PAUL SCHERRER INSTITUT

SwissFEL

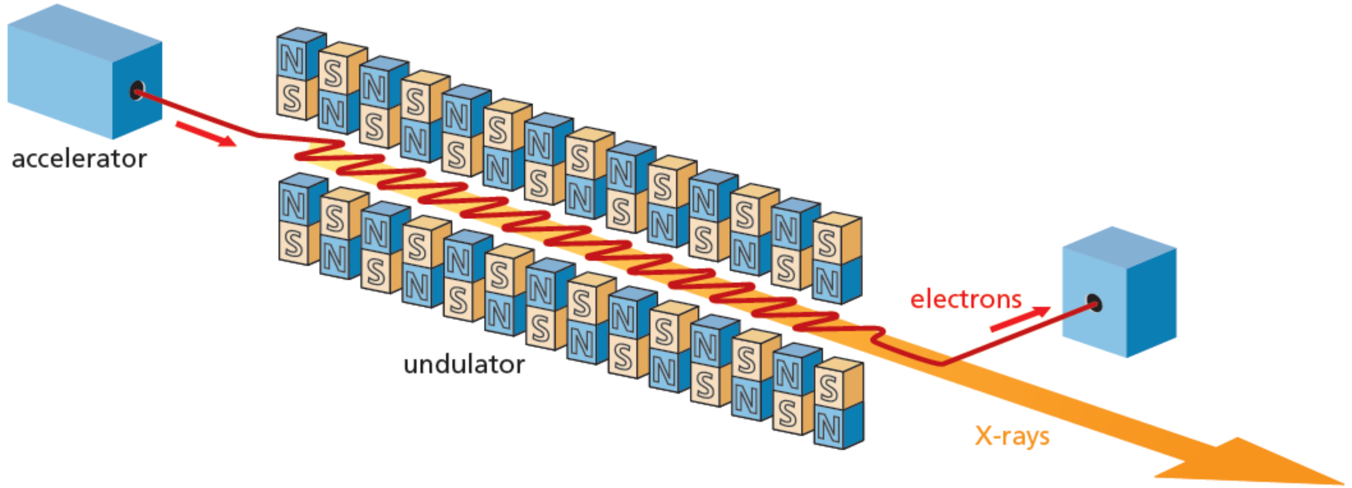
Hans-H. Braun for the SwissFEL Team :: Paul Scherrer Institut

SwissFEL, the Hard X-ray Free Electron Laser Facility at PSI

ATS Seminar, CERN, 22 June 2017

PSI with accelerators, Aare river and Alps

X-ray Free Electron Laser SwissFEL the new large research facility at PSI



X-FEL principle

High energy electrons interact with periodic magnetic field of undulator magnet to build up an extremely short and intense X-ray pulse.

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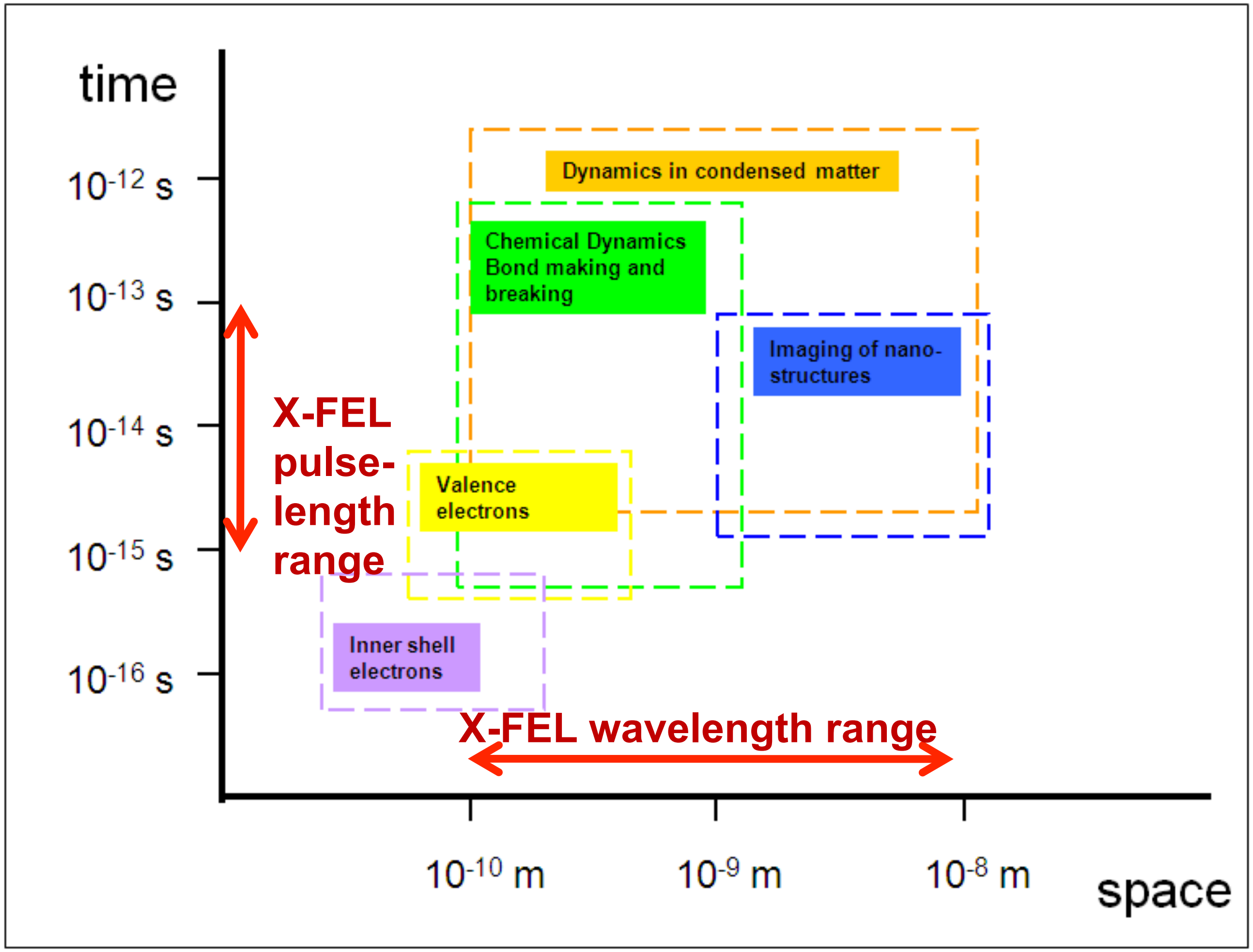
What is the X-FEL good for?



⇒ X-FEL allows for flash images with

- ***space resolution on scale of atomic bonds***
- ***time resolution on scale of fastest chemical processes***

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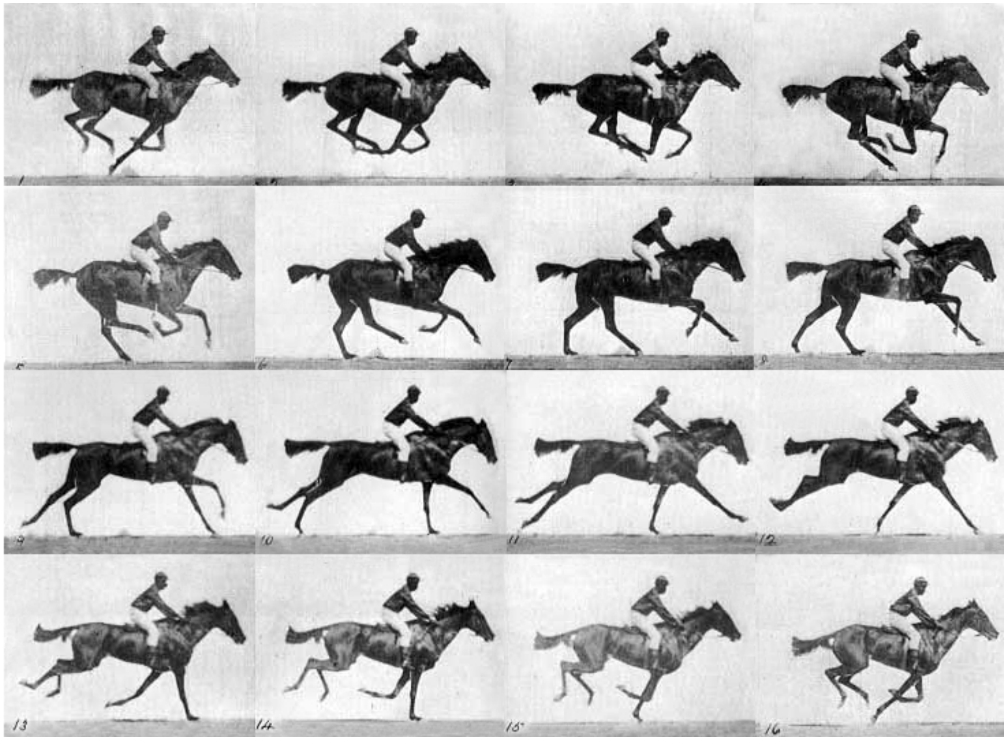
observe structure → observe function

Louis Jacques Mandé Daguerre
Portrait M. Sabatier-Blot,1844

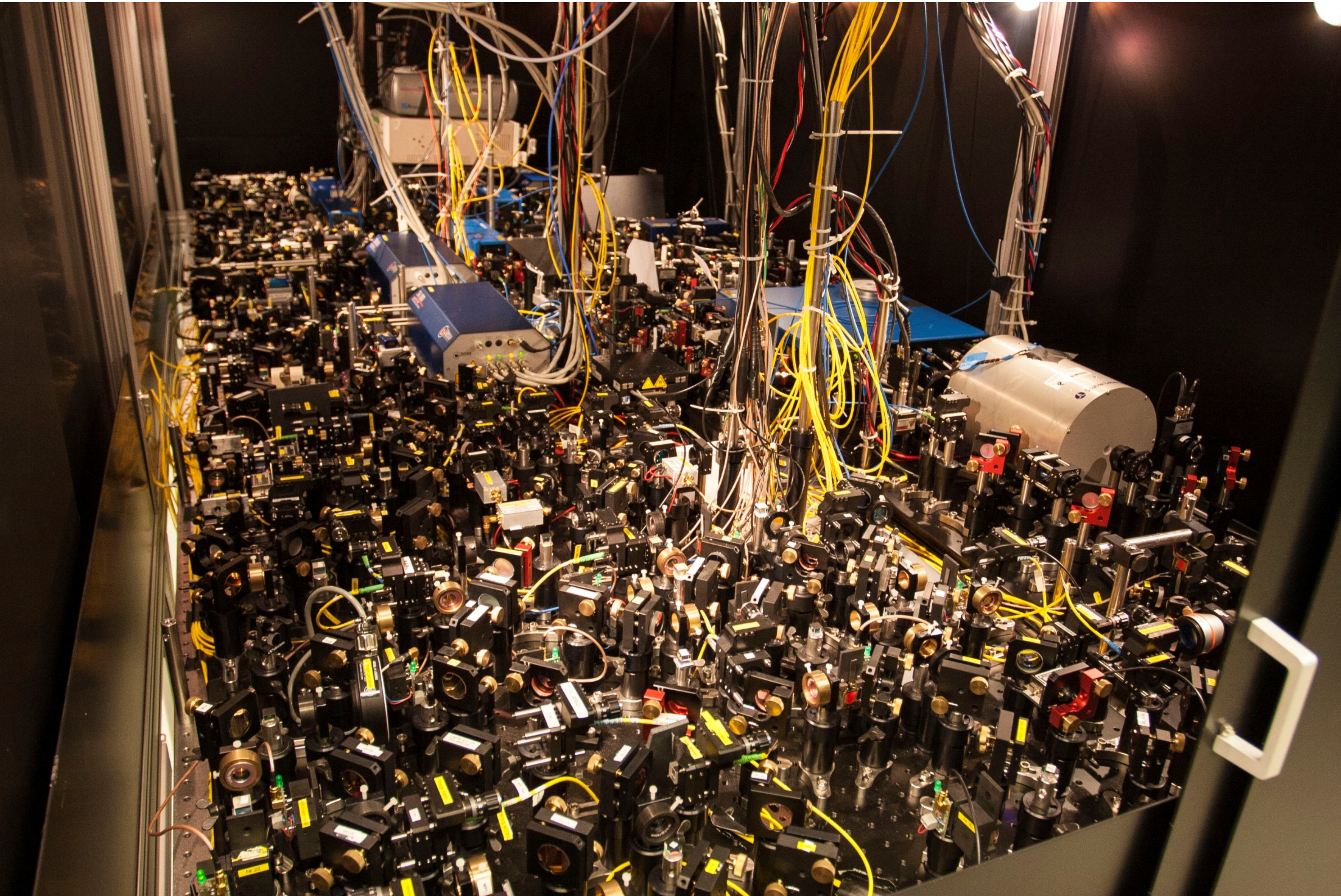
exposure time: few minutes



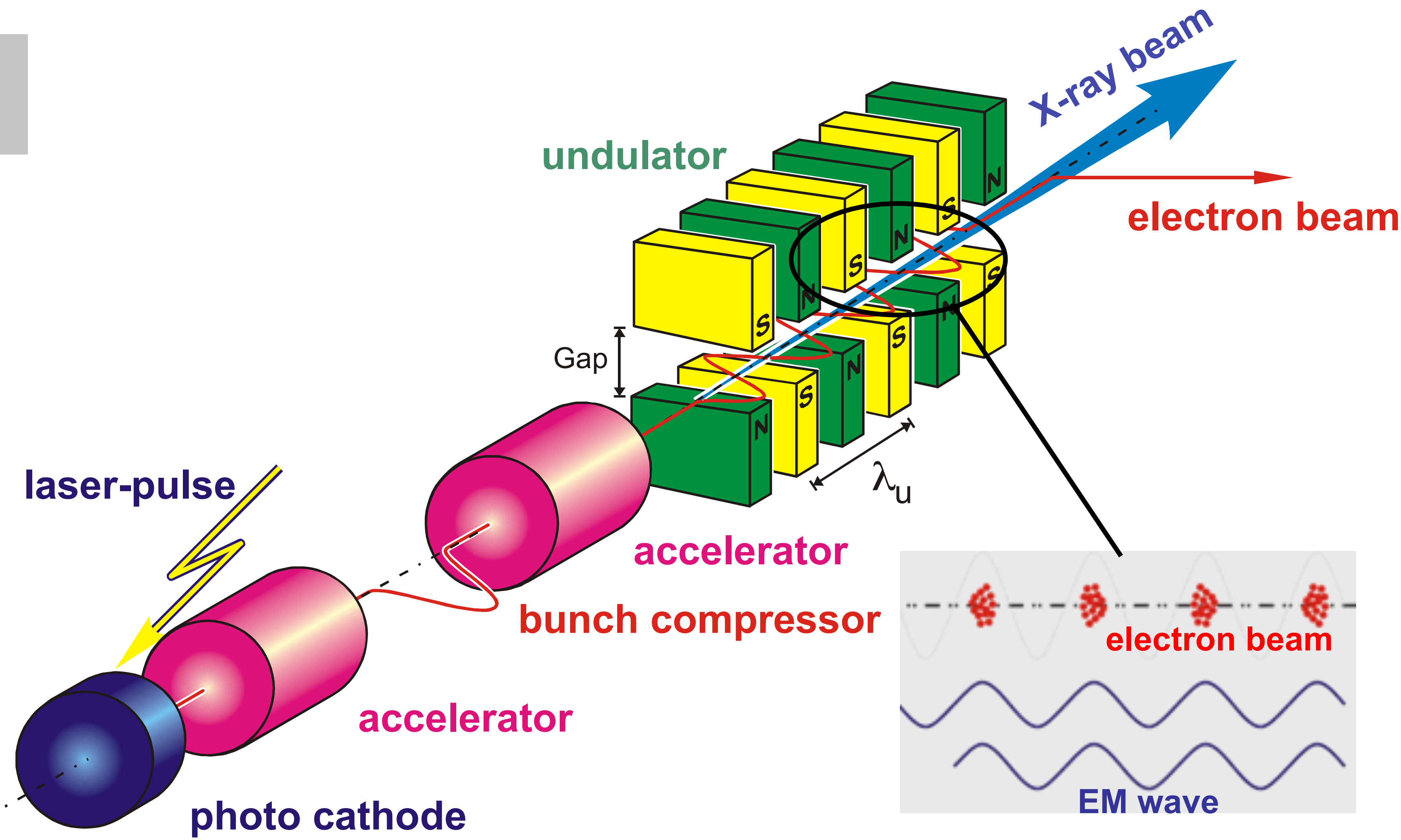
Eadweard Muybridge
The Horse in Motion, 1872

Exposure time: few milliseconds

Laser at MPQ Munich

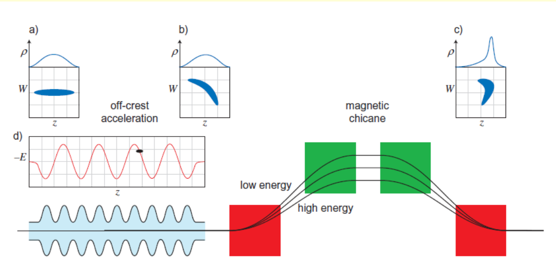


X-FEL schematic

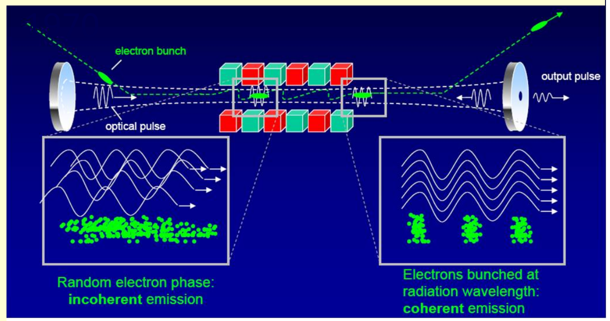


Key enabling technologies for X-FELs

Magnetic bunch compression

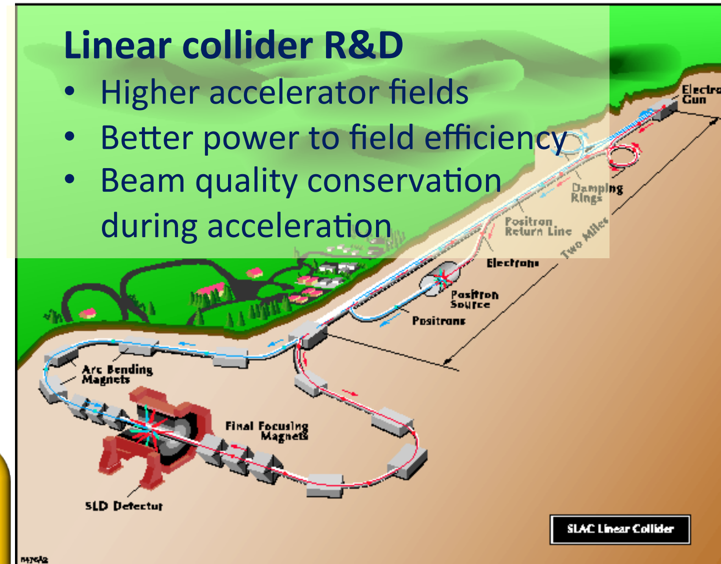


Free electron laser, John Madey,

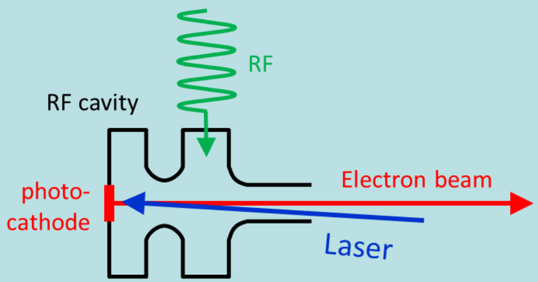


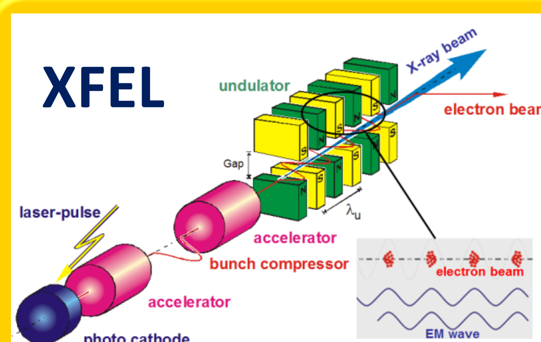
Linear collider R&D

- Higher accelerator fields
- Better power to field efficiency
- Beam quality conservation during acceleration



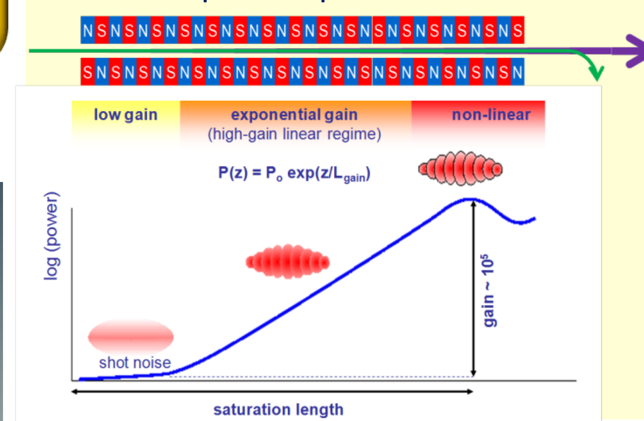
High brilliance e^- sources

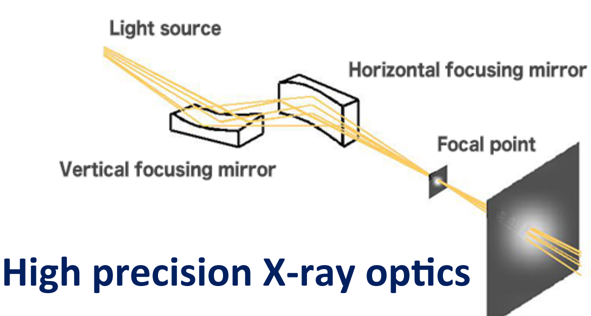




SASE

=Self amplified spontaneous emission

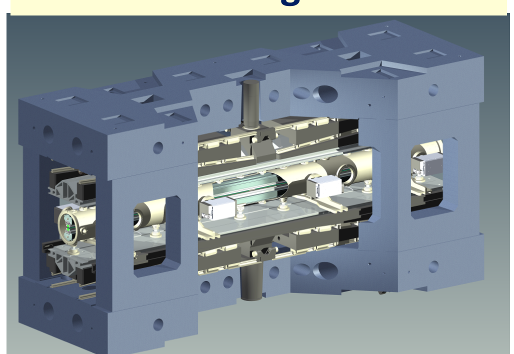




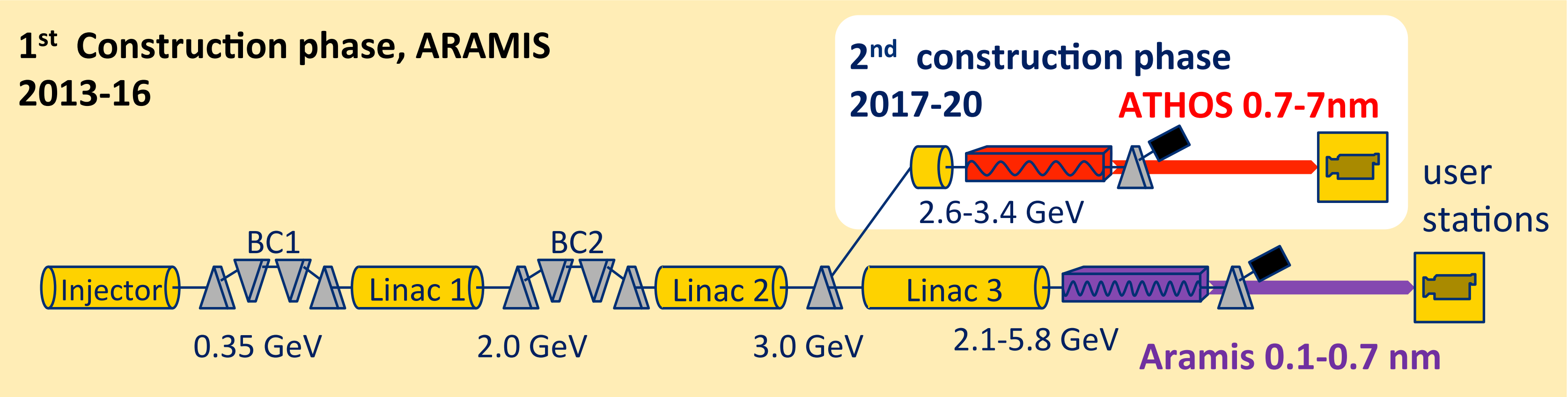
High precision X-ray optics

Kirkpatric-Baez(K-B) optical system
(Total reflection and elliptical mirror)

Undulator magnets



SwissFEL in a nutshell



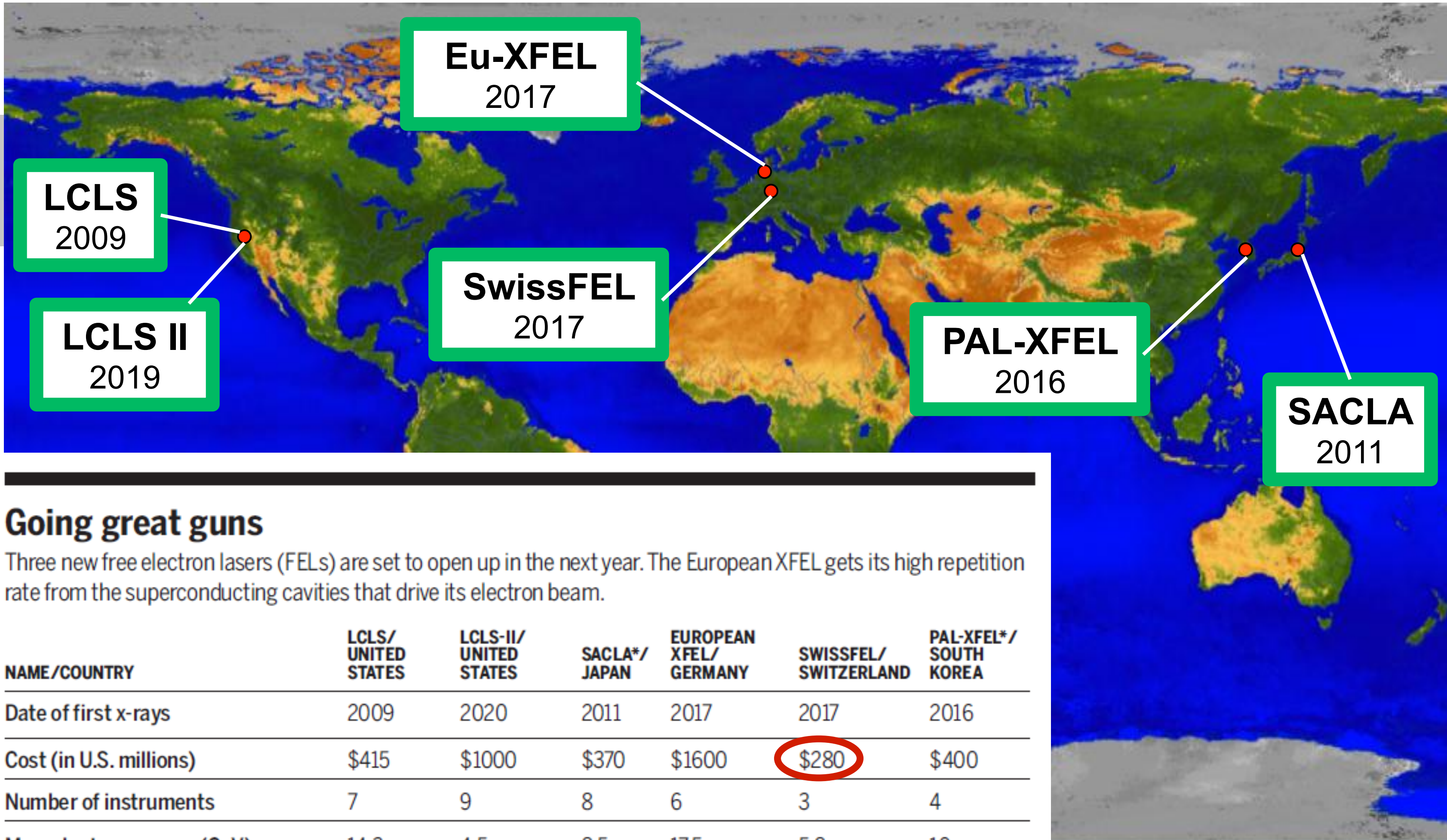
ARAMIS
Hard X-ray FEL, λ = 0.1-0.7 nm
Linear polarization, variable gap, in-vacuum undulators
First users 2017

ATHOS
Soft X-ray FEL, λ = 0.7-7.0 nm
Variable polarization, Apple II undulators
First users 2020

Main parameters

Wavelength from	1 Å - 70 Å
Photon energy	0.2-12 keV
Pulse duration	1 fs - 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz

X-FELs worldwide



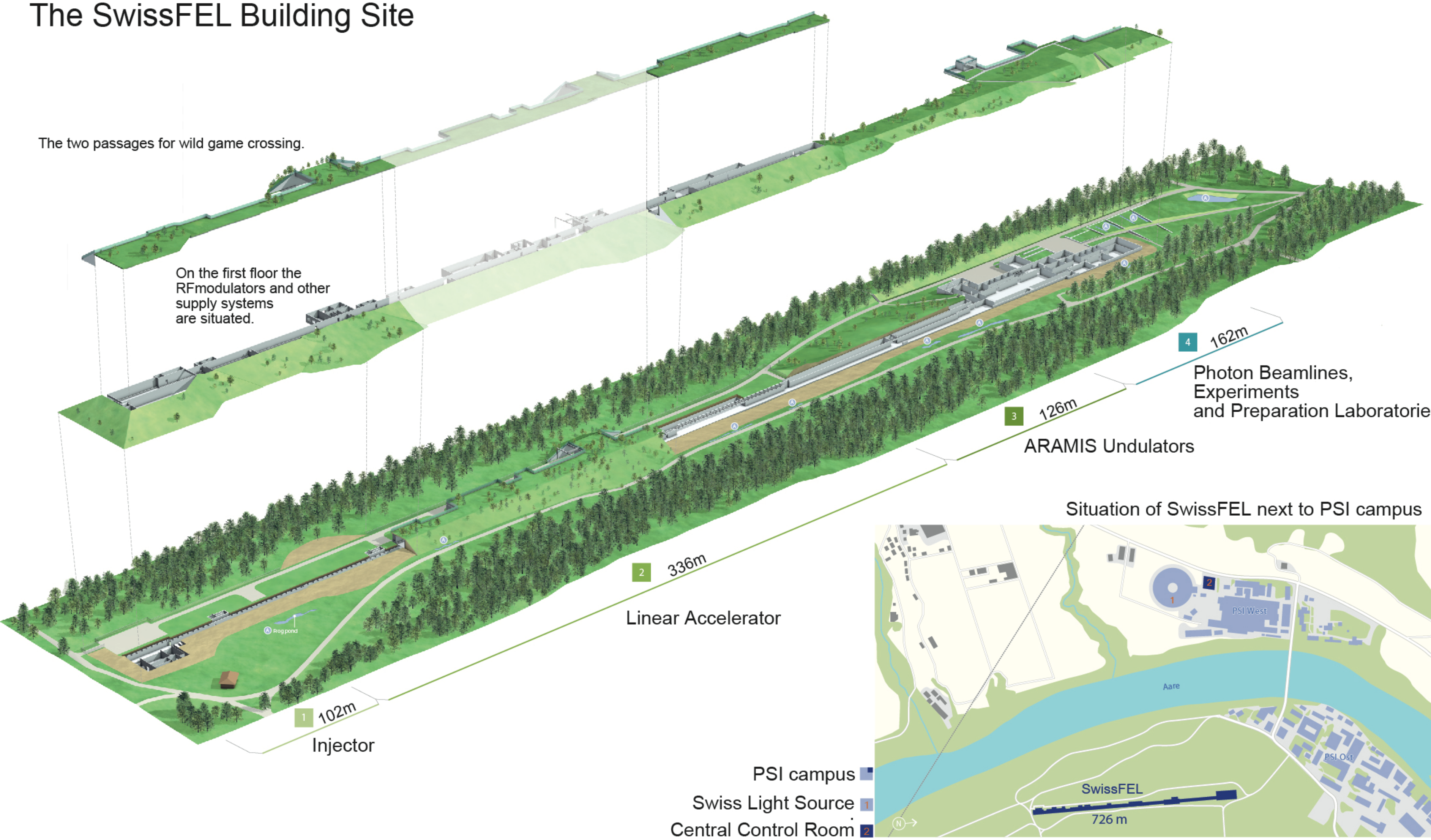
Going great guns

Three new free electron lasers (FELs) are set to open up in the next year. The European XFEL gets its high repetition rate from the superconducting cavities that drive its electron beam.

NAME/COUNTRY	LCLS/ UNITED STATES	LCLS-II/ UNITED STATES	SACLA*/ JAPAN	EUROPEAN XFEL/ GERMANY	SWISSFEL/ SWITZERLAND	PAL-XFEL*/ SOUTH KOREA
Date of first x-rays	2009	2020	2011	2017	2017	2016
Cost (in U.S. millions)	$415	$1000	$370	$1600	$280	$400
Number of instruments	7	9	8	6	3	4
Max. electron energy (GeV)	14.3	4.5	8.5	17.5	5.8	10
Min. pulse duration (femtoseconds)	15	15	10	5	2	30
Pulses per second	120	1,000,000	60	27,000	100	60

**SACLA is the Spring-8 Angstrom Compact free electron Laser and PAL-XFEL is the Pohang Accelerator Laboratory X-ray Free Electron Laser*

The SwissFEL Building Site

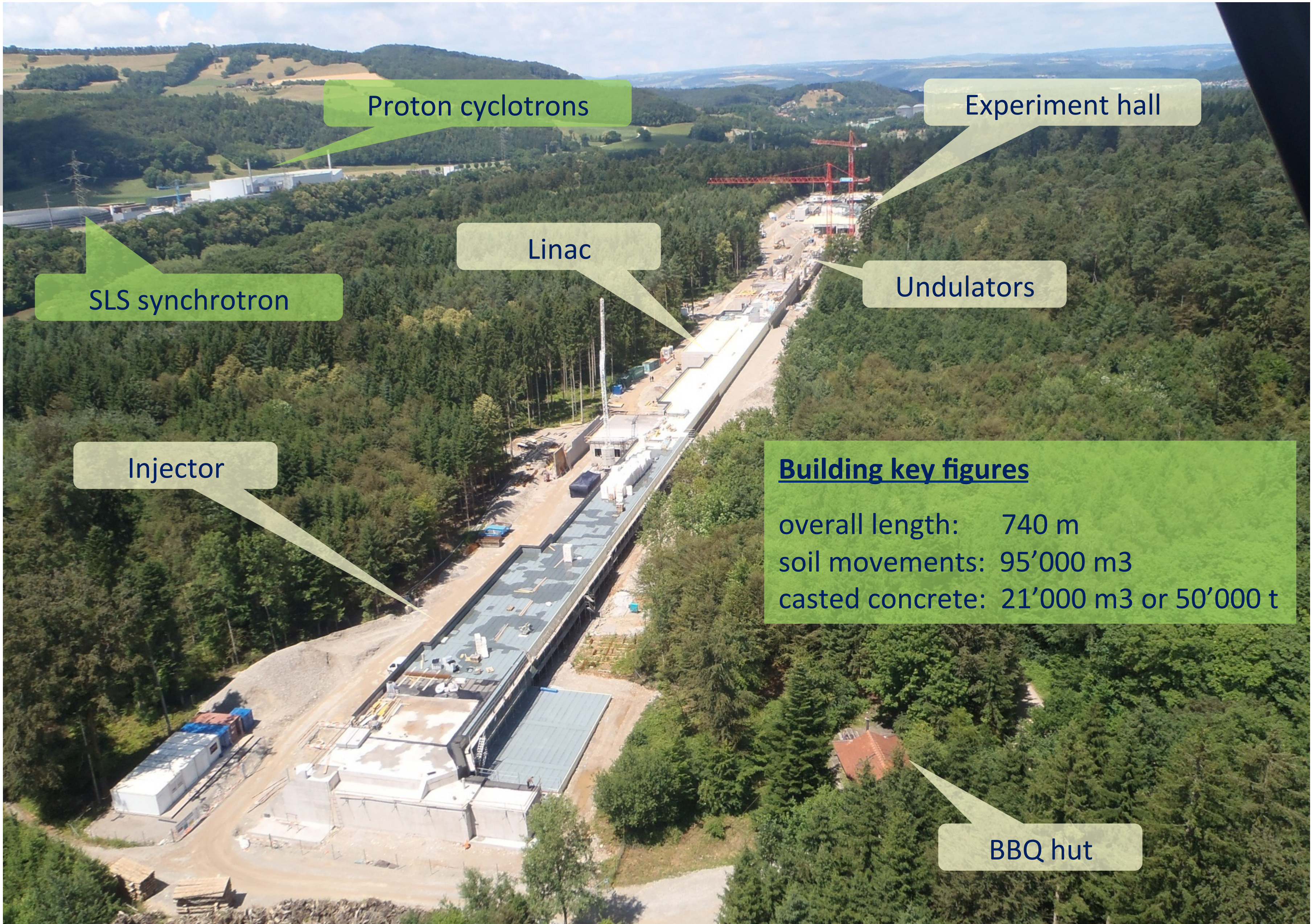


SwissFEL building evolution I

May 2013
Construction site after forest clearance

SwissFEL building evolution II

construction site, July 2014

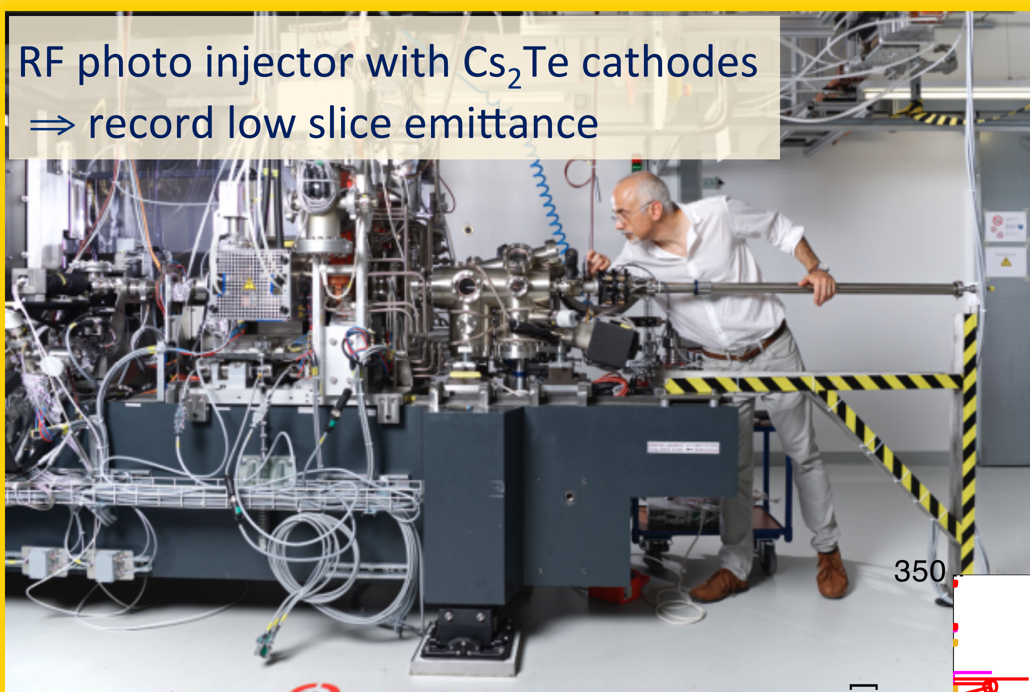


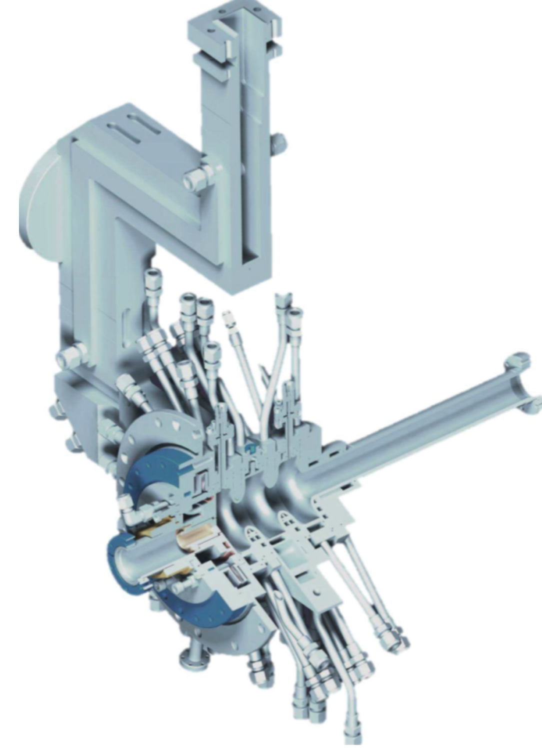
SwissFEL building evolution III
completed building, Jan'16

Jan'16, wild game crossing commissioned with first users

SwissFEL technical highlights I

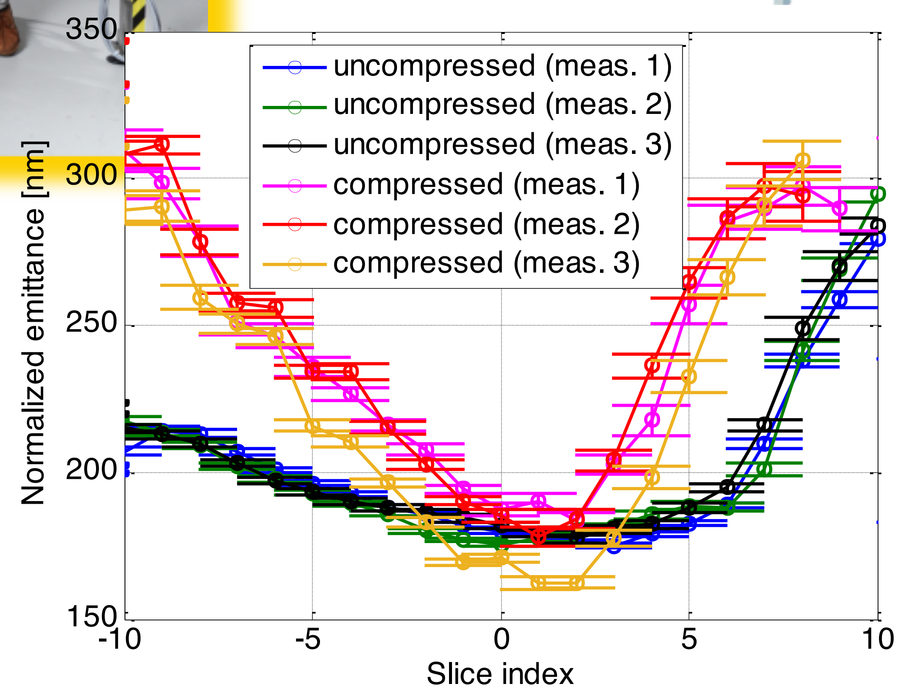
RF photo injector with Cs_2Te cathodes
⇒ record low slice emittance



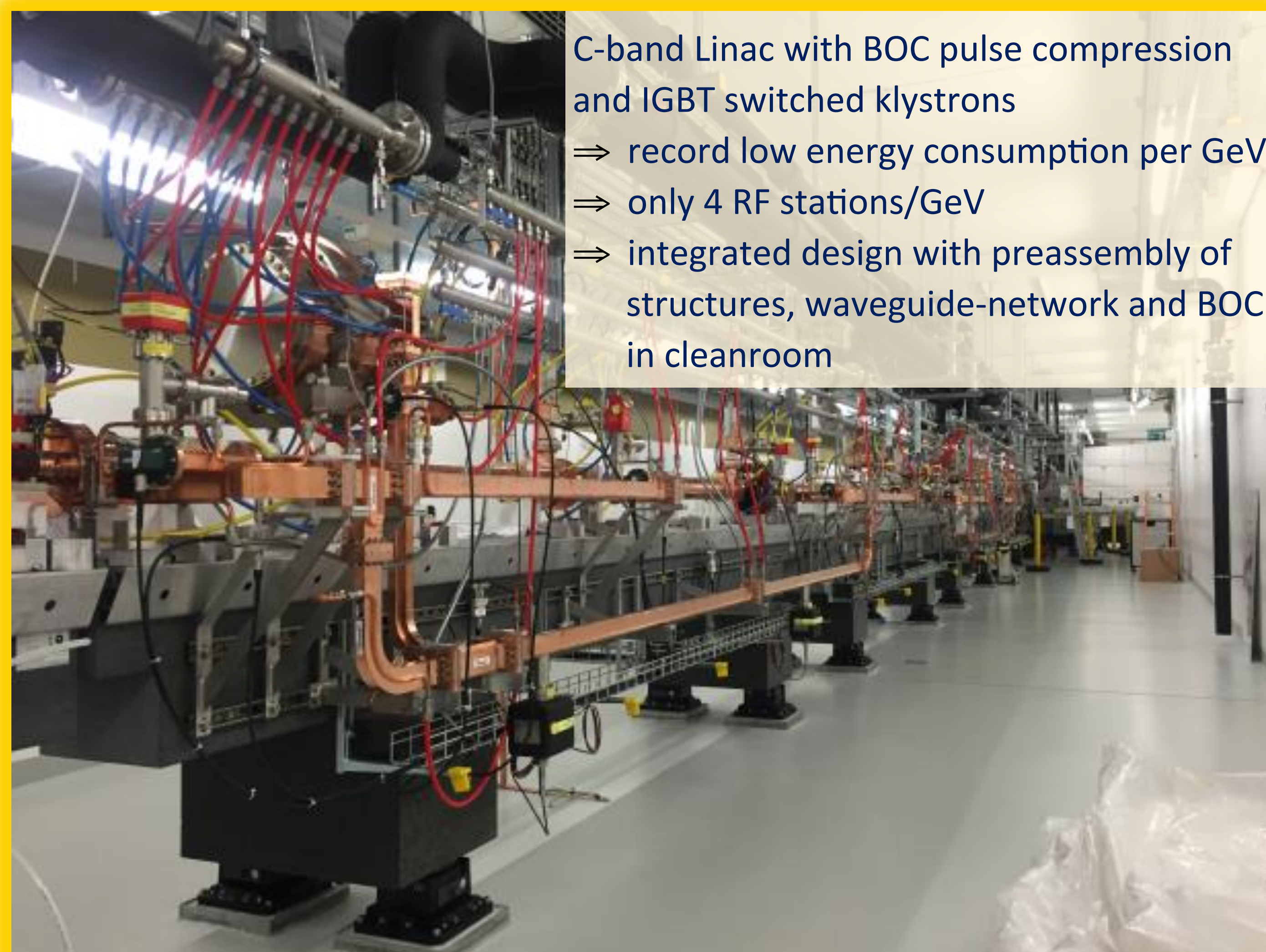


For Q_B= 200pC (SwissFEL nominal)

- Core slice emittance smaller than 200 nm (design value for SwissFEL is 430 nm)
- Slice emittance preserved in the core when compressing to 150 A



SwissFEL technical highlights II



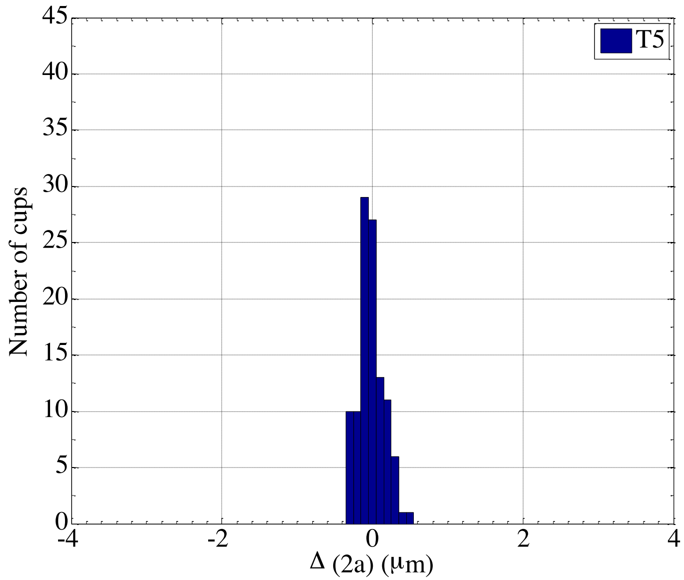
C-band Linac with BOC pulse compression and IGBT switched klystrons

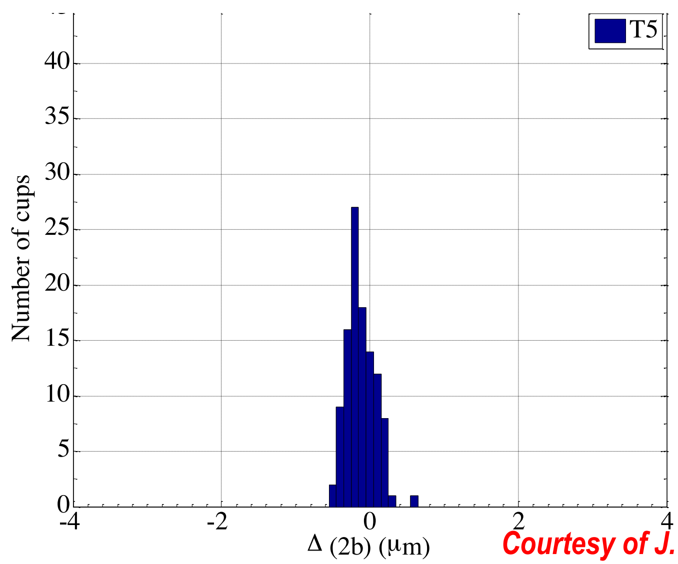
⇒ record low energy consumption per GeV

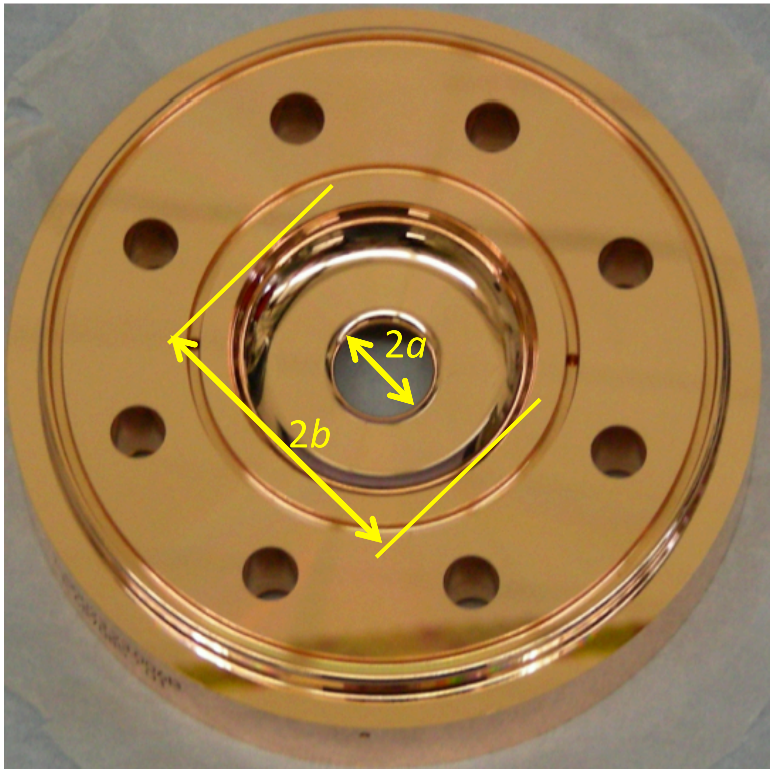
⇒ only 4 RF stations/GeV

⇒ integrated design with preassembly of structures, waveguide-network and BOC in cleanroom

C-band Structure Cups: production by VDL-ETG Switzerland machined “on tune”



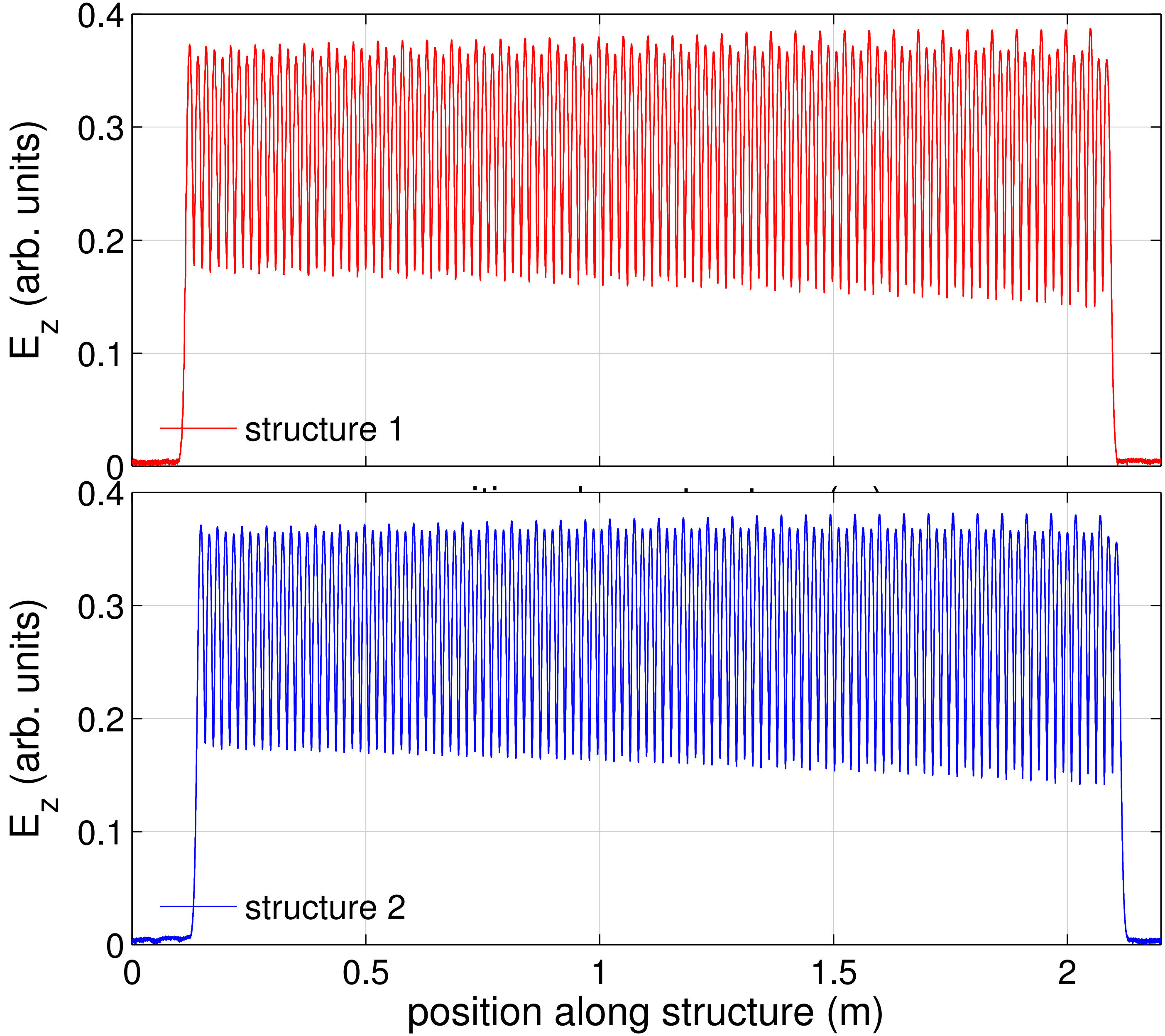




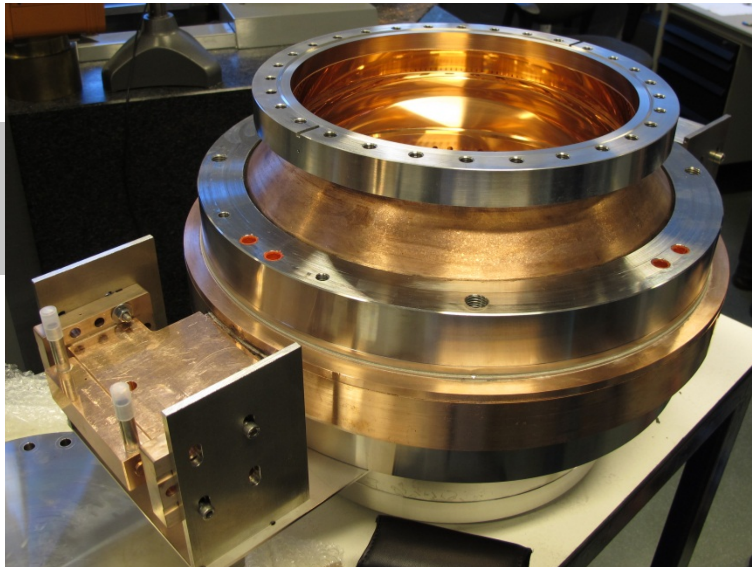
Courtesy of J.Y. Raguin

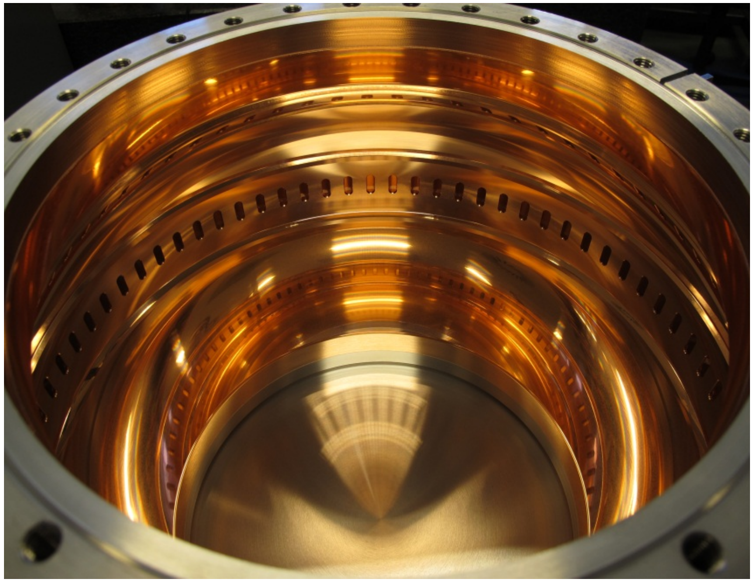
Typical examples of metrology on a structure: on top histogram iris diameter ,
on bottom histogram iris cell diameter

2 m C-band structure: longitudinal field distribution



C-band BOC Pulse compressor





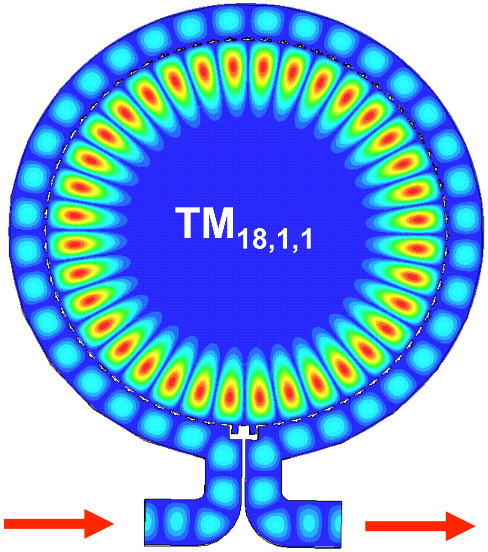
RF design:

- ✓ Single cavity
- ✓ Whispering gallery mode
- ✓ intrinsic high Q>200000

Mechanical design:

Simple and robust design:

- ✓ Inner body from a single piece
- ✓ Two brazing steps
- ✓ Machined on tune



Comparison power consumption for RF plants

Beam energy

SwissFEL	5.8 GeV
SACLA	8.0 GeV
LCLS	13.6 GeV

small emittance
short period undulators

Accelerating field

SwissFEL	28 MV/m
SACLA	35 MV/m
LCLS	17 MV/m

compromise between
power consumption
and facility length

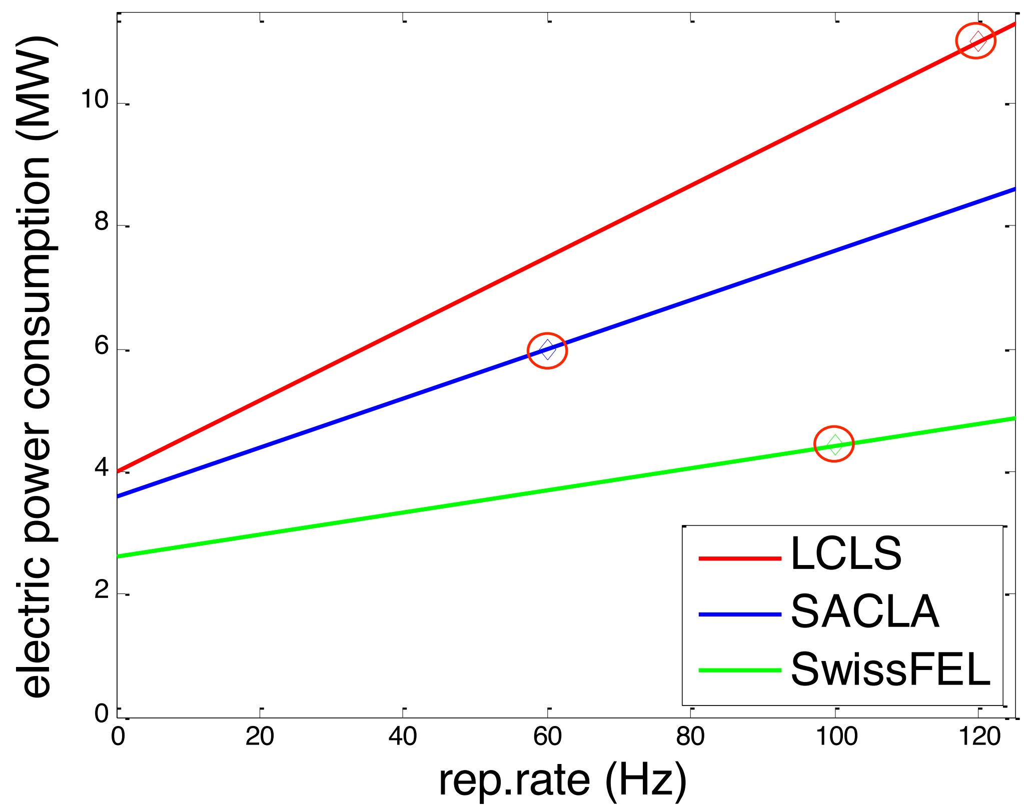
$$P_{HF} = \frac{V \cdot E}{R'}$$

Effective* Impedance

SwissFEL	168 MΩ/m
SACLA	125 MΩ/m
LCLS	80 MΩ/m

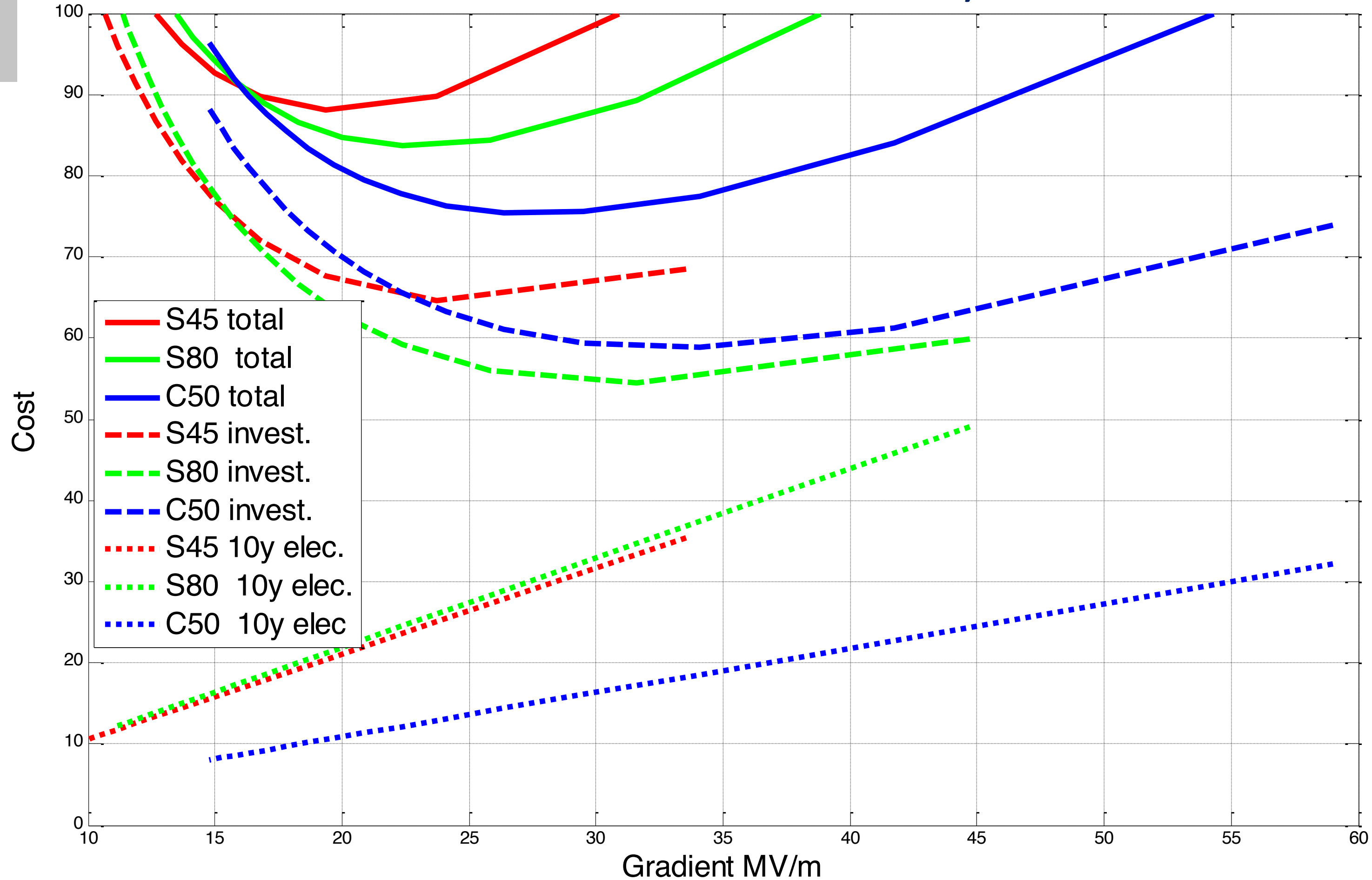
C band frequency
structure geometry
pulse compression

*not classical shunt impedance
but with correction for pulse compression
(Klystron power to effective energy gain)



Cost optimization for SwissFEL linac

Cost vs. gradient for S-band with 45 MW klystron,
S-band with 80MW klystron
and C-band with 50 MW klystron

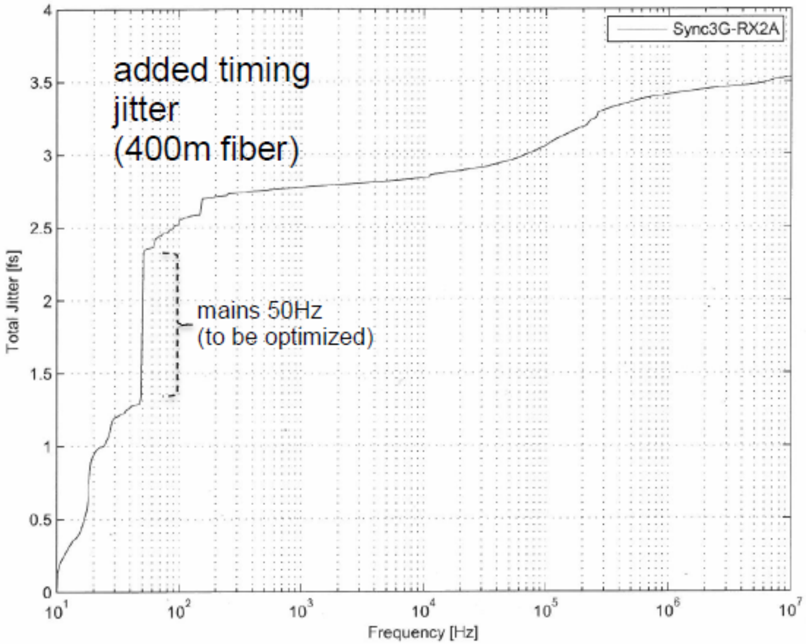


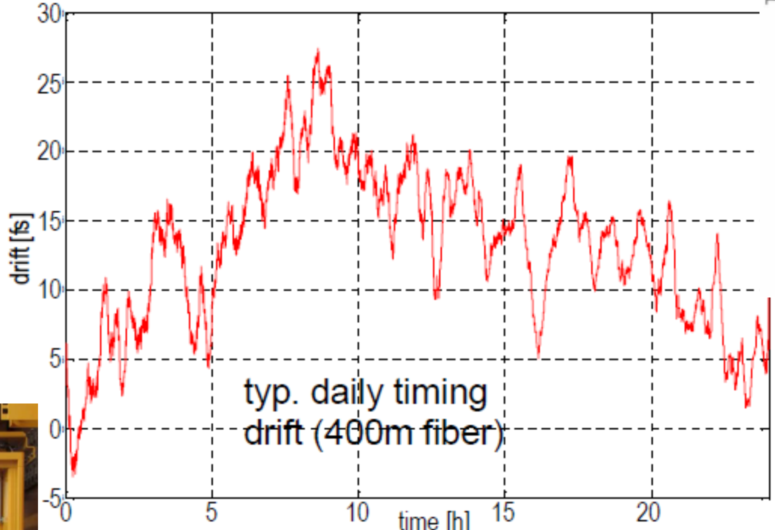
Advantage of C-band is in real-estate needs and electricity consumption

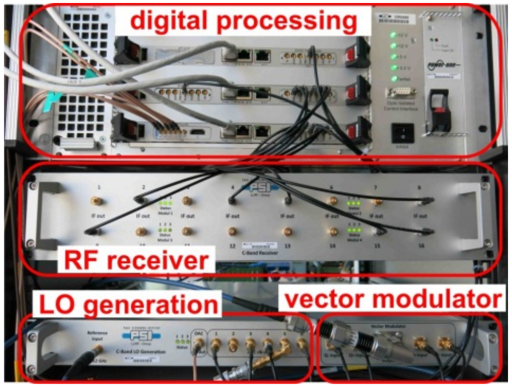
Reference distribution and LLRF

Results with I-Tech/PSI S-band (2.9988GHz) link

Influence of temperature, humidity variations and mechanical vibrations are compensated by group delay control.
Further drift reduction expected.







C-band LLRF prototype system

Solid-state modulators

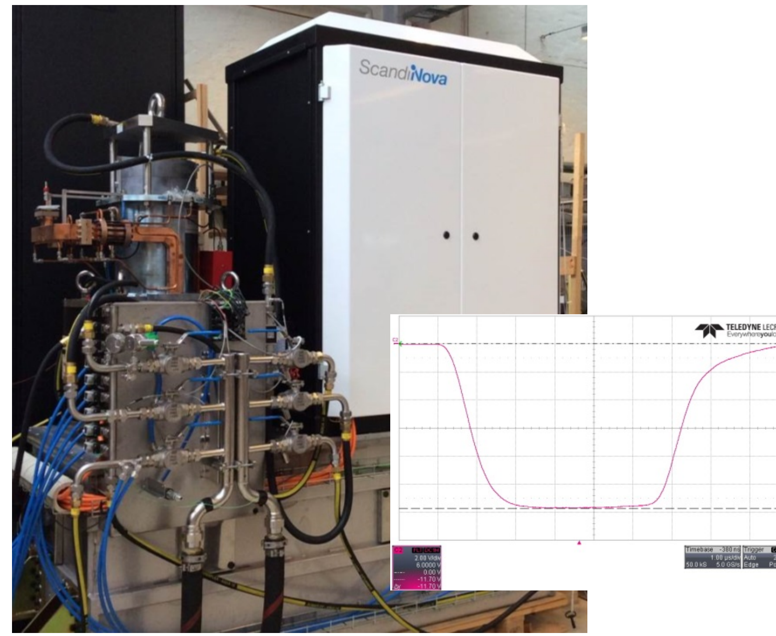
Two types were successfully qualified at PSI

50 MW / 3µs RF, 370kV / 344A / < 15 ppm voltage stability pulse to pulse @ 100 Hz

AMPEGON

13 modulators (Linac 1, Linac 2)
4 in operation, 4 under commissioning
5 expected July - October

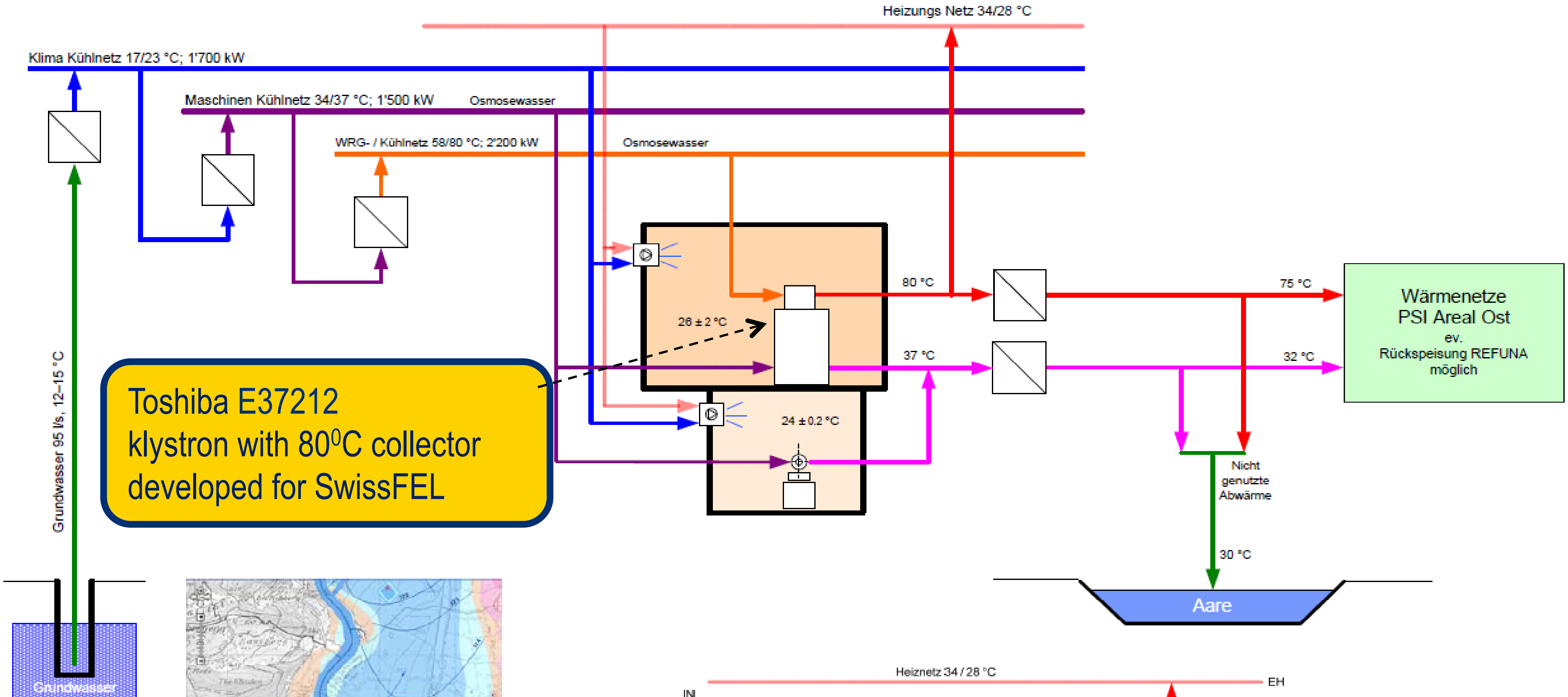
ScandiNova

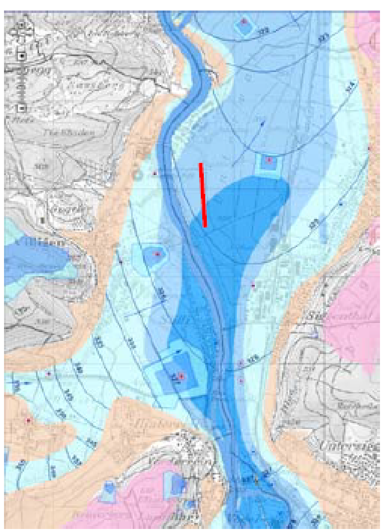


6 K2 type in operation (injector)
1 K2-3 type (Linac 3) under commissioning
12 K2-3 expected July – November

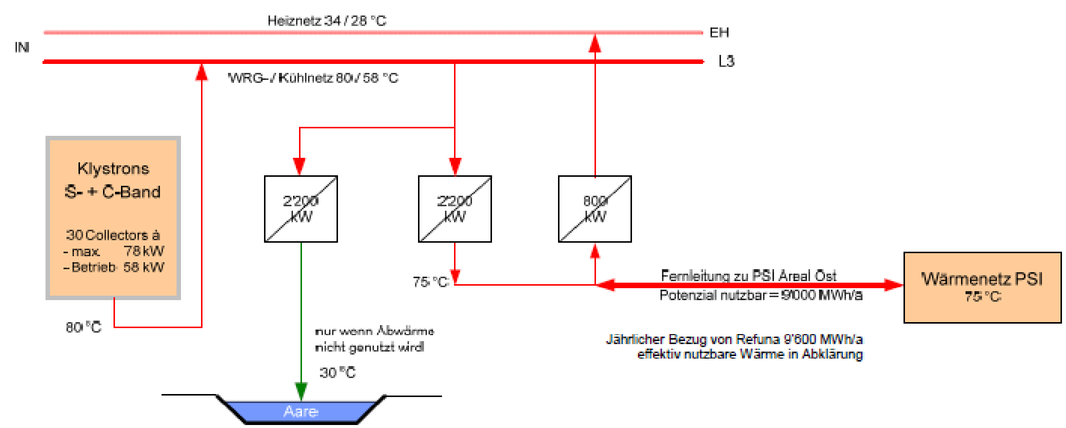
⇒ delivery schedule drives commissioning schedule

Energy recovery for SwissFEL





Grundwasserkarte



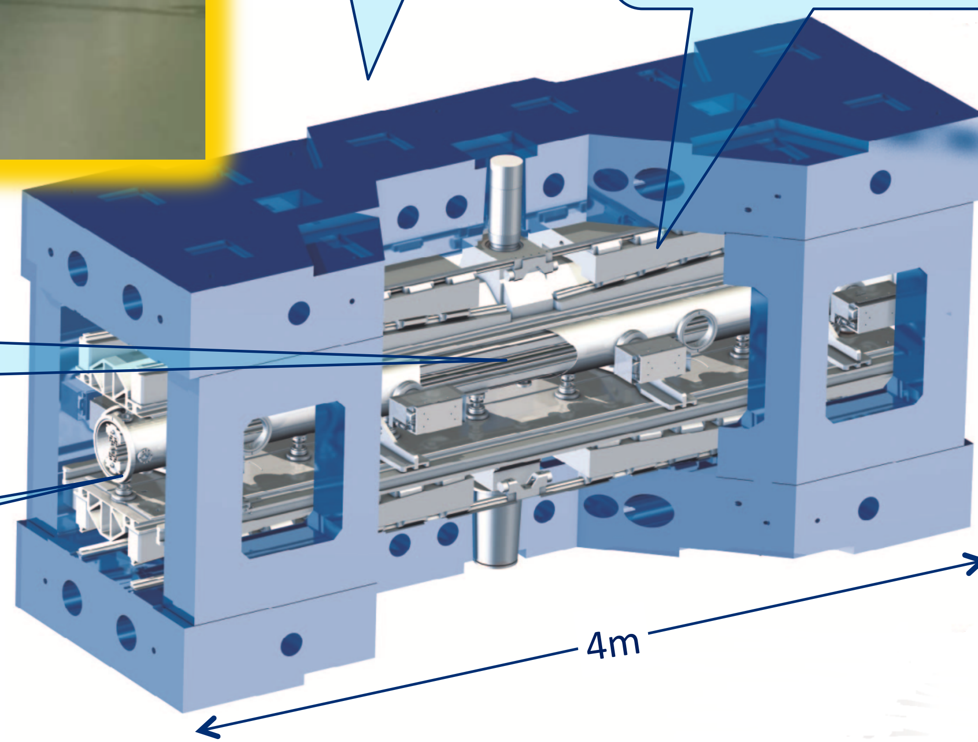
Wärmerückgewinnung

SwissFEL technical highlights III

U15 undulator

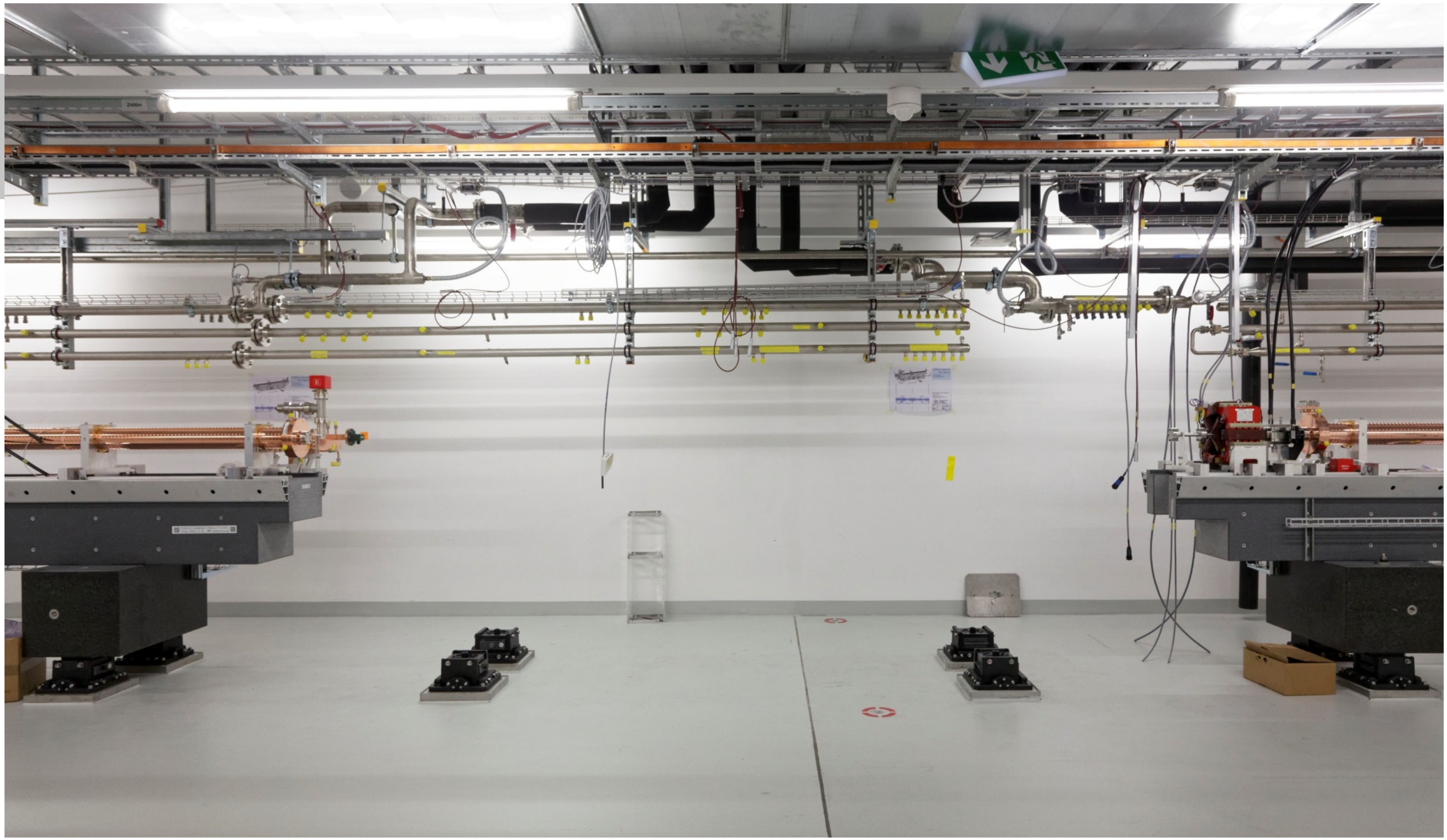
nominal working point: λ_U=15 mm, K=1.2, g=4.5mm

ARAMIS FEL consists of 13 x U15

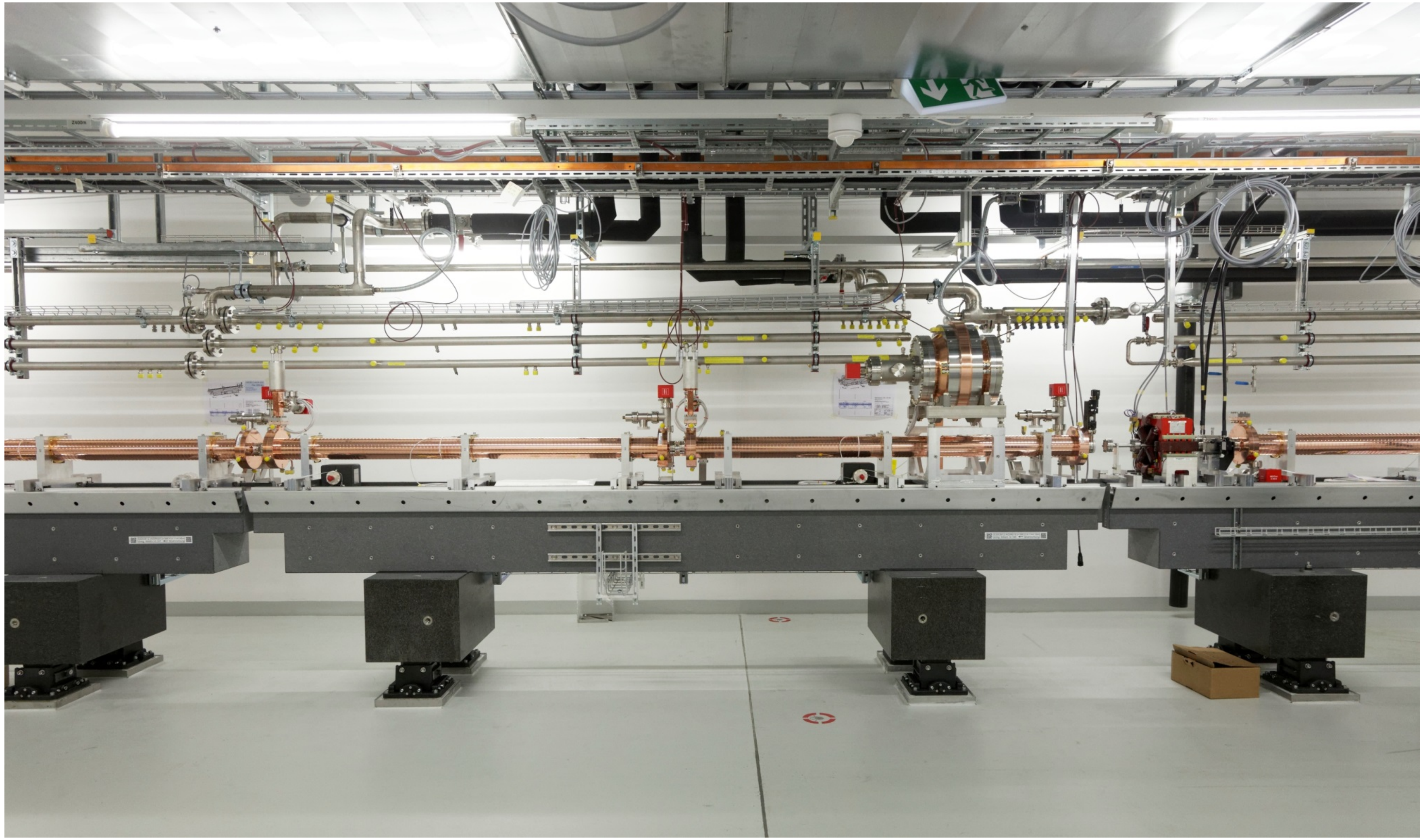


SwissFEL installation progress

Installation of last Linac girder: Sept. 13, 2016



Installation of last Linac girder: Sept. 13, 2016

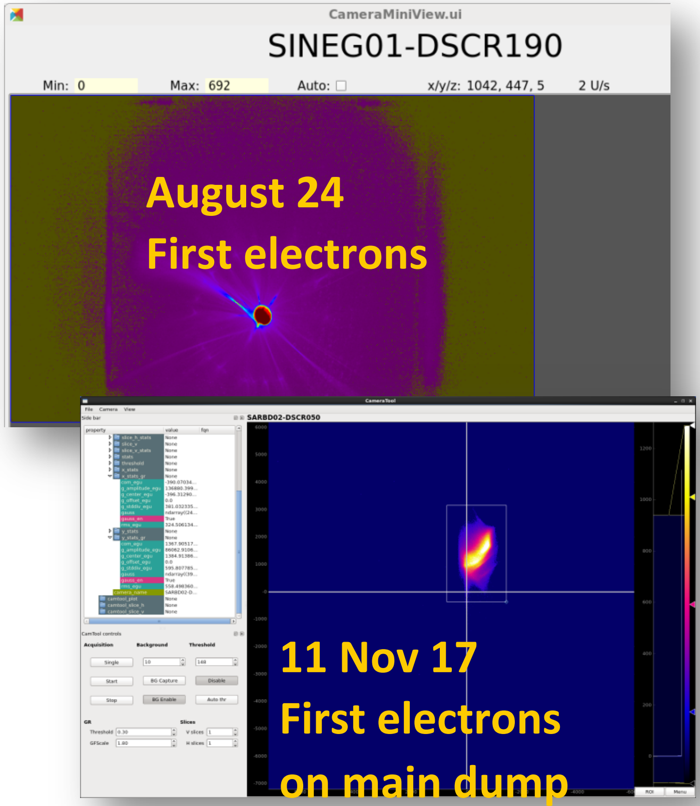


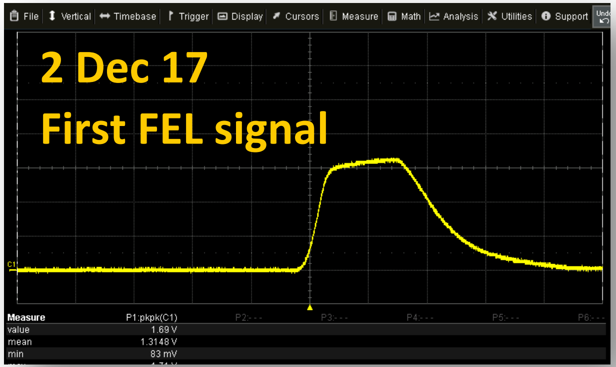
2016, October 7
Beamline complete from Photo-injector to beam dump

SwissFEL in 100 seconds

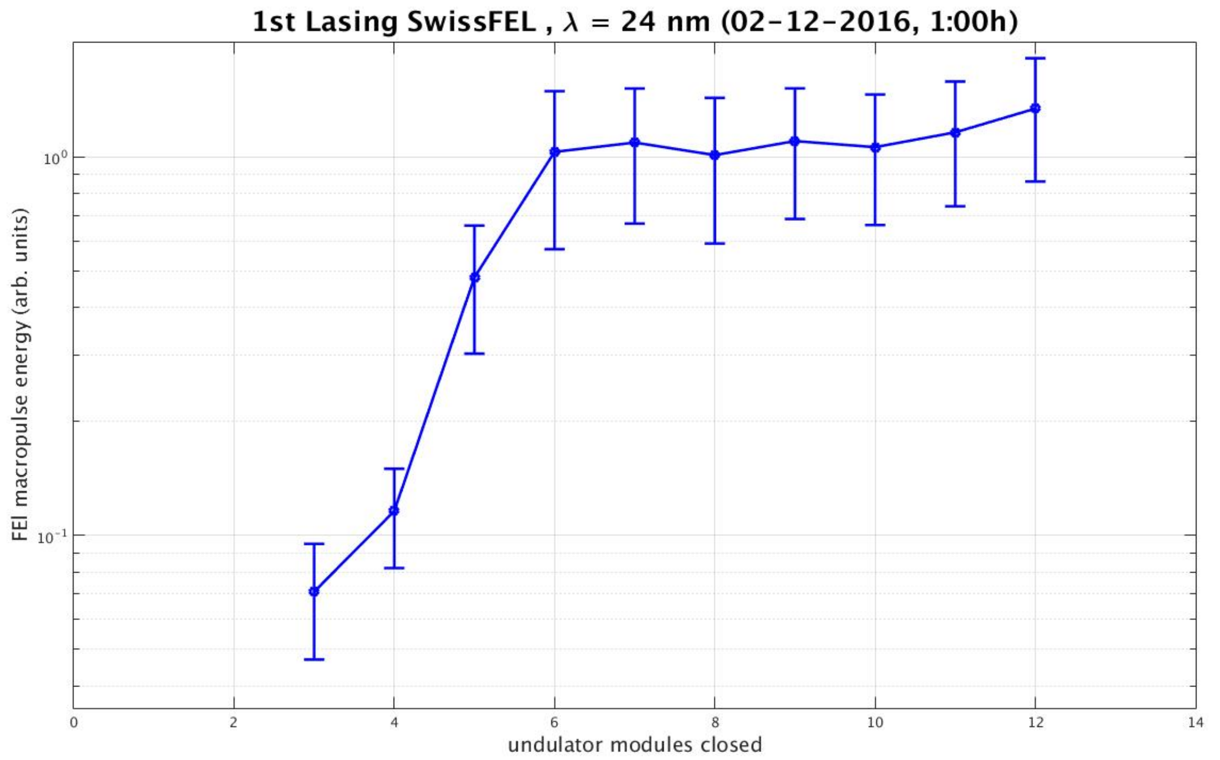
Commissioning Progress in 2016

Date	achievement
August 24	First free electrons from gun with 7.9MeV
September 7	First electrons to injector beam dump
September 8	First acceleration with one C-band module
October 7	Beam line injector to main dump completed and under vacuum
November 11	First beam transport through undulators to main dump
December 2	First lasing at 345 MeV, 24 nm
December 5	Inauguration ceremony & party





First lasing at moderate wavelength on 2.12.2016



Obtained with only 345 MeV beam energy, signal measured with Si-Diode (half the injector RF + 1 main linac C-band RF station)

Mainly a systems test!

5.12.2016 SwissFEL, the Inauguration

**On December 5th 2016, PSI held an
inauguration ceremony for its new l
arge-scale research facility SwissFEL,
with Johann N. Schneider-Ammann,
President of the Swiss Confederation,
in attendance.**

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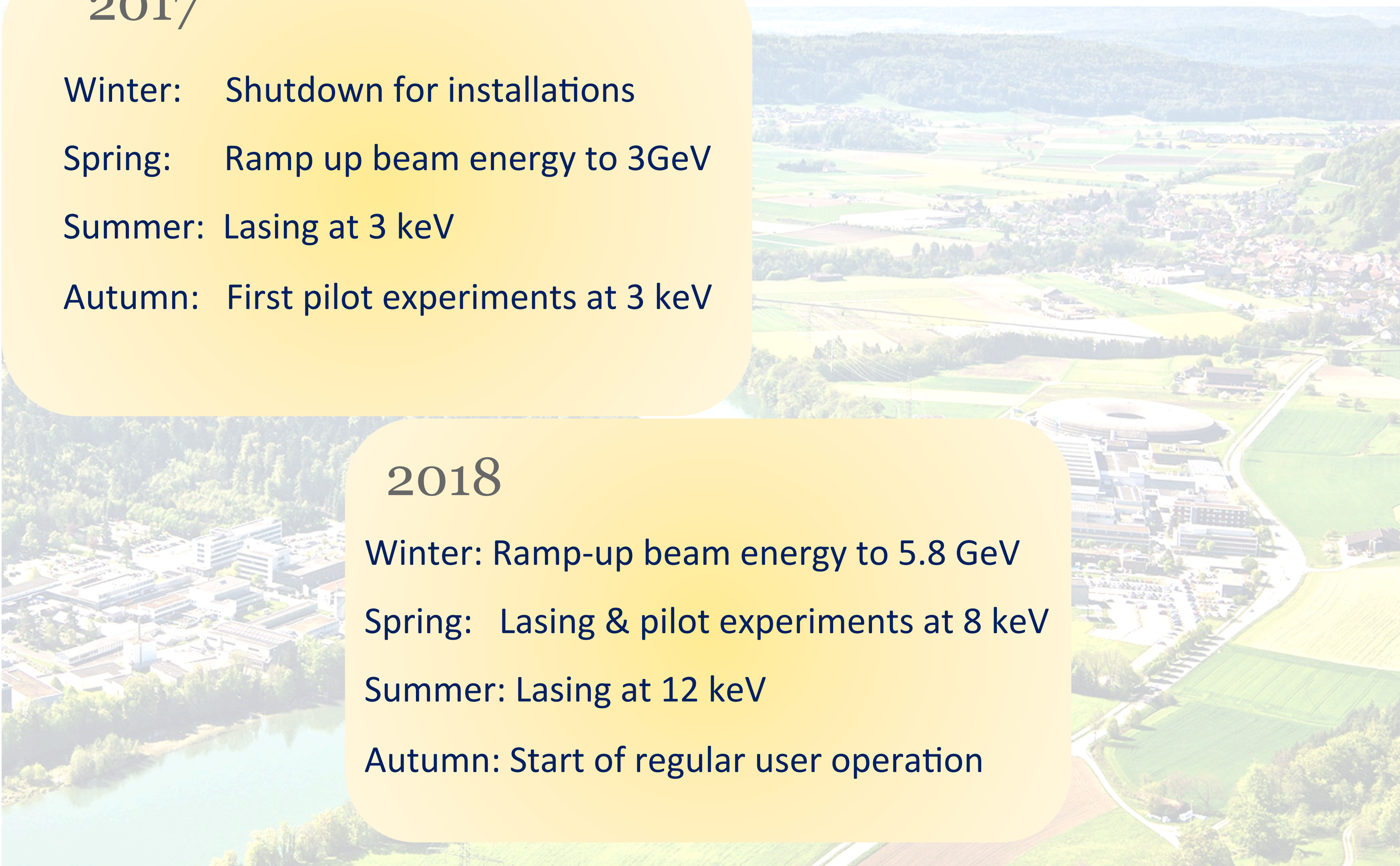
Program 2017 & 2018



2017

Winter: Shutdown for installations

Spring: Ramp up beam energy to 3GeV

Summer: Lasing at 3 keV

Autumn: First pilot experiments at 3 keV

2018

Winter: Ramp-up beam energy to 5.8 GeV

Spring: Lasing & pilot experiments at 8 keV

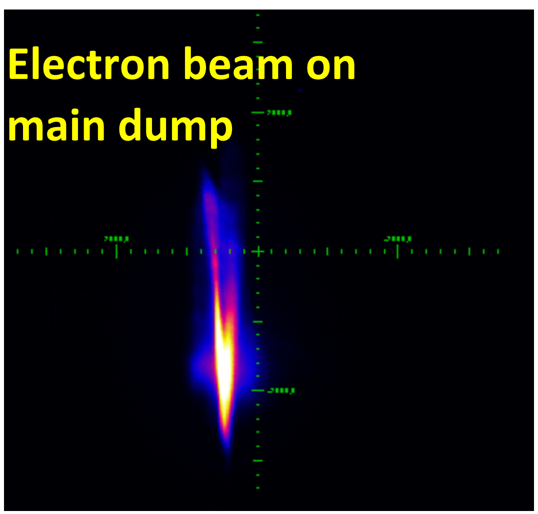
Summer: Lasing at 12 keV

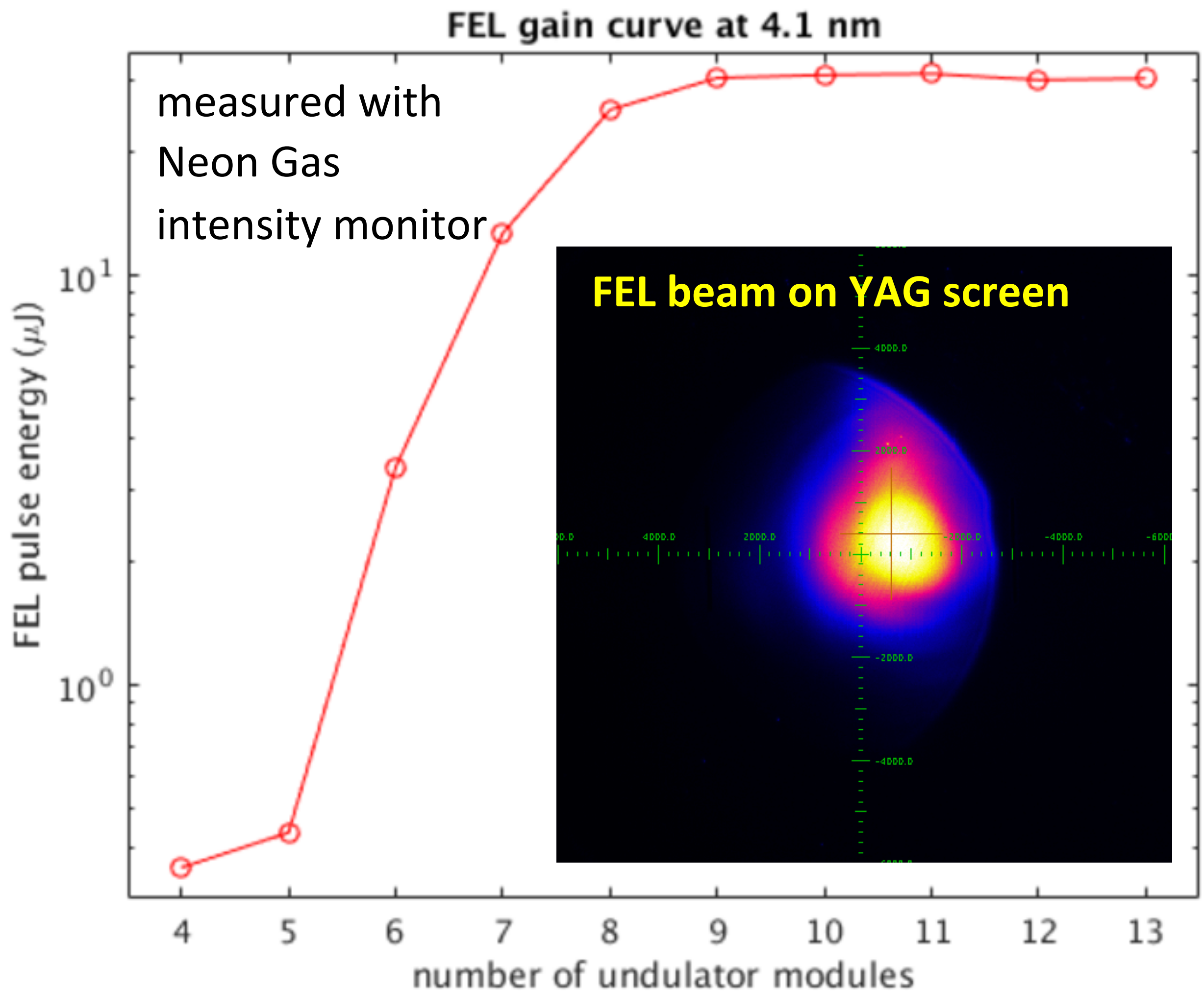
Autumn: Start of regular user operation

Commissioning progress May 15, 2017

First Lasing in nominal SwissFEL wavelength range (0.1-5.0 nm)!

E_{e^-}	0.91	GeV
q_B	145	pC
b.l. (rms)	≈0.4	ps
K	1.2	
λ_{FEL}	4.1	nm
W_{FEL}	≈30	μJ





Establishing SASE at 4.1nm

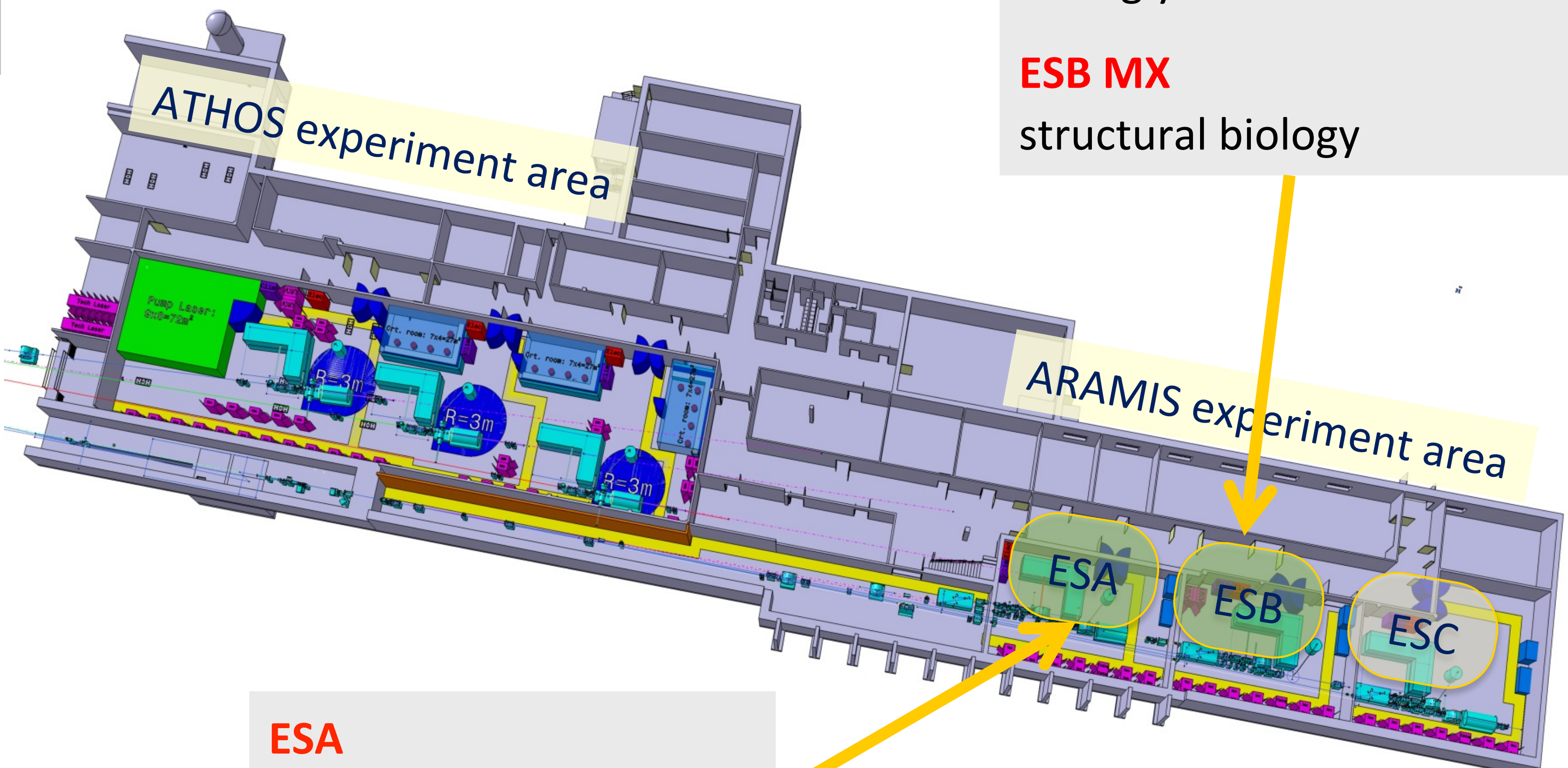
- careful set-up of gun and cathode laser
- careful transverse optics measurement and matching in injector region
- computed optics in linac and undulators
- set-up of bunch compression in BC1 with deflecting cavity
- steering according to BPM centers
- so far no special alignment procedures were required in undulator region
- measured pulse energy is consistent with theoretical expectations

$\Rightarrow$ We are positive that with the addition of more RF stations
we can proceed to shorter wavelength

Photon Beamlines and Experiments

ESB
Ultrafast dynamics in solid matter, strongly correlated electron systems

ESB MX
structural biology



ESA
Ultrafast photochemistry and photobiology

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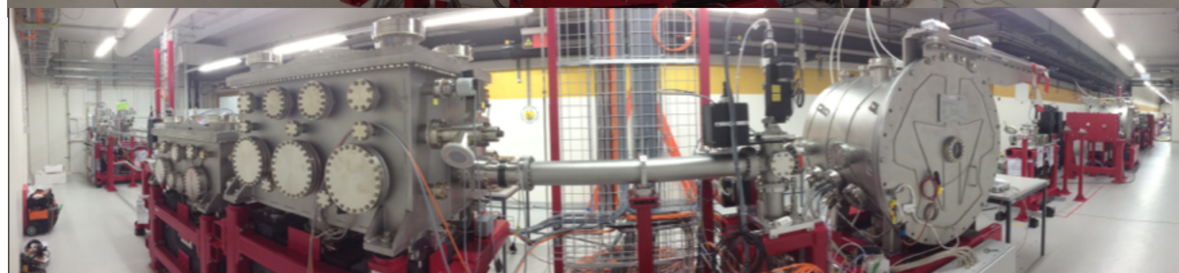
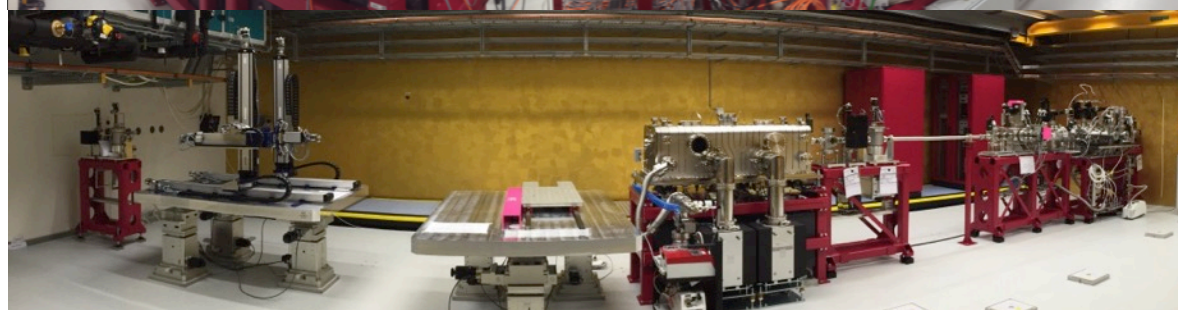
ARAMIS beamline

Front-End

Optical hutch

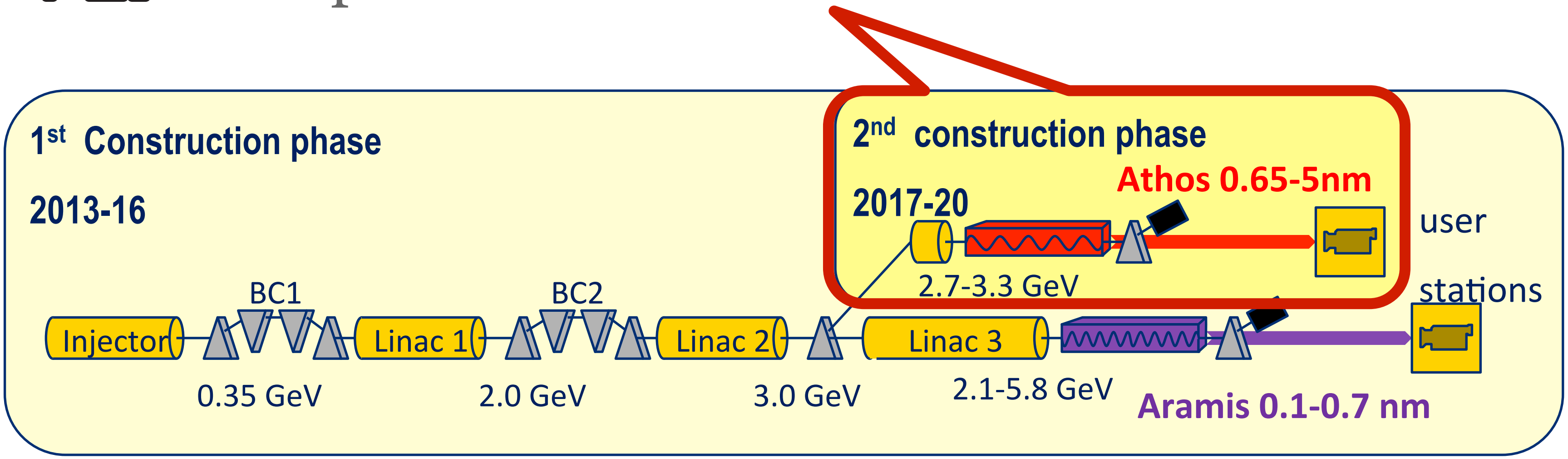


ESA hutch



ESB hutch

Preparation for ATHOS



ATHOS

Soft X-ray FEL, λ=0.65-5.0 nm

full polarization control withU38 Apple-X Undulators

Switch Yard: already installed in phase 1

Extraction done at constant energy of 3 GeV

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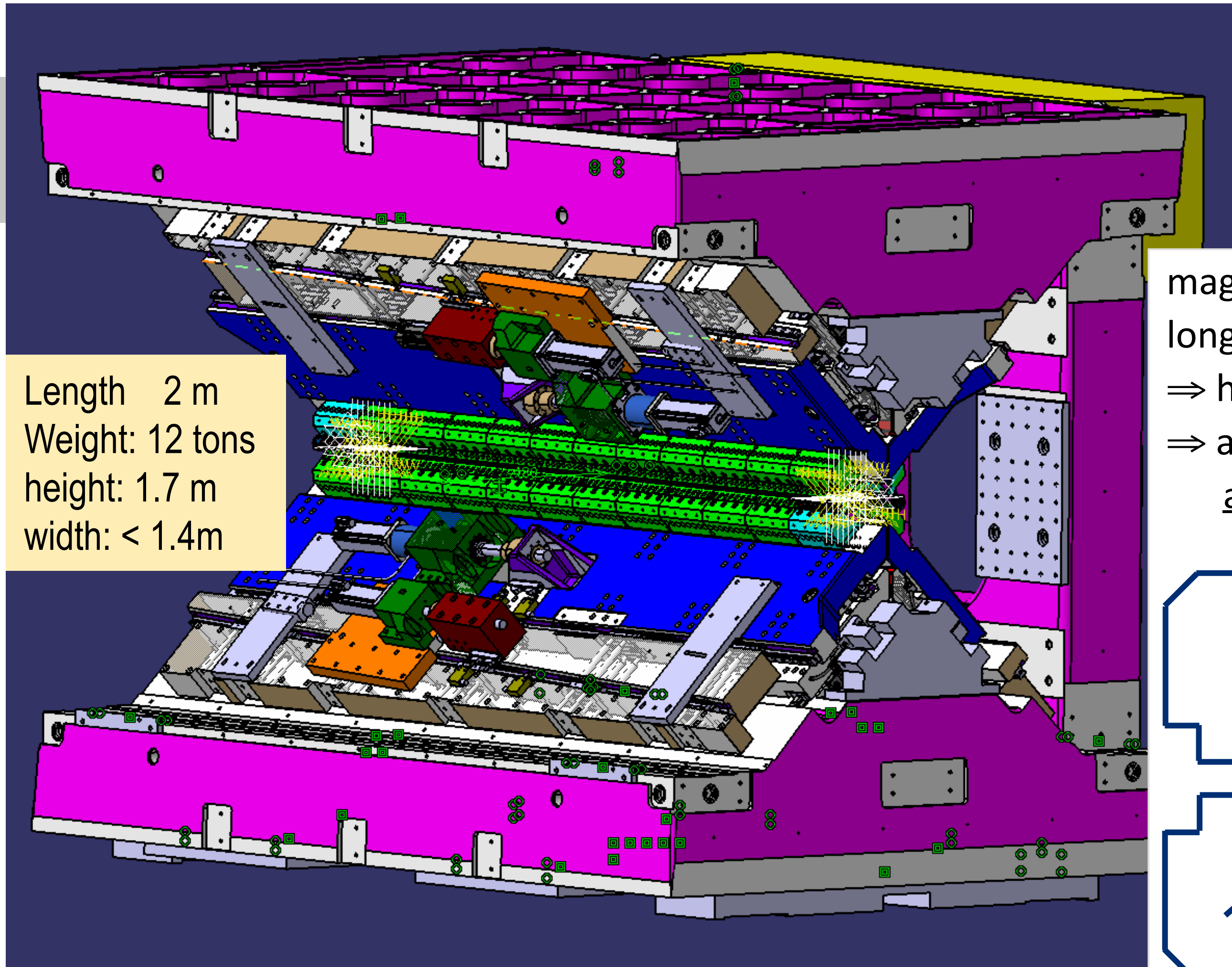
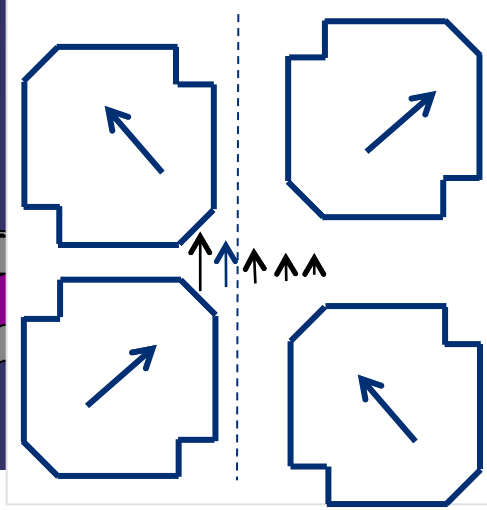
UE38 Apple X undulator for ATHOS, prototype construction has started



Length 2 m
Weight: 12 tons
height: 1.7 m
width: < 1.4m

magnet arrays with longitudinal and radial shift
⇒ highest flexibility
⇒ adjustable polarization and gradient



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SwissFEL control room photo gallery (selection)