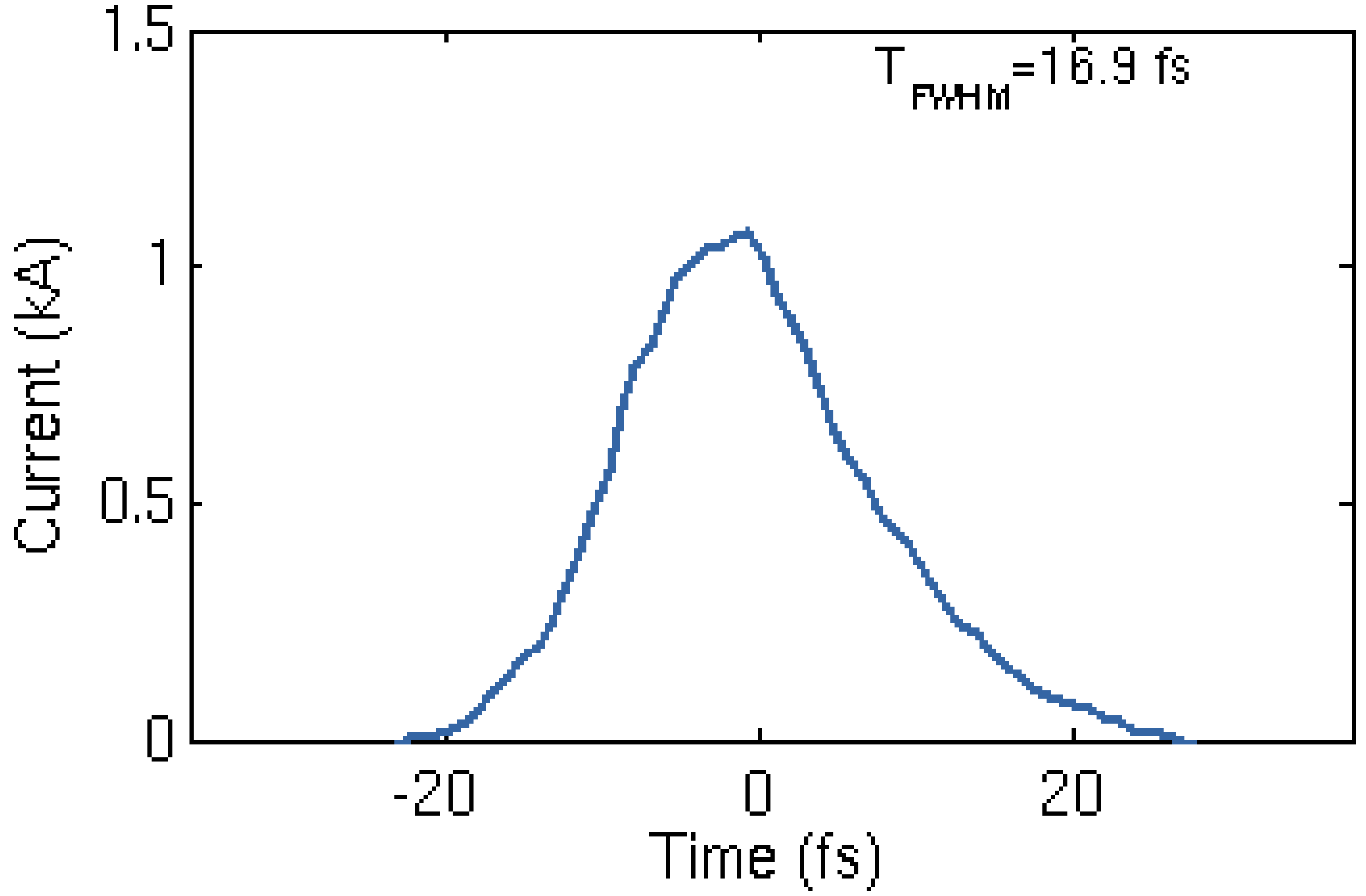
Lasing off



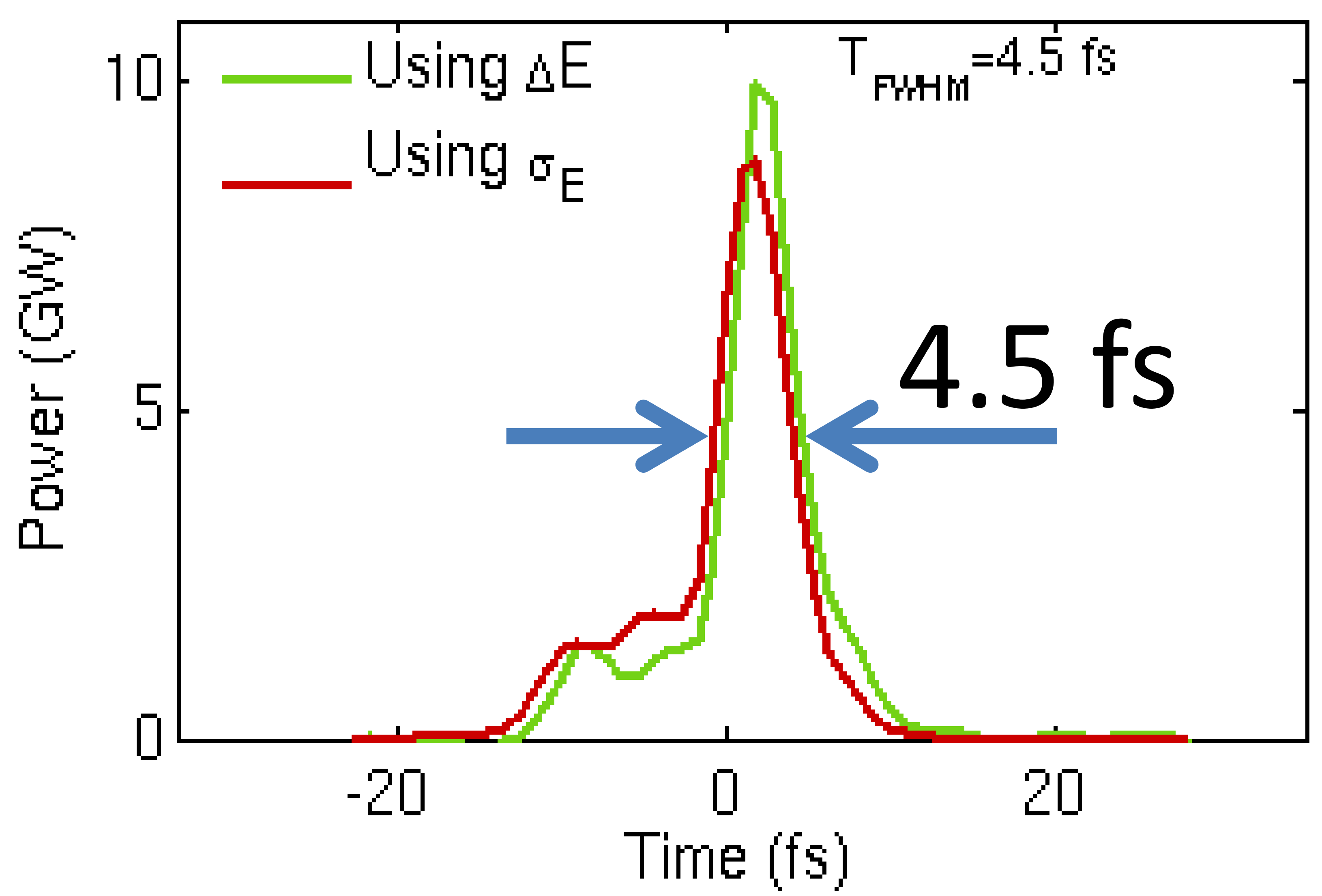
Lasing on



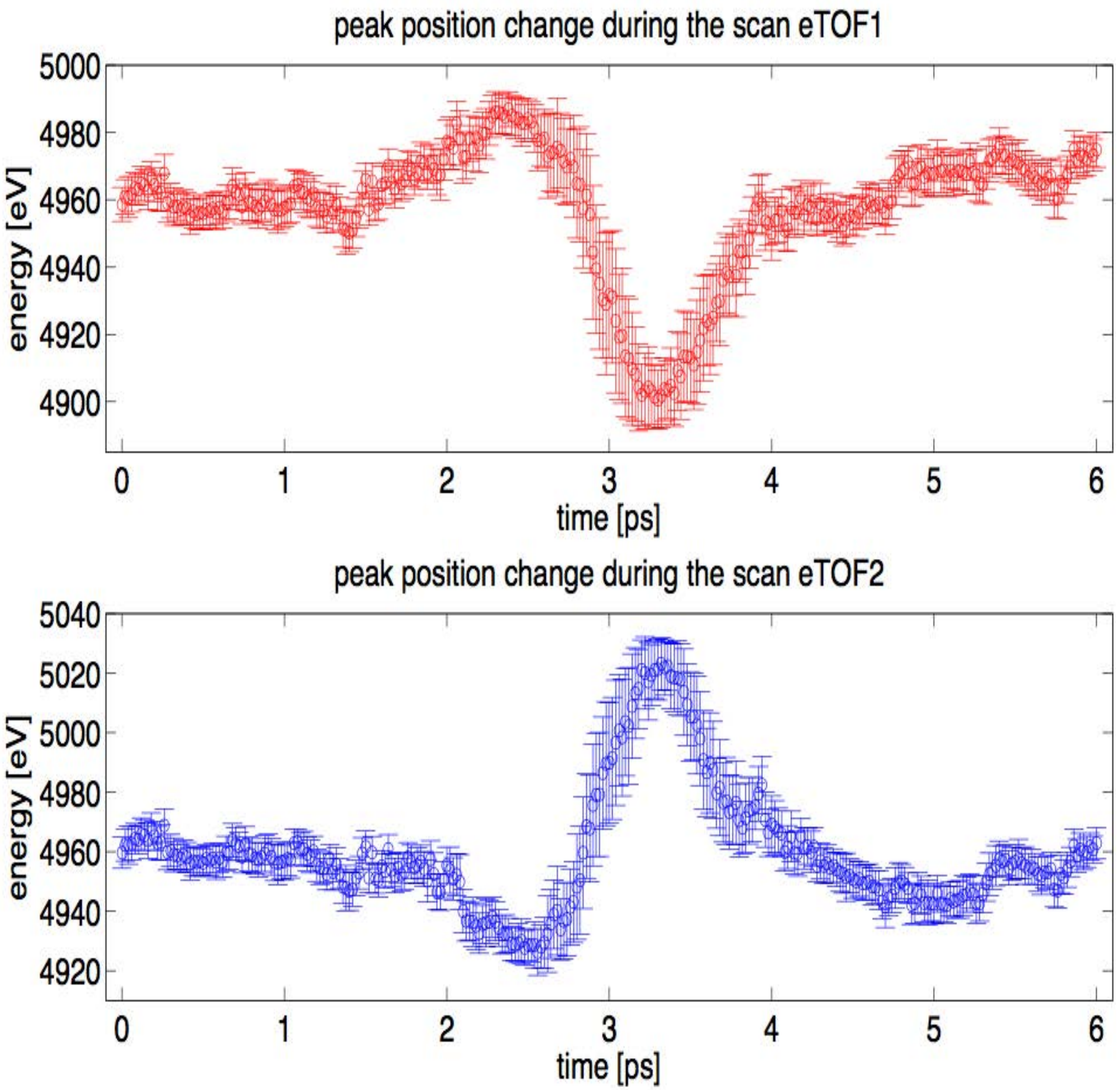
electrons

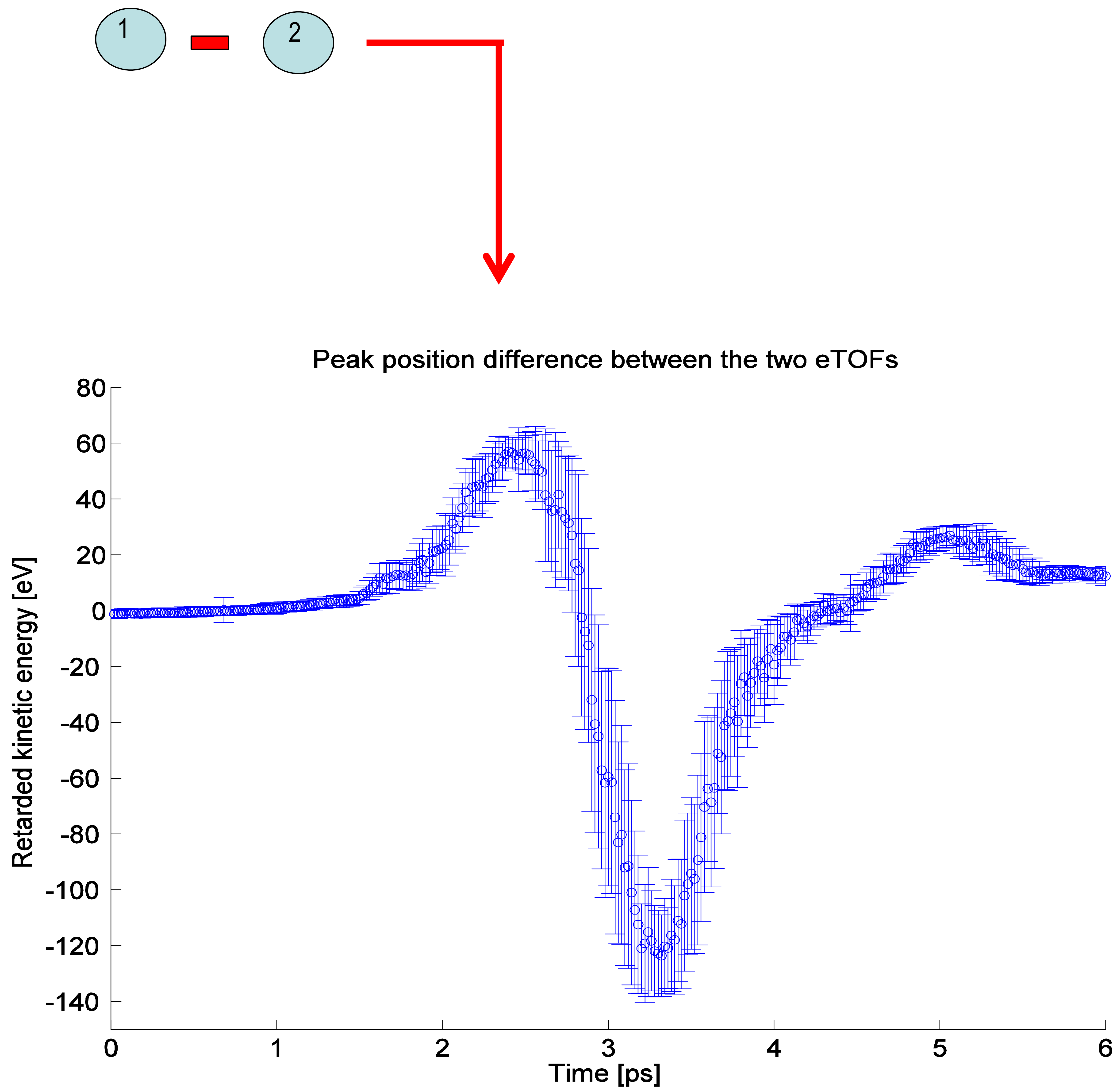


X-rays

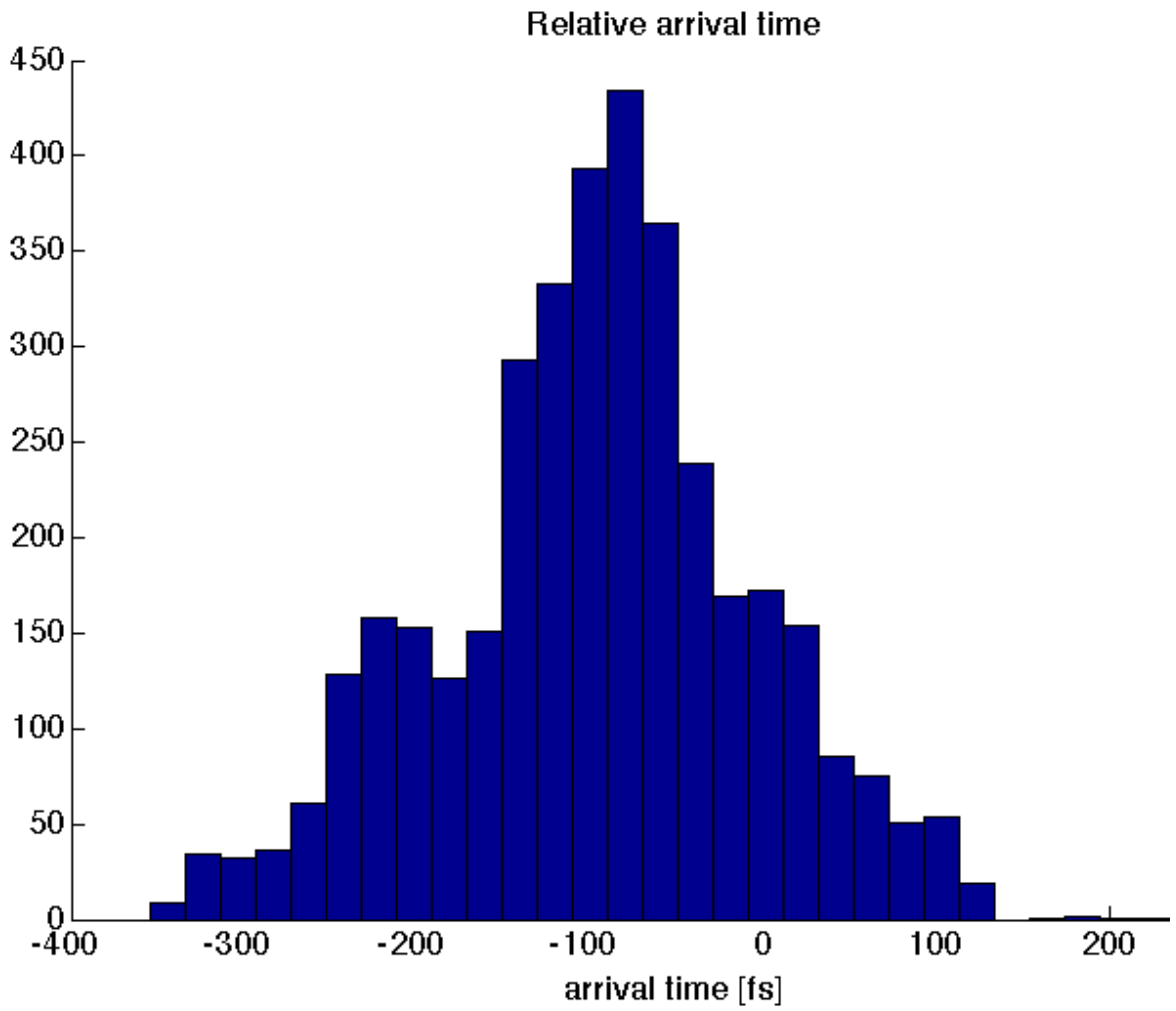


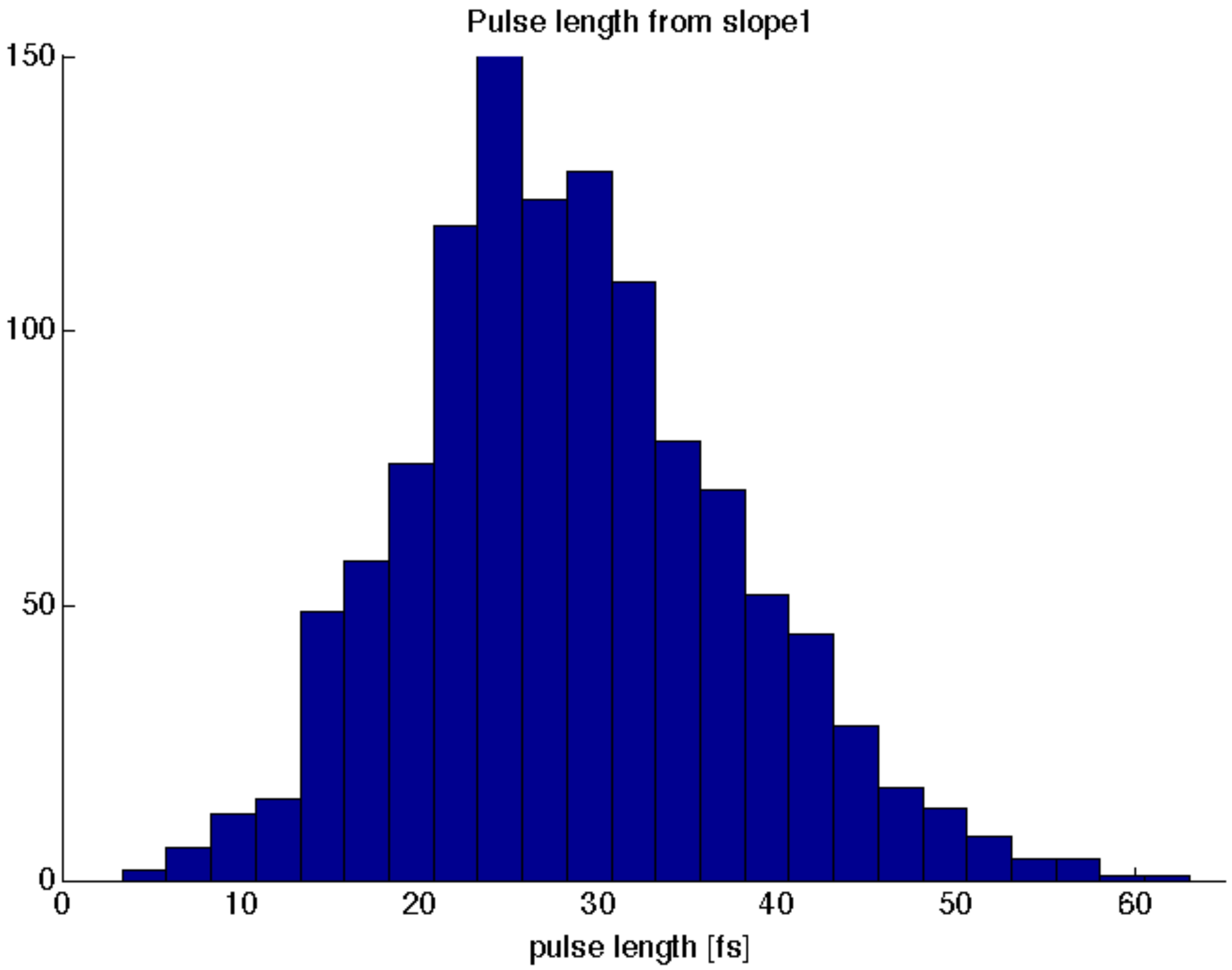

STEFAN KAESDORF
LeCroy
Encoders:



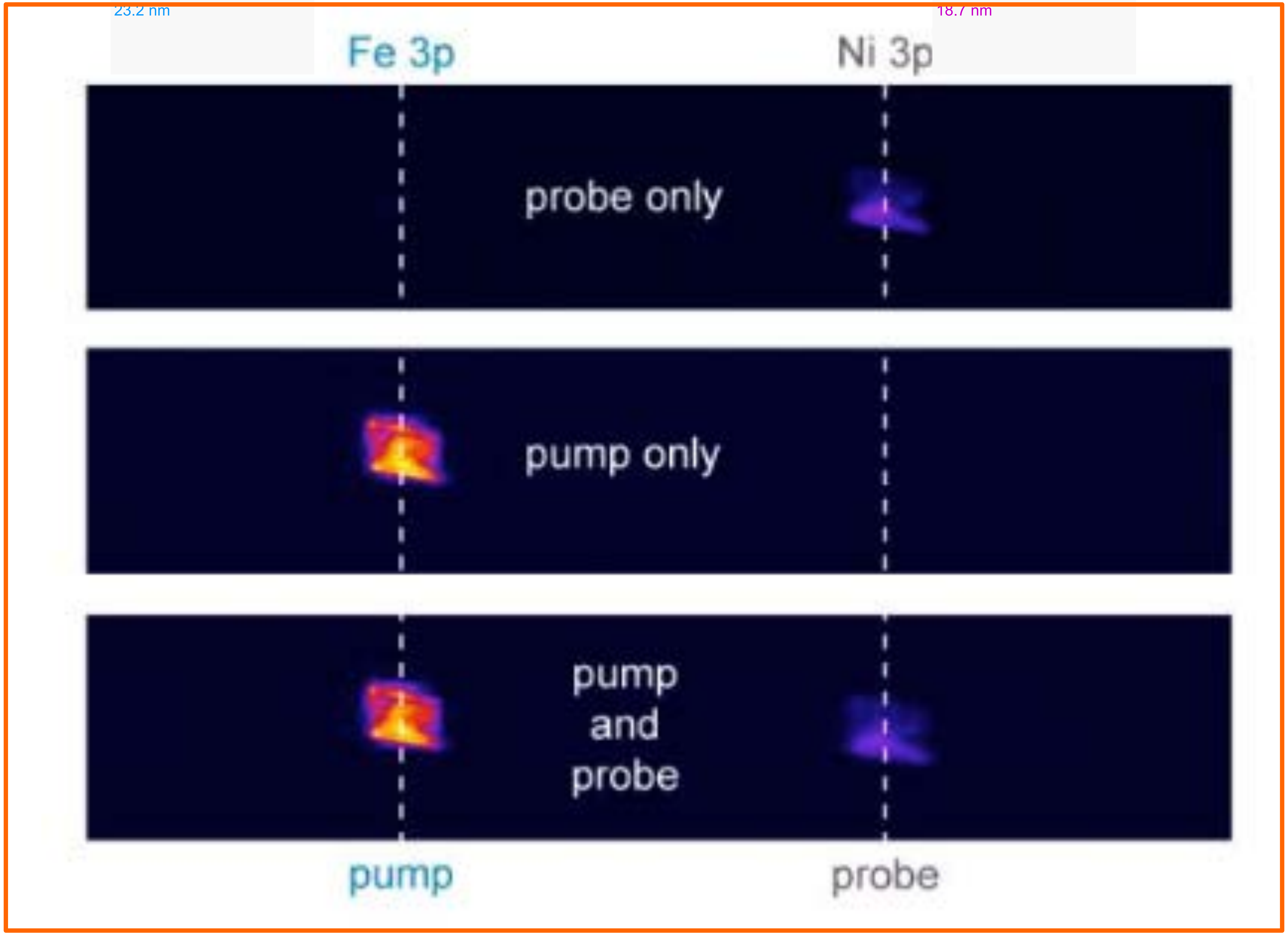


Pavle Juranić et al., JINST 9 P03006 (2014)

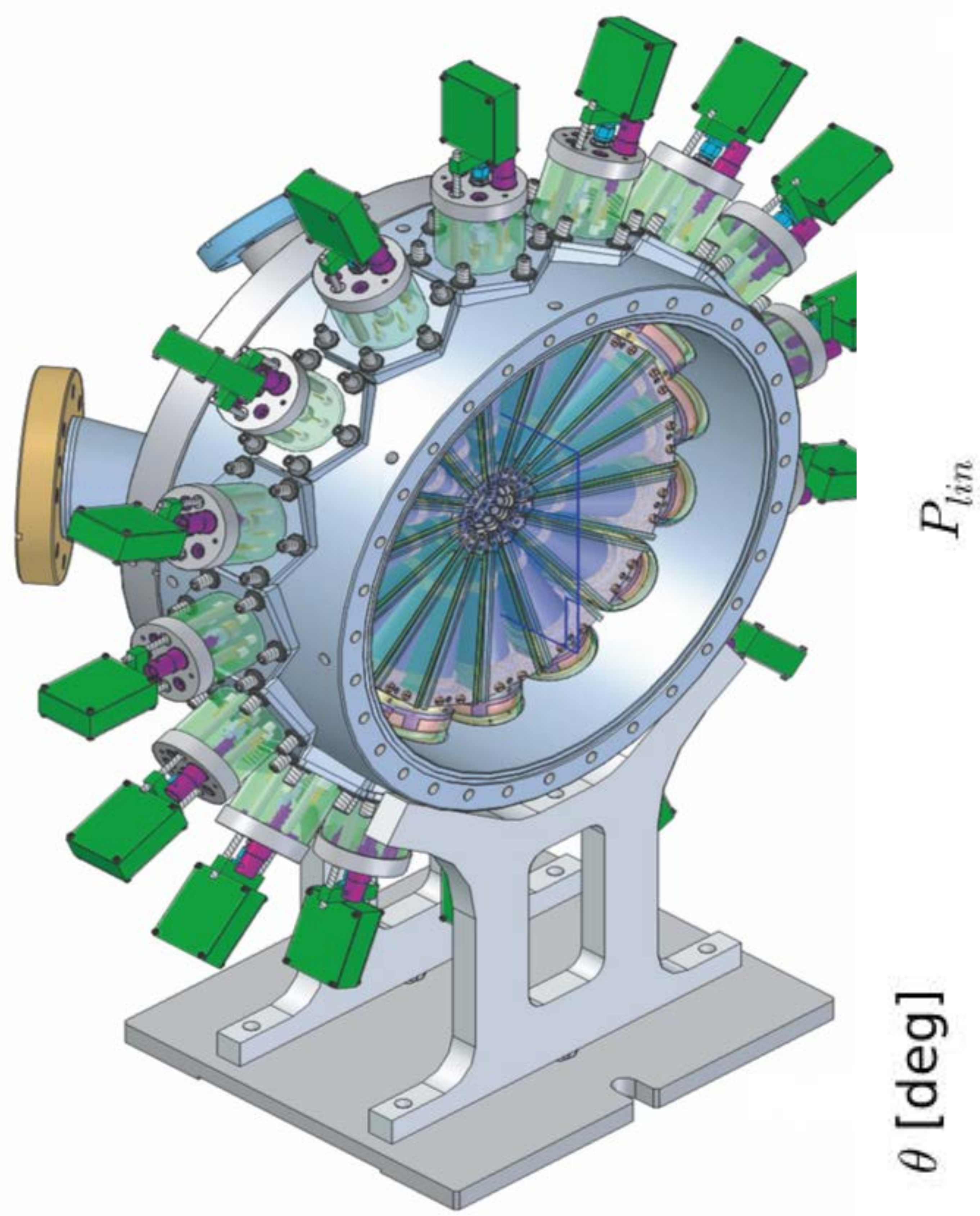




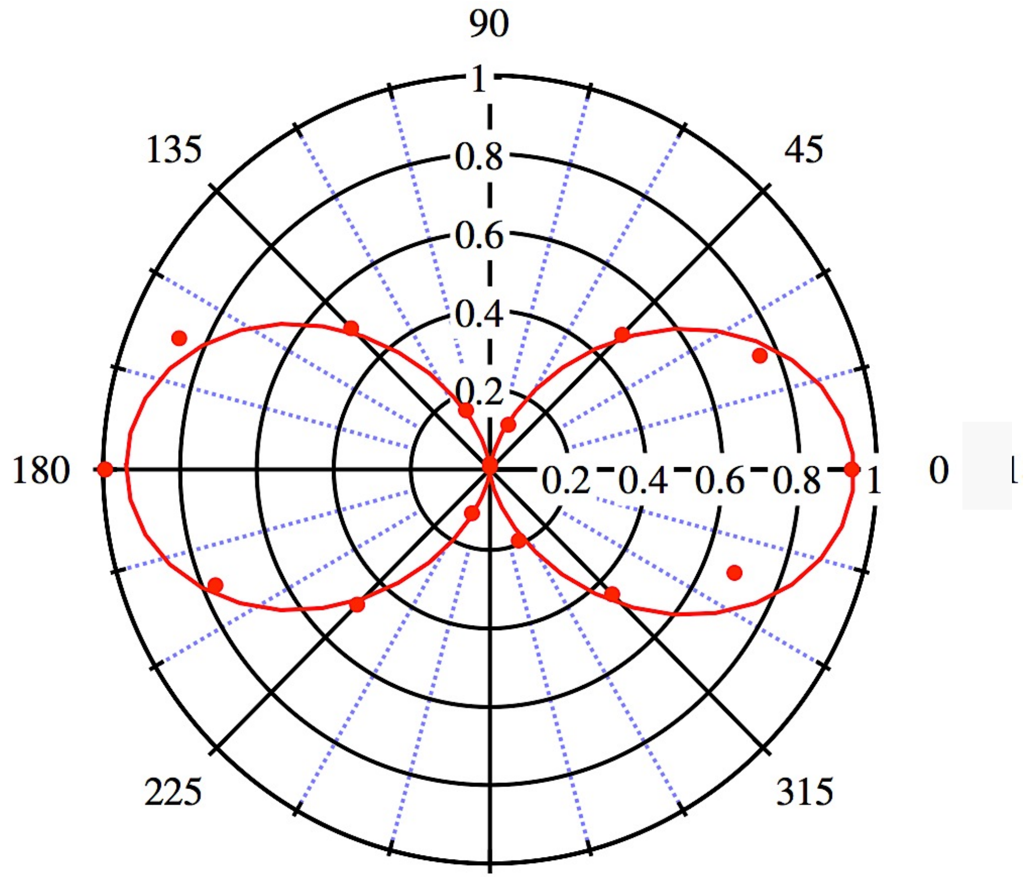
Pavle Juranić et al., FEL 2014

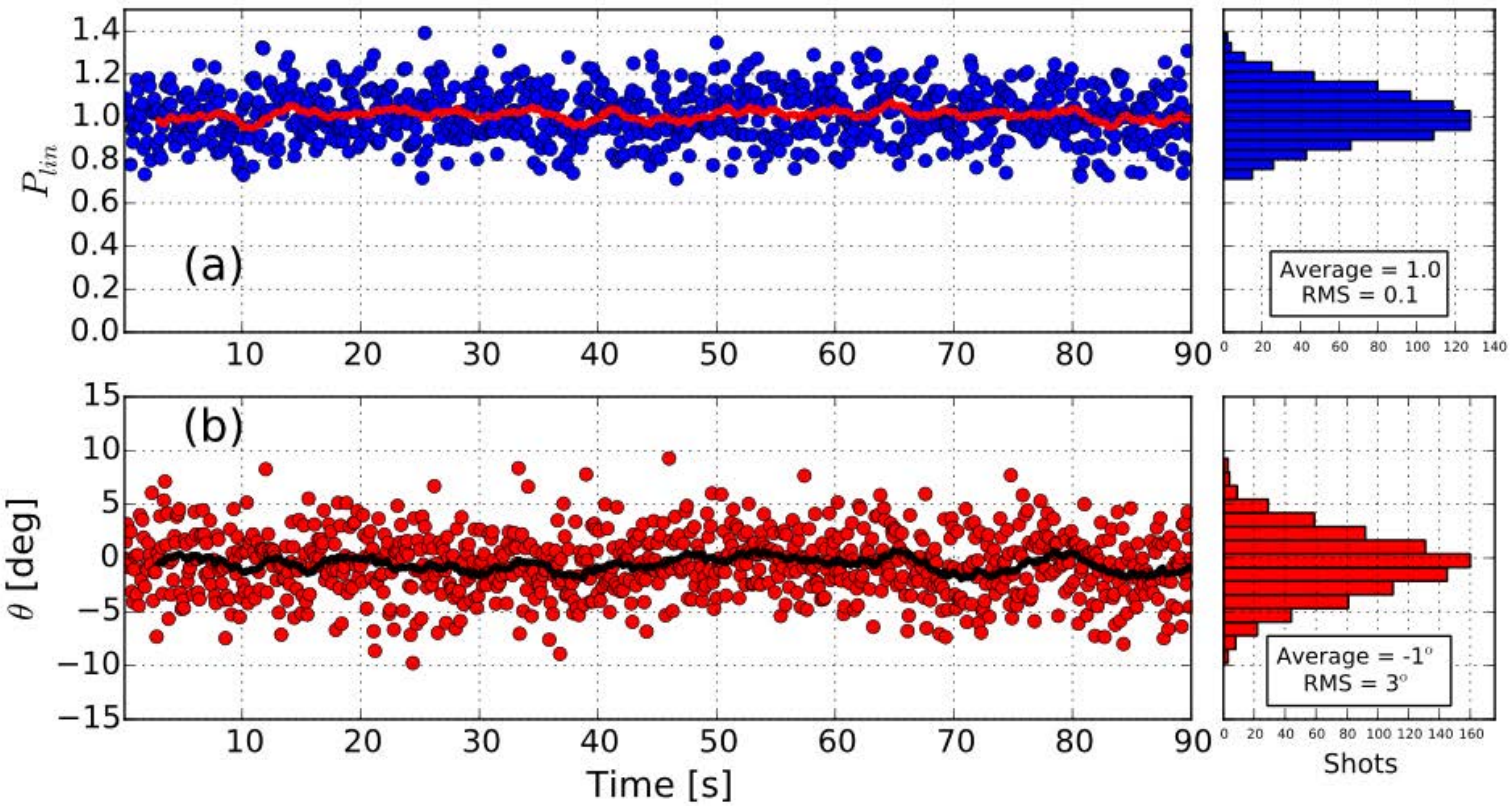

23.2 nm
18.7 nm
Fe 3p
Ni 3p
probe only
pump only
pump
and
probe
pump
probe

Shot-to-shot characterization of the polarization

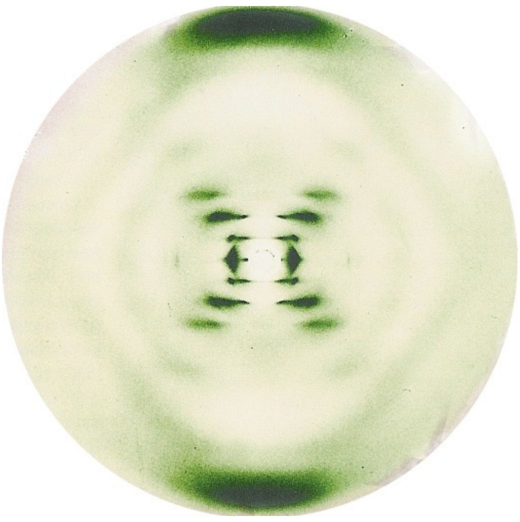


Horizontal Polarization

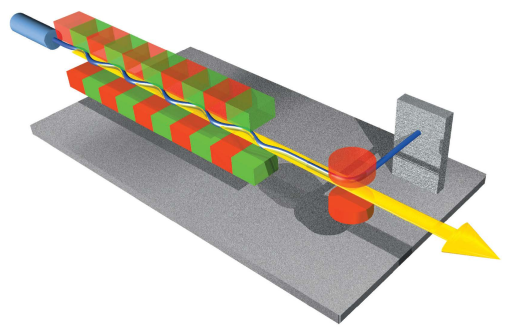




Stability most probably dominated by the statistical fluctuations on the e-TOF signal



>Motivation



>Physical processes in a free electron laser

>Free electron lasers for XUV and X-Rays

>Components of a free electron laser

Slides available at: http://www.ischebeck.net

Thank you for slides, illustrations, photos and movies:

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Questions?

Nick Veasey