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Florian Löhl :: Paul Scherrer Institut

Introduction to SwissFEL

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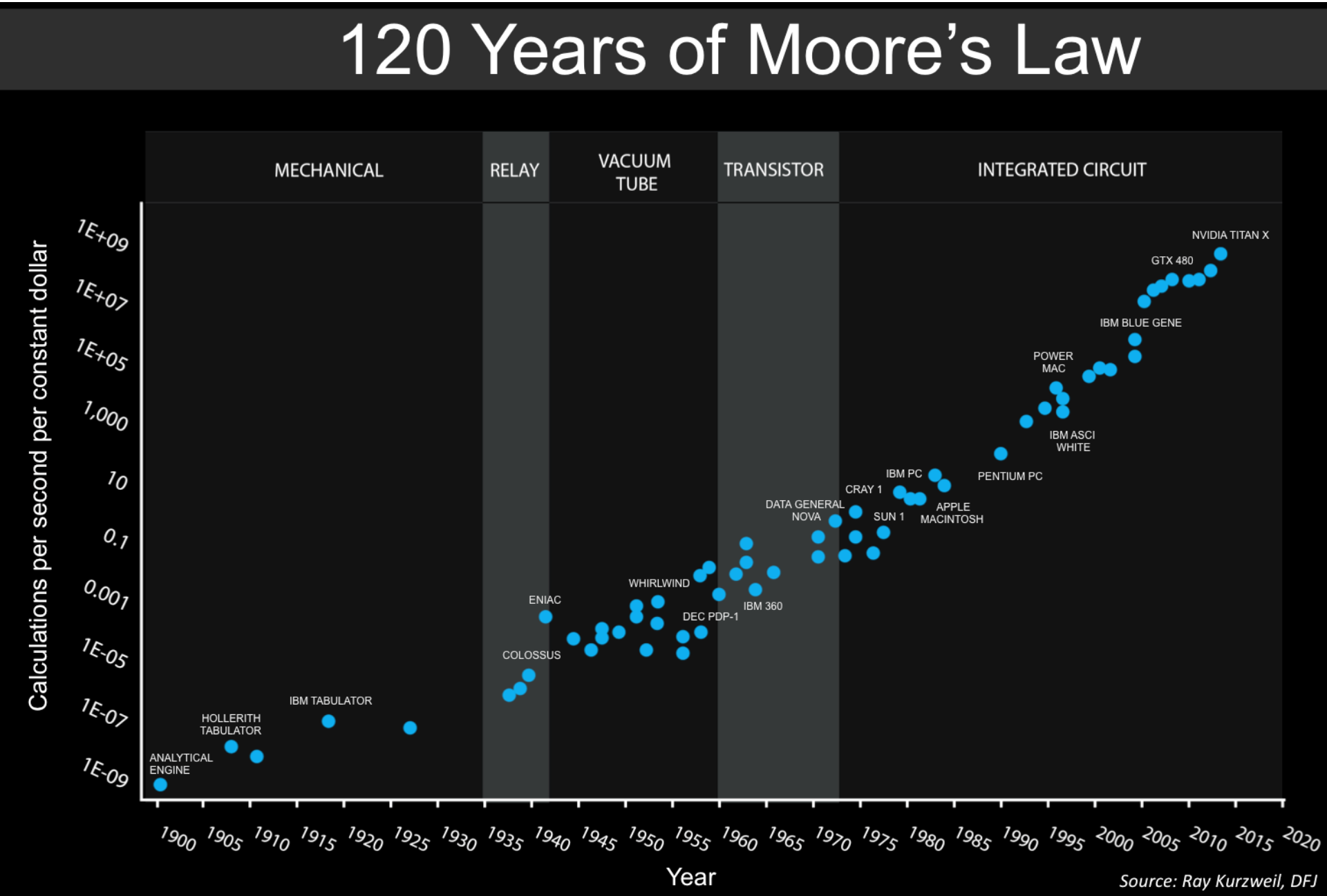
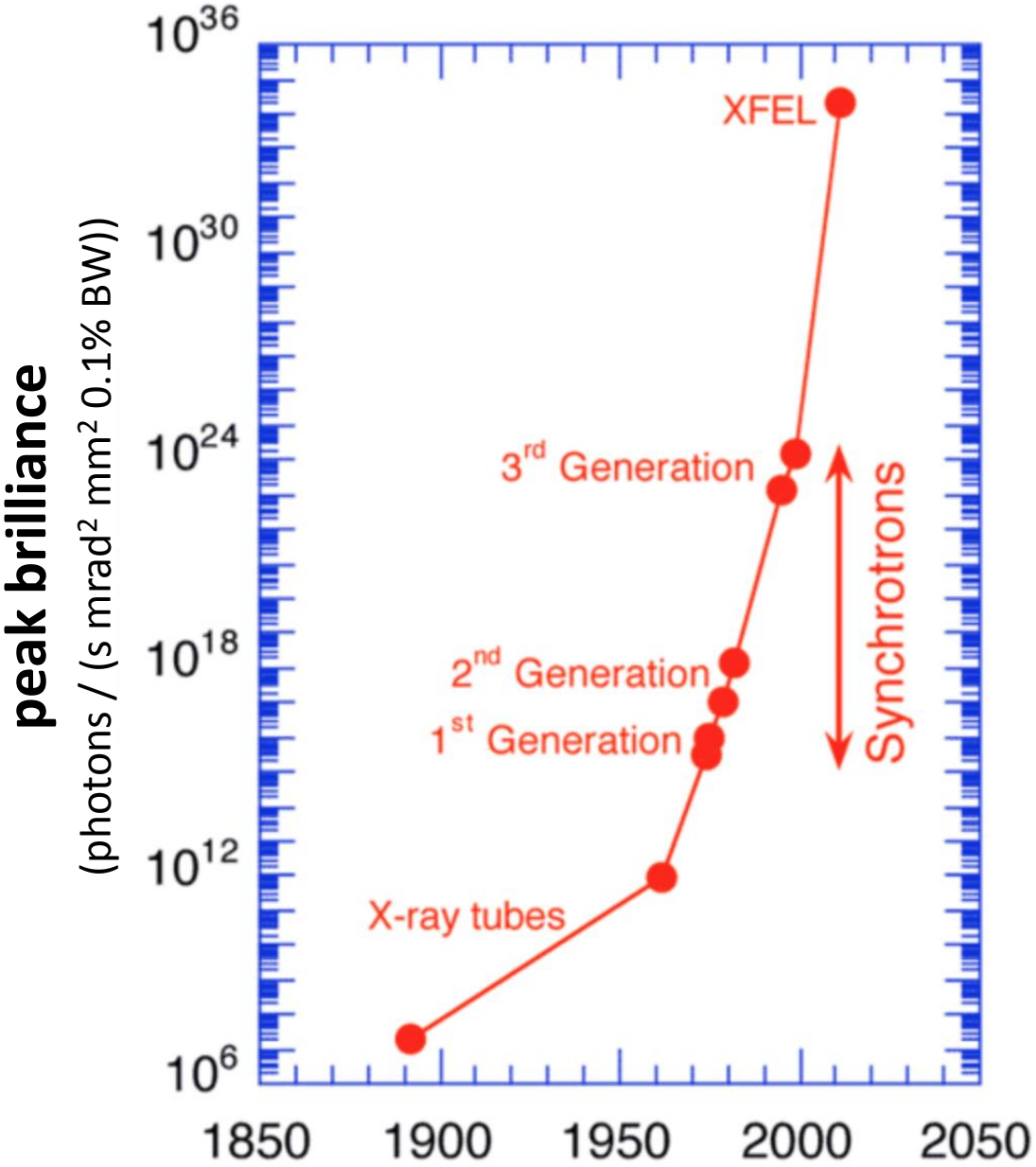
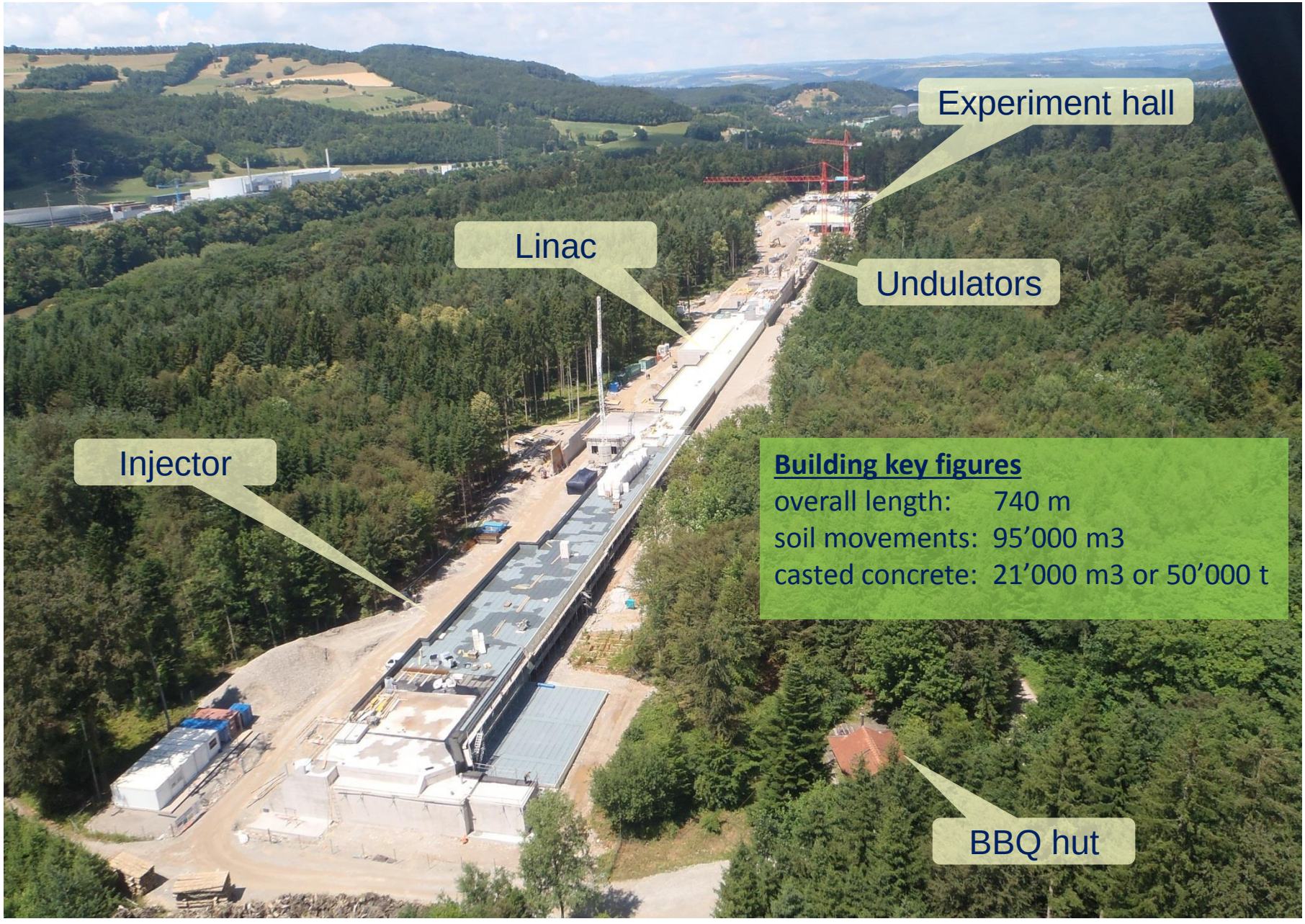
A very fast development…



An even faster development…



SwissFEL construction site (July 2014)



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SwissFEL construction site (June 2015)

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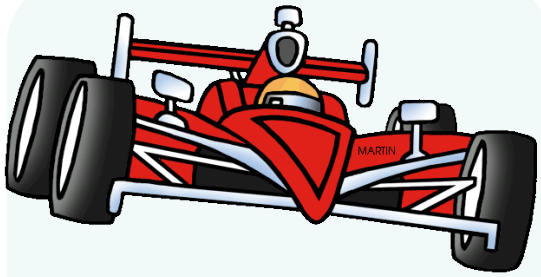
What is inside of the building?



accelerator

light generator

experimental station

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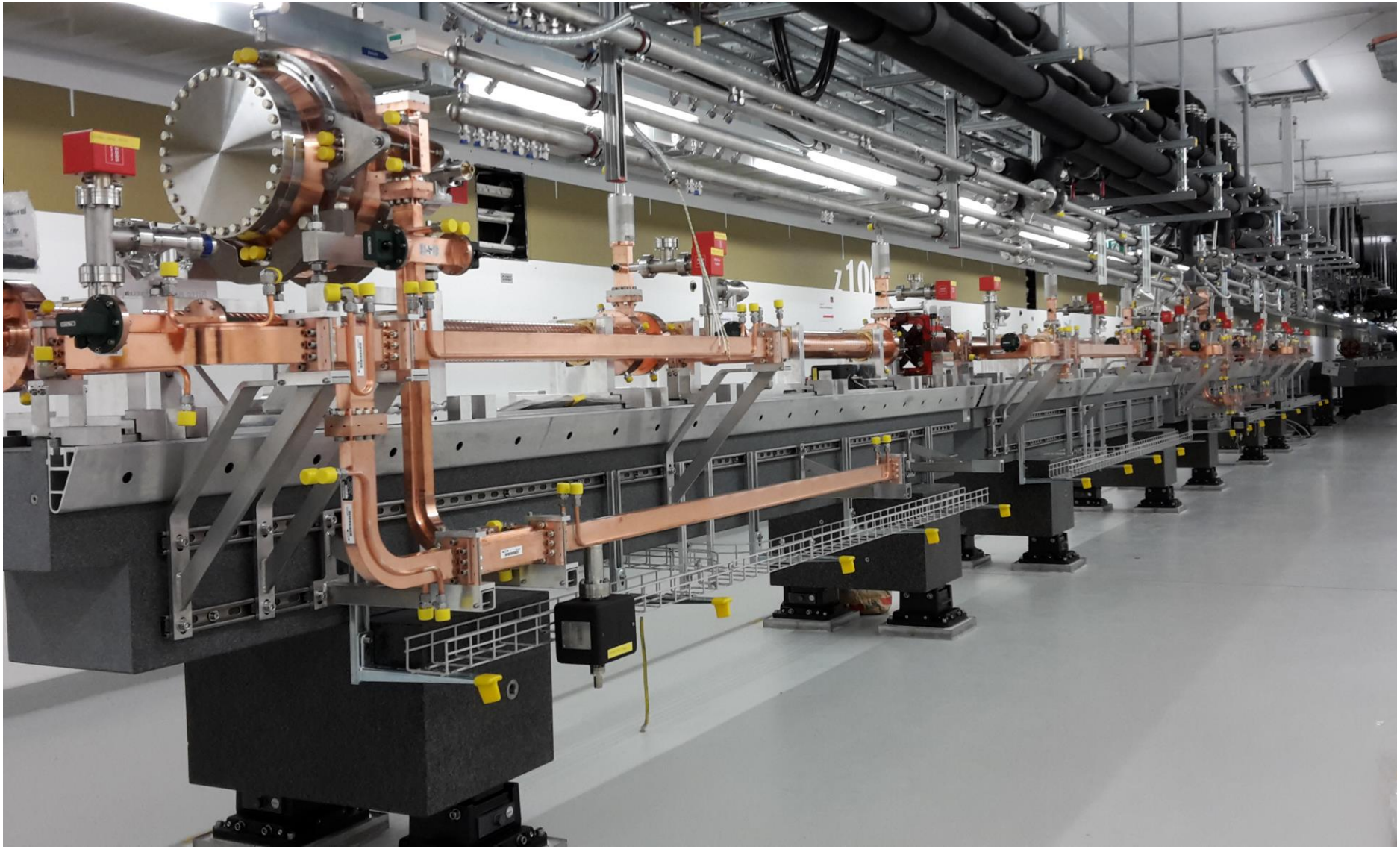
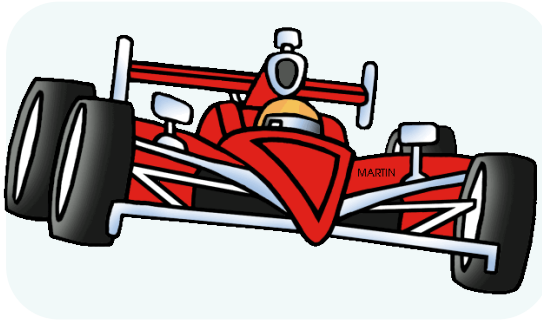
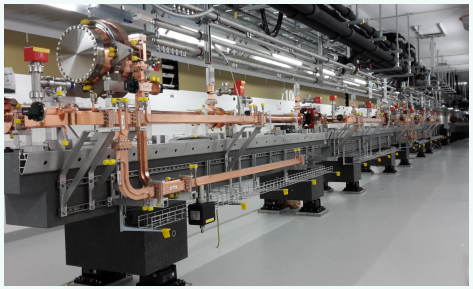
The accelerator…

looks in reality like this:



A comparison





Accelerated object	racing driver	electrons
Maximum acceleration	1.5 g	1.8×10^{18} g
Maximum velocity	370 km / h	300'000 km / s Nominal energy: 5.8 GeV reached: 18.9.2018
Gasoline consumption	43 l / 100 km	electric (50 µW / electron) (3 - 5 MW)

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The light generator…

is in reality a slalom track with 7000 curves:

The payoff

Typical light power	ca. 5 W	50’000’000’000 W
Illuminated area	typ. many m^2	few μm^2 Corresponds to focus of all the energy the sun sends to earth to an area of 2 x 2 mm^2
Wavelength	ca. 500 nm	0.1 nm (≙ 12.4 keV)
Exposure time	CW	few (10) fs

Comparison of different light sources

Optical short pulse lasers

Pulse duration:	+++	(few fs)
Pulse energy:	+++	(many mJ)
Wavelength:	- - -	(~800 nm)

→ Fastest processes can be analyzed

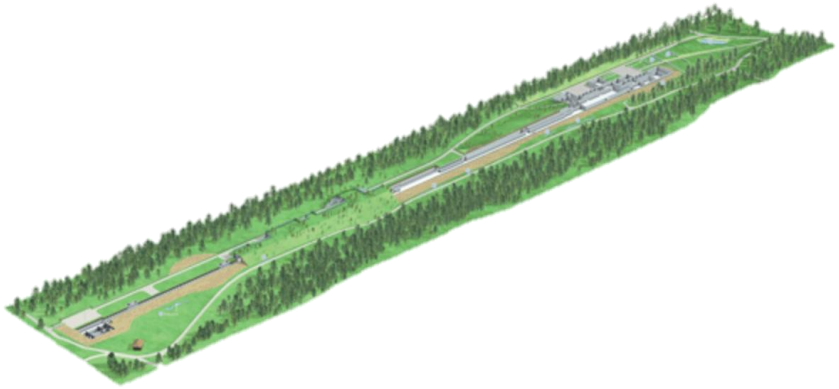
→ Spatial resolution very limited

Synchrotrons

Pulse duration:	o	(few ps)
Pulse energy:	o	(< nJ)
Wavelength:	+++	(~ 0.1 nm)

→ Temporal resolution limited

→ Wavelength allows for atomic resolution



X-ray free-electron lasers

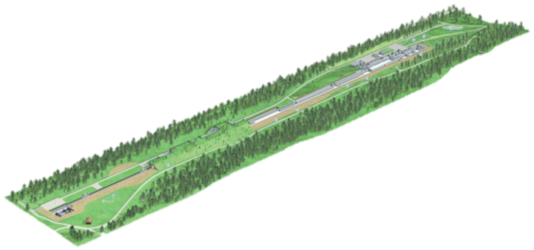
Pulse duration:	+++	(few fs)
Pulse energy:	++	(few mJ)
Wavelength:	+++	(~ 0.1 nm)

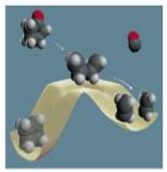
→ Fastest processes can be analyzed

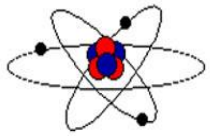
→ Wavelength allows for atomic resolution

Time scales

Synchrotron **X-ray free-electron laser**







Time

1s 1ms 1µs 1ns 1ps 1fs 1as

- 1 picosecond = 1 ps = 10^{-12} s = 0.000000000001 s
- 1 femtosecond = 1 fs = 10^{-15} s = 1 ps / 1000 = 0.000000000000001 s
- 1 attosecond = 1 as = 10^{-18} s = 1 fs / 1000 = 0.0000000000000001 s

The importance of the exposure time

The importance of the exposure time

Principle of an accelerator-based light source

- When charged particles are accelerated, they emit light
- ‘Bending’ a particle beam is an acceleration:

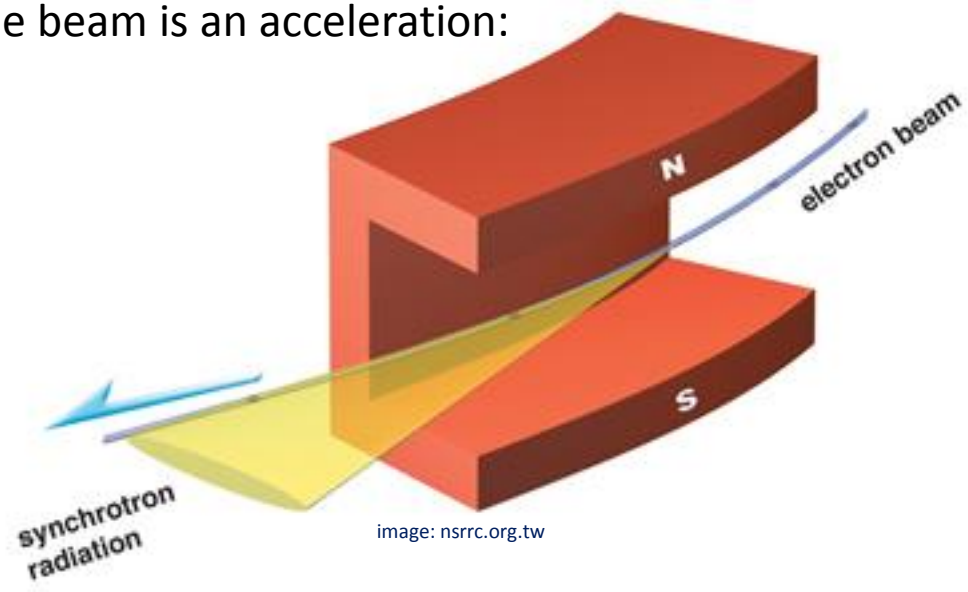


image: nsrrc.org.tw

- The most efficient magnets for this process are so-called undulators:

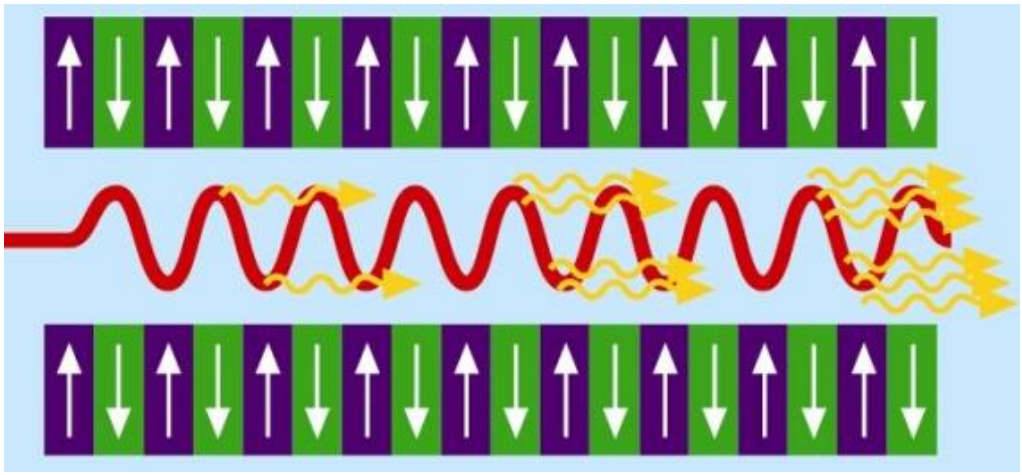
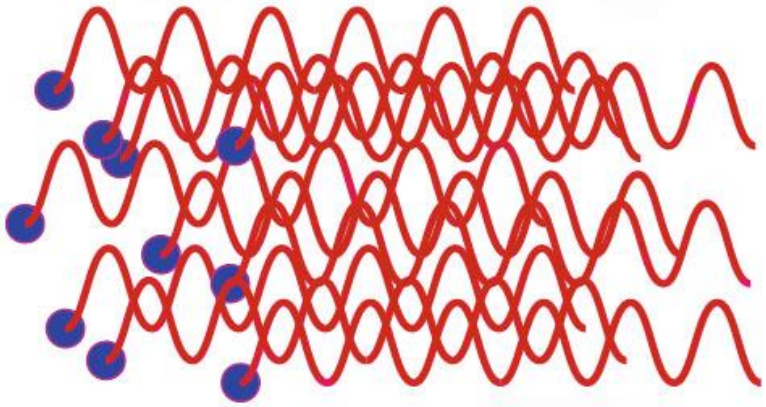


image: desy.de

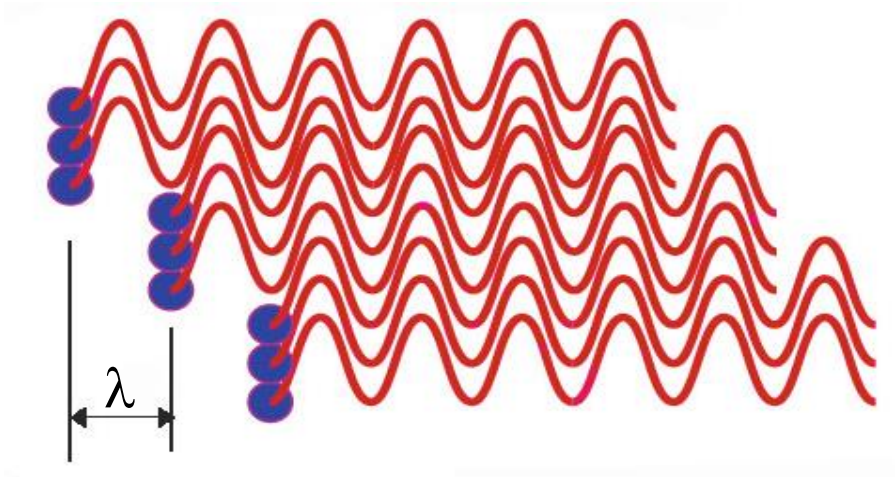
Loss in efficiency of the ‘normal’ light from an undulator:



$$E \propto \sqrt{N}$$

$$I \propto N$$

What if we could arrange the electrons such that they would all radiate in phase?

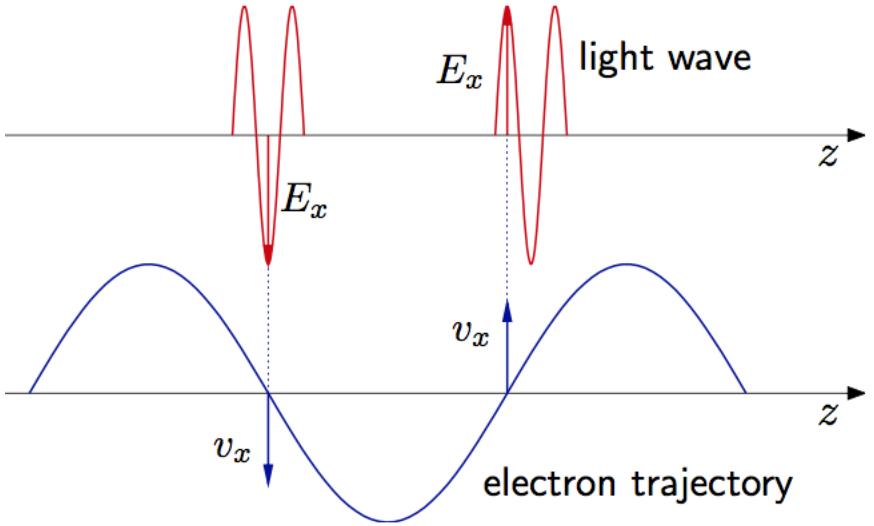


$$E \propto N$$

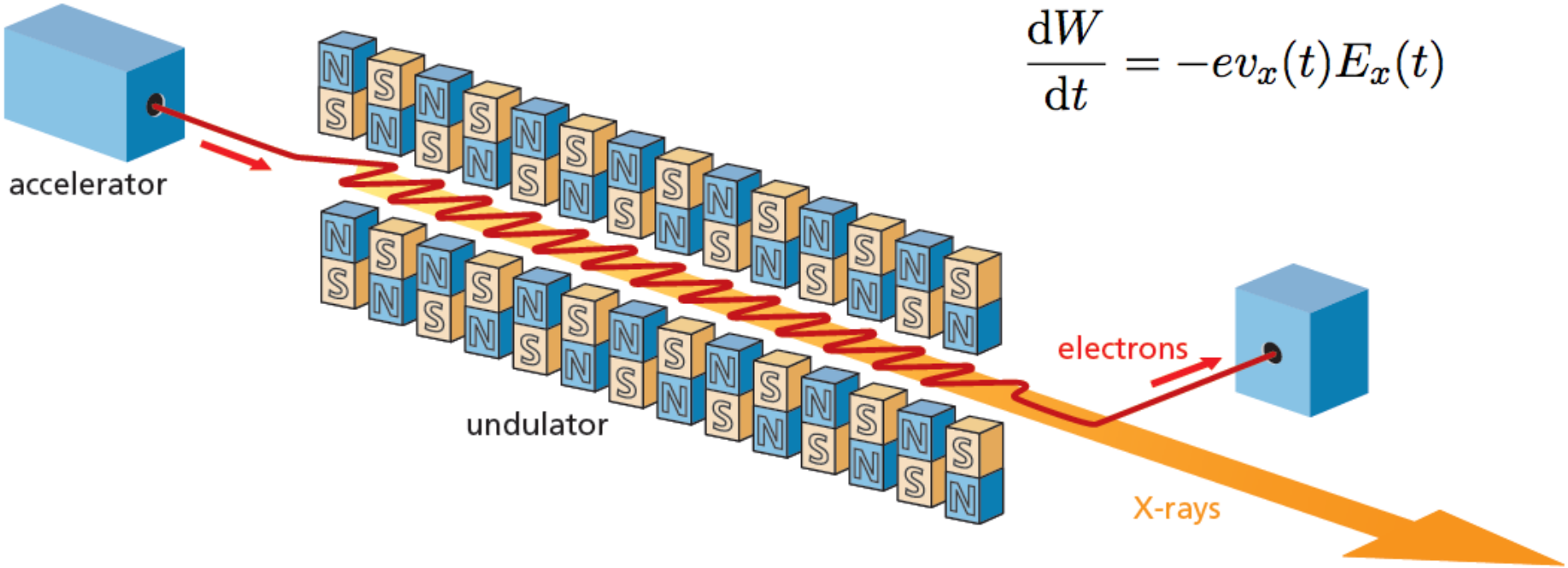
$$I \propto N^2$$

How does a free-electron laser work?

- A **very long undulator** is used
- A **very good electron beam** is required
- At the beginning of the undulator, the electrons emit light
- This light interacts with the electron beam
- This causes an exponential growth of the emitted light



$$\frac{\mathrm{d}W}{\mathrm{d}t} = -ev_x(t)E_x(t)$$



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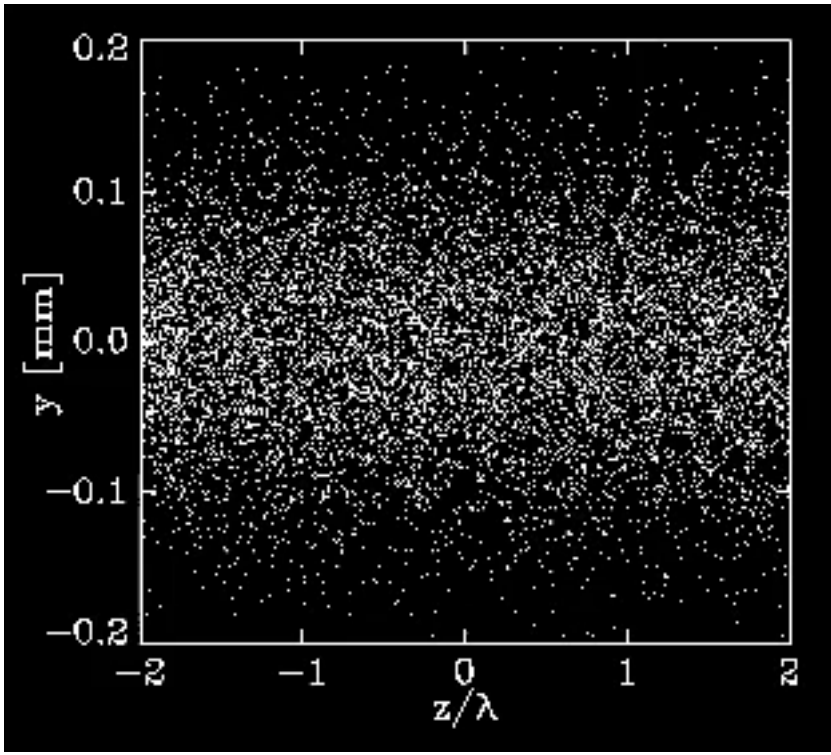
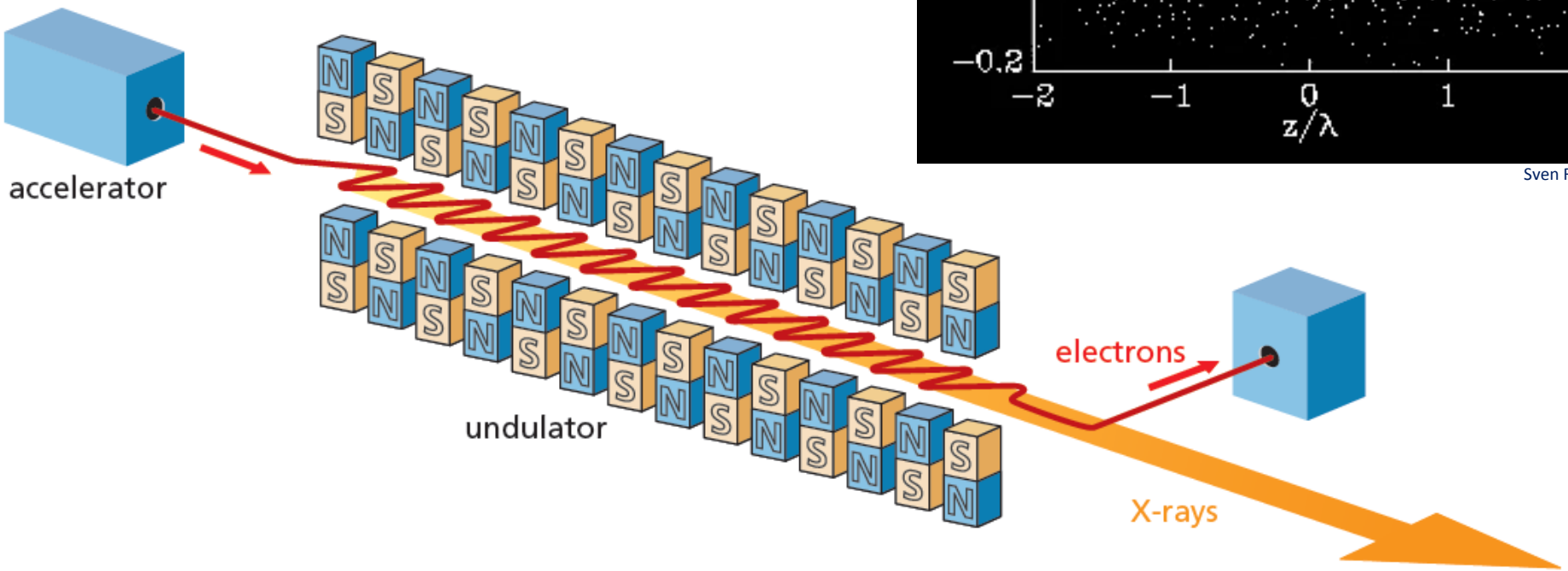
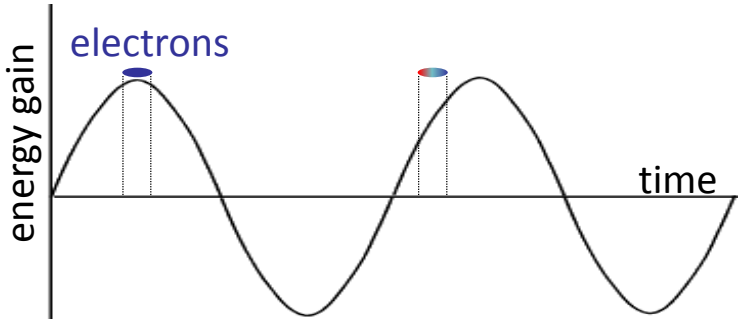


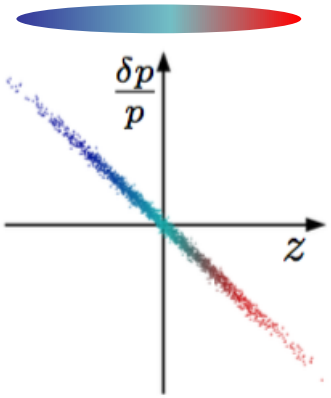
Sven Reiche



How do you generate femtosecond electron bunches

Acceleration of electrons in accelerating structures:





The first x-ray source (Röntgen, 1895)

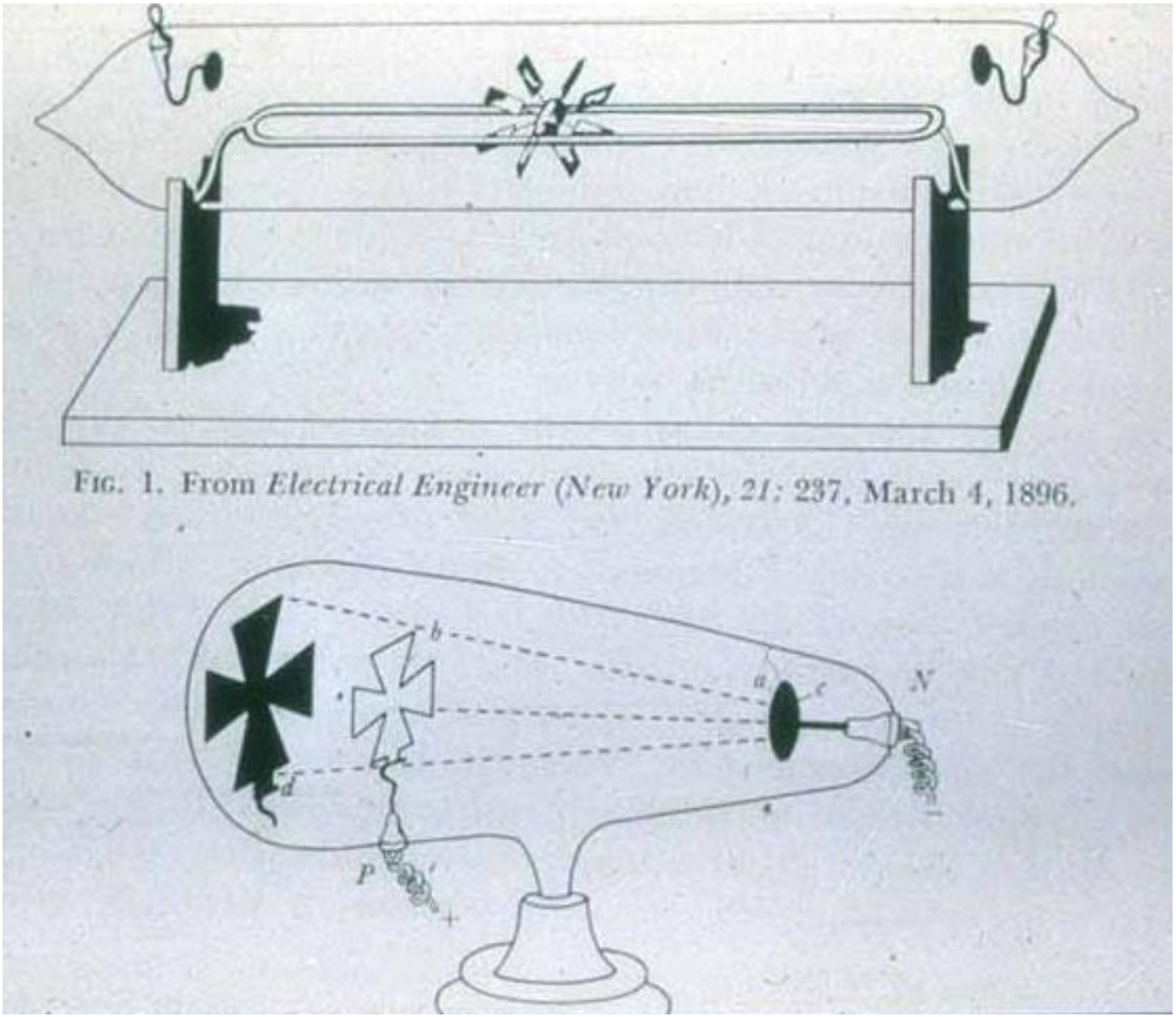
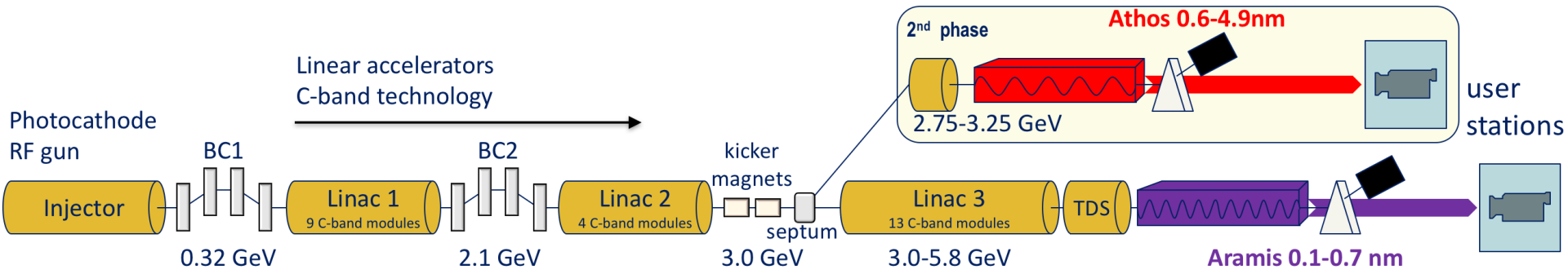
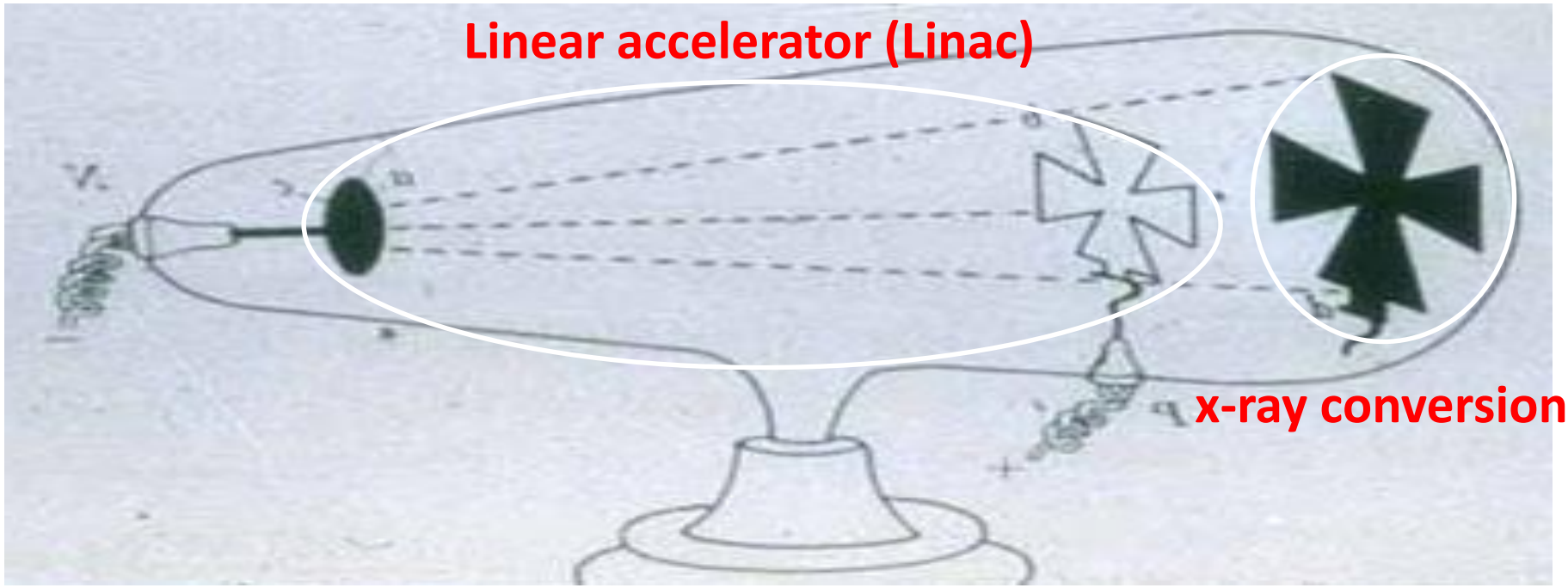


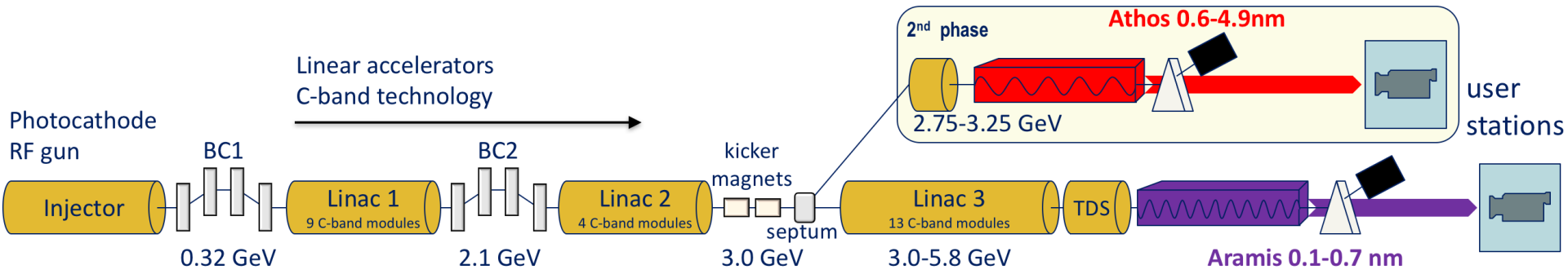
FIG. 1. From *Electrical Engineer (New York), 21:* 237, March 4, 1896.

SwissFEL


Linear accelerators
C-band technology
Photocathode
RF gun
BC1
BC2
kicker
magnets
2nd phase
Athos 0.6-4.9nm
user
stations
Injector
Linac 1
9 C-band modules
Linac 2
4 C-band modules
septum
Linac 3
13 C-band modules
TDS
2.75-3.25 GeV
0.32 GeV
2.1 GeV
3.0 GeV
3.0-5.8 GeV
Aramis 0.1-0.7 nm


Linear accelerator (Linac)
x-ray conversion

SwissFEL



ARAMIS

Hard X-ray FEL, λ=0.1-0.7 nm

Linear polarization, variable gap, in-vacuum undulators

First users 2017

Operation modes: SASE & self seeded

ATHOS

Soft X-ray FEL, λ=0.6-4.9 nm

Variable polarization, Apple-X undulators (2 m length)

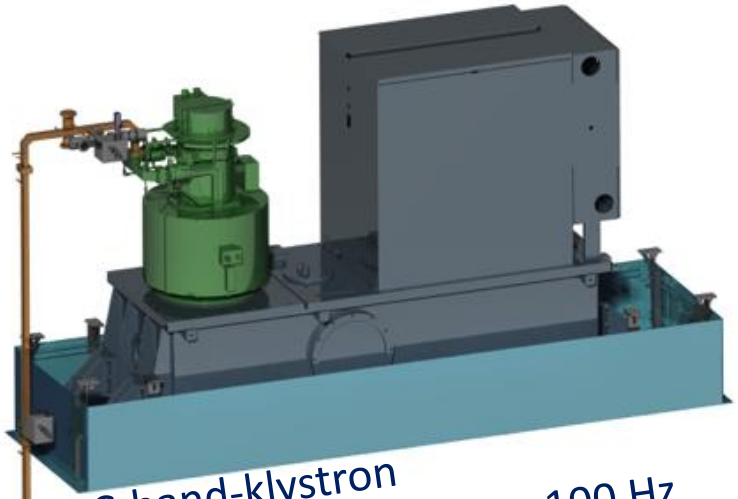
First users 2020?

Operation modes: SASE & self seeded & many more

Main parameters

Wavelength from	0.1nm–4.9nm
Photon energy	0.25-12 keV
Pulse duration	1 fs - 20 fs
e^- Energy (0.1 nm)	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz

The SwissFEL main linac

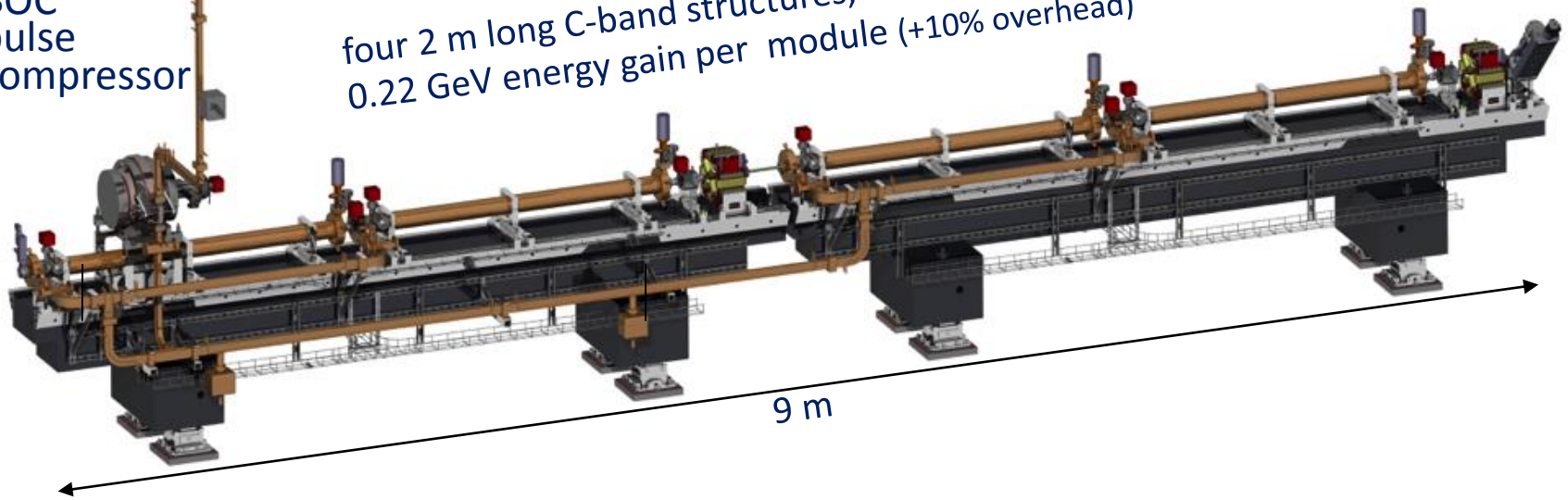


C-band-klystron
5.7 GHz, 50 MW, 3 µs, 100 Hz

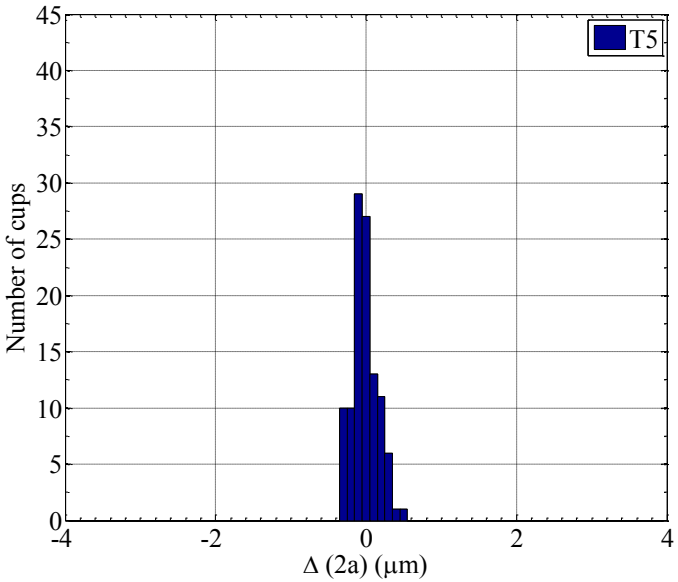
Main LINAC	#
LINAC module	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structure	104
Waveguide splitter	78
Waveguide load	104

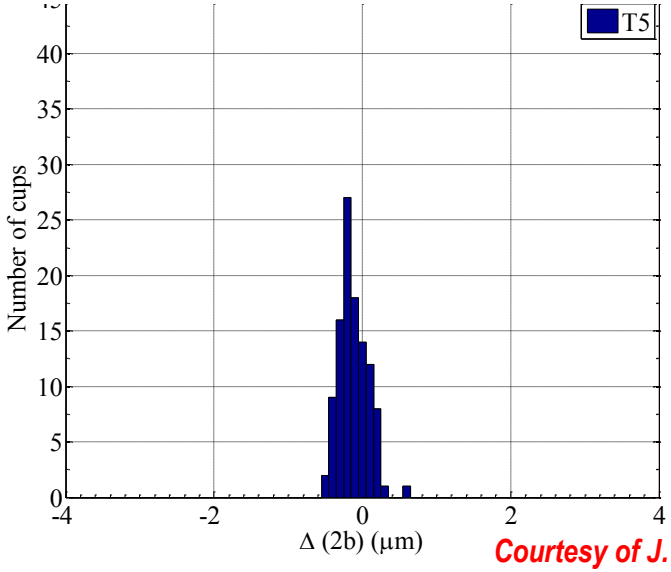
BOC
pulse
compressor

four 2 m long C-band structures, 28 MV/m
0.22 GeV energy gain per module (+10% overhead)

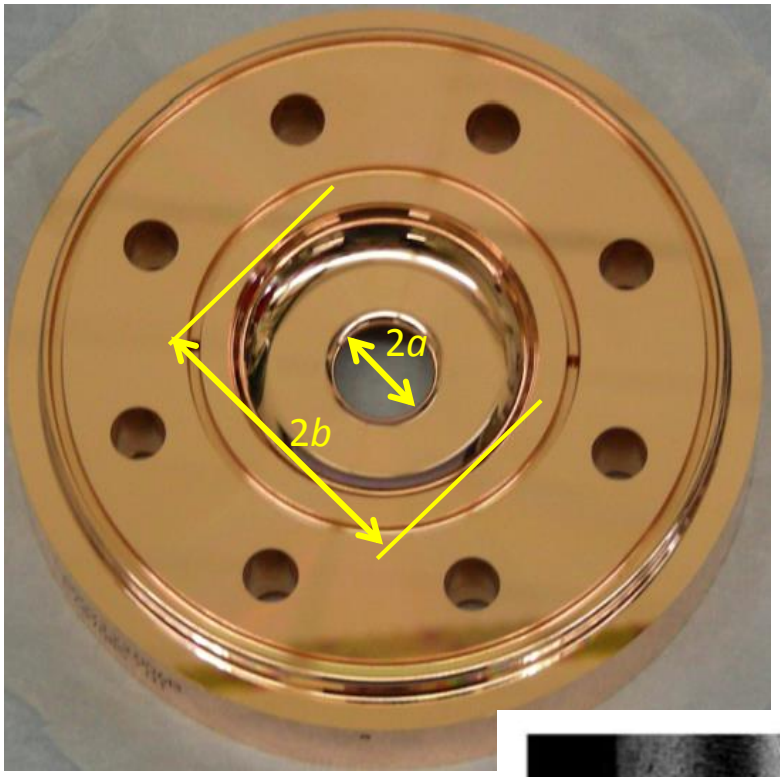


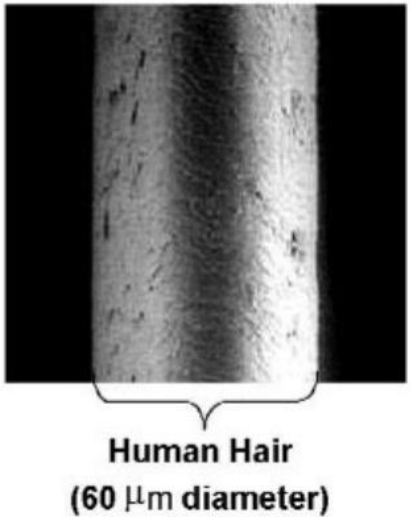
Precision manufacturing of copper disks in Trübbach





Courtesy of J.Y. Raguin





Typical examples of metrology on a structure:
Top: histogram iris diameter; Bottom: histogram iris cell diameter

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C-band module assembly

Girders were pre-assembled in a storage hutch

C-band module assembly

Movement of girder into assembly hutch

C-band module assembly

Installation of girders
into assembly hutch

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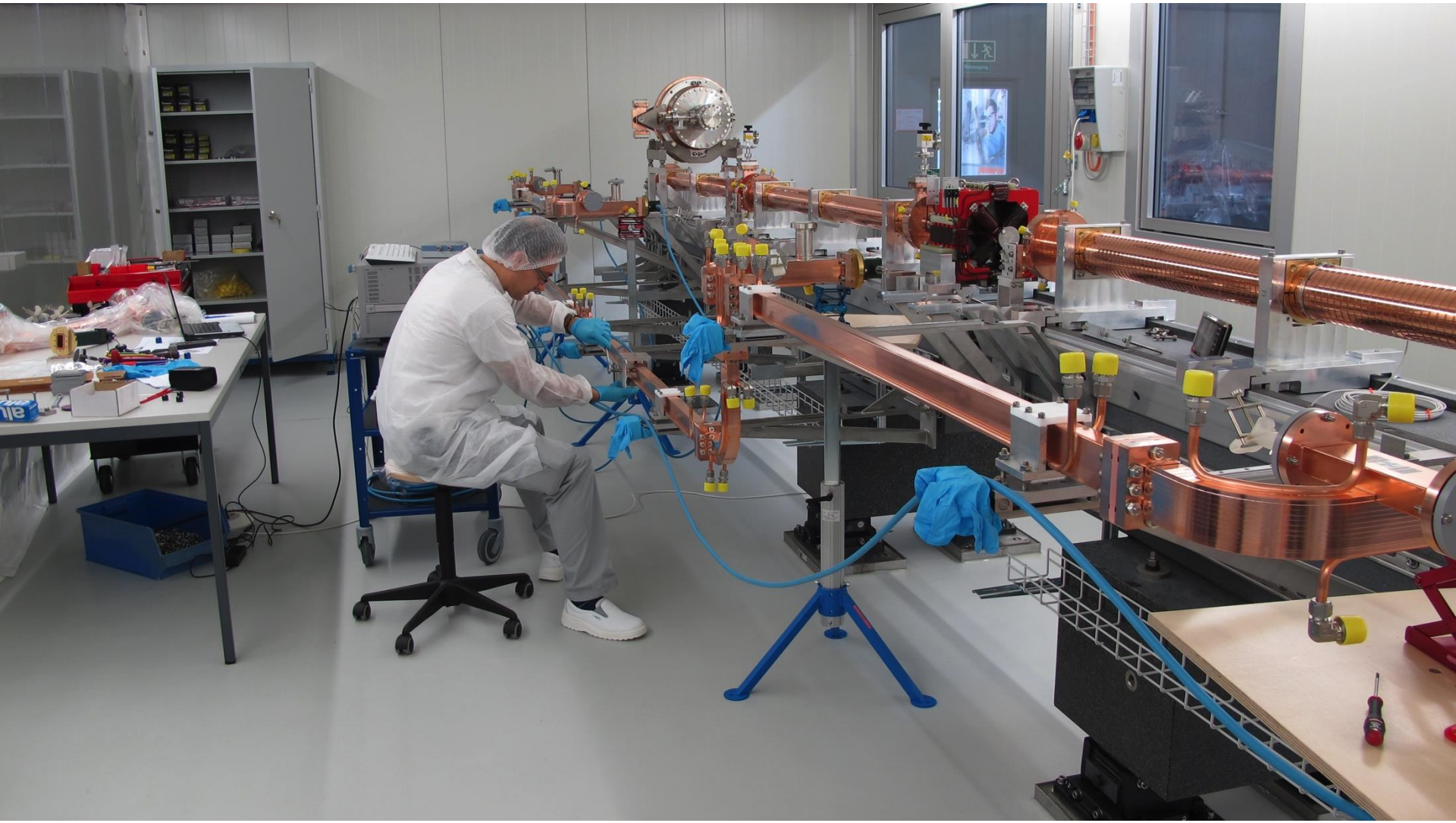
C-band module assembly



Installation and tuning of waveguides (waveguides delivered from MHI-MS)

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Girder installation in SwissFEL

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Accelerator module in the SwissFEL tunnel

SwissFEL undulators

Transport of undulators in SwissFEL building
with air-cushion vehicle

Courtesy of Romain Ganter

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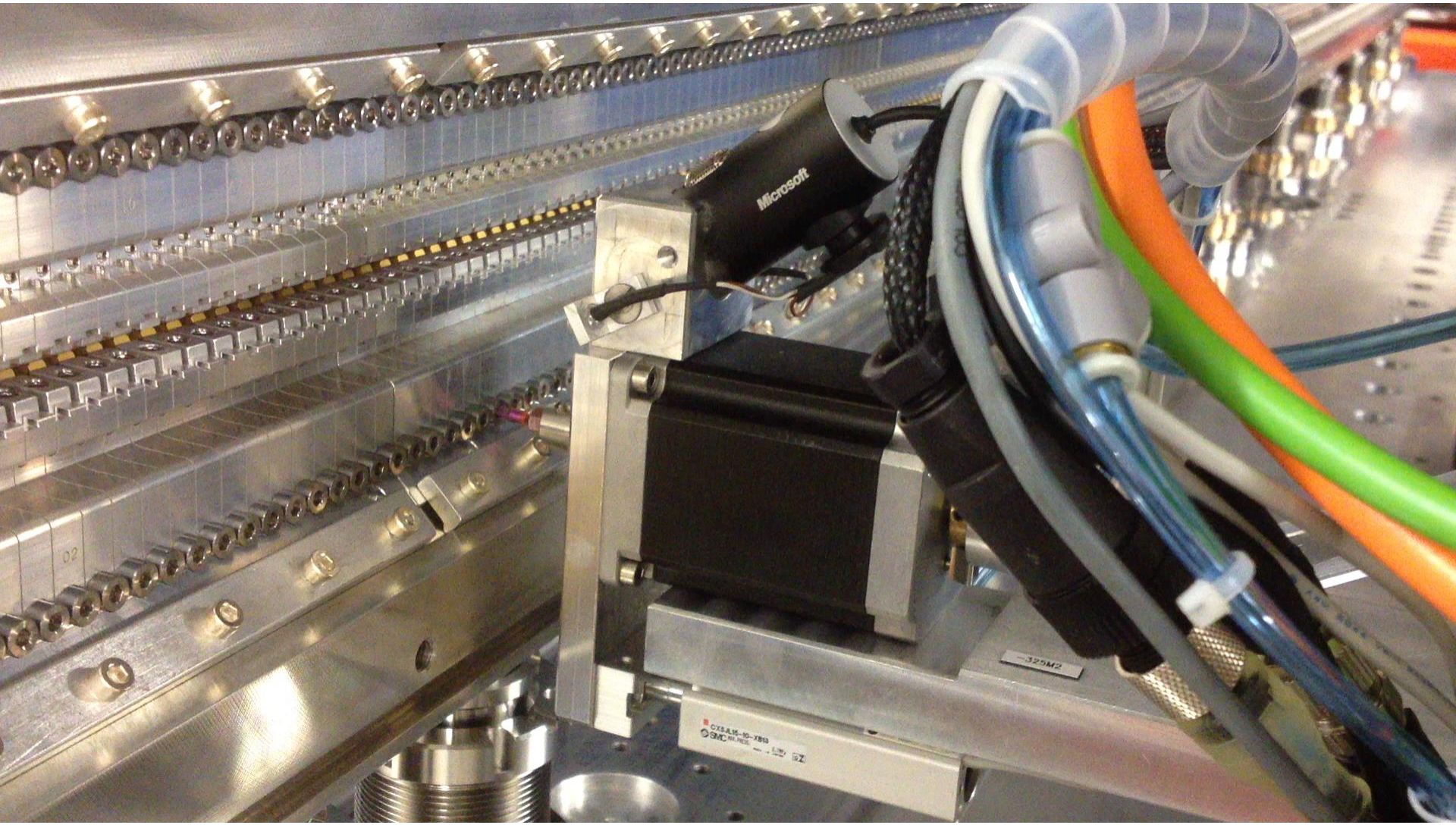
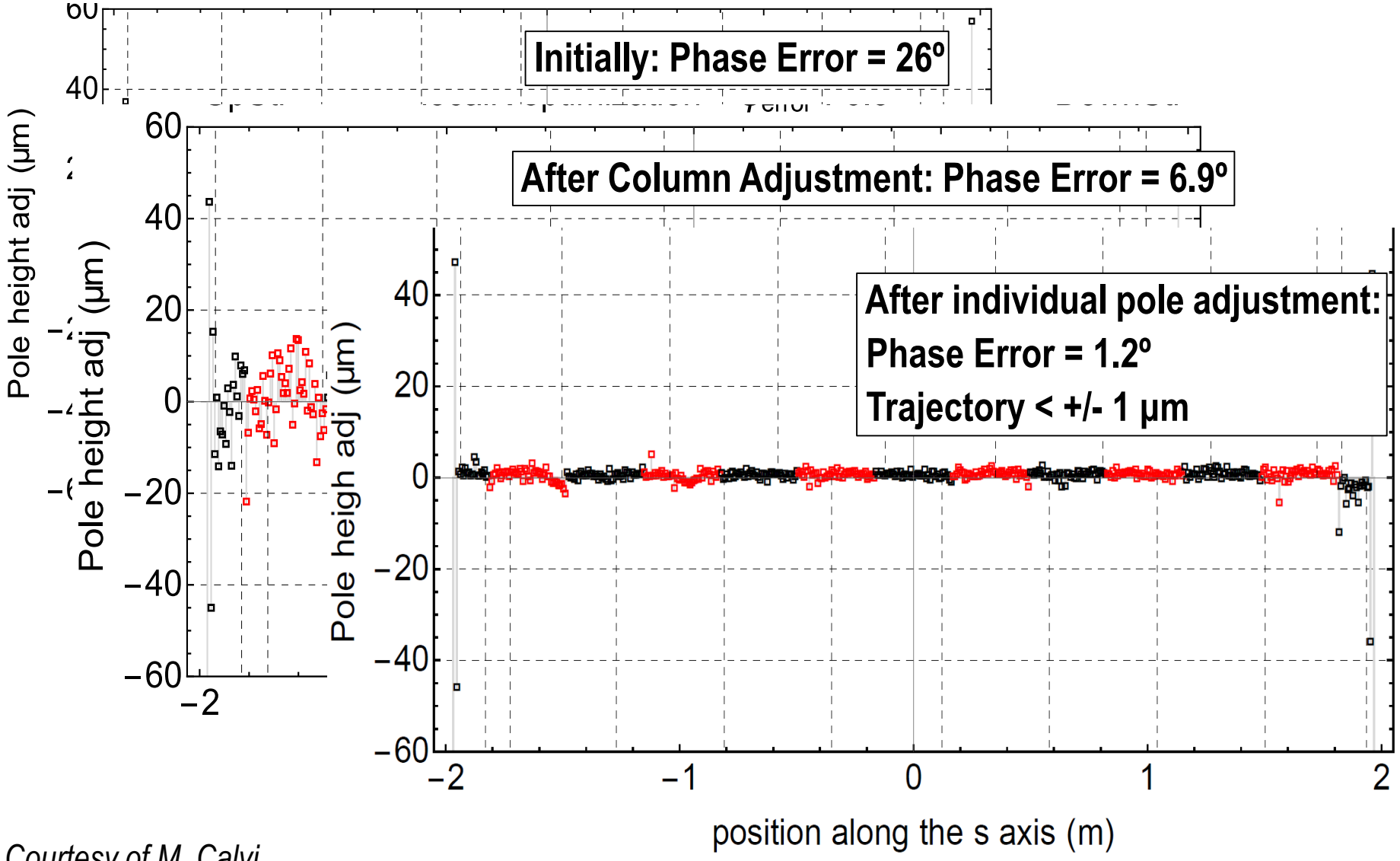
Adjustment of the undulator magnets



Effect of the adjustments on the field errors



Courtesy of M. Calvi

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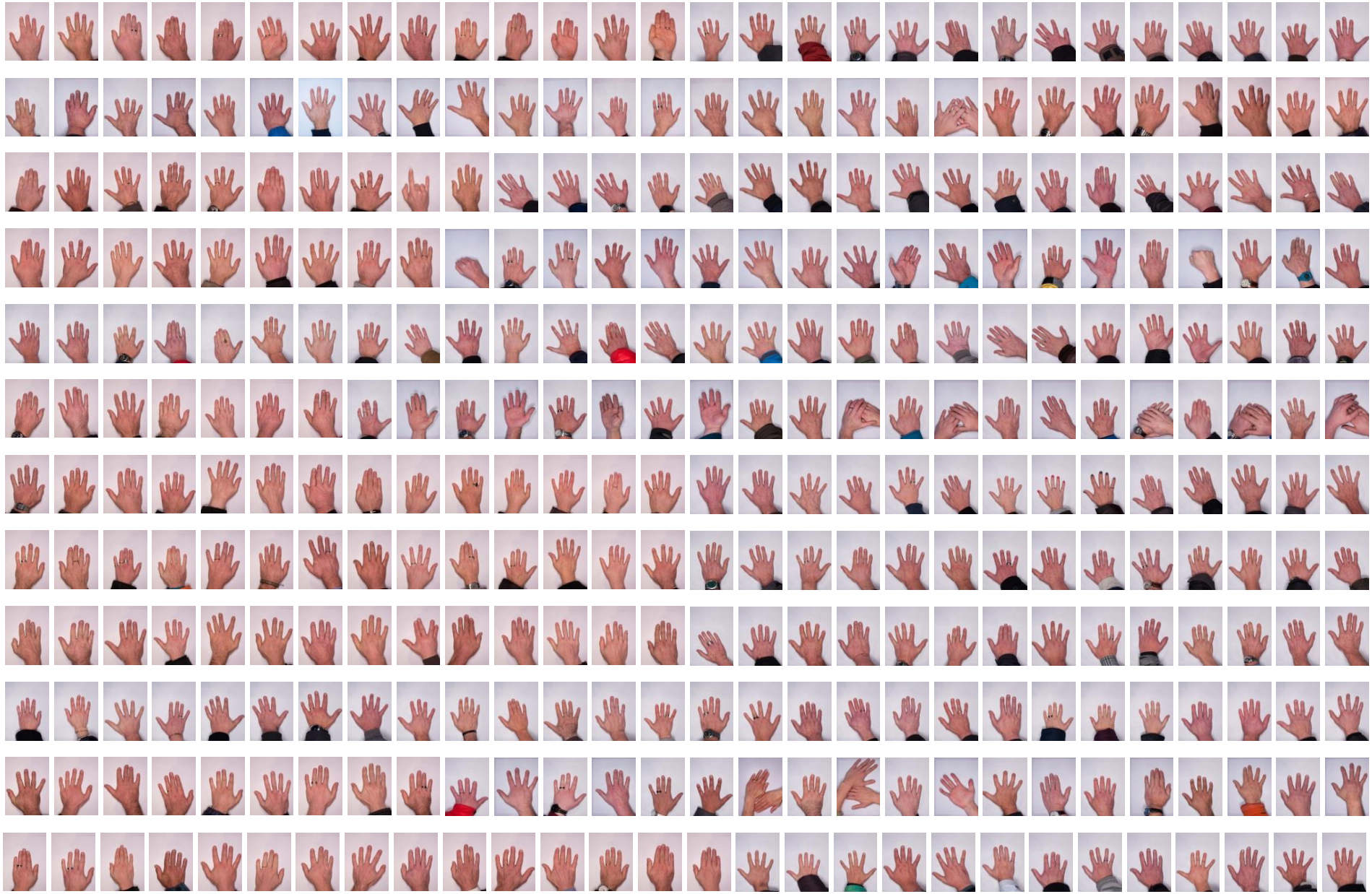
Thank you for your attention!



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