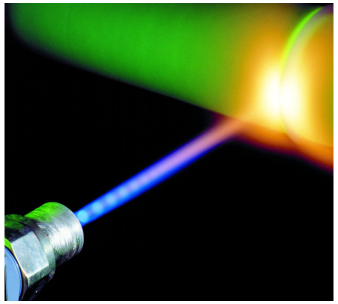
Wir schaffen Wissen – heute für morgen

Paul Scherrer Institute

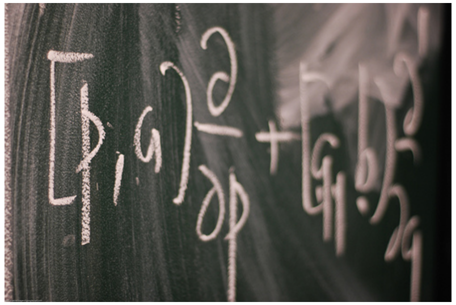
Sven Reiche

SwissFEL – A Compact, National X-ray Free-electron Laser Facility at Paul Scherrer Institute

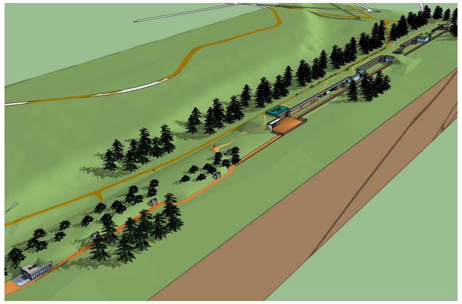
Outline



Free-Electron Lasers as a Scientific Tool



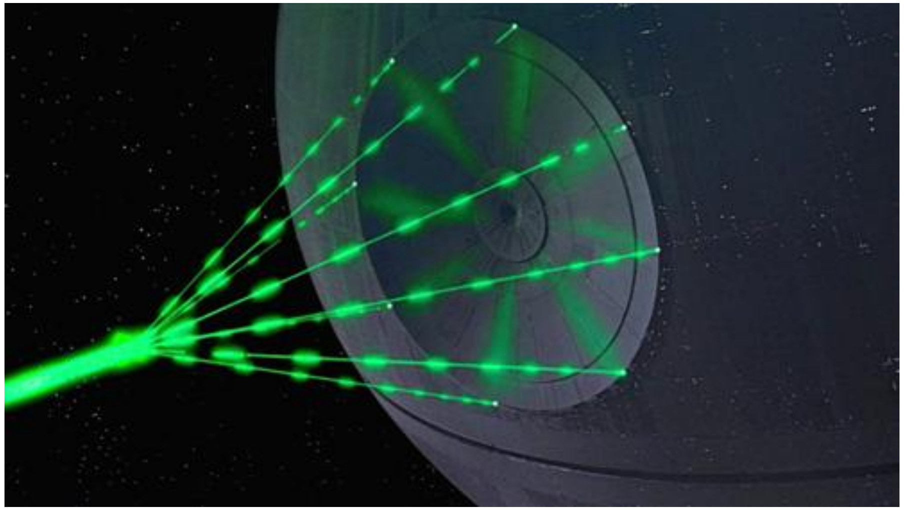
Working Principle of a Free-Electron Laser



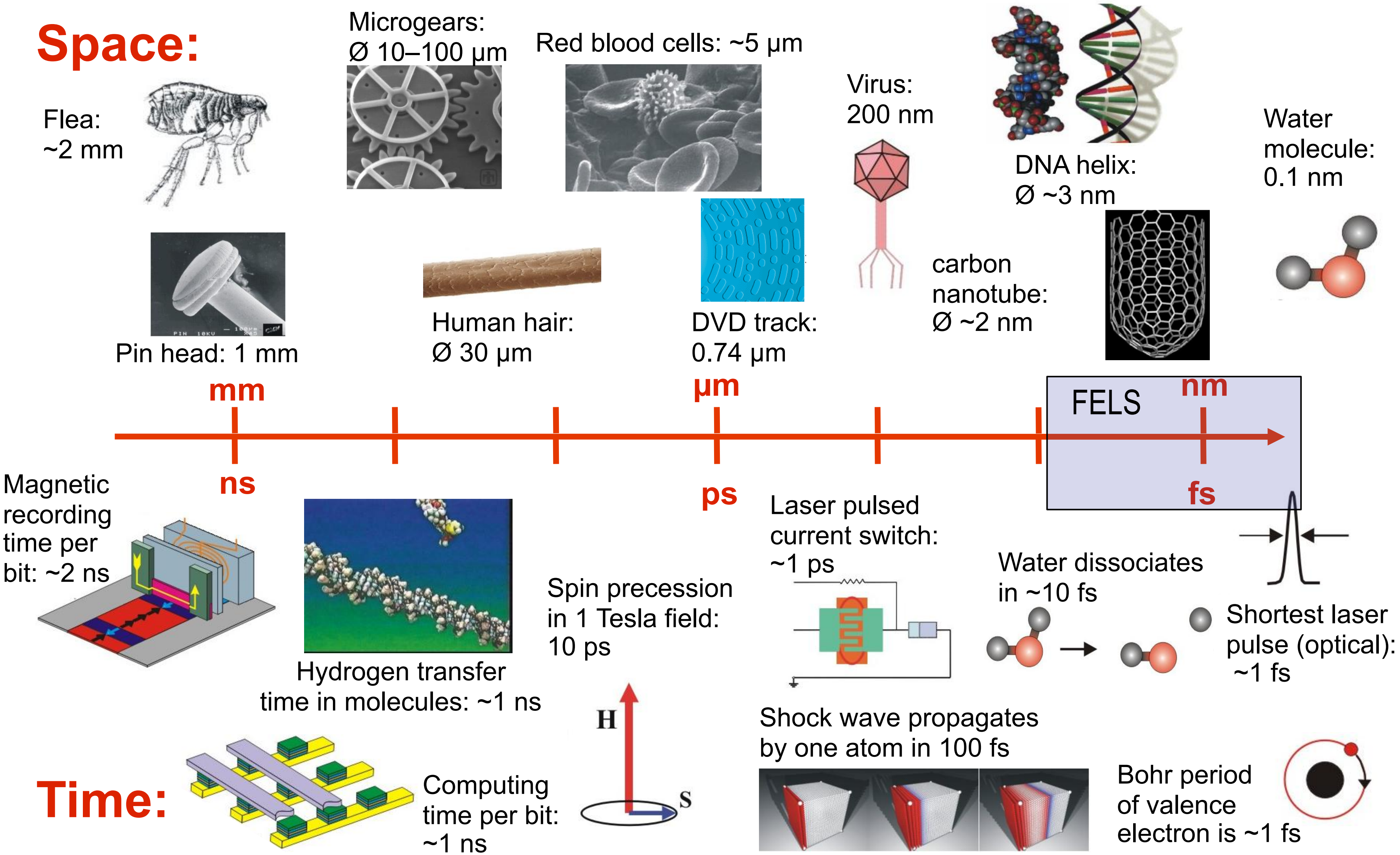
The SwissFEL Project at PSI

The SwissFEL Injector Test Facility

Free-Electron Laser -
A Very Bright Light Source



Exploring the Smallest & Fastest…



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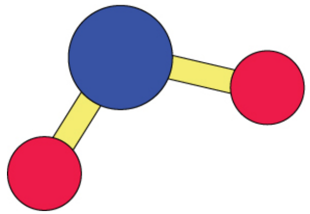
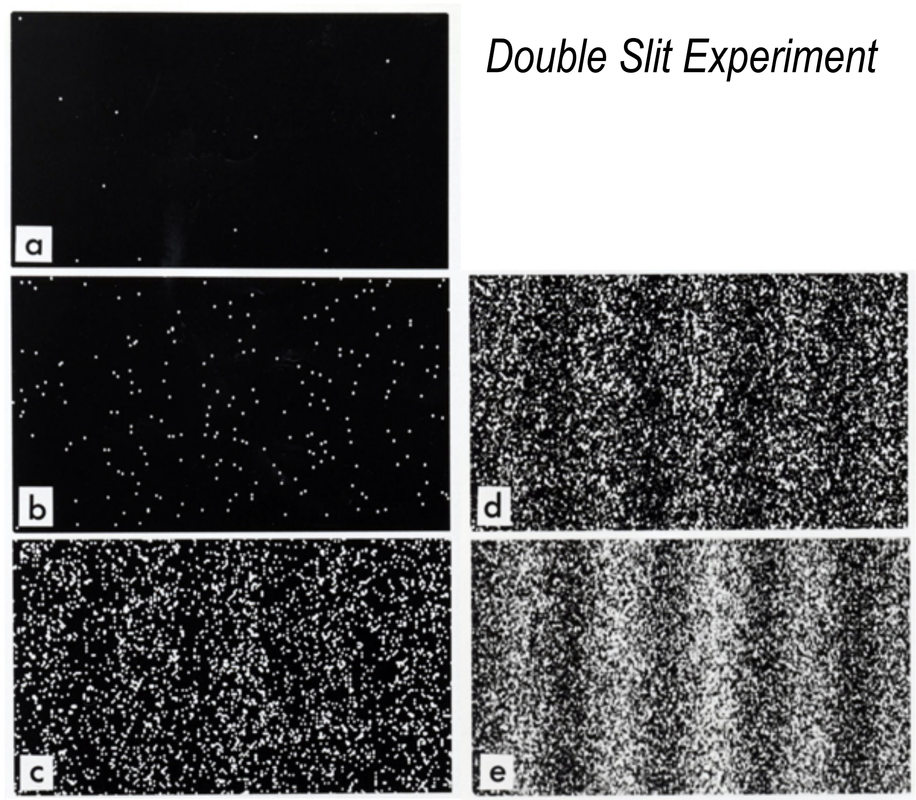
FEL as a Fast, High-Resolution Microscope

X-ray wavelength to resolve atoms



High photon flux to overcome small cross sections

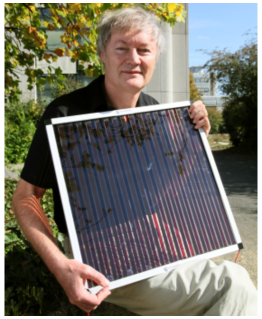


Double Slit Experiment

Femtosecond strobe to resolve atomic motion

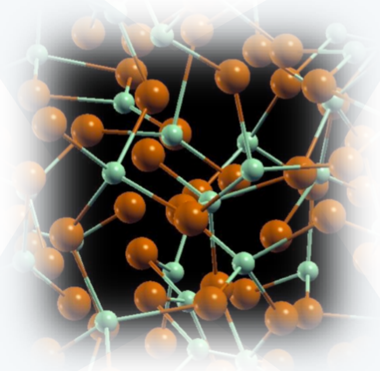
SwissFEL – Deeper Microscopic Insight into Materials

visualize
chemical,
physical, and
biological
processes on the
atomic scale



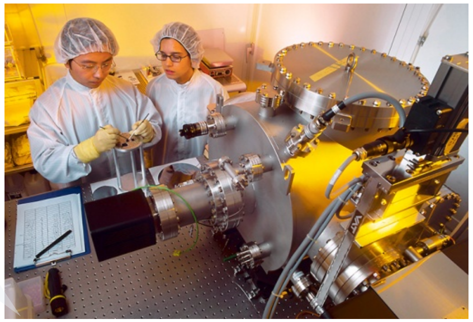
**energy technologies
for a sustainable world**

**environmental systems
and technologies**



in real time

**engineering for
life sciences**

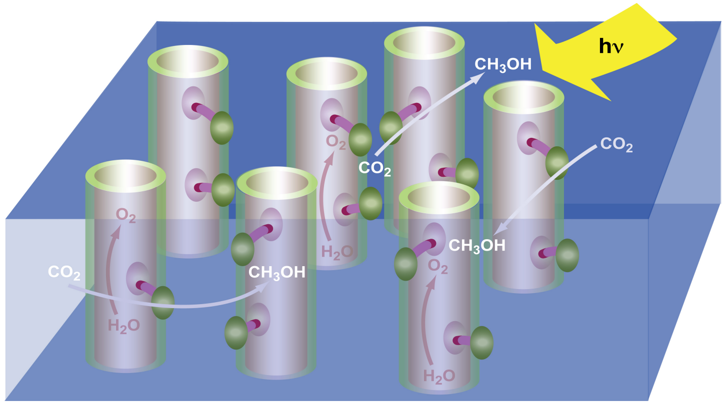


**advanced manufacturing
technologies**

SwissFEL – Key Experiments

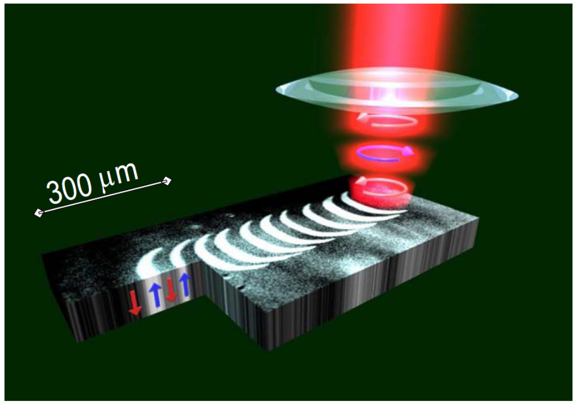
Resolving Catalytic Reaction

CO_2-neutral Artificial Photosynthesis



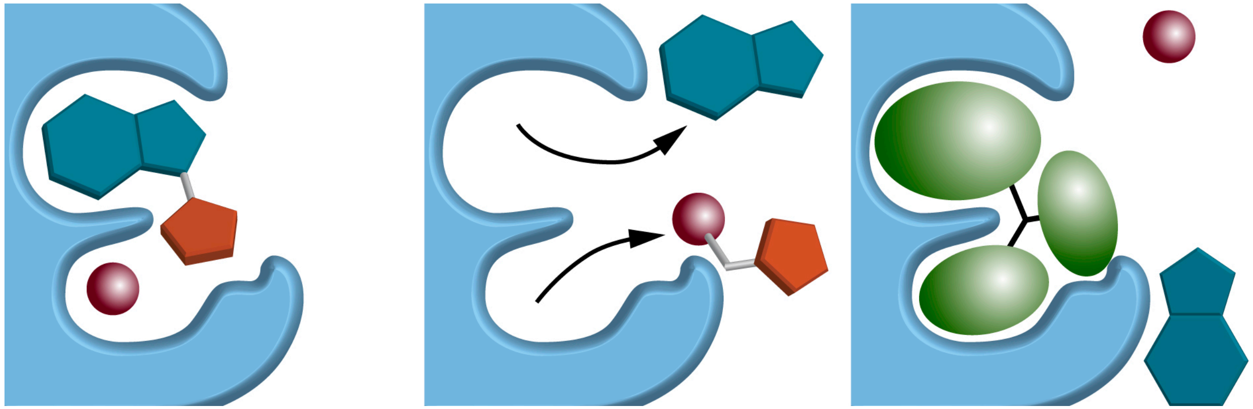
Ultrafast Switching of Magnetic Domains

Faster Media Storage



Membrane Protein Imaging

Tailor-made Medication



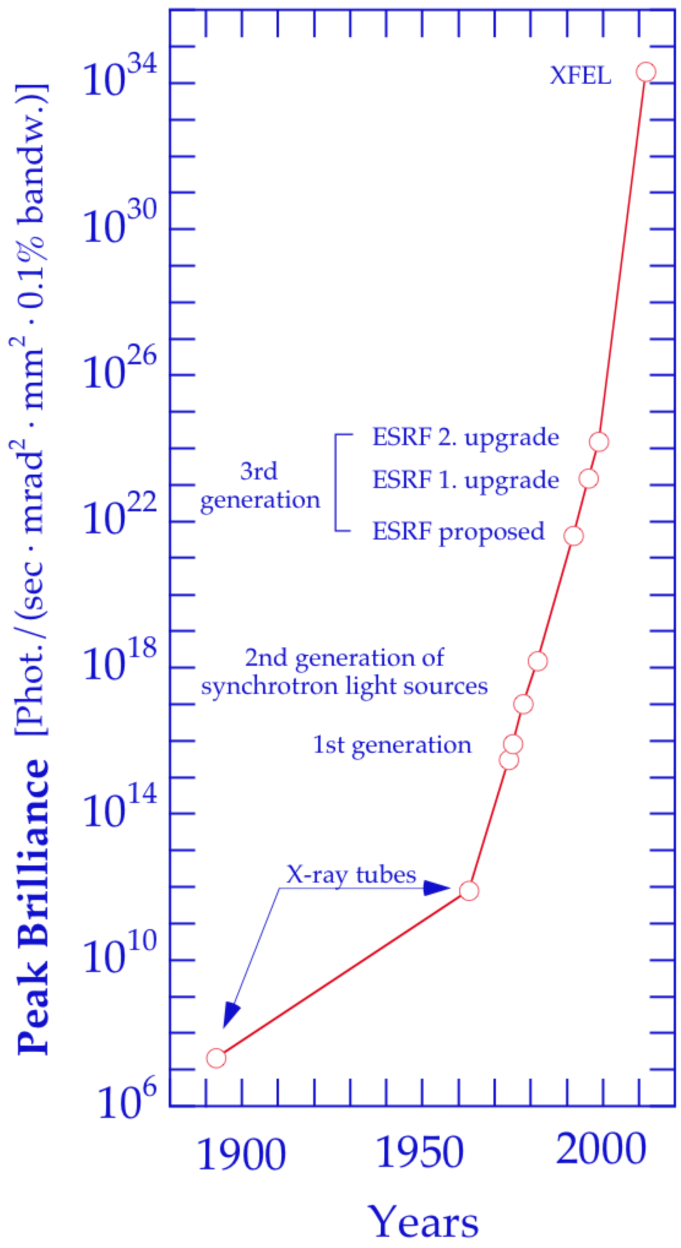
Light Sources

1st Generation: Synchrotron radiation from bending magnets in high energy physics storage rings

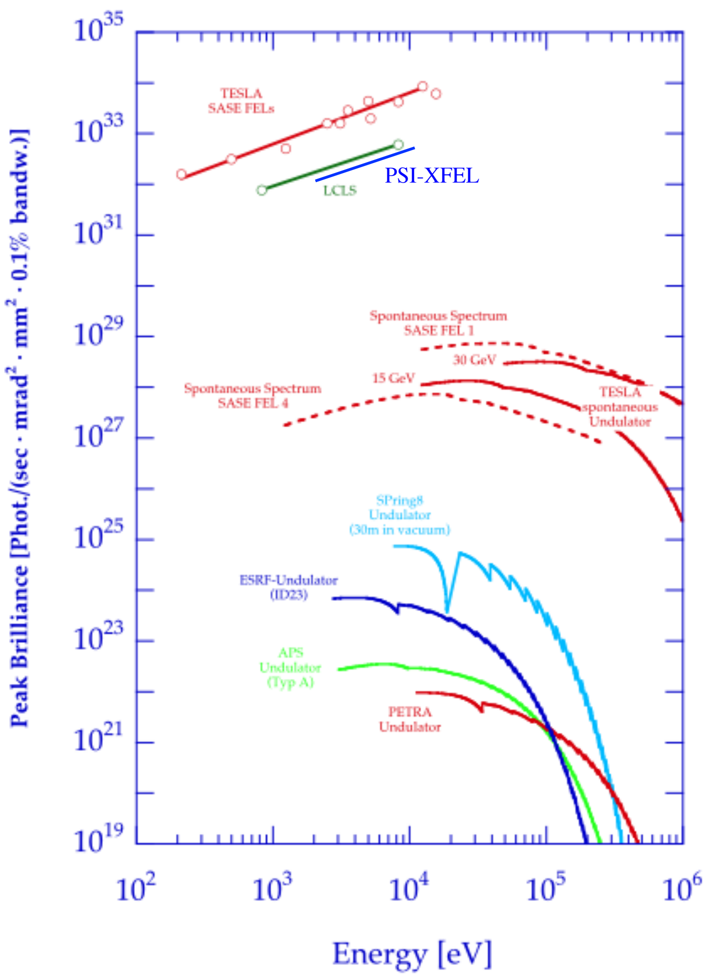
2nd Generation: Dedicated storage rings for synchrotron radiation

3rd Generation: Dedicated storage rings with insertion devices (wigglers/undulators)

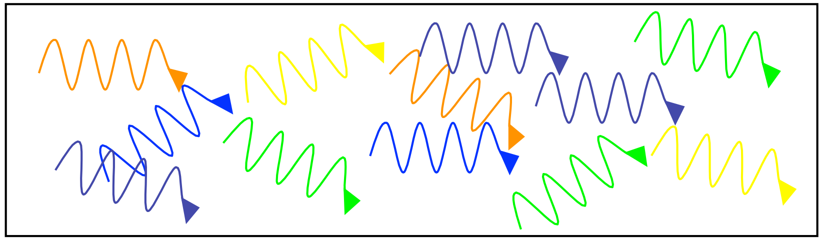
4th Generation: Free-Electron Lasers



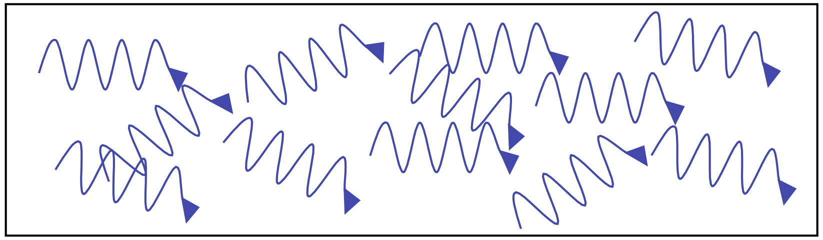
FEL as a Brilliant Light Source



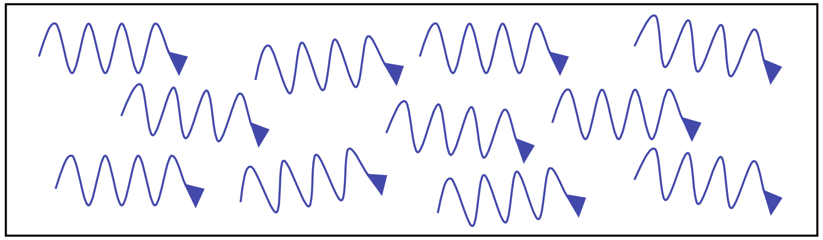
High photon flux



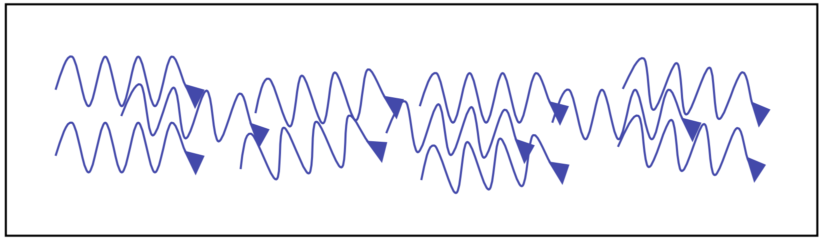
Small freq. bandwidth



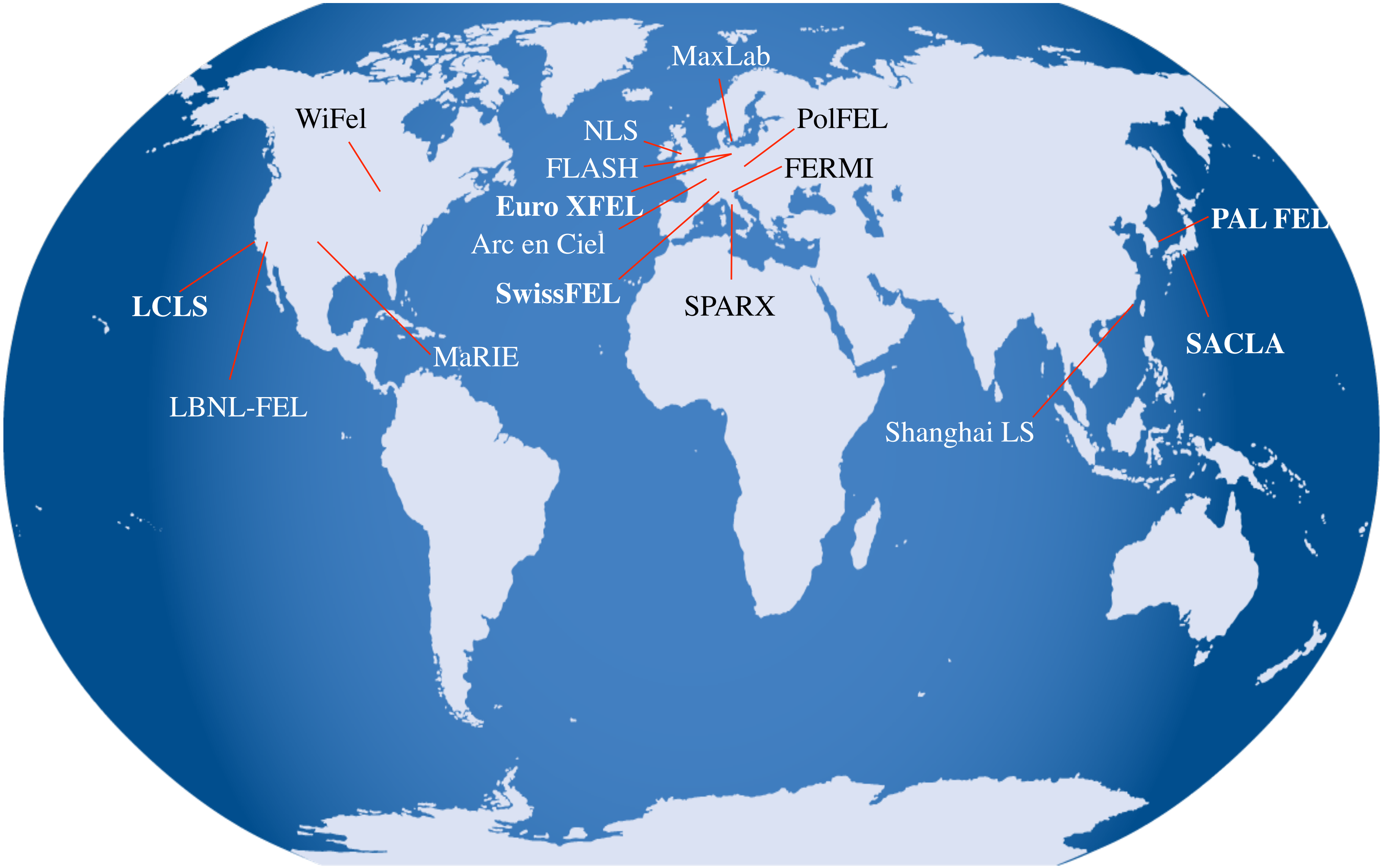
Low divergence



Small source size



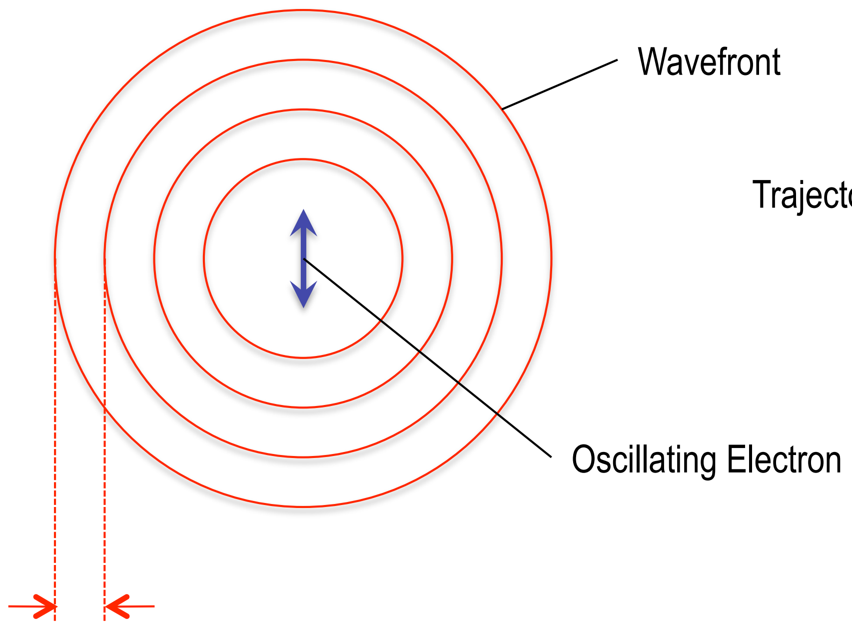
X-ray/VUV FEL Projects Around the World



Free-Electron Laser Theory- A Crash Course

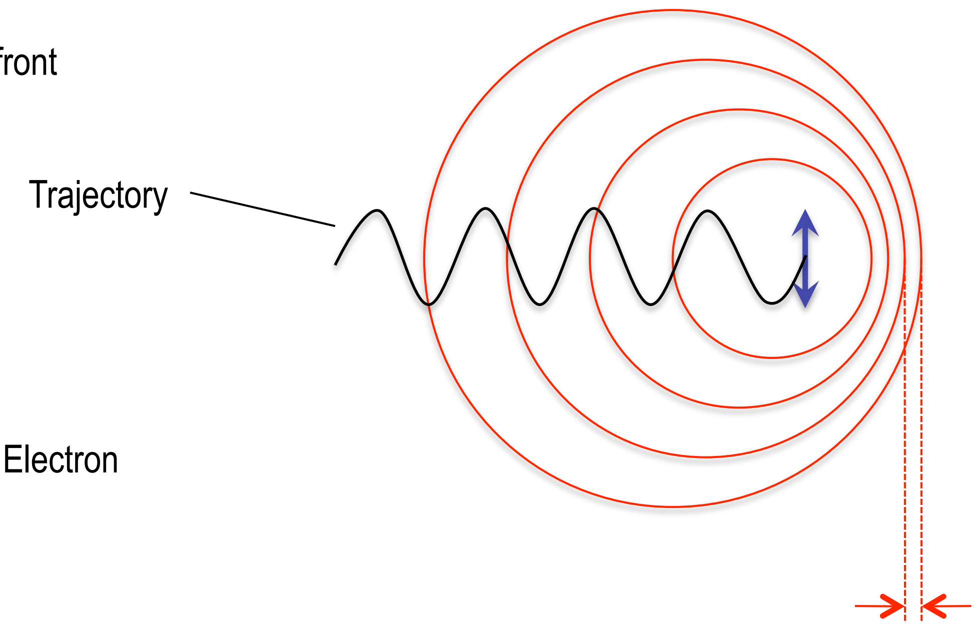
Controlling the Wavelength – The Idea

Dipole Radiation (Antenna)



$$\lambda = c \cdot T$$

Dipole Radiation + Doppler Shift



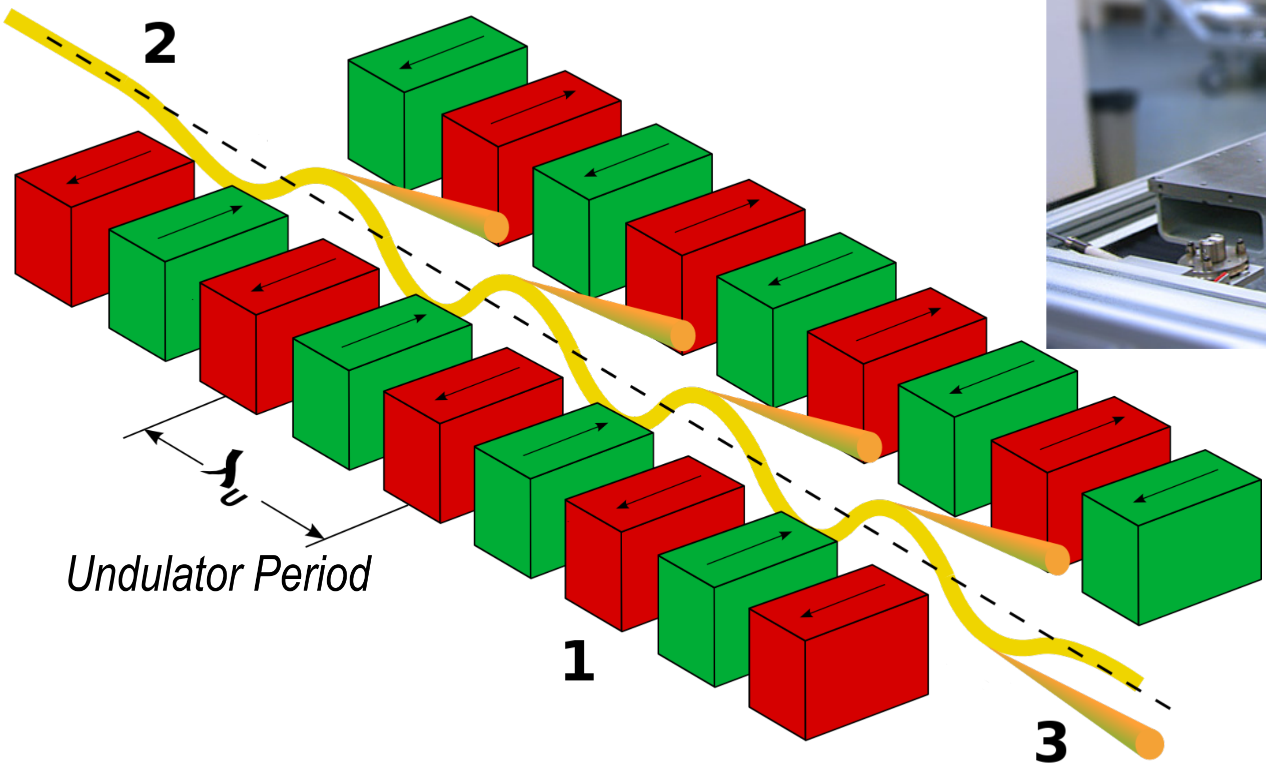
$$\lambda = \left(c - v_z\right) \cdot T$$

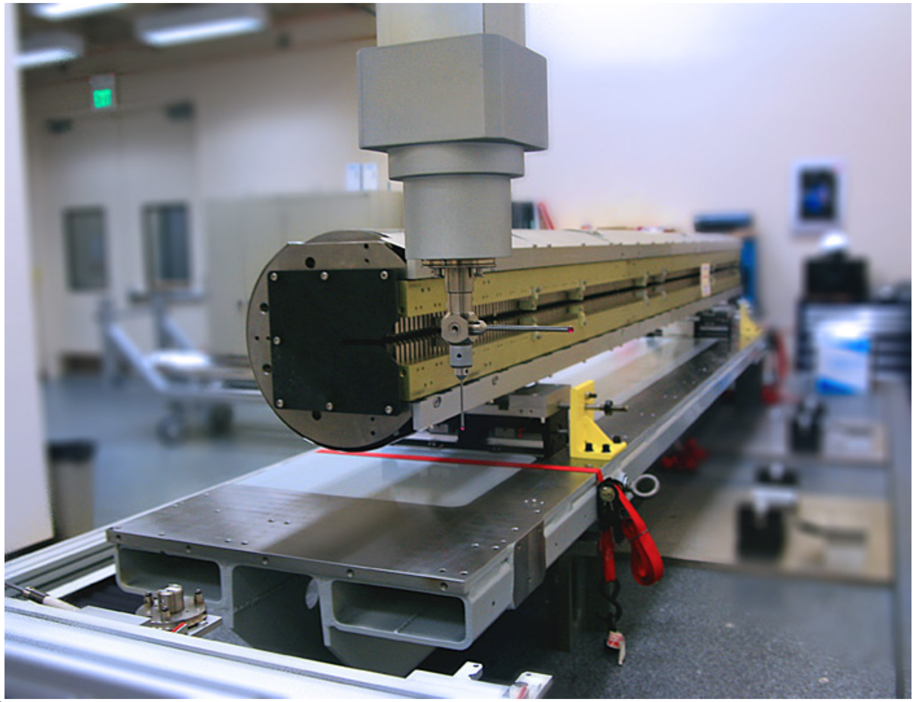
(forward direction)

For relativistic electrons the longitudinal velocity v_z is close to c, resulting in very short wavelength (blue shift of photon energy)

Forcing the Electrons to Wiggle…

… by injecting them into a period field of an wiggler magnet (also often called undulator).





Wiggler module from the LCLS XFEL

Motion in Wiggler (using a magic trick...)

Hamilton Function

$$H = \sqrt{\left(\vec{p} - e\vec{A}\right)^2 c^2 + m^2 c^4}$$

Vector potential of undulator field

$$A_x = \frac{B_0}{k_u}\sin(k_u z) \Leftrightarrow B_y = \partial_z A_x$$

Constants of motion:

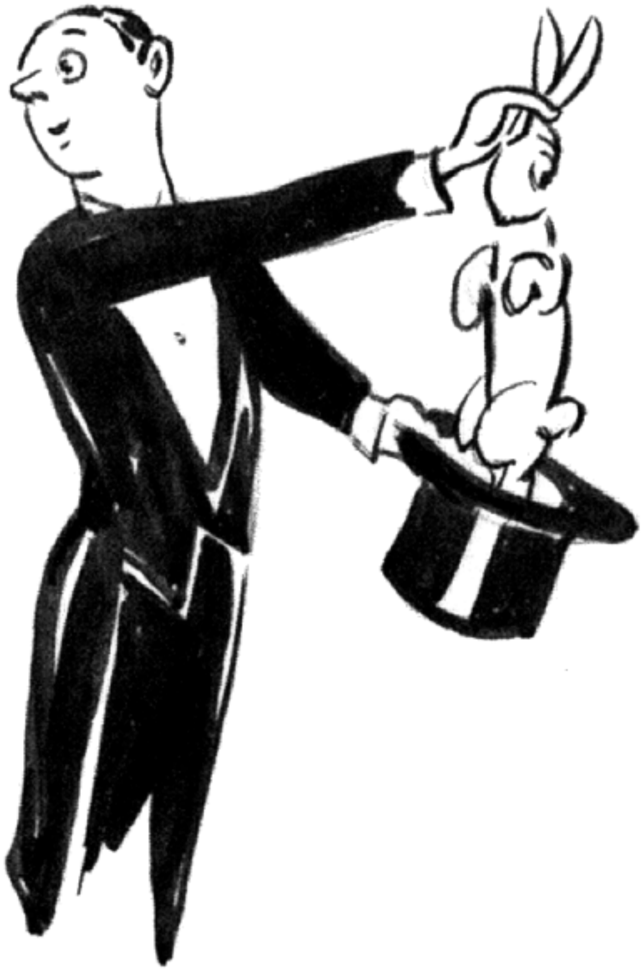
1. Canonical momentum p_x=0 (*H independent of x*)
2. Total energy H=γmc^2 (*H independent of t*)

1.) $p_x = \gamma mc\beta_x + eA_x$ $\Rightarrow$ $\beta_x = -\frac{eB_0}{\gamma mck_u}\sin(k_u z)$

2.) $\frac{1}{\gamma} = \sqrt{1 - \beta_x^2 - \beta_z^2}$ $\Rightarrow$ $\beta_z \approx 1 - \frac{1}{2\gamma^2} - \frac{\beta_x^2}{2}$

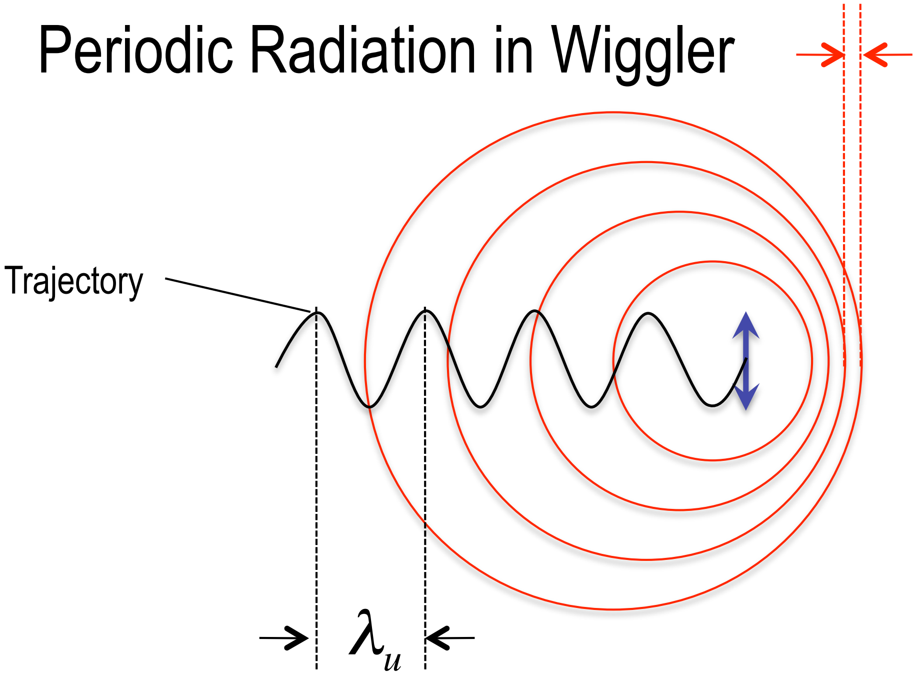
Combining undulator parameters into a constant

$$K = \frac{eB_0}{mck_u} \approx 0.93 \cdot B_0[\mathrm{T}] \cdot \lambda_u[\mathrm{cm}]$$



The FEL Wavelength

Periodic Radiation in Wiggler



$$\lambda = \left(1 - \langle \beta_z \rangle\right) \lambda_u$$

We take the average longitudinal velocity:

$$\langle \beta_z \rangle \approx 1 - \frac{1}{2\gamma^2} - \frac{K^2}{4\gamma^2} \qquad \langle \sin^2(k_u z) \rangle = \frac{1}{2}$$

FEL Wavelength

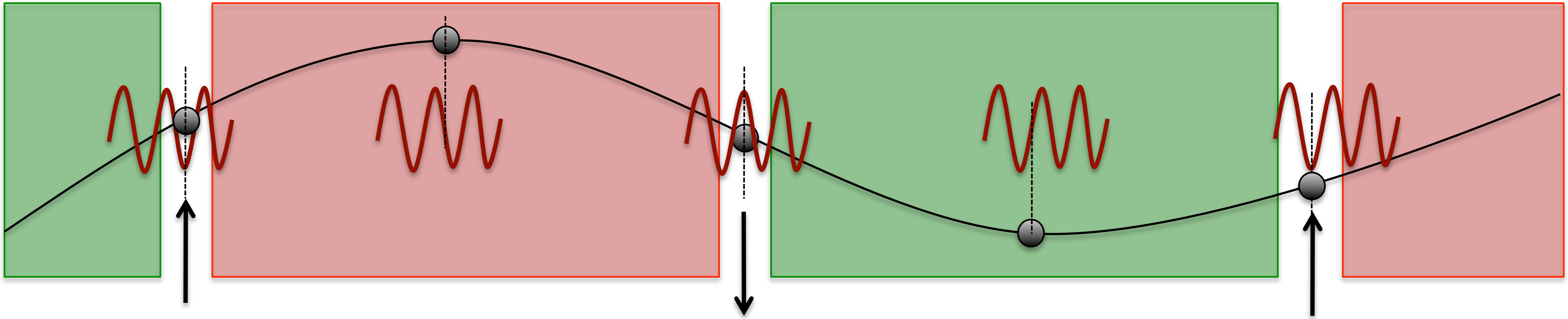
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

SwissFEL Parameters

λ_u	15 mm
K	1.2
E	5.8 GeV
γ	12000
λ	1 Å

Step I : Interaction Electrons with Radiation Field

- The transverse oscillation allows to couple with a co-propagating field
- Depending on electron position and radiation phase the electron either moves with or against radiation field: $d\gamma / dz \propto \beta_x E_x \propto (K/\gamma)\sin(k_u z)\cdot E_0 \exp(ikz - i\omega t + i\phi)$



- After half undulator period:
  - Transverse oscillation has reversed its direction
  - Field has slipped by 180 degree.

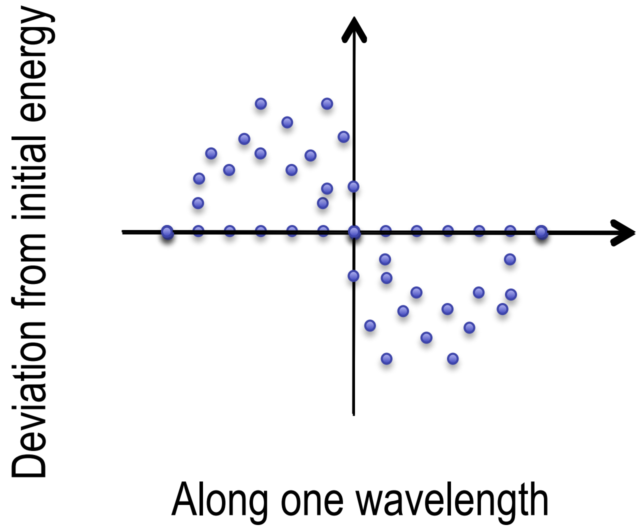
Energy change can be accumulated over many periods

Step II : Bunching

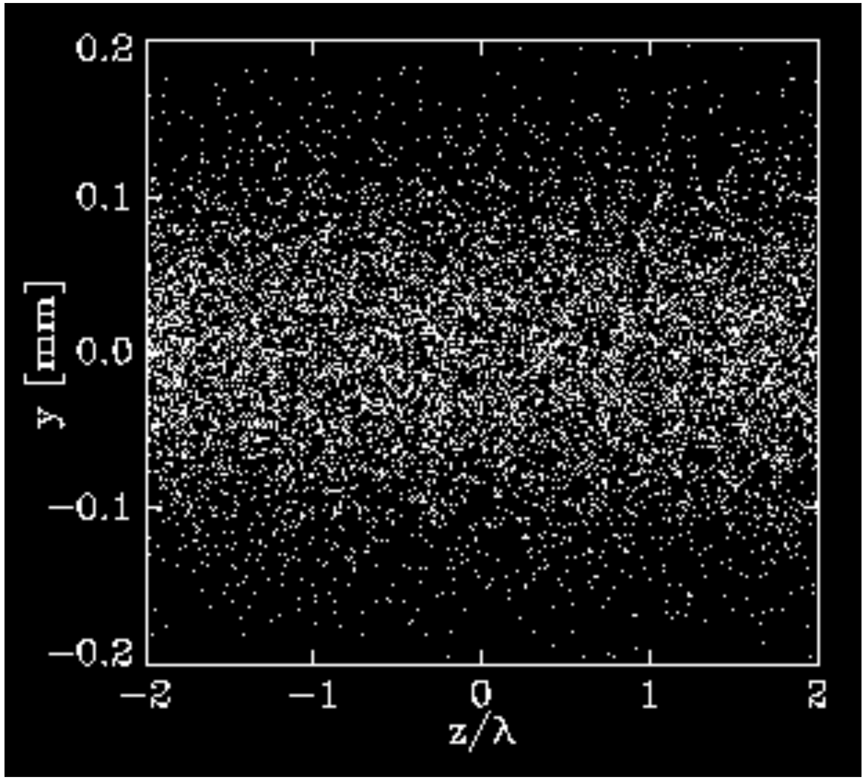
- Energy gets modulated by radiation field over many periods
- Electrons, gaining energy, get faster and move forward with respect to field
- Electrons, loosing energy, are falling back.

Electrons tend to bunch within one wavelength of radiation field

Longitudinal Phasespace



Physical Space



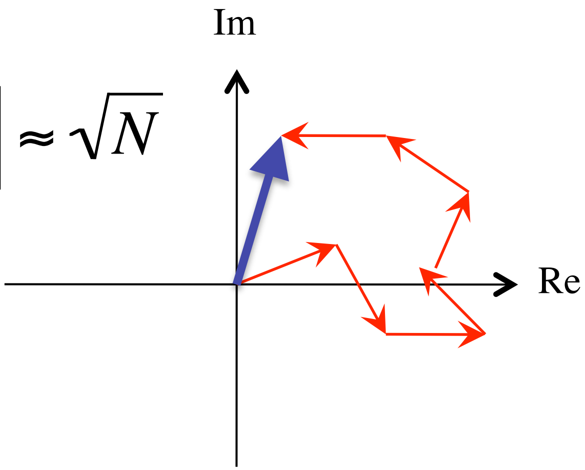
Step III : Coherent Emission

- The electrons are spread out over the bunch length with its longitudinal position δz_j.
- The position adds a phase $\phi_j = k\delta z_j$ to the emission of the photon.

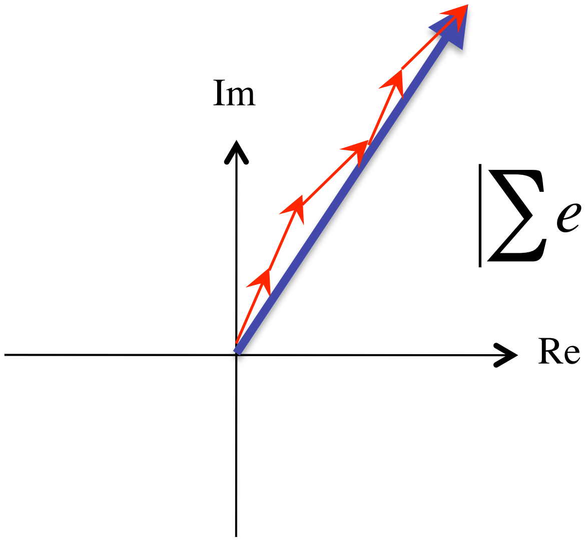
$$E(t) \propto \sum_j e^{i(kz_j - \omega t)} = e^{i(k\langle z\rangle - \omega t)} \cdot \sum_j e^{ik\delta z_j}$$

Electrons spread over wavelength:
Phasor sum = random walk in 2D

$$\left|\sum e^{i\phi}\right| \approx \sqrt{N}$$



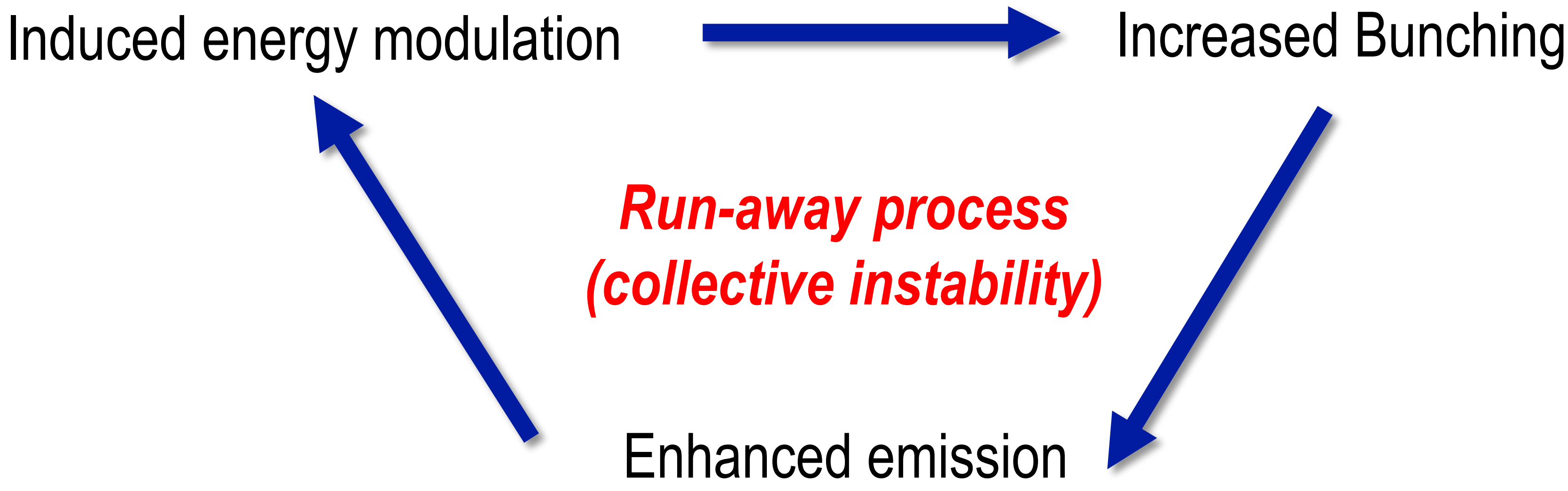
Electrons bunched within wavelength:
Phasor sum = Add up in same direction



$$\left|\sum e^{i\phi}\right| \approx N$$

Power ~ $|E|^2$ -> Possible Enhancement: N

The FEL Process



The FEL process is an exponential run-away process

The coupling strength (and thus the quality of the FEL) is given by the FEL Parameter

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

Typical values for X-ray FEL: 10^{-3}-10^{-4}

FEL benefits from high current and small beam sizes

(I: Current, σ_x: Beam Size, I_A~17 kA, f_c ~0.8)

SwissFEL
A Compact X-ray Facility

Optimizing the FEL (Namely Brilliance)

Photon Brilliance

$$B = \frac{\#\ photons}{\Delta T \cdot \Delta\omega/\omega \cdot \Delta x \cdot \Delta x' \cdot \Delta y \cdot \Delta y'}$$

Fourier Limited ($\Delta T \cdot \Delta\omega/\omega$): $\sim\lambda$

Diffraction Limited ($\Delta x \cdot \Delta x' \cdot \Delta y \cdot \Delta y'$): $\sim\lambda^2$

Electron Brilliance

$$B = \frac{Q}{\Delta T \cdot \Delta E/E \cdot \varepsilon_x \cdot \varepsilon_y}$$

Quantum Limit

$$\left(\geq \frac{Q}{2e\hbar^3}\right)$$

FEL Process converts electron brightness into photon brightness

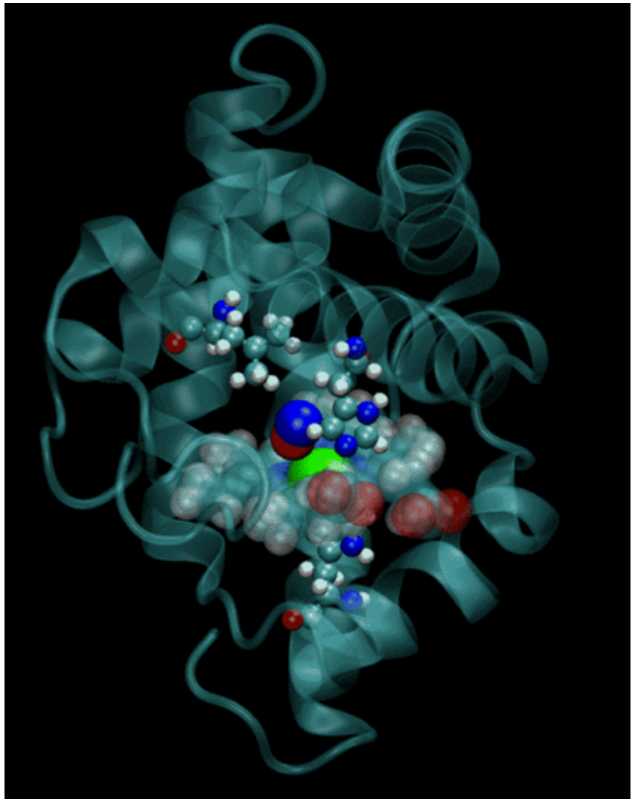
Electron brightness can be much smaller but needs only to be smaller than photon brightness:

$$\Rightarrow \quad N_{ph} E_{ph} / \Delta T \approx \rho N_e E_e / \Delta T \qquad \frac{\Delta E}{E} < \rho \qquad \frac{\varepsilon_N}{\gamma} < \frac{\lambda}{4\pi}$$

High Current — Low Energy Spread — Low Emittance

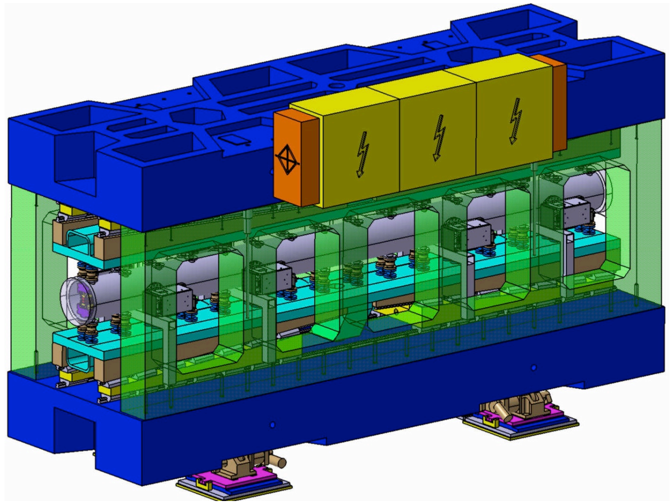
SwissFEL Design Strategy

1) Reaching 1 Ångstrom Wavelength for Atomic Resolution



2) Compact Undulator to lower Beam Energy

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



→ E ~ 6 GeV

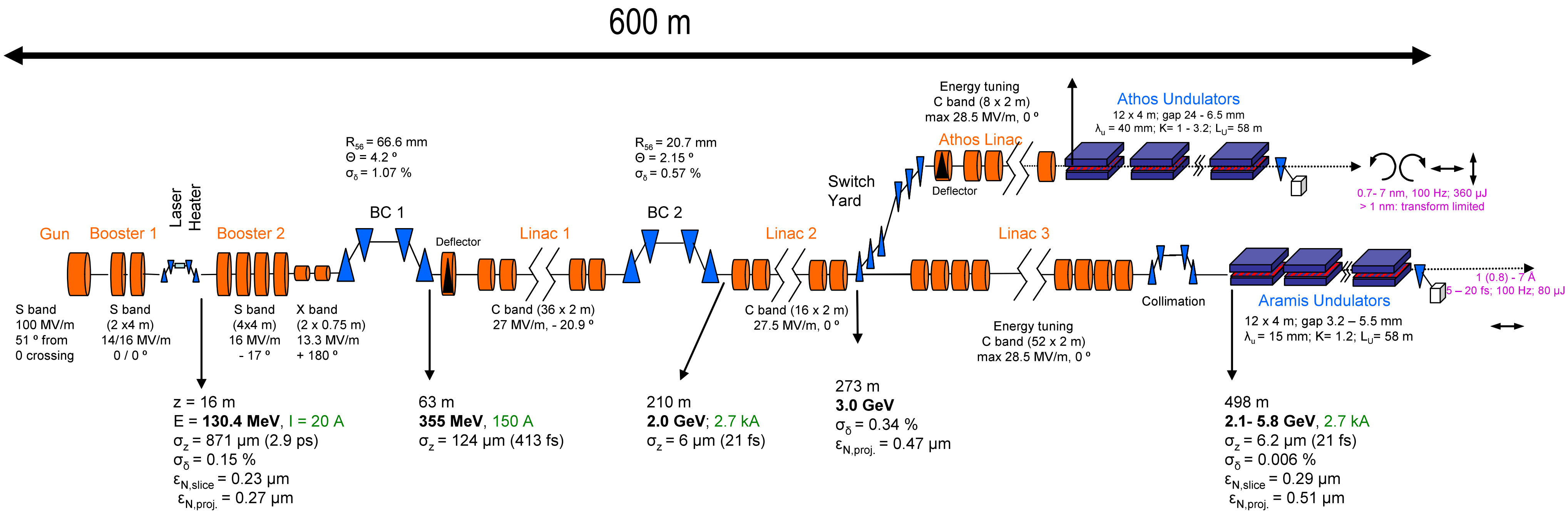
3) Low emittance electron beam source

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

→ ε_n ~ 0.3 mm mrad

4) Efficient beam generation, acceleration and compression

Layout SwissFEL

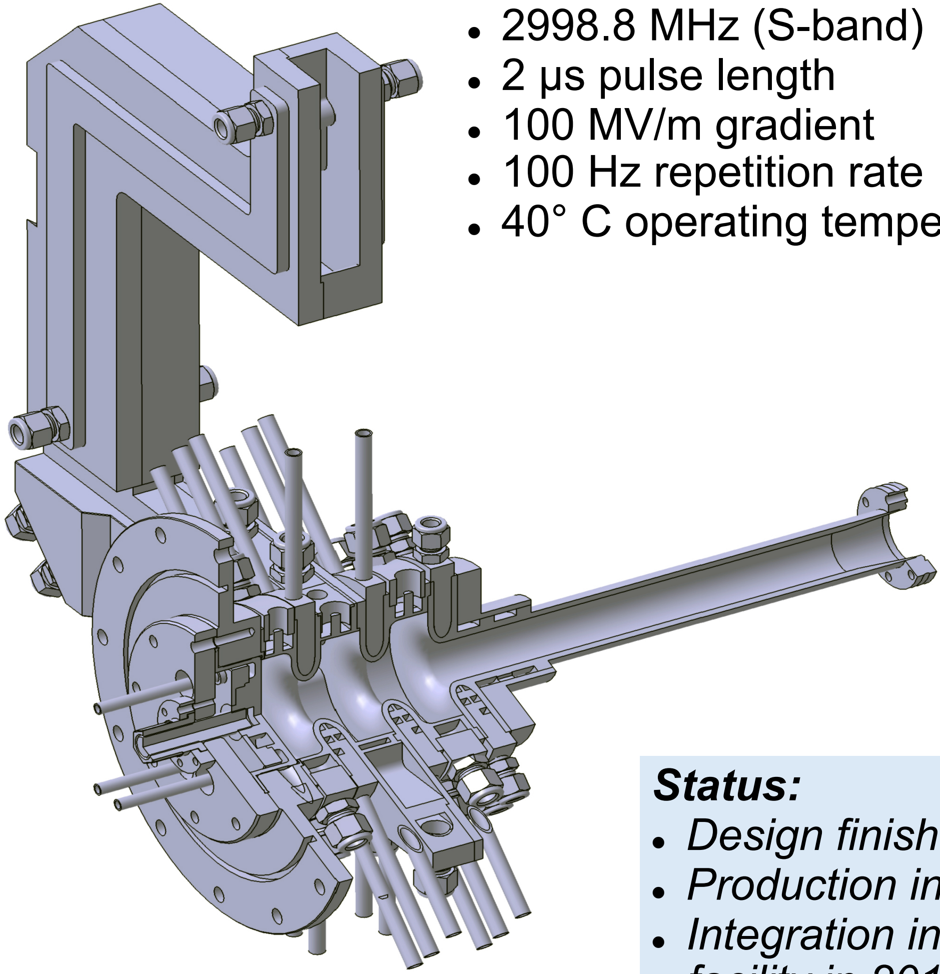


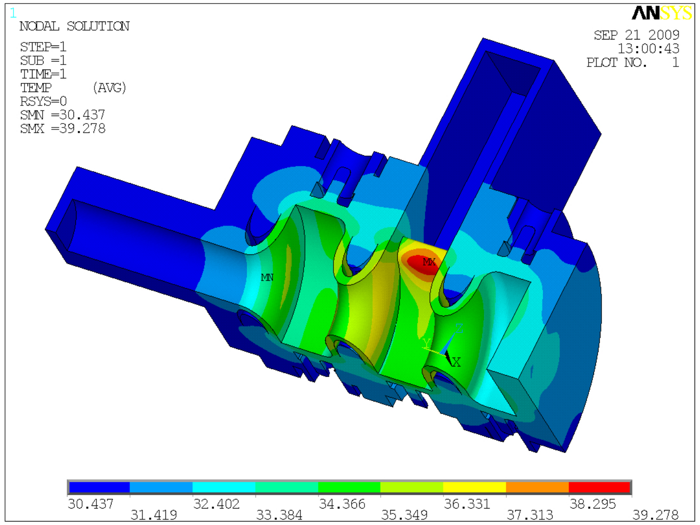
Technology choice:

- RF photo-electron gun (2.5 cell), S-band
- 2 Stage compression at highest energy possible to minimize RF tolerances
- C-band linac (less RF stations, real estate and mains power than S-band, chirp removal after BC 2)
- X-band for linearizing phase space before BC 1
- 2 bunch operation (28 ns) with distribution to Aramis and Athos at 100 Hz
- Laser Heater to mitigate microbunch instability

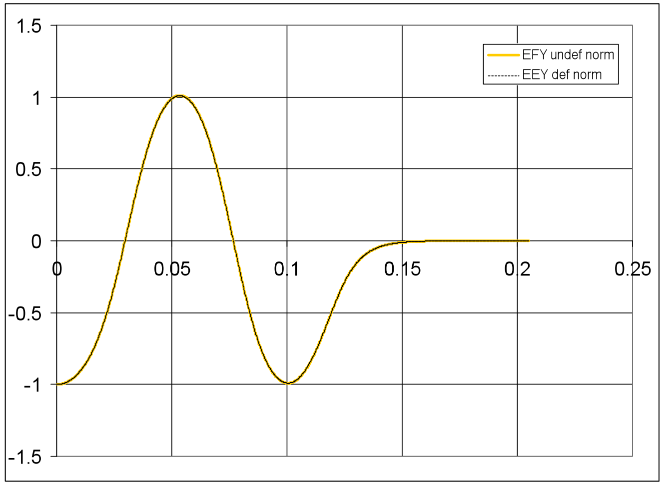
PSI-developed RF Gun

- 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.



On-axis E-field

Status:
- *Design finished*
- *Production in 2011*
- *Integration into test facility in 2012*

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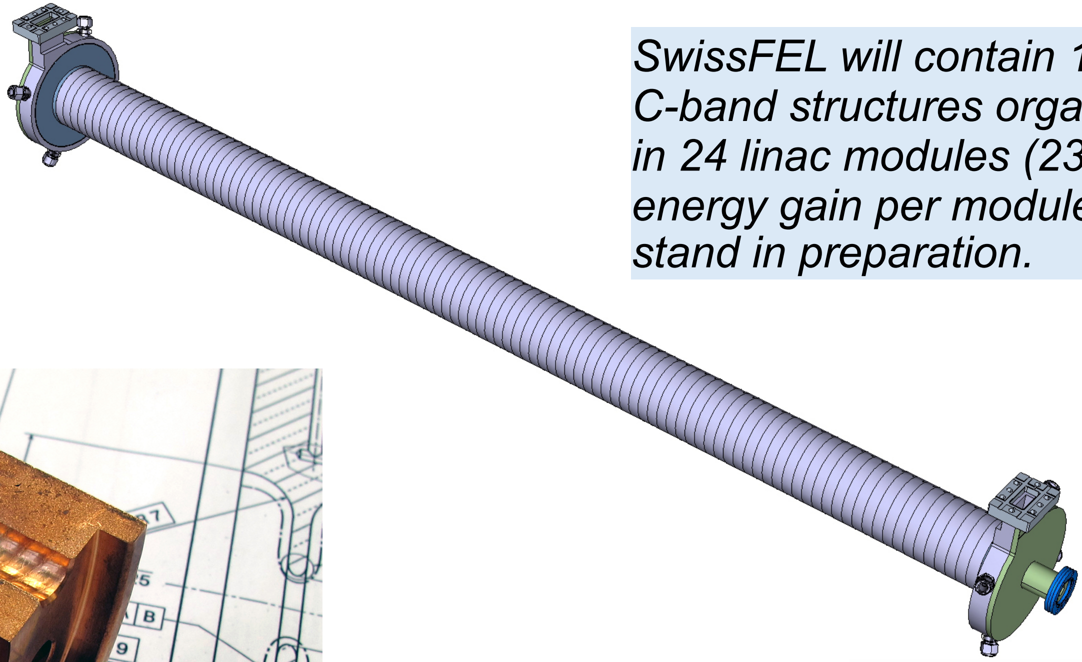
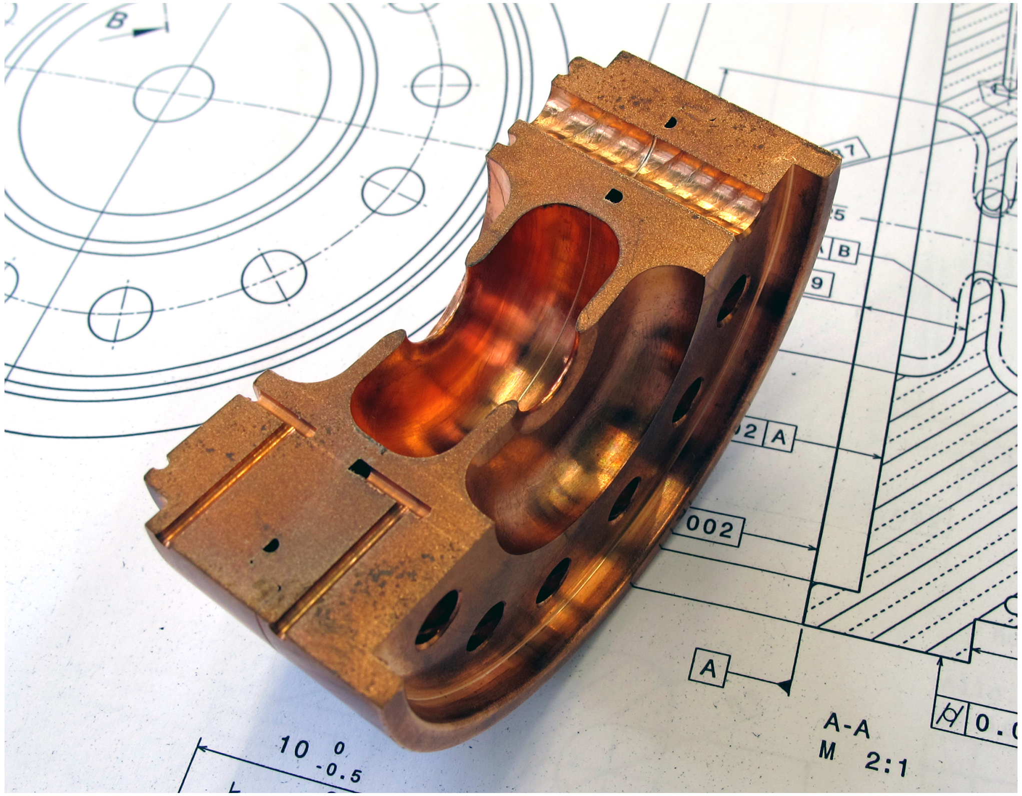
Main Linac: C-band technology

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

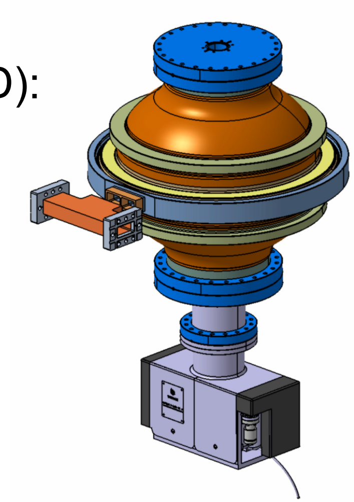


SwissFEL will contain 104 C-band structures organized in 24 linac modules (236 MeV energy gain per module). Test stand in preparation.



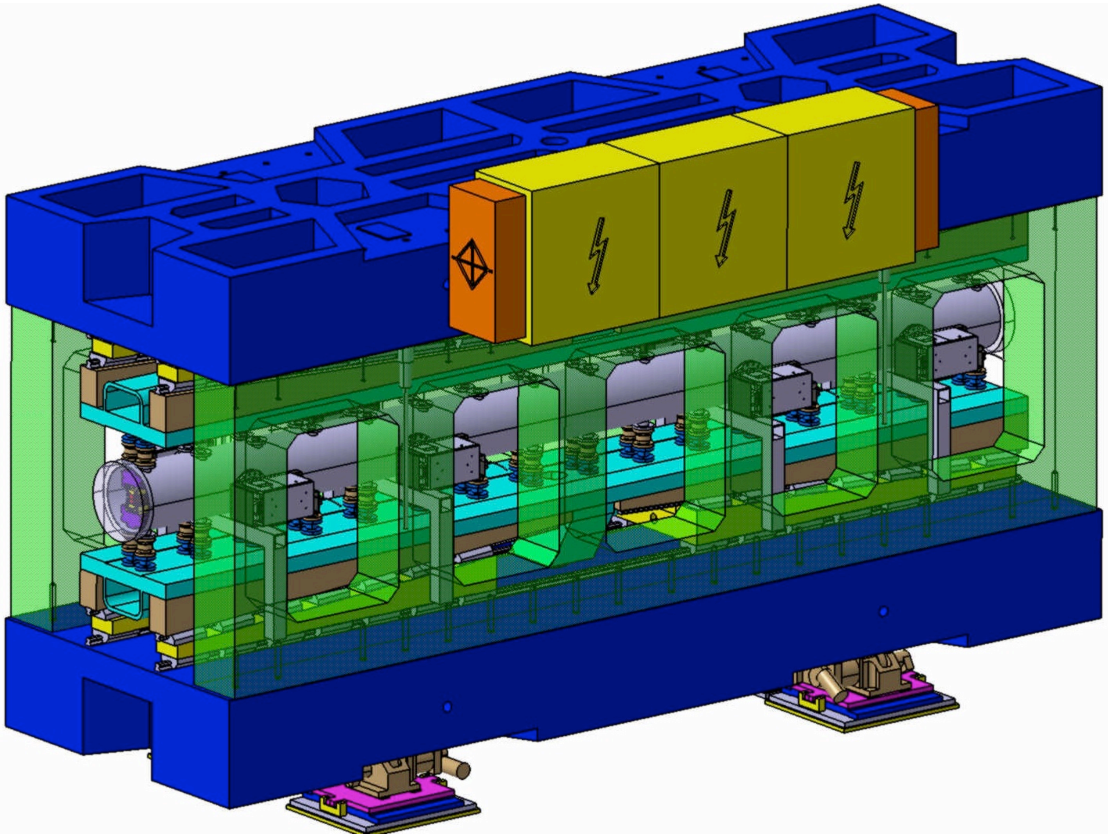
Pulse compressor (SLED):

- 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)

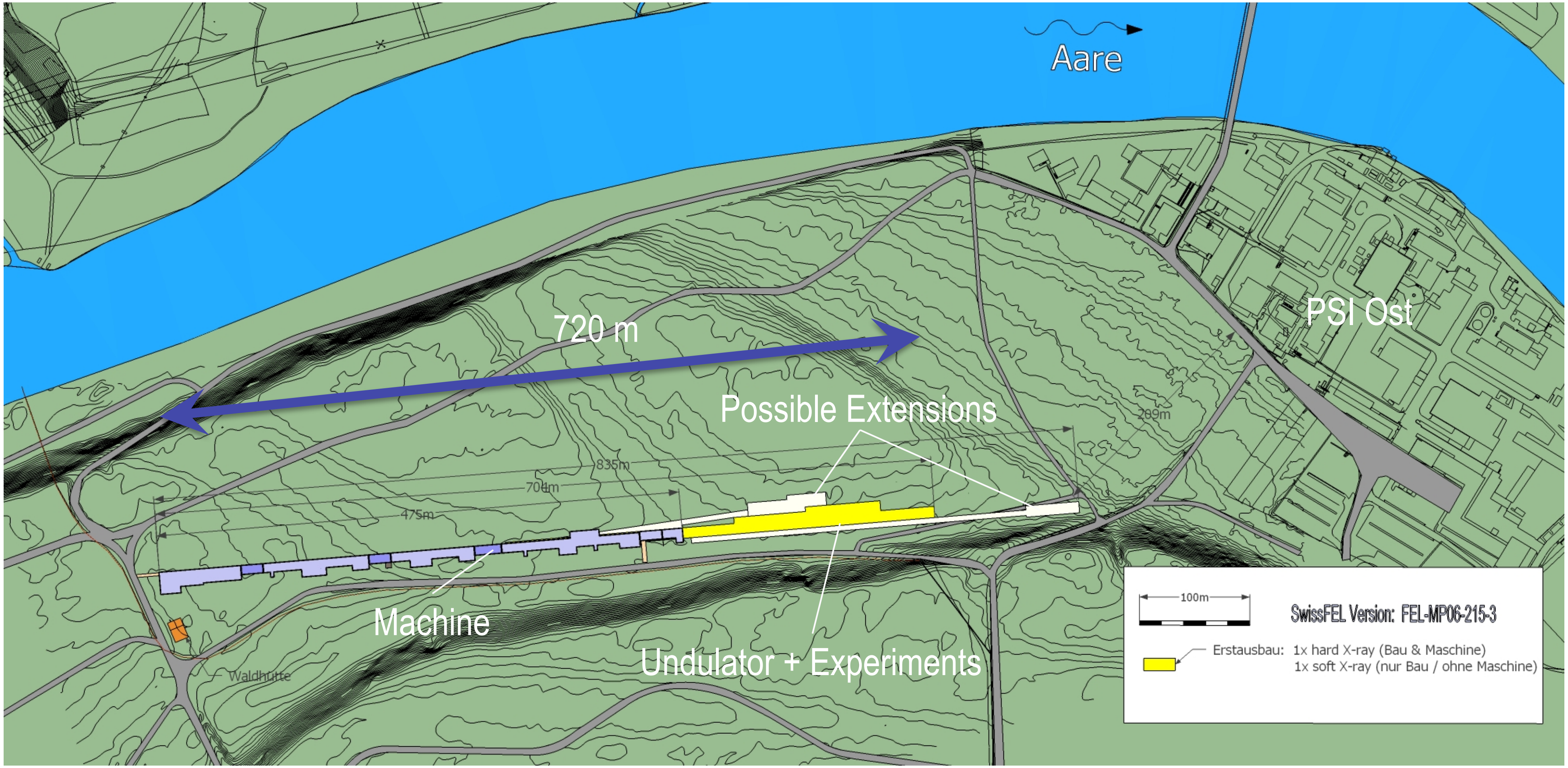
- Hybrid in-vacuum undulator
- 266 periods, each 15 mm
- Magnetic length 3990 mm
- Magnetic material: $Nd_2Fe_{14}Br$ + diffused Dy
- Gap varies between 3 and 20 mm
- At a gap of 4.2 mm, maximum B_z is 1 T



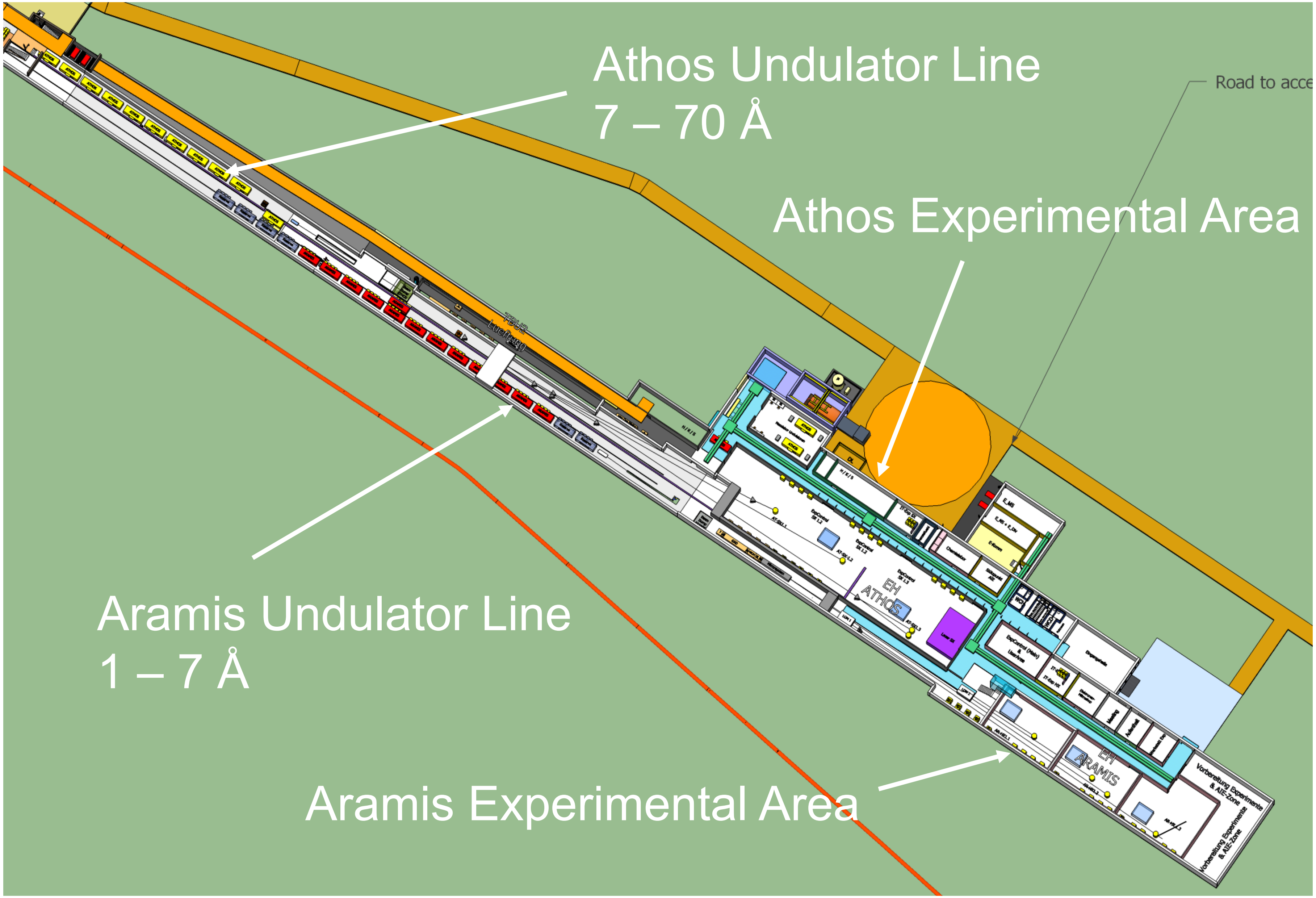
The SwissFEL ARAMIS beamline will comprise 12 undulators of this type. Test of prototype foreseen in injector test facility.

SwissFEL Building

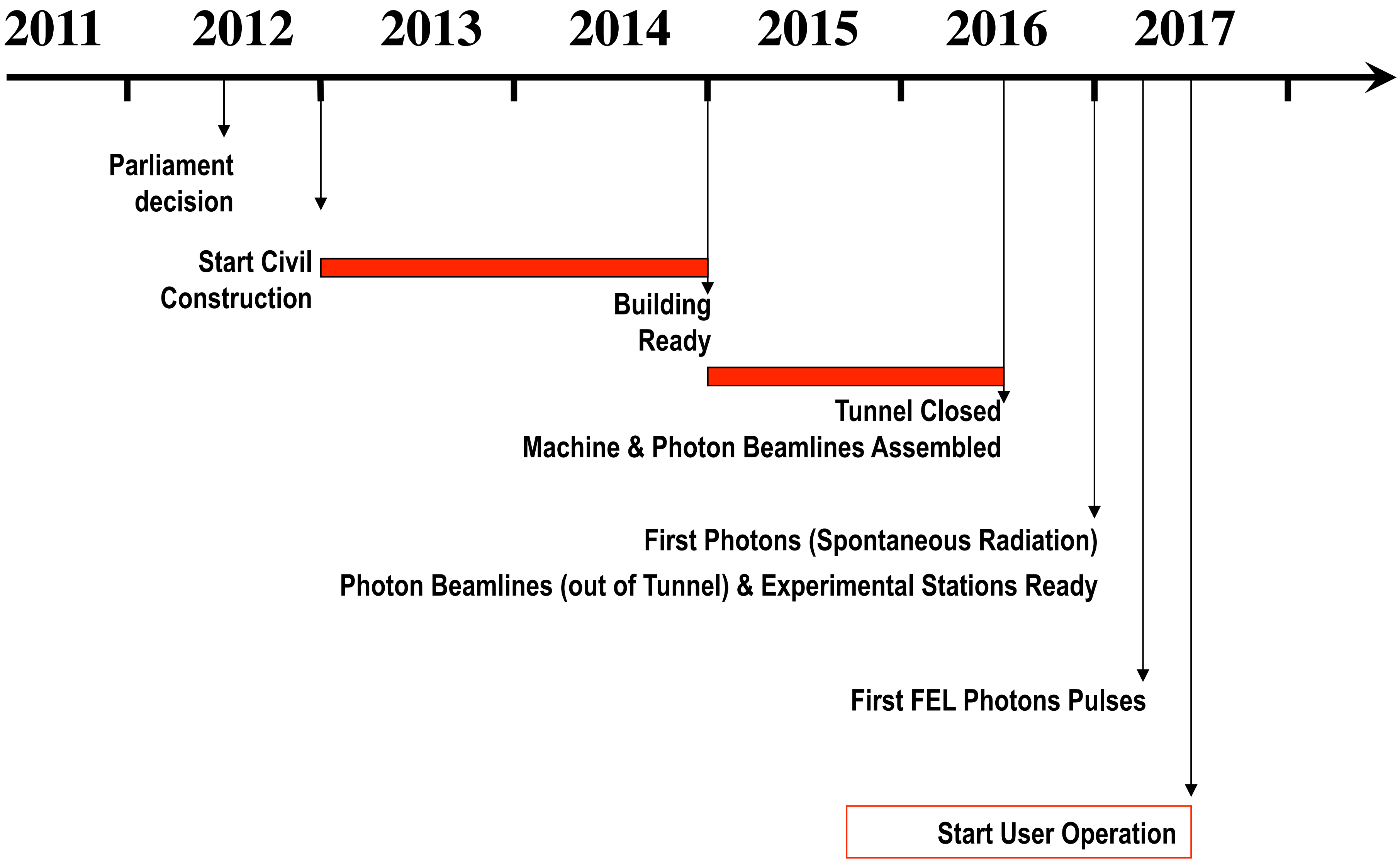
SwissFEL Site



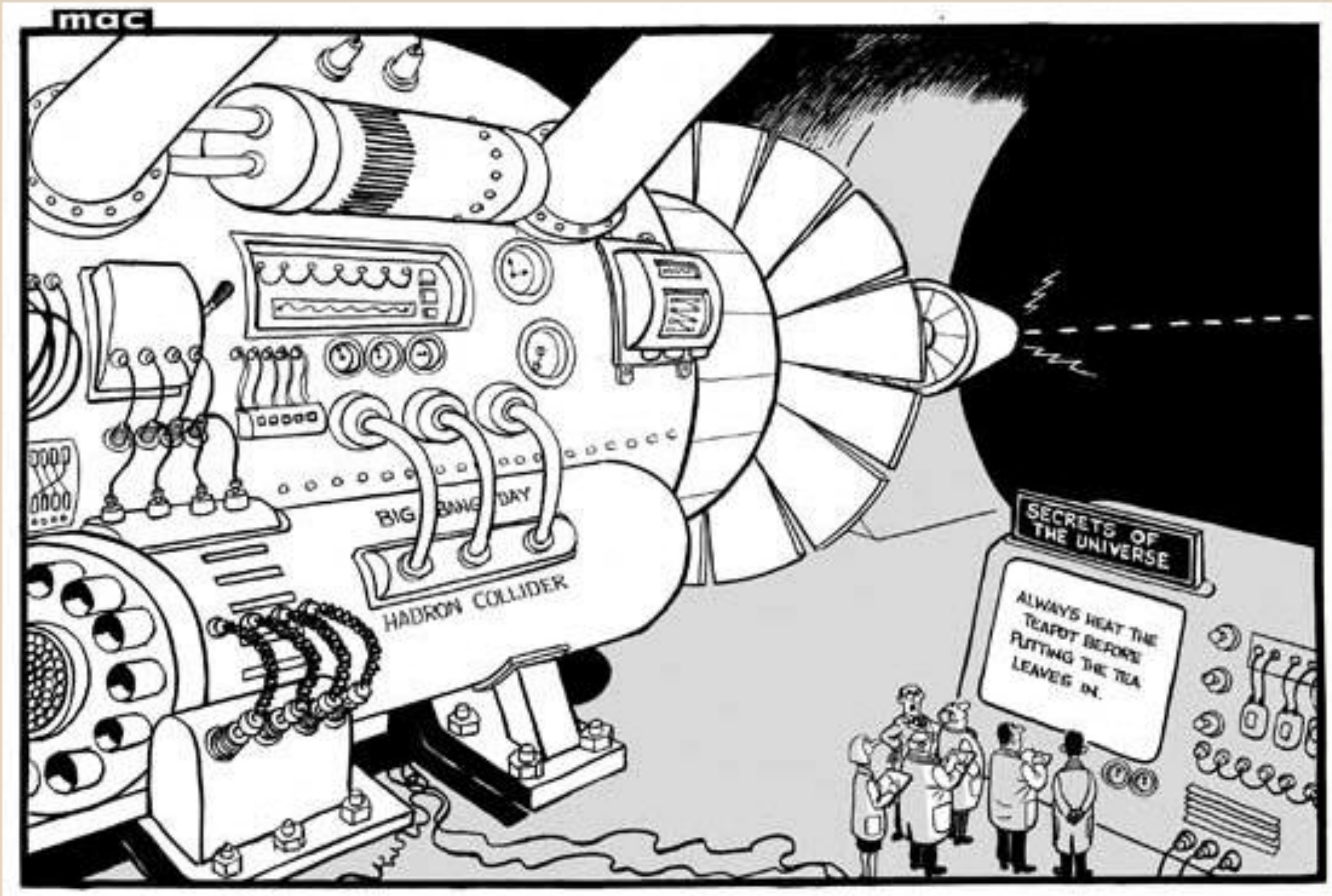
SwissFEL Layout



SwissFEL Timeline



SwissFEL Injector Test Facility

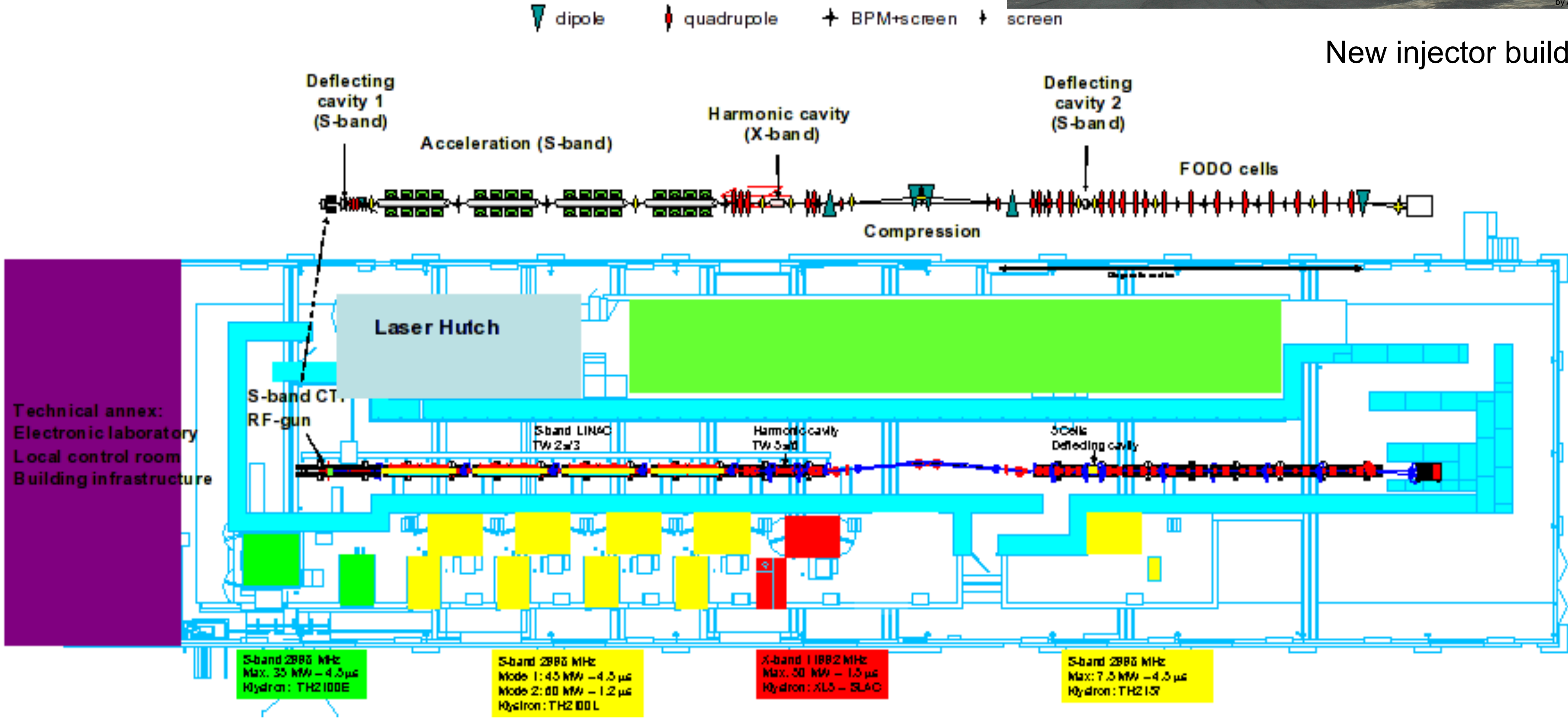


"Remind me. How much did we spend on this machine?"

SwissFEL Injector Test Facility

- 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

New injector building

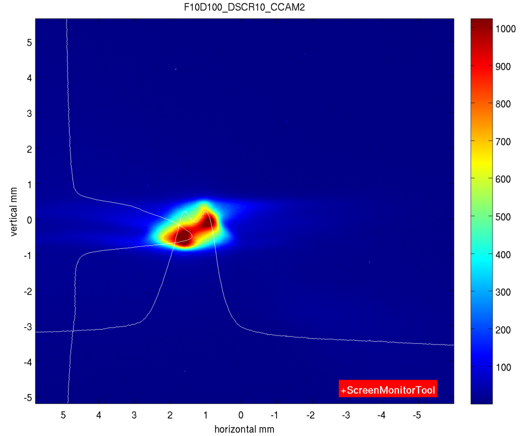


SwissFEL Injector Test Facility

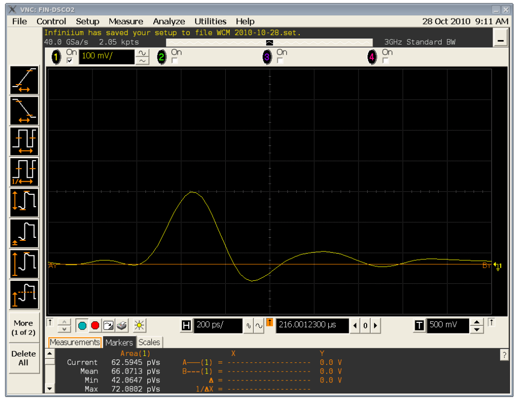
Official inauguration (24 August 2010)

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

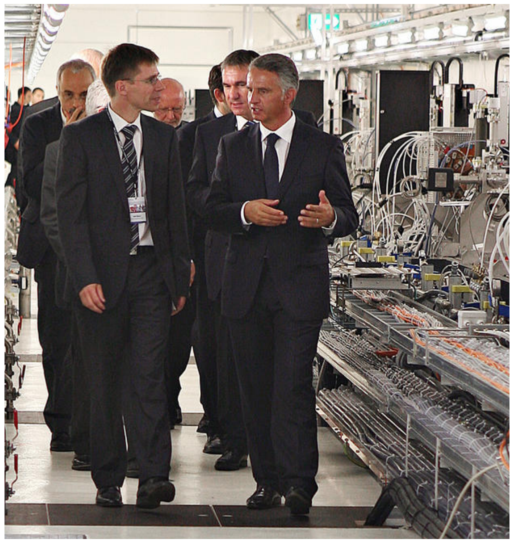
Button connected to laser shutter.



Beam on LuAG screen in front of beam dump.



Signal from Wall Current Monitor after the RF gun.



Visit to the injector tunnel.

The Burkhalter beam:

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

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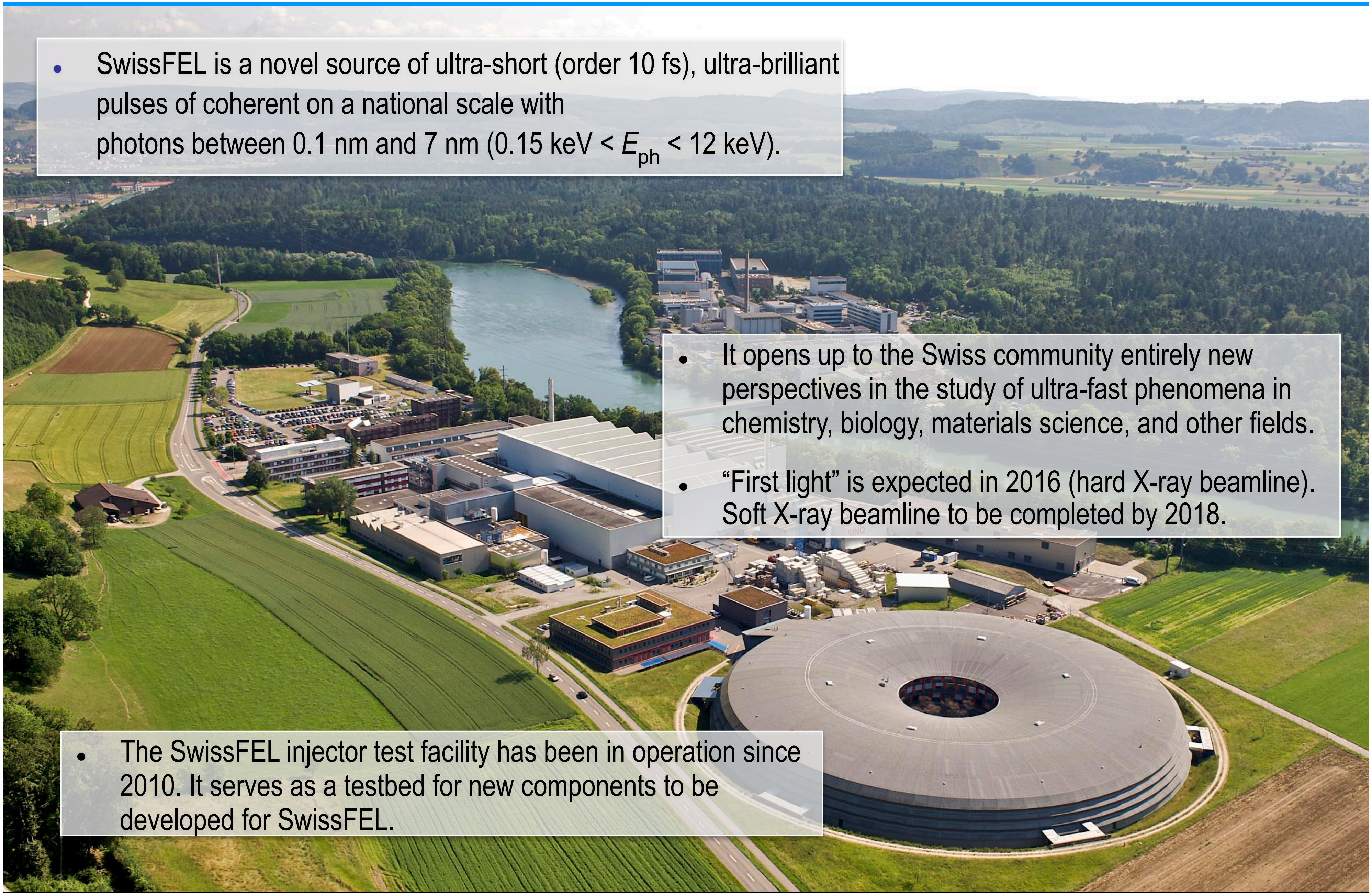
Summary



- SwissFEL is a novel source of ultra-short (order 10 fs), ultra-brilliant pulses of coherent on a national scale with photons between 0.1 nm and 7 nm (0.15 keV < E_{ph} < 12 keV).

- It opens up to the Swiss community entirely new perspectives in the study of ultra-fast phenomena in chemistry, biology, materials science, and other fields.

- “First light” is expected in 2016 (hard X-ray beamline). Soft X-ray beamline to be completed by 2018.

- The SwissFEL injector test facility has been in operation since 2010. It serves as a testbed for new components to be developed for SwissFEL.