



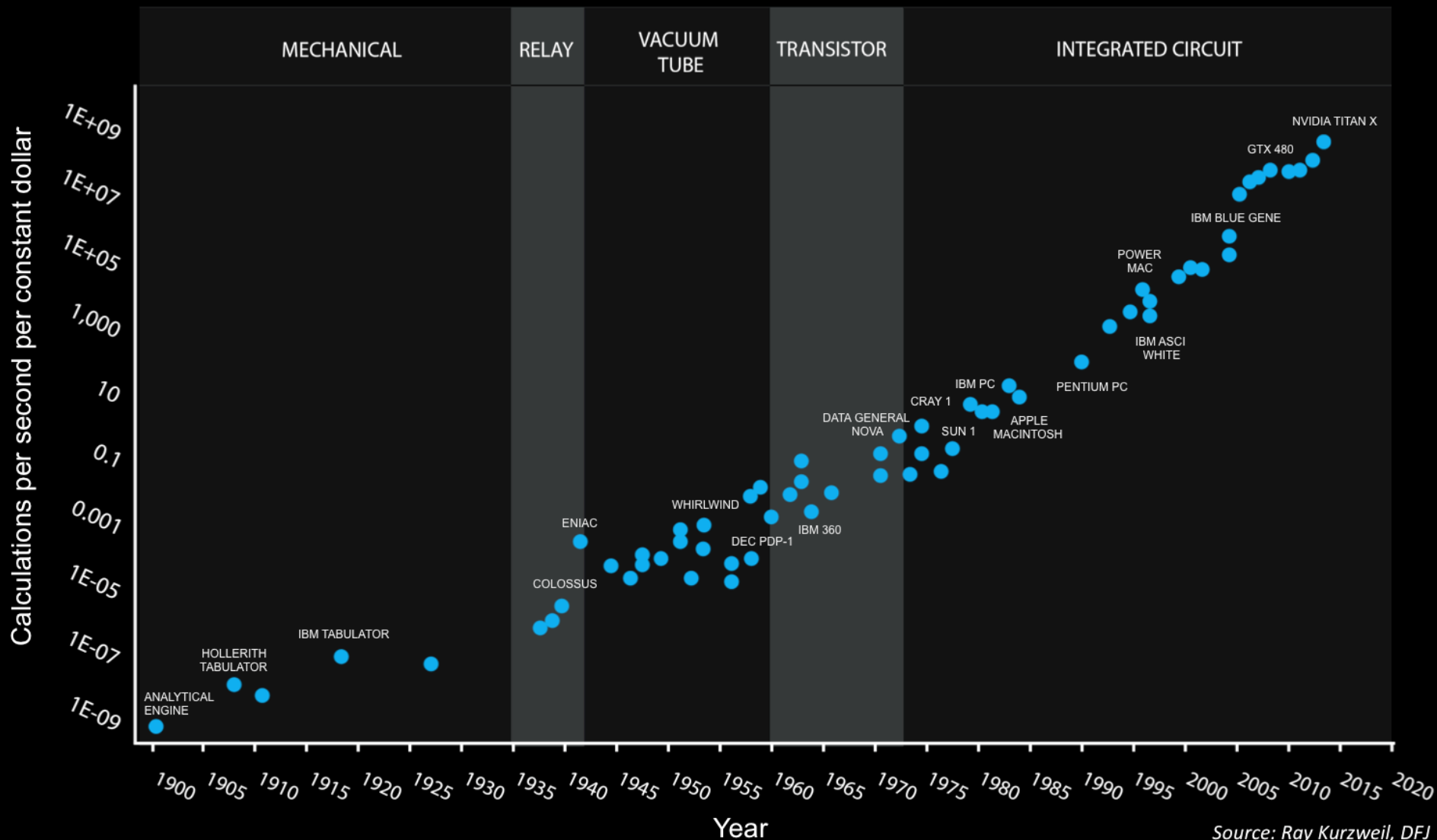
WIR SCHAFFEN WISSEN – HEUTE FÜR  
MORGEN

Florian Löhli :: Paul Scherrer Institut

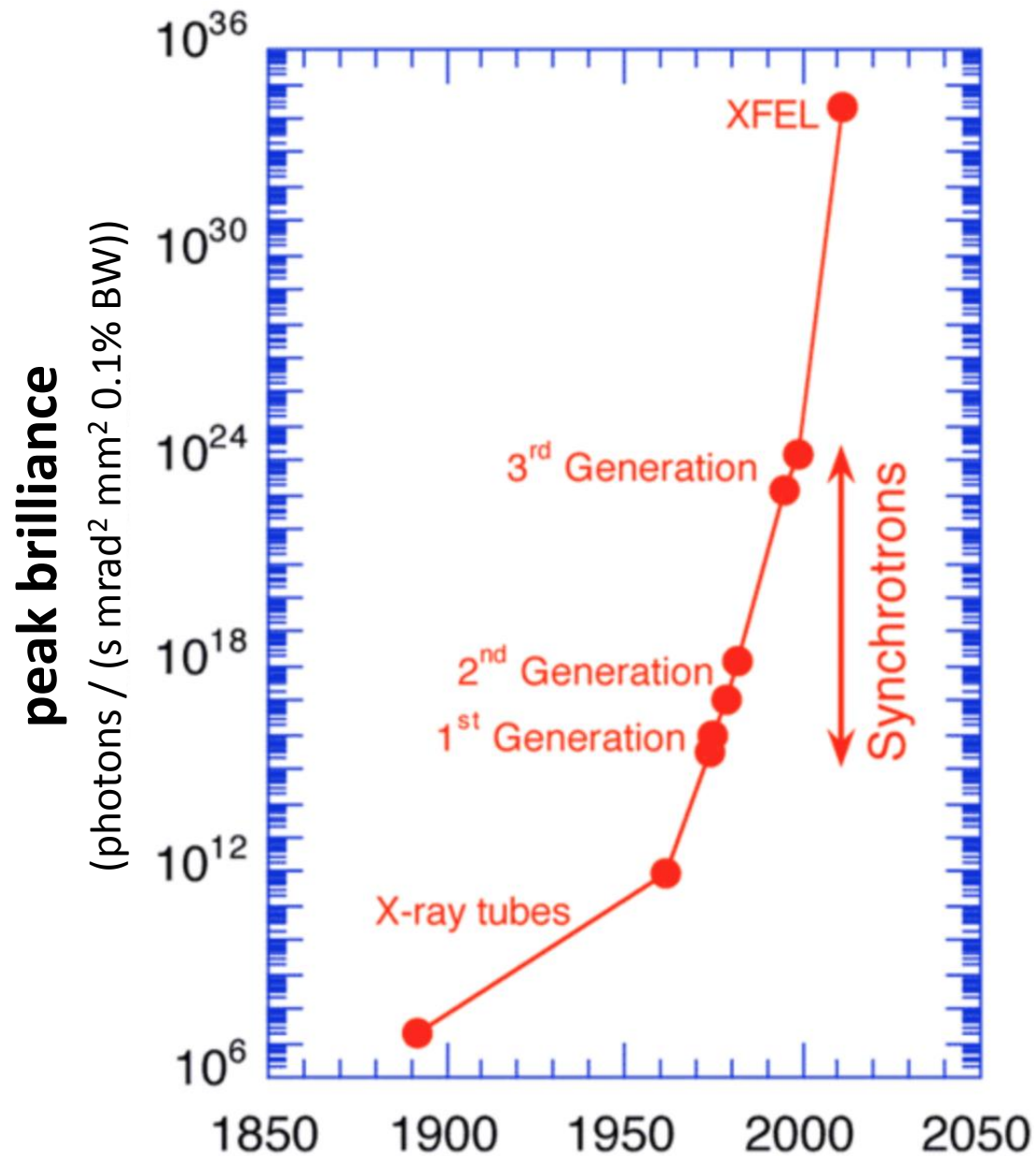
# Introduction to SwissFEL

A very fast development...

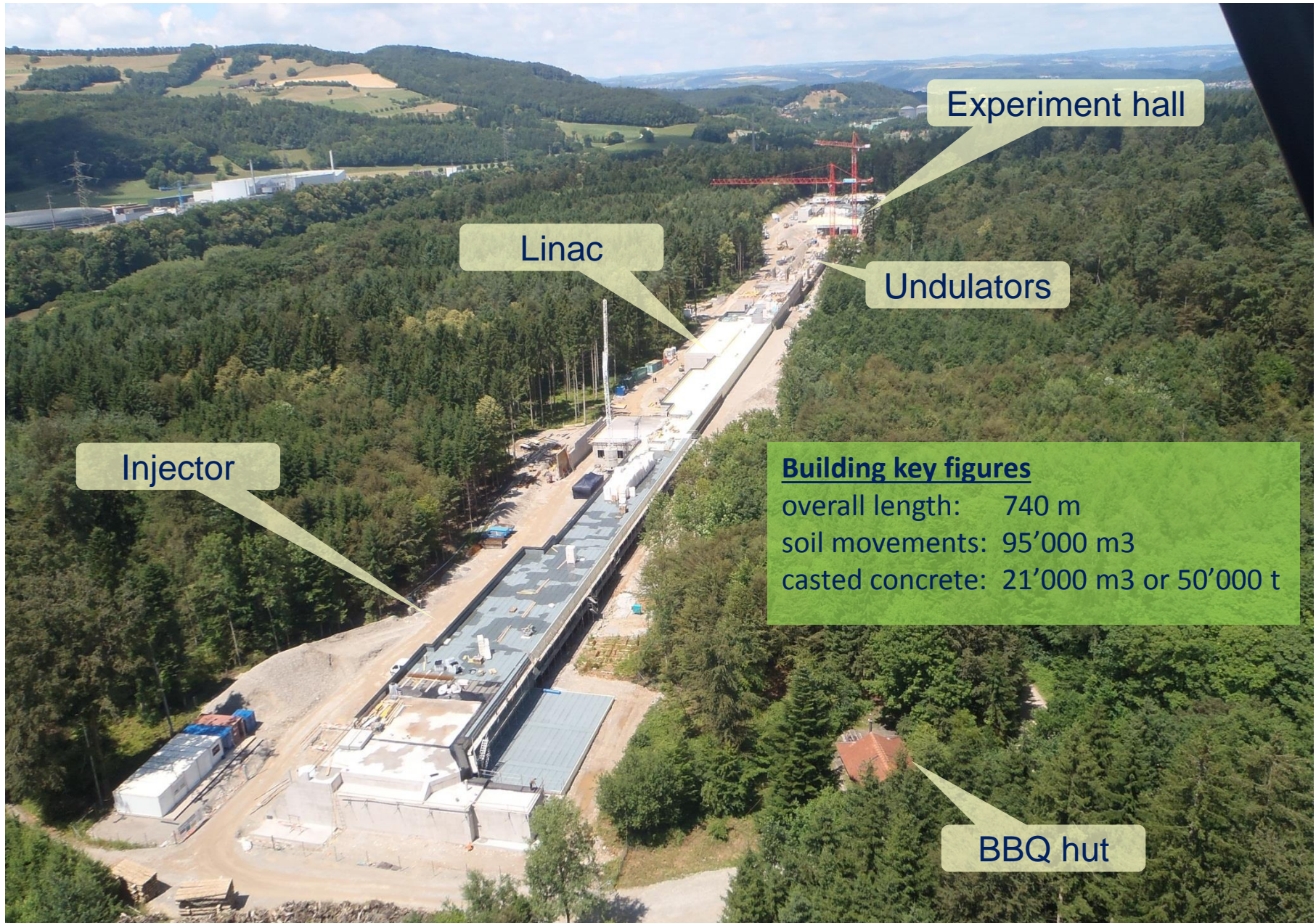
# 120 Years of Moore's Law



## An even faster development...



## SwissFEL construction site (July 2014)



# SwissFEL construction site (June 2015)





# What is inside of the building?

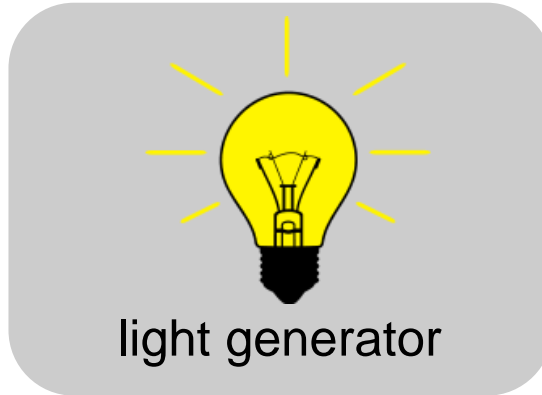
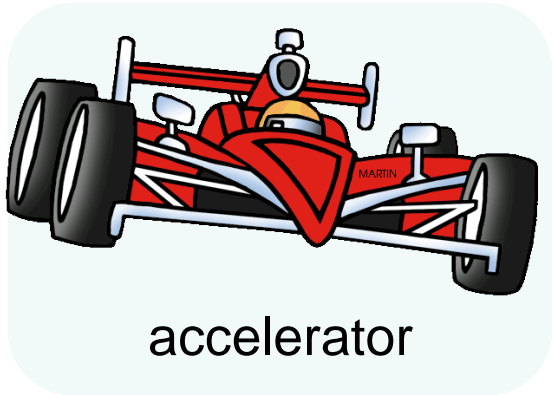


# SwissFEL tunnel in spring 2015

Follow the SwissFEL beam  
Total length: 736 m



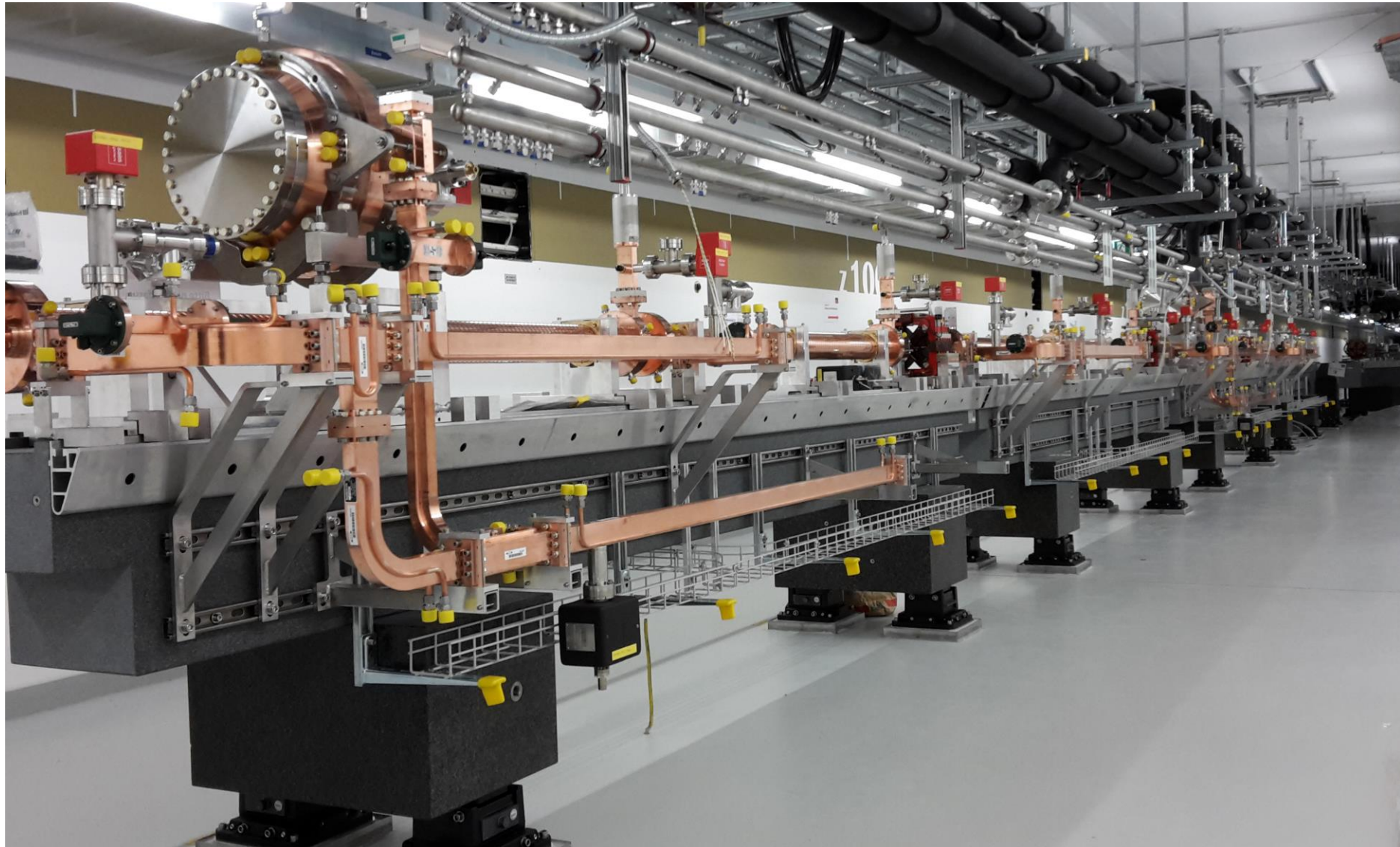
# What is inside of the building?



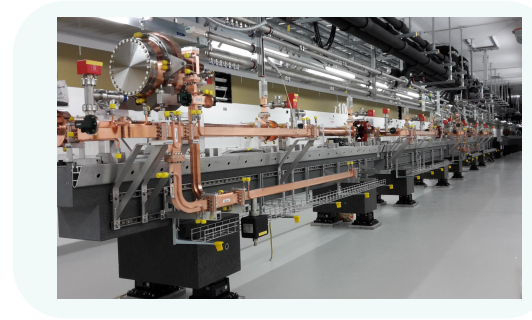
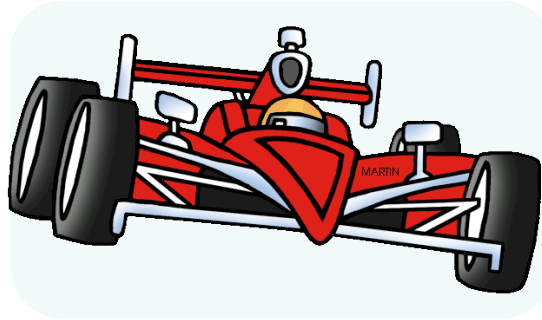


The accelerator...

looks in reality like this:



# A comparison



Accelerated object

racing driver

electrons

Maximum acceleration

1.5 g

$1.8 \times 10^{18}$  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  $\mu$ W / electron)  
(3 - 5 MW)

# 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<sup>2</sup>

few μm<sup>2</sup>

Corresponds to focus of all the energy the sun sends to earth to an area of 2 x 2 mm<sup>2</sup>

Wavelength

ca. 500 nm

0.1 nm ( $\hat{=}$  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

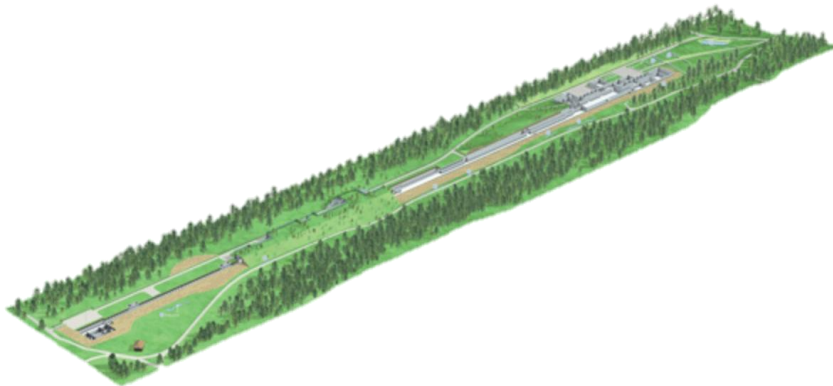
Pulse duration: o (few ps)

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)

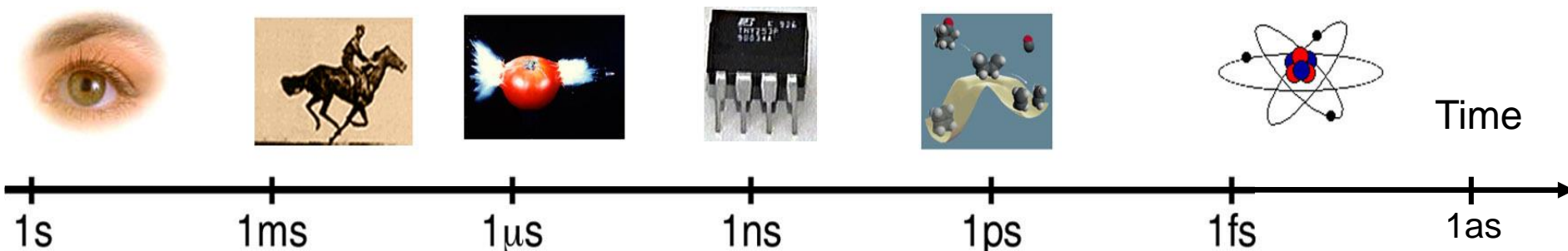
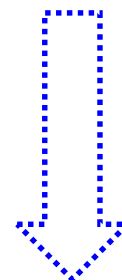
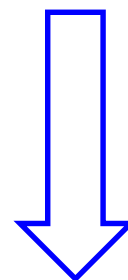
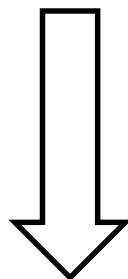
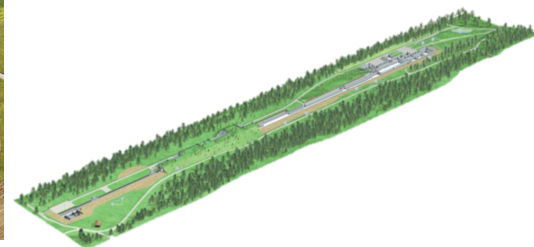
→ Fastest processes can be analyzed

→ Wavelength allows for atomic resolution

# Time scales

Synchrotron

X-ray free-electron laser



- 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 = 0.000000000000000001 s

# The importance of the exposure time



~0.5 s

# The importance of the exposure time

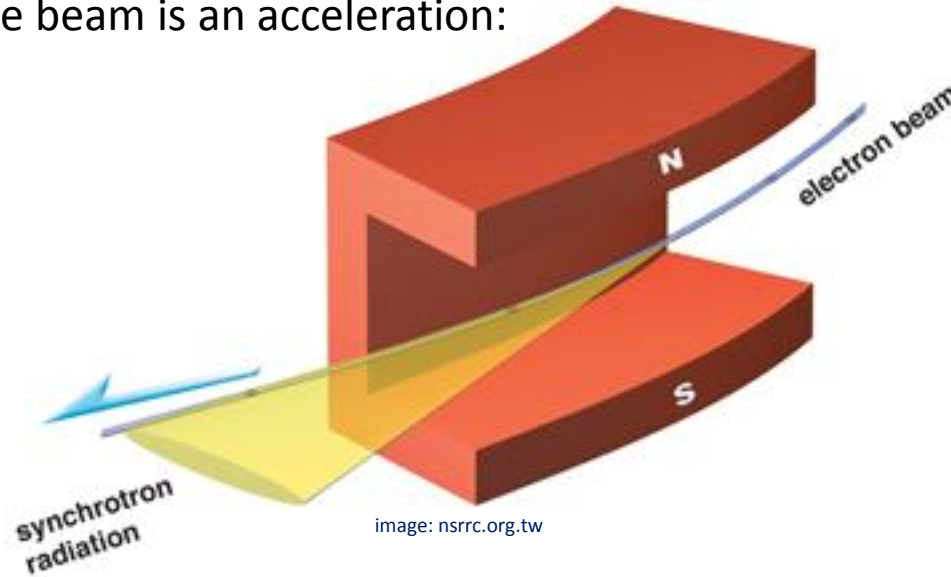


30 s

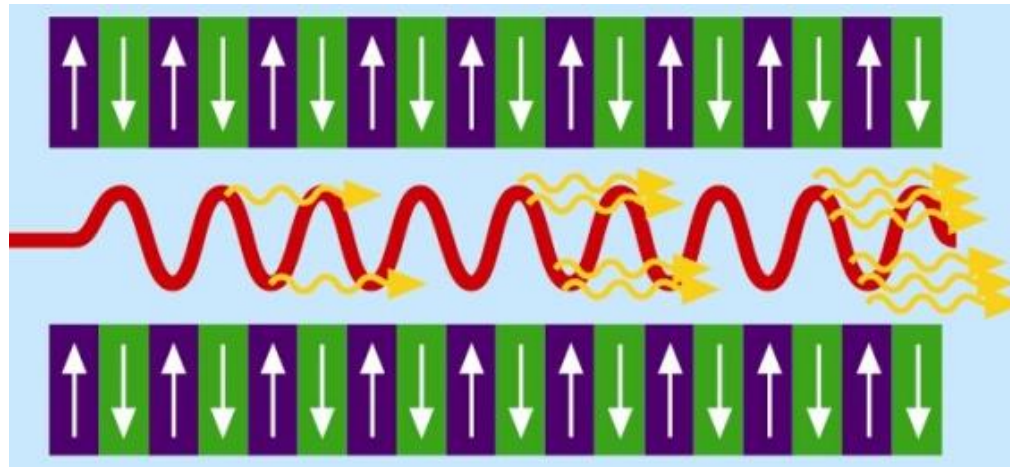


# Principle of an accelerator-based light source

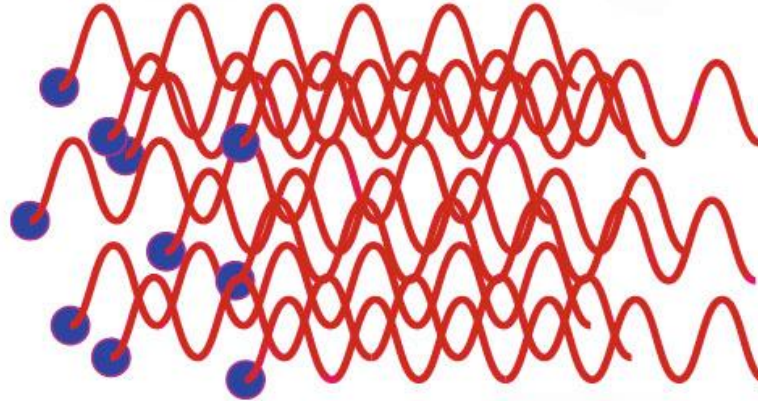
- When charged particles are accelerated, they emit light
- 'Bending' a particle beam is an acceleration:



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



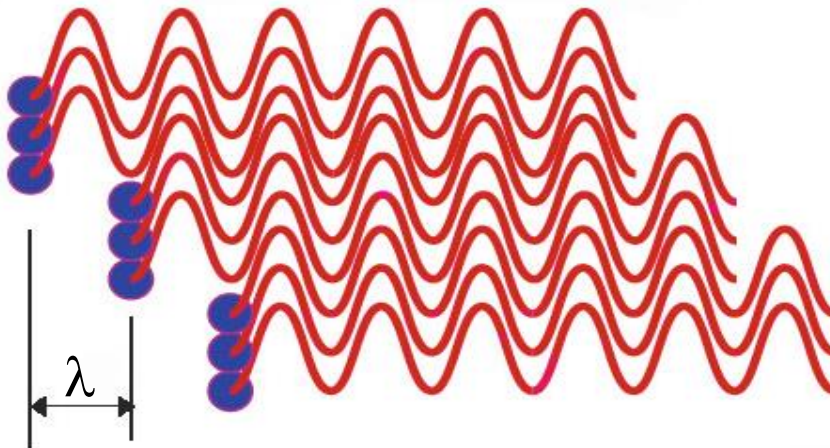
Loss in efficiency of the 'normal' light from an undulator:



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

$$I \propto N$$

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

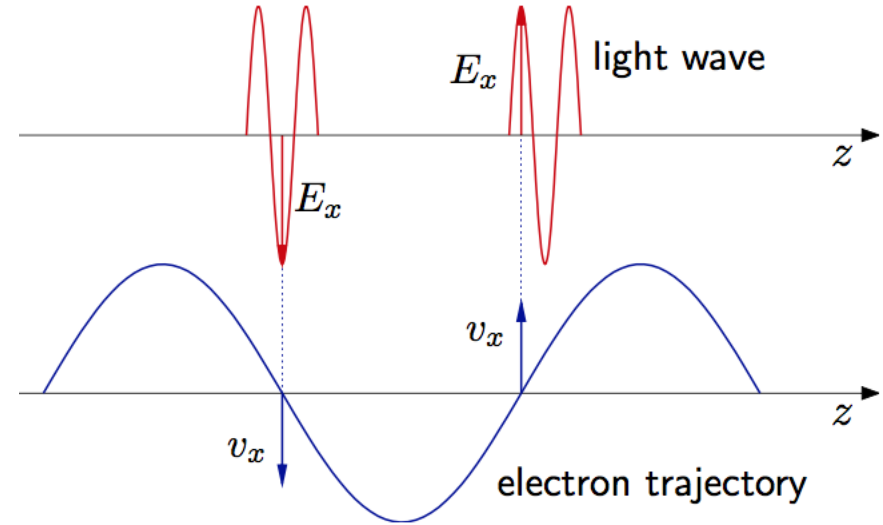


$$E \propto N$$

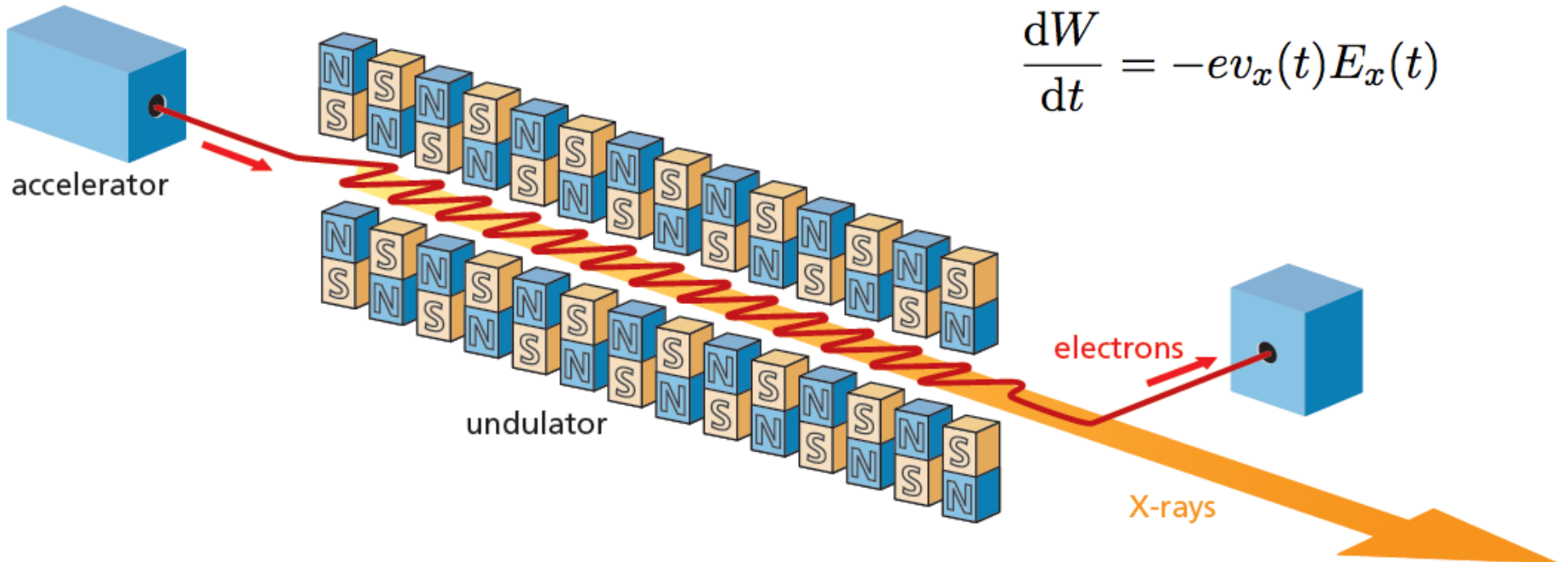
$$I \propto N^2$$

# 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

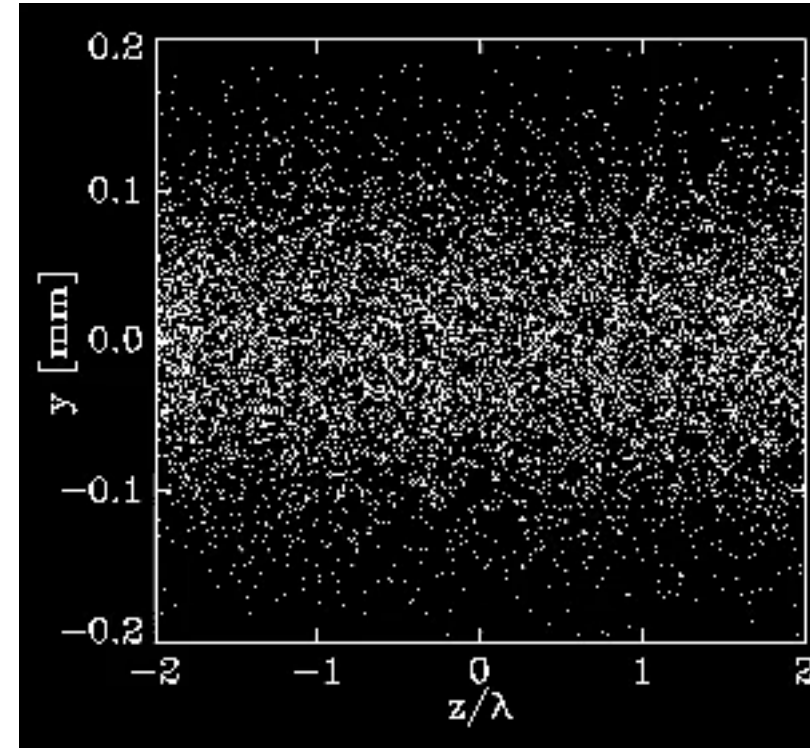


$$\frac{dW}{dt} = -ev_x(t)E_x(t)$$

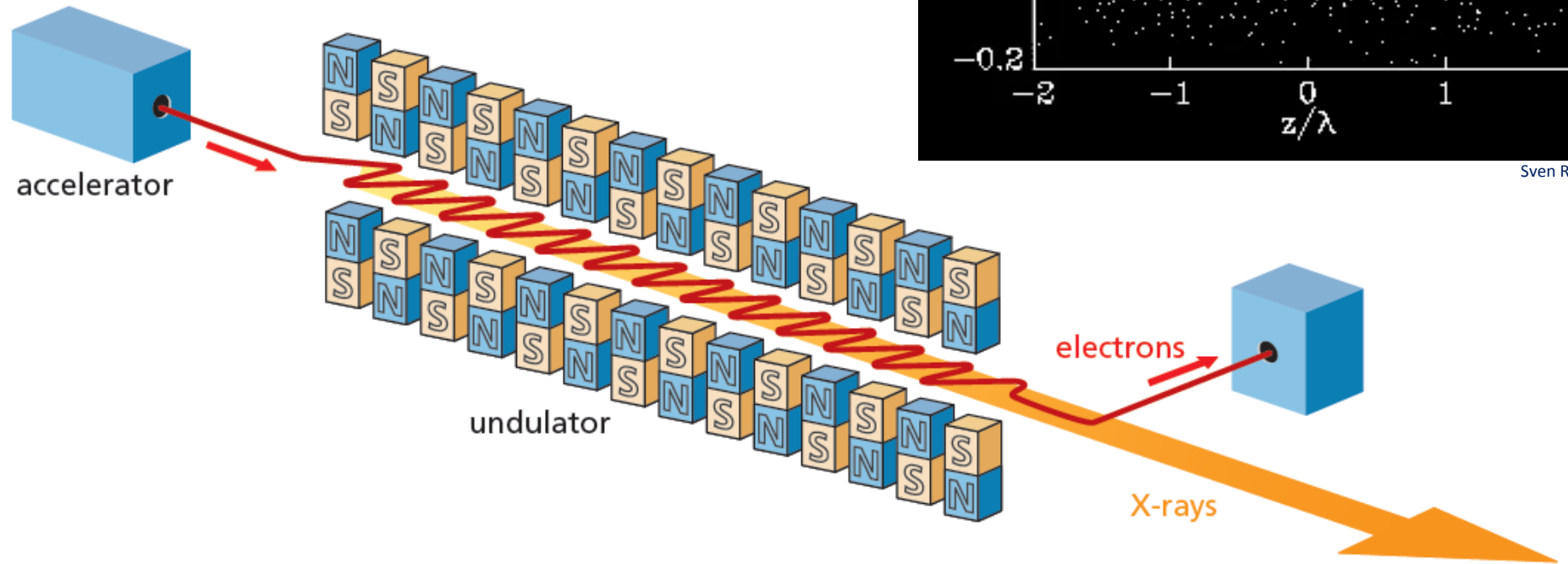


# How does a free-electron laser work?

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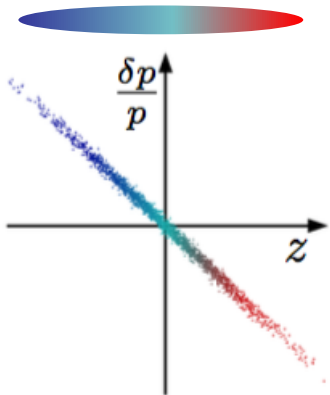
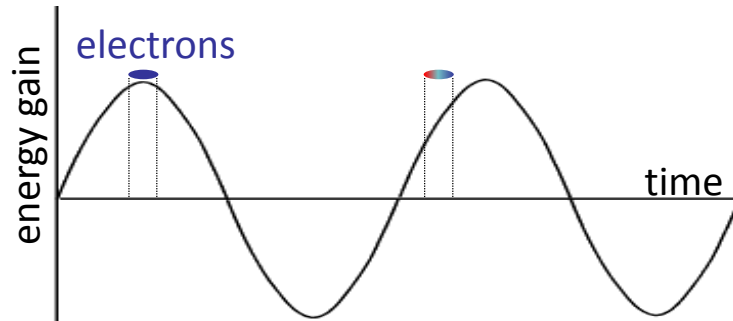


Sven Reiche



# How do you generate femtosecond electron bunches

Acceleration of electrons in accelerating structures:



## The first x-ray source (Röntgen, 1895)

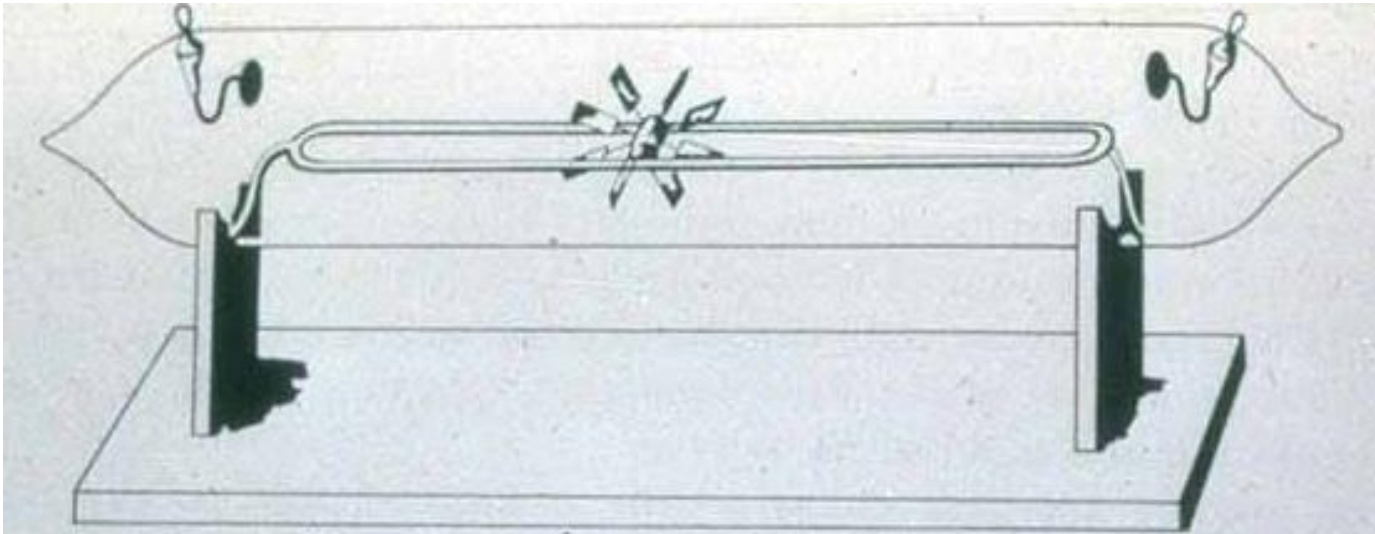
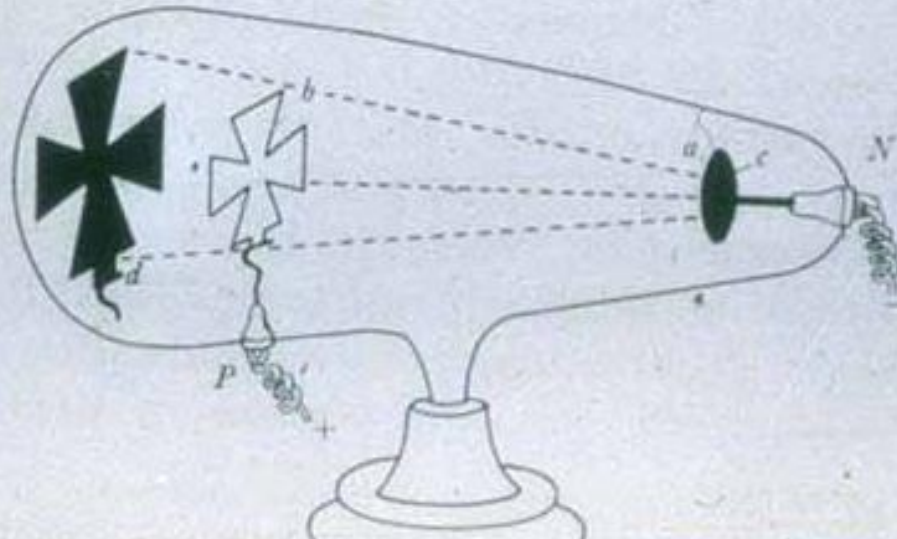
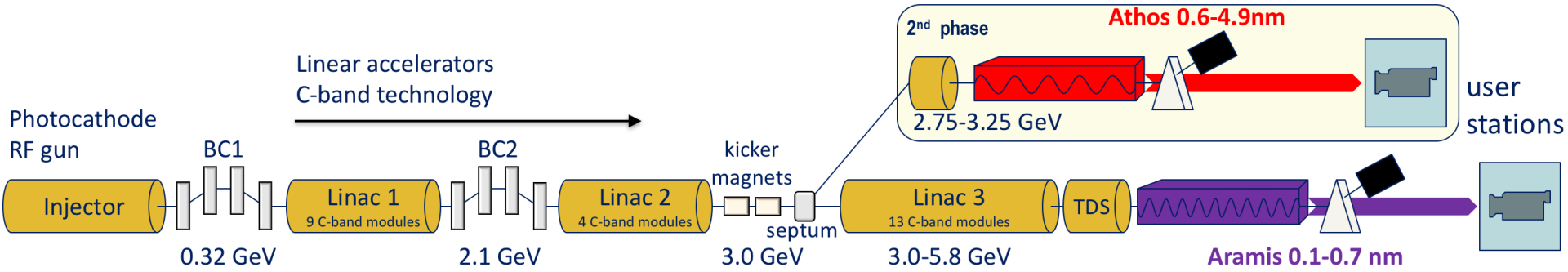


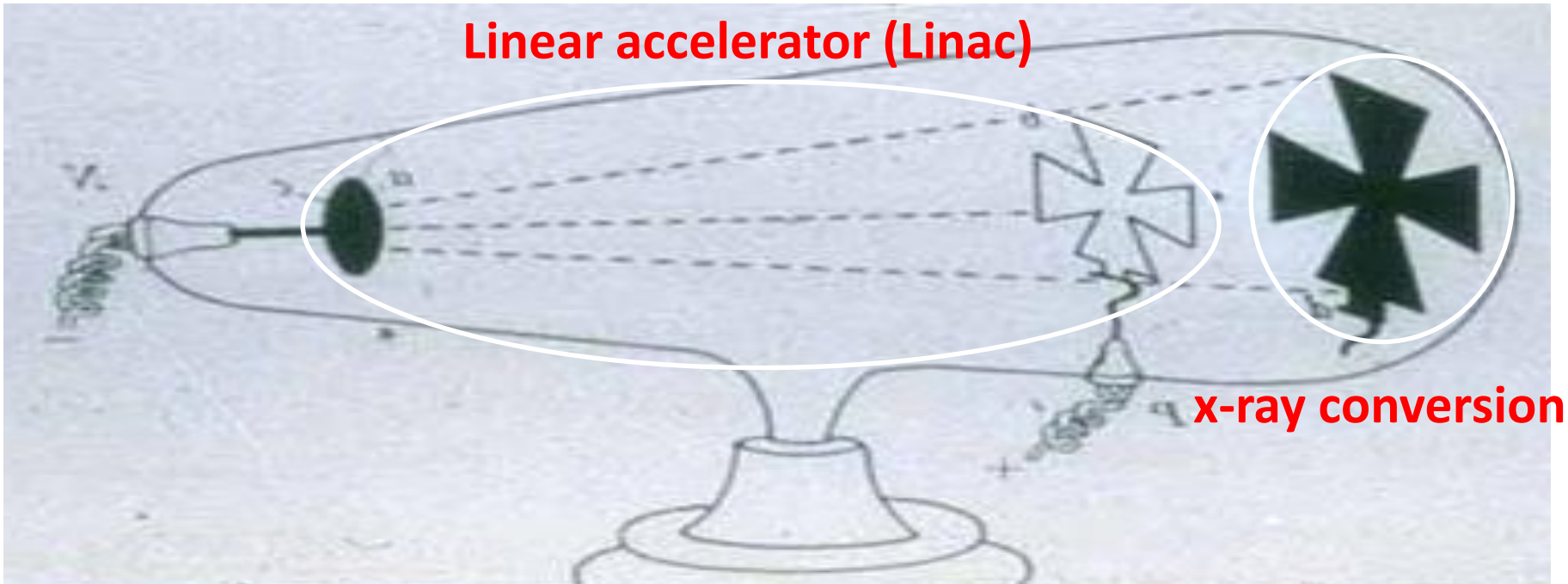
FIG. 1. From *Electrical Engineer (New York)*, 21: 237, March 4, 1896.



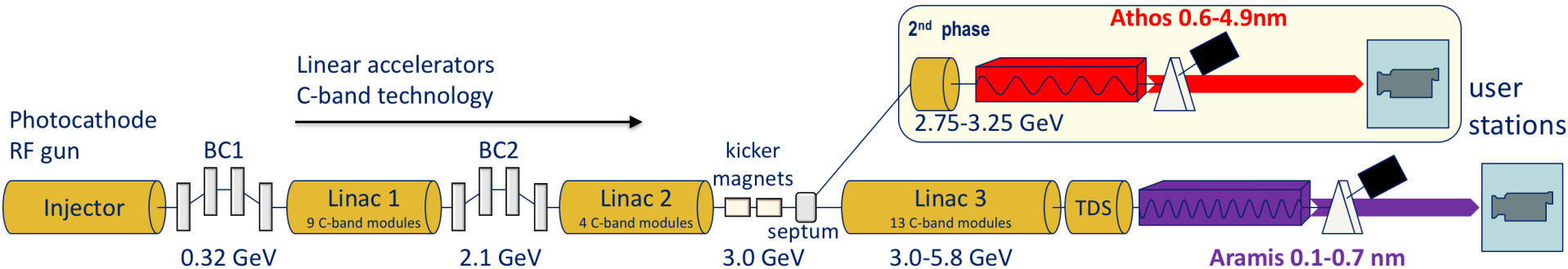
# SwissFEL



## Linear accelerator (Linac)



# SwissFEL



## ARAMIS

Hard X-ray FEL,  $\lambda=0.1-0.7$  nm

Linear polarization, variable gap, in-vacuum undulators

First users 2017

Operation modes: SASE & self seeded

## ATHOS

Soft X-ray FEL,  $\lambda=0.6-4.9$  nm

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

First users 2020?

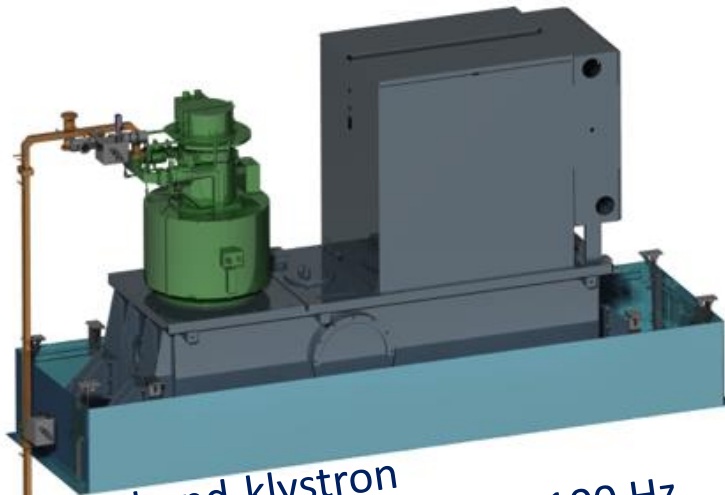
Operation modes: SASE & self seeded & many more

## Main parameters

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



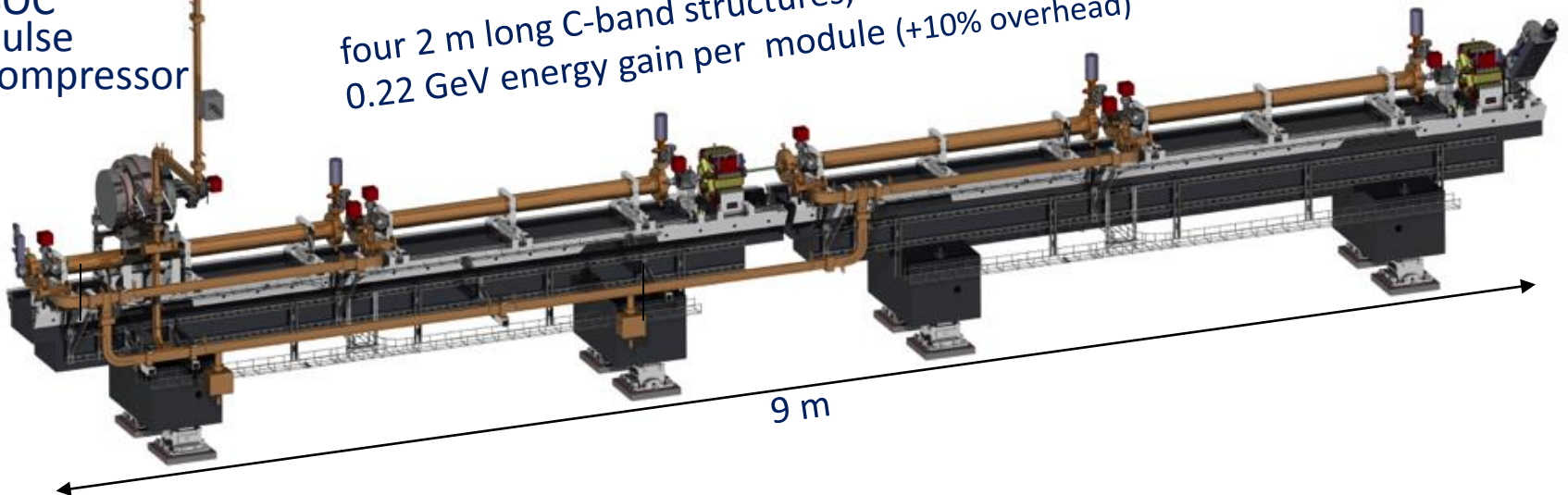
# The SwissFEL main linac



C-band-klystron  
5.7 GHz, 50 MW, 3  $\mu$ s, 100 Hz

BOC  
pulse  
compressor

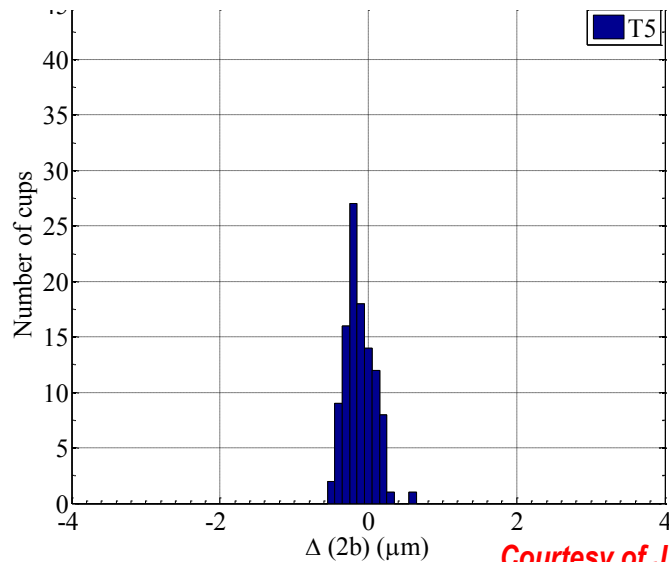
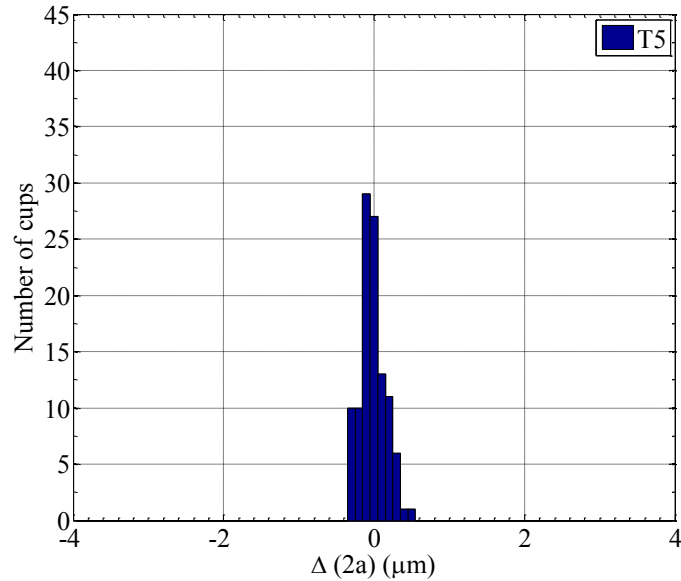
four 2 m long C-band structures, 28 MV/m  
0.22 GeV energy gain per module (+10% overhead)



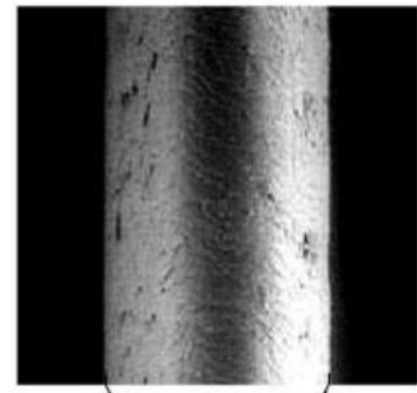
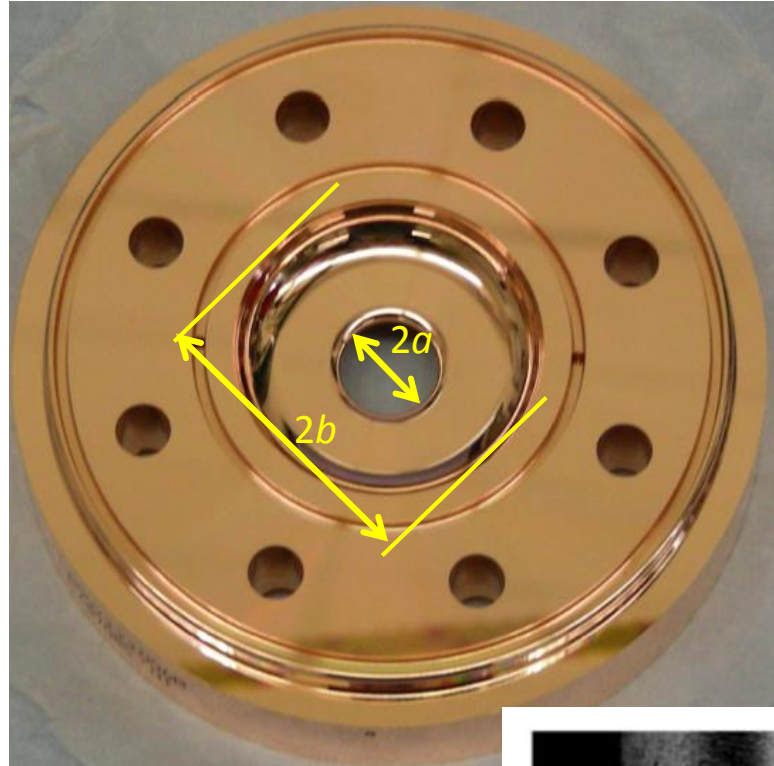
9 m

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

# Precision manufacturing of copper disks in Trübbach



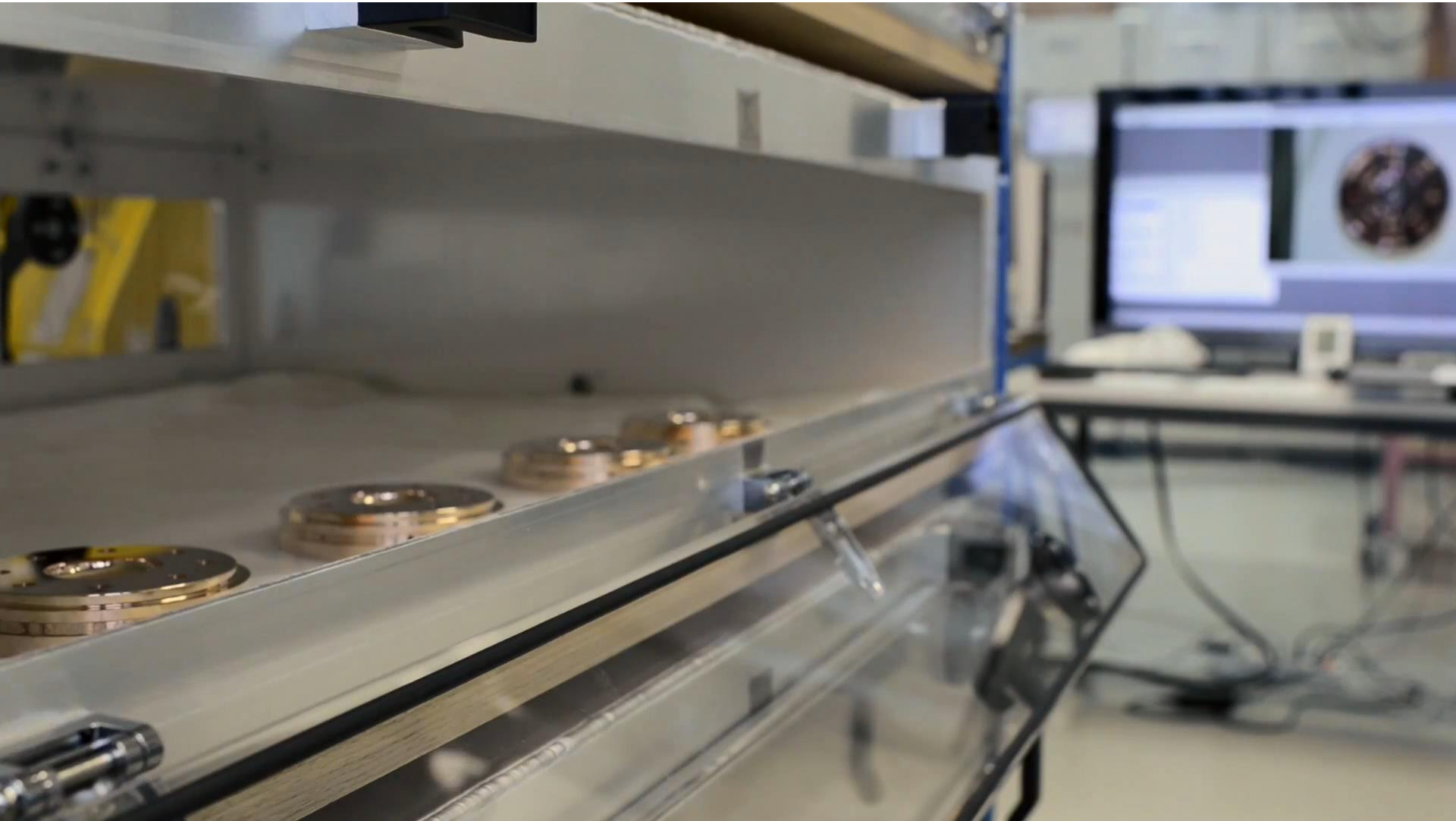
*Courtesy of J.Y. Raguin*



**Human Hair**  
**(60  $\mu\text{m}$  diameter)**

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

# Assembly of an accelerator structure at PSI



# 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

# C-band module assembly



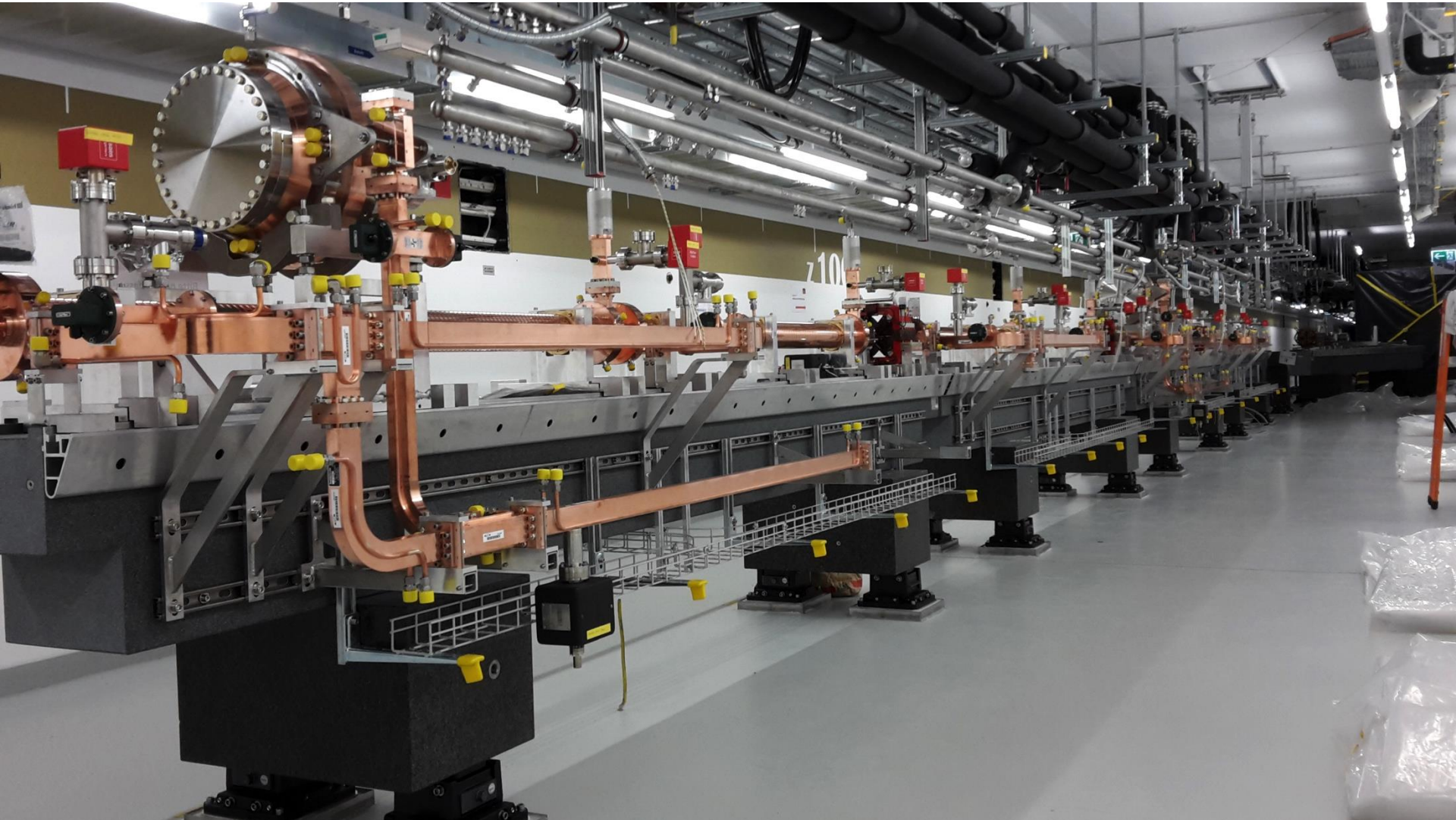
Installation and tuning of waveguides (waveguides delivered from MHI-MS)

# Girder installation in SwissFEL





# Accelerator module in the SwissFEL tunnel

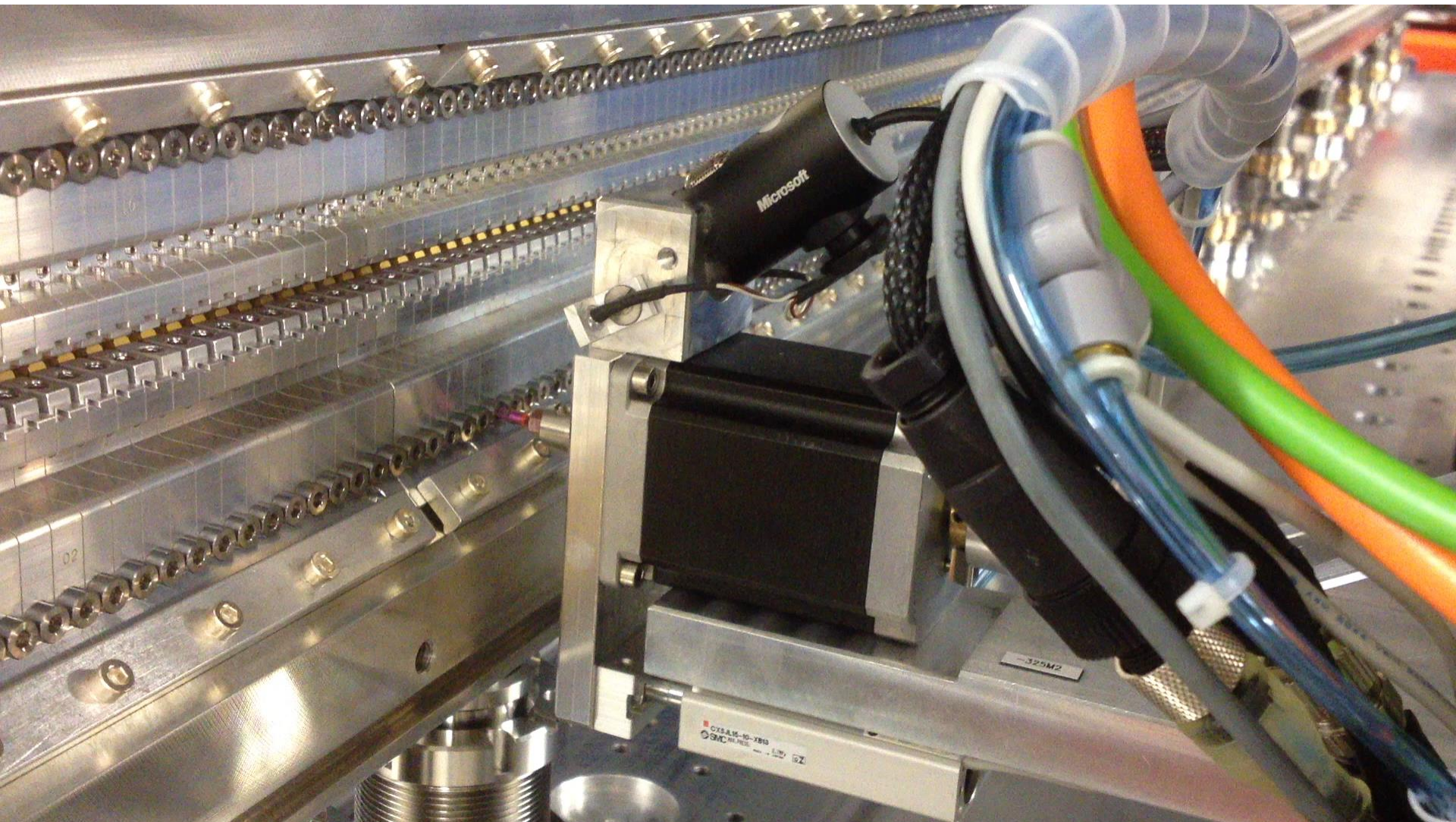


# SwissFEL undulators

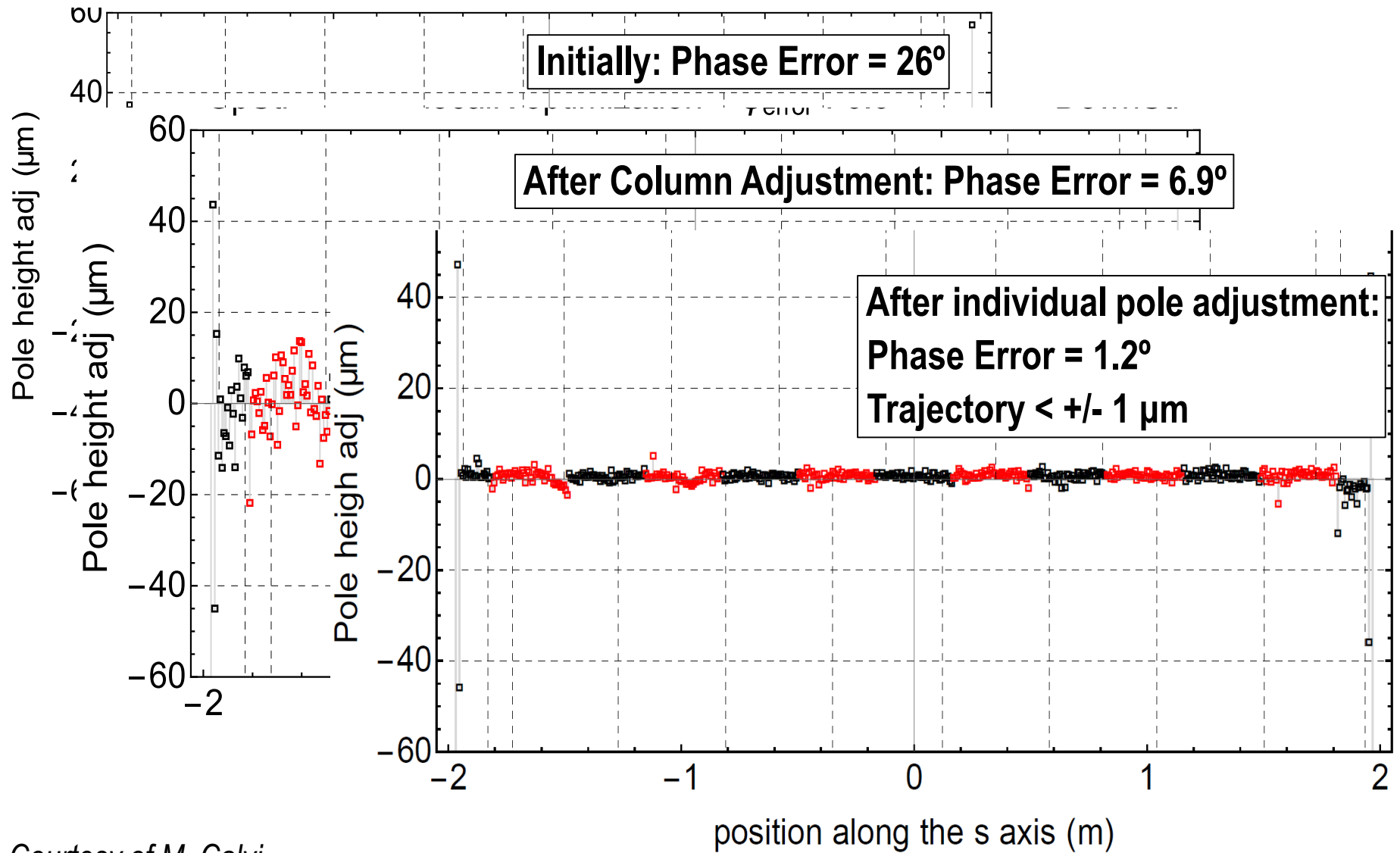
Transport of undulators in SwissFEL building  
with air-cushion vehicle



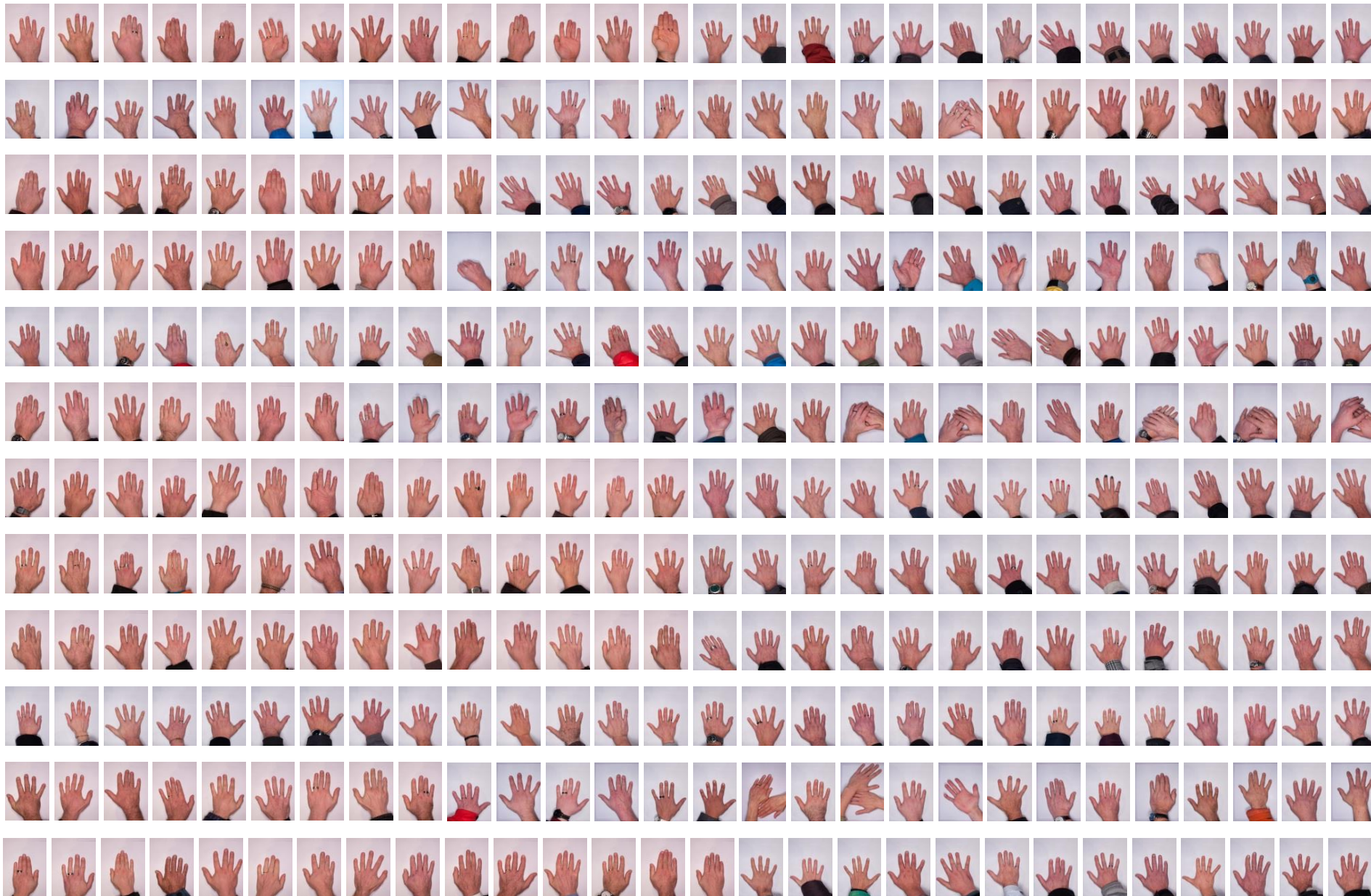
# Adjustment of the undulator magnets



## Effect of the adjustments on the field errors



# Thank you for your attention!





Thank you for your attention!



# Summer student position

<https://www.psi.ch/en/pa/job-opportunities/32415-trainee>

## Trainee

Performance optimization of the free-electron laser SwissFEL

## Your tasks

During the last years, an optimizer was used during the operation of SwissFEL which generated large sets of data of the optimization process. Your task will be to analyze the existing sets of data and to further extend the existing optimizer by additional optimization routines that will allow for a faster and more stable convergence. An example is the implementation of 'shallow learning', but many interesting options exist, and you will help trying out the most promising alternatives. You will learn about accelerators, free-electron lasers, data analysis, and multi-parameter optimization.

## Your profile

- You study physics or computer-sciences (minimum 4 semesters)
- You have an interest in analyzing data, programming, and testing your work on the accelerator of SwissFEL
- Experience with programming in C++ and scripting languages such as Matlab or python is desired
- You are open-minded, communicative and enjoy working in an international team
- You have not yet completed your Master's thesis

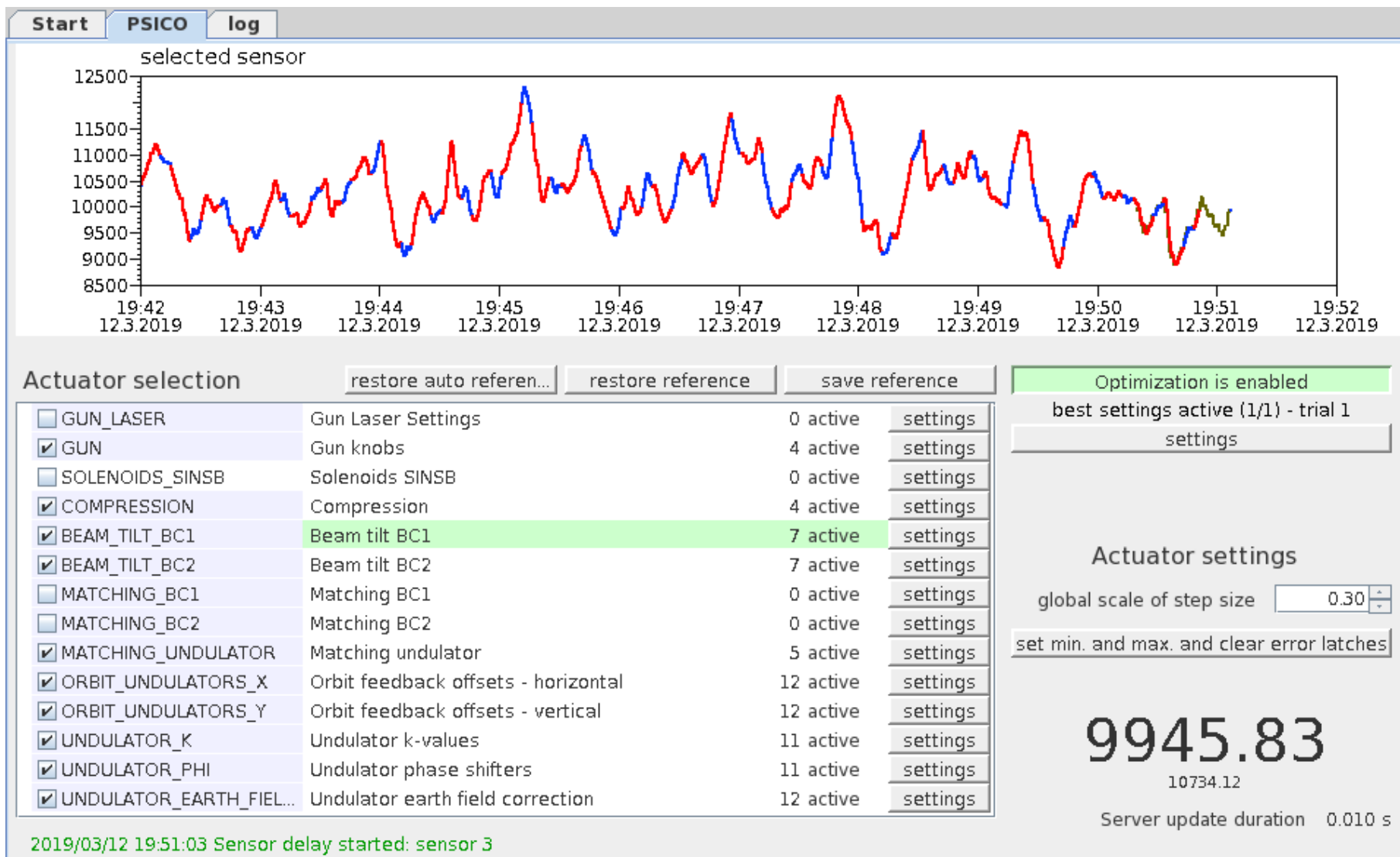
## We offer

Our institution is based on an interdisciplinary, innovative and dynamic collaboration.

The contract will be limited to 3 months.

For further information, please contact Dr Florian Löhl, phone +41 56 310 35 26.

# PSICO – automated machine optimization







# Example of PSICO tuning at 9 keV

