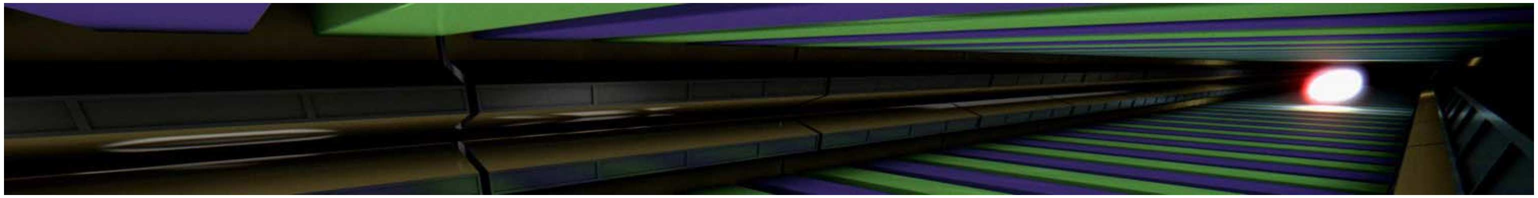


Free-electron lasers as sources of extremely brilliant x-ray radiation (Introduction European XFEL)

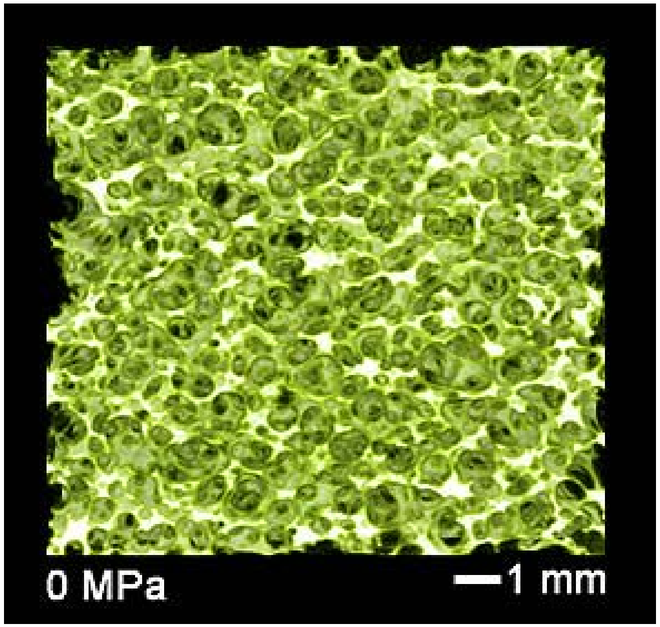
Winter School of Synchrotron Radiation,

Liptovsky Jan, Slovakia, Feb 01 – 04, 2011

Thomas Tschentscher

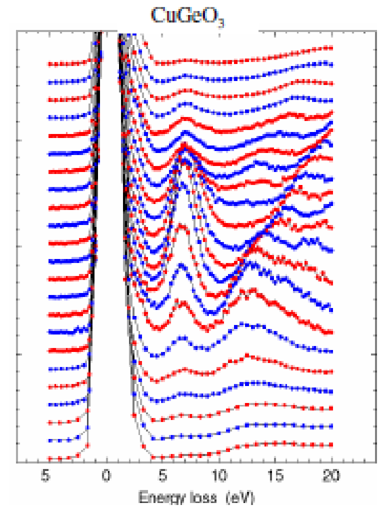
thomas.tschentscher@xfel.eu

Synchrotron radiation sources

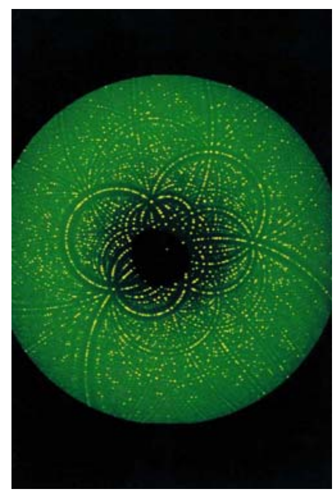


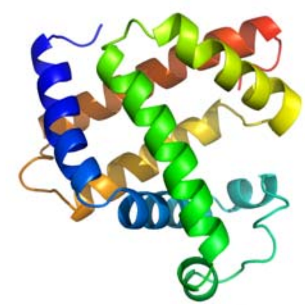
Imaging
[Metallic foam (ESRF),
Adv. Mat. 19, 1957 (2007)]

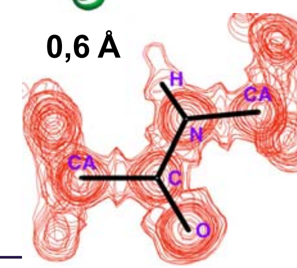
High resolution
x-ray spectroscopy
[RIXS, Cu K-edge,
courtesy J. Hill]

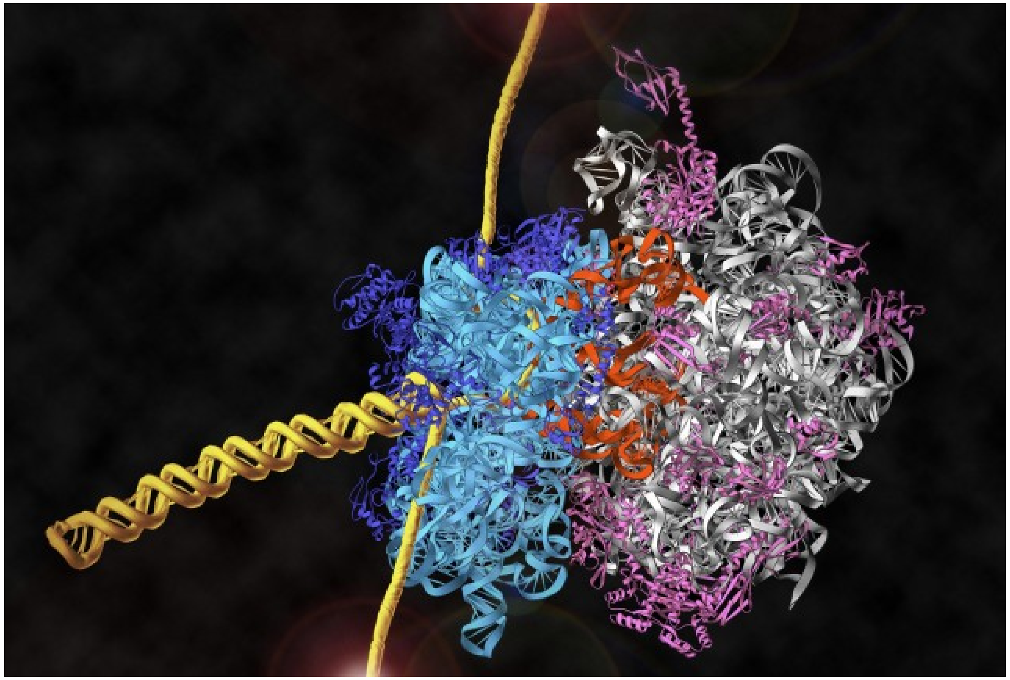


High resolution
3-dimensional structures
by x-ray diffraction









Structure of the Ribosome

Venkatraman Ramakrishnan,
Thomas A. Steitz, Ada E. Yonath
Nobel prize Chemistry 2009

Beyond synchrotron radiation …

Investigation of dynamic processes

- ultrafast, pico- & femtosecond phenomena govern many physical, chemical and biological processes

Investigation of nano-scale, disordered, non-crystalline matter

- geometrical structures of particles and bio-systems
- properties of matter at un-common length scales

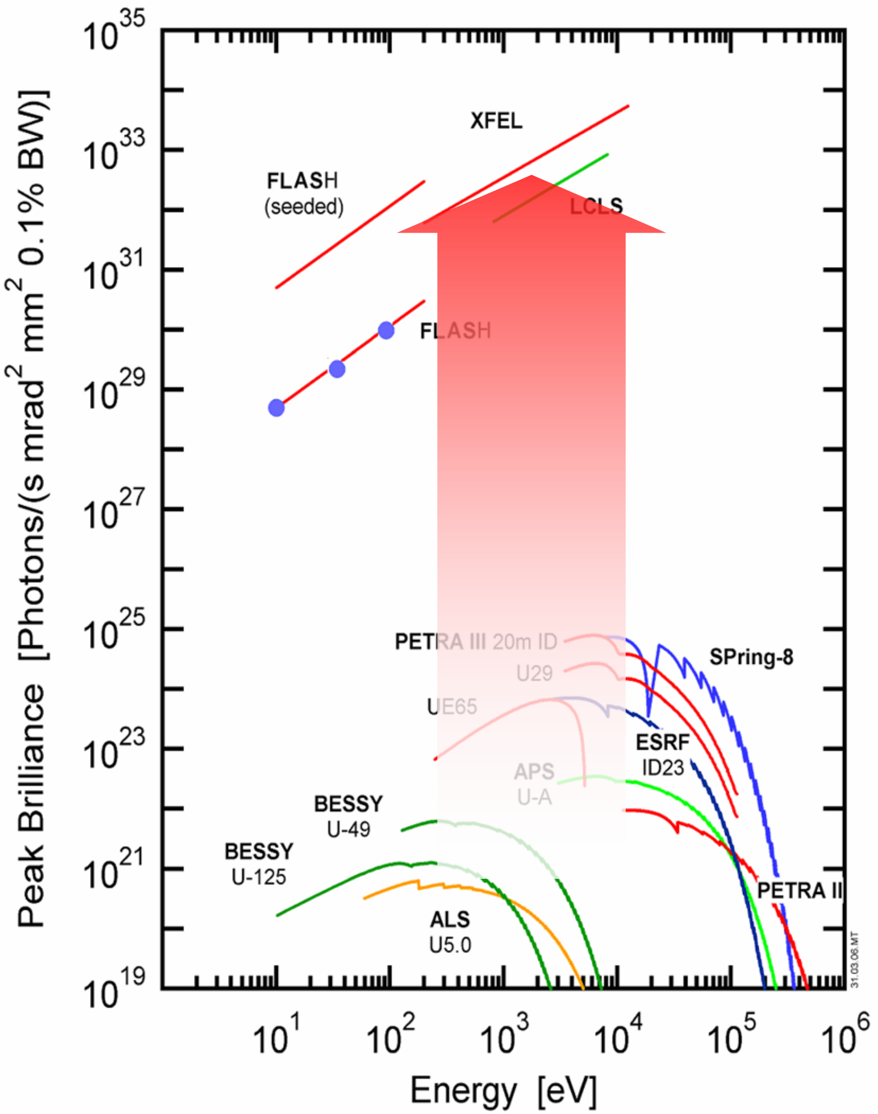
Investigation of highly excited matter

- x-ray excitation and non-linear phenomena
- measurement of extremely short-living states

Often combination of these techniques are required

⇒ X-Ray Free-Electron Laser sources open new scientific possibilities

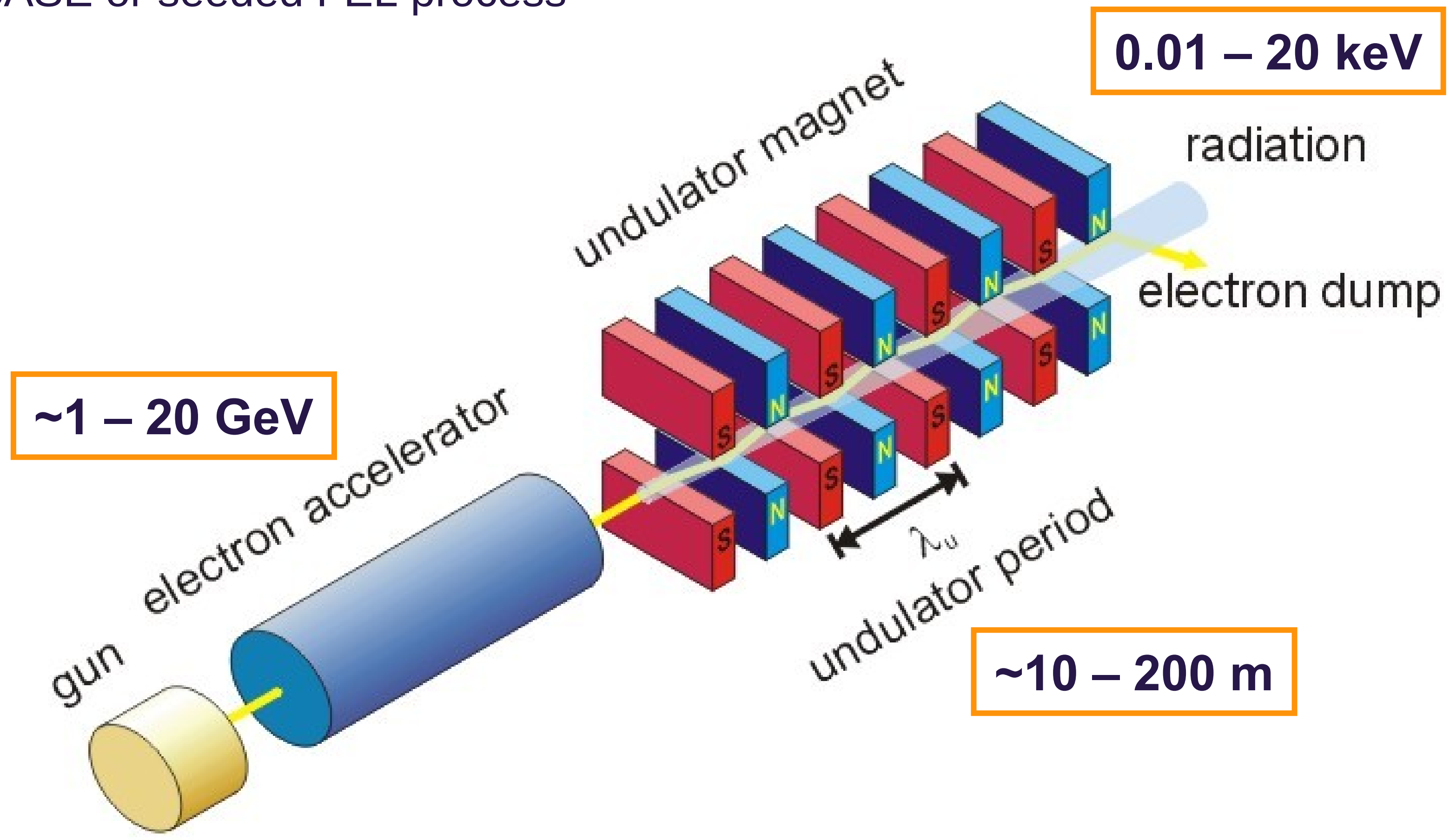
Photons per phase space volume and bandwidth element



⇒

- **Atomic resolution**
- **Ultrafast pulses**
- **Coherence**
- **High intensities**

- low emittance high energy energy accelerator
- SASE or seeded FEL process



FEL process requires small emittance

FEL radiation power *P* grows exponentially with undulator distance *z*

$$P \propto \left(z / L_G \right)$$

… but only if

- time-sliced energy spread $\sigma_{e,slice} << 10^{-3}$

  and
- transverse slice emittance $\varepsilon_{tr,slice} \leq \lambda / 4\pi$

Power gain length L_G

$$L_G \propto \left(\varepsilon / I_P \right)^{-1/3}$$

peak current

FEL power saturates at ~20 L_G

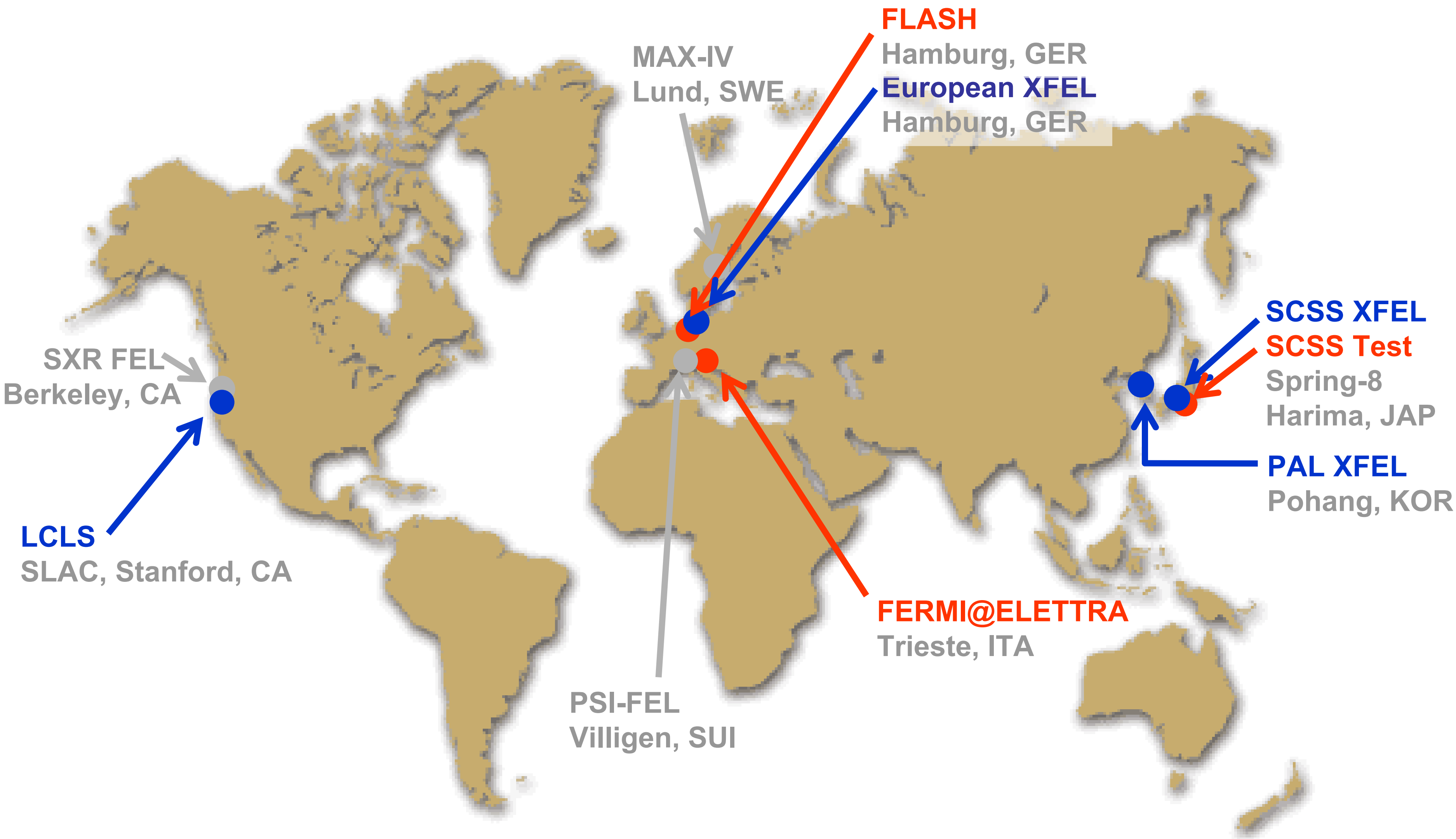
⇒ **SASE performance depends exponentially on e⁻ beam quality (emittance & peak current!)**

Outline

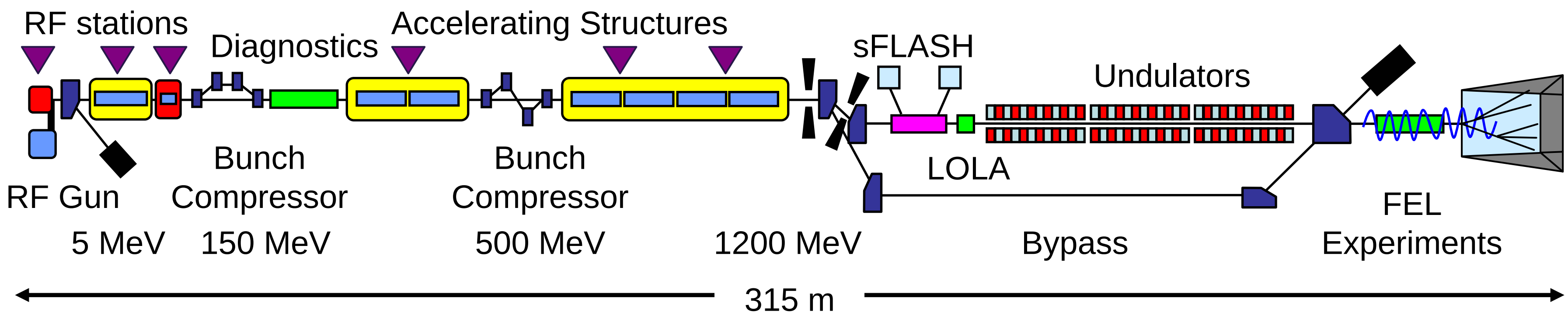
- **Motivation & Opportunities**
- **X-ray Free-Electron Lasers worldwide**
  - Working machines
  - FLASH & European XFEL in Hamburg
  - International competition
- **The European XFEL project**
  - Overview
  - Science instruments
  - Status of construction
  - High repetition rate operation
- **Conclusions**

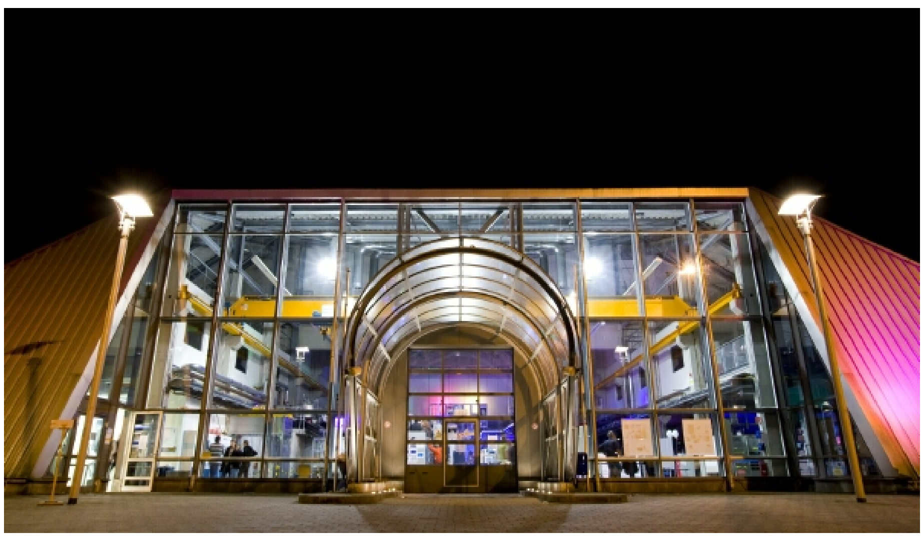
1971	Principle of FEL operation (J. Madey)
1980	Principle of X-ray generation in undulator (Kondratenko & Saldin)
1984	Principle of high gain (Bonifacio & Pellegrini & Narducci)
1995	Decision to build FLASH
2001	FLASH lases at 12 eV
	Decision to build LCLS
	Initial proposal for European XFEL (TESLA XFEL laboratory)
2005	FLASH lases at 100 eV
2007	Decision to build European XFEL
2008	Start construction European XFEL
2009	LCLS lases at 8000 keV
2010	FLASH lases in water window (at 300 eV)
2011	New FELs in operation FERMI@ELETTRA, SCSS(SP-8)

Soft/Hard X-ray FELs worldwide

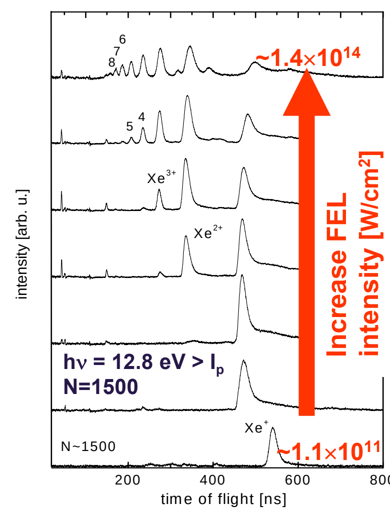


The first User Facilty : FLASH @ DESY



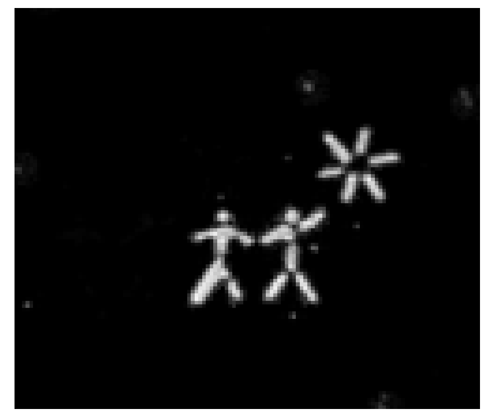


2001



H. Wabnitz et al., Nature 420, 482 (2002)

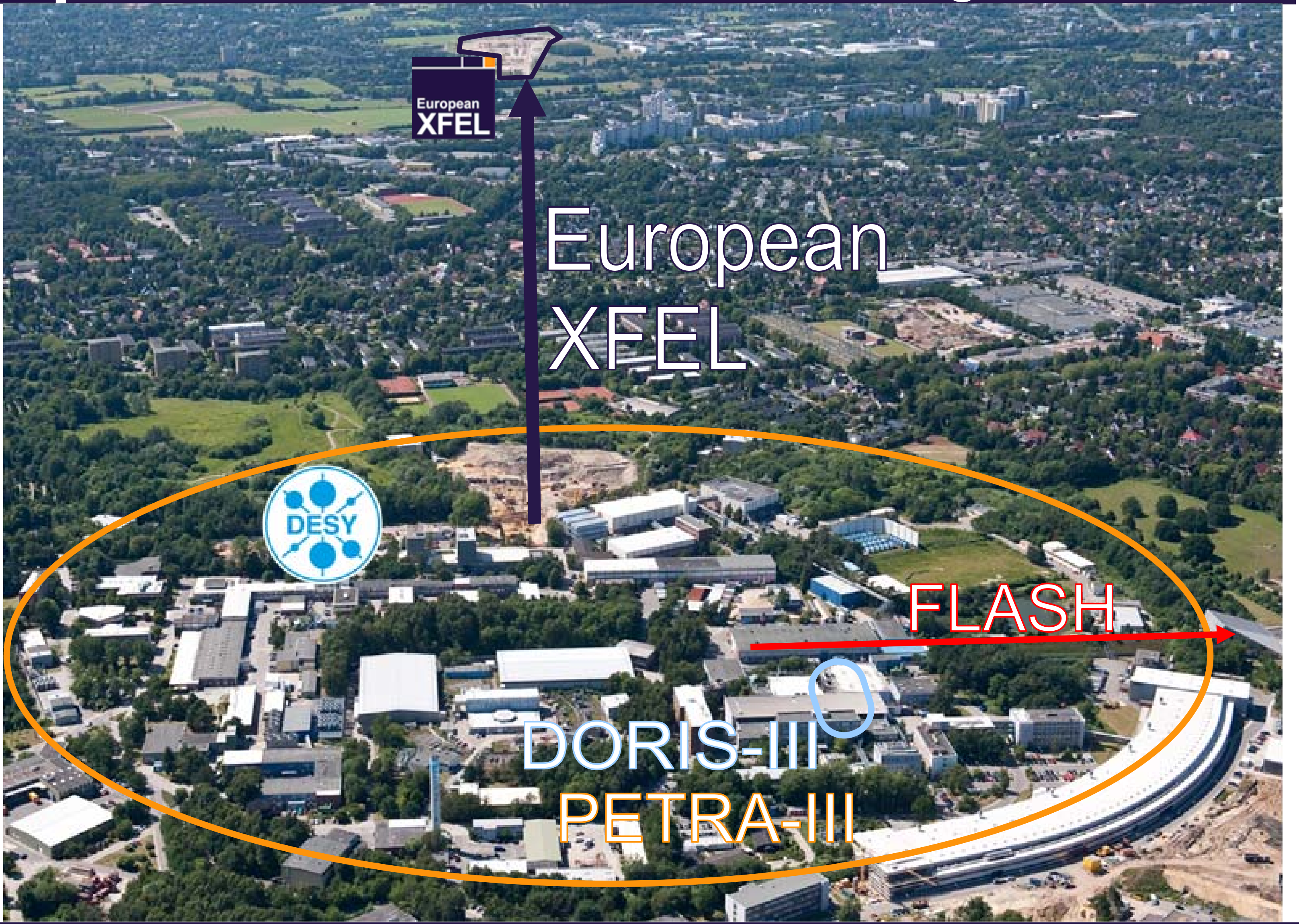
2005



H. Chapman et al., Nature Phys. 2, 839 (2006)

see presentation S. Toleikis

Photon science facilities in Hamburg-Bahrenfeld



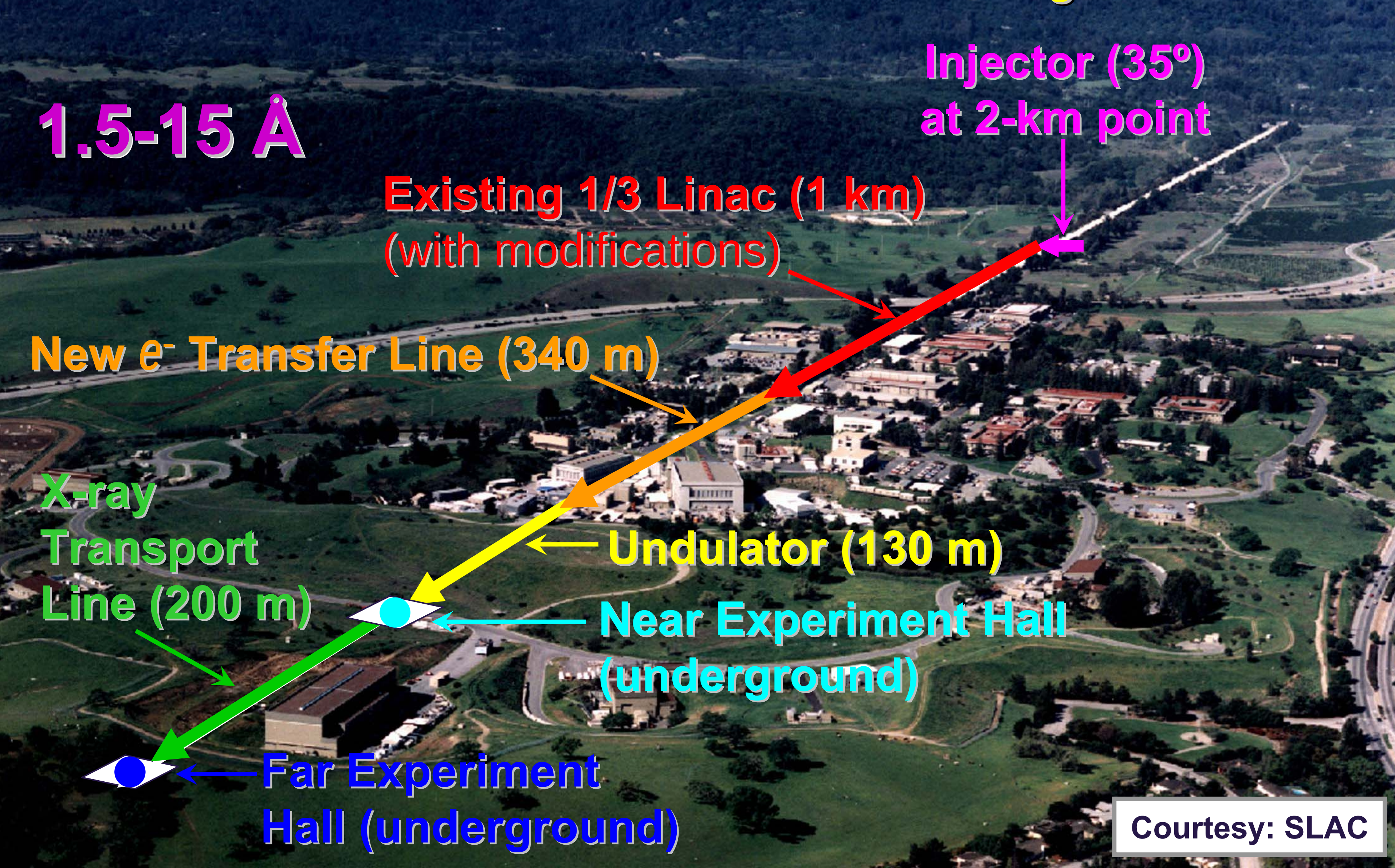
FLASH & European XFEL

FLASH is an important test-bed for the European XFEL

- Super-conducting low emittance accelerators
  - → **Basic principle, low emittance, diagnostics, synchronisation, …**
- Proof-of-principle of FEL radiation
  - → **short-wavelength SASE mode, HHG seeding, …**
- Transport of FEL radiation
  - → **coherence properties, damage, diagnostics, …**
- Additional instrumentation
  - → **Detectors, lasers, sample delivery, DAQ/data, …**
- FEL user experiments operation
- New FEL science
- Education of young scientists

Linac Coherent Light Source at *SLAC*

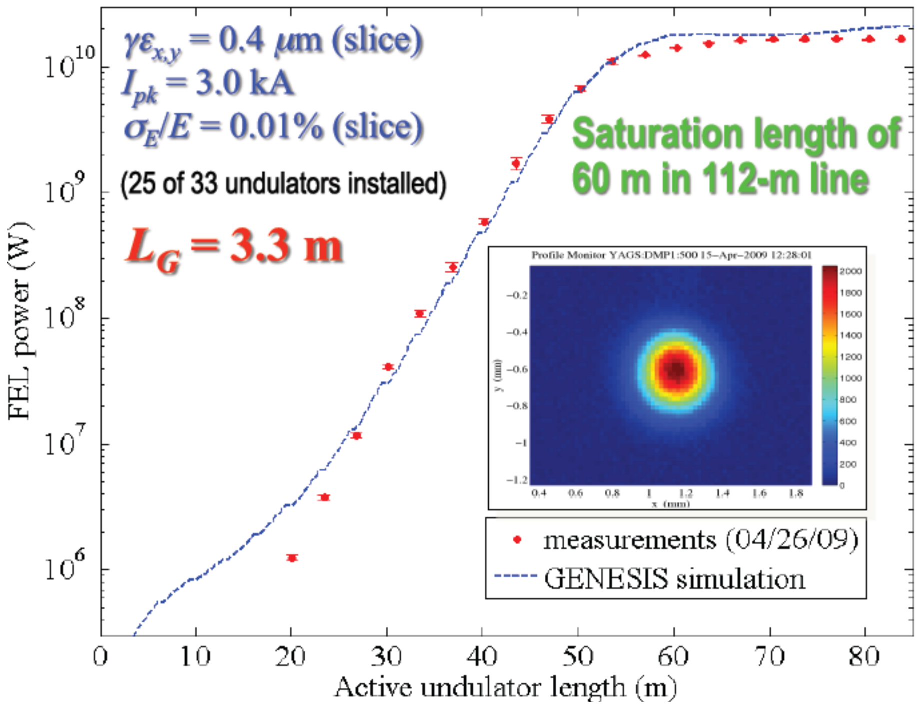
X-FEL based on last 1-km of existing linac



LCLS FEL undulator

Start of operation: 2009

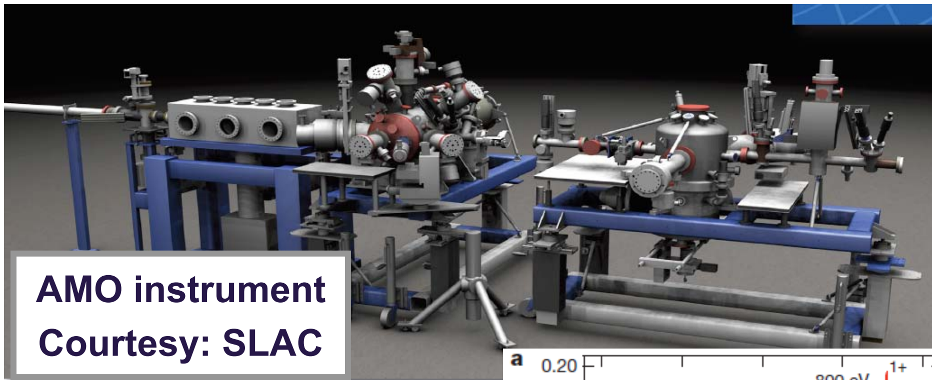
April: First FEL beam

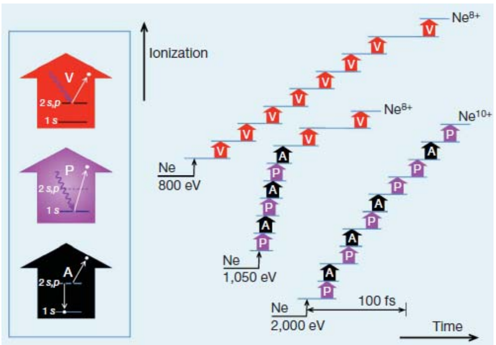


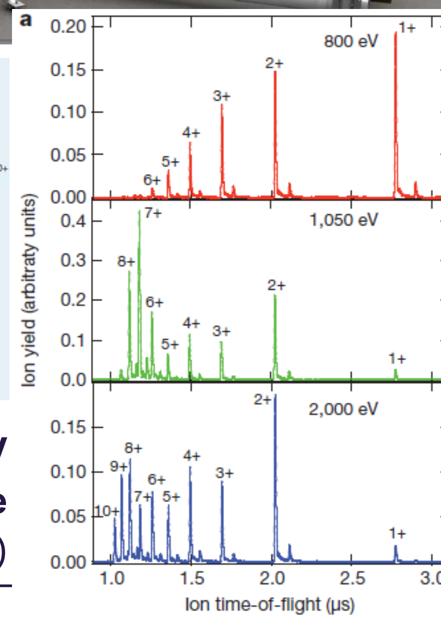
LCLS startup performance at ħω=8 keV

P. Emma et al., Nature Phot. 4, 641 (2010)

October: First experiments







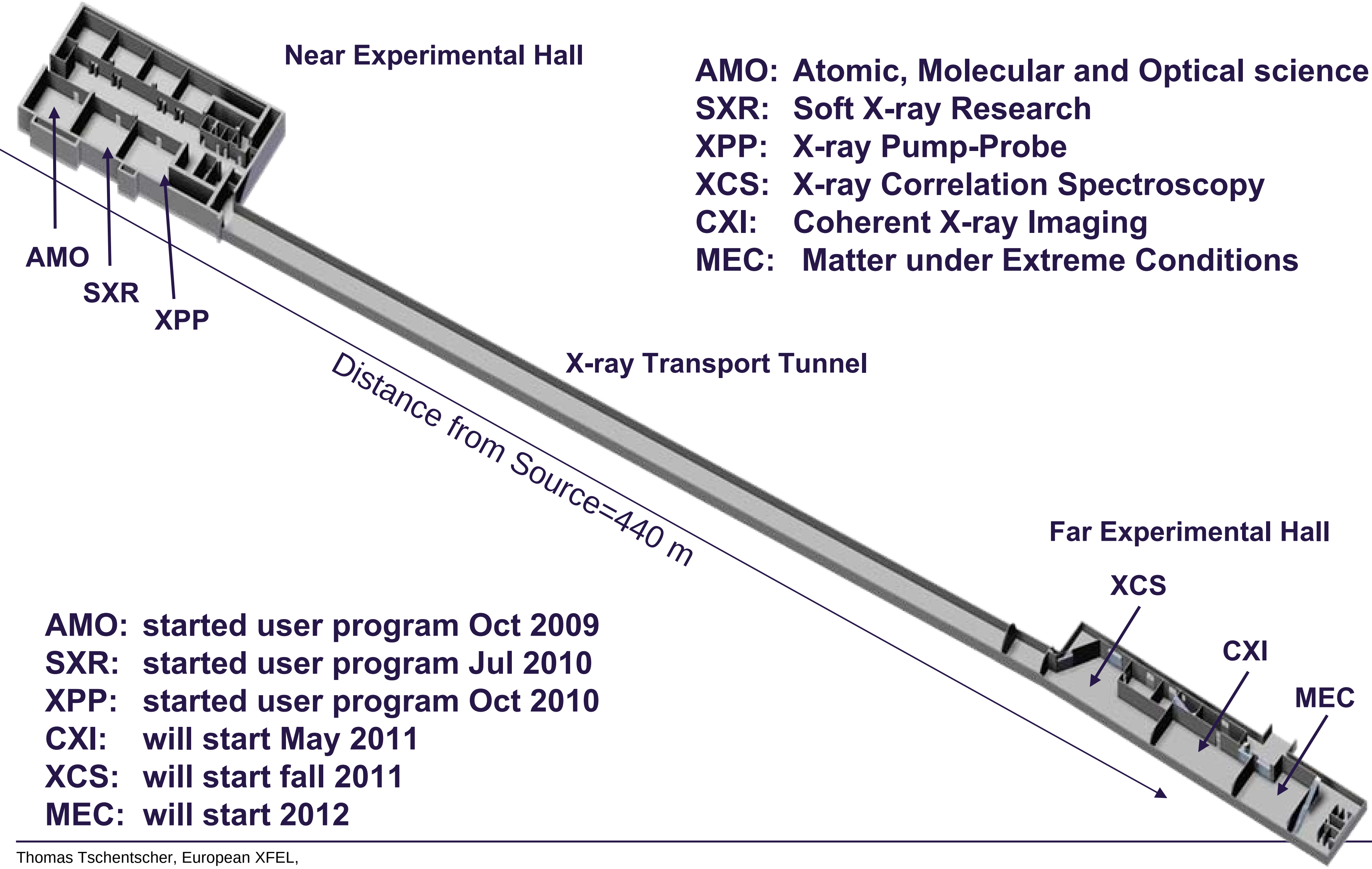
LCLS, ħω=800, 1050, 2000 eV
Ultrahigh photoionization in Ne

L. Young et al., Nature 466, 56 (2010)

European XFEL

LCLS instruments

AMO: Atomic, Molecular and Optical science
SXR: Soft X-ray Research
XPP: X-ray Pump-Probe
XCS: X-ray Correlation Spectroscopy
CXI: Coherent X-ray Imaging
MEC: Matter under Extreme Conditions



AMO: started user program Oct 2009
SXR: started user program Jul 2010
XPP: started user program Oct 2010
CXI: will start May 2011
XCS: will start fall 2011
MEC: will start 2012

Other hard x-ray FEL projects

SCSS

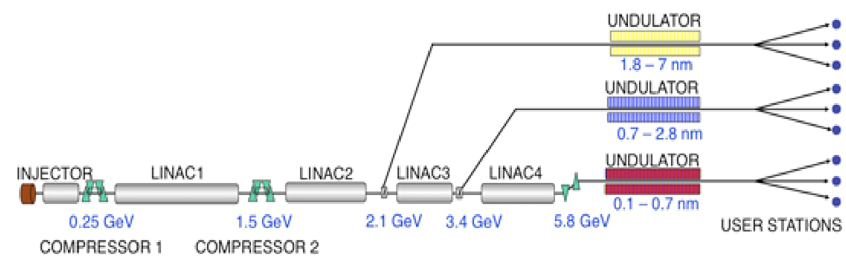
- Spring-8 (Harima, Japan)
- ~1 – 15 keV; 60 Hz; 8 GeV
- start spring 2011

PAL XFEL

- Pohang Light Source, Corea
- 1 – 12 keV; 50 Hz; 6 GeV (?)
- start 2015

SwissFEL (funding pending)

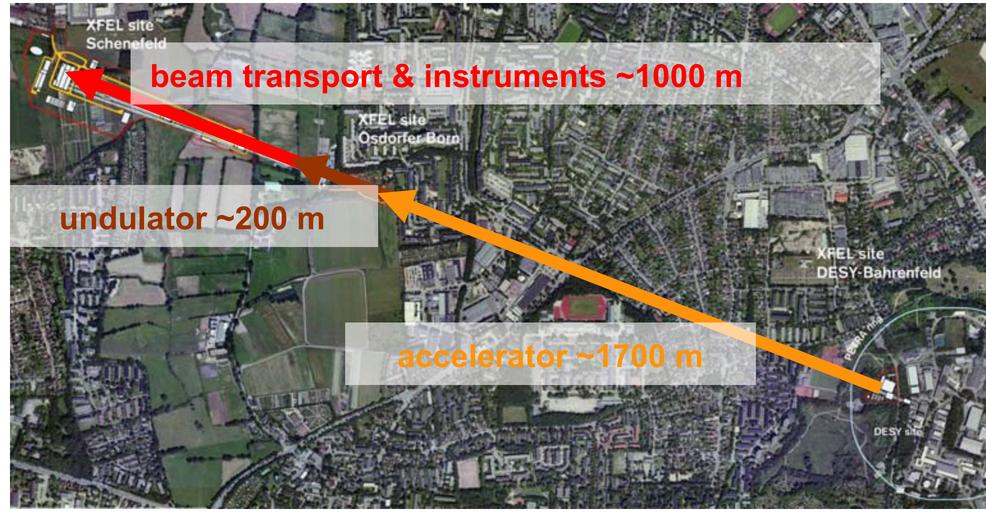
- PSI/SLS, Switzerland
- 0.2 – 15 keV, 100 Hz, 6 GeV
- start 2016



Outline

The European XFEL

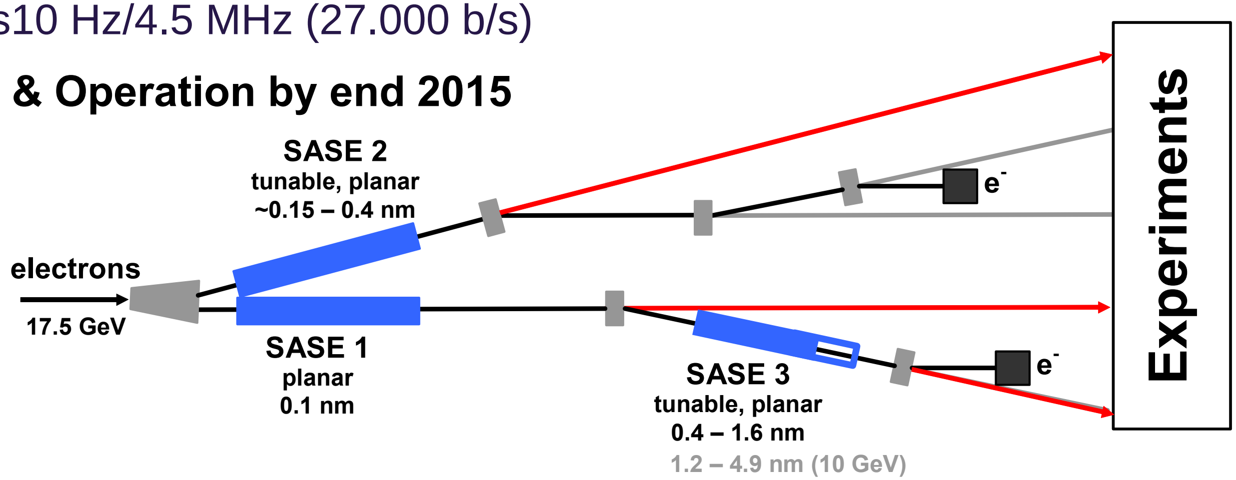
International research infrastructure for the application of soft & hard X-ray FEL radiation in user experiments by a multi-disciplinary science community.

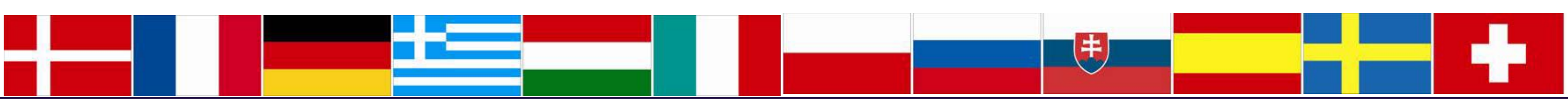


FEL characteristics

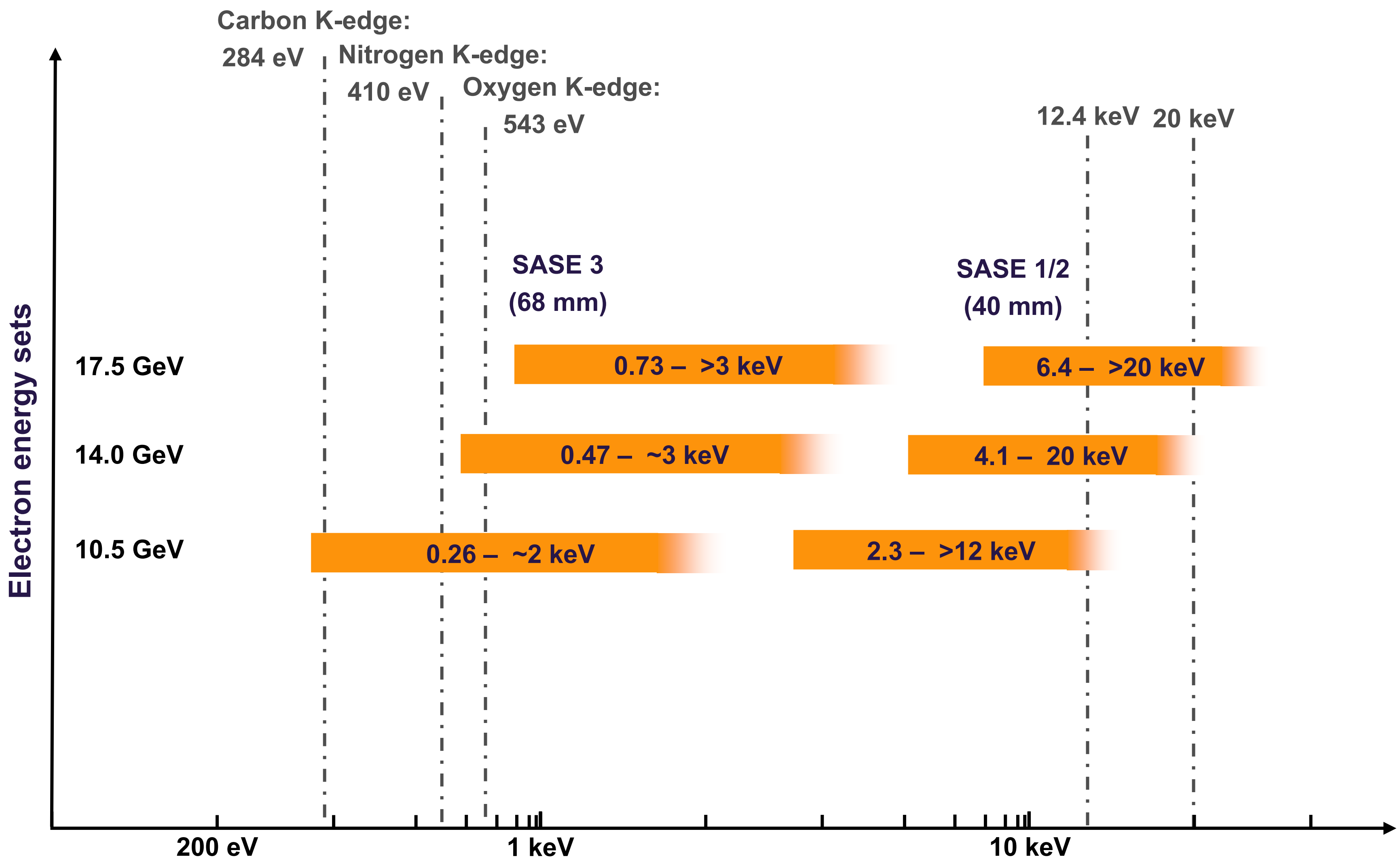
- X-ray range 0.3 – ~20 keV
- Pulse duration 5 – 100 fs
- Rep. rates10 Hz/4.5 MHz (27.000 b/s)

First beam 2014 & Operation by end 2015





Undulator ħω ranges

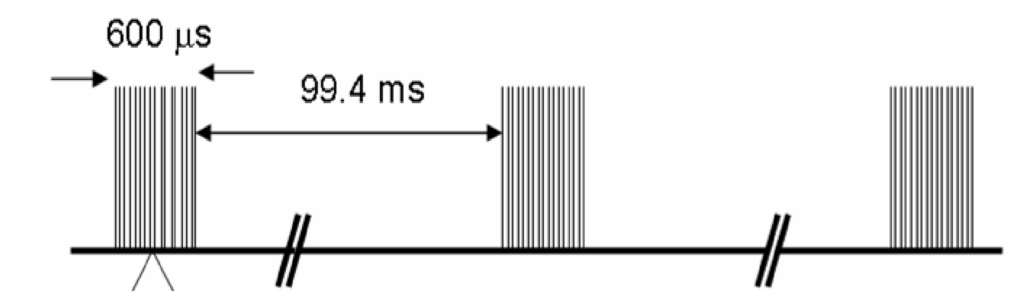


updated layout, Feb 2011

Increase capacity: High bunch repetition rate

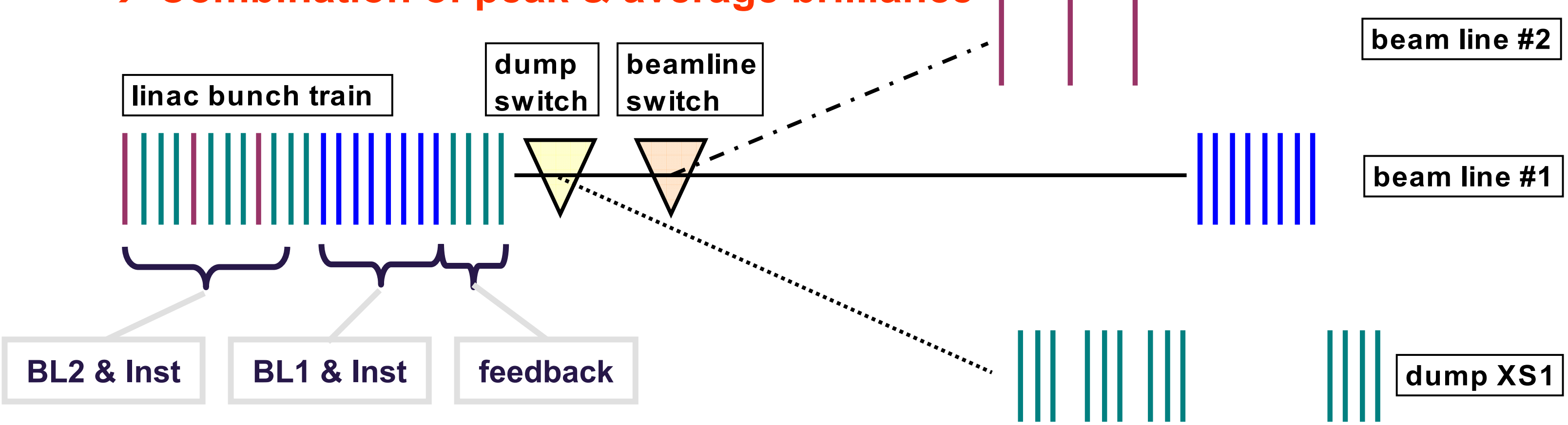
Electron bunch delivery

- pulsed SCRF
  - → **FLASH**
  - → **European XFEL**

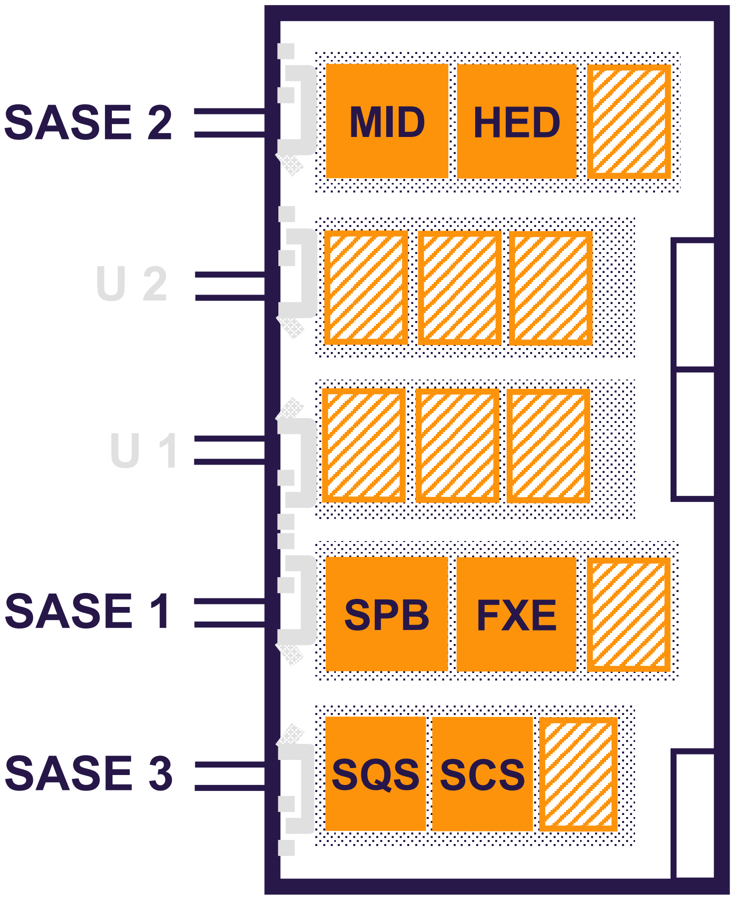


Advantages for user operation

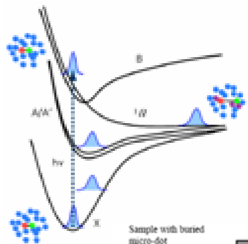
- enables stabilization by intra-bunch feedback
- higher flexibility of operation for simultaneous user experiments
- large number of delivered FEL pulses
  - → **Combination of peak & average brilliance**



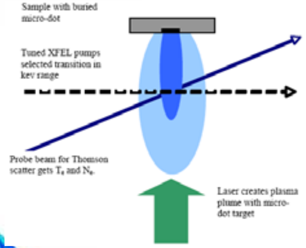
The suite of instruments



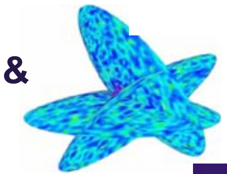
FXE Femtosecond X-ray Experiments



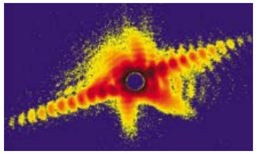
HED High Energy Density Science



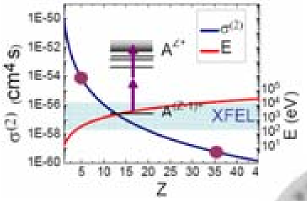
SPB Single Particle & Biomolecules



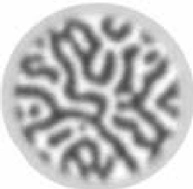
MID Materials Imaging & Dynamics



SQS Small Quantum Systems



SCS Spectroscopy & Coherent Scattering



European XFEL

Where European XFEL excels

Super-conducting electron accelerator

- high rep. rate and average brilliance, possibility to upgrade to cw-mode

X-ray beam transport

- extraordinary mirrors to transport coherent beam
- extreme power optics (~2 kW)
- innovative optics (thin-crystal diamond monochromator, beam-splitter)

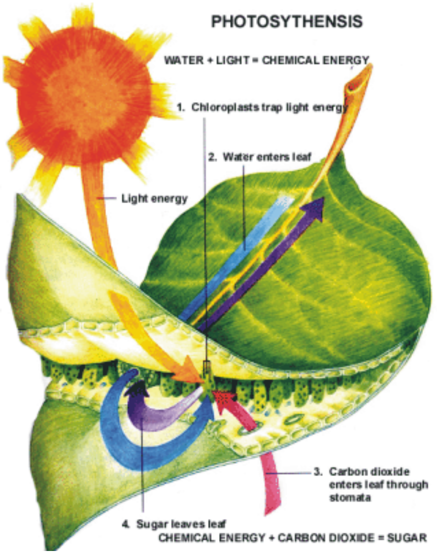
Scientific instruments

- provide state-of-the art instrumentation offering new science
- equipped for high rep. rate

Instrumentation

- suite of ancillary instrumentation required for FEL experiments running at high rep. rate
  - ➔ **lasers,**
  - ➔ **sample exchange & injection schemes,**
  - ➔ **area & line detectors,**
  - ➔ **data aquisition,**
- user facility mode

Science & application drivers



Reaction chemistry

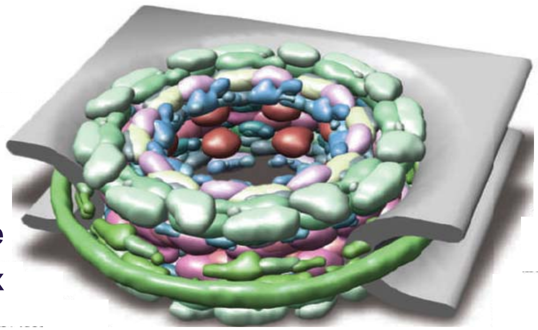
- time-resolved atomic structures
- catalysts, photo-chemistry
- develop new processes & products

Complex materials

- combine atomic & electronic structure
- functional materials, magnetism
- develop new materials

Life sciences

- atomic structure → function
- mol., complexes, cells
- develop new treatments



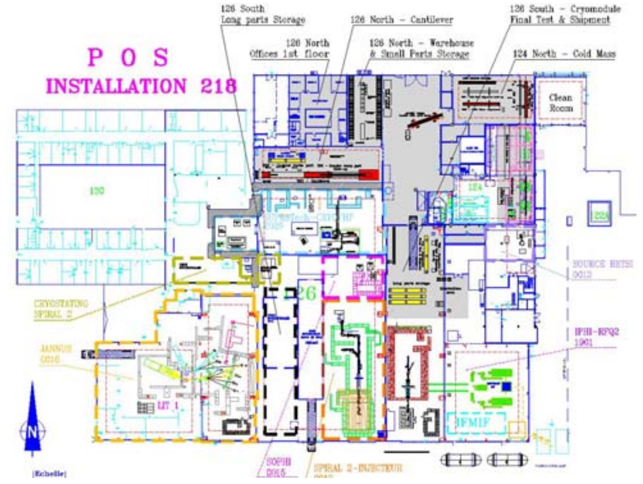
Nuclear pore complex

… these are only few examples out of a long list of research problems in many scientific disciplines from biology via physics to geo-sciences

Status European XFEL accelerator

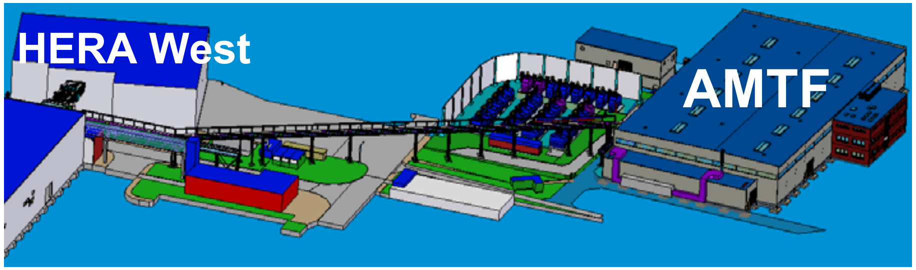
International collaboration builds super-conducting accelerator

- Accelerator consortium established
  - ➔ **Builds sc-accelerator through (mainly) in-kind contributions**
  - ➔ **DESY leads consortium**



irfu cea saclay

- In-kind contribution process accelerates
  - ➔ **module assembly**
  - ➔ **power couplers**
  - ➔ **electro-magnets**
  - ➔ **dumps**
- Tendering / purchasing large items started
  - ➔ **Niobium cavities**
  - ➔ **Module cold masses**
- Test facilities currently set up
  - ➔ **AMTF, cavity TF, WATF**



Civil construction progress

July 2010 – start of drilling tunnels

TULA inauguration Jun 30, 2010

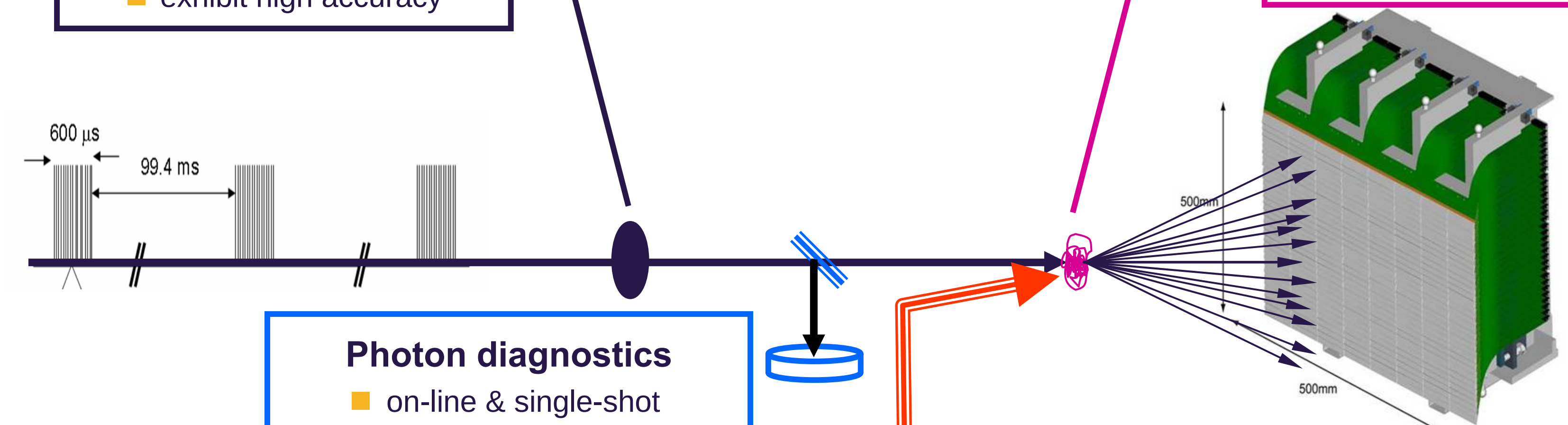
TULA again at XS1 (second tunnel completed)

XS1 Dec 2010

High repetition rate operation

X-ray optics
- withstand repetition rate
- exhibit high accuracy

Sample delivery
- match repetition rate
- positioning

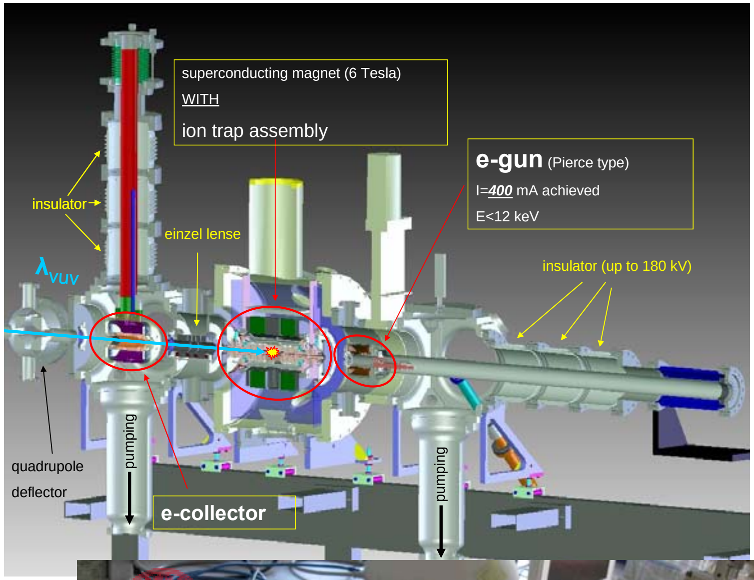


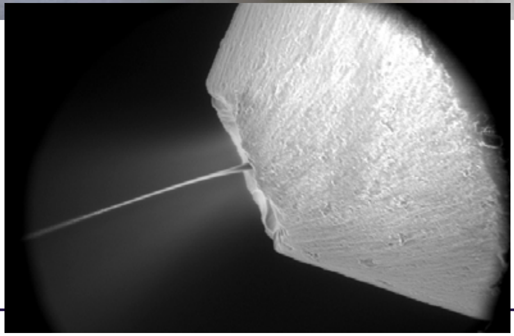
Photon diagnostics
- on-line & single-shot
- match repetition rate

Optical laser
- match repetition rate
- provide ~mJ excitation energy

Detectors
- match frame rate
- large data amounts

FEL experiments at high repetition rate





Atomic & high-field physics

- ultra-dilute samples
  - ➔ **gases (residual, ultra-clean, …)**
  - ➔ **traps (EBIT, ion beams, …)**
- particle injectors
  - ➔ **cluster sources**

Life sciences / structural biology

- particle injectors
  - ➔ **single molecules or entire cells**
- jets
  - ➔ **cells and molecules inside liquid phase**
  - ➔ **nano-crystals**

Chemistry/Solid-state physics

- jets
  - ➔ **solutions**
  - ➔ **particles inside liquid**

Conclusions

X-ray FELs for the soft and hard regimes have proven to show excellent beam properties. The European XFEL has started constructions and early experiments are scheduled for 2015.

♦

FEL science has only just started. Experiments have exploratory character and fields have to be established. In the soft x-ray regime this process is in full swing. Hard x-ray experiments only started in 2010. Coming years will enable to establish new fields.

♦

The European XFEL faces an exciting period of R&D at the highest level. The x-ray systems construction now starts. The are ample opportunities to get involved in the definition and possibly in the realisation of these.

There will be opportunities to join science teams, too !