The PSI Particle Accelerators

Thomas Schietinger
with help from Joachim Grillenberger, Andreas Streun, and many others

PSI, 16 July 2014

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- **The 2010s: the X-ray Free-Electron Laser – SwissFEL**
- **The 2020s: SLS-2.0**

Historical overview

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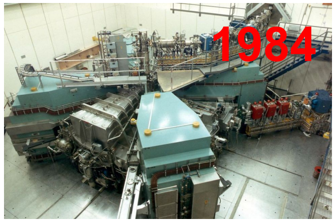
1968:
Foundation of SIN
(Swiss Institute for Nuclear Physics)

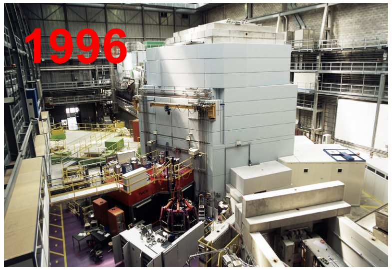
Proton Cyclotron

High-Power upgrade (Injector-2)



1988:
SIN and EIR merge to become PSI
(Paul Scherrer Institute)

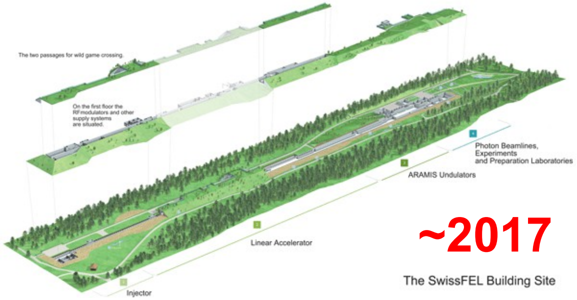
Neutron Spallation Source – SINQ



1970 — 1980 — 1990

Synchrotron Light Source – SLS

X-ray Free Electron Laser – SwissFEL



New ultrabright Synchrotron Light Source – SLS-2.0

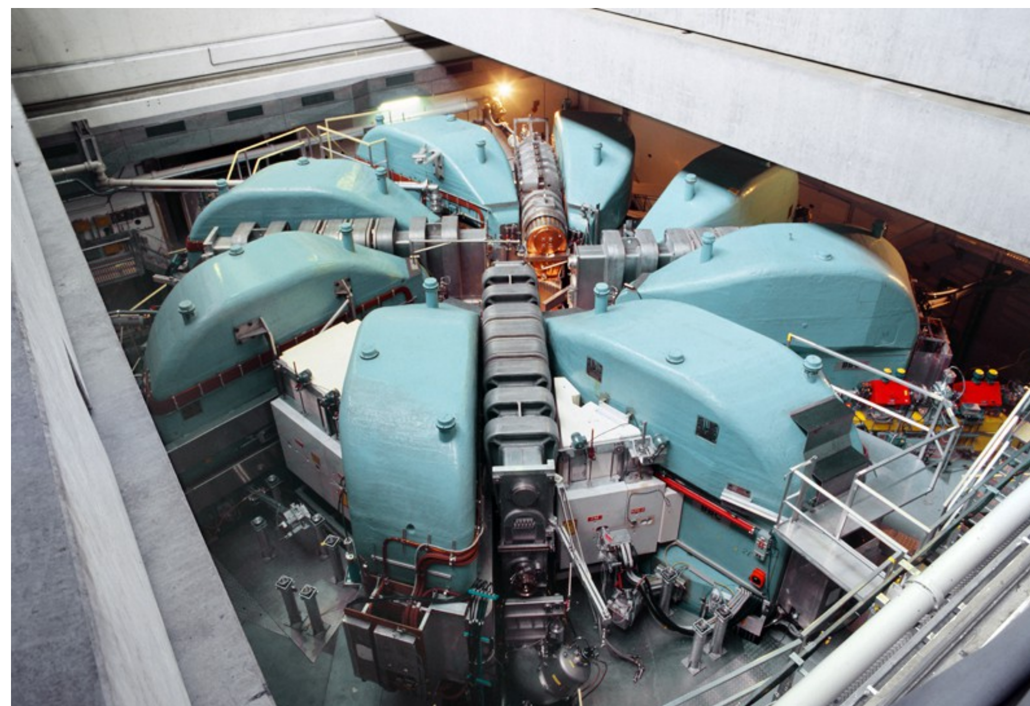
Image: ECOS

2000 — 2010 — 2020

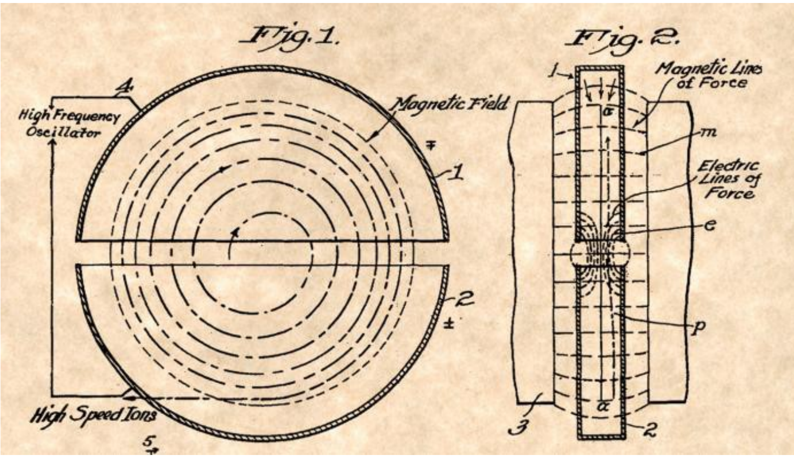
In the 1970s...

In the 1970s...

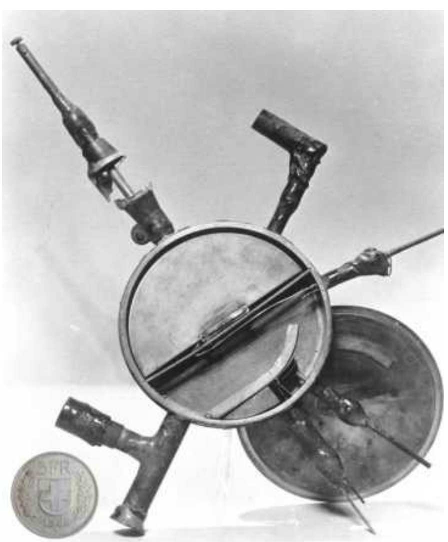
...the Proton Ring Cyclotron



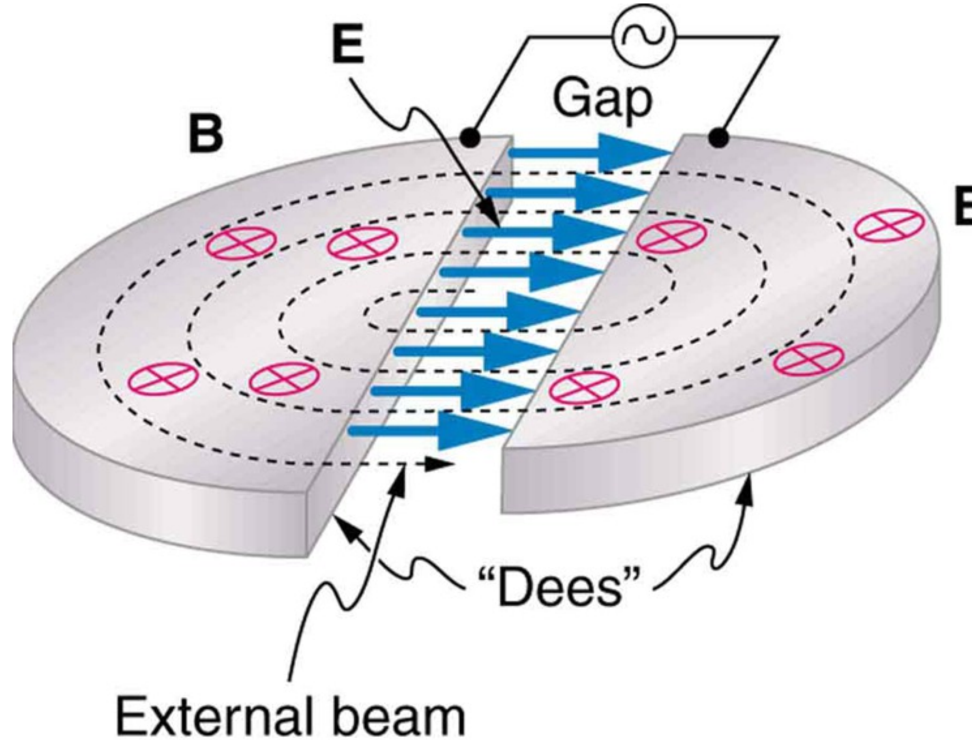
Cyclotron principle



Cyclotron patent, Ernest Lawrence, 1932



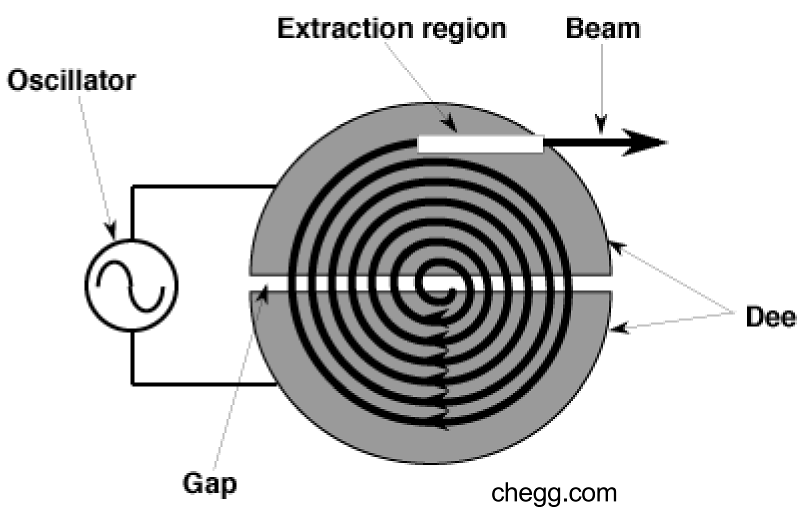
Early cyclotrons

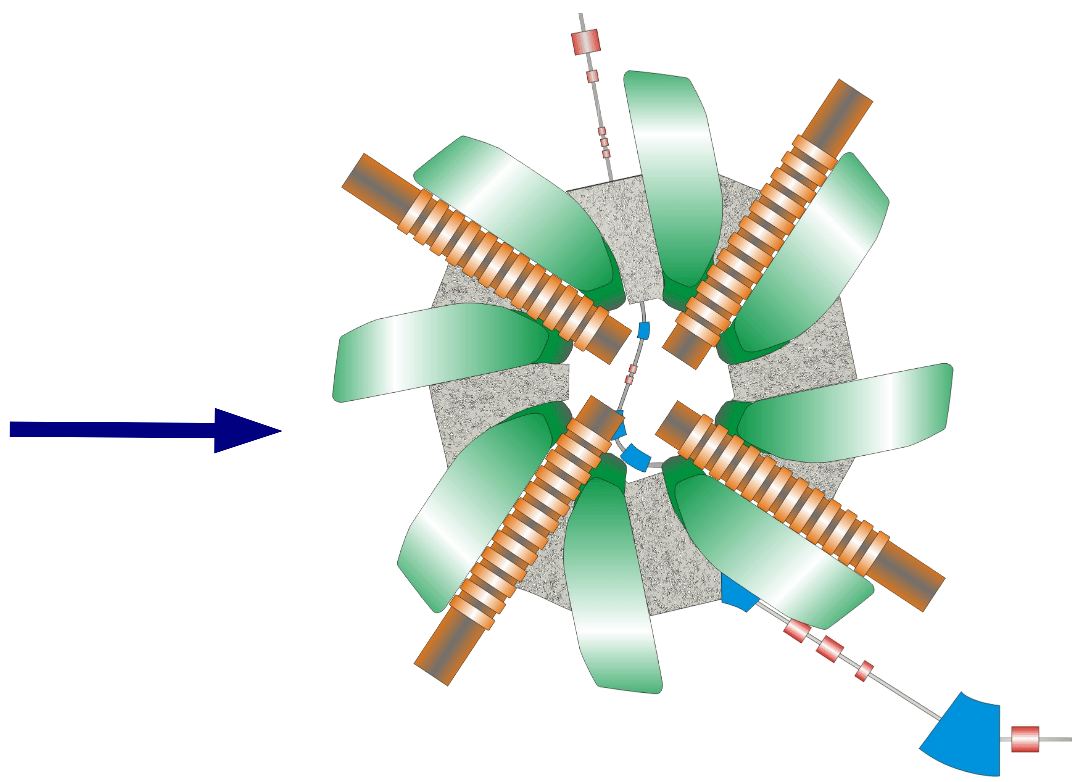


Ring Cyclotron

- Advantage:
  Accelerating (RF resonators) and bending (magnets) components can be separated into sectors

- Disadvantage:
  A dedicated accelerator for injection is needed!





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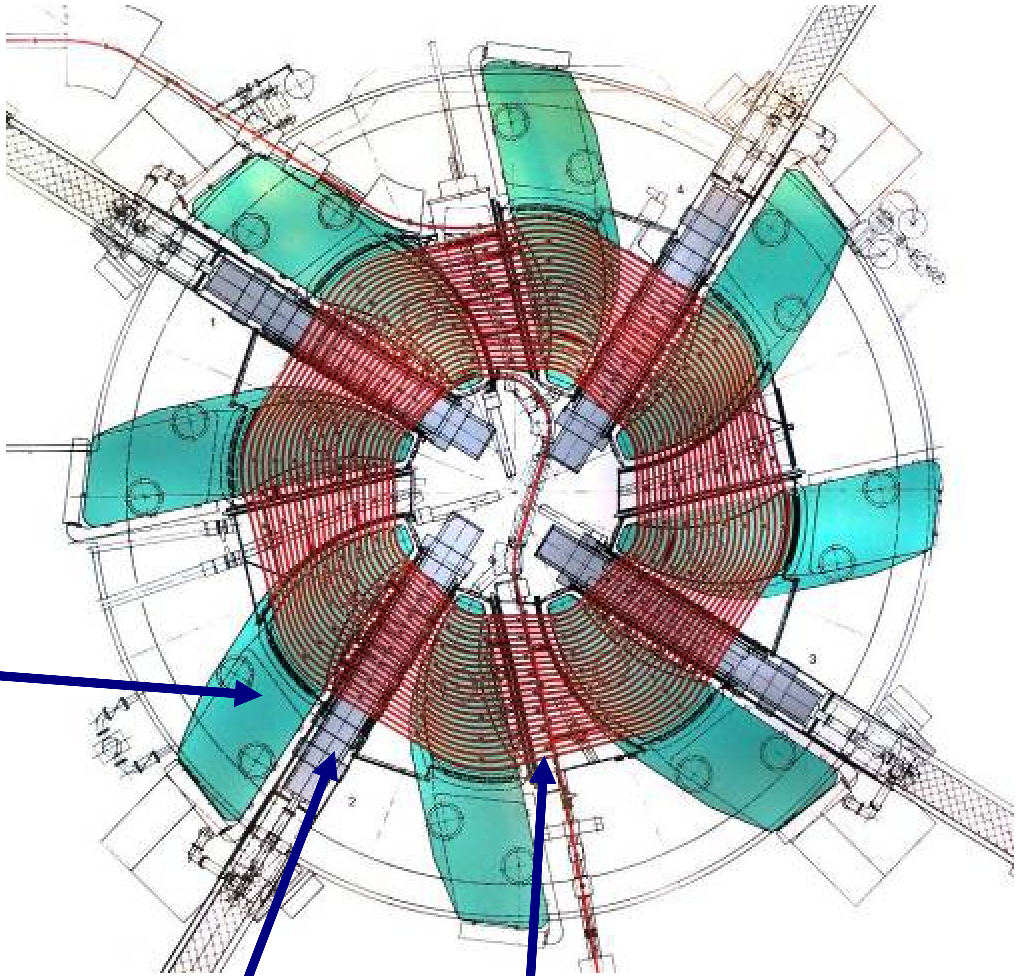

0.9 T sector magnet

50 MHz resonator

150 MHz (3rd harmonic) resonator

PSI ring cyclotron

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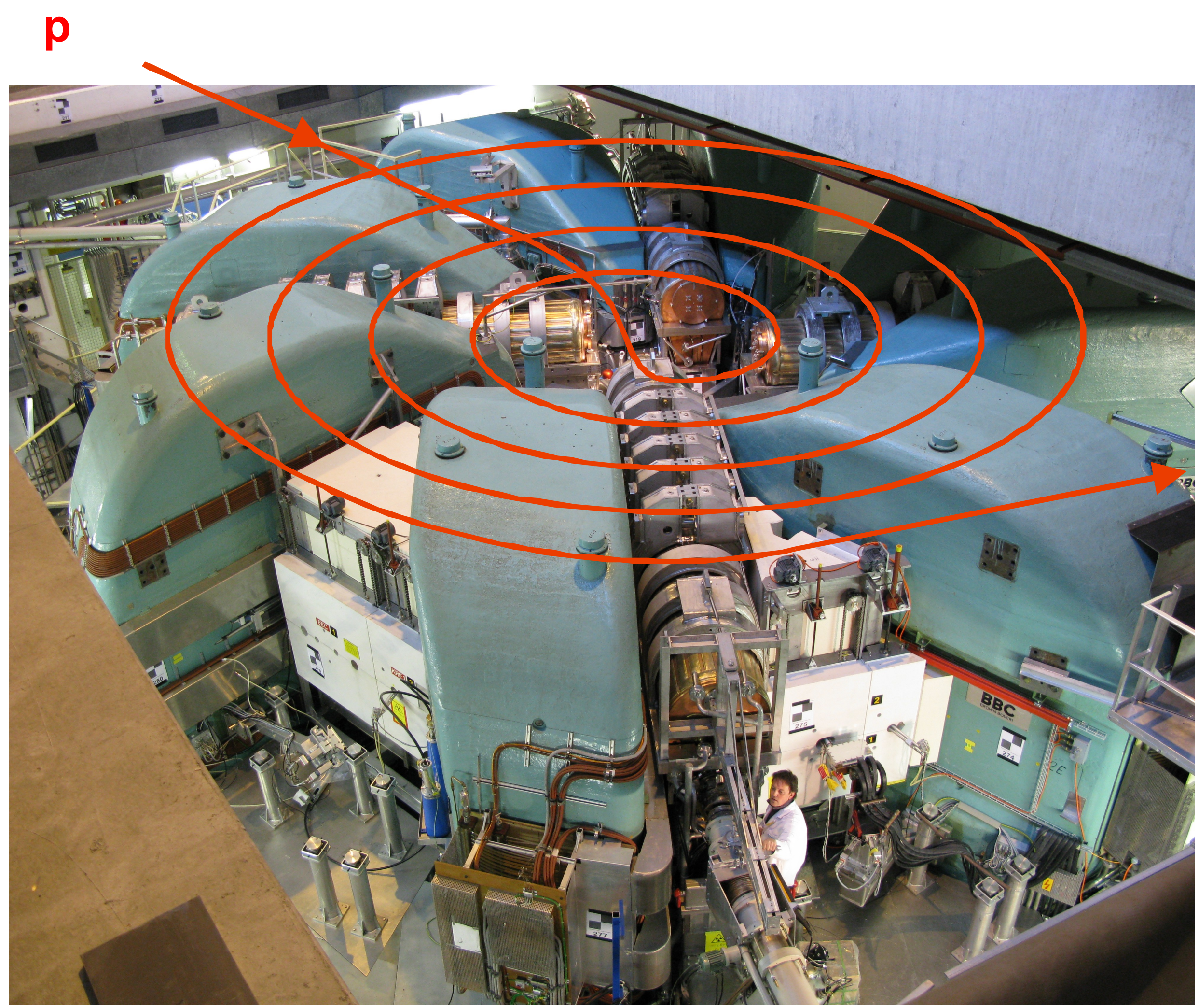
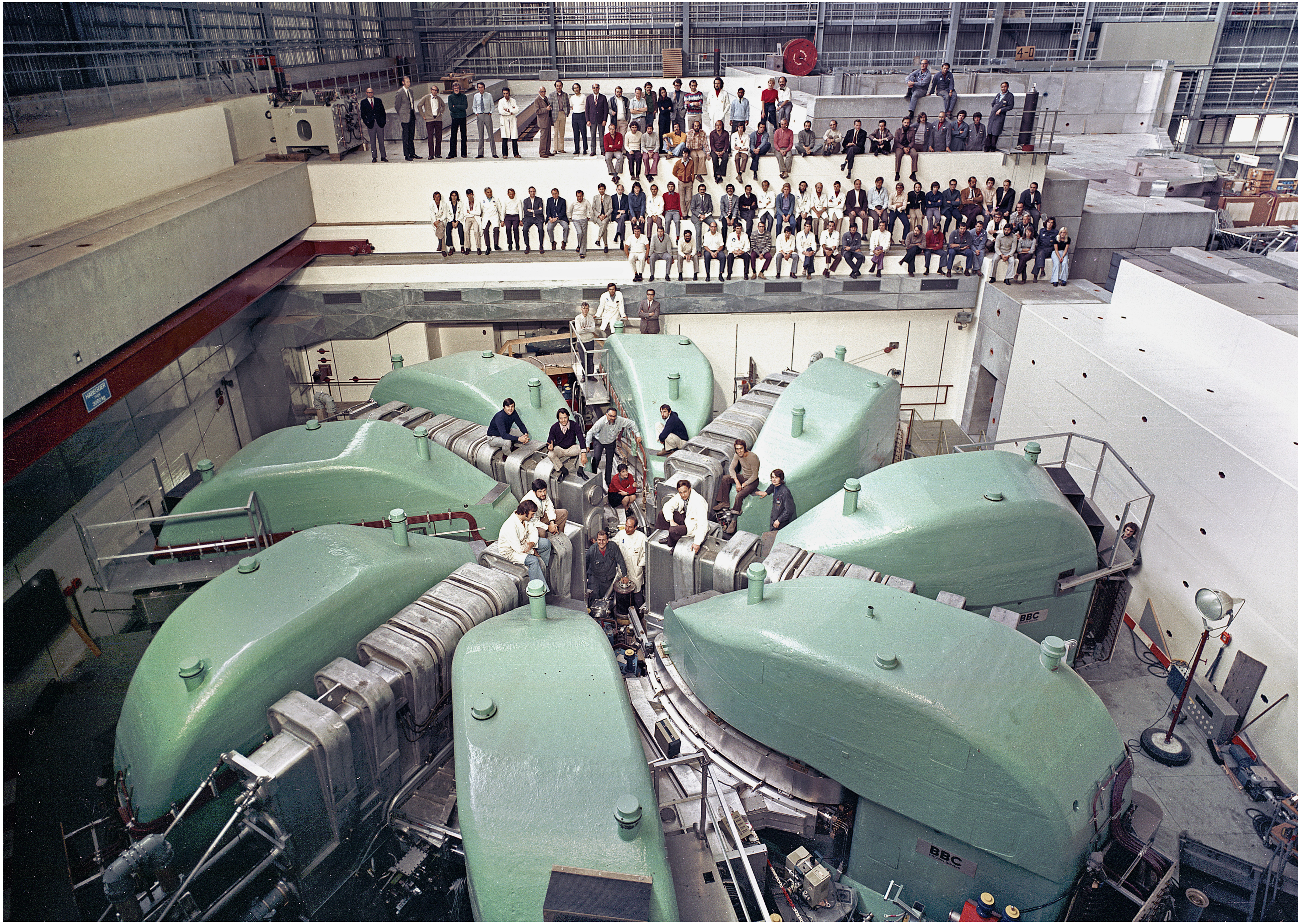
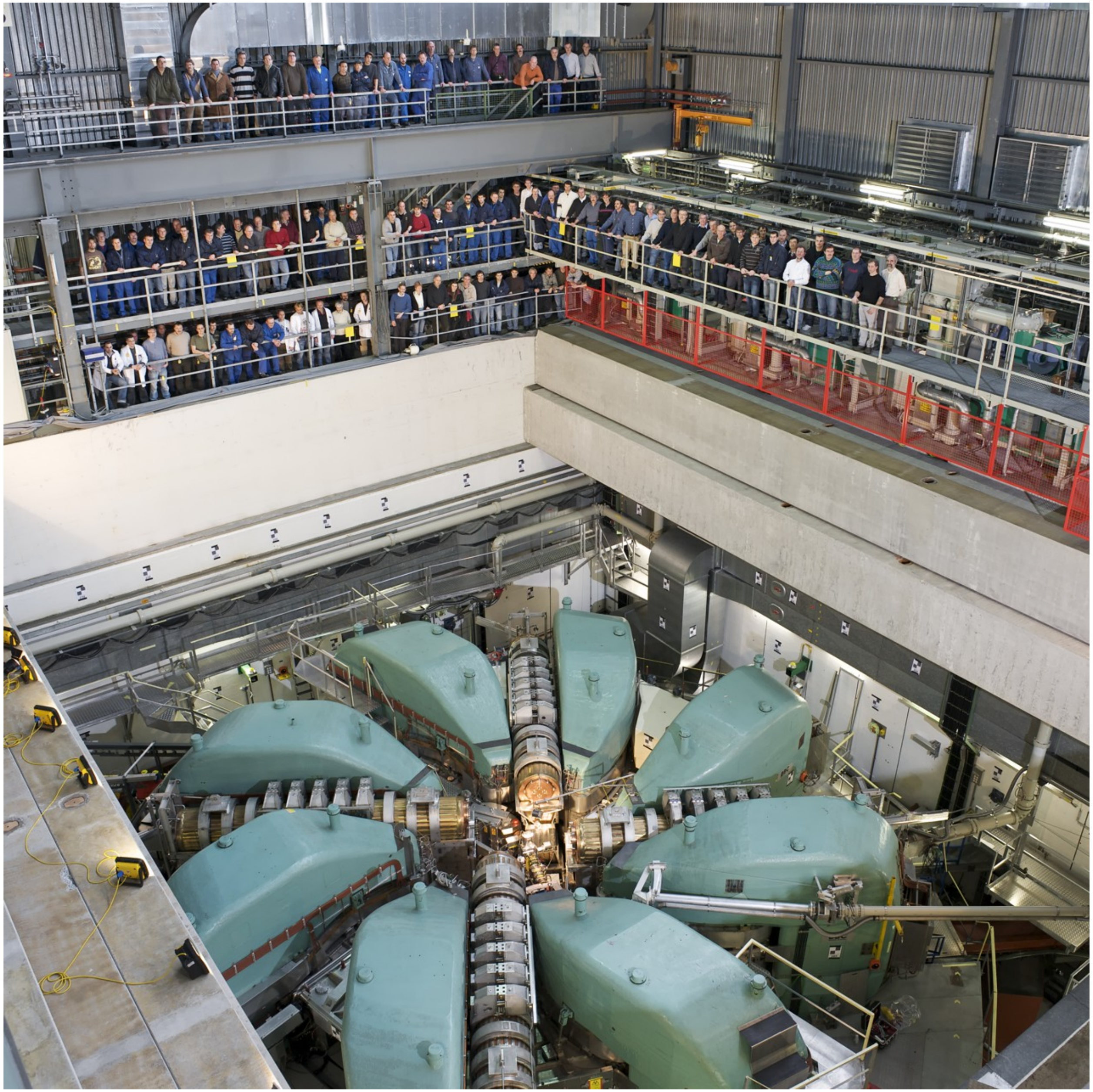
Parameter	Value
Sector magnet field	0.6–0.9 T
Magnet weight	250 t
Cavity voltage	850 kV
Frequency	50.63 MHz
Beam energy	72 → 590 MeV
Beam current (max.)	2.4 mA
Extraction radius	4.5 m
Number of turns	185
Relative losses (2.4 mA)	1–2 x 10^{-4}



Proton cyclotron in 1974



Proton cyclotron in 2009



Original injector cyclotron

- Commercial cyclotron (Philips, 1972)
- 72 MeV energy, limited current
- Later used stand-alone for isotope production
- Decommissioned since 2010
- Will be shipped to China for further use.

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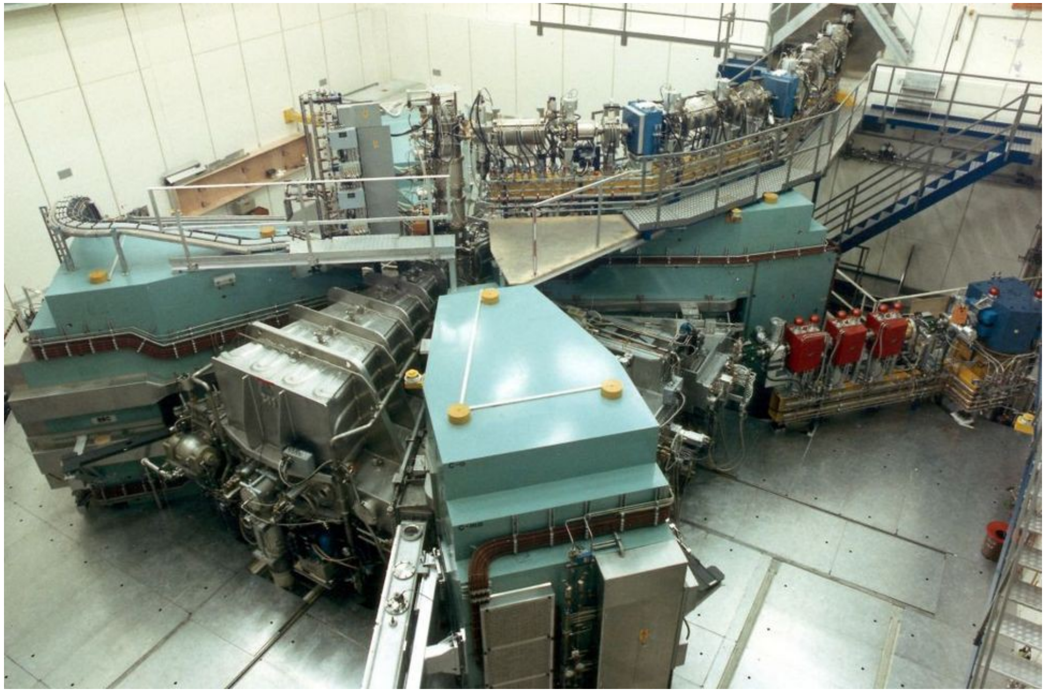
In the 1980s...

In the 1980s...

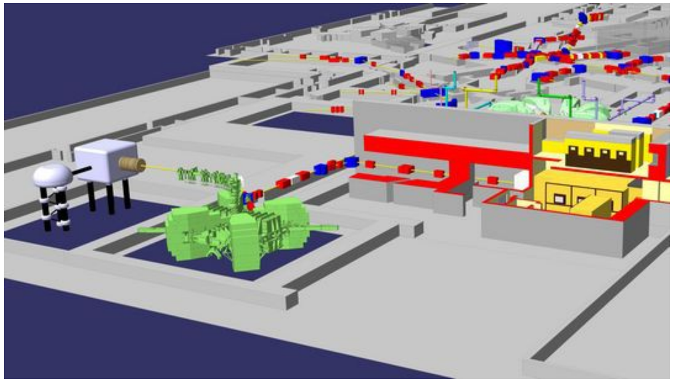
...the High-Power Upgrade

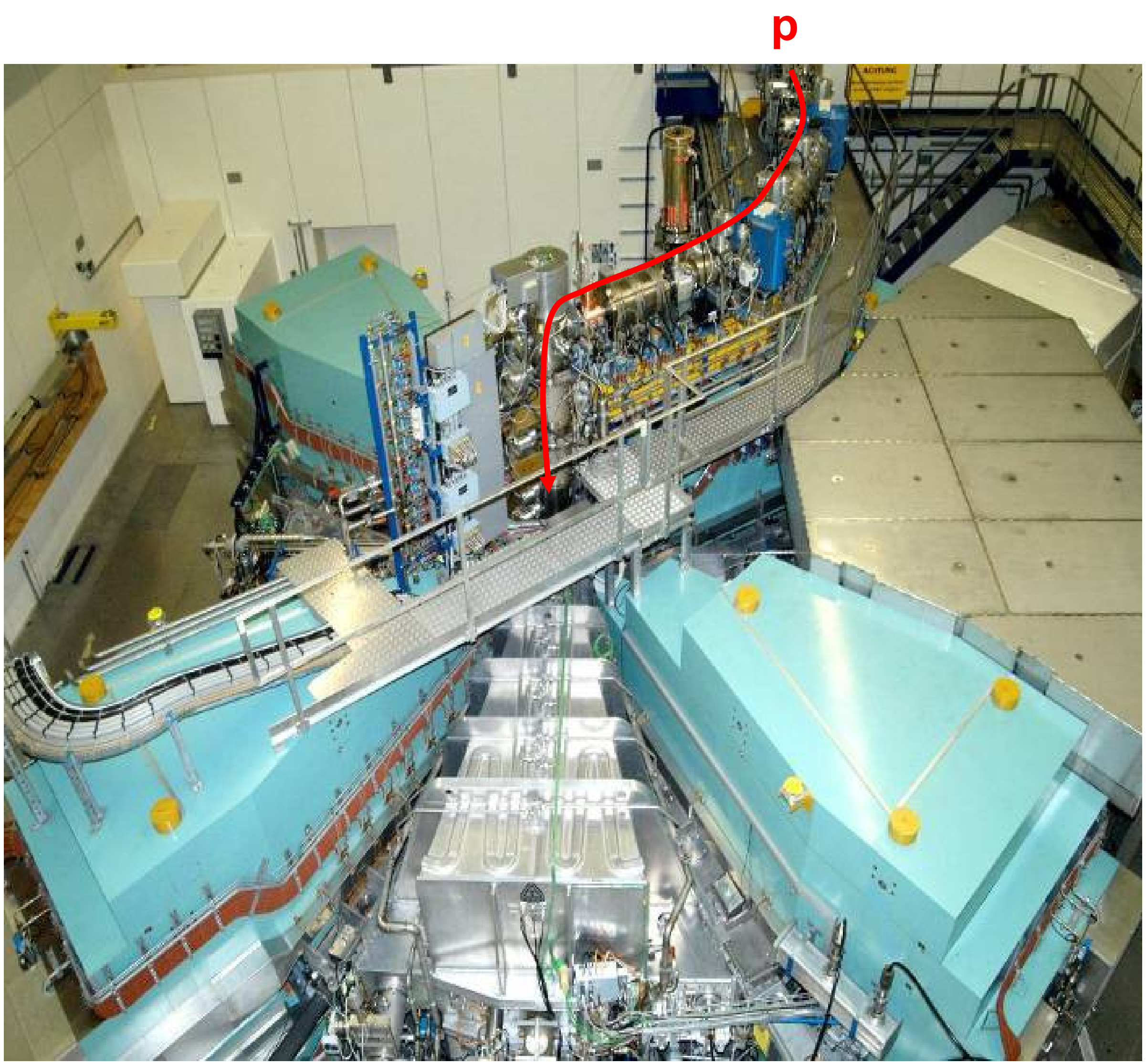


Injector-2 Cyclotron (72 MeV)

- Also ring cyclotron design
- Needs its own injector!

Parameter	Value
Sector magnet field	0.33–0.36 T
Magnet weight	180 t
Cavity voltage (50 MHz)	450 kV
Cavity voltage (150 MHz)	40 kV
Beam energy	0.87→ 72 MeV
Beam current (max.)	2.7 mA
Extraction radius	3.5 m
Number of turns	81





Cockcroft-Walton Pre-Accelerator

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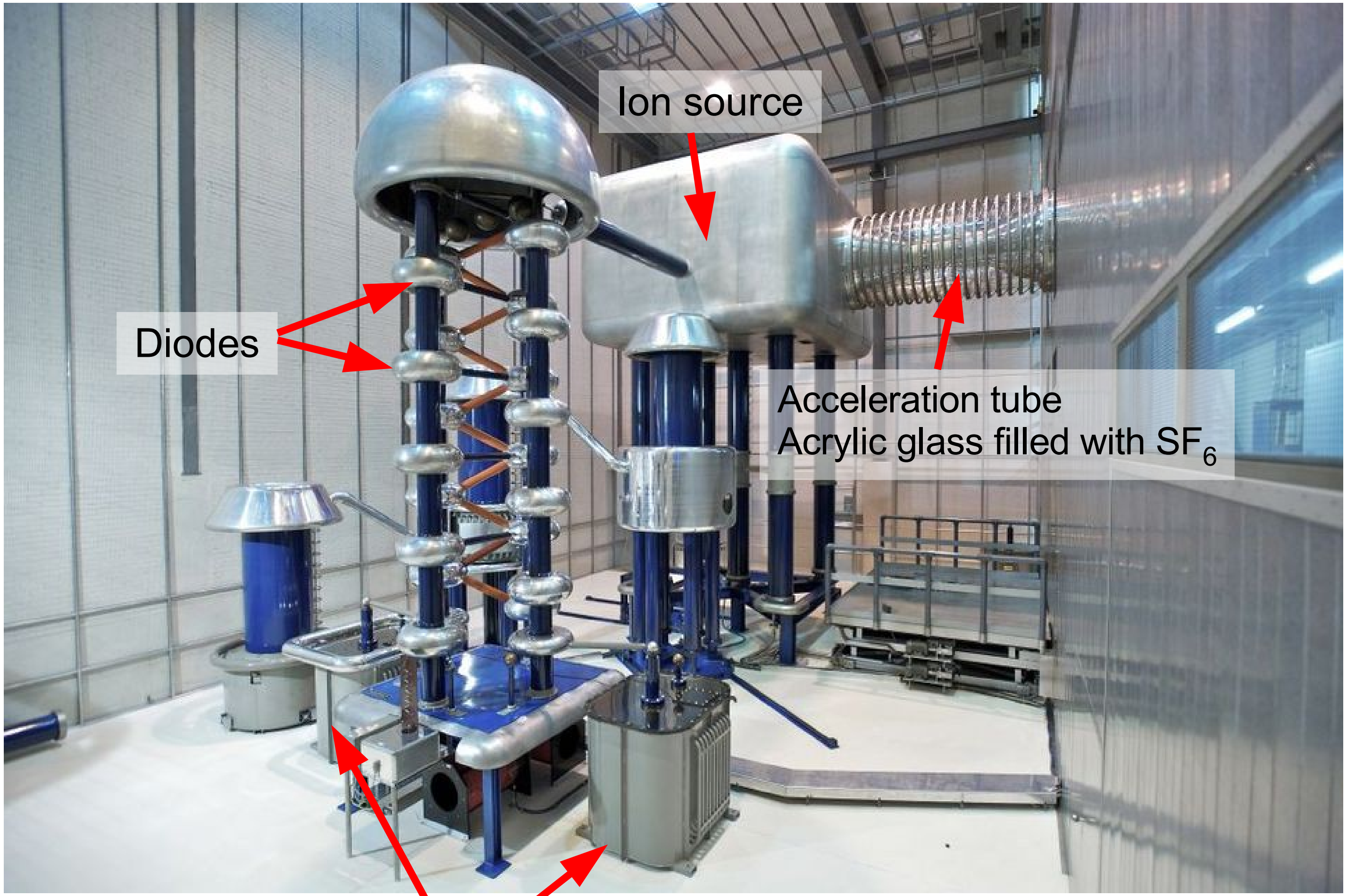
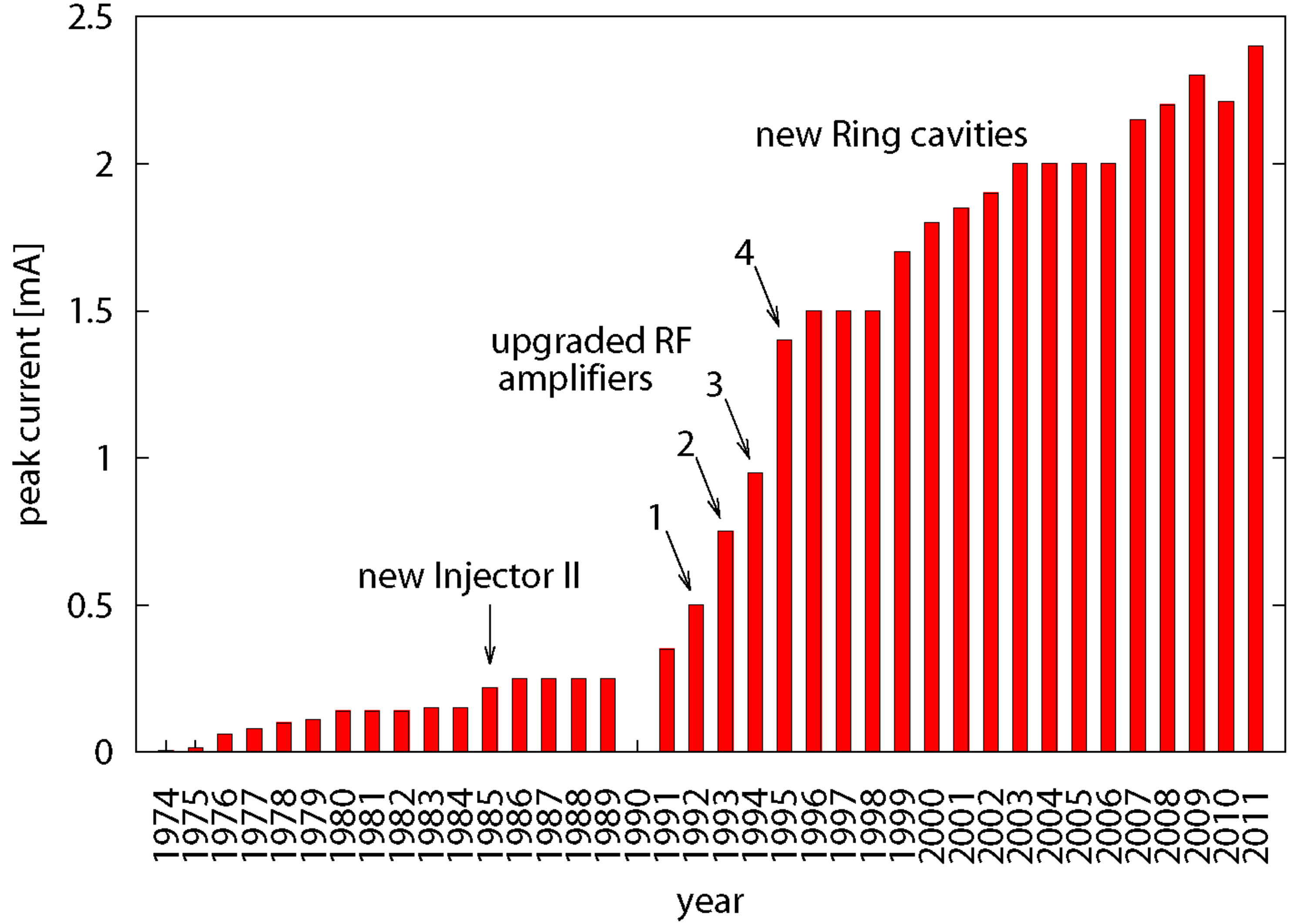
Parameter	Value
Beam energy	870 keV
Beam current (max.)	30 mA
Beam current (op.)	10 mA

HV cascade 810 kV



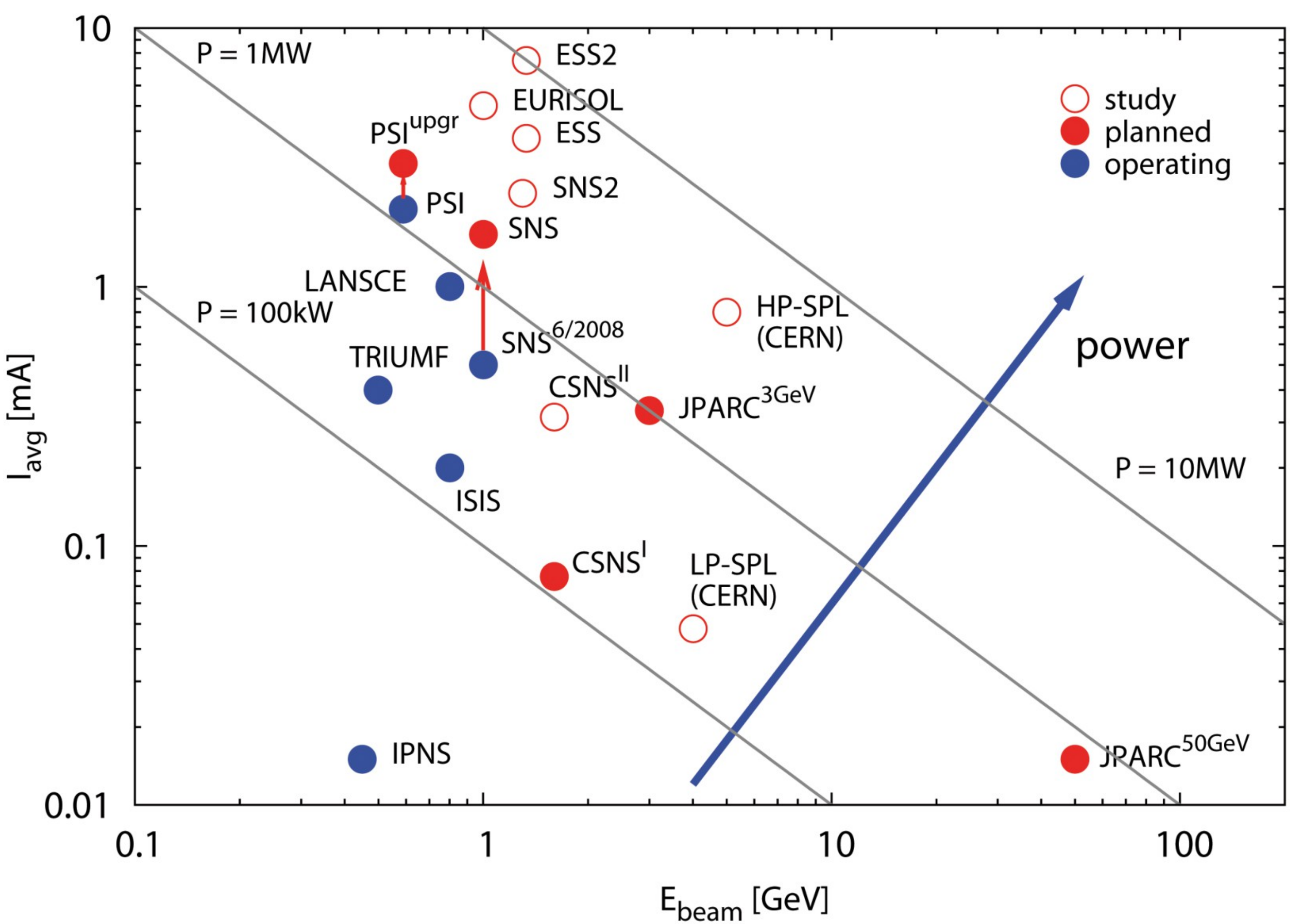
Isolation Transformers

Development of peak current



Proton sources worldwide

PSI current: 2.2 mA ≙ 1.3 MW
Upgrade plan: 3.0 mA ≙ 1.8 MW



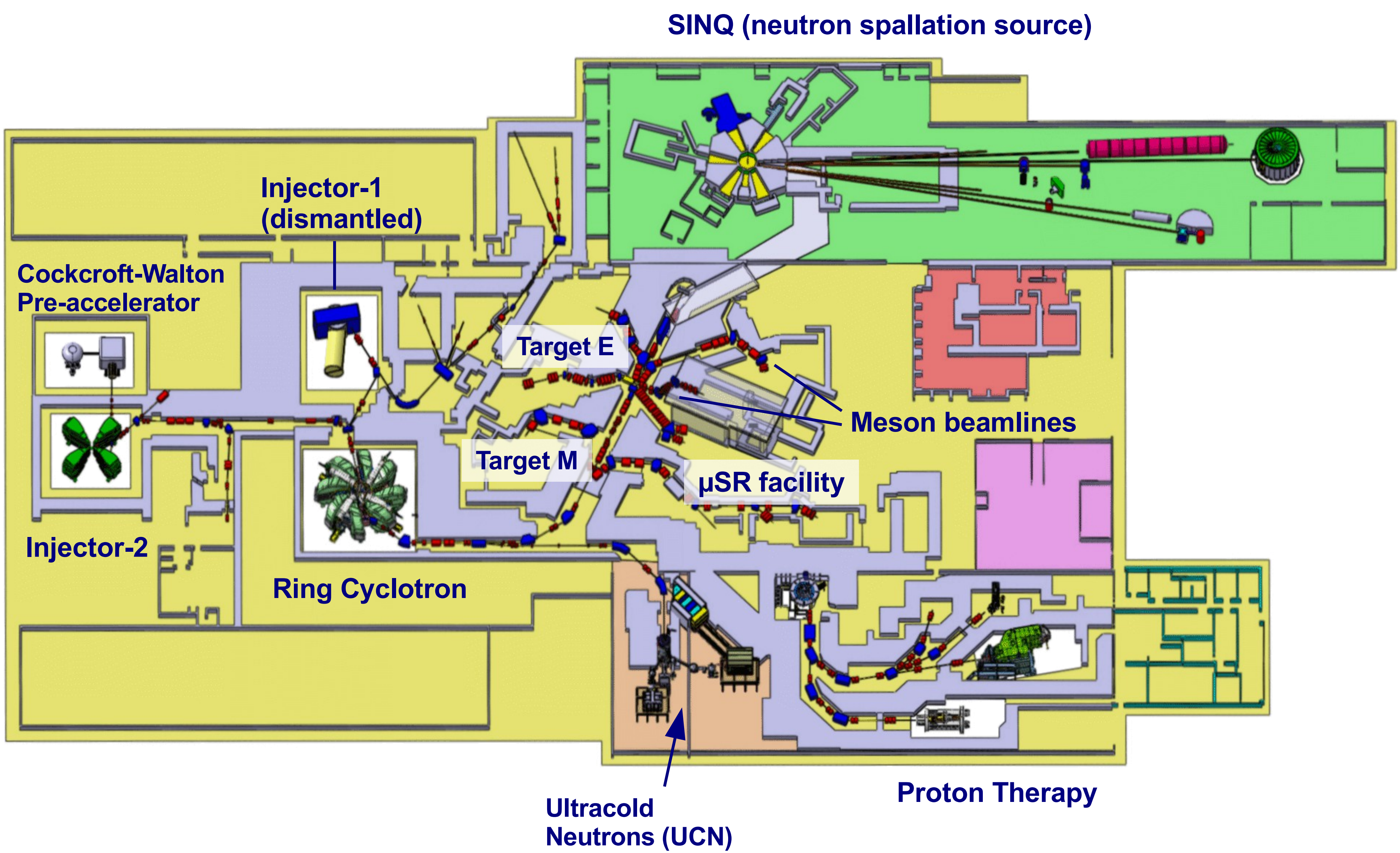
Applications of the proton facility

- Main interest is in *secondary particles.* Two targets (thick and thin) produce:
  - **Pions**
    - elementary particle research (rare decays)
    - early trials with particle therapy ("piotron")
  - **Muons** (decay product of pions)
    - Elementary particle research (decay constants, rare decays, e.g., $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$).
    - Muon spin spectroscopy (μSR) – use the muon as a magnetic spin probe in materials.

Graphite target wheel (target station E)

- Neutron production:
  - Small lead spallation source (since 2010) for the production of **ultra-cold neutrons** (elementary particle research, e.g. neutron EDM)
  - Large lead spallation source (since 1994) for the production of a **wide spectrum of neutrons** (→ SINQ)
- Protons: no direct scientific application, but **proton therapy**
  - Initially directly at the proton cyclotron
  - Now with a dedicated small cyclotron (→ PROSCAN project)

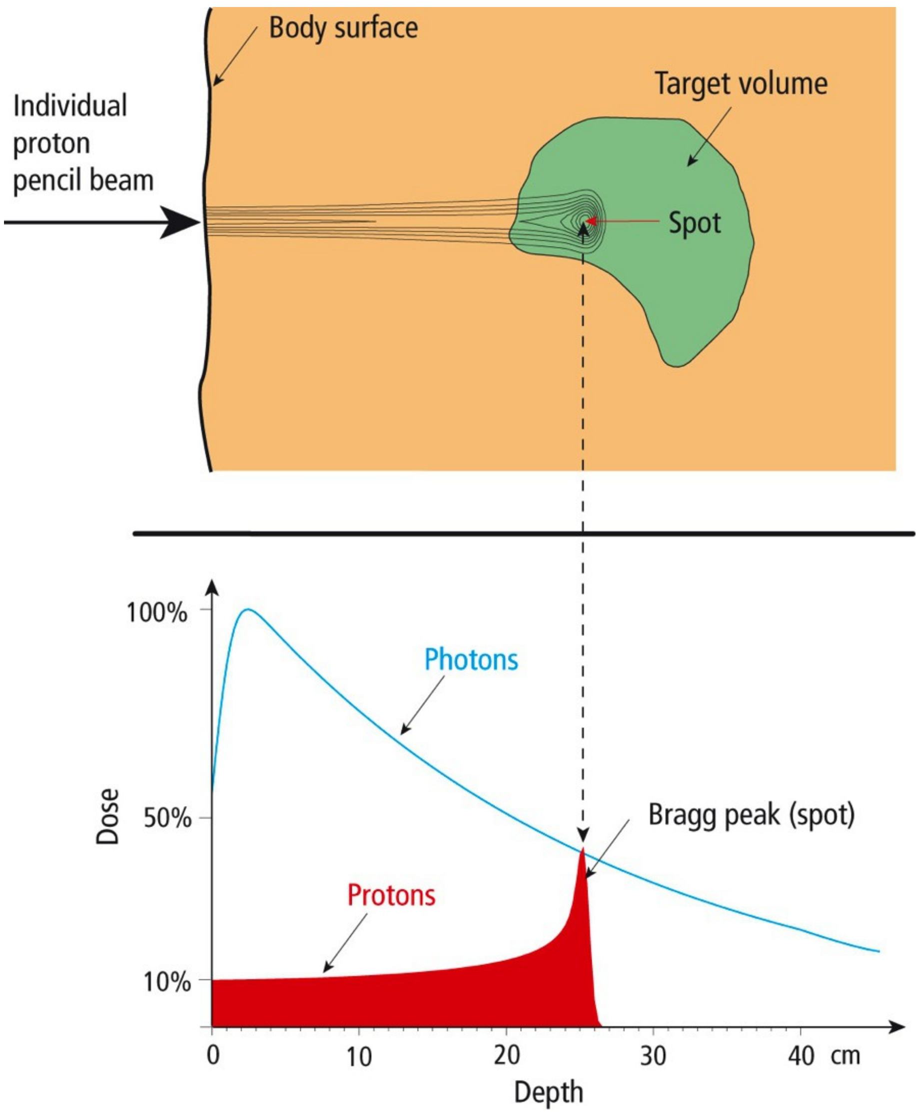
Proton Facility Layout (HIPA)



Proton therapy – PROSCAN

Radiation facility (Gantry) for proton therapy.

Why protons?



COMET cyclotron

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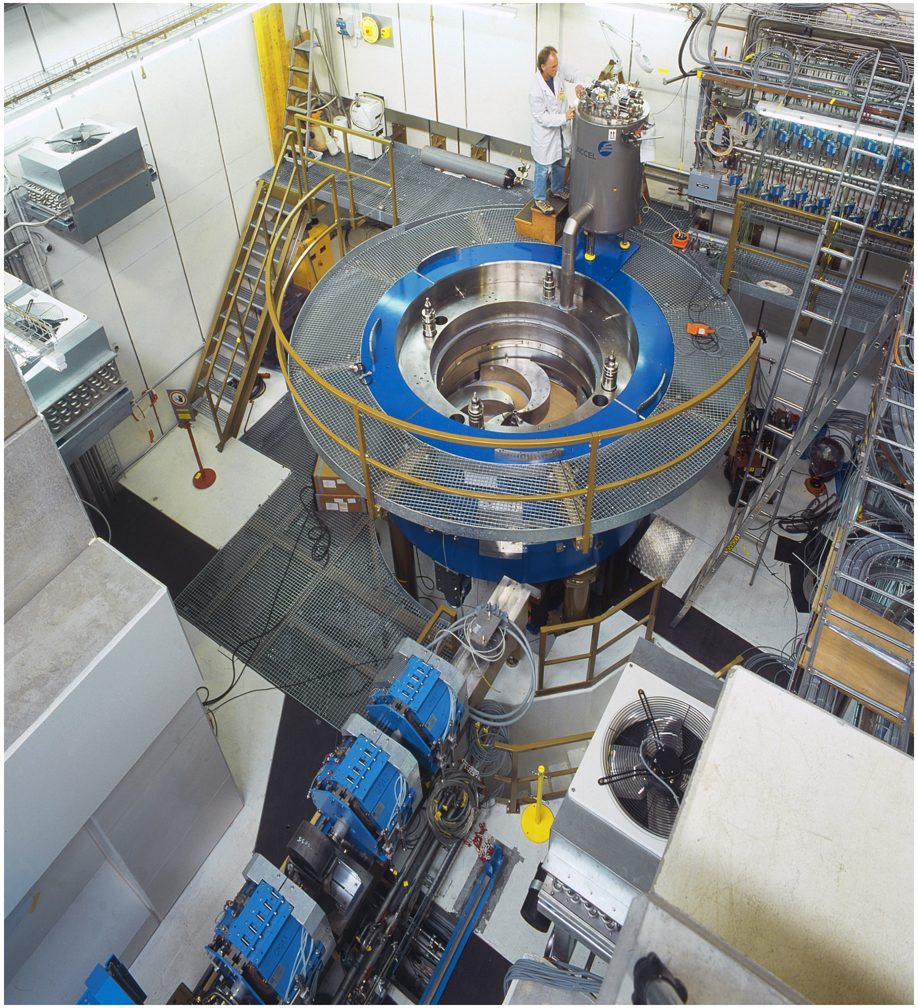
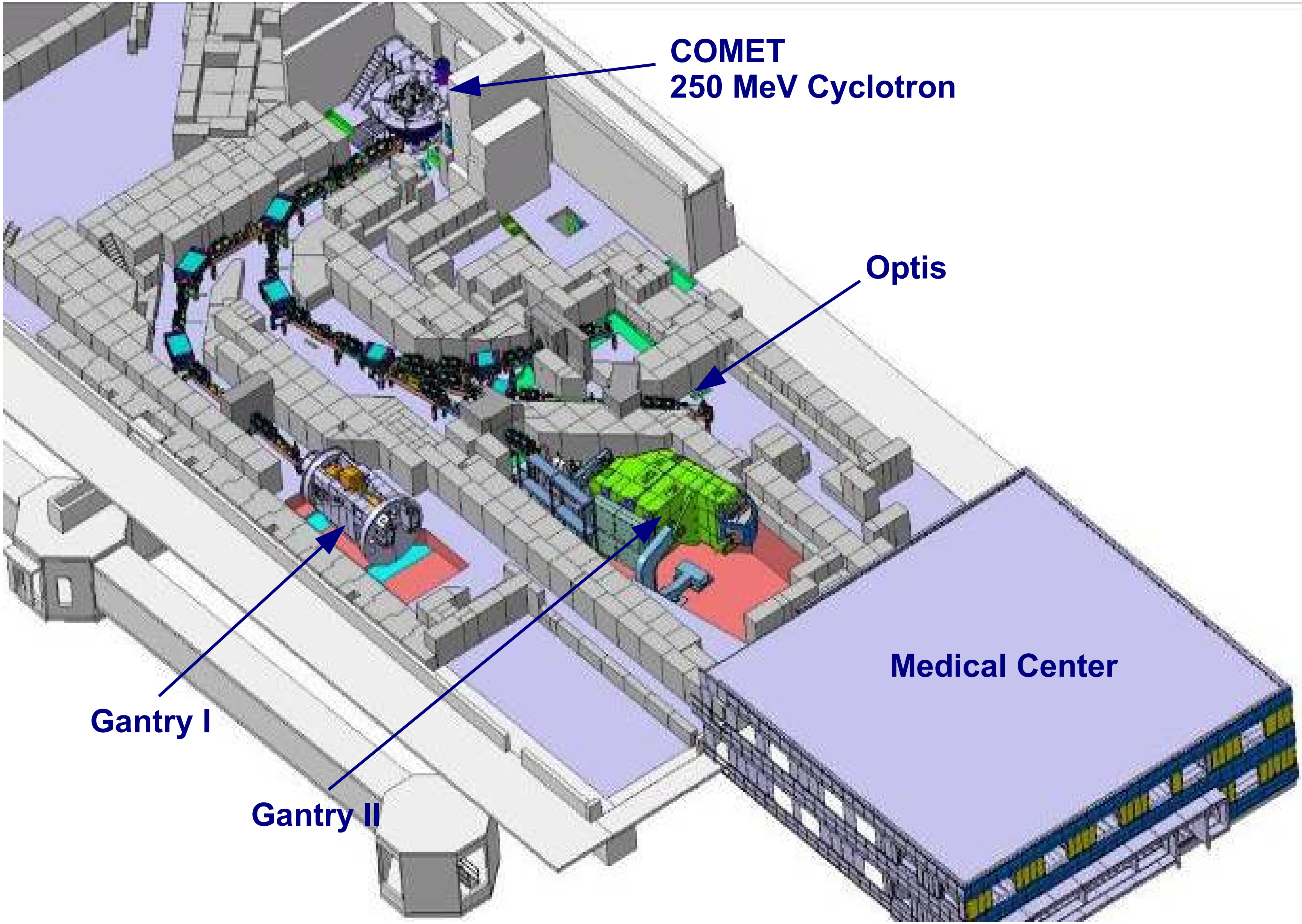
- Compact cyclotron optimized for proton therapy
- Collaboration between PSI and industry (Accel, now Varian)

Parameter	Value
Diameter	3.175 m
Height	1.38 m
Weight	90 t
Magnetic field	2.4–3 T
Beam energy	250 MeV
Beam current	1–850 nA
Number of turns	630



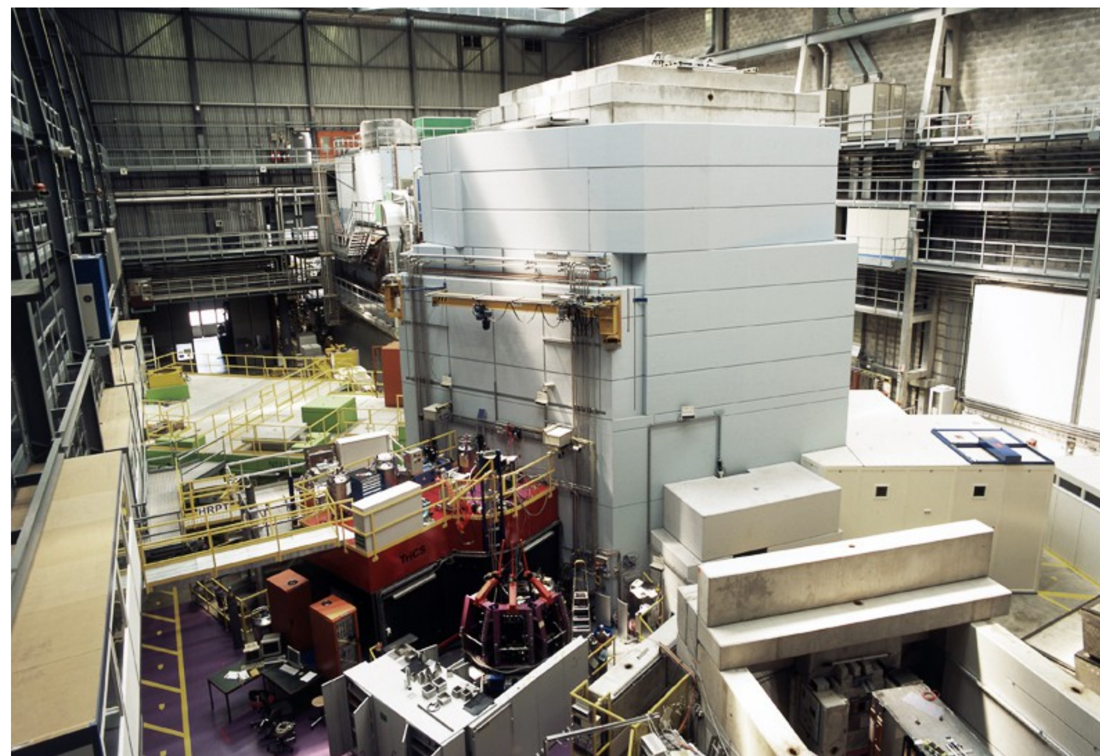
Project PROSCAN



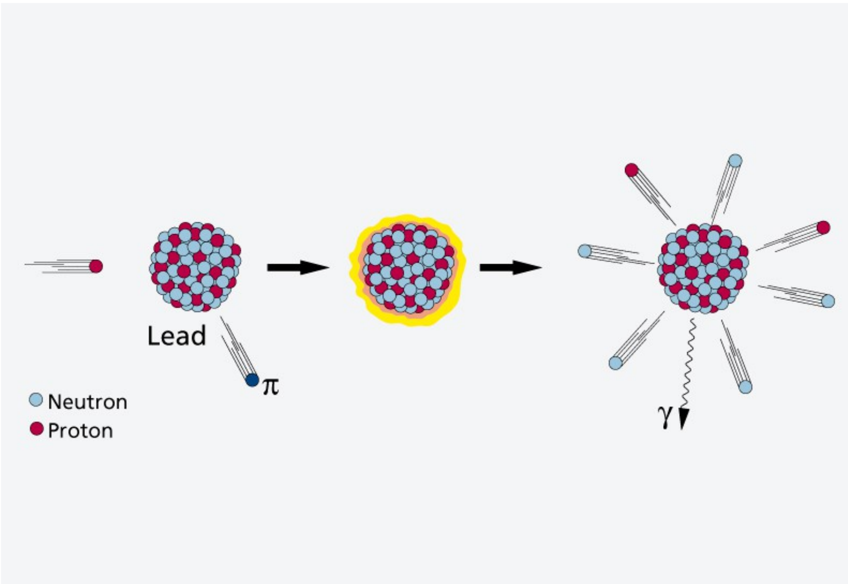
In the 1990s...

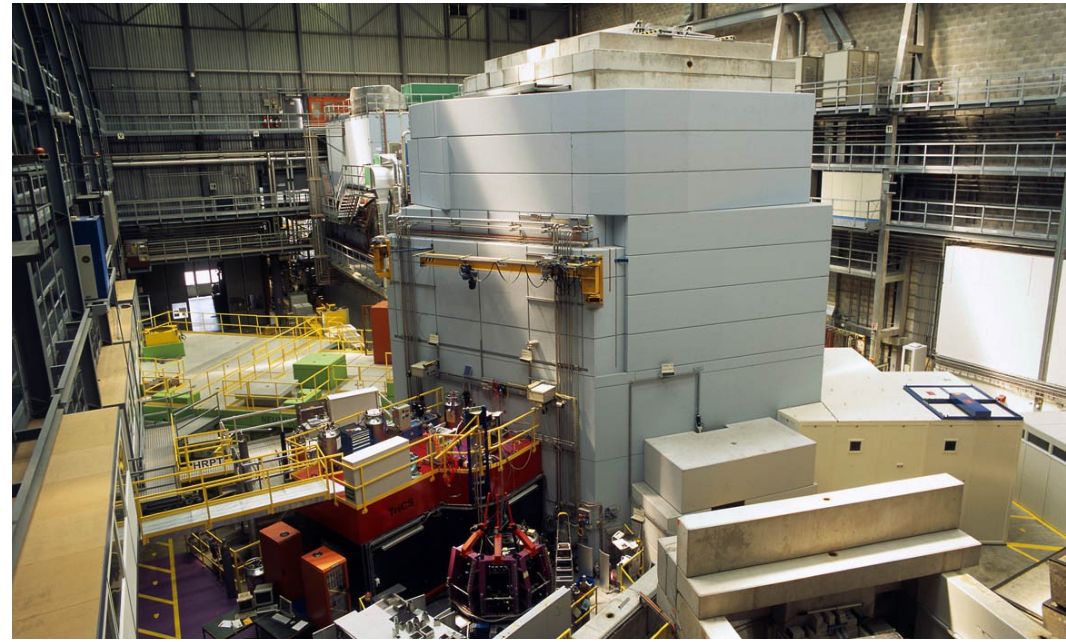
In the 1990s...

...the Neutron Spallation Source (SINQ)

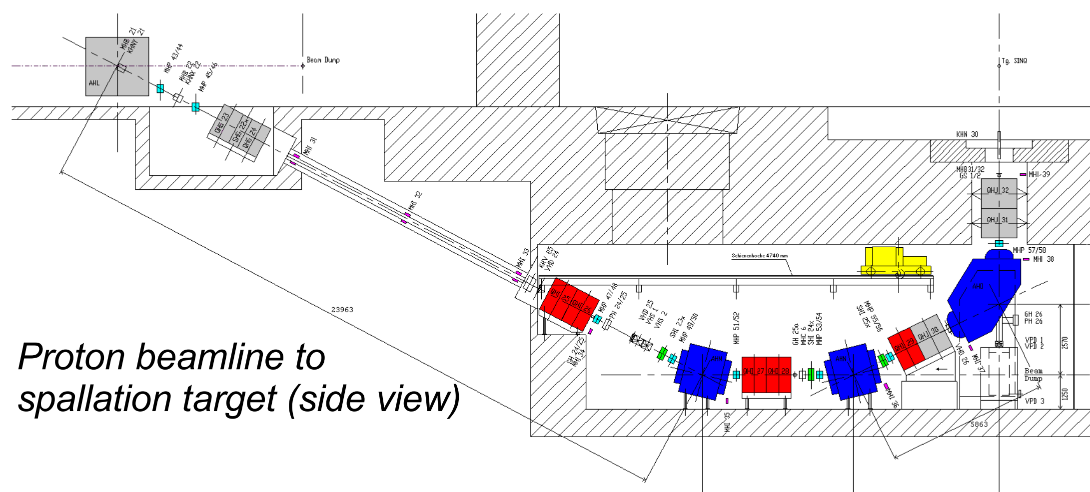


Neutron spallation



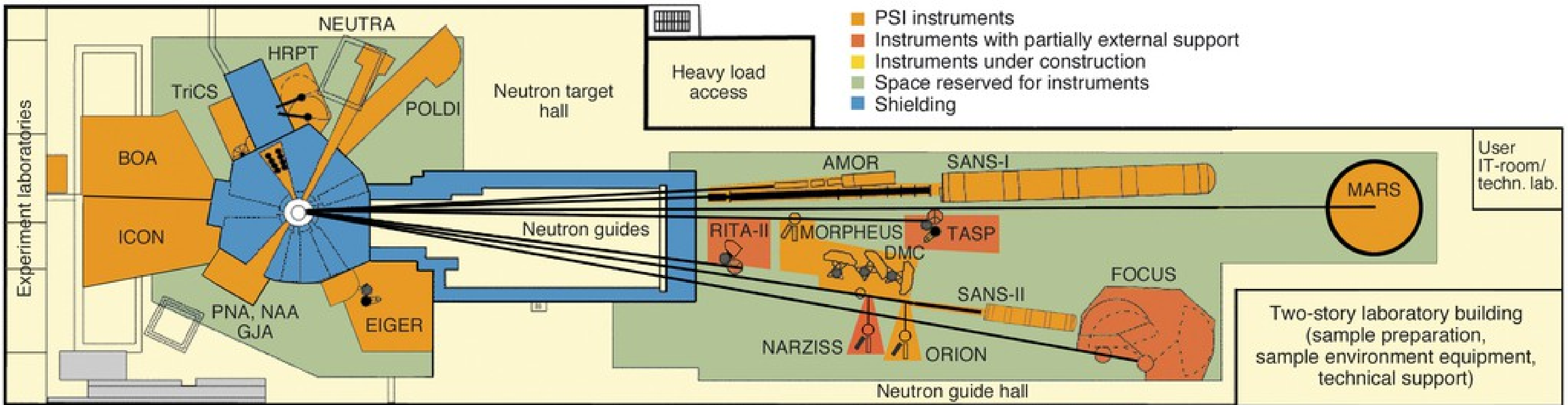


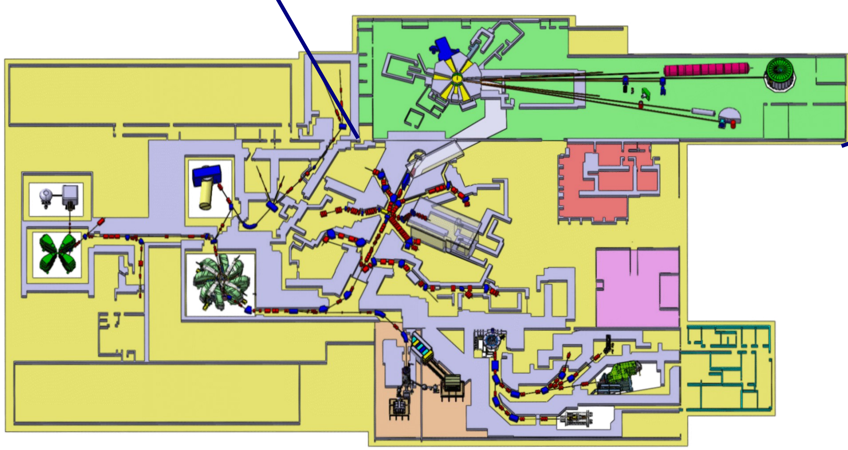
- Spallation: safer and more efficient than fission!
- Beam power on lead target: 0.75 MW
- Neutron flux: 10^{14} n/cm^2/s



Proton beamline to spallation target (side view)

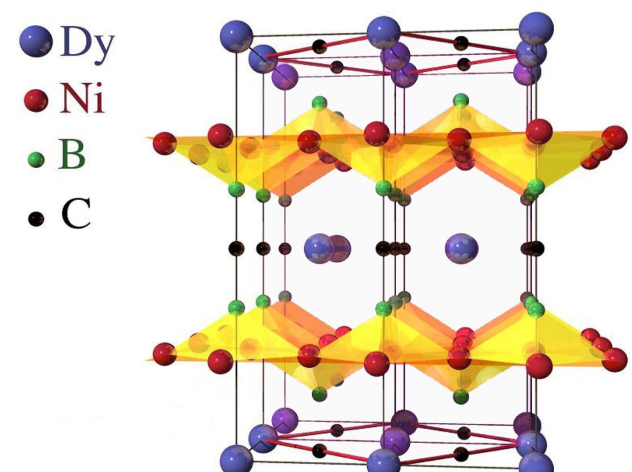
SINQ hall and beamlines





Neutron scattering off crystal structures determines atom configurations and interatomic distances!

- Wavelength neutrons: ~0.1 nm
- Crystal cell size: ~0.1 nm



Neutron imaging (radiography)

Scanning of large objects without destruction, even during use (e.g. engines). Hidden objects become visible!

X-ray image

Neutron radiography

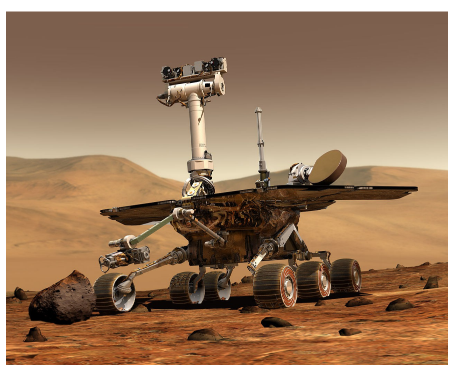
In the 2000s:

facebook

Google

YouTube

Broadcast Yourself™

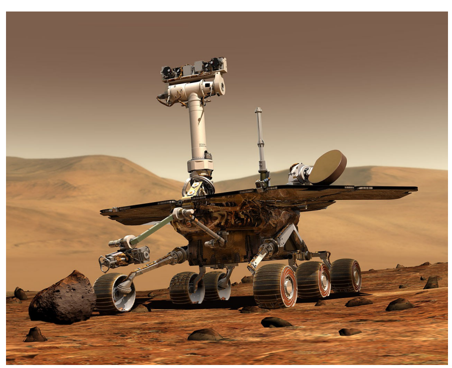


In the 2000s:

facebook

Google

YouTube
Broadcast Yourself™

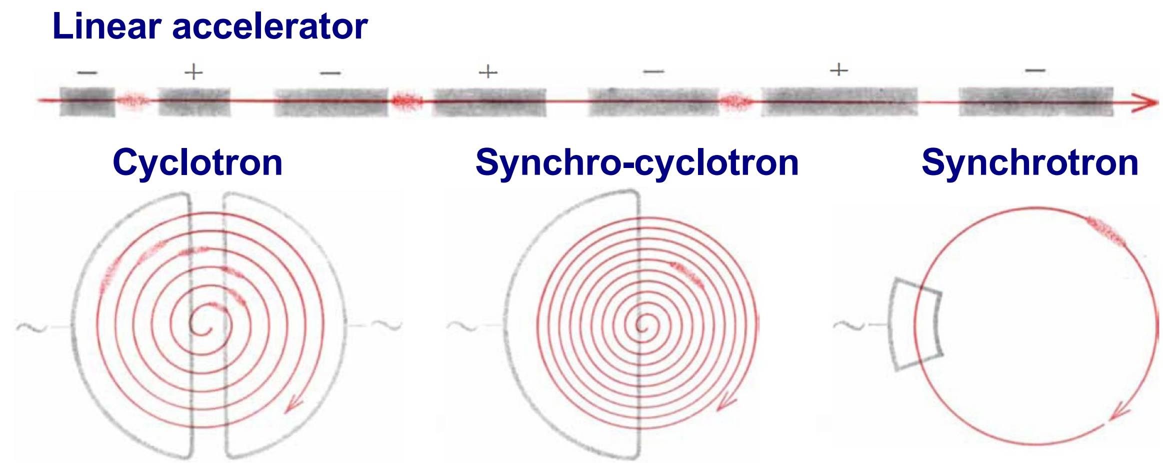


...the Synchrotron Light Source (SLS)

From the cyclotron to the synchrotron

- Cyclotrons and synchro-cyclotrons (larger orbit with increasing energy) become impractical at higher energies
- Synchrotron solution: one orbit for all energies!
  - The magnetic bending field must increase *synchronous* to the energy gain of the particles
  - The accelerator becomes a true ring!
  - So-called “strong-focusing” scheme allows efficient use of magnetic components
- All modern circular high-energy machines (HERA, Tevatron, LHC,...) are based on the synchrotron principle.

Accelerator types *(Scientific American, May 1953)*



ACCELERATOR TYPES are shown in diagram above. In linear accelerator (*top*) bunches of particles cross each gap between drift tubes just when the oscillating charges on the tubes are such as to give an accelerating kick. Cyclotron (*bottom left*) and synchro-cyclotron (*bottom center*) send particles repeatedly through the same gap in larger and larger circles. Synchrotron (*bottom right*) keeps particles on same circular path for whole acceleration by changing the strength of the magnetic field that makes particles travel in circle.

SLS: two-ring concept!

- Booster synchrotron to accelerate electrons to 2.4 GeV
- Storage ring to keep electrons at constant energy for stable **X-ray emission**

Swiss Light Source (SLS)

Swiss Light Source (SLS)

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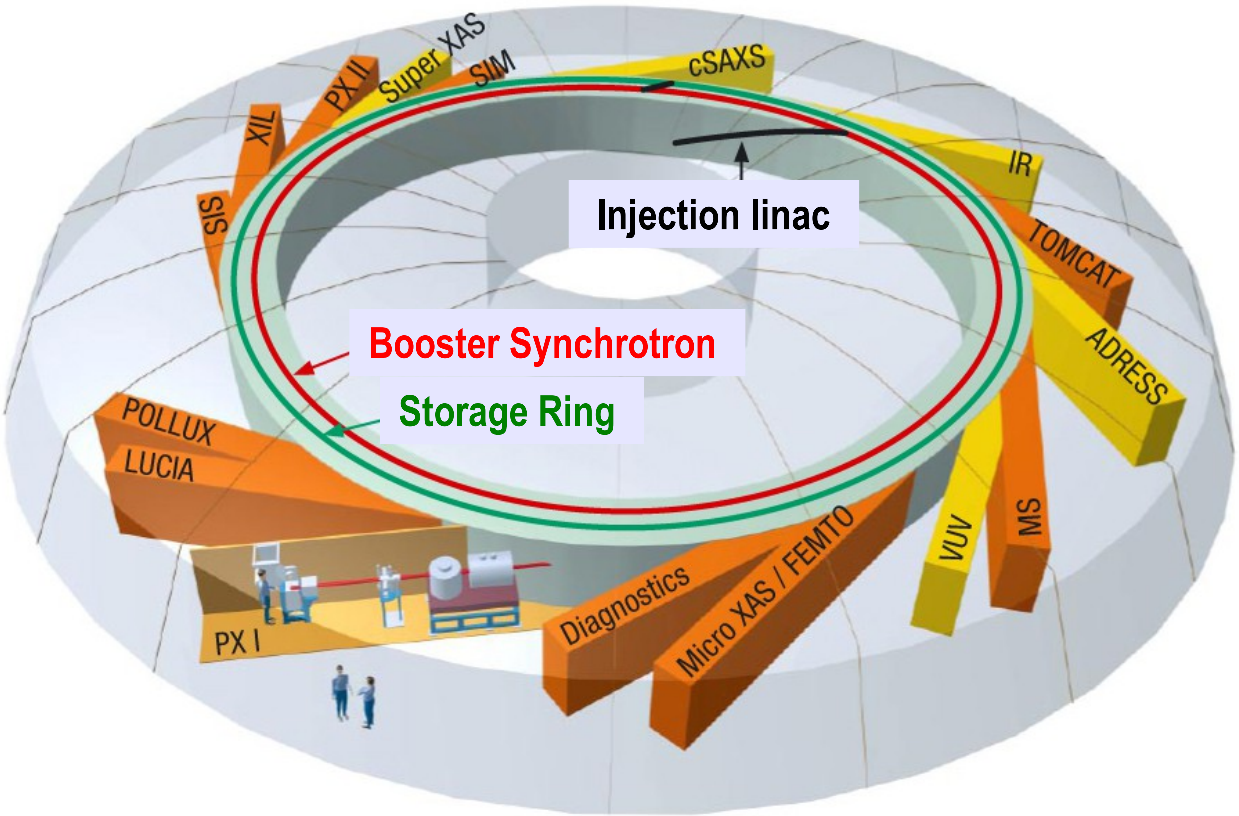
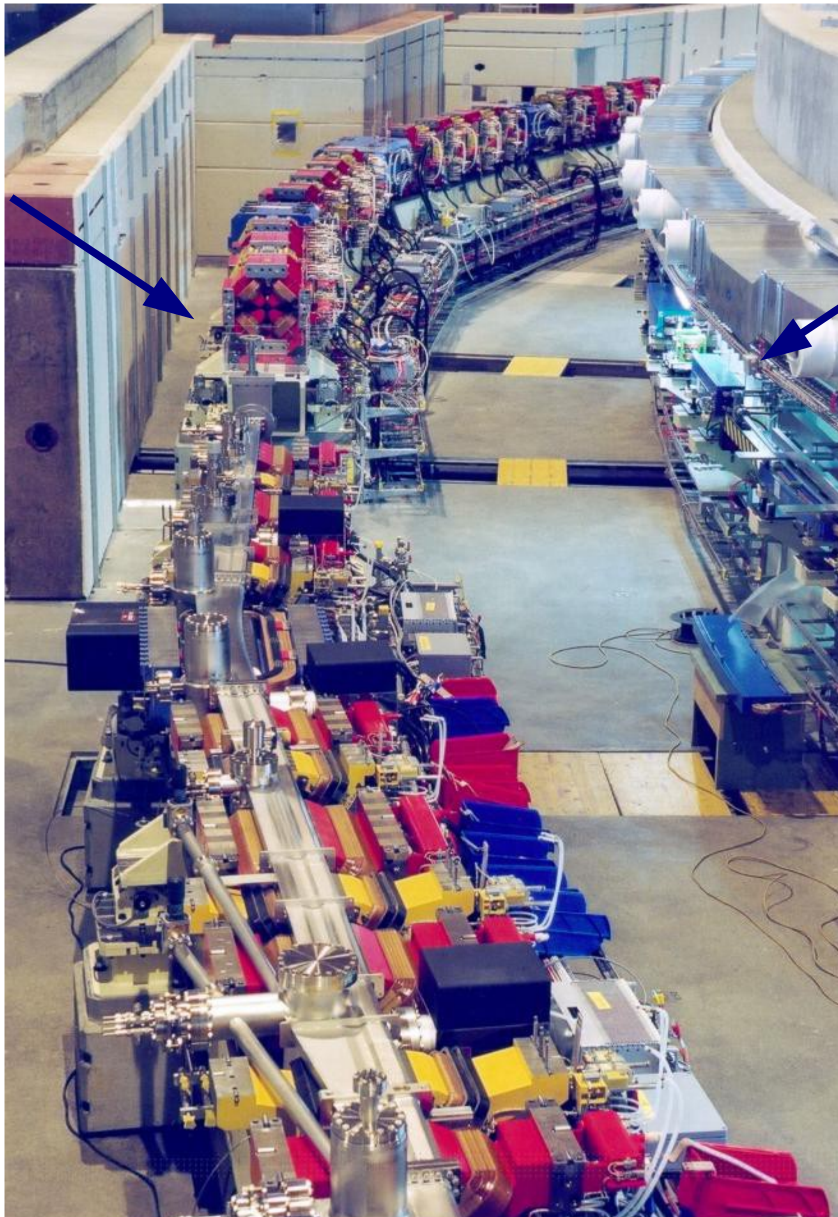
Booster Synchrotron	
Beam energy	0.1 → 2.4 GeV
Circumference	270 m
Magnetic bending field	0.72 T
RF frequency	500 MHz
Peak RF voltage	0.5 MV
Beam current (max.)	12 mA

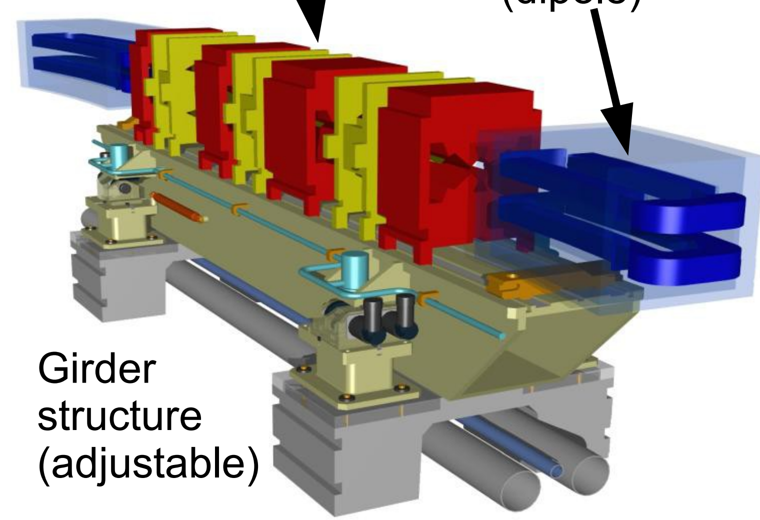
Injection Linac	
Beam energy	100 MeV
RF frequency	2997.92 MHz
Cycling rate	3.125 Hz
Charge / pulse	1 nC

Storage Ring	
Beam energy	2.4 GeV
Circumference	288 m
Magnetic bending field	1.4 T
RF frequency	500 MHz
Peak RF voltage	2.6 MV
Beam current	400 mA
Radiation loss per turn	512 keV
Beam lifetime	~8 h



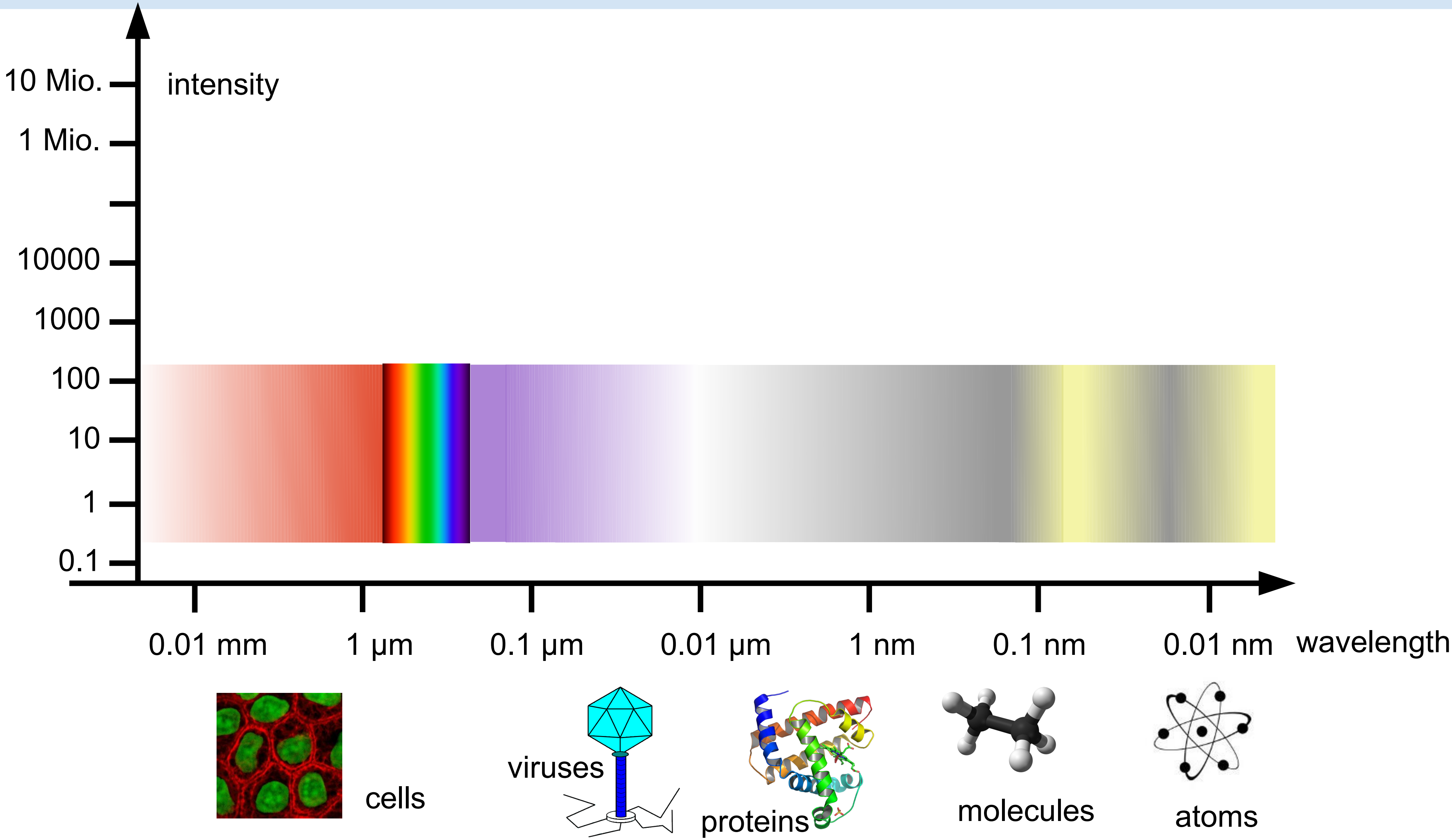
SLS tunnel


Storage Ring
Booster

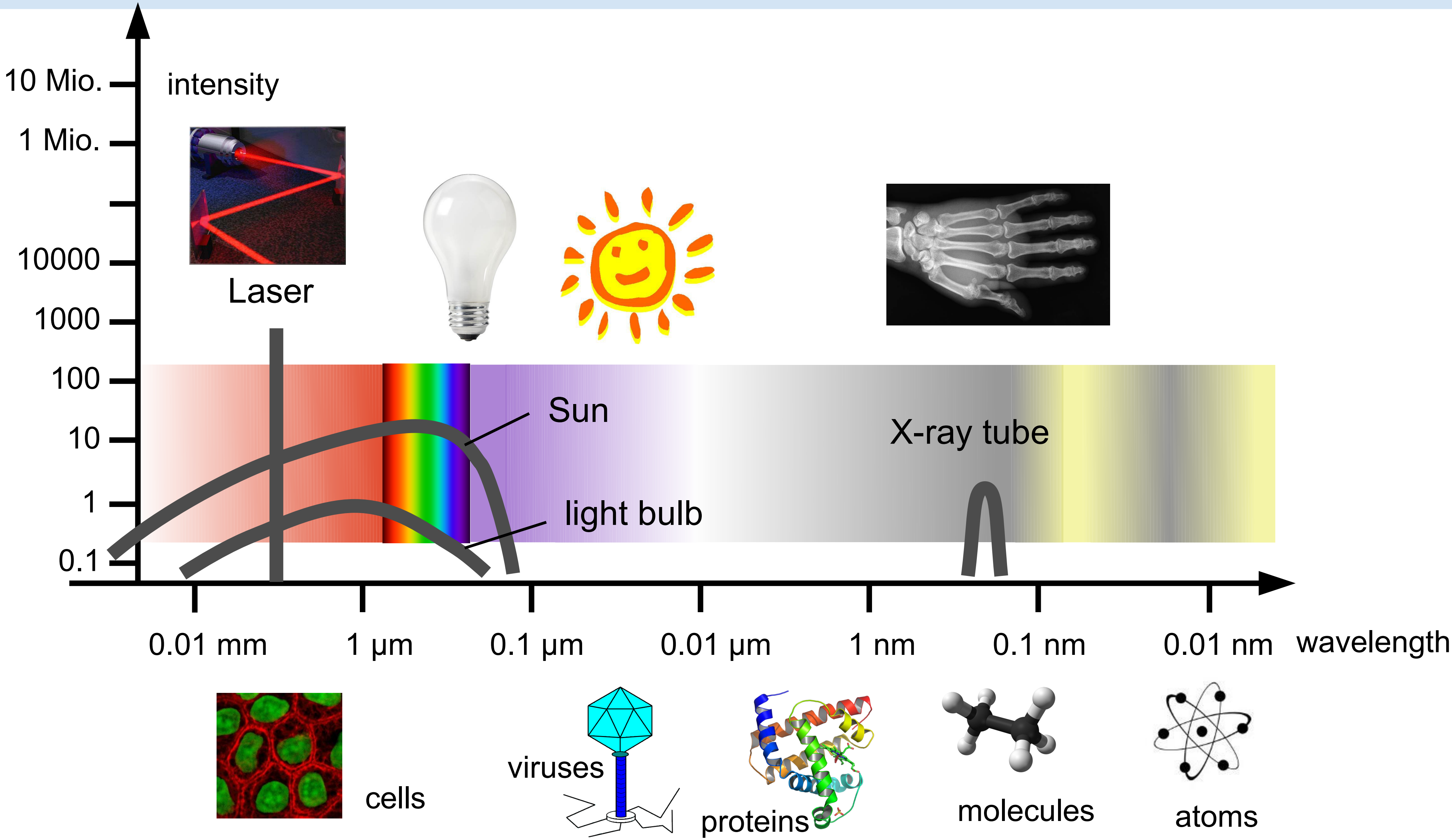

Focusing magnets (quadrupoles and sextupoles)
Bending magnet (dipole)
Girder structure (adjustable)

Two light sources...

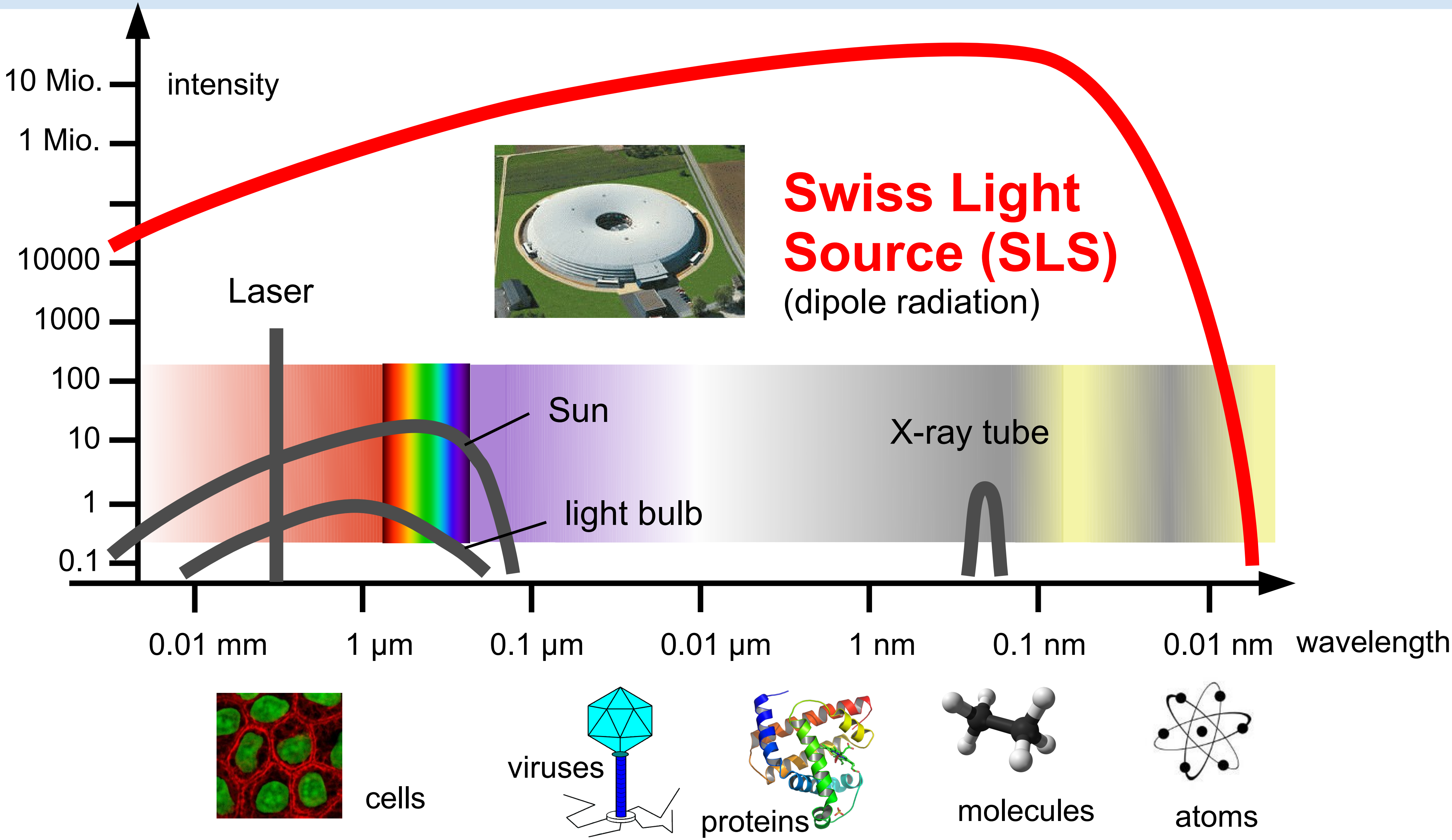
SLS spectral brightness



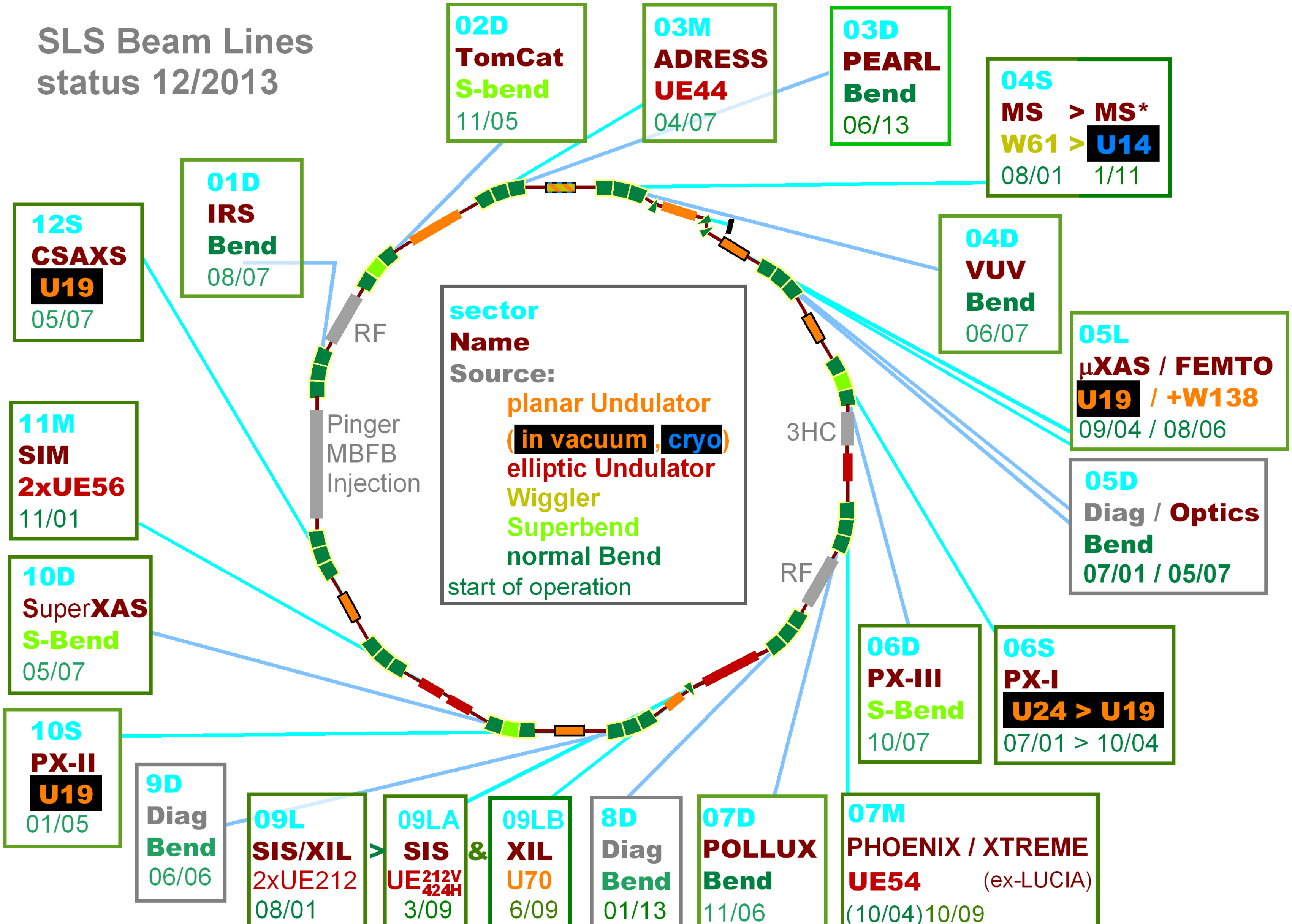
SLS spectral brightness



SLS spectral brightness

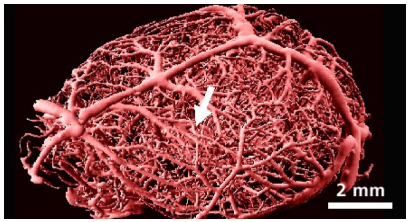


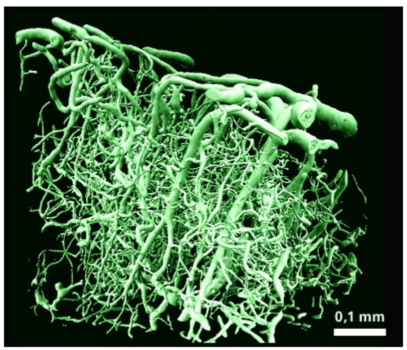
SLS beamlines (12/2013)



SLS applications (examples)

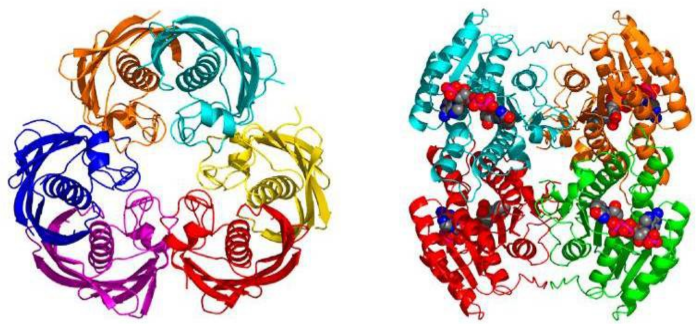
Microtomography





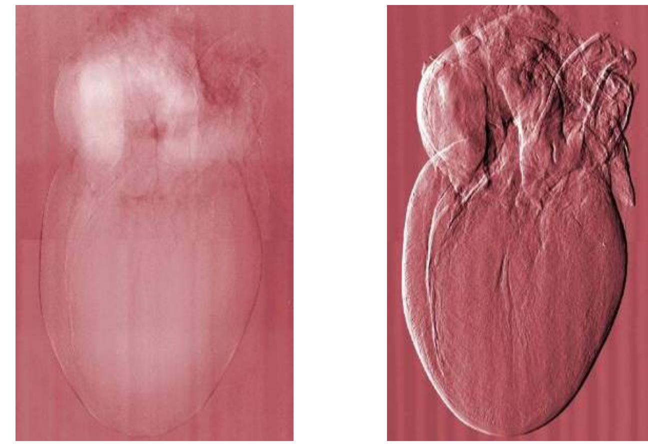
Blood vessels in the brain of mouse suffering from Alzheimer disease.

Protein Cristallography



Structures of two important enzymes of Malaria agent.

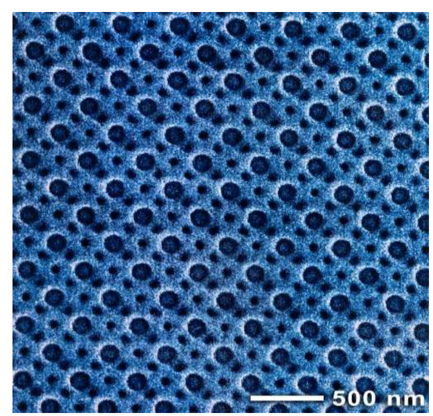
Phase Contrast Microscopy



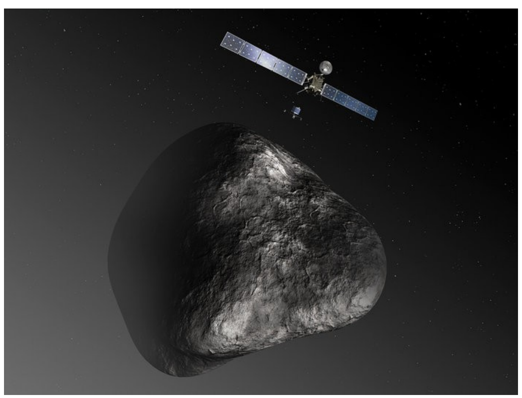
Rat heart with conventional (left) and phase contrast X-ray imaging (right).

Nanolithography

Nanopattern edged with interfering X-ray beams.



In the 2010s...



In the 2010s...

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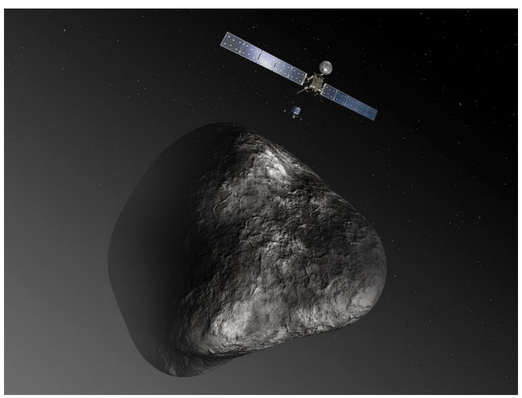
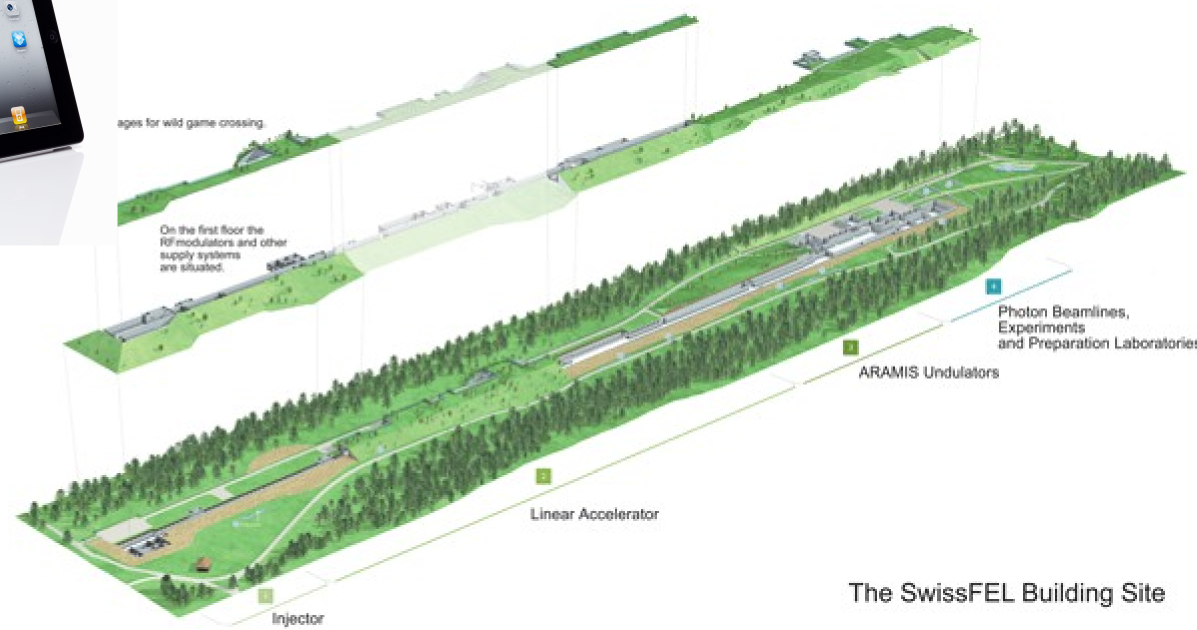
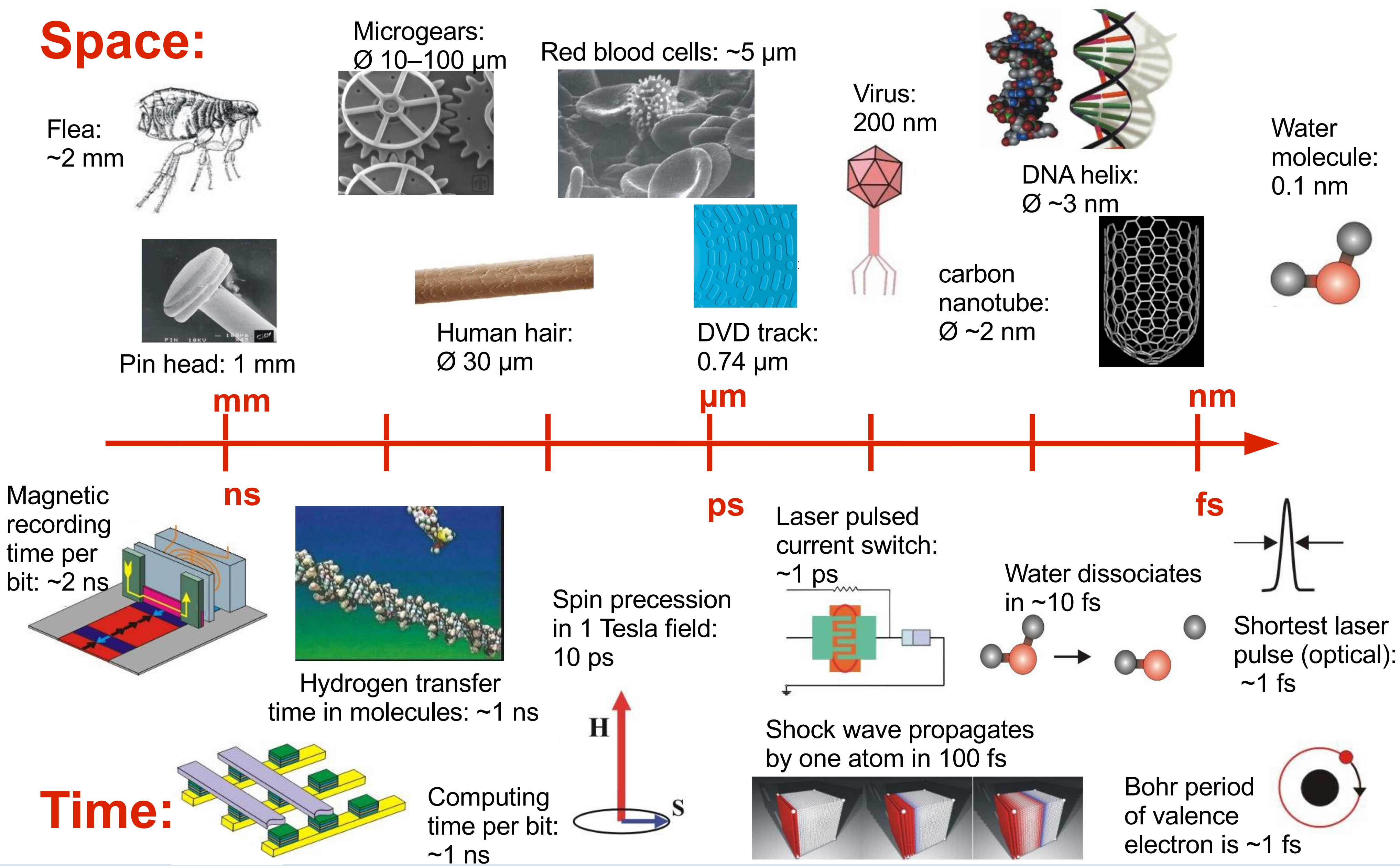


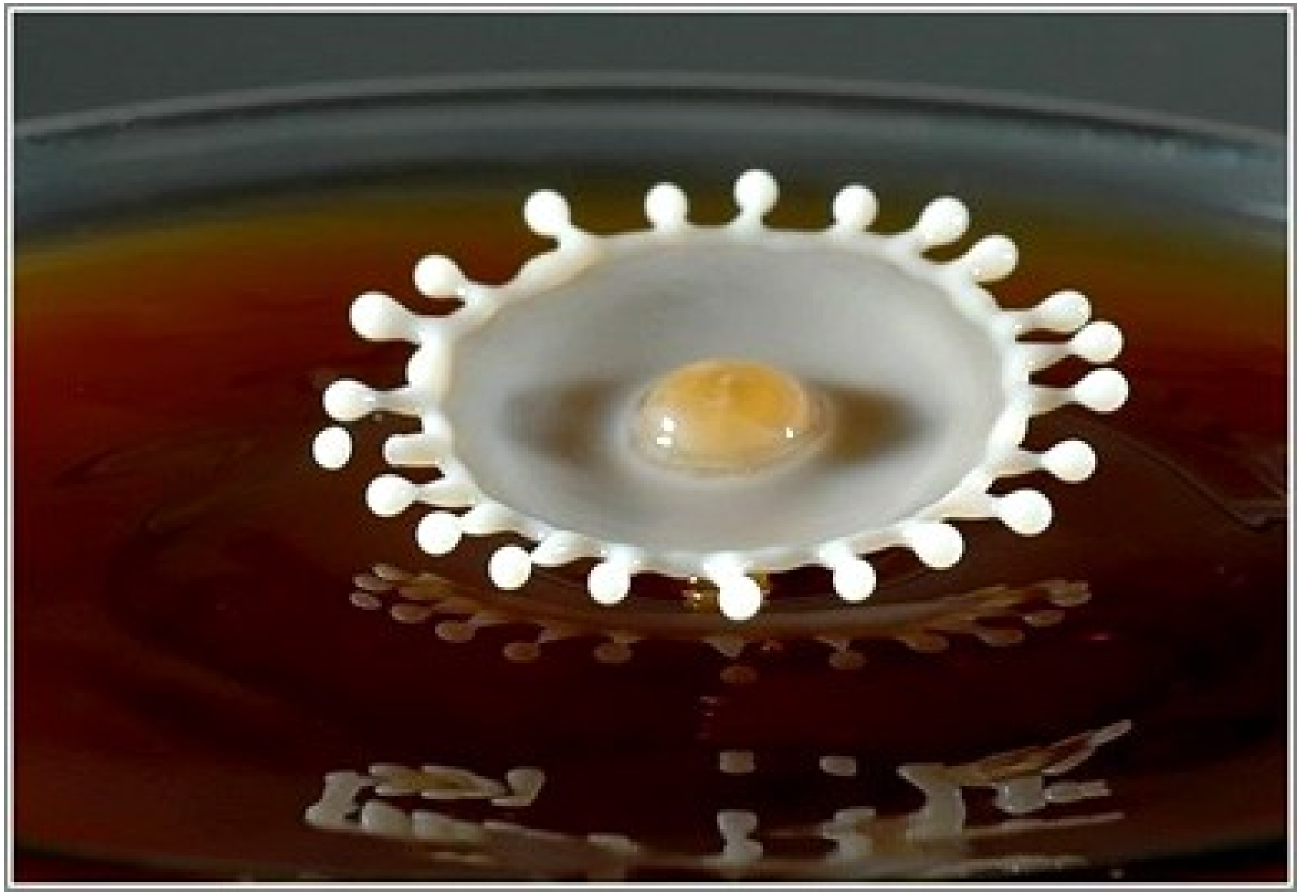
… the X-Ray Free-Electron Laser (SwissFEL)



Distances and time-spans in nature and technology



Advancing knowledge through time resolution



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Advancing knowledge through time resolution

Advancing knowledge through time resolution

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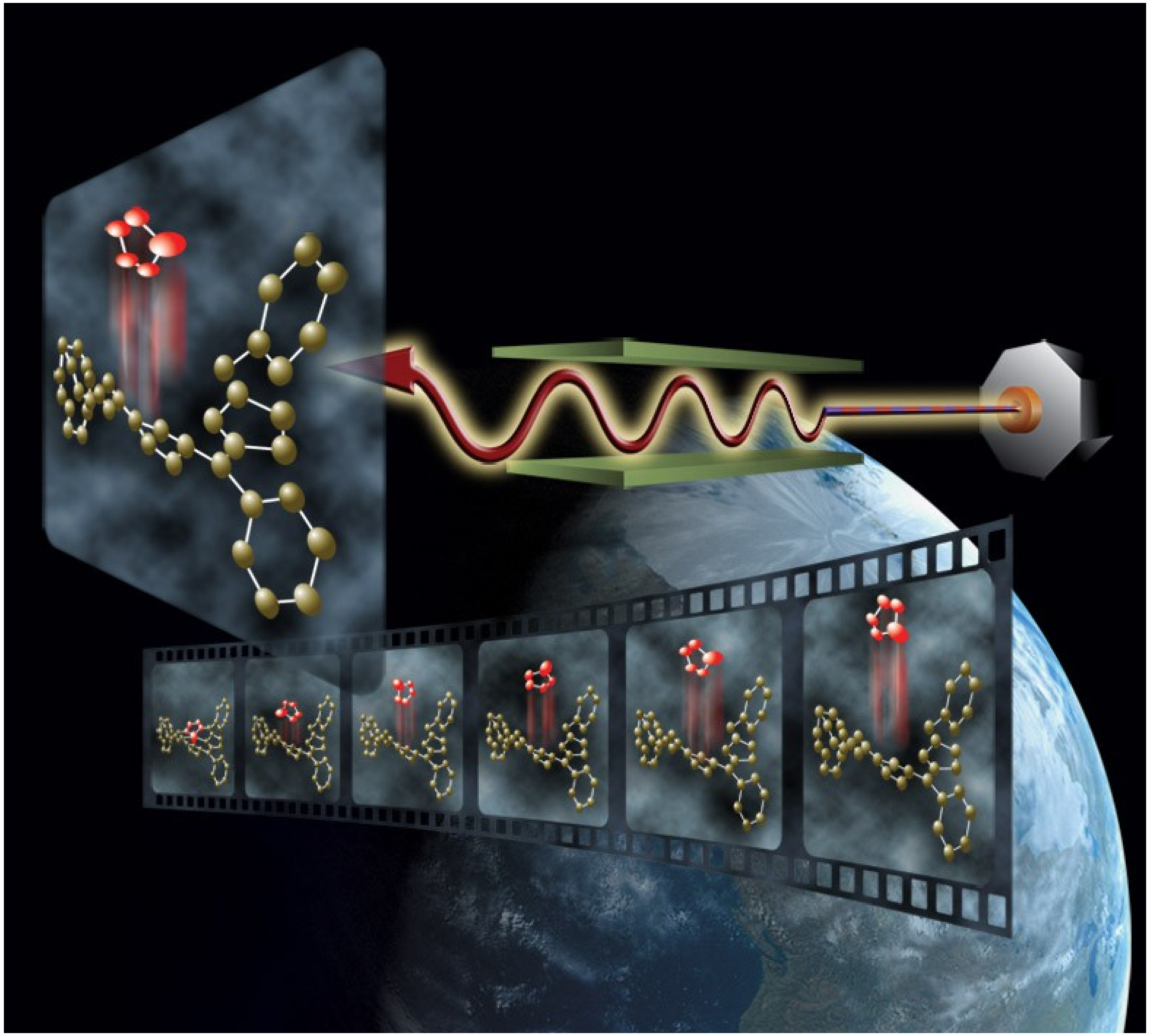
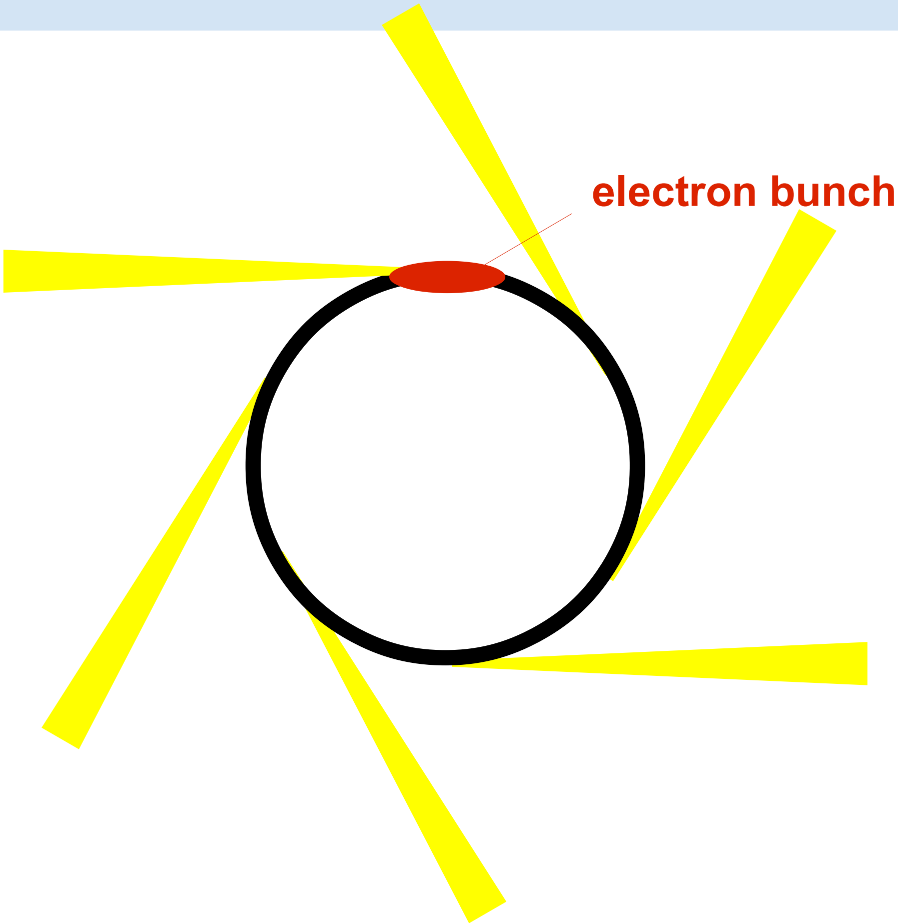


Image: LCLS, SLAC

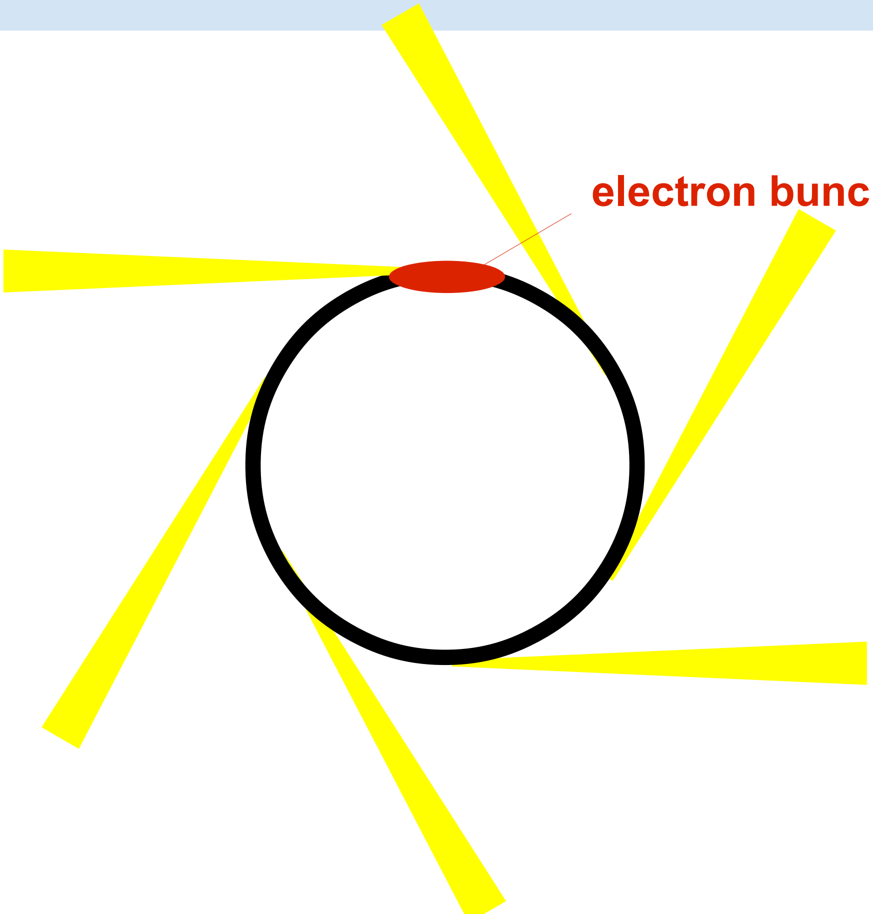
Round or straight?



Circular accelerator:

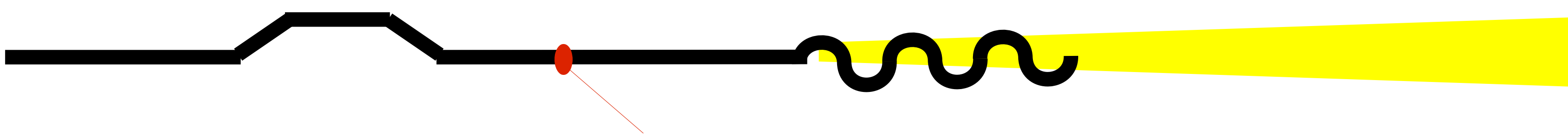
- Electrons continuously emit light
- Electron bunches diverge
- Ultra-short pulses are *not* possible (limit of ~100 ps from RF bunching)

Round or straight?

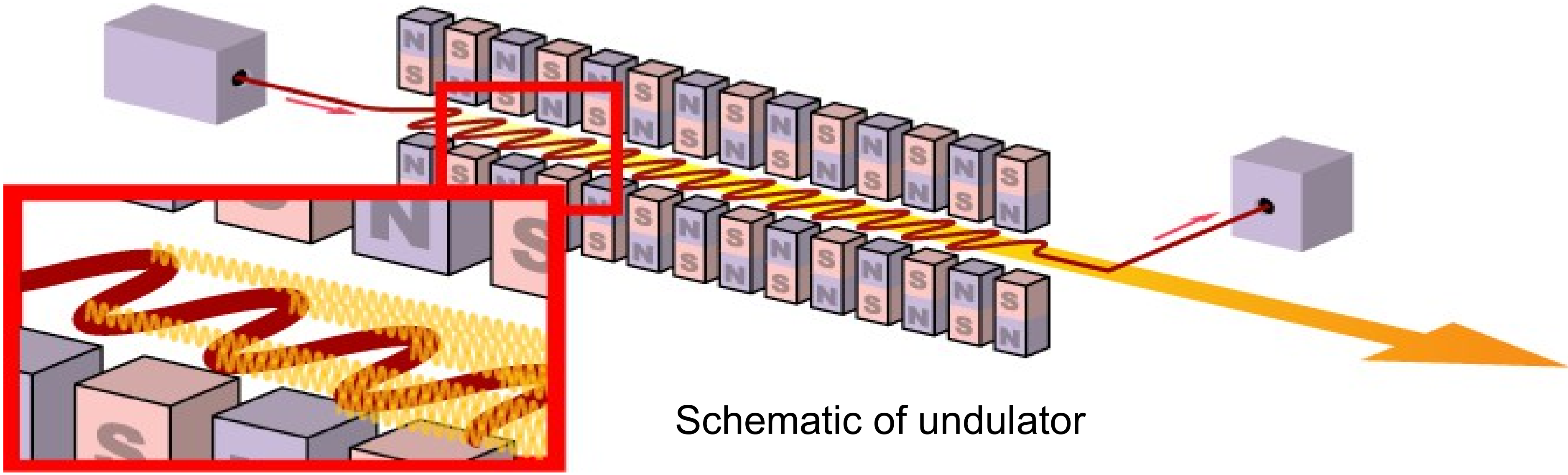


Circular accelerator:
- Electrons continuously emit light
- Electron bunches diverge
- Ultra-short pulses are *not* possible (limit of ~100 ps from RF bunching)

Linear accelerator:
- Electrons do not emit light
- Electron bunches remain compact
- Emission of ultra-short (order 10 fs) light pulses is possible thanks to “undulator”



Undulator radiation



Schematic of undulator

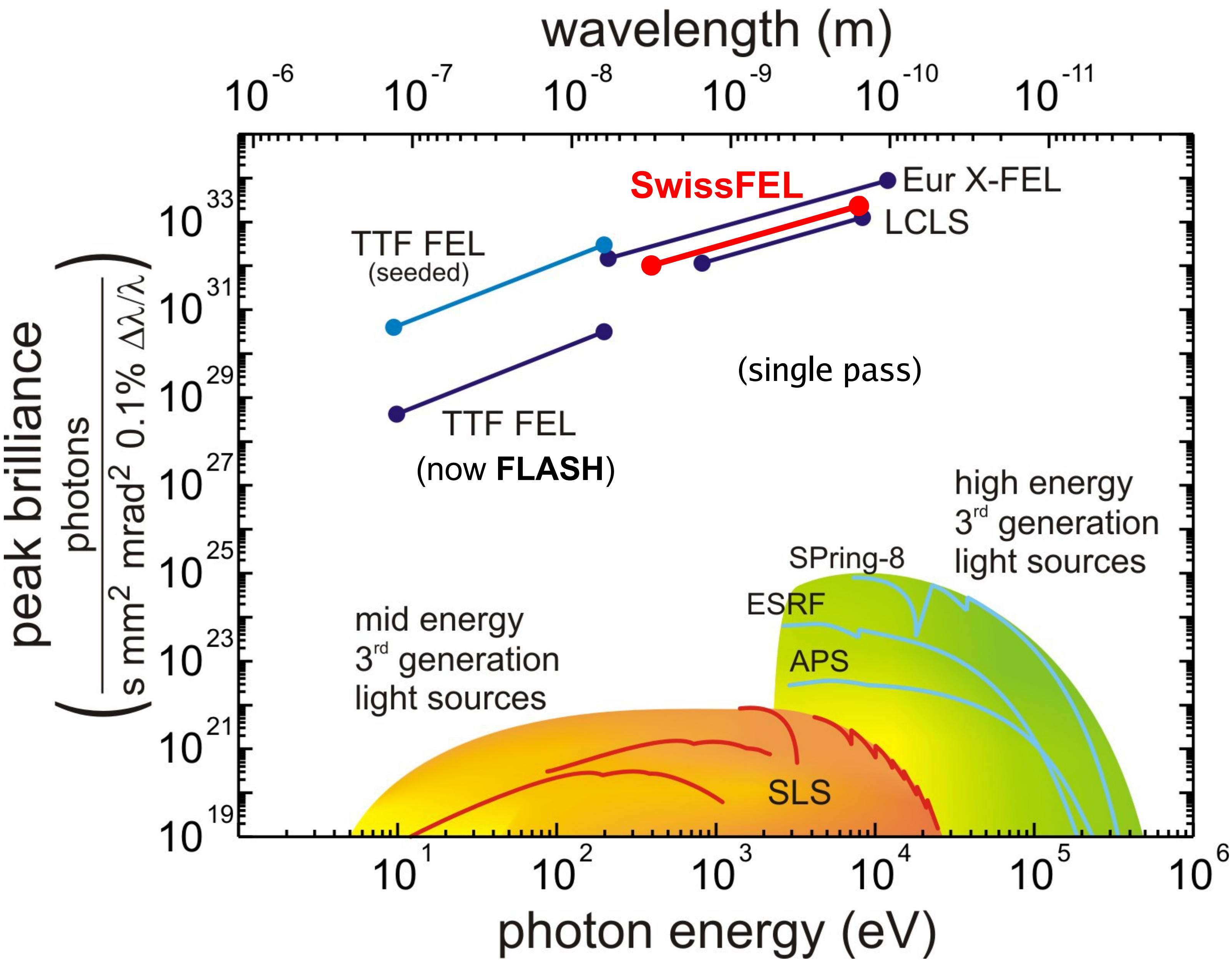
The light waves of a certain wavelength add coherently (constructive interference), if

- the electron beam has high brightness (low emittance at high current)
- the magnets have the right spacing and gap (undulator parameter *K*)
- the undulator is long enough (gain length)

"Free-Electron Laser" (FEL)

Revolutionizing X-ray science

PAUL SCHERRER INSTITUT



X-ray FELs worldwide

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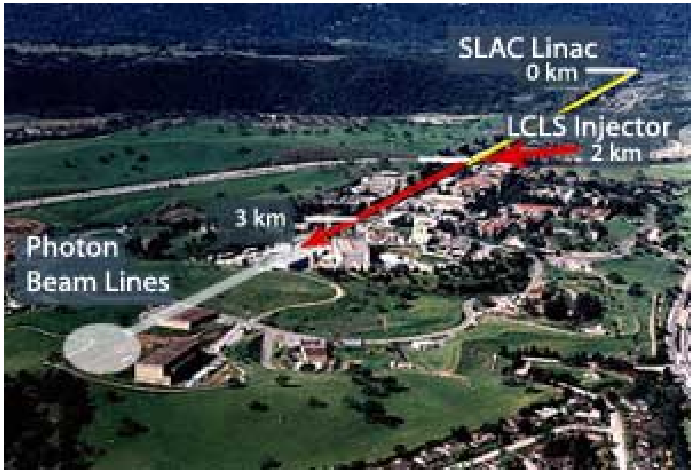
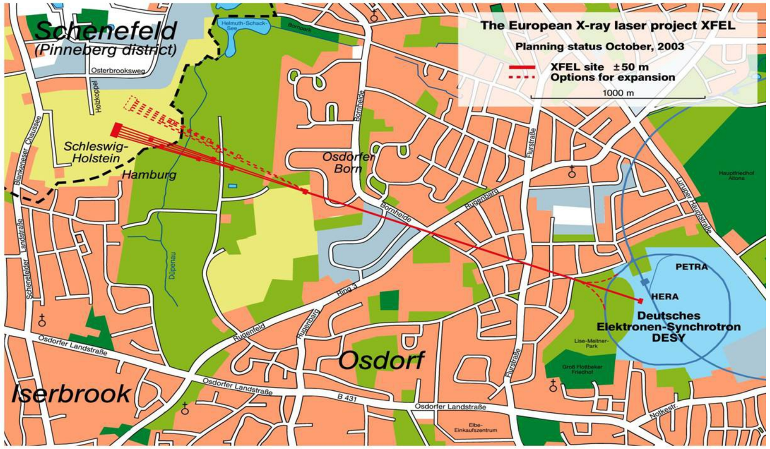
SCSS, SPring-8, Japan

LCLS, SLAC, Stanford



European XFEL, DESY, Hamburg



X-ray FELs worldwide

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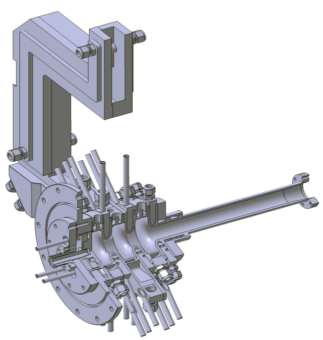
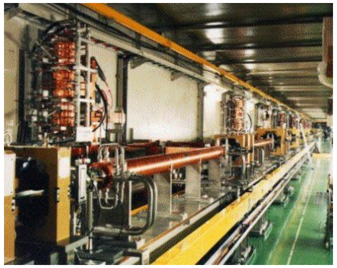
	LCLS (USA)	SCSS (Japan)	European XFEL	SwissFEL (CH)
Start of operation	2009	2011	2015	2017
Length [km]	3.0	0.75	3.4	0.7
Beam energy [GeV]	13.6	8	17.5	6
Min. wavelength λ_{min} [nm]	0.15	0.1	0.1	0.1
Peak brilliance at λ_{min} [10^{33} photons/s/mm^2/mrad^2/0.1% BW]	2.4	5.0	5.0	1.3

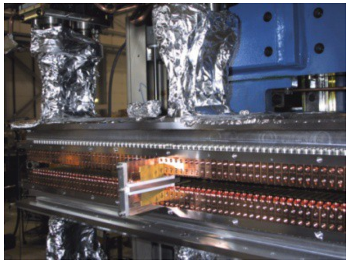
Ingredients of an X-ray FEL

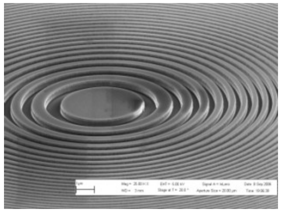
Generation of high-brightness electron beam | **Electron beam acceleration** | **X-ray generation with FEL process (SASE)** | **X-ray transport and focussing**

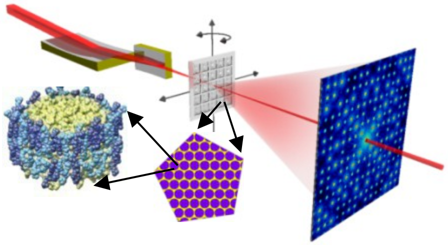
- **Electron gun** → **Linear accelerator** →
  - **Undulator** → **Experiments**
  - **Undulator** → **Experiments**
  - **Undulator** → **Experiments**











SwissFEL layout

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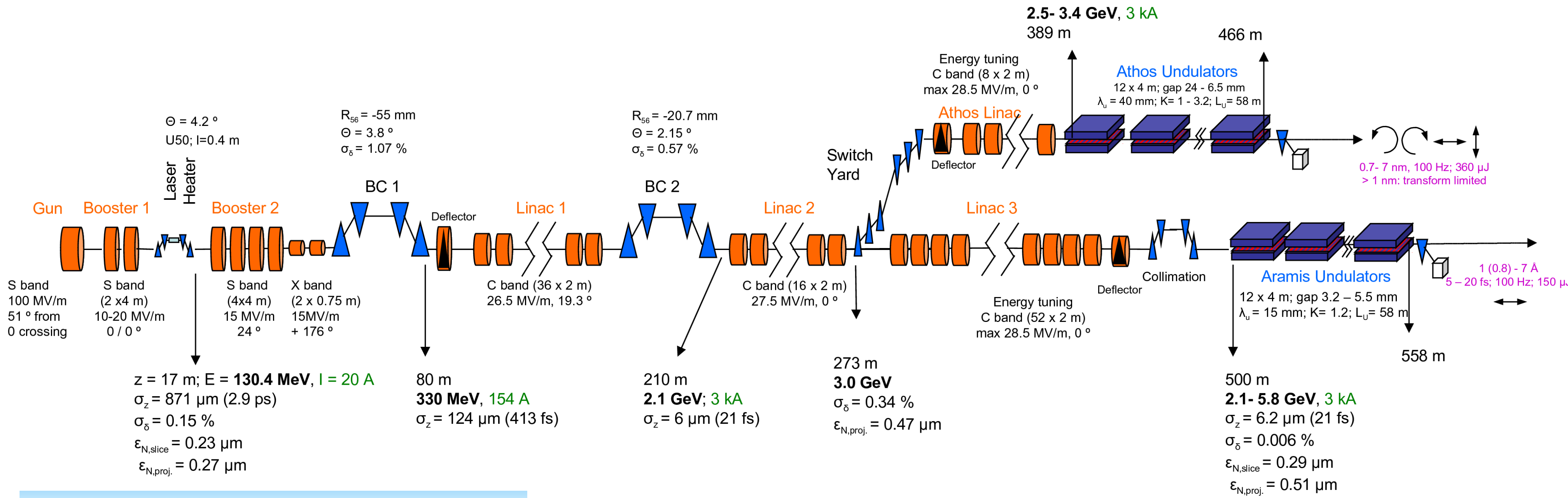
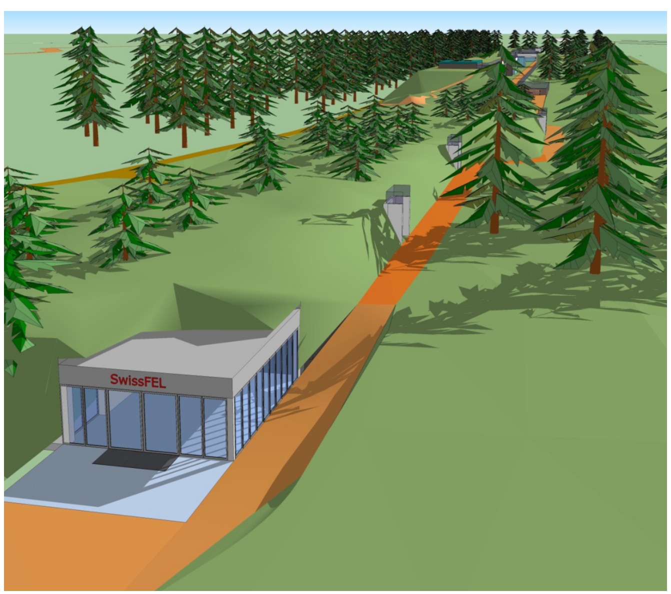
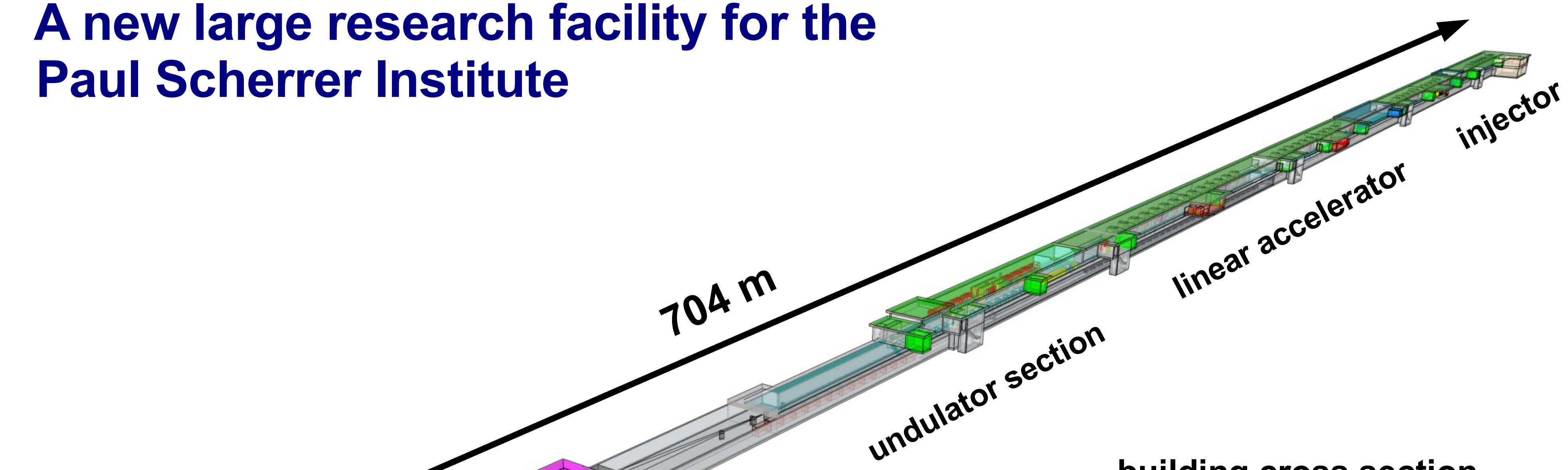




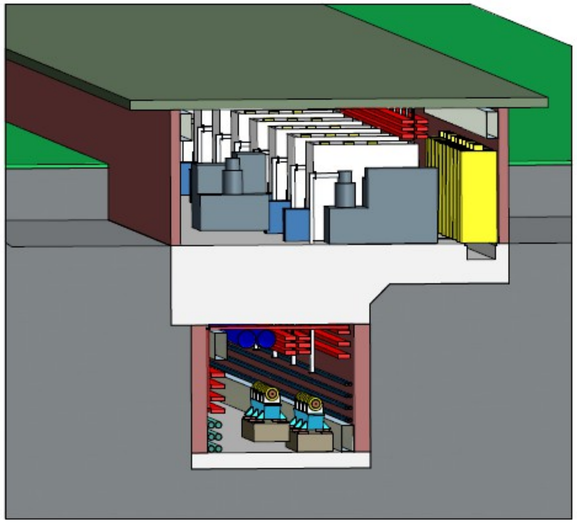
SwissFEL key parameters	
Final electron energy	5.8 GeV
RF frequency	3 / 5.7 GHz
Bunch charge	10–200 pC
Pulse duration	1–20 fs
Repetition rate	100 Hz
Photon wavelength	1–70 Å

SwissFEL building

A new large research facility for the Paul Scherrer Institute



building cross section



SwissFEL Construction Site (May 2014)

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SwissFEL Construction Site (May 2014)

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SwissFEL Construction Site (May 2014)

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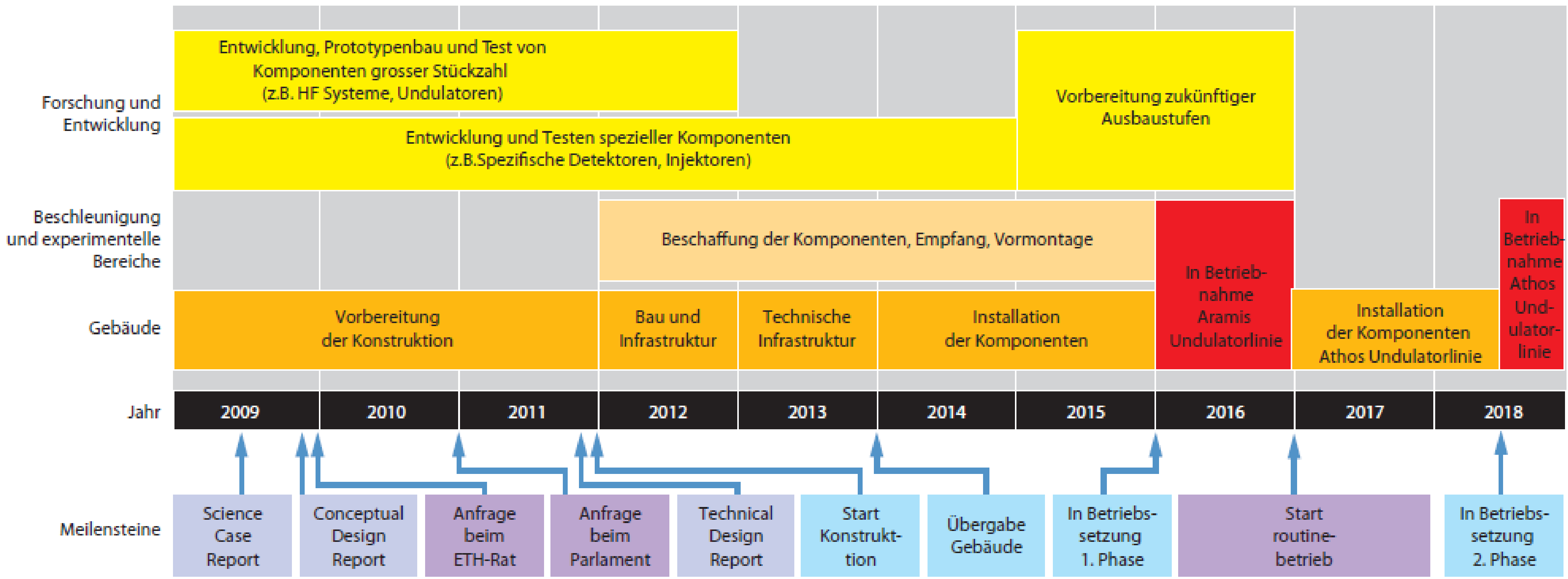
Project Schedule



Important milestones:

2010	**Conceptual Design Report**
2012	**Approval by Swiss Parliament**
2013	**Start Construction**
2014	**Building Completed**
2017	**Start Operation (Phase 1)**

SwissFEL Injector Test Facility

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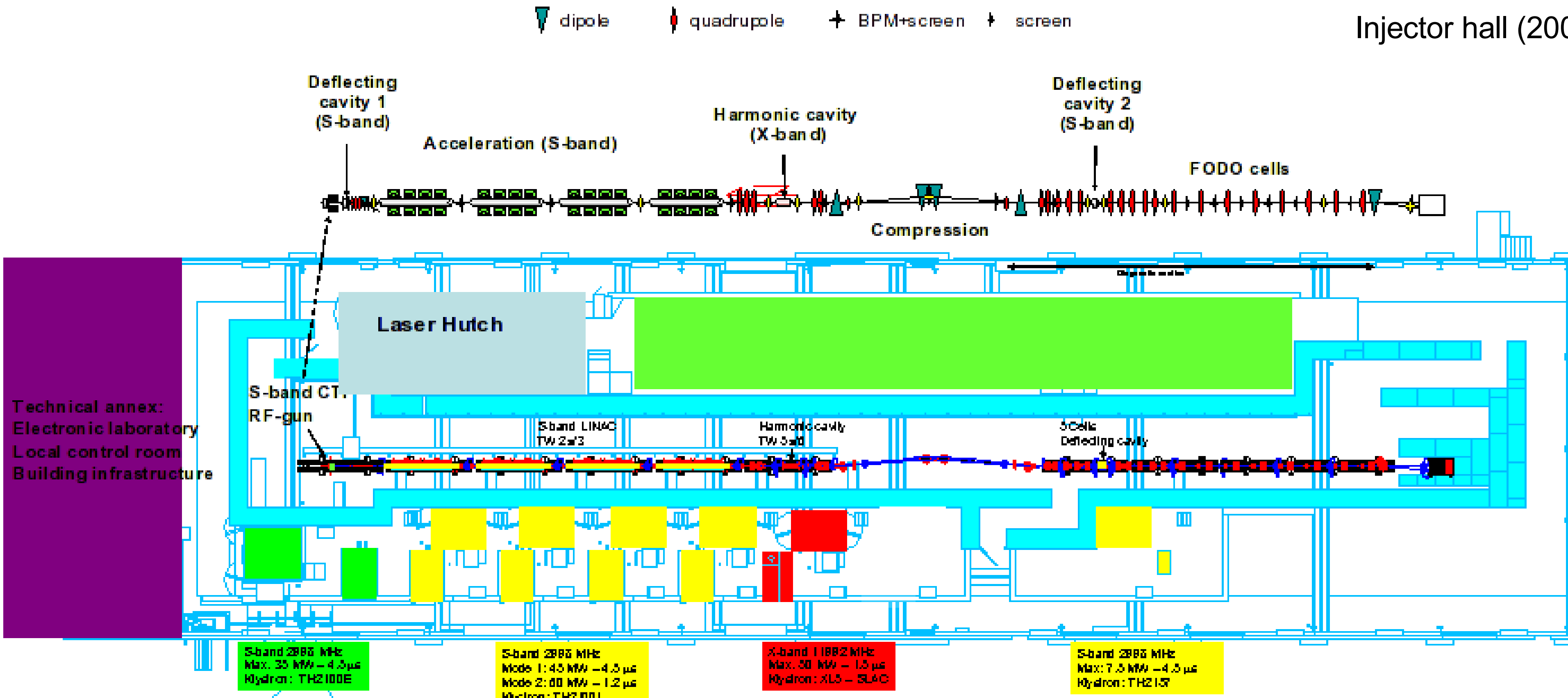
- Electron gun and first accelerating section (first ~50 m of SwissFEL)
- Test of components and procedures needed for SwissFEL
- Will be moved to final SwissFEL location in 2015

Injector hall (2009)

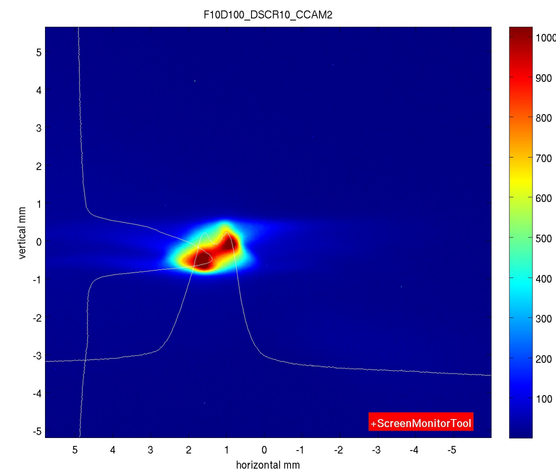


SwissFEL Injector Test Facility

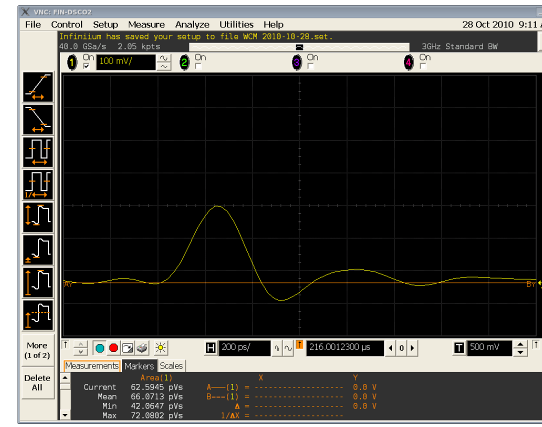
Official inauguration (24 August 2010)

Keep it simple for the Federal Councillor: one button, two signals

Button connected to laser shutter.



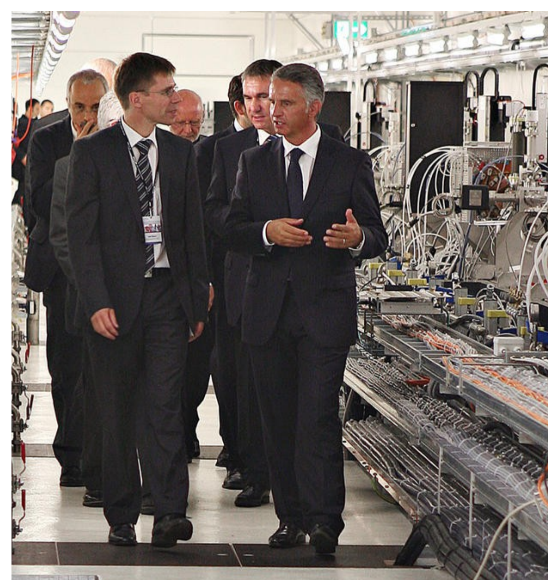
Beam on LuAG screen in front of beam dump.



Signal from Wall Current Monitor after the RF gun.

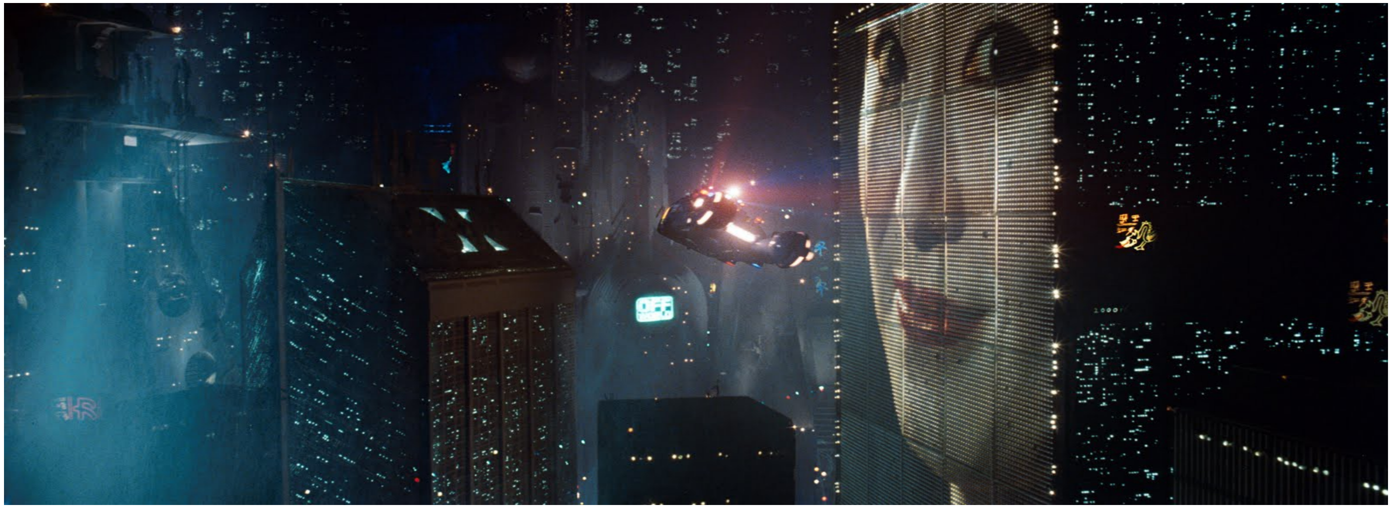
The Burkhalter beam:

- ~35 pC charge
- ~160 MeV energy
- ~0.5 MeV energy spread

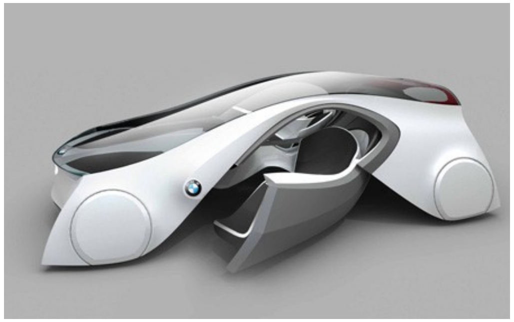


Visit to the injector tunnel.

In the 2020s...

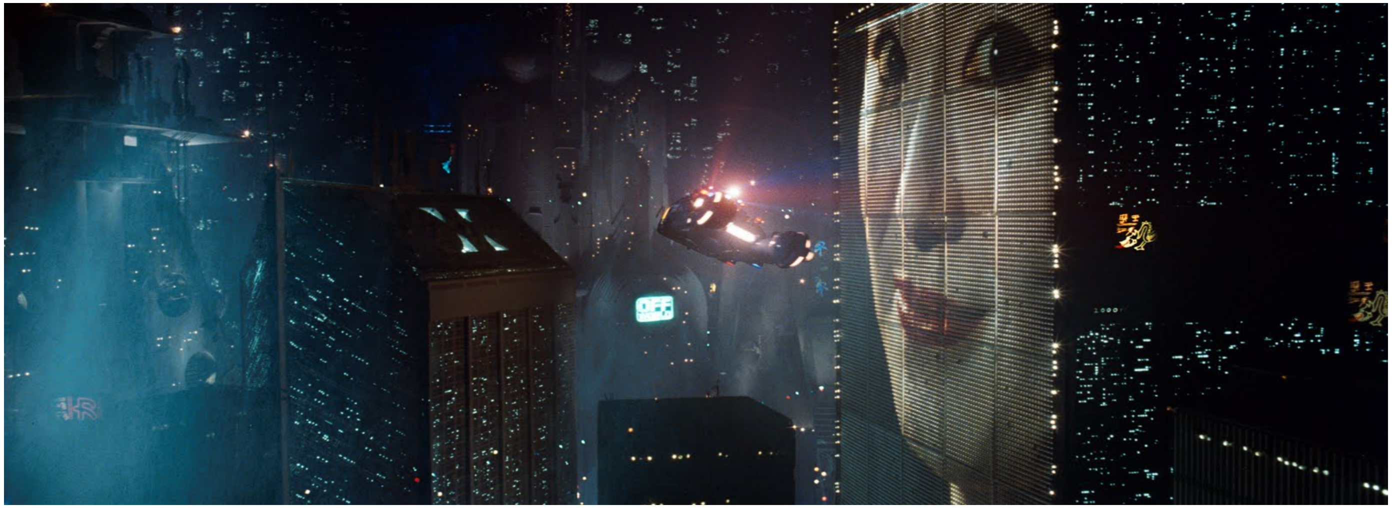


yankodesign.com



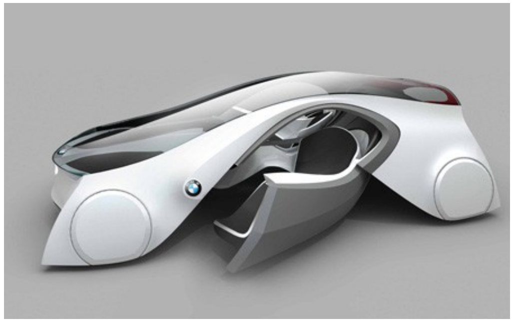
BMW ZX-6 concept

In the 2020s...



...SLS-2.0!

yankodesign.com

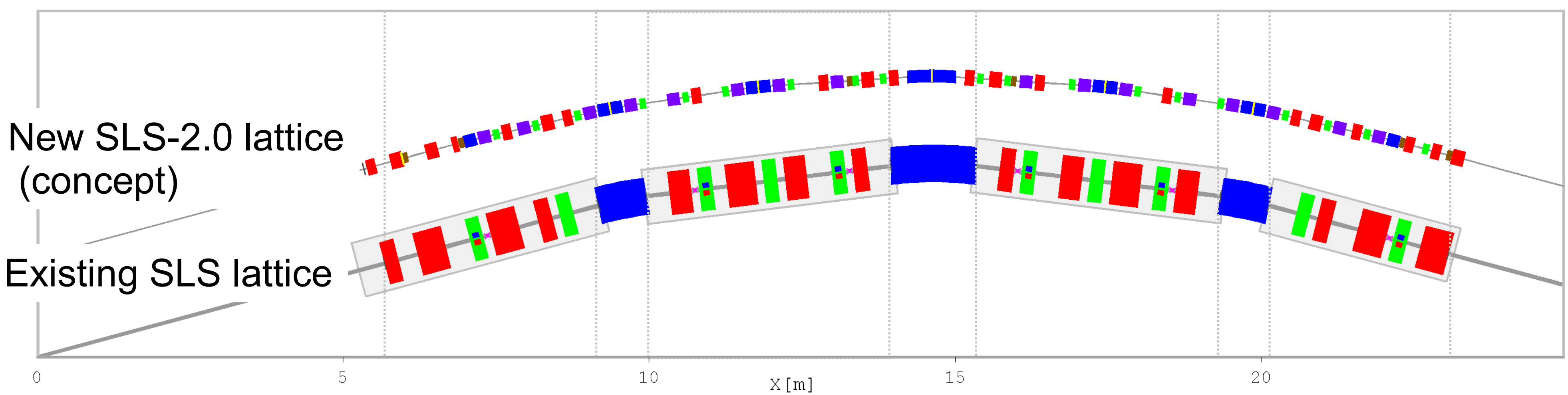


BMW ZX-6 concept

SLS-2.0 Concept

- Improvements in magnet and other technologies allow *more compact components.*
- New ring design with many short bending magnets with *small deflection angles* gives *dramatic reduction in emittance*, therefore much *higher brilliance.*
- *Design study* in progress.
- Realization in the *period 2021–24* (if funding can be secured).

Image: ECOS



Summary

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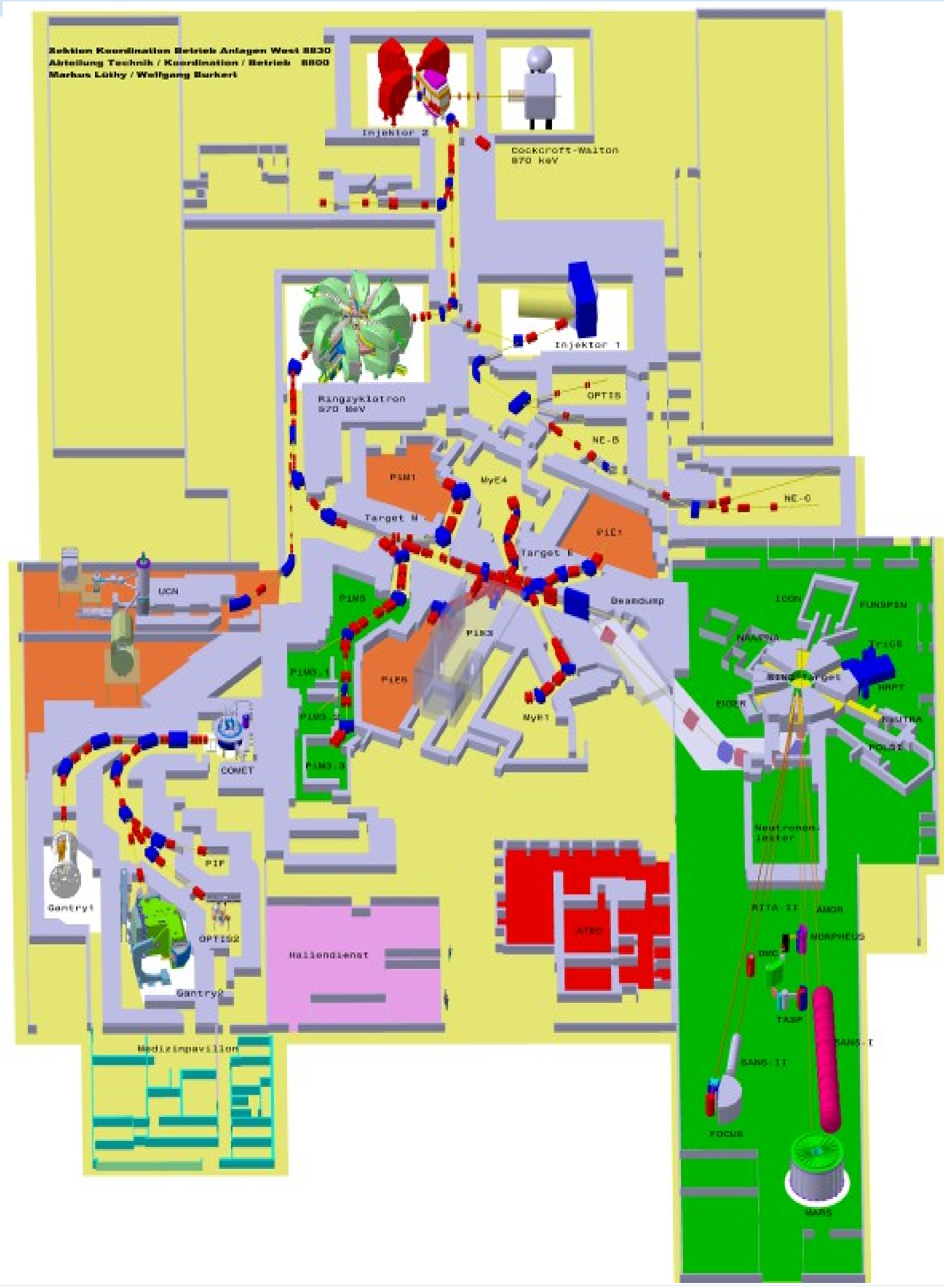
- By realizing about one large facility / upgrade per decade, the Paul Scherrer Institute has been able to stay competitive throughout a wide spectrum of natural sciences – since the 1970s!
- The availability of pions, muons, neutrons, and X-ray photons as probes in the same lab is worldwide unique.
- With SwissFEL under construction and SLS-2.0 on the horizon, the future looks even brighter!

Thank you for your attention!

Spare slides...

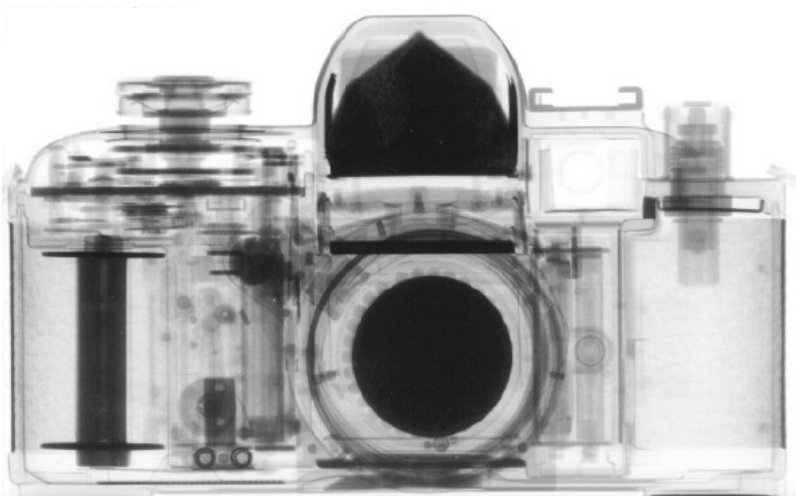
HIPA Layout



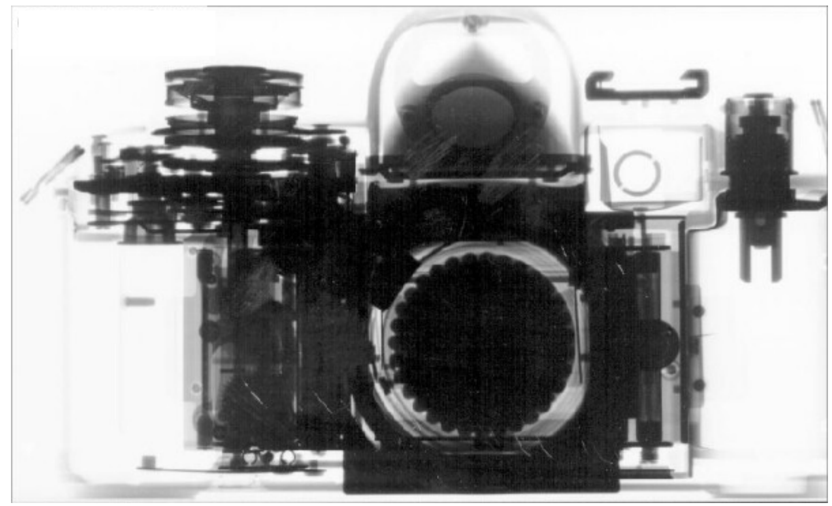
Injektor 2
Cockcroft-Walton
870 keV
Injektor 1
Ringzyklotron
590 MeV
OPTIS
NE-B
NE-C
PiM1
MyE4
Target M
PiE1
Target E
UCN
PiM3
Beamdump
PiE3
PiM3.1
PiE5
PiM3.2
PiM3.3
MyE1
COMET
PIF
Gantry1
OPTIS2
Gantry2
Hallendienst
ATEC
Medizinpavillon
FUNSPIN
TriCS
HRPT
EIGER
NEUTRA
POLDI
Neutronen-
leiter
RITA-II
AMOR
MORPHEUS
TASP
SANS-I
SANS-II
FOCUS
MARS

Neutron imaging

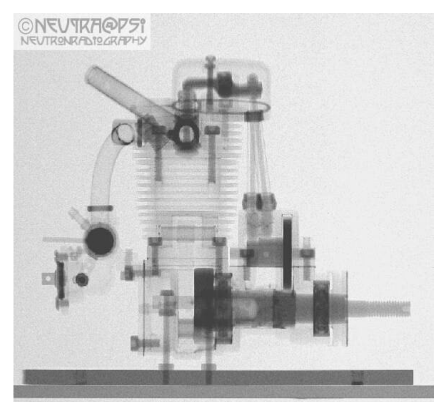
Scanning of large objects without destruction, even during use! The inner workings become visible.

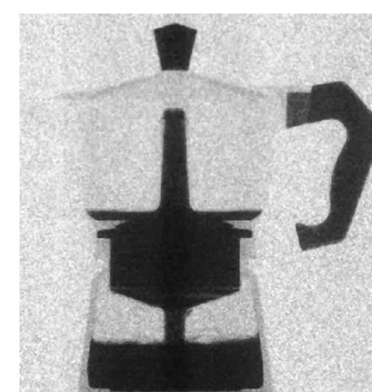


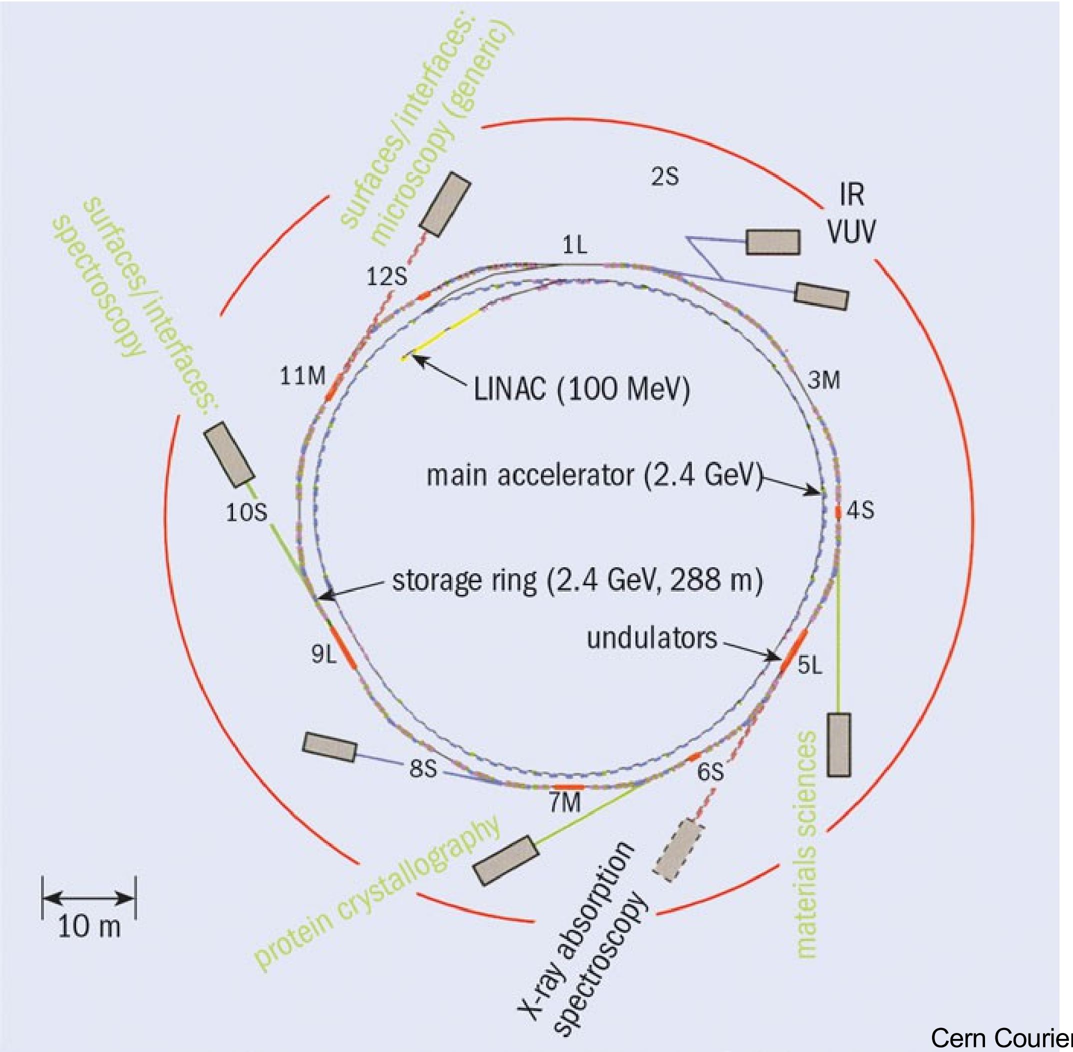
Neutron radiography



X-ray image

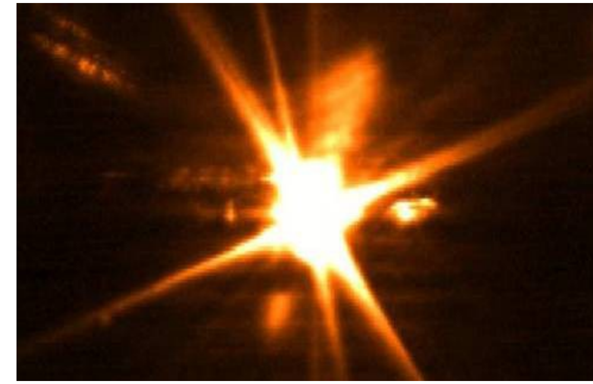


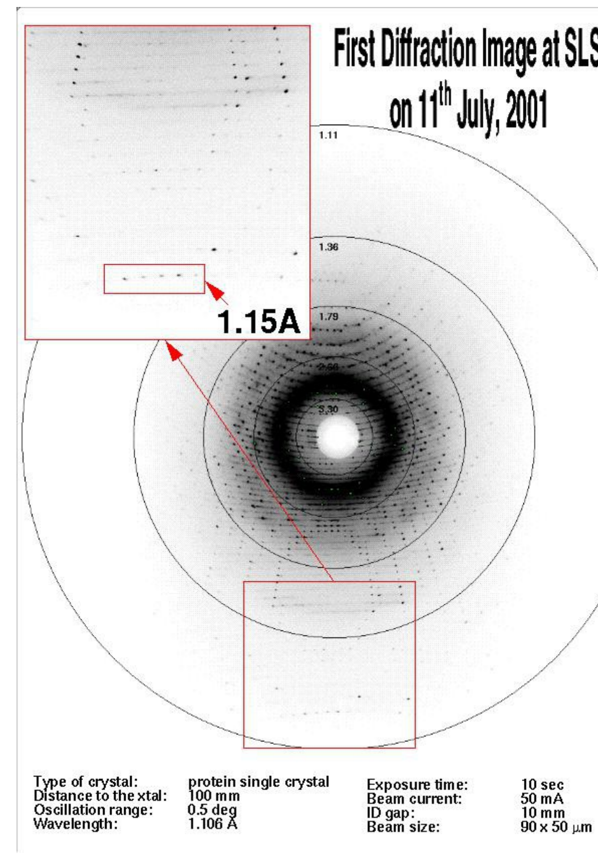




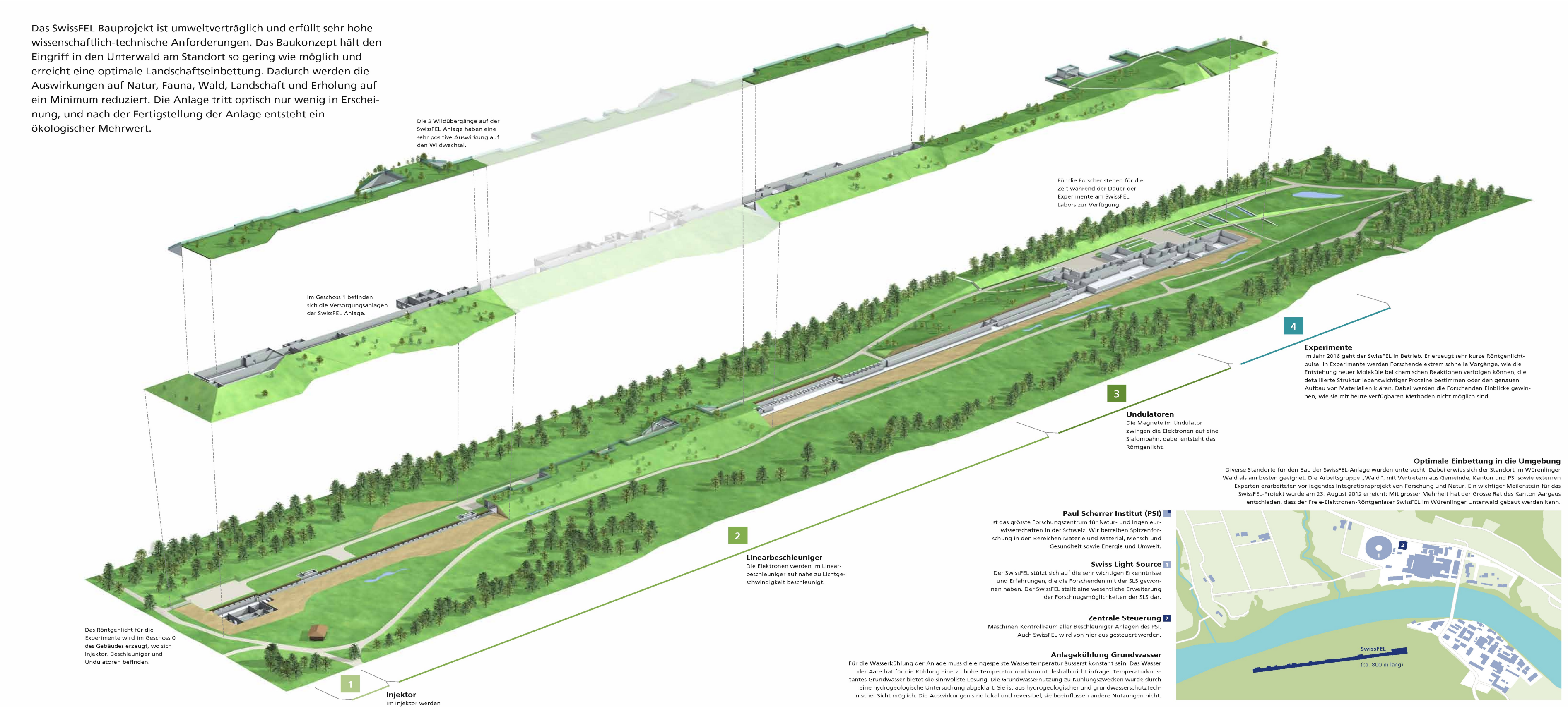
Cern Courier

	1990	First ideas for a **Swiss Light Source**
	1993	Conceptual **Design** Report
June	**1997**	**Approval** by Swiss Government
June	**1999**	Finalization of **Building**
Dec.	**2000**	First **Stored Beam**
June	**2001**	Design current **400 mA** reached **Top up** operation started
July	**2001**	First **experiments**
Jan.	**2005**	**Laser beam slicing "FEMTO"**
May	**2006**	**3 Tesla super bends**
	2010	**~completion: 18 beamlines**
Dec.	**2011**	Vertical emittance record: 1 pm





SwissFEL site



SwissFEL Construction (Oct. 2013)

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SwissFEL Construction (April 2014)

Microbunching

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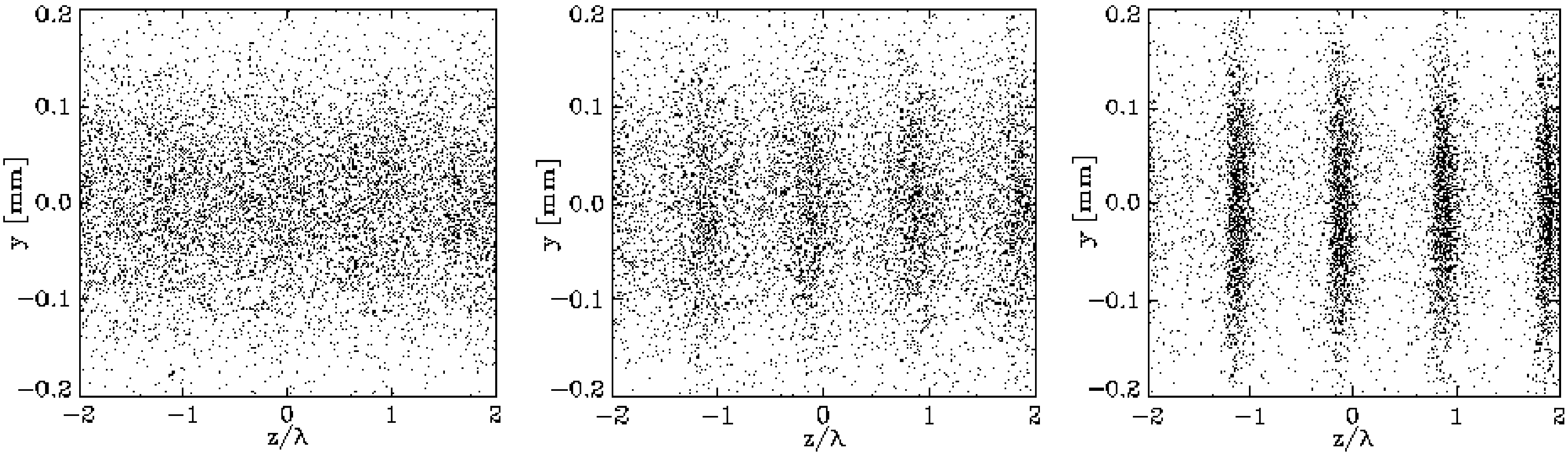
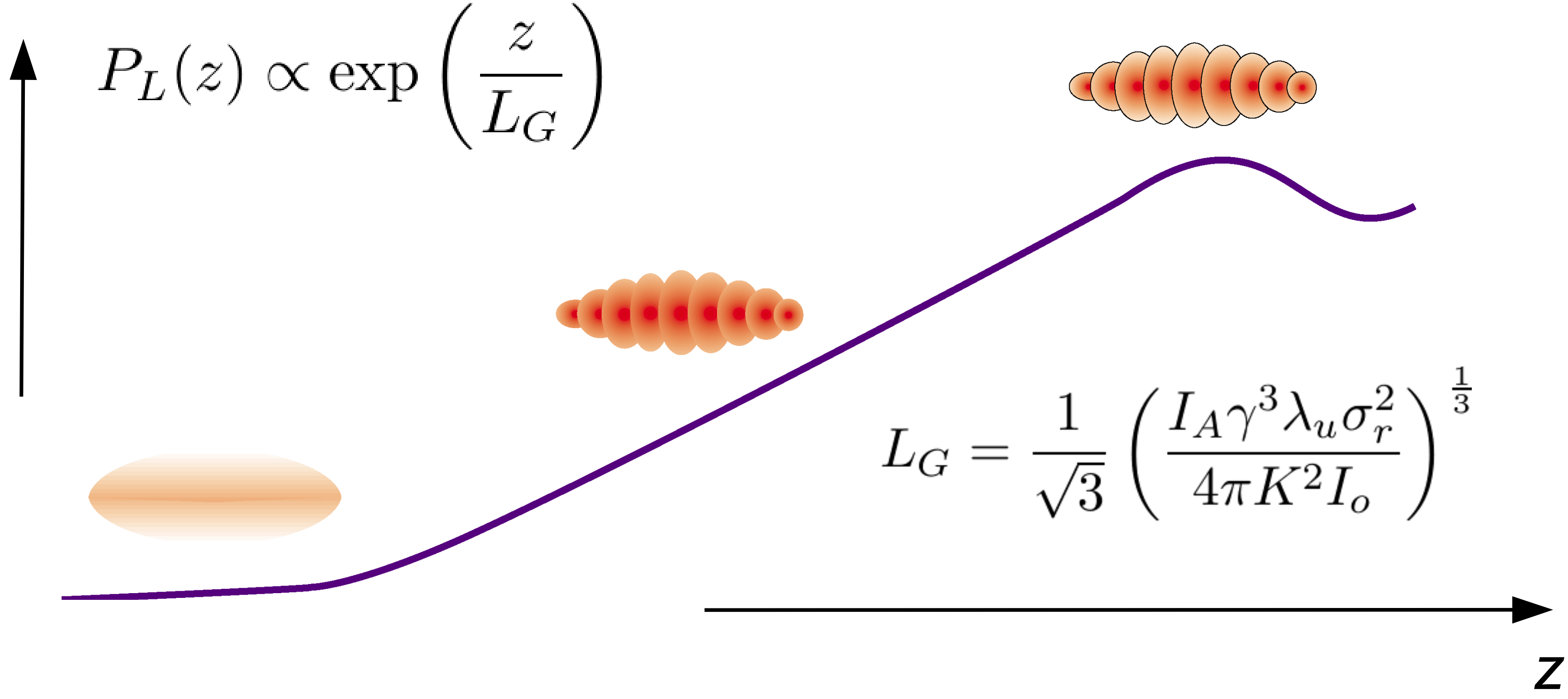


- Interaction with an external (seeding) wave or spontaneous undulator radiation (SASE) gives rise to density modulations along the bunch.
- Coherent emission of radiation of wavelength λ_L with power $P \sim N^2$.
- Increased field strength further amplifies the “micro-bunching”.

Self Amplified Spontaneous Emission (SASE)



$$P_L(z) \propto \exp\left(\frac{z}{L_G}\right)$$

$$L_G = \frac{1}{\sqrt{3}}\left(\frac{I_A \gamma^3 \lambda_u \sigma_r^2}{4\pi K^2 I_o}\right)^{\frac{1}{3}}$$

- During the build-up of the micro-bunch density modulations the output intensity increases exponentially along the undulator
- At some point this process stops. This saturation point should be reached within an acceptable undulator length (SwissFEL: ~60 m)

Comparison to conventional Laser

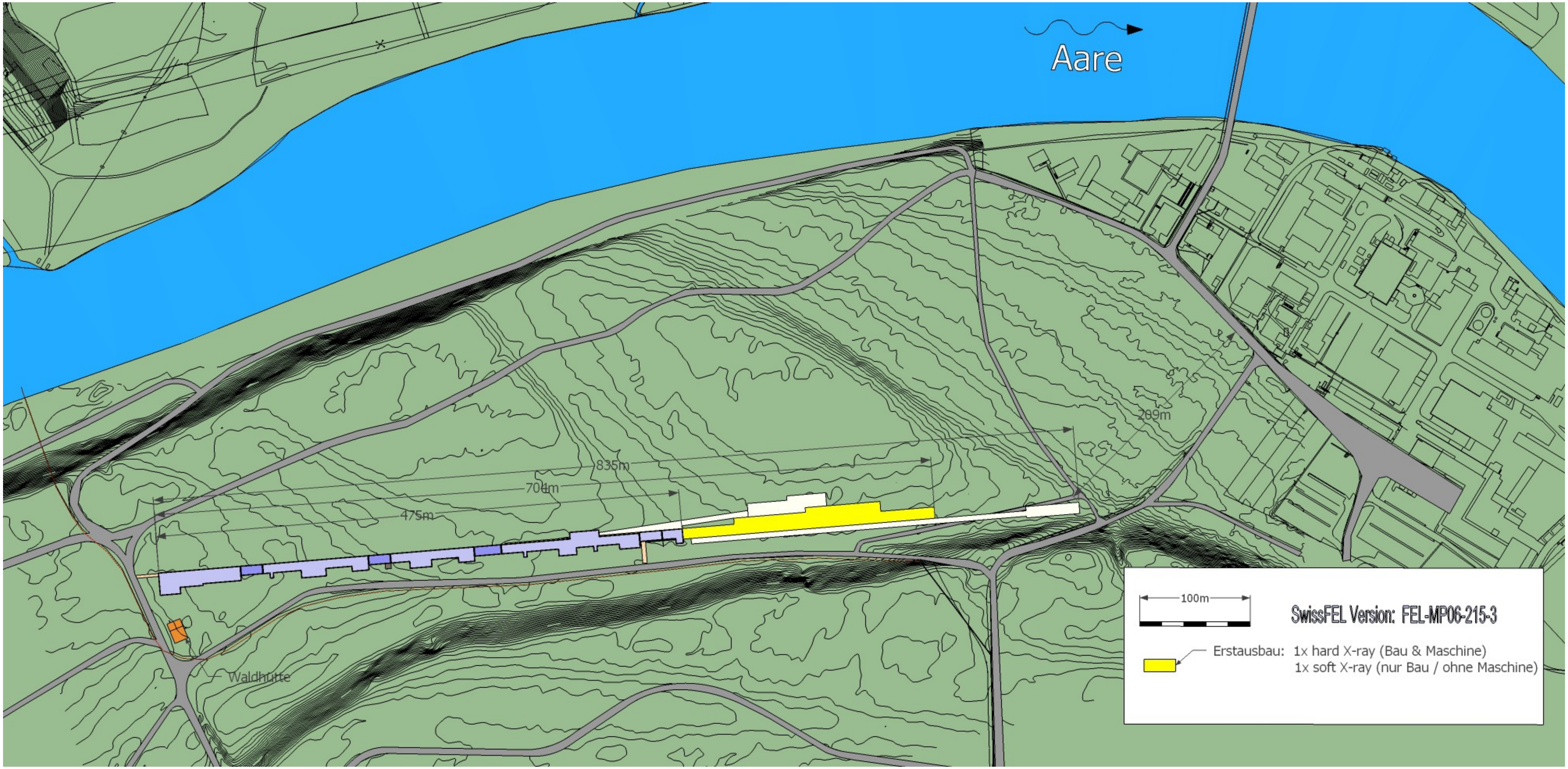
	LASER	FEL
Characteristics	Source of narrow, monochromatic and coherent light beams	
Configuration	Oscillator or amplifier	
First demonstration	1960	1977
Laser medium	Solids, liquids, gases	Vacuum with electron beam in periodic magnetic field
Energy storage	Potential energy of electrons	Kinetic energy of electrons
Energy pump	Light or applied electric current	Electron accelerator
Theoretical basis	Quantum mechanics	Relativistic mechanics and electrodynamics
Wavelength definition	Energy levels of laser medium	Electron energy, magnetic field strength and period

Comparison to conventional light source

	SLS	SwissFEL
Peak brilliance [photons/s/mm²/mrad²/0.1% BW]	10^{21}	10^{33}
Average brilliance [photons/s/mm²/mrad²/0.1% BW]	5×10^{18}	5×10^{22}
Total photon flux	8×10^{20} (around the ring)	2.6×10^{12}
Total photon power	200 kW	5 mW
Fractional energy loss of electrons to photons	100%	0.05%
Average electron current	400 mA	20 nA
Photon pulse length	100 ps	20 fs

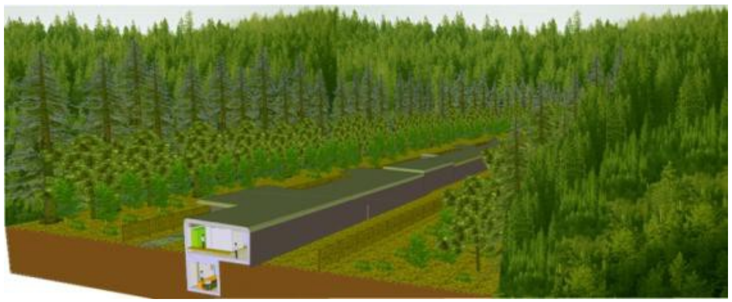
⇒ SwissFEL is a very brilliant photon source, but a poor source in terms of total photon flux!

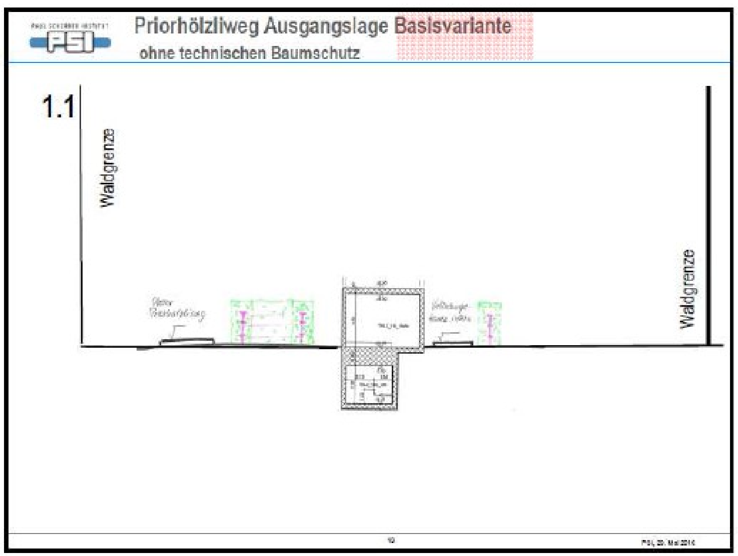
SwissFEL site



Site optimization (task force “forest”)

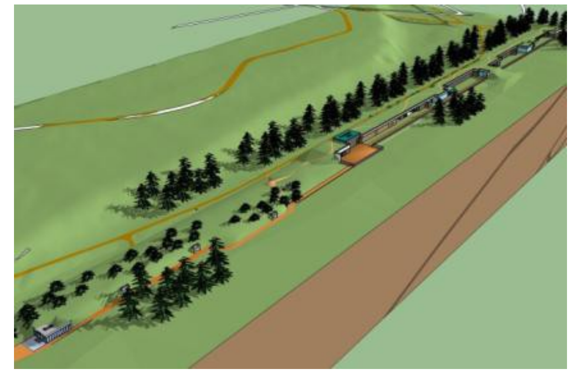
1st Meeting (Jan. 2010)

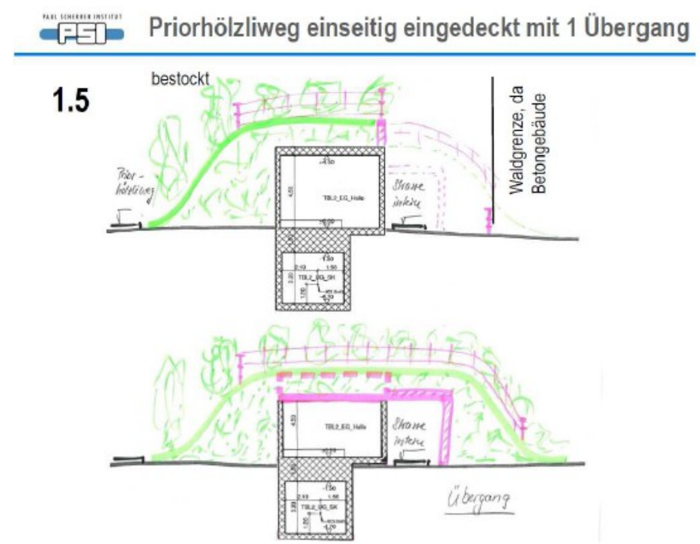




Temporary Forest Clearing	4.6 ha
Permanent Forest Clearing	4.4 ha
Additional Investment	- Mio.

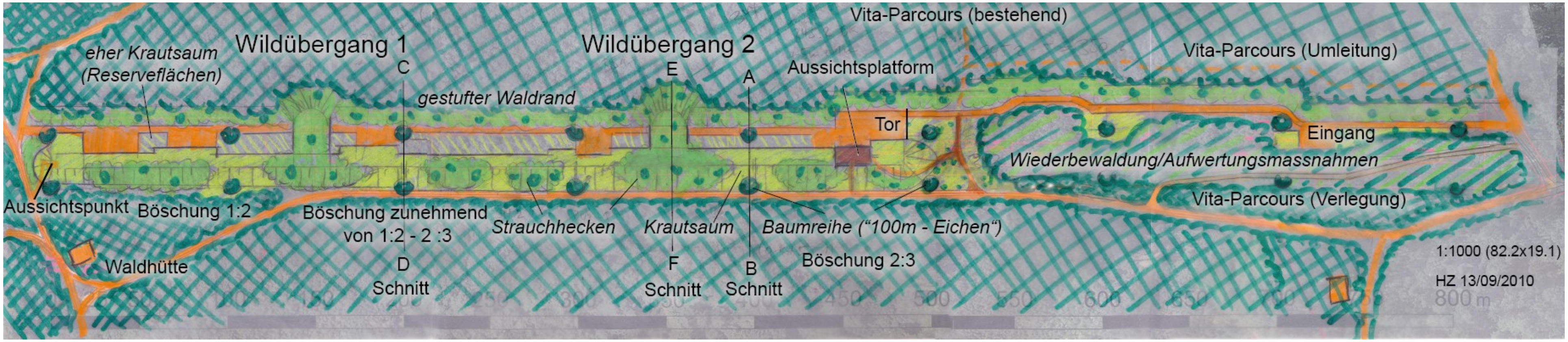
5th Meeting (Sept. 2010)





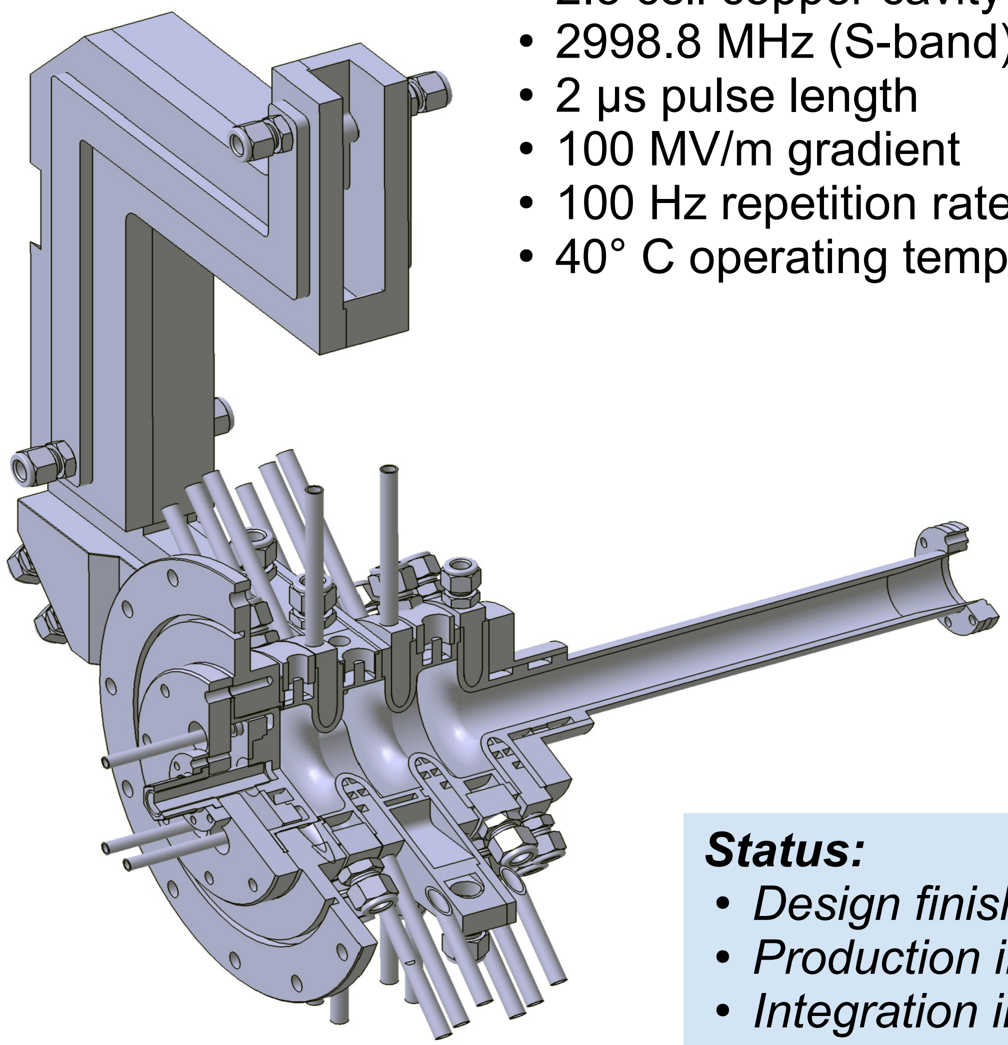
Temporary Forest Clearing	4.2 ha
Permanent Forest Clearing	0.7 ha
Additional Investment	12.1 Mio.

High-Tech – embedded in nature

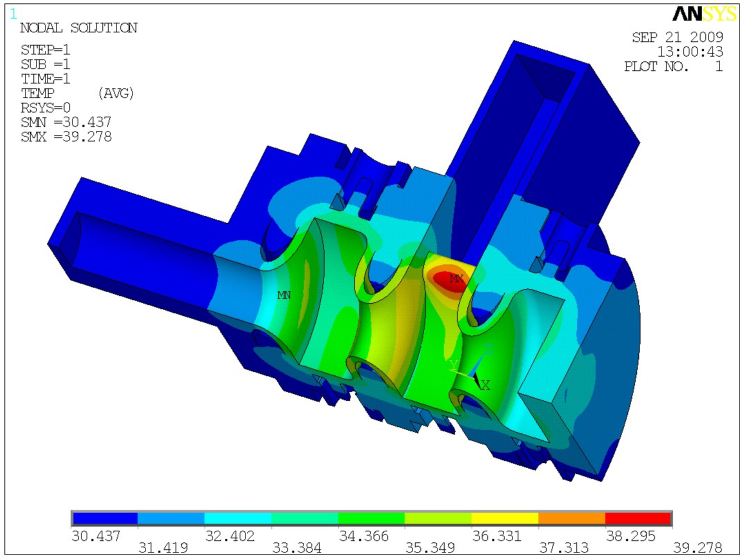


18 October 2013

PSI-developed RF Gun

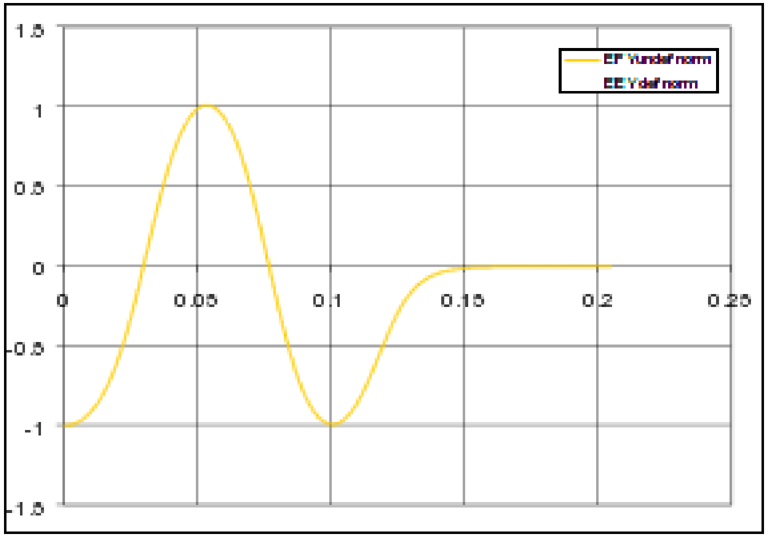


- 2.5 cell copper cavity
- 2998.8 MHz (S-band)
- 2 μs pulse length
- 100 MV/m gradient
- 100 Hz repetition rate
- 40° C operating temperature



Thermal analysis of cavity.

Status:
- *Design finished*
- *Production in 2013*
- *Integration into test facility in 2014*

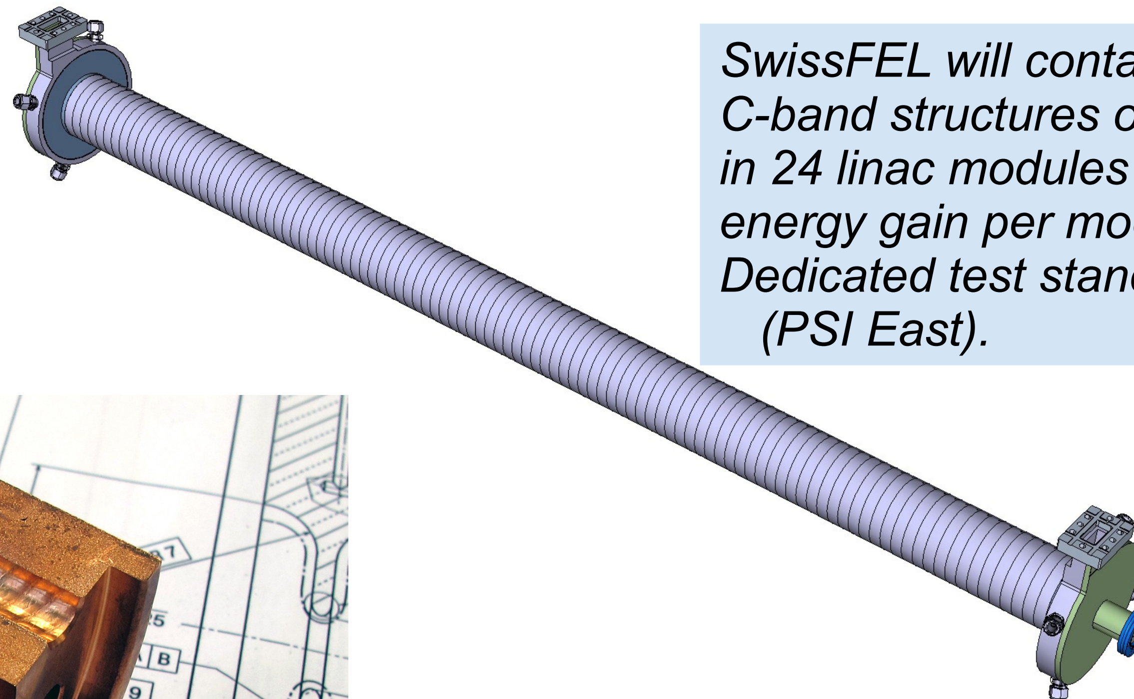


On-axis E-field

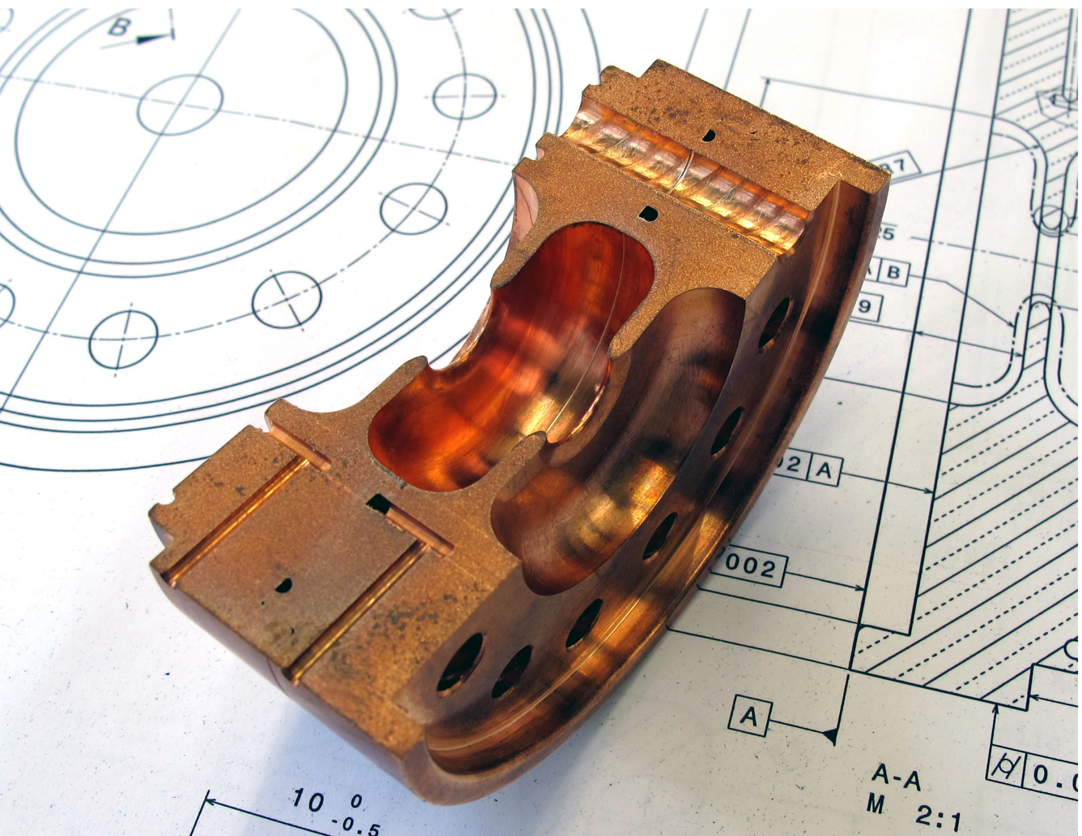
Main Linac: C-band technology

PAUL SCHERRER INSTITUT PSI

- 2050 mm long structure
- 110 cells per structure
- 5712 MHz (C-band)
- 28.8 MV/m gradient

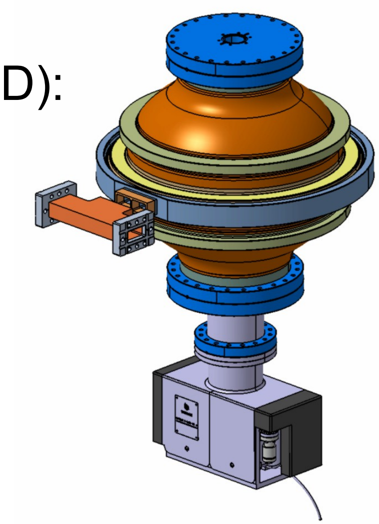


SwissFEL will contain 104 C-band structures organized in 24 linac modules (236 MeV energy gain per module). Dedicated test stand set up (PSI East).



Pulse compressor (SLED):

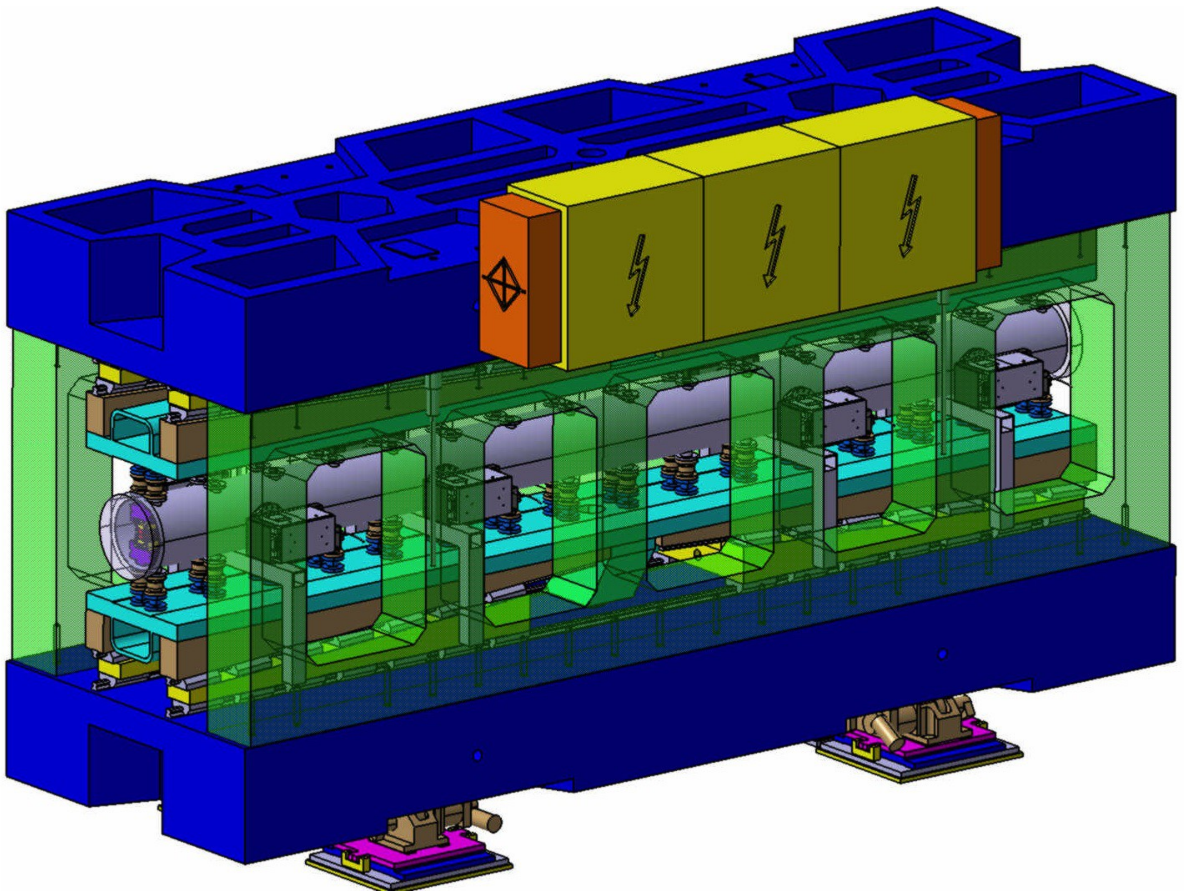
- accumulates the energy of the incoming "long" pulse and releases a short pulse
- 40 MW, 2.5 µs → 120 MW, 0.5 µs
- Q = 220'000



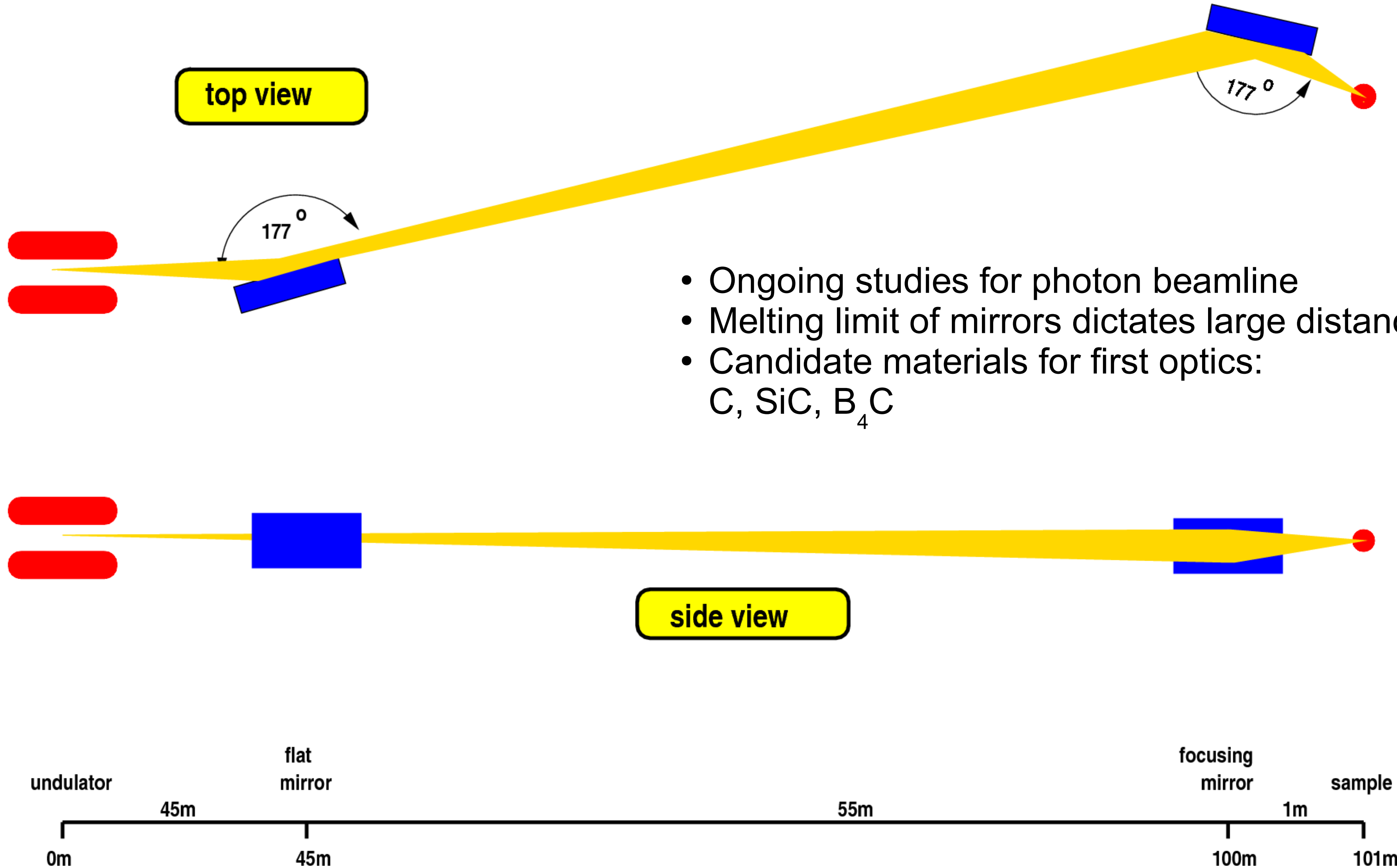
Undulator development (hard X-ray)

- Hybrid in-vacuum undulator
- 266 periods, each 15 mm
- Magnetic length 3990 mm
- Magnetic material:
  $Nd_2Fe_{14}Br$ + diffused Dy
- Gap varies between 3 and 20 mm
- At a gap of 4.2 mm,
  maximum B_z is 1 T

The SwissFEL ARAMIS beamline will comprise 12 undulators of this type. Test of prototype in injector test facility in Jan./Feb.!



Photon beamline (hard X-ray)



- Ongoing studies for photon beamline
- Melting limit of mirrors dictates large distances
- Candidate materials for first optics: C, SiC, B_4C

Photon beamline (soft X-ray)