Mission impossible:

The SwissFEL project in 17 min.

Thomas Schietinger, PSI

Swiss Institute for Particle Physics
Annual Meeting

25 August 2009

The SwissFEL project at PSI

and possible applications in fundamental physics

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  - Health
  - Information technology
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  - Axions
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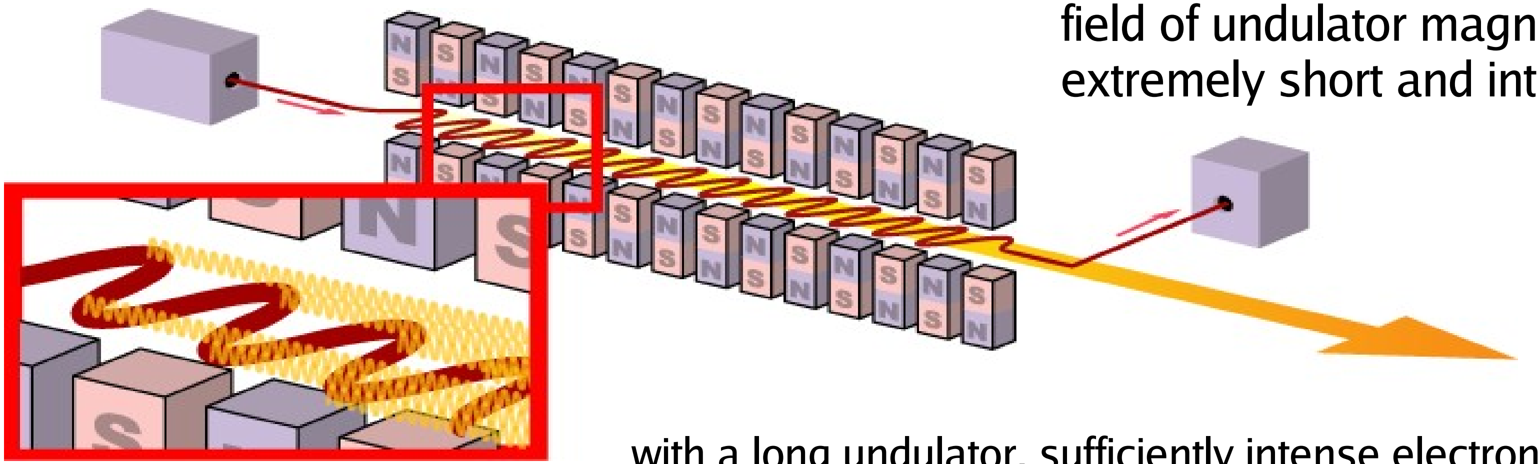
The Free Electron Laser



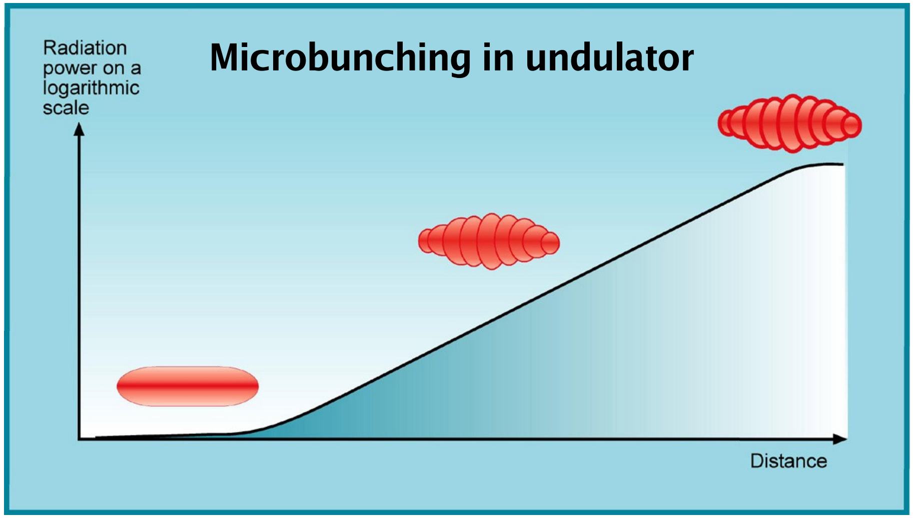
FEL principle:

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

with a long undulator, sufficiently intense electron beam, the synchrotron radiation of a certain wavelength is amplified as a result of **microbunching** in the electron beam
(SASE = Self-Amplified Spontaneous Emission)

Similar to synchrotron radiation (from circular light sources), but:

- wavelength tunable
- more coherence
- shorter pulses
- higher power



Comparison to conventional Laser

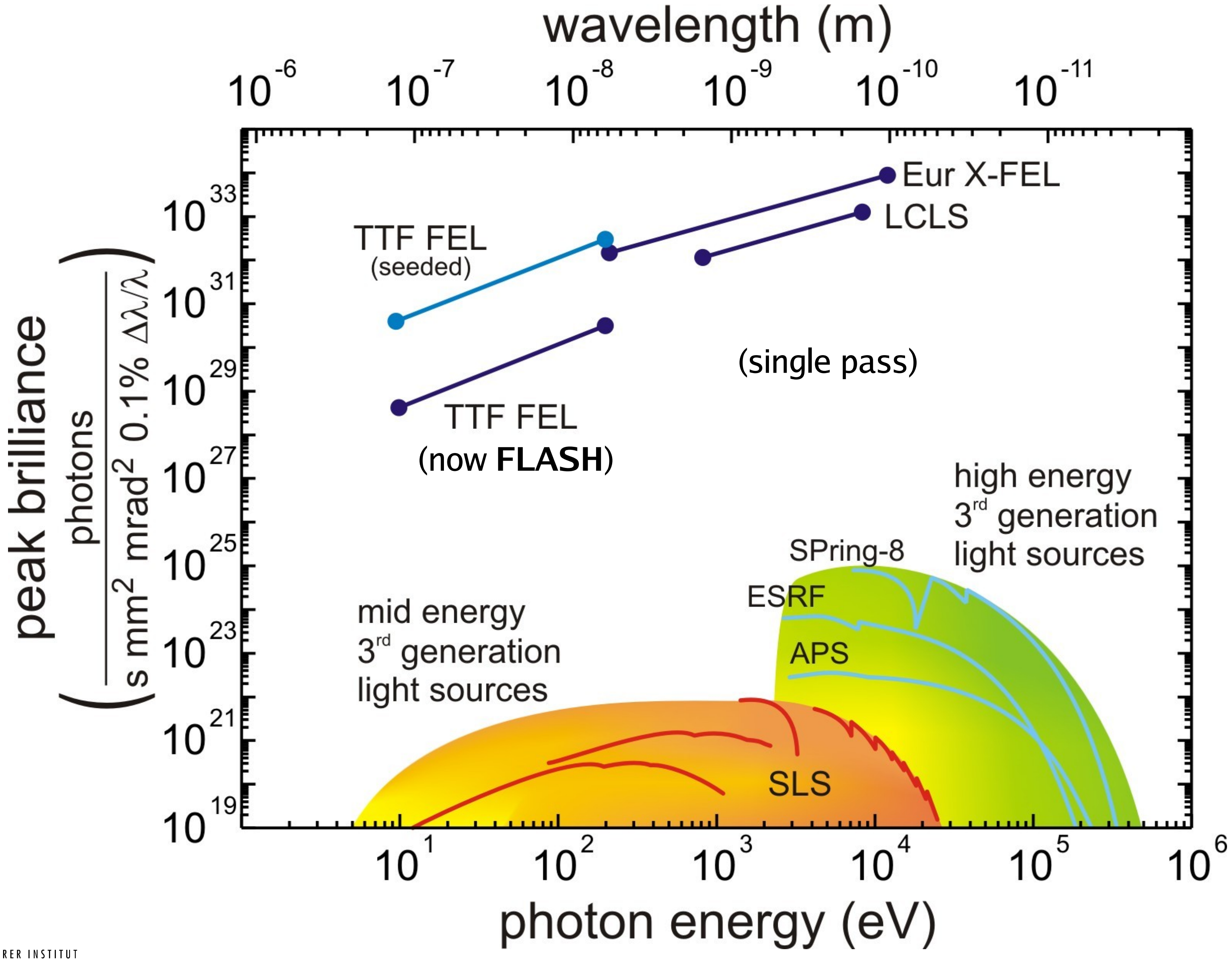
	LASER	FEL
Characteristics	Source of narrow, monochromatic and coherent light beams	
Configuration	Oscillator or amplifier	
First demonstration	1960	1977
Laser medium	Solids, liquids, gases	Vacuum with electron beam in periodic magnetic field
Energy storage	Potential energy of electrons	Kinetic energy 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

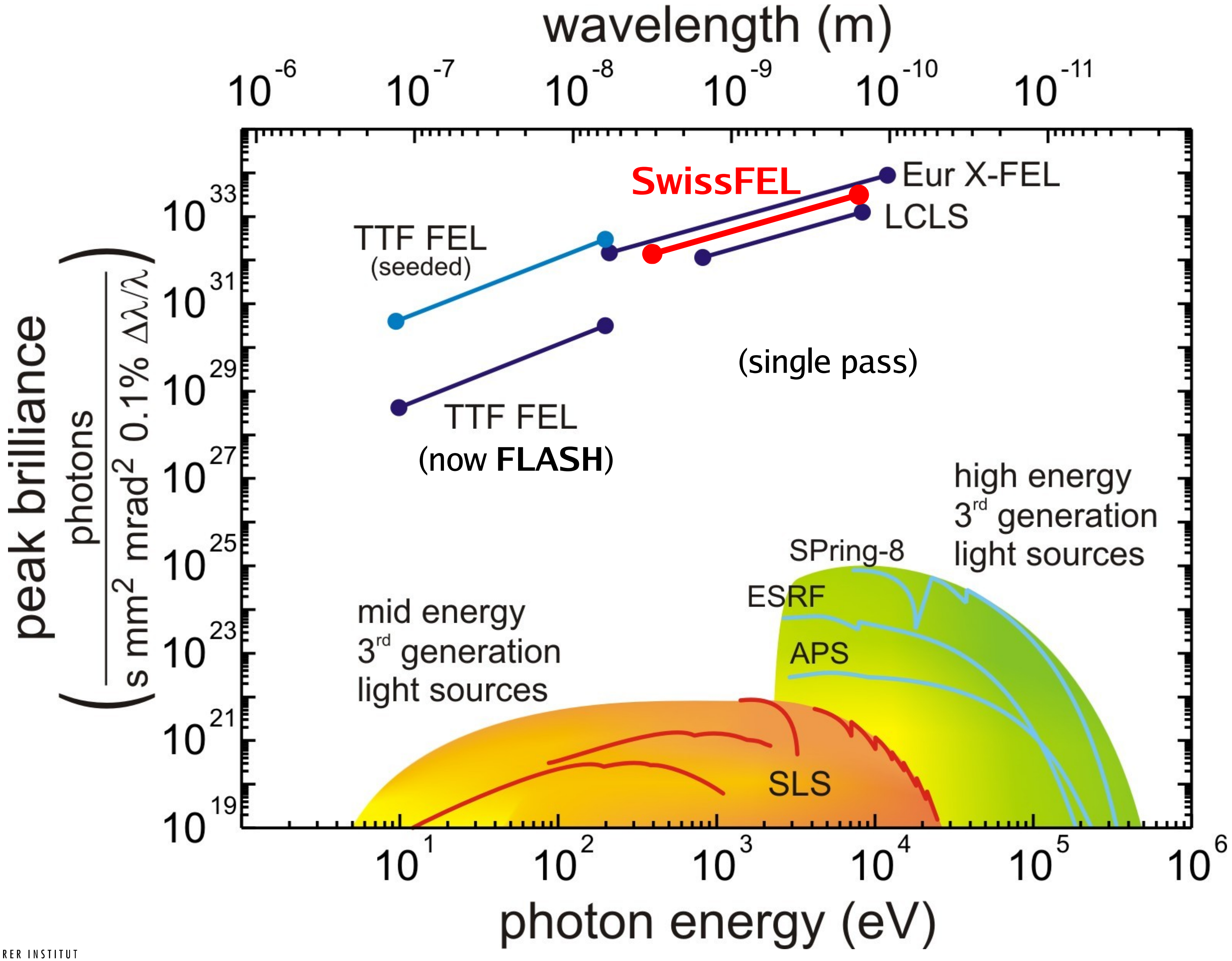
	SLS	SwissFEL
Peak brilliance **[photons/s/mm^2/mrad^2/0.1% BW]**	10^{21}	10^{33}
Average brilliance **[photons/s/mm^2/mrad^2/0.1% BW]**	5×10^{18}	5×10^{22}
Total photon flux	8×10^{20} (around the ring)	2.6×10^{12}
Total photon power	200 kW	5 mW
Fractional energy loss of electrons to photons	100%	0.05%
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!

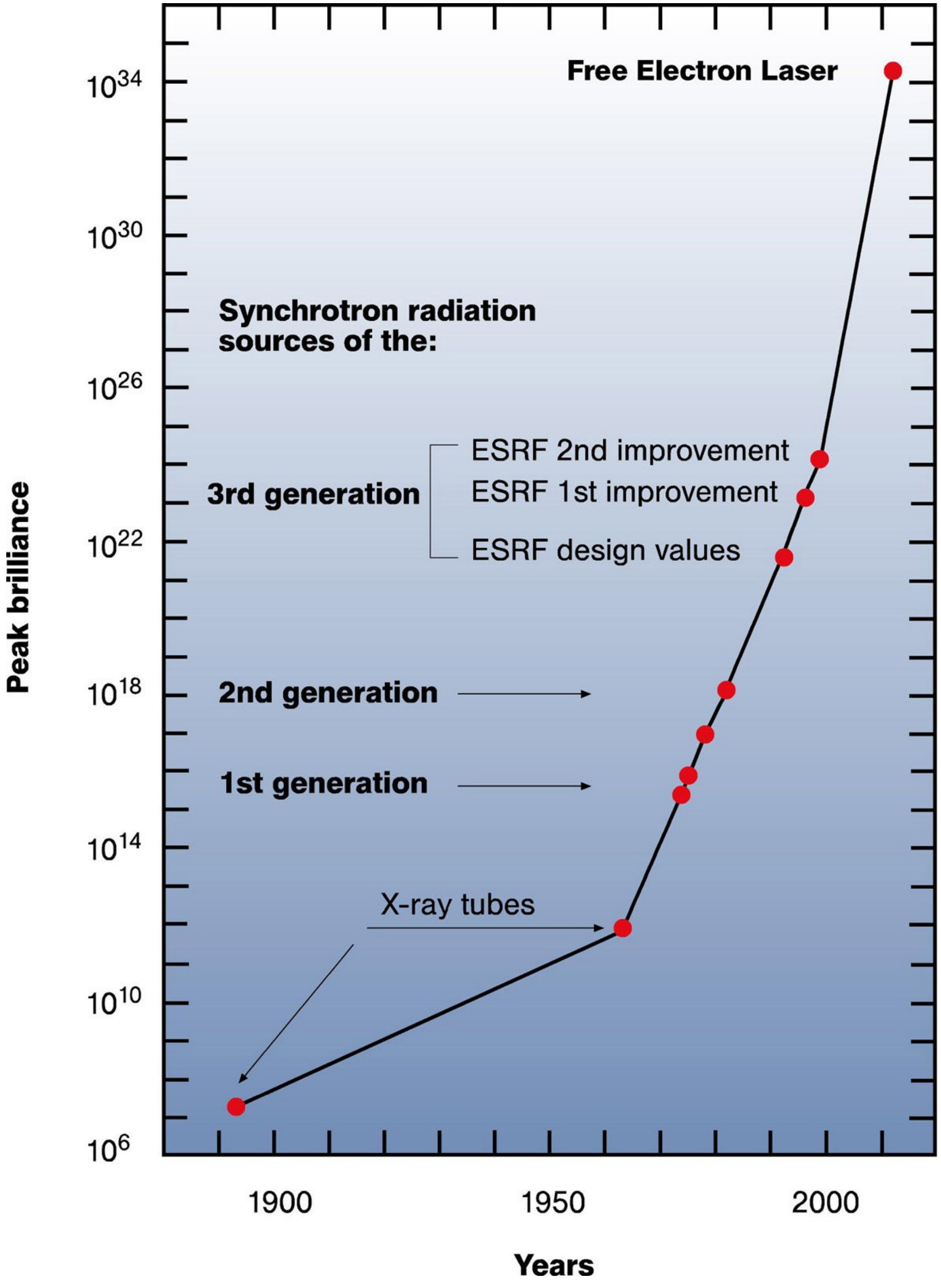
Revolutionizing X-ray science



Revolutionizing X-ray science

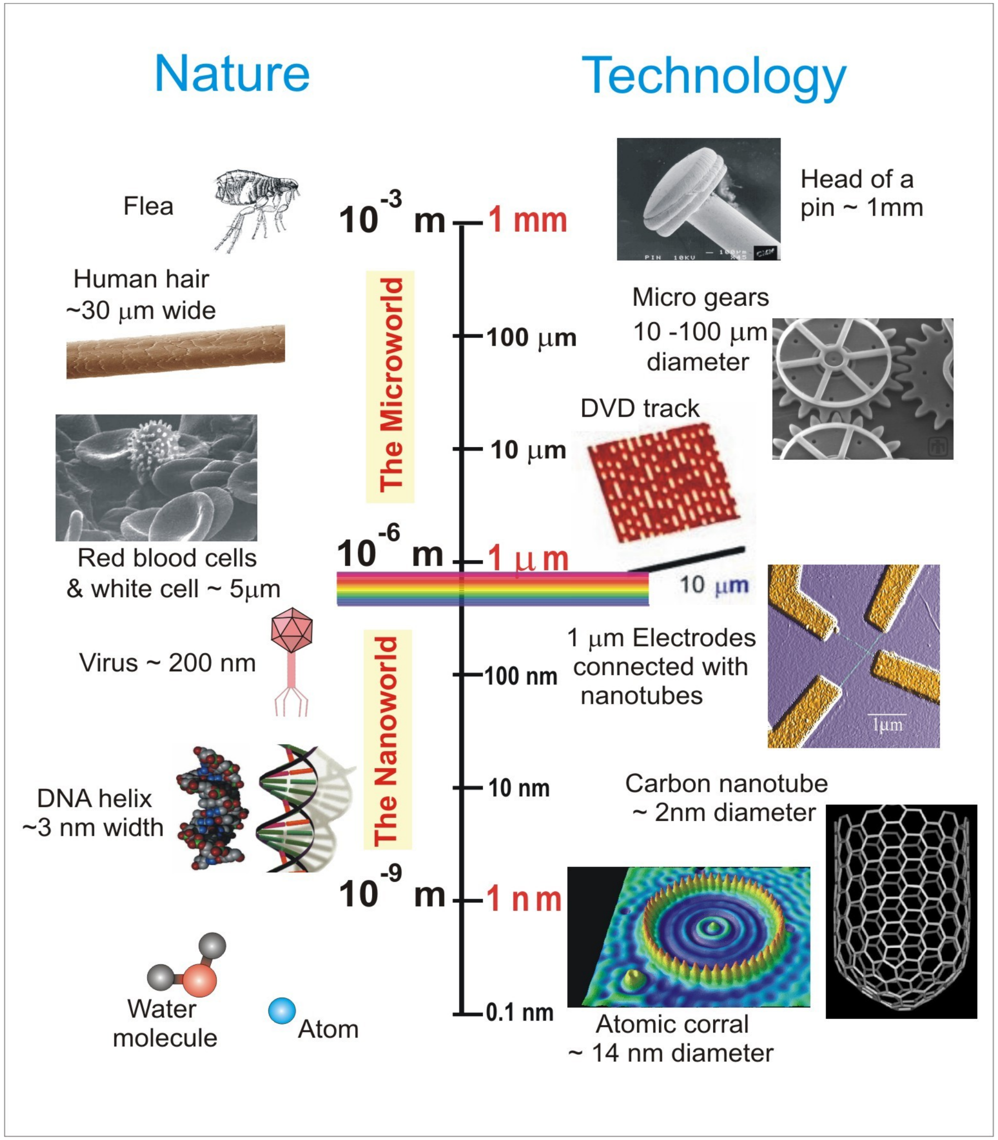


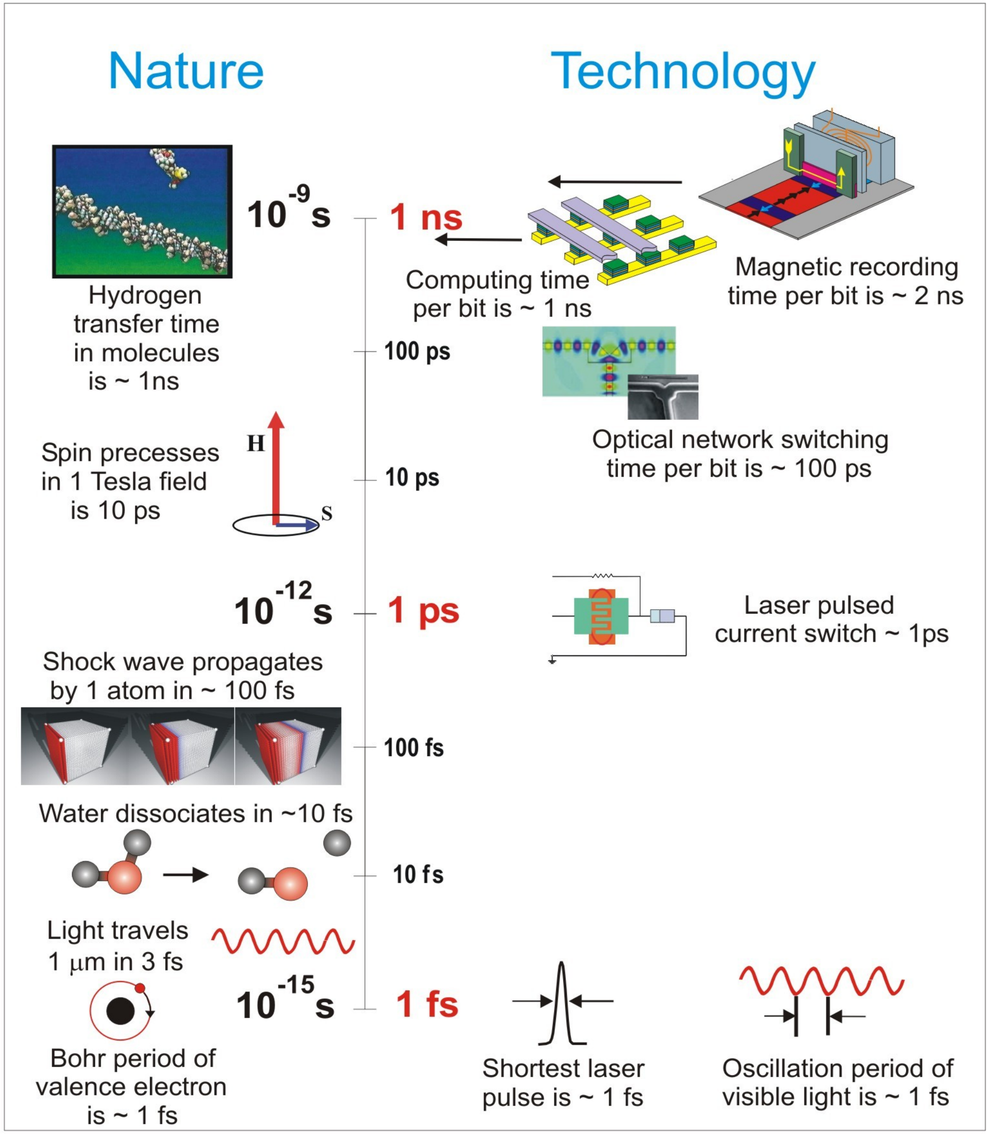
Historical perspective



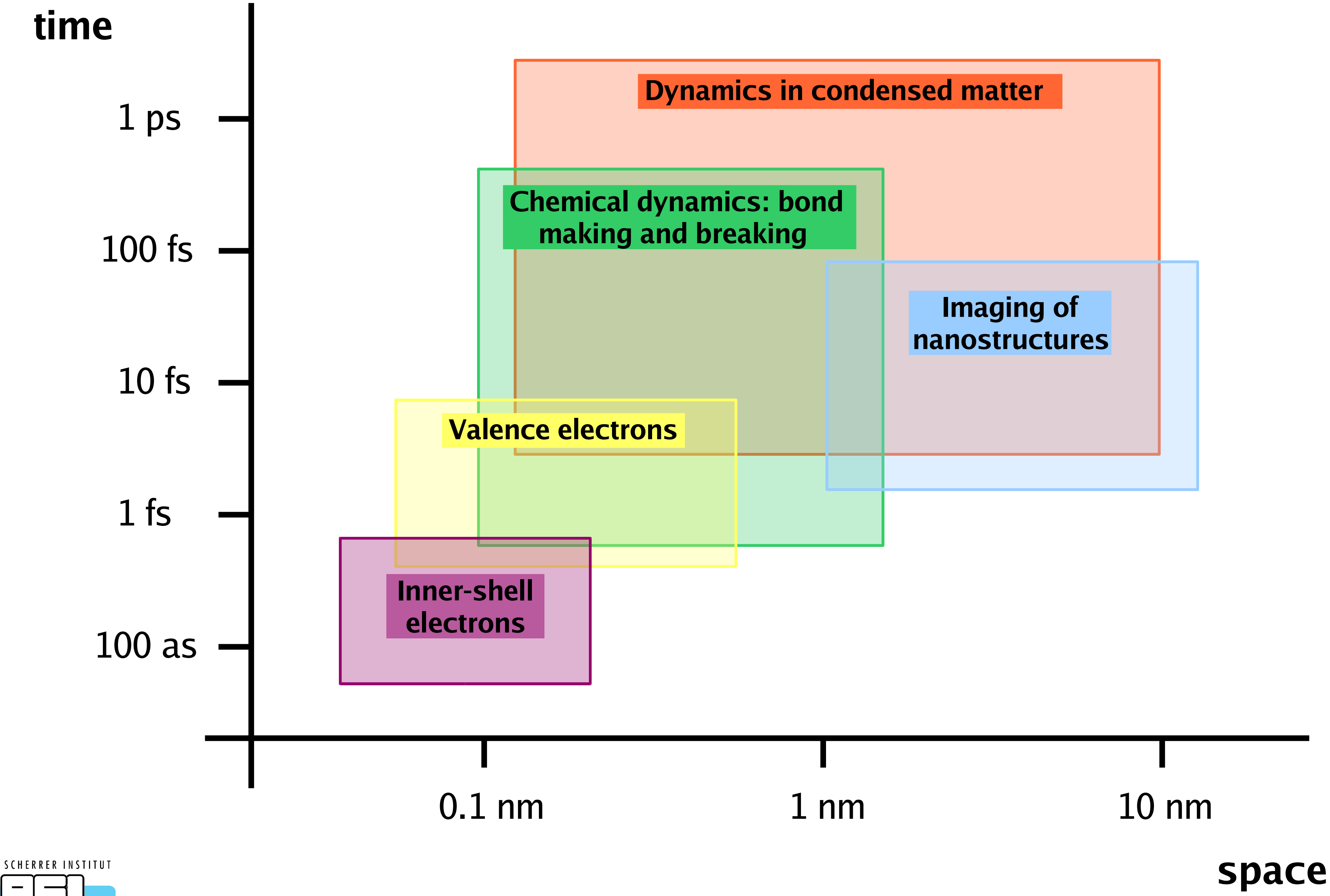
X-ray FELs open up the world of the

ultra-small *...and...* ultra-fast!

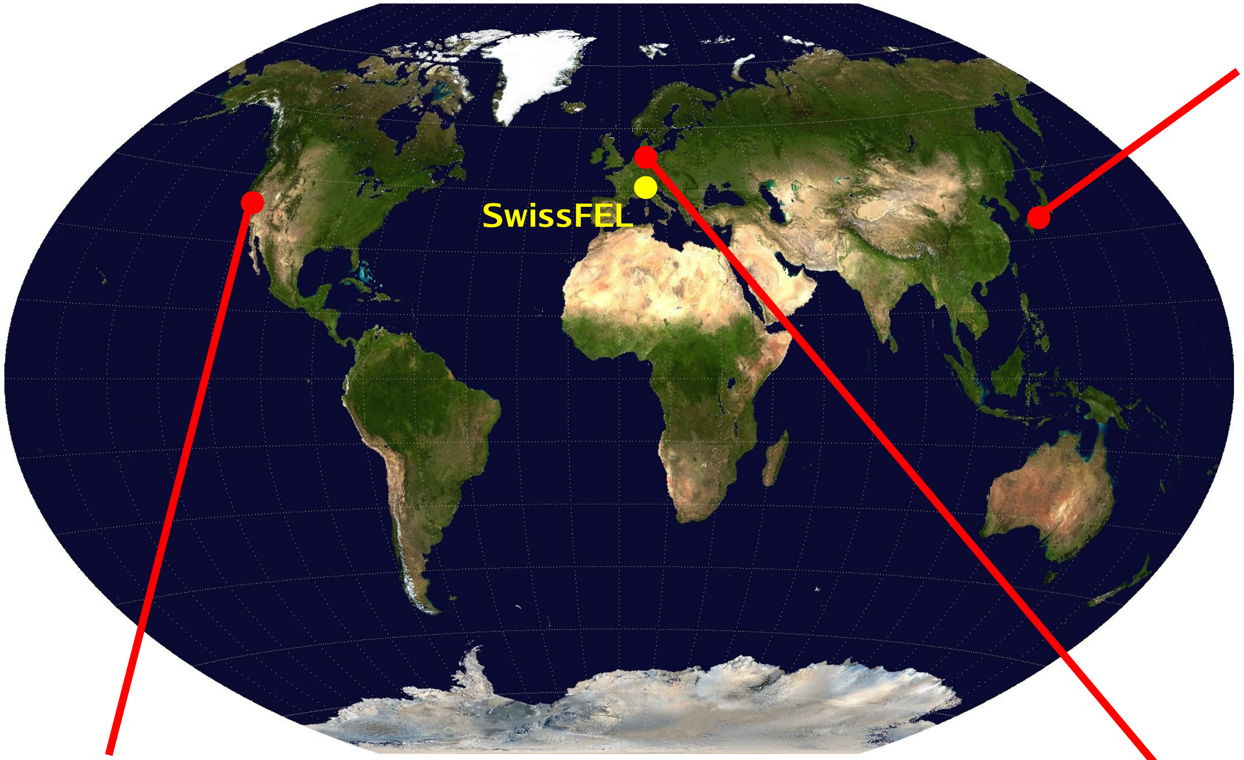




X-ray FELs open up the world of the ultra-small and ultra-fast!



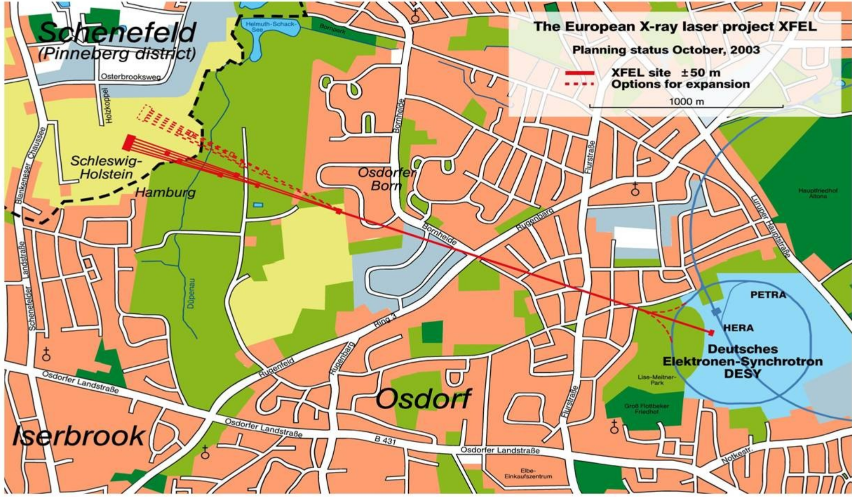
X-ray FELs worldwide



SCSS, SPring-8, Japan

LCLS, SLAC, Stanford

European XFEL, DESY, Hamburg



X-ray FELs worldwide

	LCLS (USA)	SCSS (Japan)	European XFEL	SwissFEL (CH)
Start of operation	2009	2011	2014	2016
Length [km]	3.0	0.75	3.4	0.8
Beam energy [GeV]	13.6	8	17.5	6
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

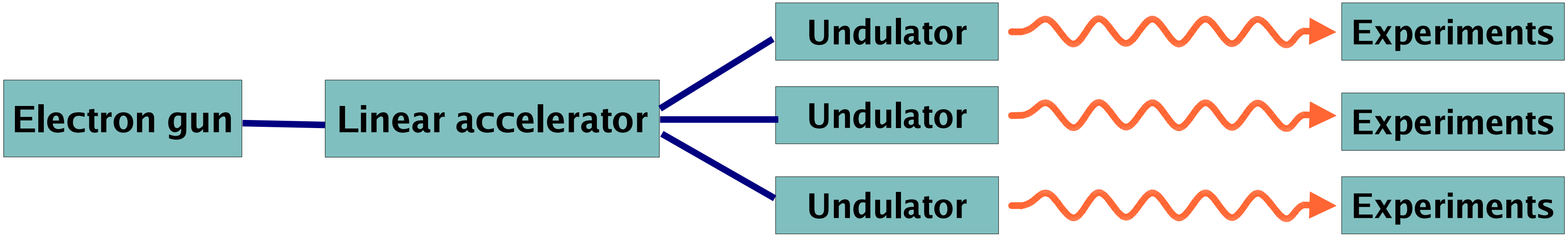
Ingredients of an X-ray FEL

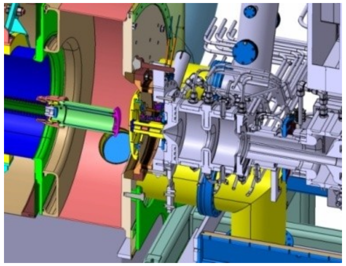
Generation of high-brightness electron beam

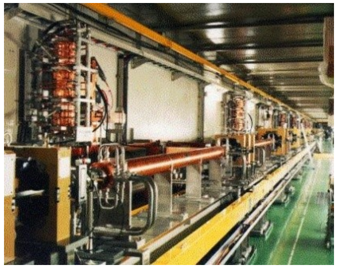
Electron beam acceleration

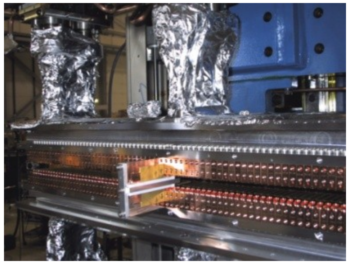
X-ray generation with FEL process (SASE)

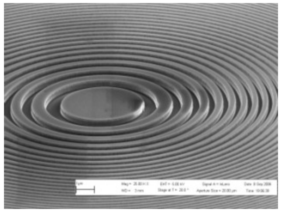
X-ray transport and focussing

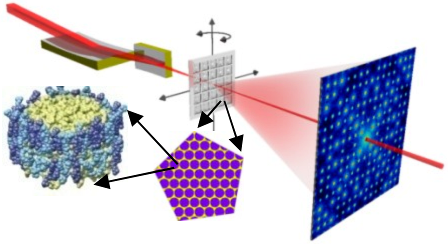






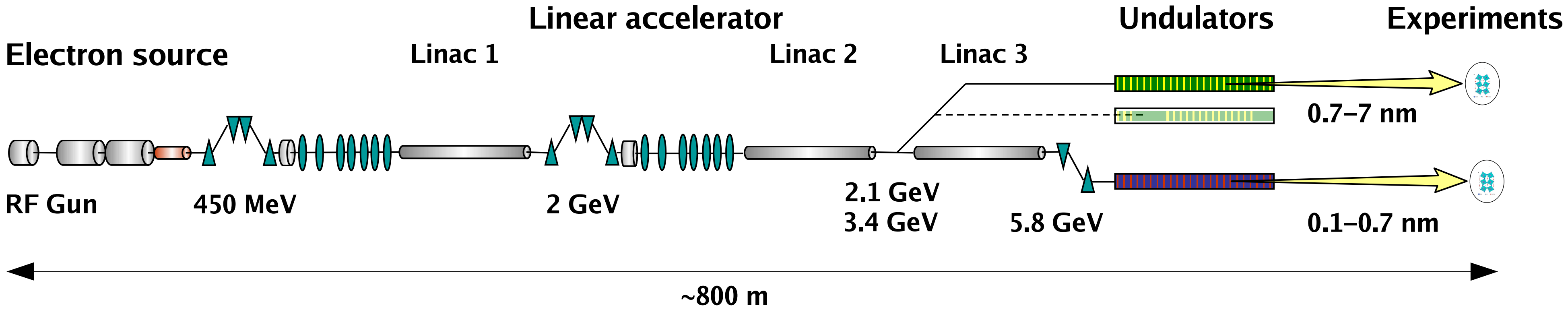






SwissFEL

schematic layout



Linear accelerator

Undulators

Experiments

Electron source

Linac 1

Linac 2

Linac 3

0.7–7 nm

RF Gun

450 MeV

2 GeV

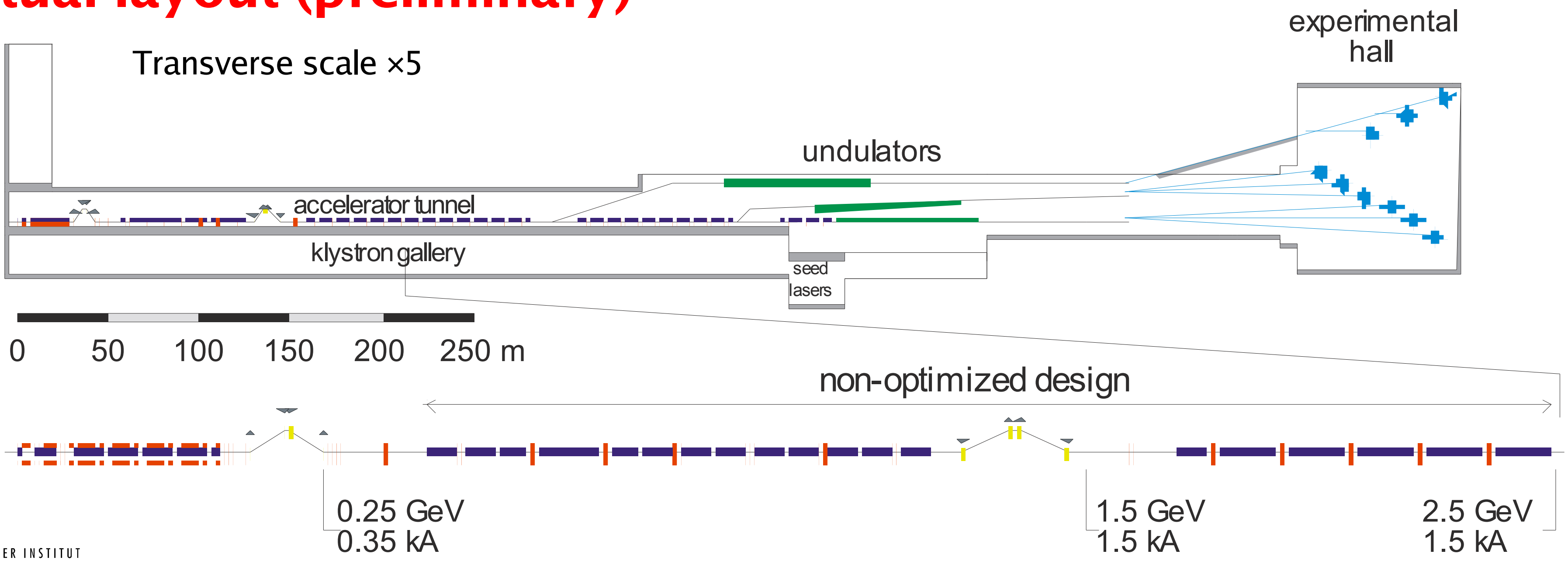
2.1 GeV
3.4 GeV

5.8 GeV

0.1–0.7 nm

~800 m

actual layout (preliminary)



Transverse scale ×5

experimental hall

undulators

accelerator tunnel

klystron gallery

seed lasers

0 50 100 150 200 250 m

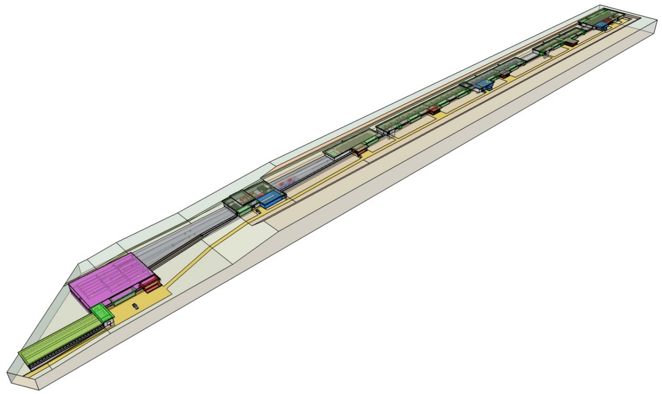
non-optimized design

0.25 GeV
0.35 kA

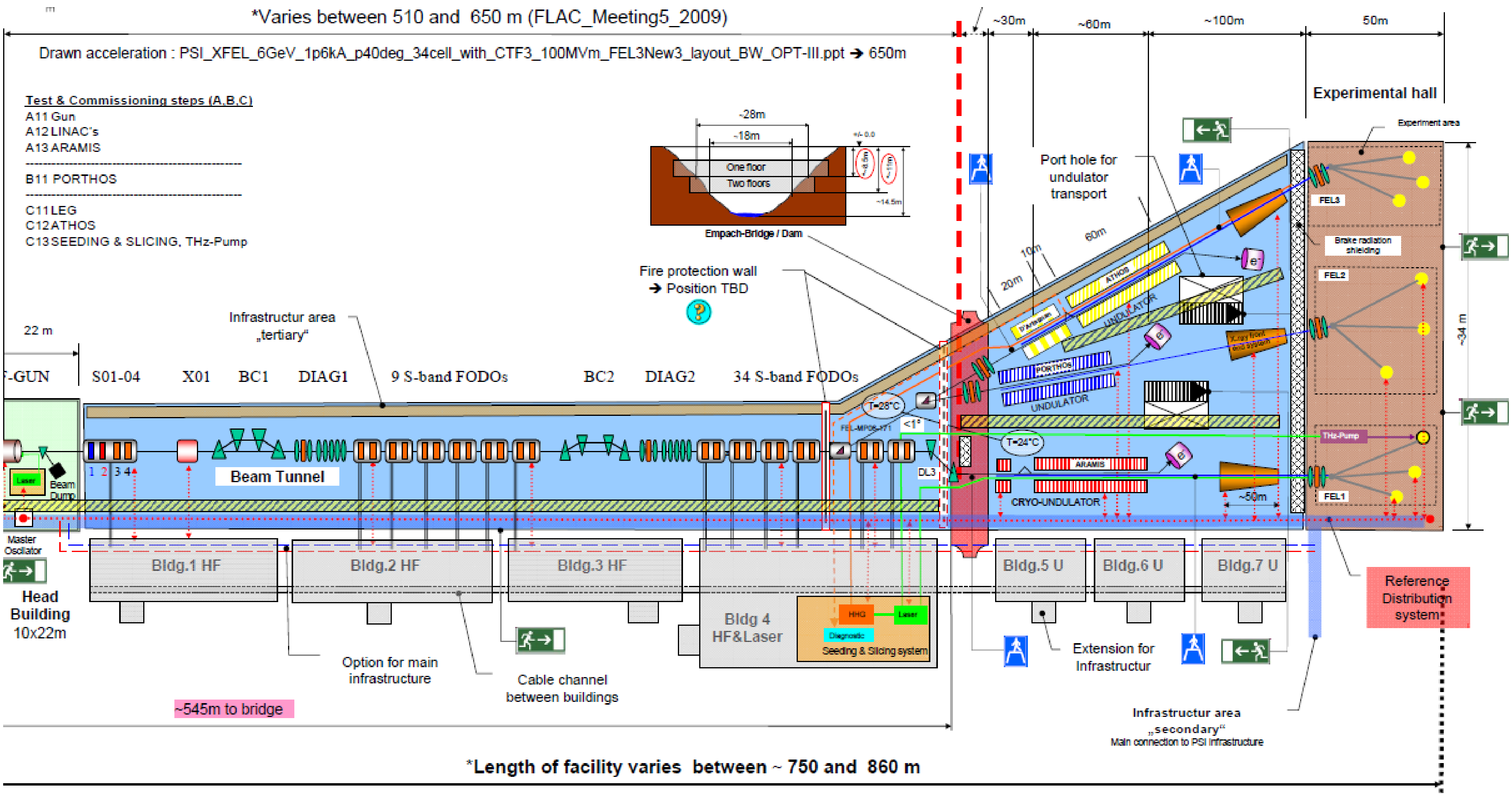
1.5 GeV
1.5 kA

2.5 GeV
1.5 kA

SwissFEL infrastructure



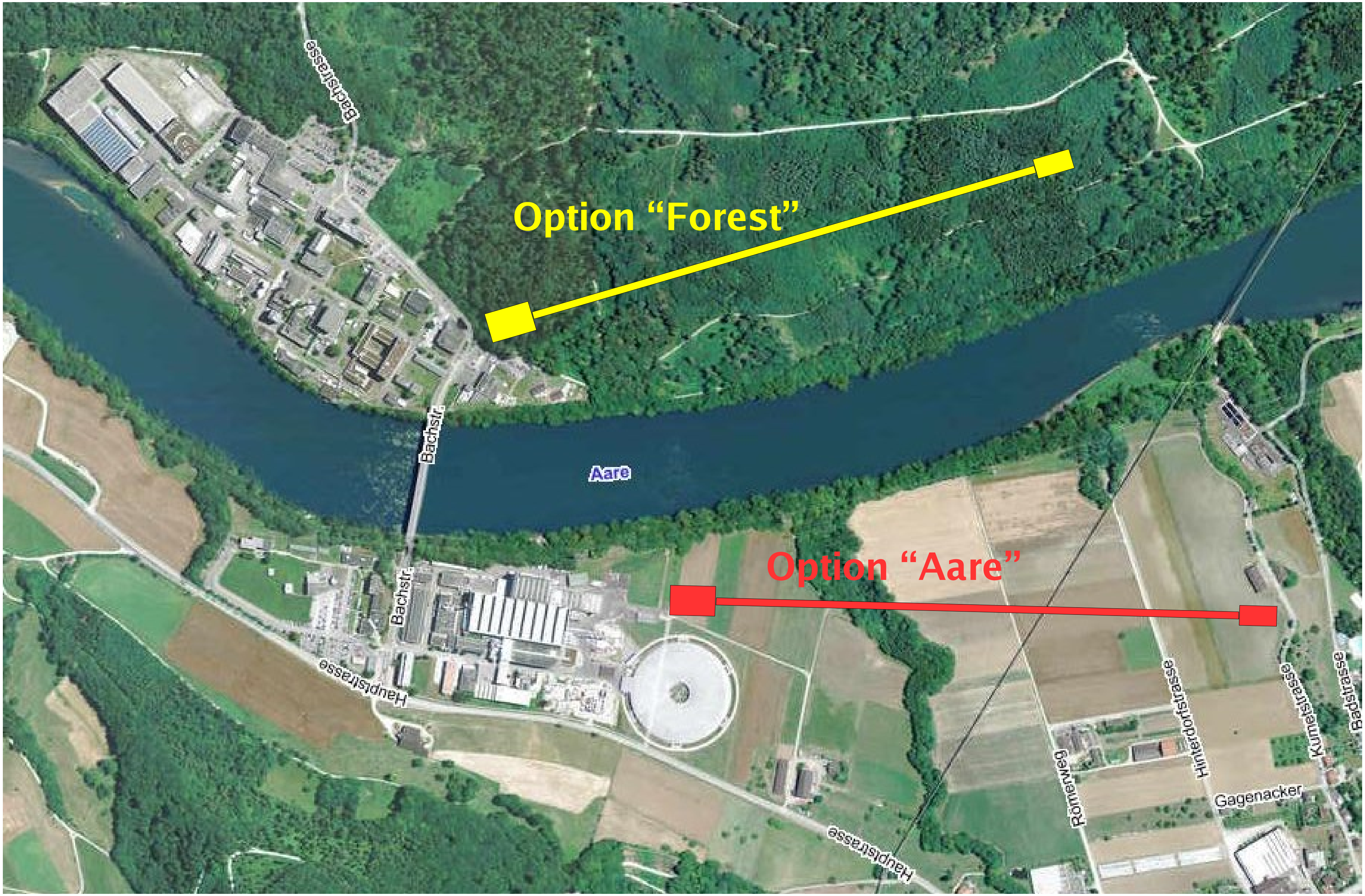
Planning is well under way!



PAUL SCHERRER INSTITUT

PSI

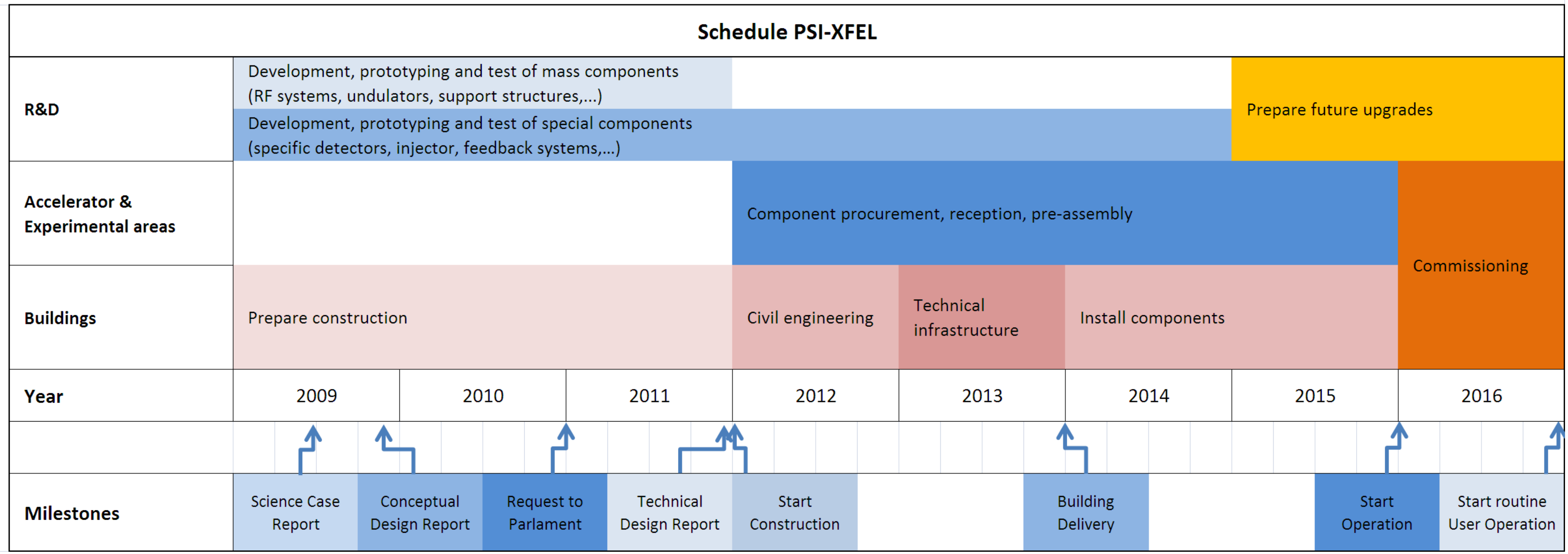
Possible sites



Possible schedule

Preparatory research & development:

since 2004	**Development of high-brightness electron gun**
since 2009	**Construction of 250 MeV test injector**



Most important milestones:

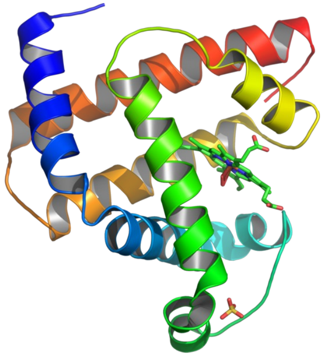
2009	**Conceptual design report**
2010	**Request to parliament**
2011	**Technical Design Report**
2012	**Start construction**
2016	**Start operation**

Applications

Three examples from three domains that are highly relevant to society:

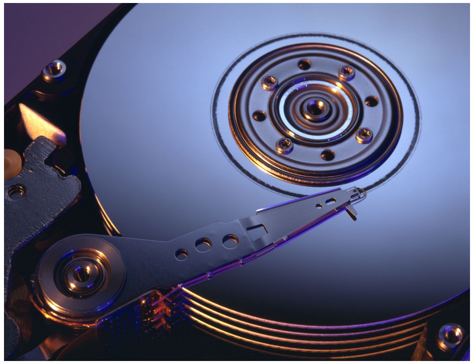
1) Energy:

understanding the Haber-Bosch process



2) Health:

determining the structure of proteins



3) Information technology:

utilizing ultrafast magnetization dynamics

Energy: the Haber-Bosch process

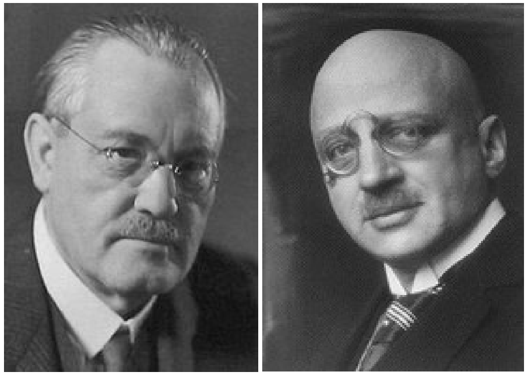
Synthesis of ammonia using iron oxide as surface catalyzer

Production of artificial fertilizer

Sustains 40% of the world population

Uses a lot of energy!

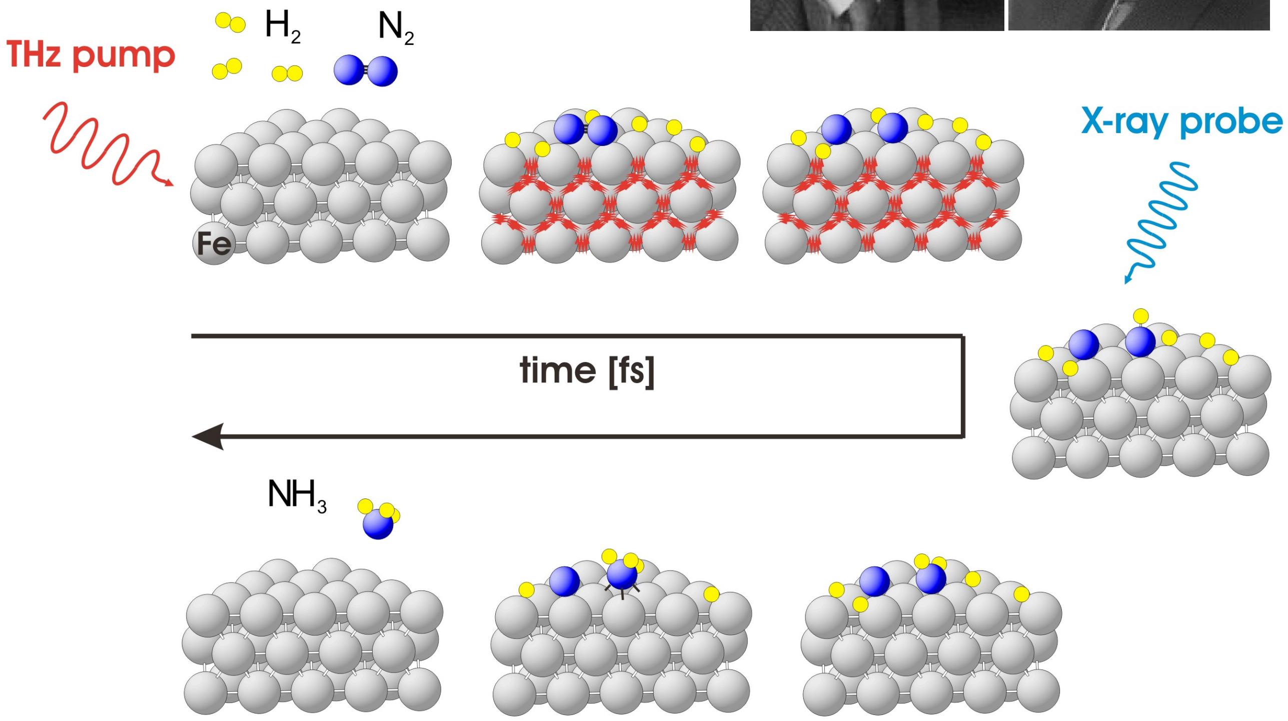
$$N_2 + 3H_2 \rightarrow 2NH_3$$

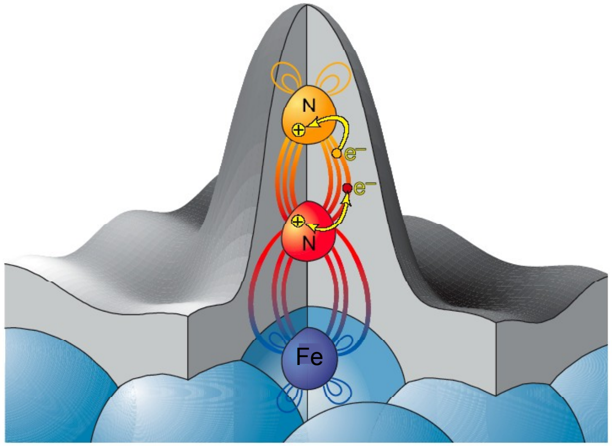


Details of chemical process still poorly understood (fs scale)

Step-by-step imaging with ultra-short X-ray pulse from FEL

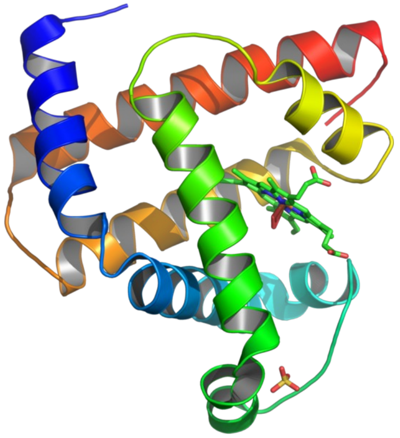
Trigger reaction with THz “pump” (THz radiation source foreseen near experimental area)

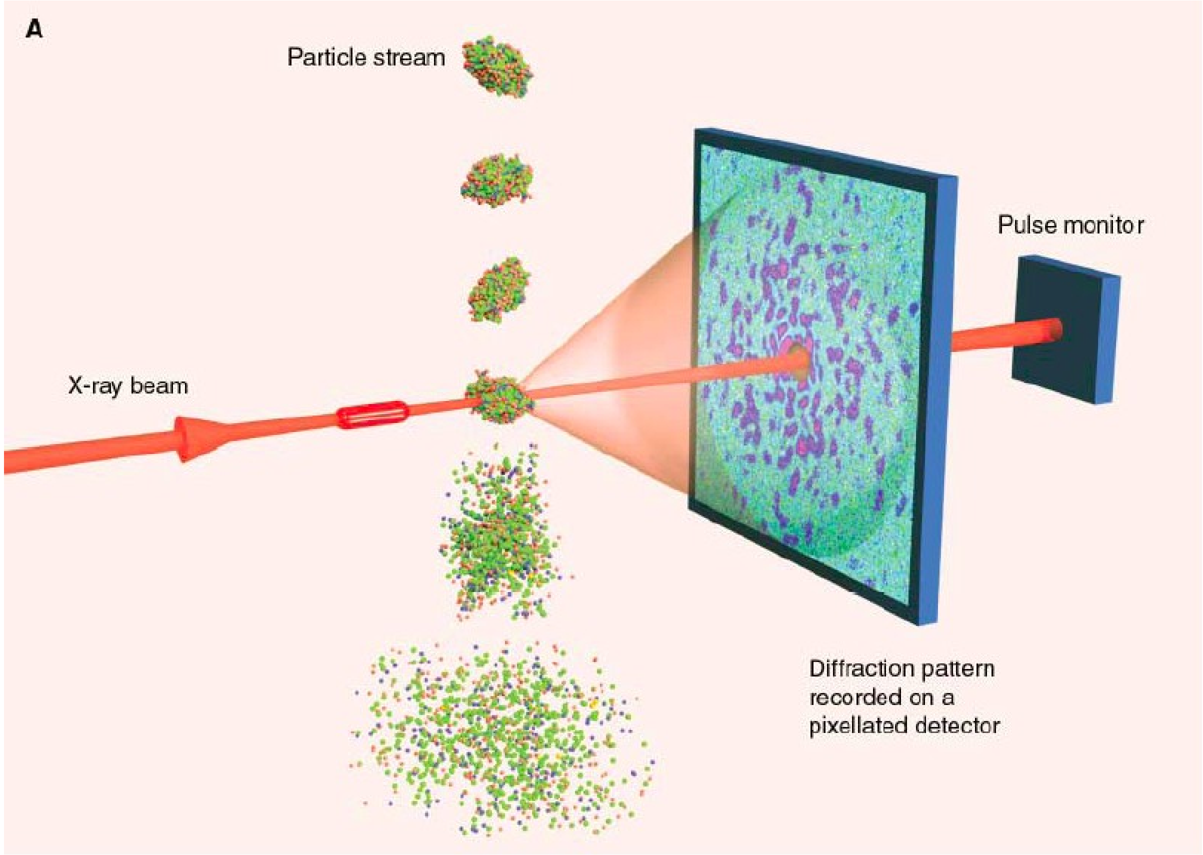




H. Ogasawara, D. Nordlund, A. Nilsson, Proceedings 27th International FEL Conference (2005)

Health: Protein structure



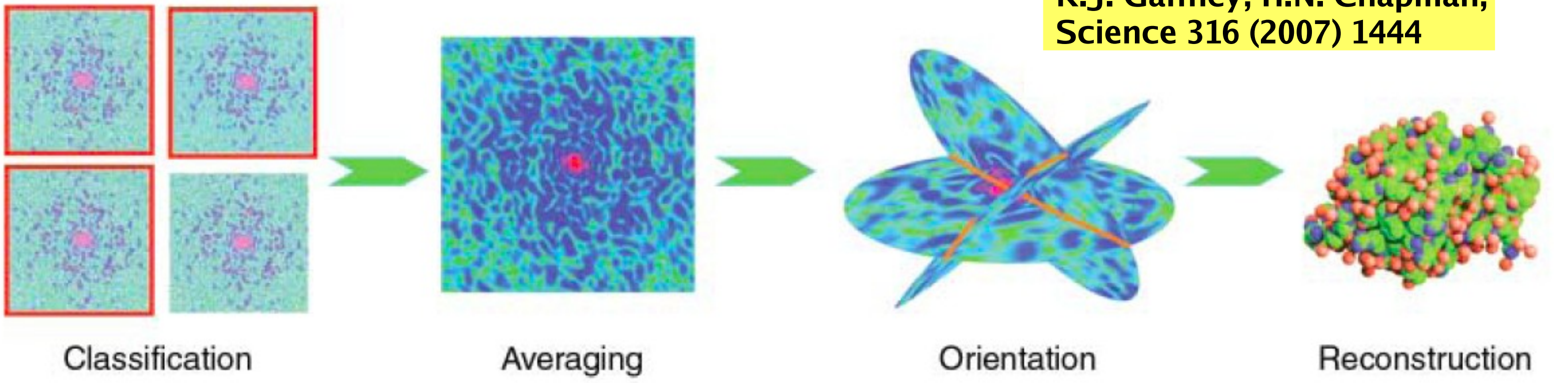


Synchrotron light (SLS) can analyze structure of crystallized proteins.

But many proteins cannot be crystallized!

With the ultrashort X-ray FEL pulse, full 3D reconstruction of molecules becomes possible.

K.J. Gaffney, H.N. Chapman, Science 316 (2007) 1444

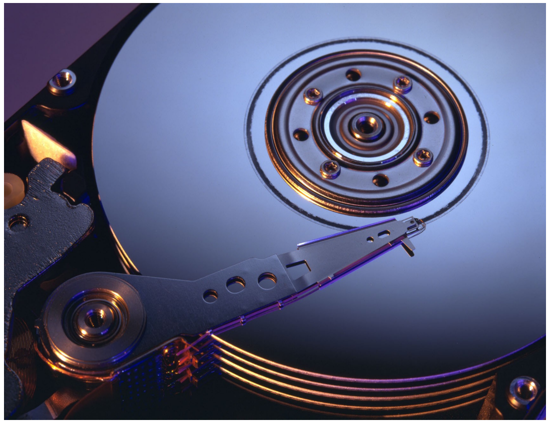


Computing: Magnetization dynamics

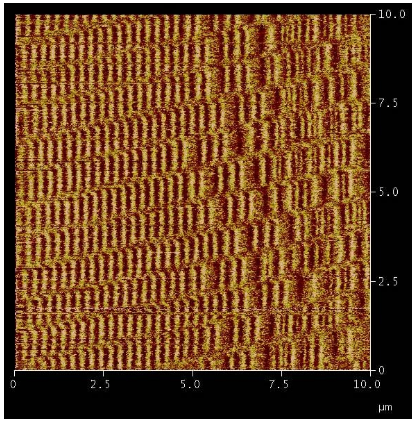
How fast can you write to magnetic storage medium?

Recent research indicates new route to controlled ultrafast switching of magnetic vortices with ultrashort magnetic pulses (“exchange explosion”).

B. Van Waeyenberge et al., Nature 444 (2006) 441

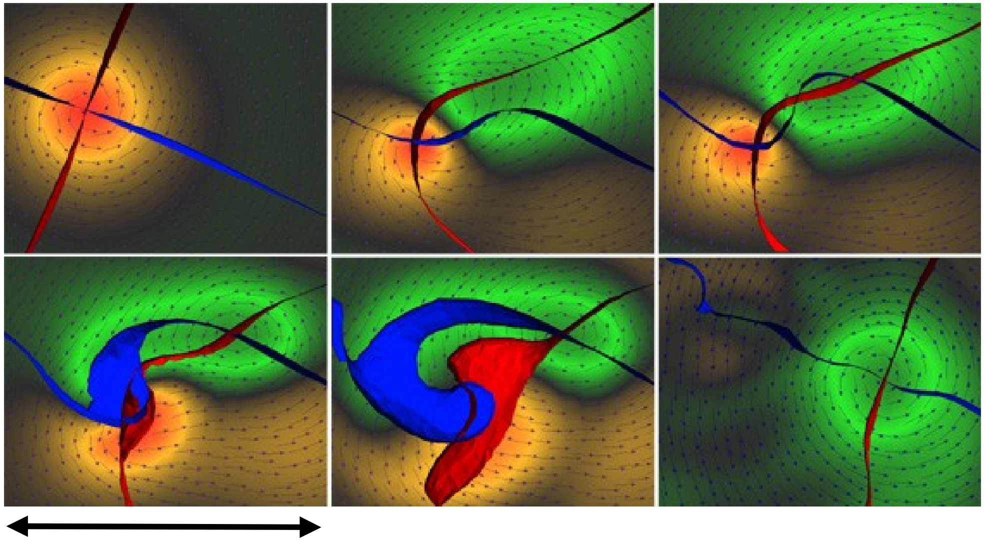


Commercial hard disk drive



Magnetic information on a hard disk (MFM image)

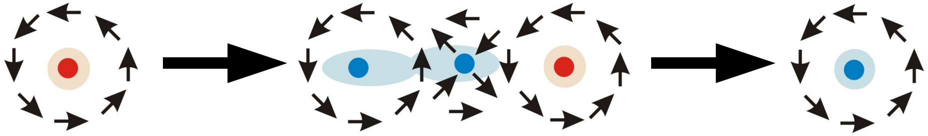
Simulation: core reversal by a field pulse (80 mT, 60 ps)



60 nm

Time step: 10 ps

R. Hertel, S. Gliga, M. Fahnle, C.M. Schneider, Phys. Rev. Lett. 98 (2007) 117201



Mechanism can be studied at SwissFEL in conjunction with THz source (300 mT, <1 ps)

Fundamental physics opportunities?

Two types of applications:

1) **Extend classical laser experiments to the X-ray regime**

Laser spectroscopy

Search for axions, i.e., light, weakly interacting (pseudo-) scalars

2) **exploit the extremely high electromagnetic fields available at the focus of a Free Electron Laser**

Ultrahot matter: Coulomb-barrier suppression ionization: instant absorption of GeV laser energy per nucleon

Quantum vacuum (non-linear QED, creation of Schwinger e^+e^- pairs a.k.a. “vacuum boiling”)

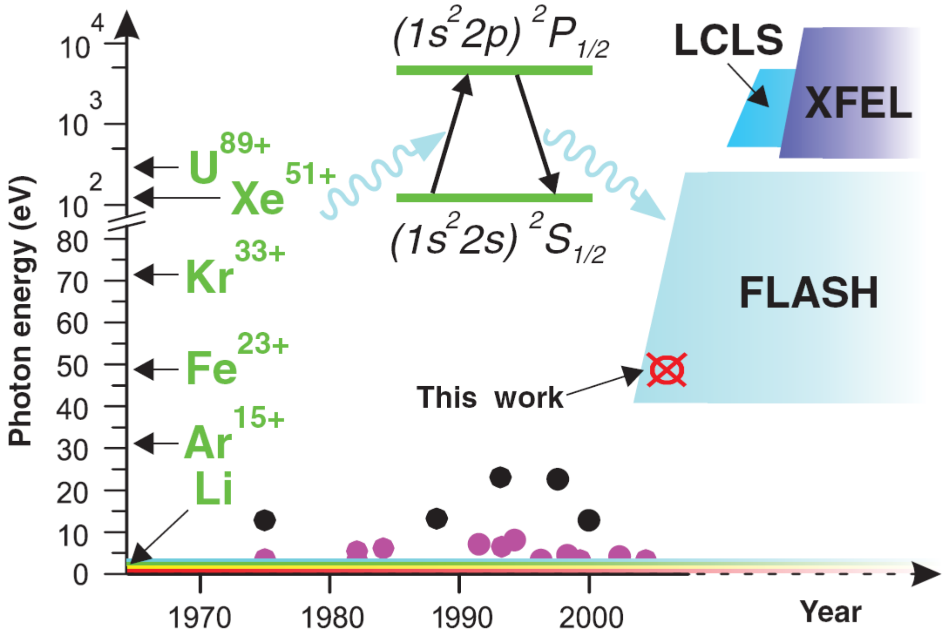
Horizon physics: the Unruh effect (“acceleration radiation”)

Good introductory reviews:

T. Tajima, Plasma Phys. Rep. 29 (2003) 231

A. Ringwald, hep-ph/0112254

X-ray laser spectroscopy



High-resolution resonant laser excitation of single electron transitions in highly charged ions (HCI)

Test of QED (and hence the SM) at ultra-high electromagnetic fields, up to 10^{18} V/m!

But: test is limited by theoretical uncertainties (mainly from interelectron interaction)

Highly relevant for astrophysics, as HCI constitute a dominant fraction of the visible matter in stars, supernovae, stellar clouds, jets etc.

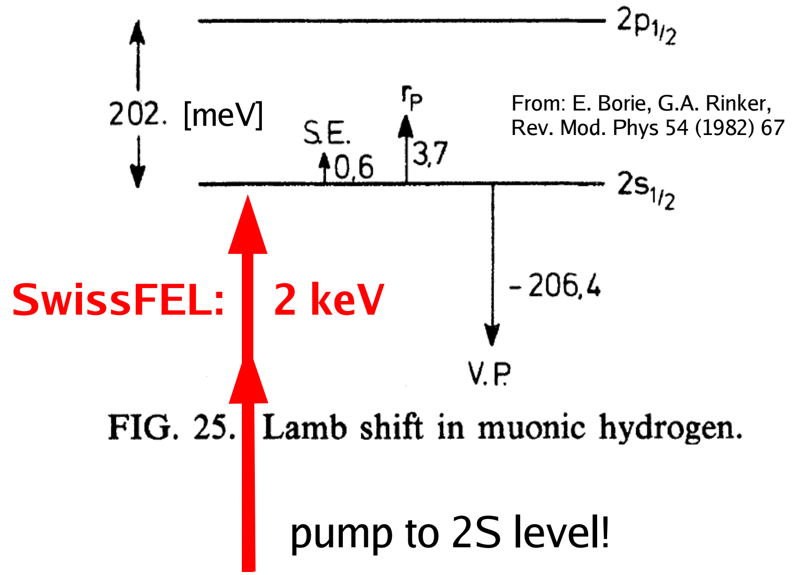
Successful proof-of-principle experiment at FLASH studying Li-like iron (Fe^{23+}).

S.W. Epp et al.,
Phys. Rev. Lett. 98 (2007) 183001

In principle, SwissFEL could also be used to study muonic atoms, e.g. **Lamb shift in muonic hydrogen** (Ch. Bressler)

muon source at PSI nearby, **if** Western site is chosen

Would require major additional development...



From: E. Borie, G.A. Rinker, Rev. Mod. Phys 54 (1982) 67

FIG. 25. Lamb shift in muonic hydrogen.

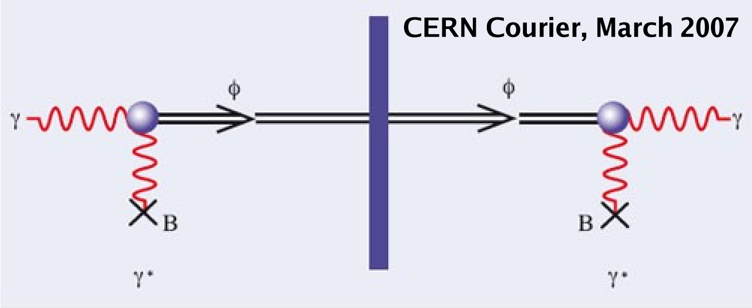
pump to 2S level!

Axion searches

Axion: hypothetical light weakly coupling (pseudo-) scalar particle

Best limits so far from solar experiments (axion production from photons inside the sun, reconversion to observable photons in dipole magnet on Earth)

Laser experiments ("light shining through a wall") represent an alternative, but up to now less sensitive approach to search for axions (or any light [pseudo]scalar boson)

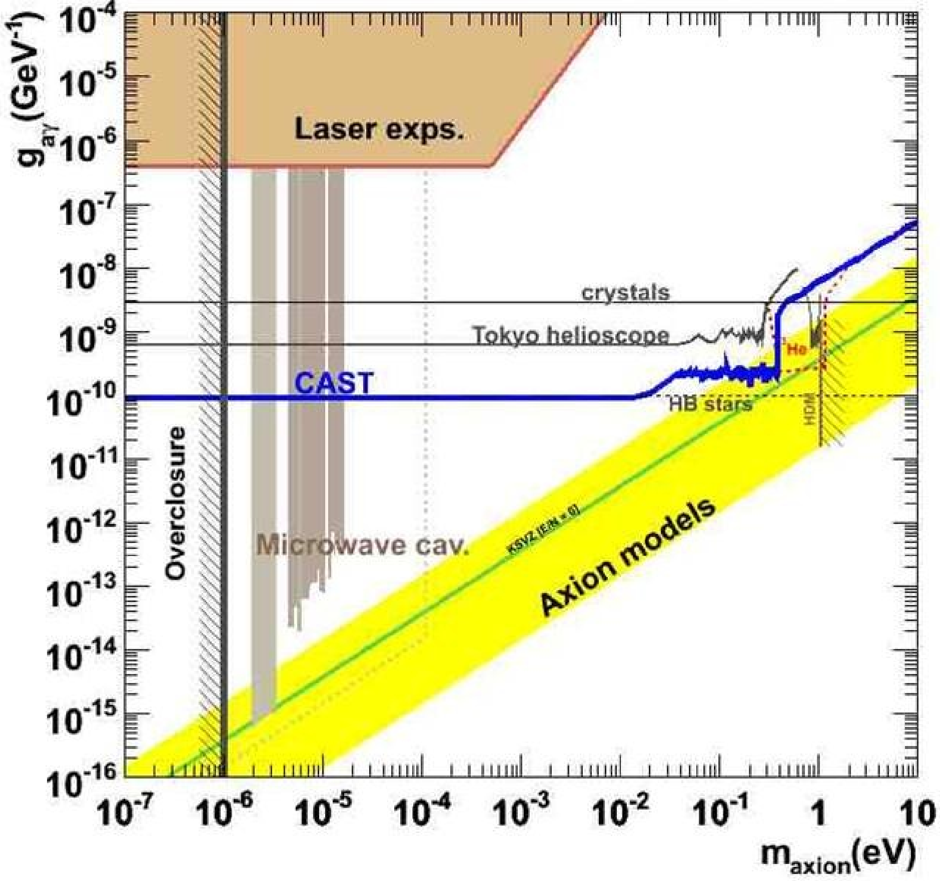


CERN Courier, March 2007

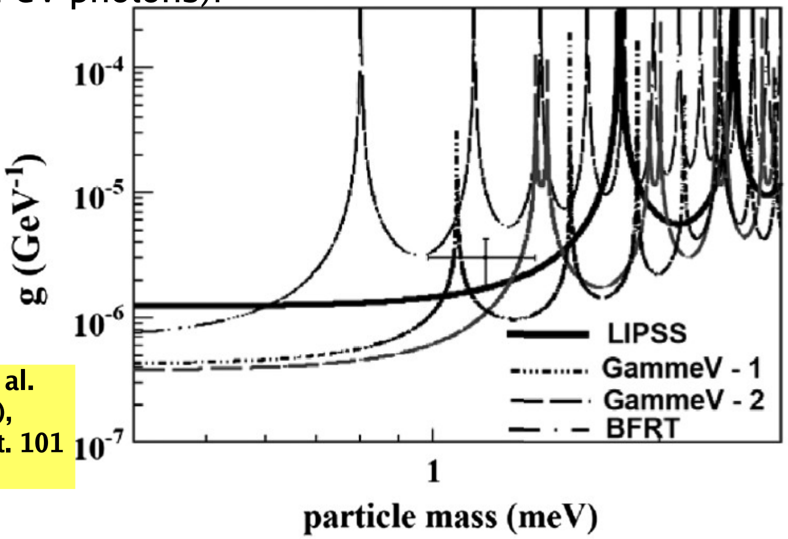
Both production and regeneration of axions are under laboratory control

Free Electron Lasers have the potential to bridge the gap between laser and solar experiments

Source: http://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=2582:

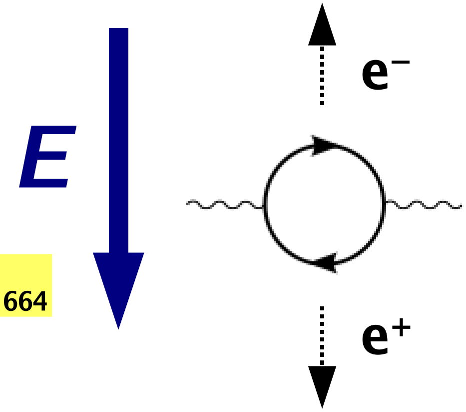


Experiment at Jefferson Lab Free Electron Laser (1.32 eV photons):



A. Afanasev et al. (LIPSS Collab.), Phys. Rev. Lett. 101 (2008) 120401

Extreme *E* fields (1):
the structure of the quantum vacuum



Julian Schwinger
(1918-1994)

At extremely high electromagnetic fields, vacuum polarization is ripped open and free e^+e^- pairs are produced.

J. Schwinger,
Phys. Rev. 82 (1951) 664

The observation of such **Schwinger pairs** would represent a powerful test of QED and has been suggested for X-ray FELs.

A. Ringwald,
Phys. Lett. B 510 (2001) 107

Necessary field (Schwinger field):

$$E_S = \frac{m_e c^2}{e\lambda_e} = \frac{m_e^2 c^3}{e\hbar} = 1.3 \times 10^{18}\ \text{V/m}$$

SwissFEL pulse:

10^{11} photons of 12.4 keV in 20 fs (peak power of 10 MW), focussed on an area of $100 \times 100\ \text{nm}^2$:

$$I = 10^{24}\ \text{W/m}^2 = \tfrac{1}{2}\, \varepsilon_0\, c\, E^2$$

$$\boldsymbol{E = 3 \times 10^{13}\ \text{V/m}}$$

Not realistic for the current configuration!

But: future advances in peak power and X-ray focusing may bridge the gap!

Example (Ringwald): peak power in the TW range combined with focusing at the diffraction limit (0.1 nm) results in fields of the order of 10^{17} V/m

But competition from CPA table-top lasers!

T. Tajima, G. Mourou,
Phys. Rev. STAB 5 (2002) 031301

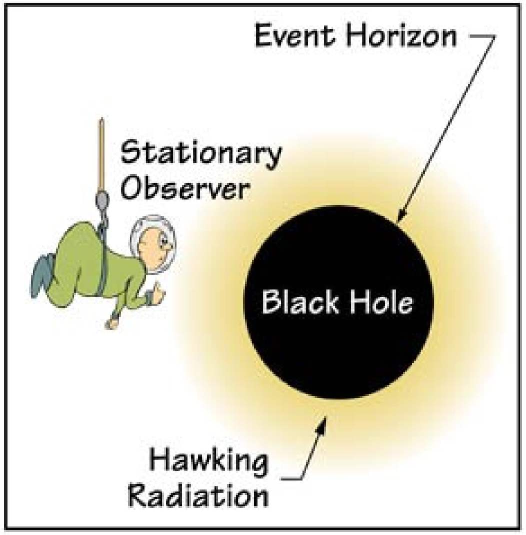
Extreme *E* fields (2): Horizon physics

For a sufficiently strong laser field, the transverse acceleration experienced by an electron positioned at the laser focus becomes comparable to the acceleration near a black hole.

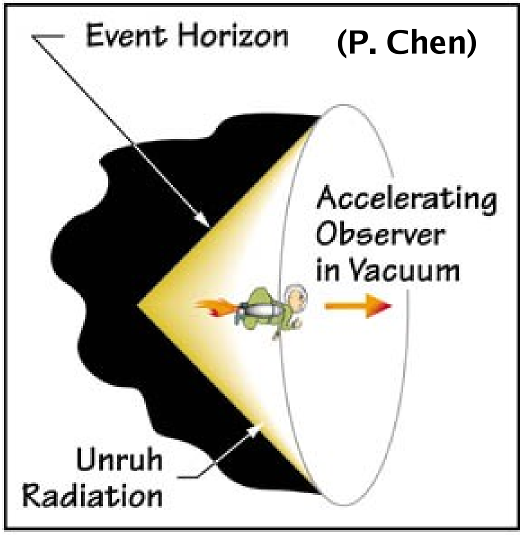
By virtue of the equivalence principle, the accelerated electron's event horizon must emerge at a finite distance.

Radiation from this horizon is equivalent to Hawking radiation but for historical reasons is called “acceleration radiation” or **Unruh radiation.**

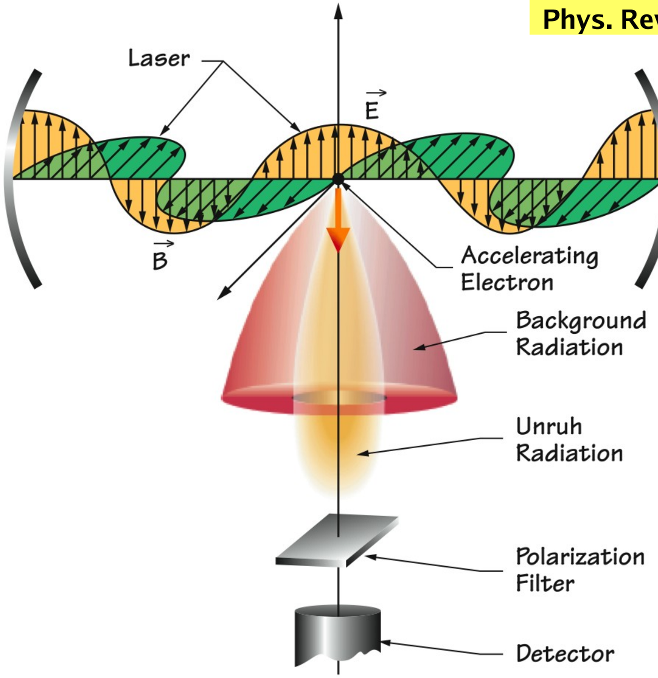
W.G. Unruh,
Phys. Rev. D 14 (1976) 870



A stationary observer outside the black hole would see the thermal Hawking radiation.



An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.



(P. Chen)

Source: http://home.slac.stanford.edu/pressreleases/2000/20000606.htm

Detection of this radiation is in principle possible according to Chen and Tajima.

P. Chen, T. Tajima,
Phys. Rev. Lett. 83 (1999) 256

Measurement of spectrum could reveal crucial information on the structure of space-time, e.g., the presence of extra-dimensions.

T. Tajima, G. Mourou,
Phys. Rev. STAB 5 (2002) 031301

But observability and interpretation of radiation still highly controversial (Ford and O'Connell).

G.W. Ford, R.F. O'Connell,
Phys. Lett. A 350 (2006) 17

E.T. Akhmedov, D. Singleton,
JETP Letters 86 (2007) 615

See also: http://www.extreme-light-infrastructure.eu/High-field_5_2.php
http://www.munich-photonics.de/research-areas/area-b1/area-b11

Extreme *E* fields (2): Horizon physics

For reasonable signal-to-noise ratio (Unruh vs. Larmor radiation) the laser light must be *relativistic*, i.e., the **normalized vector potential**

$$a_0 = \frac{eE}{m_e \omega c} \geq 1$$

Again, the acceleration reached by the current configuration of the SwissFEL falls short by a few orders of magnitude.

But the mere prospect of measuring the effect warrants some effort and thought!

SwissFEL pulse:

10^{11} photons of 12.4 keV in 20 fs (peak power of 10 MW), focussed on an area of 100 × 100 nm^2:

$I = 10^{24}\ \text{W/m}^2 = ½\ \varepsilon_0\ c\ E^2$

$\boldsymbol{E = 3 \times 10^{13}\ \text{V/m}}$

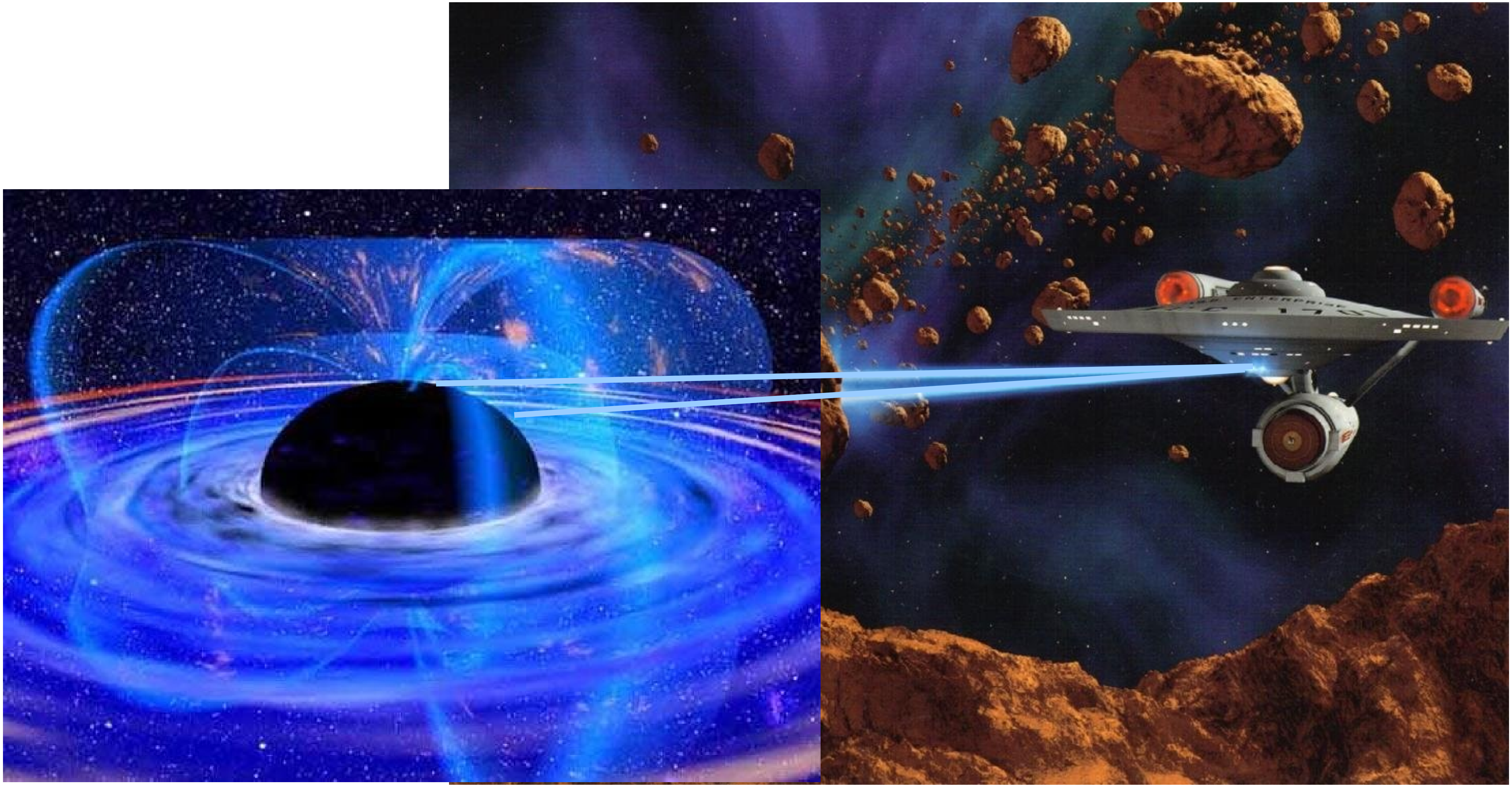
$\boldsymbol{a_0 \approx 10^{-3}}$

Further potential applications of extremely high *E* fields:

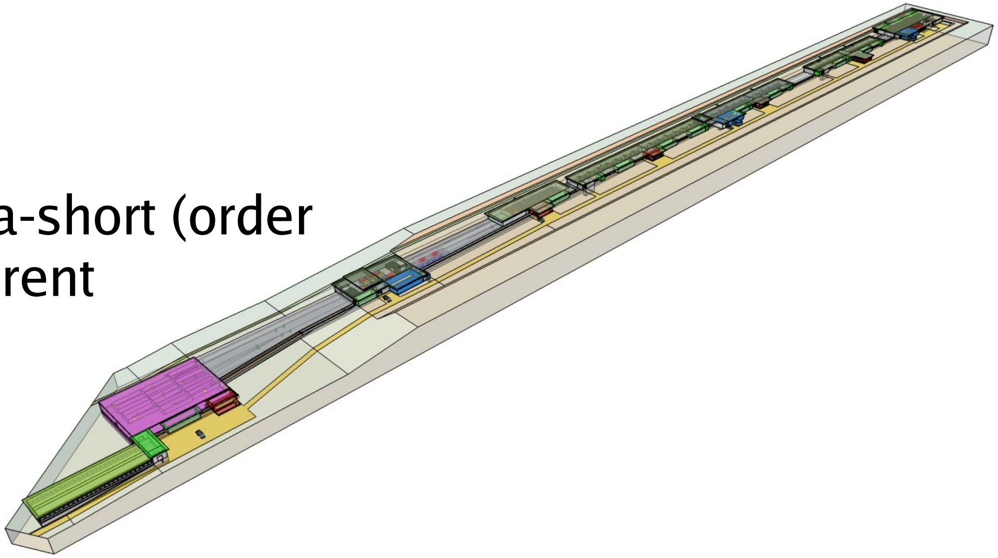
(not covered here)

- “Coulomb-barrier suppression ionization”: instant absorption of GeV laser energy per nucleon
  - ⇒ ultrahot matter (“driven quantum liquid”), quark-gluon plasma?
- Irradiation of metal target: extremely bright (coherent?) γ-source
- High-gradient wake-field acceleration through nano-hole
- Recreation of astrophysical conditions (e.g., gamma-ray bursts), …

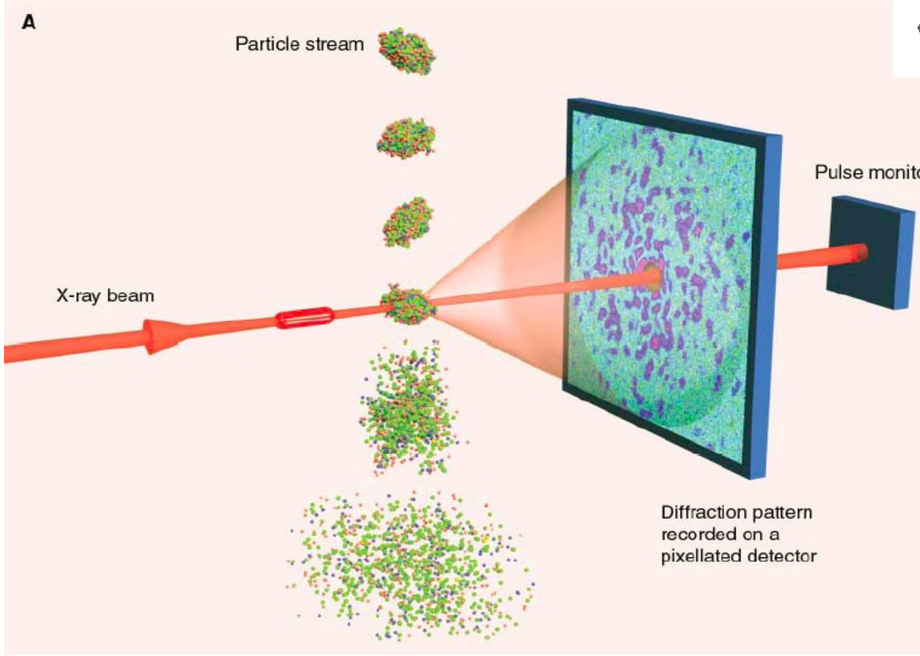
And you thought it was just another light source…



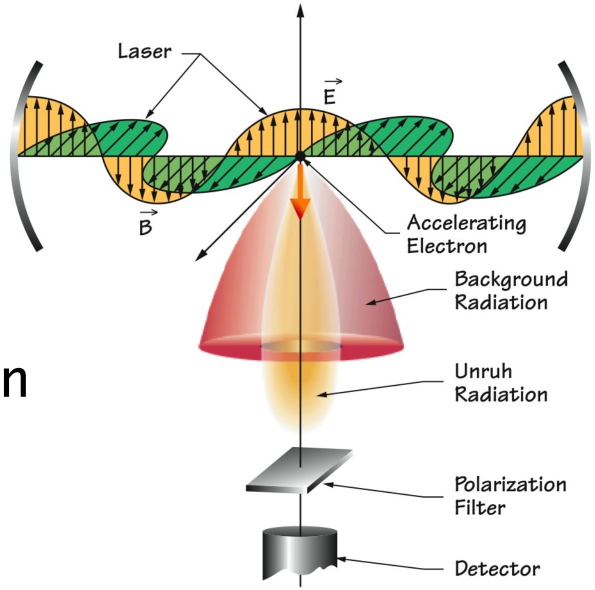
Summary



- SwissFEL is a novel source of ultra-short (order 10 fs), ultra-brilliant pulses of coherent photons with 0.1 nm < λ < 10 nm (0.12 keV < E_γ < 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.



- The photon pulses reach intensities that may even challenge fundamental physics (QED, GR)...