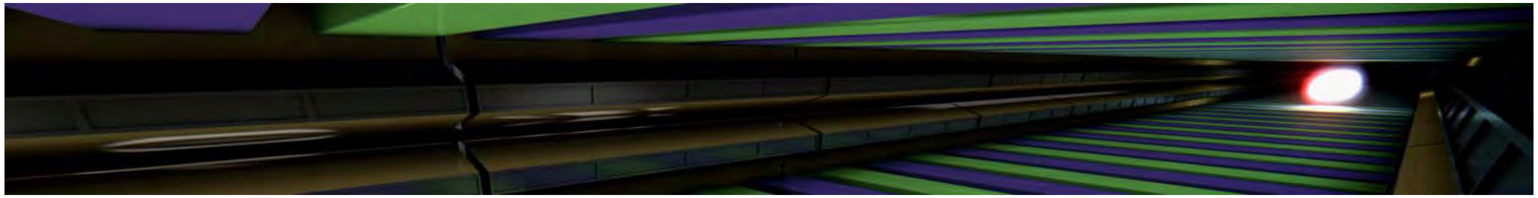


The European X-ray Free Electron Laser Project

Frank Stephan (DESY, Zeuthen site)

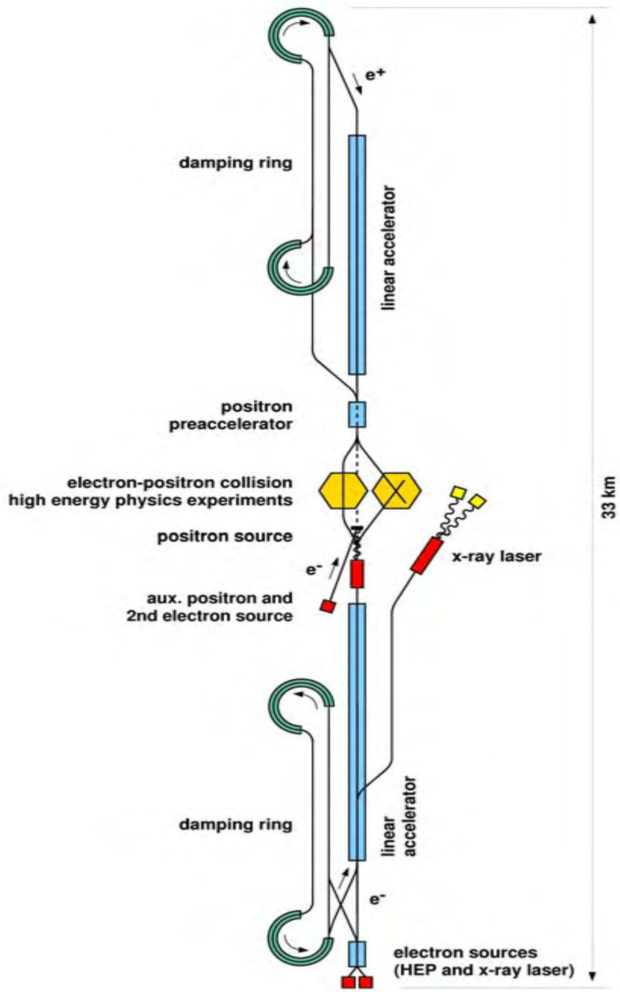
for the European XFEL Project Team

Content:

- the European XFEL
- it‘s precursor: the FLASH facility running in Hamburg, Germany
- one of the key components: the high brightness electron source

XFEL – how it began …

- 2001 – **TESLA Proposal** and Science Council Eval.
- Oct. 2002 – **X-ray FEL** with 20 GeV superconducting accelerator (TESLA-technology)
- Feb. 2003 - **Approval** by Federal Government as European project
- Nine countries signed **MoU for the Preparatory Phase** of the XFEL in January 2005
- July 2006 – **Technical Design Report**
- July 2006: **Plan Approval Process** completed
- 2009: groundbreaking started



XFEL – how it began …

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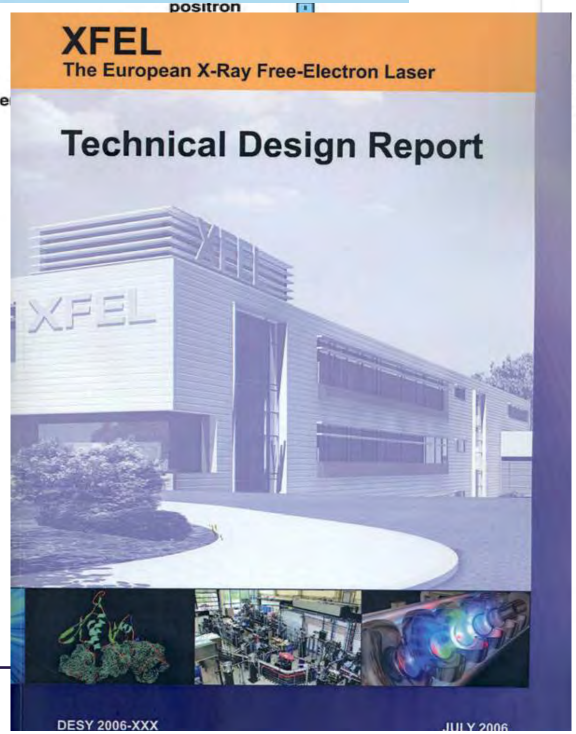
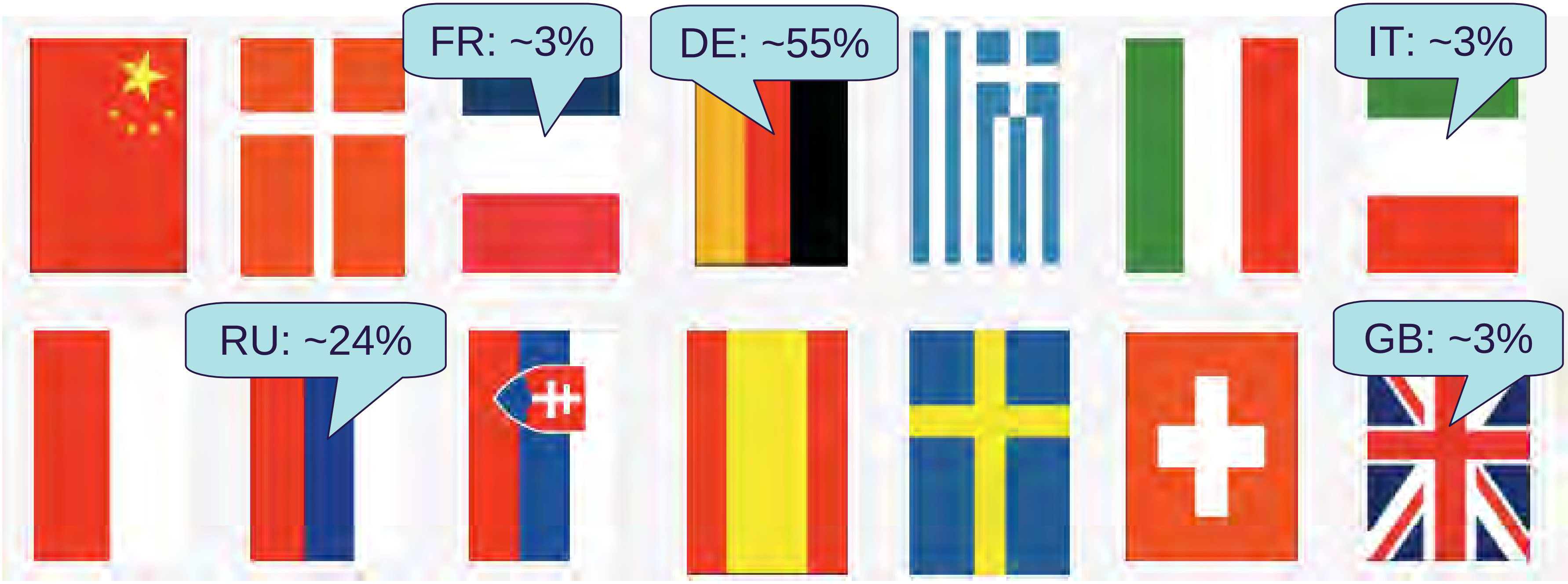


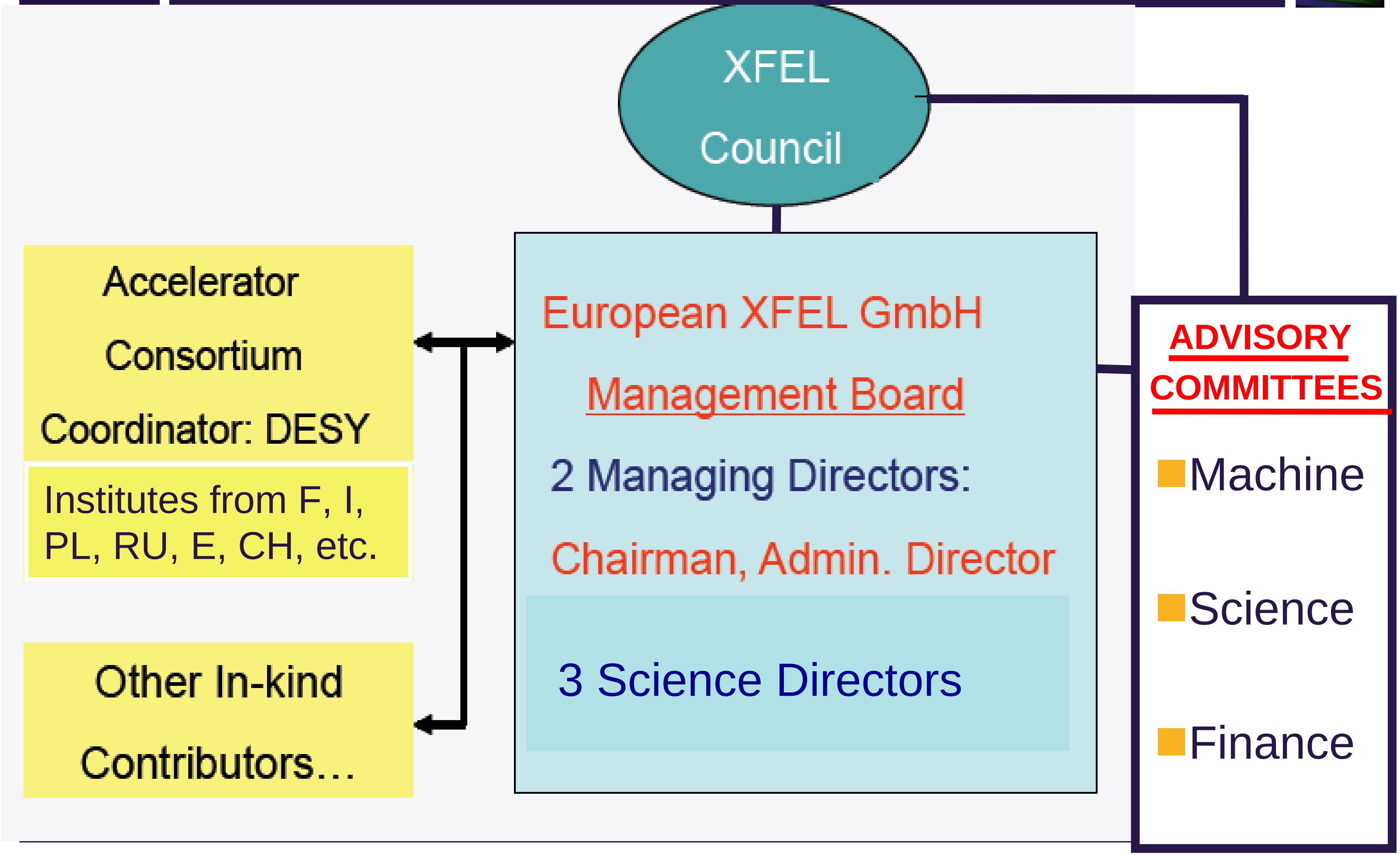
Partner countries contributing to European XFEL

Preparations are underway for the foundation (2009) of a company with research institutes of the different countries as shareholders, the European XFEL GmbH. Construction and operation of the XFEL are entrusted to this company.



= contribution to start version of XFEL (total 1050 M€, preliminary)

European XFEL project organisation

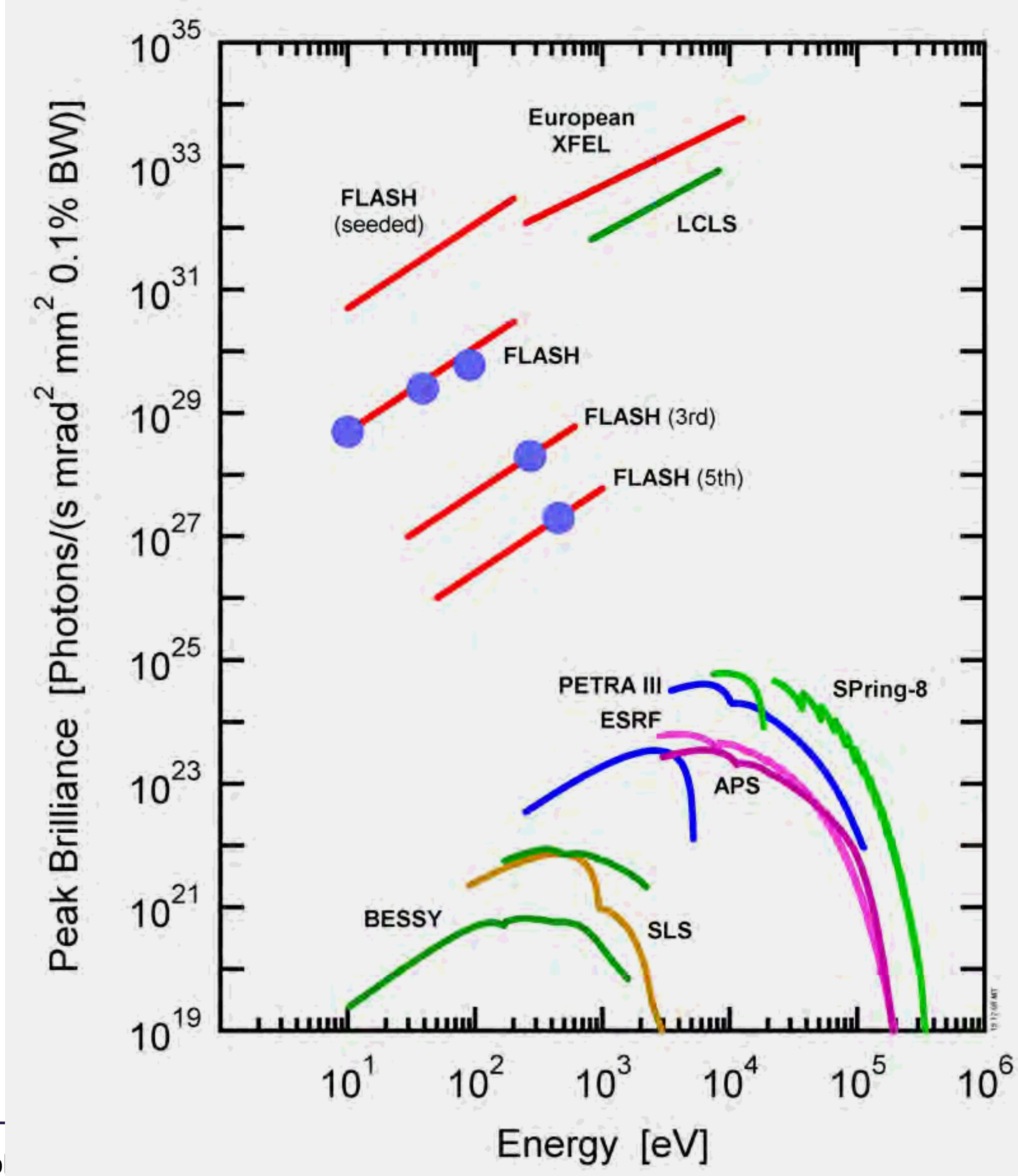


European XFEL

European XFEL - a next generation light source

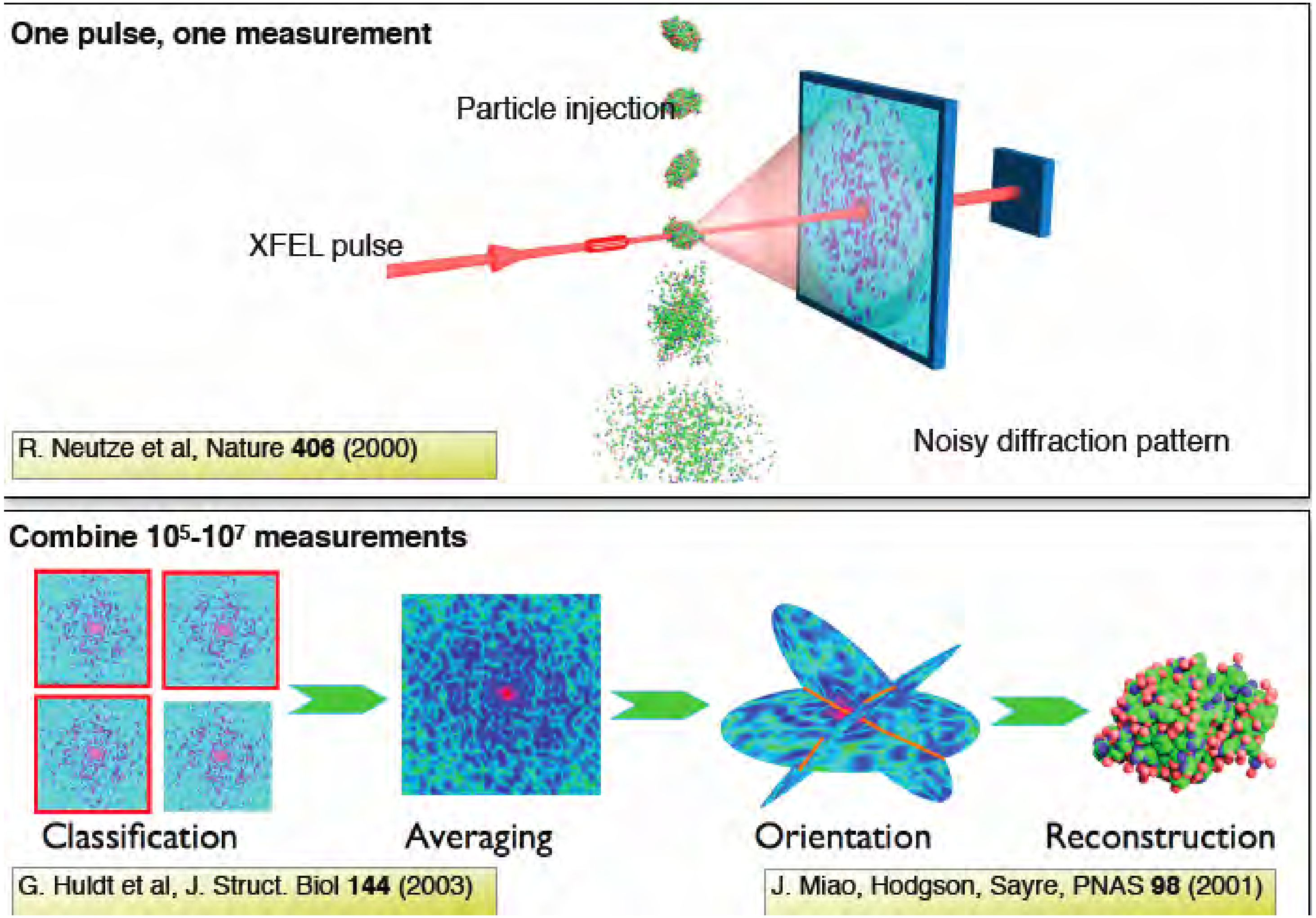
The XFEL will deliver:

- wavelength down to 0.1 nm
  ➔ **atomic-scale resolution**
- ultra-short pulses (≤ 100 fs)
  ➔ **ultra-fast dynamics**, “molecular movies”
- ultra-high peak brilliance
  ➔ investigations of **matter under extreme conditions** (**Xe**$^{21+}$)
- transverse spatial coherence
  ➔ imaging of single nanoscale objects, possibly down to individual macromolecules (**no crystallisation needed !!**)



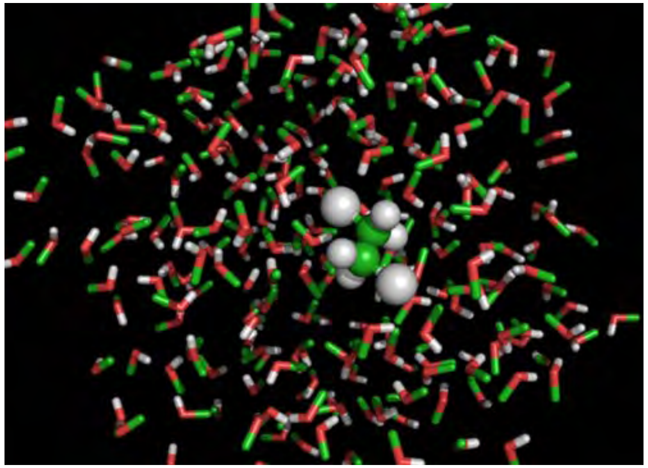
Towards single-macromolecule imaging

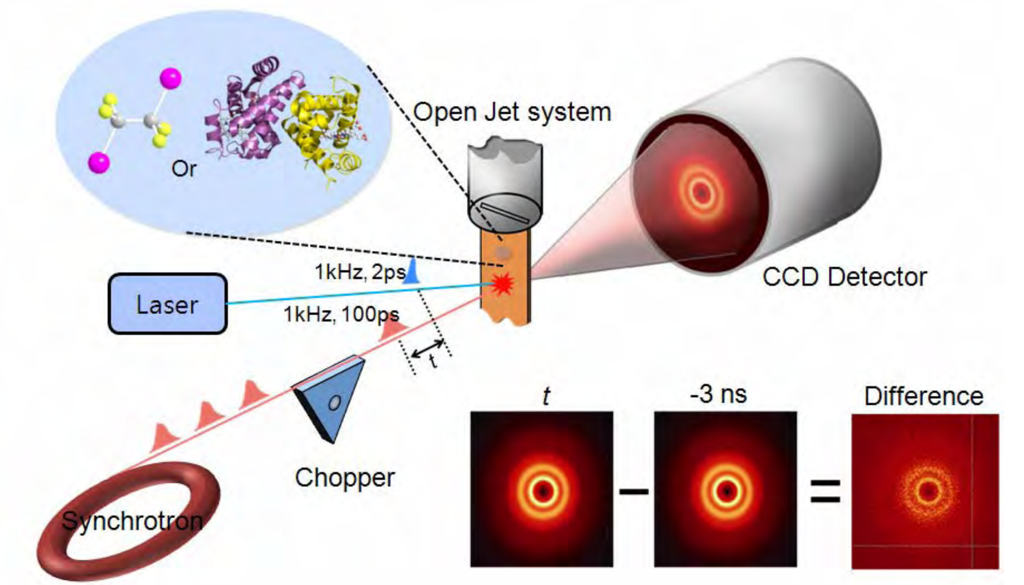
After J. Hajdu *et al.*



Solution-phase reactions

- Most reactions related with Chemistry & Biology occur in solution phase.
- Time-resolved solution scattering (diffraction) to probe reaction dynamics





photon-hungry pump-probe experiment

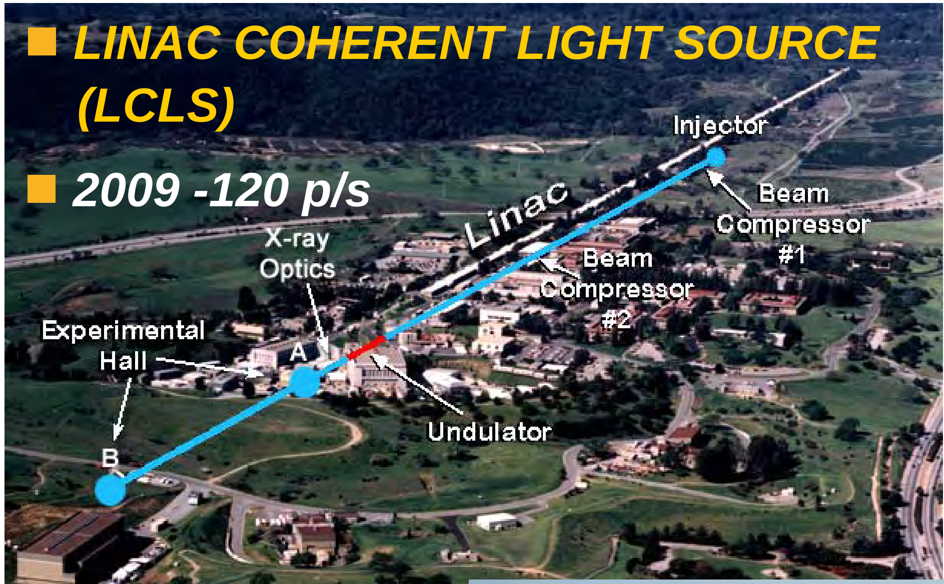
XFEL:

- Much shorter pulse (factor 1000)
- Much more photons (> factor 1000)
- Smaller bandwidth (factor 10)

Scattering is complementary to optical spectroscopy (which has highly selective sensitivity but might miss global picture)

Slide prepared from: H. Ihee (KAIST) *et al.*, 3rd XFEL users meeting, Jan. 2009

The European XFEL in the International Context



- *LINAC COHERENT LIGHT SOURCE (LCLS)*
- *2009 -120 p/s*

- *2011-60 p/s*
- *SPring-8 Compact SASE Source (SCSS)*

- *European XFEL Facility (XFEL)*
- *2014 - 30 000 p/s*

Comparison of X-ray FEL Projects

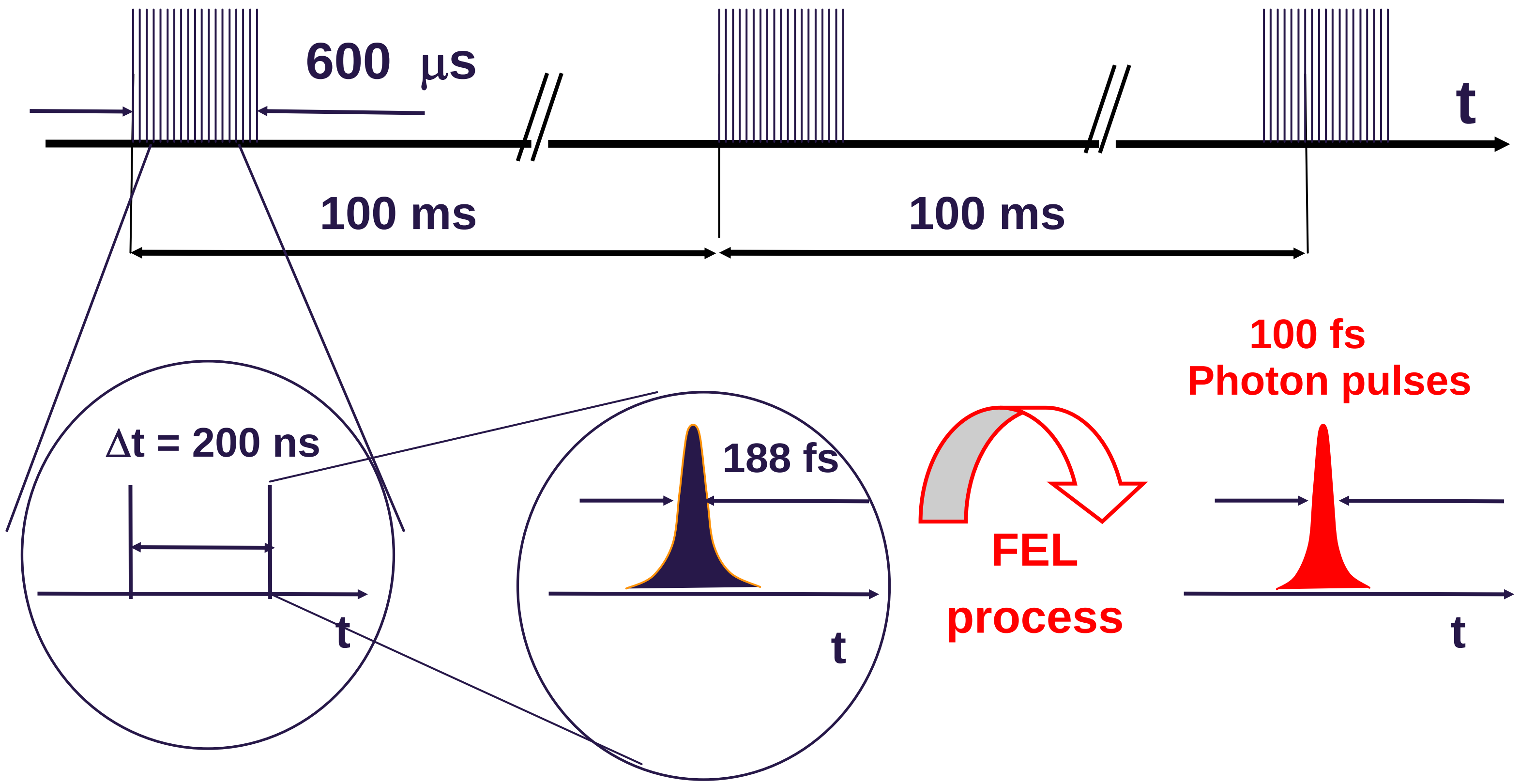
	LCLS (USA)	SCSS (JAPAN)	EUROPEAN XFEL (SASE1)
Minimum Wavelength (nm)	0.15	0.1	0.1
Peak Brilliance (phot/s/mm^2/mrad^2/0.1%BW)	8.5 10^{32}	5 10^{33}	5 10^{33}
Average Brilliance	2.4 10^{22}	1.5 10^{23}	1.6 10^{25}
Pulses/s	120	60	30 000
Pulse Duration (fs)	100 and below	500	100 and below
First Beam	2009	2011	2014

Advantages of Superconducting RF Technology for FEL’s

- Possibility to inject thousands of bunches per RF pulse;
- Small wakefields: large iris even at high gradients (design value: 24 MV/m; tested up to 35 MV/m);
- High stability, intra bunch-train feedback for high quality beam;
- Operational flexibility of time structure and energy

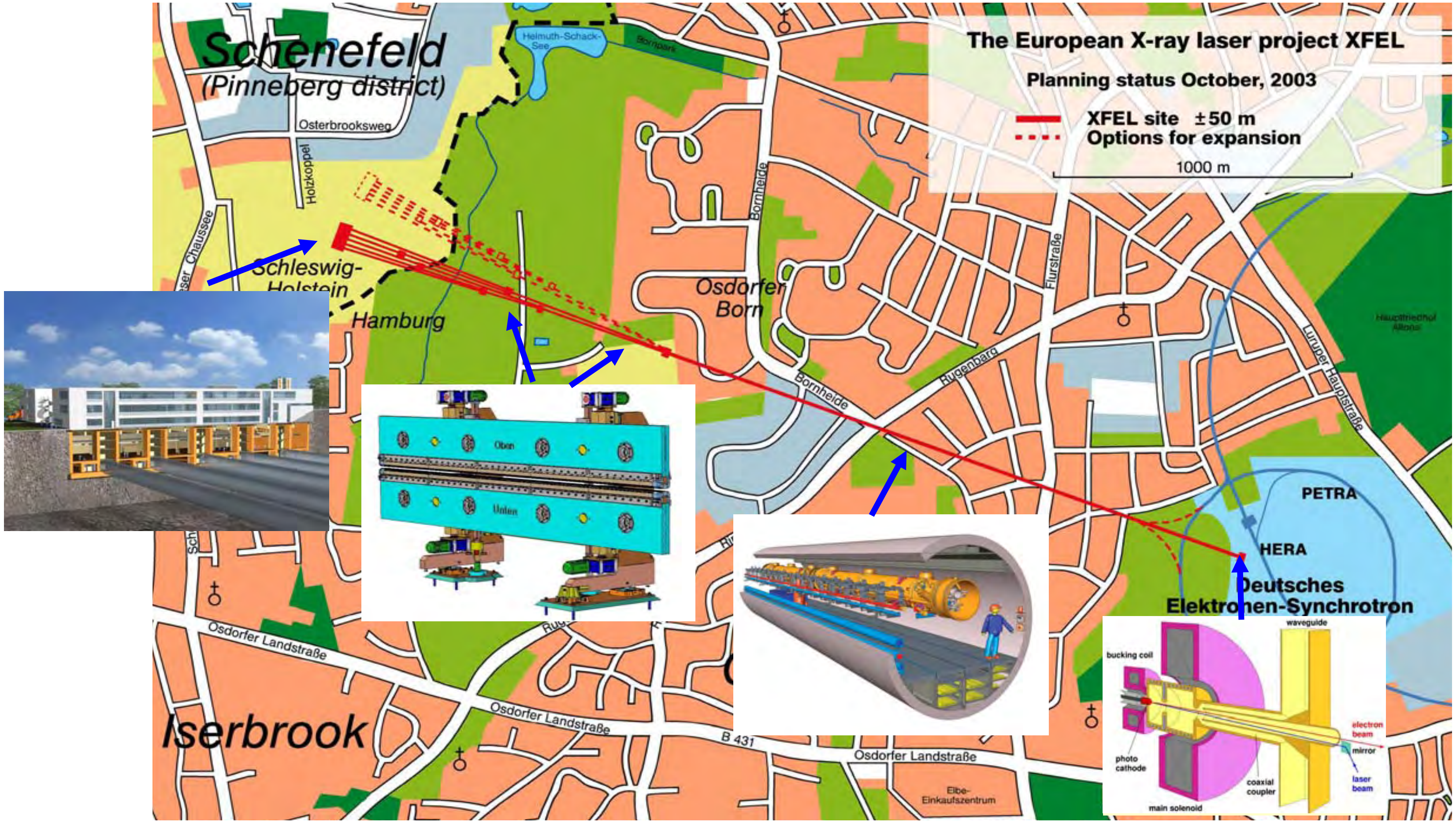
European XFEL – Time structure

Electron bunch trains (with up to 3000 bunches of 1nC each)

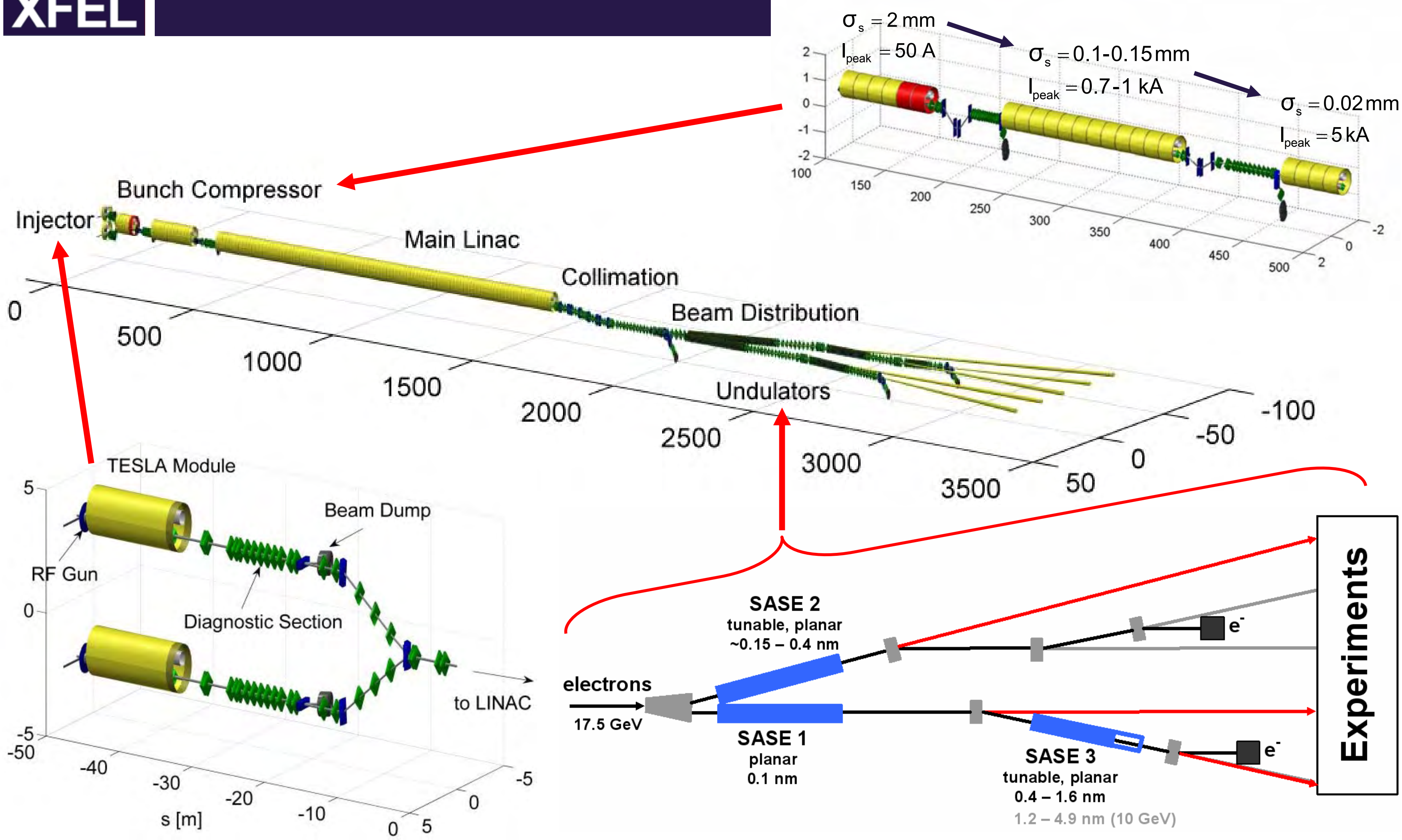


Overall layout of the European XFEL

3.4km

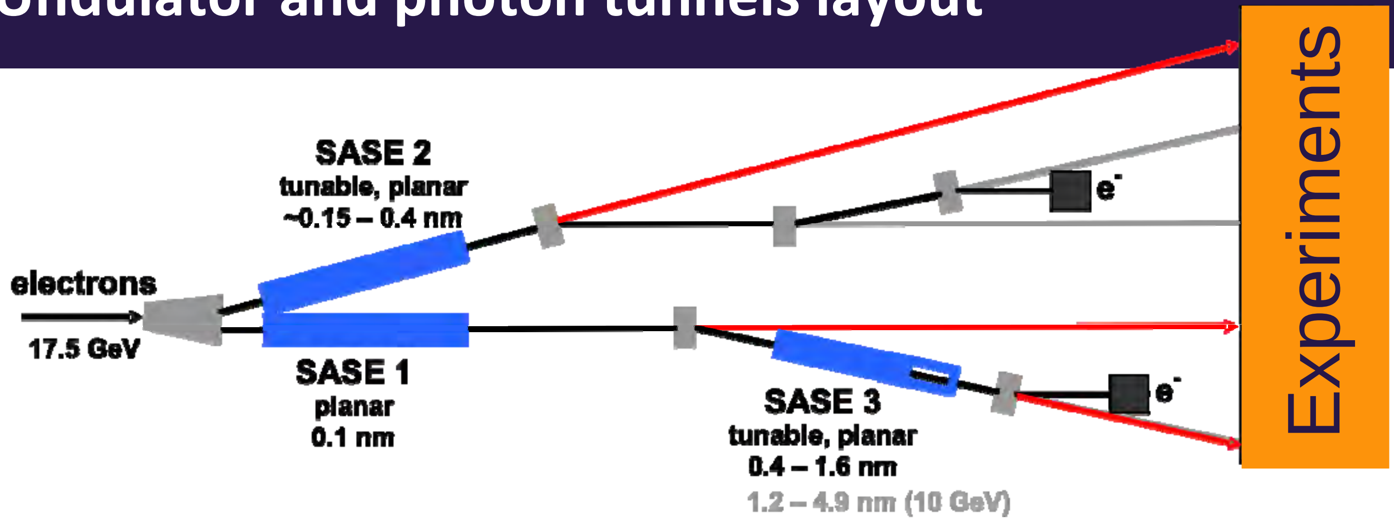


European XFEL – beam dynamic components



(„start-up“ version)

Undulator and photon tunnels layout

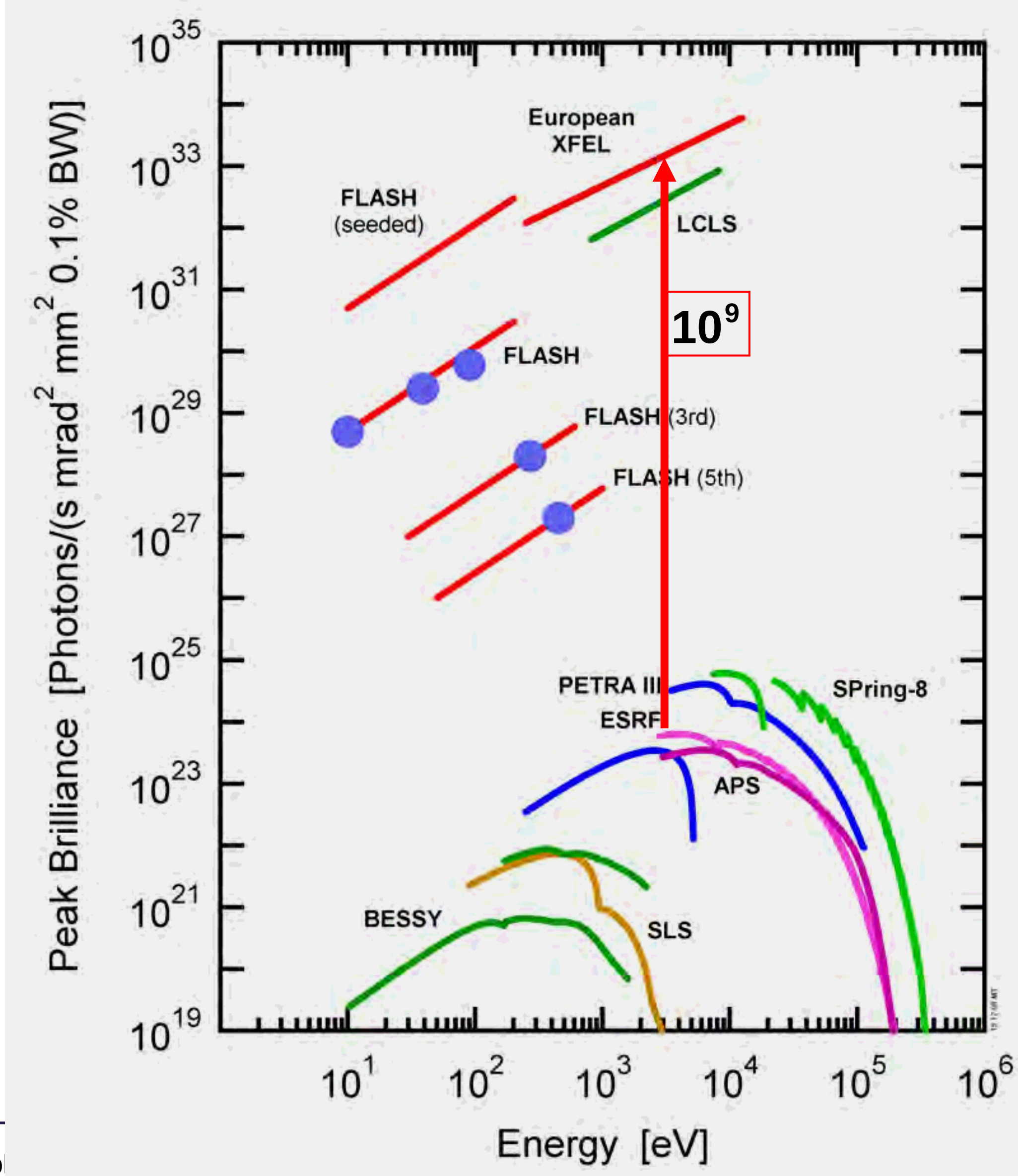


Parameter	Unit	SASE 1	SASE 2		SASE 3		
Electron energy	GeV	17.5	17.5	17.5	17.5	17.5	10.0**
Wavelength	nm	0.1	0.1	0.4	0.4	1.6	6.4
Photon energy	keV	12.4	12.4	3.1	3.1	0.8	0.2
Peak power	GW	20	20	80	80	130	135
Average power*	W	65	65	260	260	420	580
Photon beam size (FWHM)	µm	70	85	55	60	70	95
Photon beam divergence (FWHM)	µrad	1	0.84	3.4	3.4	11.4	27
Coherence time	fs	0.2	0.22	0.38	0.34	0.88	1.9
Spectral bandwidth	%	0.08	0.08	0.18	0.2	0.3	0.73
Pulse duration	fs	100	100	100	100	100	100
Photons per pulse	#	10^{12}	10^{12}	1.6×10^{13}	1.6×10^{13}	1.0×10^{14}	4.3×10^{14}
Average flux	#/s	3.3×10^{16}	3.3×10^{16}	5.2×10^{17}	5.2×10^{17}	3.4×10^{18}	1.4×10^{19}
Peak brilliance	B	5.0×10^{33}	5.0×10^{33}	2.2×10^{33}	2.0×10^{33}	5.0×10^{32}	0.6×10^{32}
Average brilliance*	B	1.6×10^{25}	1.6×10^{25}	7.1×10^{24}	6.4×10^{24}	1.6×10^{24}	2.0×10^{23}

European XFEL - a next generation light source

The XFEL will deliver:

- wavelength down to 0.1 nm
  ➔ **atomic-scale resolution**
- ultra-short pulses (≤ 100 fs)
  ➔ **ultra-fast dynamics**, "molecular movies"
- ultra-high peak brilliance
  ➔ investigations of matter under **extreme conditions** (Xe^{21+})
- transverse spatial coherence
  ➔ imaging of single nanoscale objects, possibly down to individual macromolecules (**no crystallisation needed !!**)



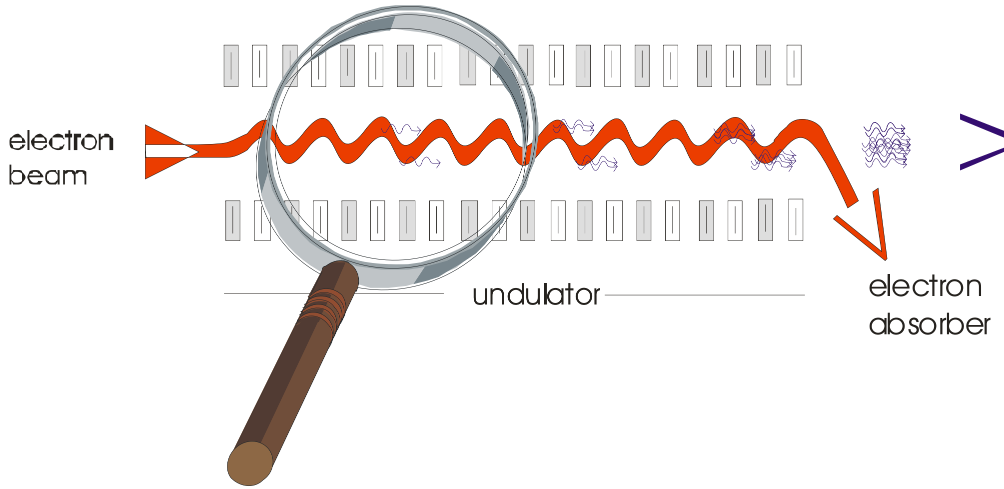
Why brilliance is ~10E+9 higher ?

- Synchrotrons: $P \sim N \cdot e^2$
- FELs (coherence):
  $P \sim (N \cdot e)^2 = N^2 \cdot e^2$,
  $N \sim 10E+9$

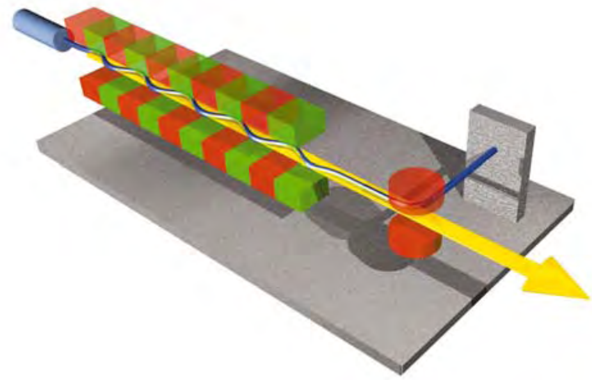
SASE FEL: How does it work?

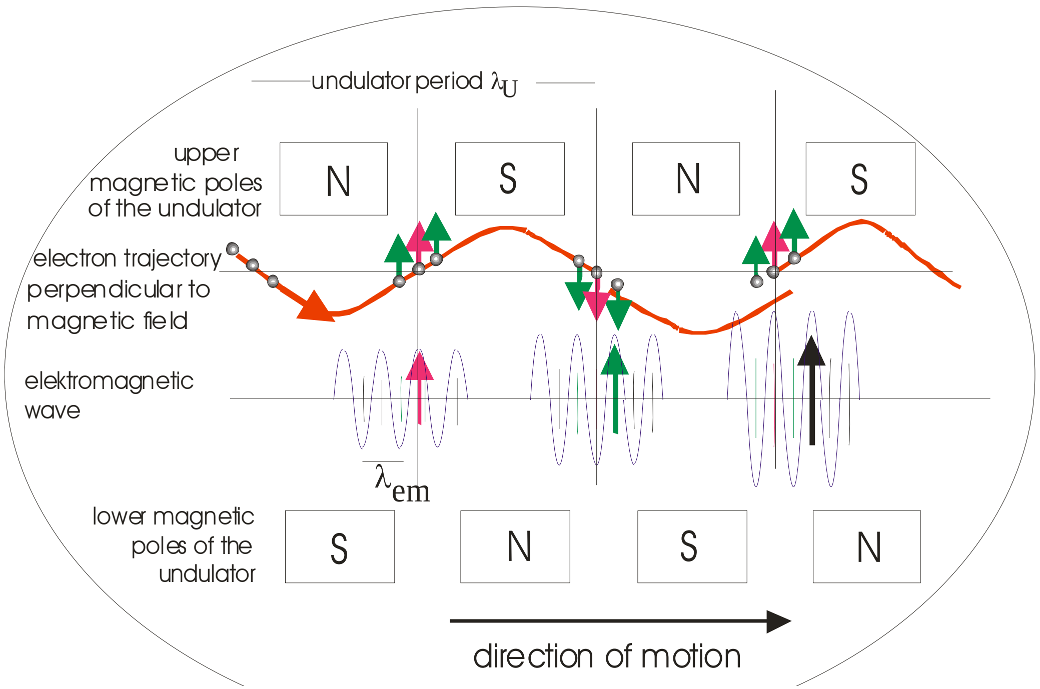
Coherent motion is all we need !!

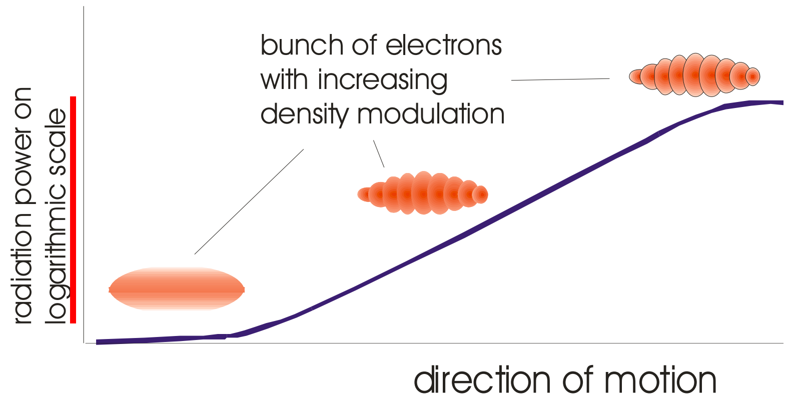
SASE FEL: How does it work?



SASE =
self amplified
spontaneous
emission





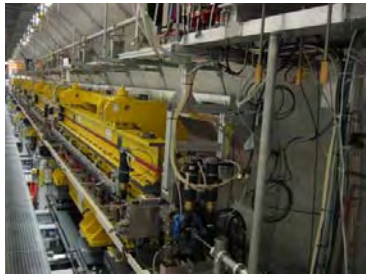


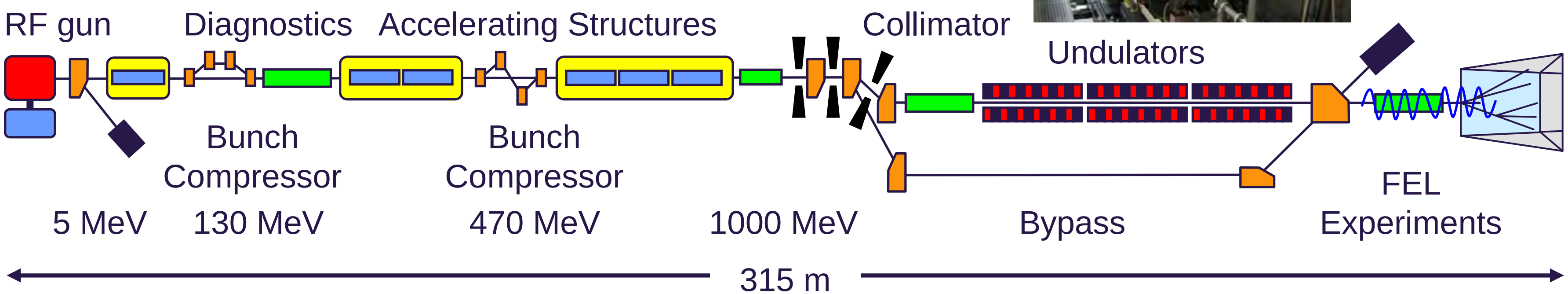
Status of realization of the European XFEL

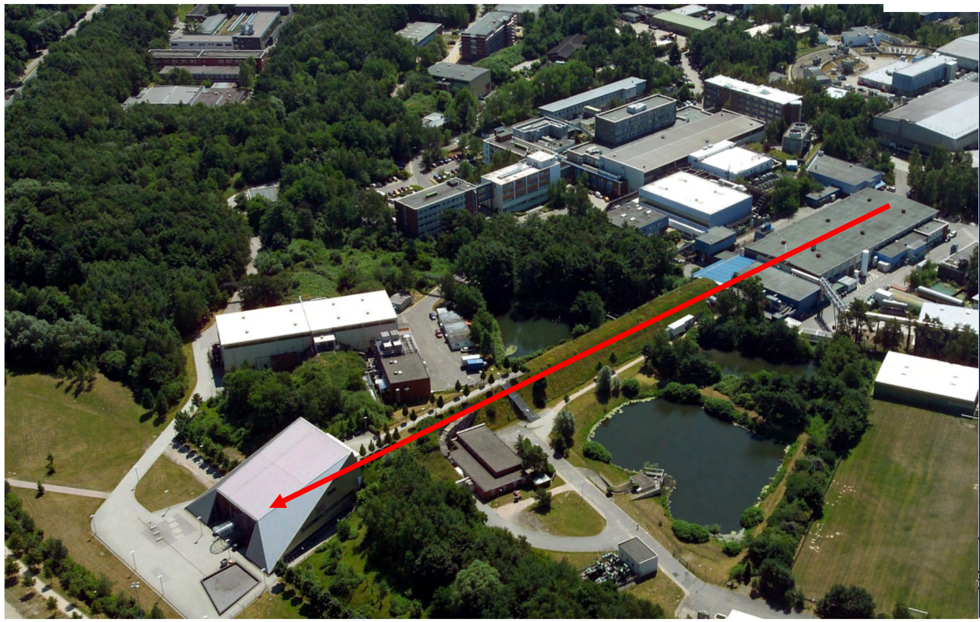
Construction of the underground buildings started!

- Contracts signed December 12, 20
- Construction started in early Janua
- http://www.xfel.eu/en/construction-

Free electron LASer in Hamburg (FLASH) → Overview







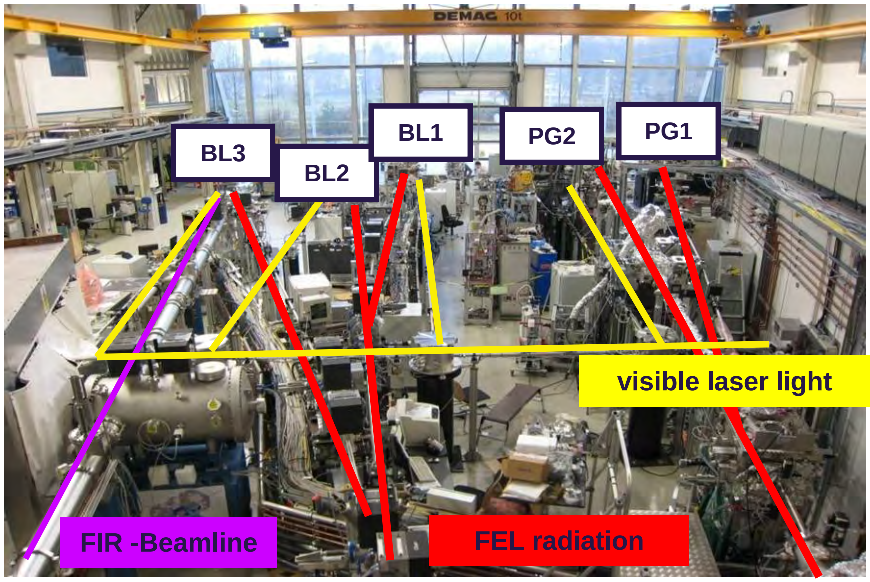
- **Jan 2005** — **first lasing at 32 nm**
- **Summer 2005** — **start of user expts.**
- **Energy range** — **~0.3 - 1 GeV**
  - **→ ~6.5 - 60 nm**
  - **~20 - 200 eV**
- **Pulse energy** — **5 - 100 μJ**
- **Pulse duration** — **~10 - 50 fs (FWHM)**
- **Peak power** — **1 - 10 GW**
- **Bandwidth $\Delta\lambda/\lambda$** — **~0.7 - 1 %**

The FLASH facility

- Routine operation as **user facility** with 6.5 – 60 nm FEL radiation
- **Pilot facility** for the XFEL – gain invaluable experience!
- **R&D** facility for specific **XFEL** and **ILC** machine developments

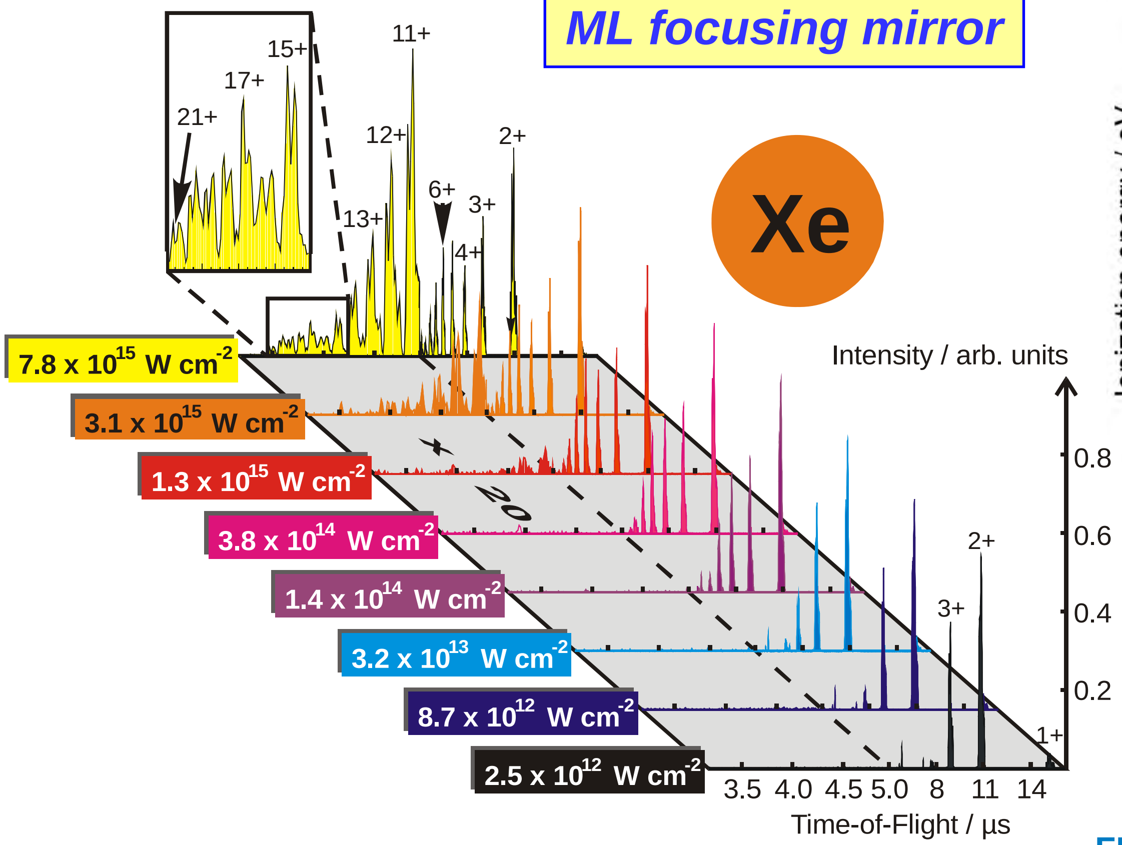
FLASH experimental hall:

- Five photon beam lines
  - large variety of experimental possibilities
  - beam is sent to one line at a given time, typical for a shift of 12 h

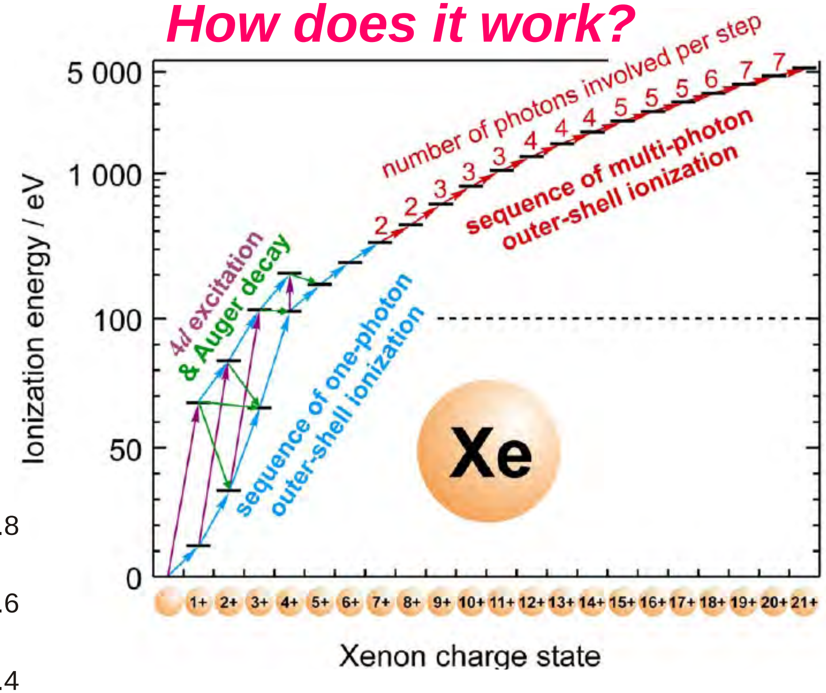


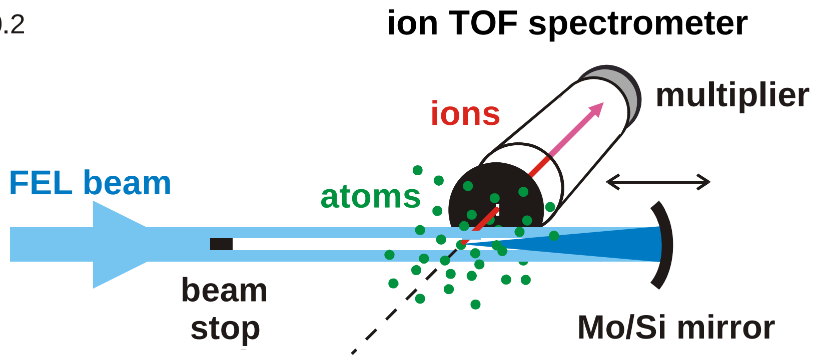
Multiphoton ionisation of Xe at 13.4 nm

20 µJ, 10 fs pulses
ML focusing mirror



How does it work?





A.A. Sorokin et al., Phys. Rev. Lett. **99**, 213002 (2007)

Coherent single-shot X-ray diffraction imaging

H. Chapman, J. Hajdu et al.

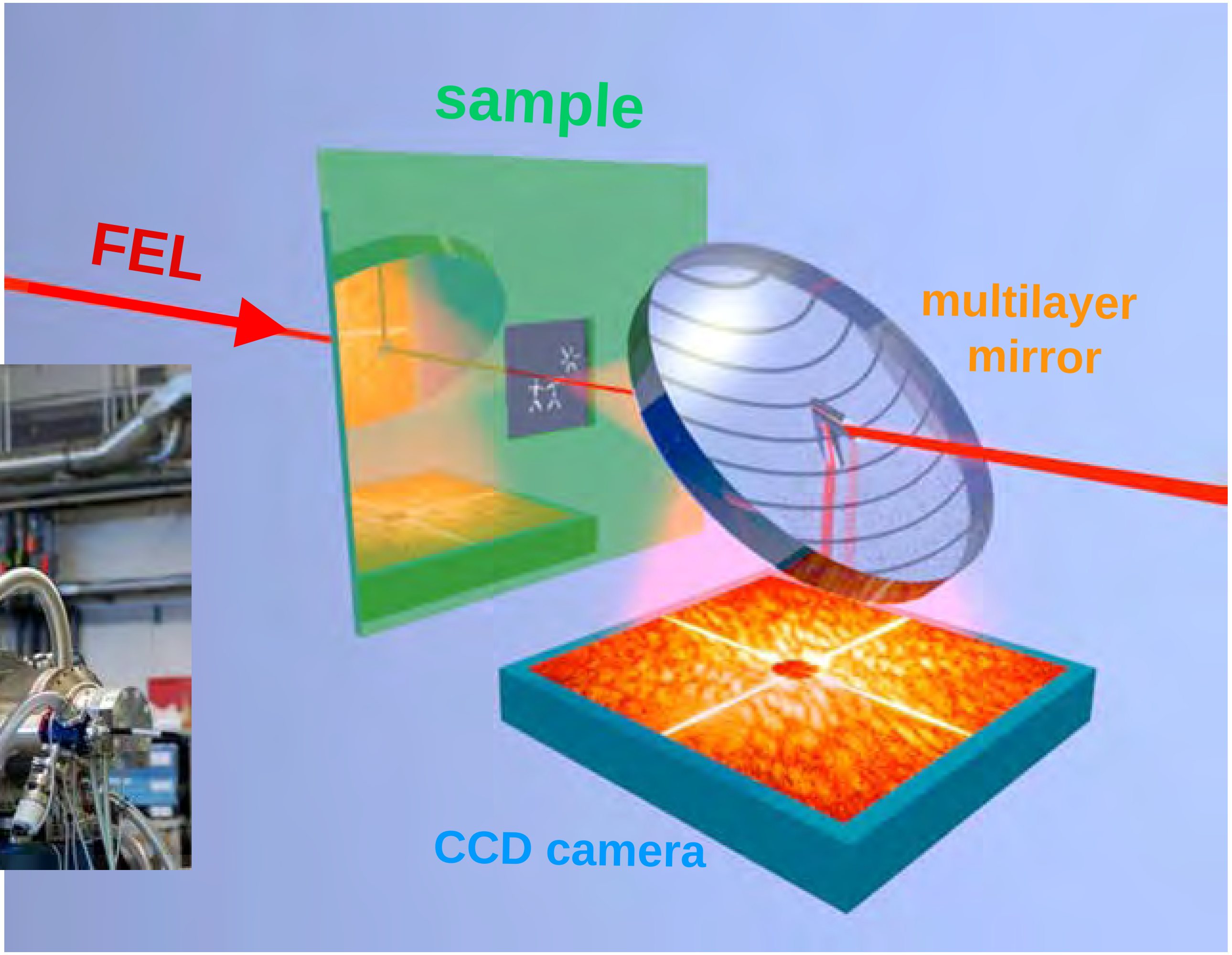
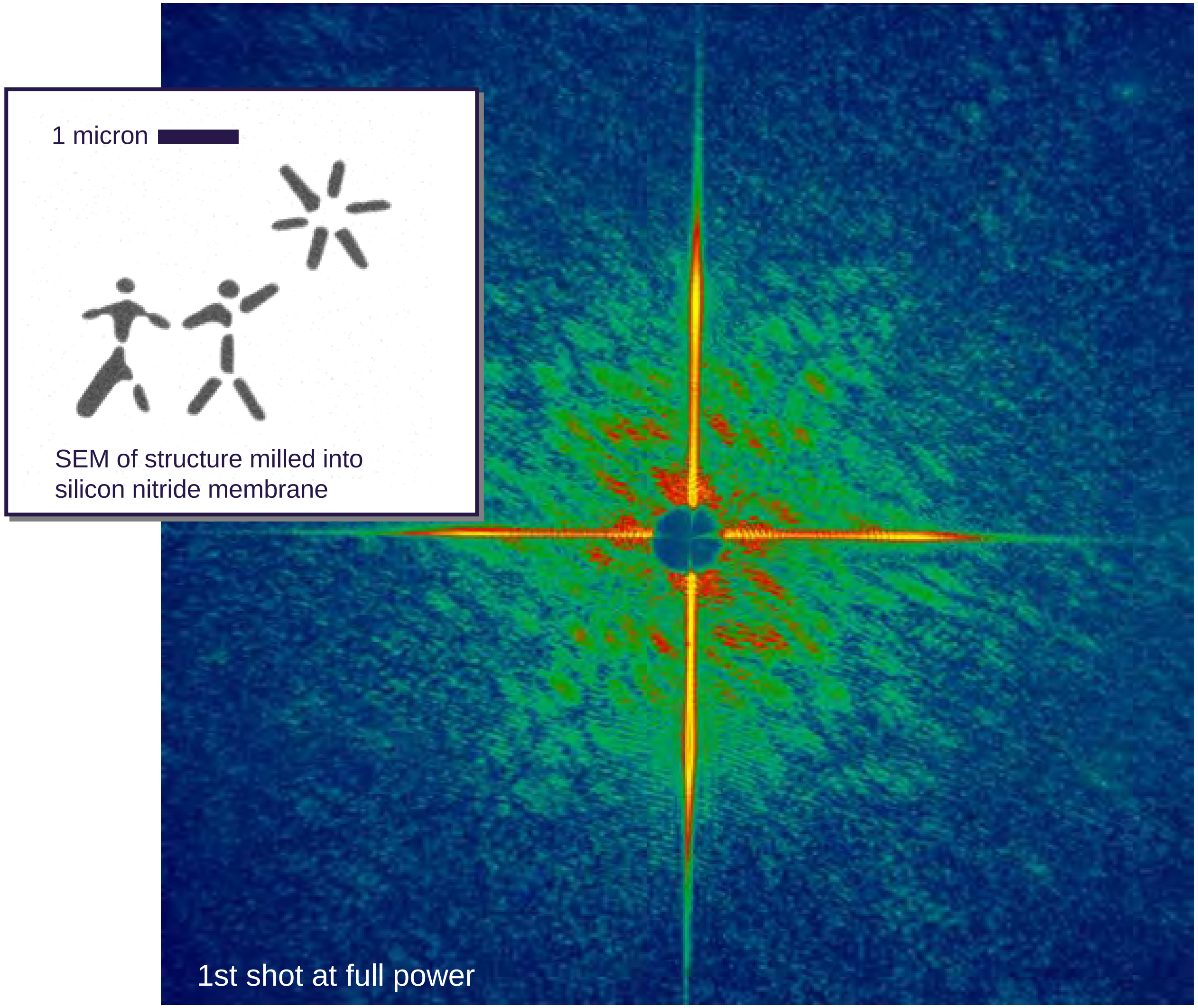
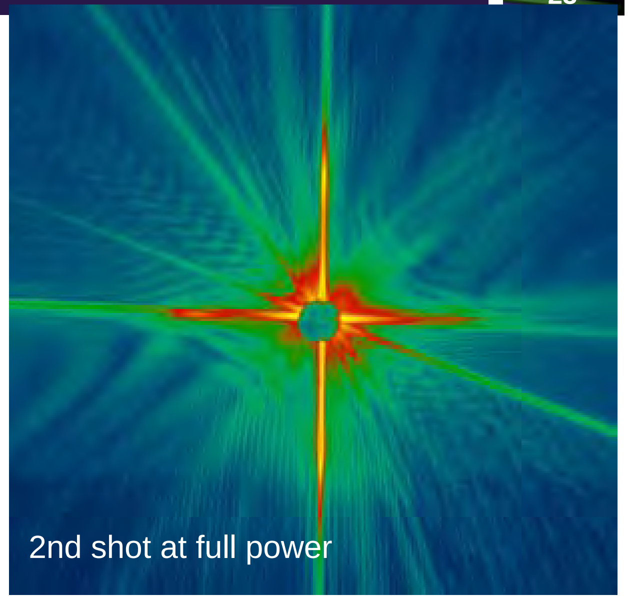
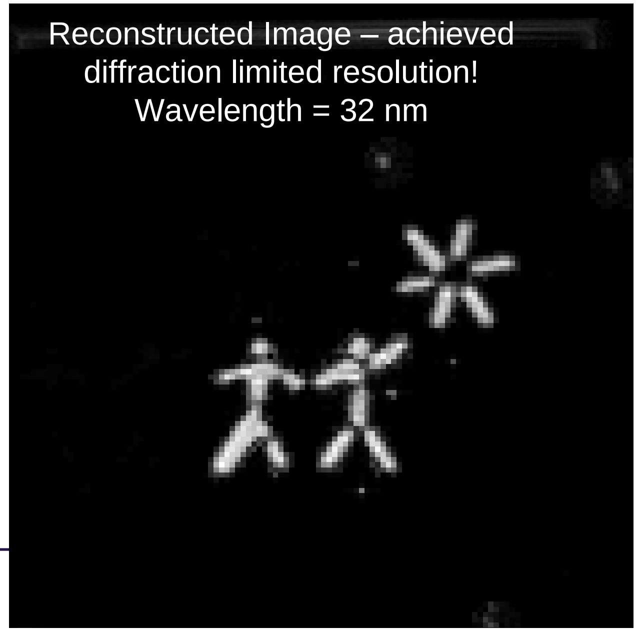


Image reconstructed from ultrafast diffraction pattern







H. N. Chapman et al., Nature Physics 2, 839-843 (2006)

Ultrafast single-shot diffraction imaging of nanoscale dynamics

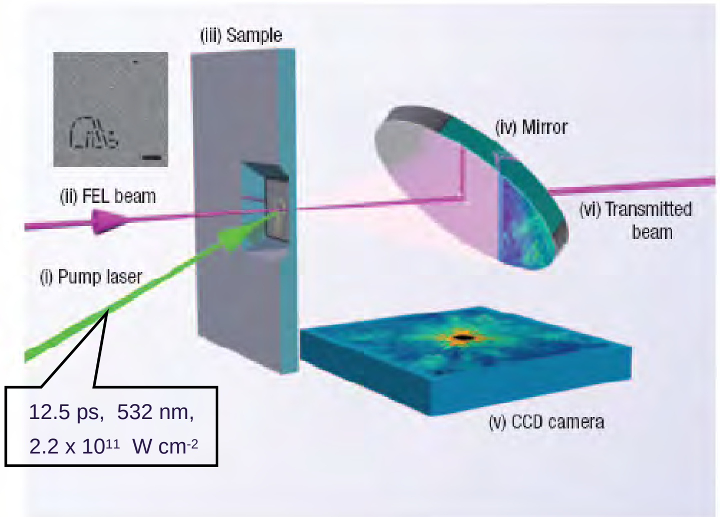
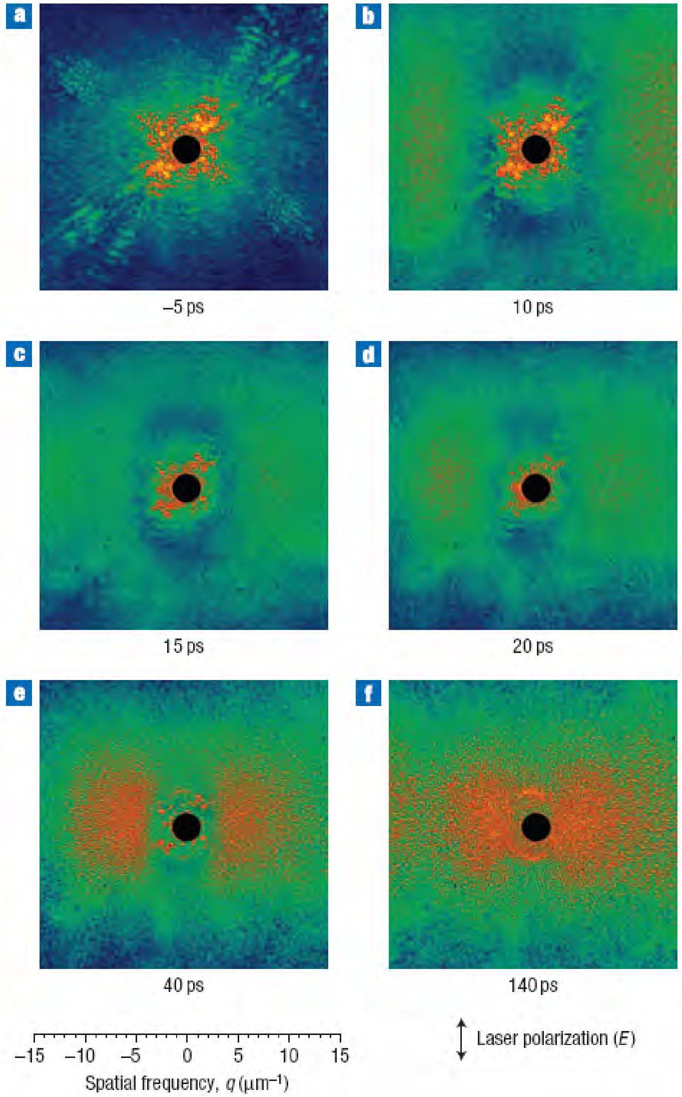


Figure 1 **X-ray dynamic diffraction imaging.** A visible-light laser beam (i) incident from the left is focused onto the sample (iii) and acts as the excitation pulse. A 10-fs duration soft X-ray pulse at a wavelength of 13.5 nm from the FEL (ii) is focused to a 20-µm spot in the same location as the visible-light laser at a continuously variable delay after the excitation pulse. The X-ray pulse diffracts from the sample, carrying information about the transient sample structure to the CCD detector (v) in the form of a coherent diffraction pattern. A 45° mirror (iv) is used to separate the direct beam from the diffracted light: the direct FEL beam (vi) passes straight through a hole in the mirror and is not detected in the CCD image. A 100-nm-thick zirconium filter over the CCD chip makes the detector blind to the laser excitation pulse. The sample (iii) consisted of a nanometre-resolution pattern etched into a silicon nitride membrane using a focused ion beam (FIB), providing a well-defined control sample so that the time evolution of a known structure could be observed. The path length from sample to CCD is 53 mm and the detected numerical aperture is 0.25, giving a spatial resolution of 27 nm in the sample plane.



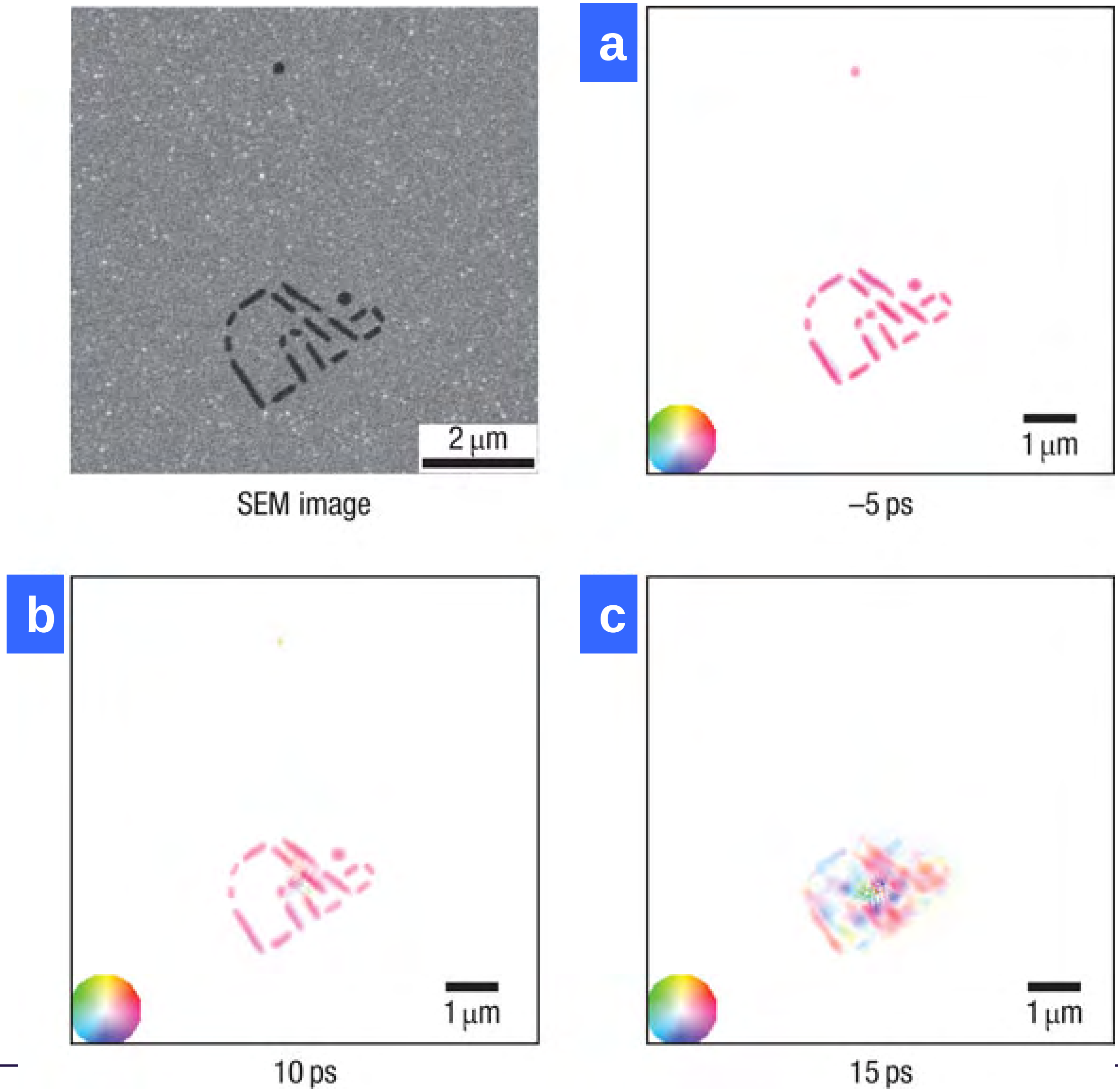
A. Barty et al.,

Nature Photonics 2,

415 - 419 (2008)

Te

Continued: → True "high speed recording" of an explosion

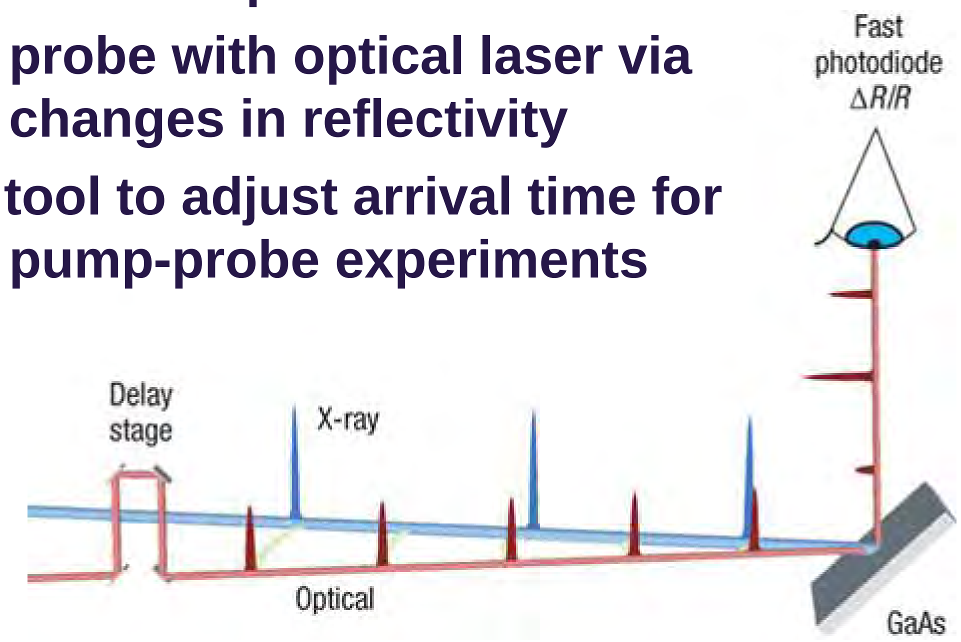


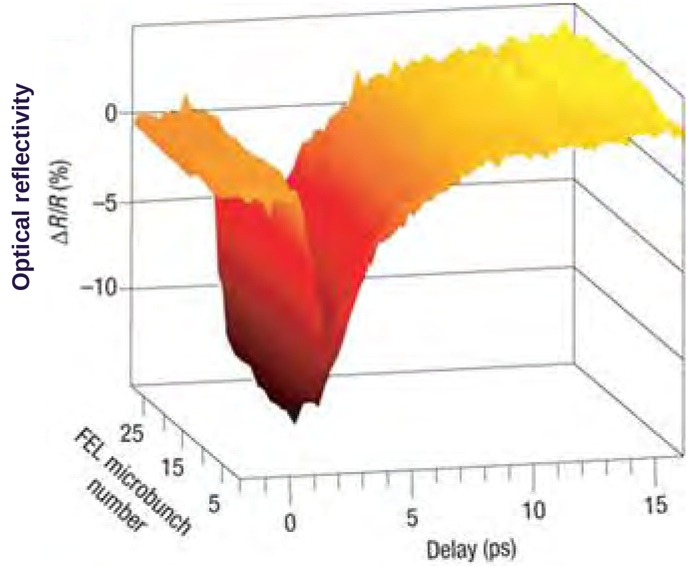
Femtosecond X-ray/optical cross-correlator

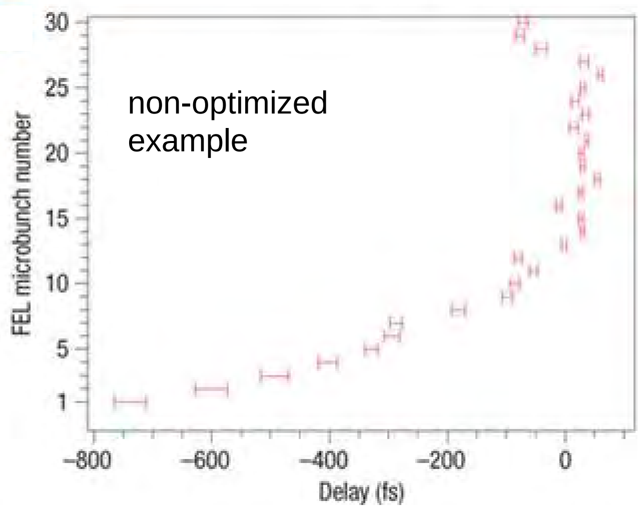
FU Berlin, Uni HH, DESY

- use GaAs crystal
- change optical properties with FEL pulse
- probe with optical laser via changes in reflectivity

→ tool to adjust arrival time for pump-probe experiments







C.Gahl et al., Nature Photonics 2, 165-169 (2008)

One XFEL key component:
→ the high brightness electron source

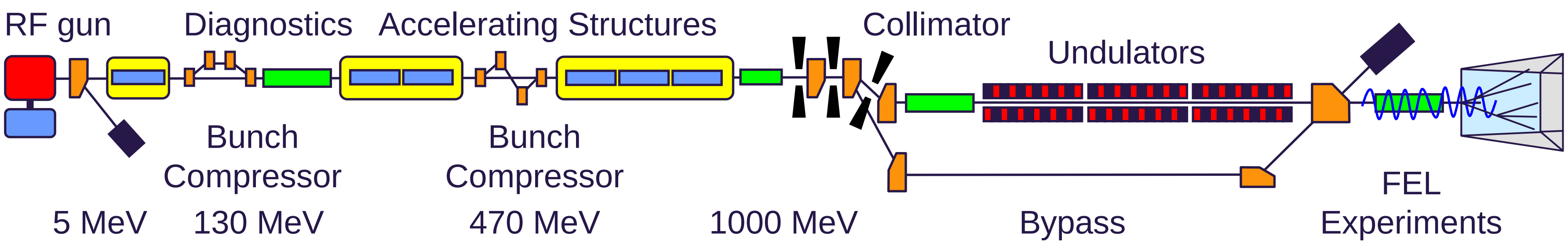
Why electron injector is so important …. ???

Any linac based short wavelength, high brilliance light source (e.g. SASE-FELs) contains the following main components:

- **electron source**
- **accelerating sections** → **e.g. wakefields, coupler kicks**
  - in between: **bunch compressor(s)** → **e.g. coherent synchrotron radiation (CSR)**
- **undulator** to produce FEL radiation
- electron **beam dump**
- **photon beamline(s)** for the users

} **increase normalized emittance**

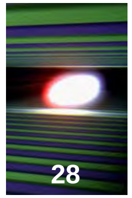
Example: FLASH



property of linacs: beam quality will DEGRATE during acceleration in linac

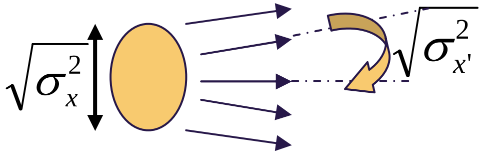
➔ electron source has to produce lowest possible emittance !!

What is Emittance ?



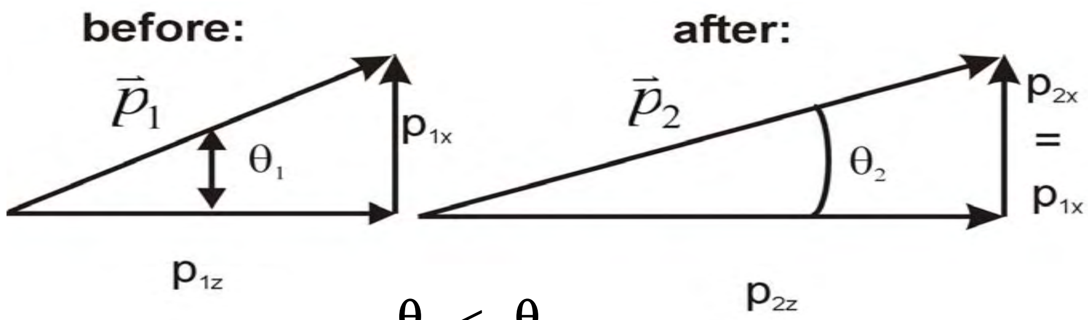
long.: ε_z ~ (e⁻ bunch length) • (energy spread of e⁻ bunch)

trans.: $\varepsilon_{x,y}$ ~ (e⁻ beam size) • (e⁻ beam angular divergence)



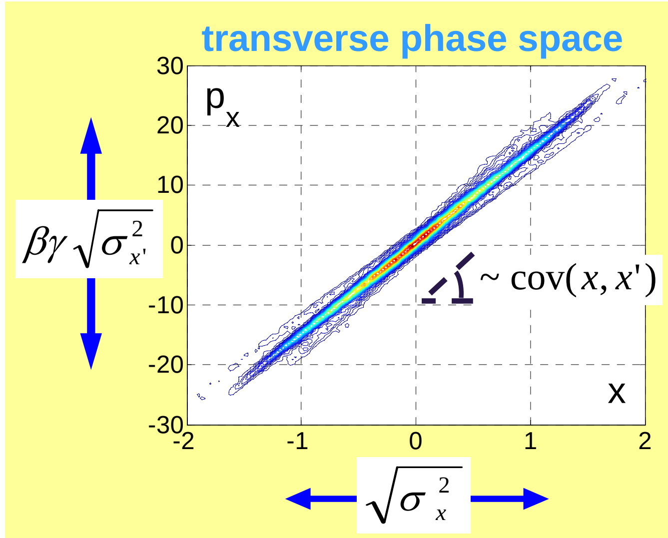
ε = 6 dimensional phase space volume occupied by given # of particles

effect of acceleration on transverse emittance (adiabatic damping):



$\theta_2 < \theta_1$

$\Rightarrow$ angular divergence is reduced $\Rightarrow \beta \bullet \gamma \bullet \sqrt{\sigma_{x'}^2}$

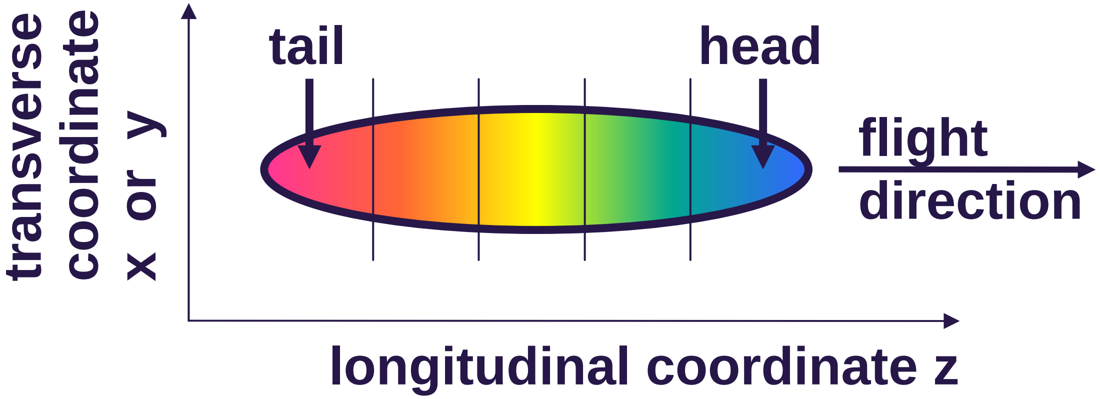


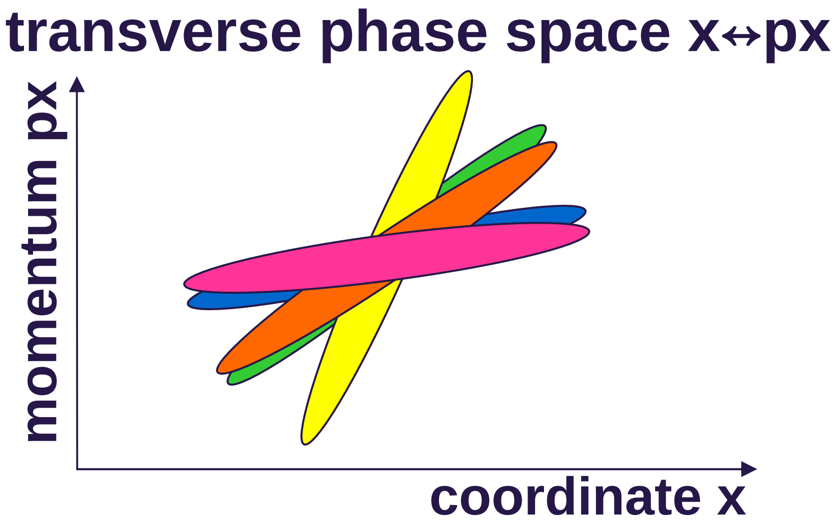
$\Rightarrow$ normalized RMS transverse emittance:

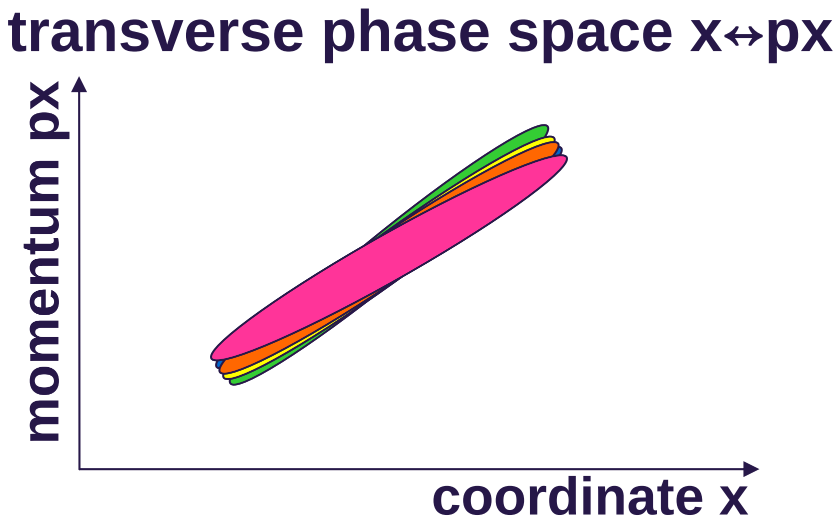
$$\varepsilon_x^n = ß \bullet \gamma \bullet \sqrt{\sigma_x^2 \bullet \sigma_{x'}^2 - \mathrm{cov}^2(x, x')} \, ; \quad ß = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1 - ß^2}}, \quad x' = \frac{dx}{ds}$$

(ε^n is conserved in general)

Slice Emittance vs. Projected Emittance





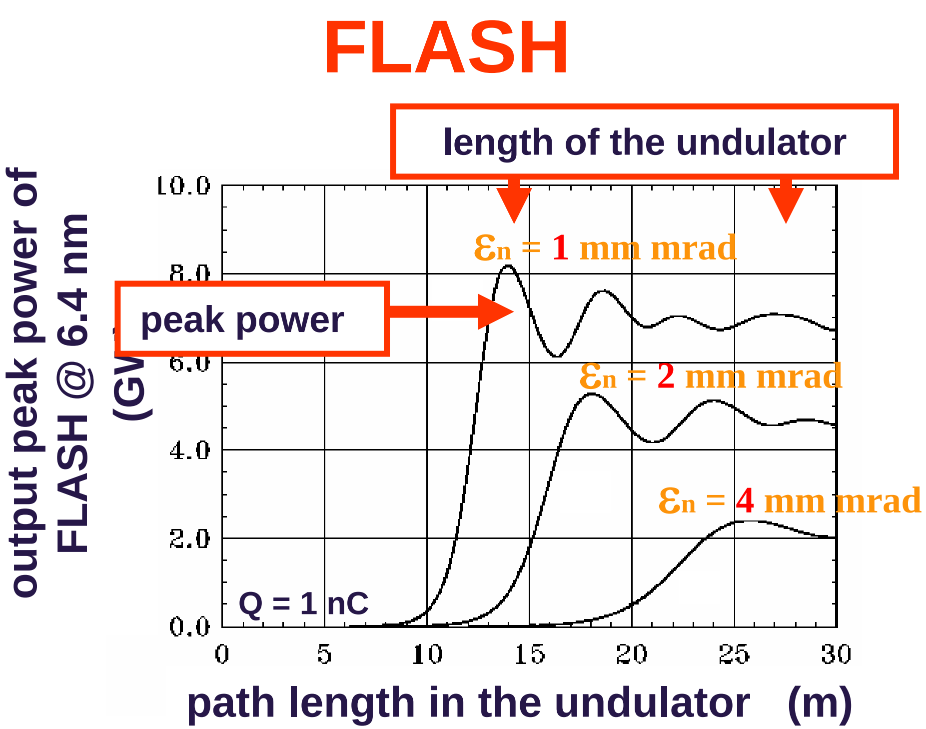


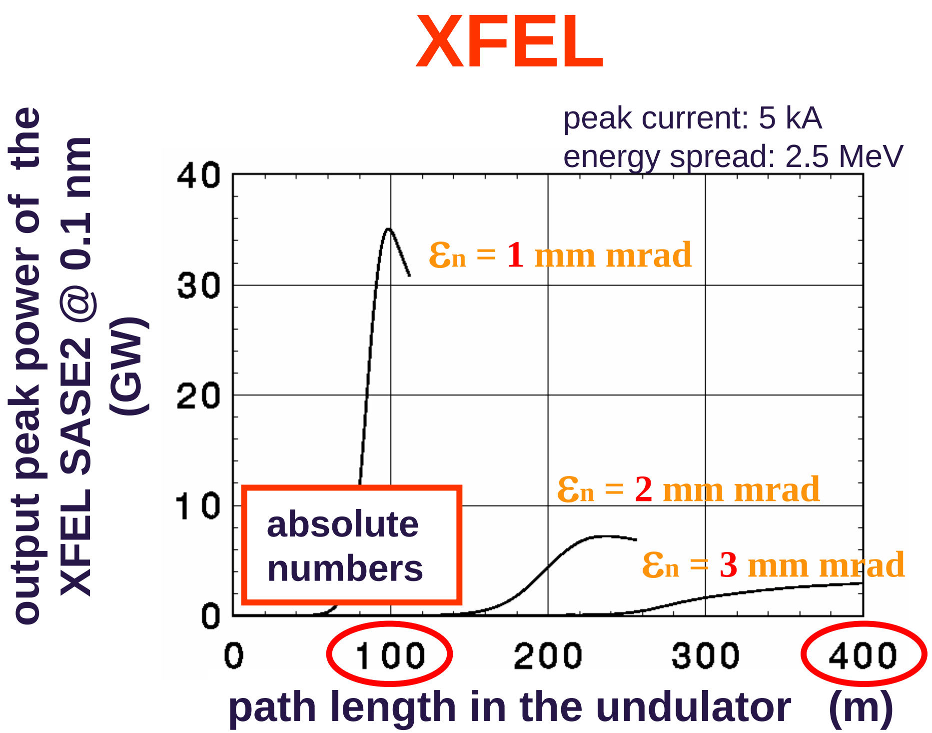
large ← projected emittance → small

➔ **meas. projected emittance ≥ slice emittance ↔ FEL process**

Why electron injector is so important ...

- Why emittance must be small ...





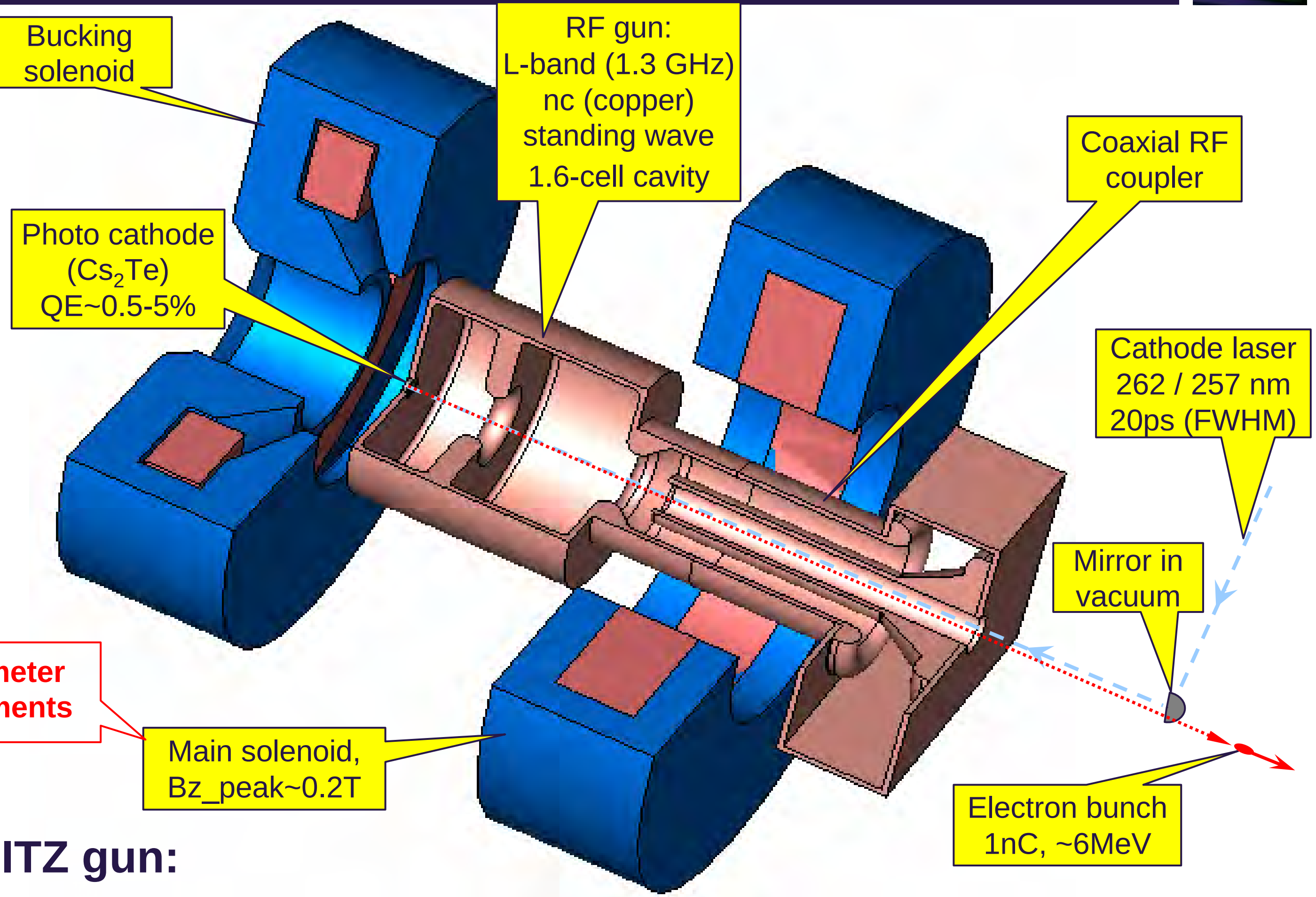
- **XFEL goal:** 0.9 mm mrad@injector = 1.4 mm mrad@undulator
- **if even smaller emittance ⇒ new horizons:**
  shorter wavelength, higher repetition rate

Most prominent solution: Photo Cathode RF Gun

Example:
PITZ gun

(Photo Injector Test facility at DESY, Zeuthen site)

PITZ Photo Injector Test Facility Zeuthen

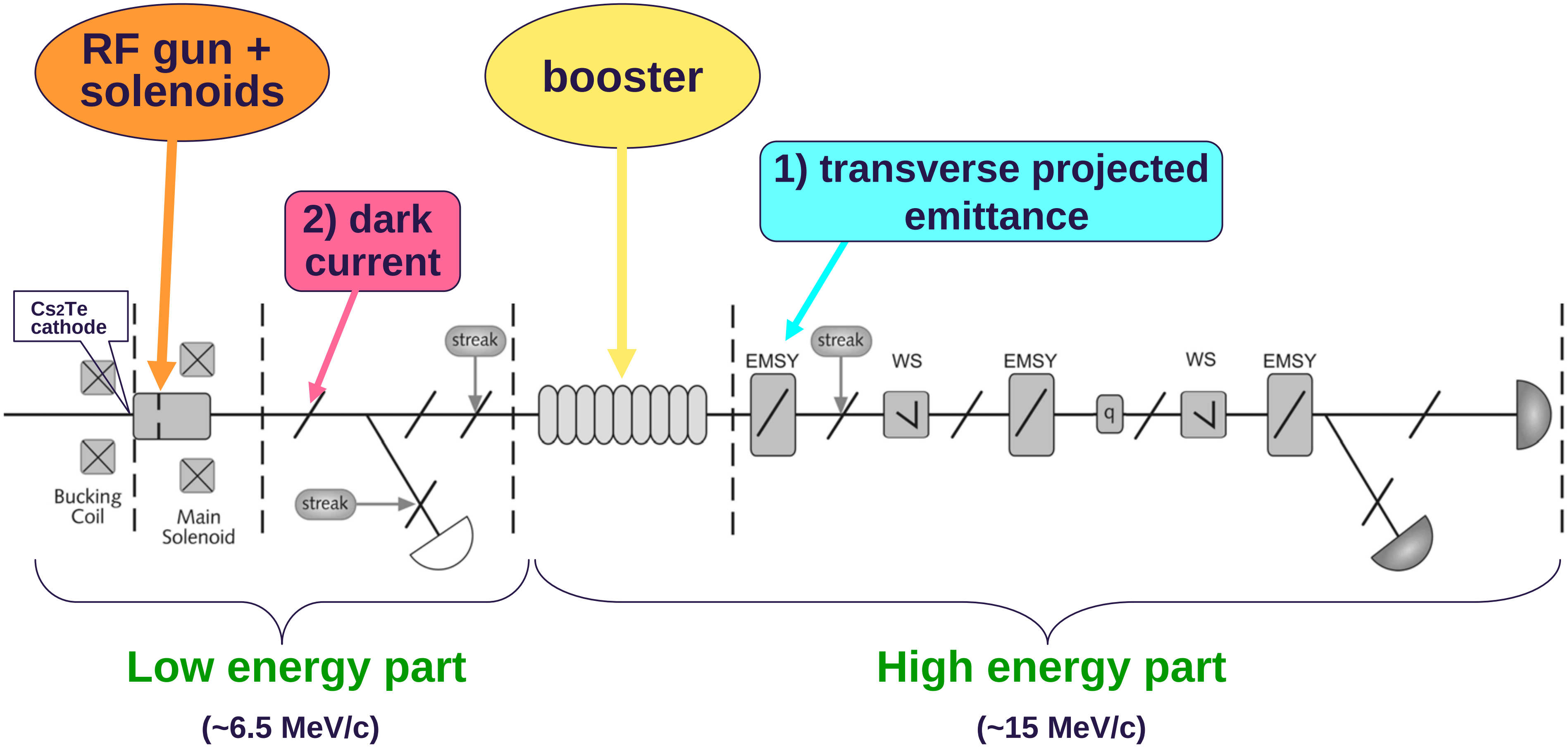


Main properties of PITZ gun:

- **1.3 GHz cavity, coaxial RF coupler (flexible solenoid position)**
- **Capable of high average power → long electron bunch trains (SC linac)**
- **Very low normalized transverse emittance**

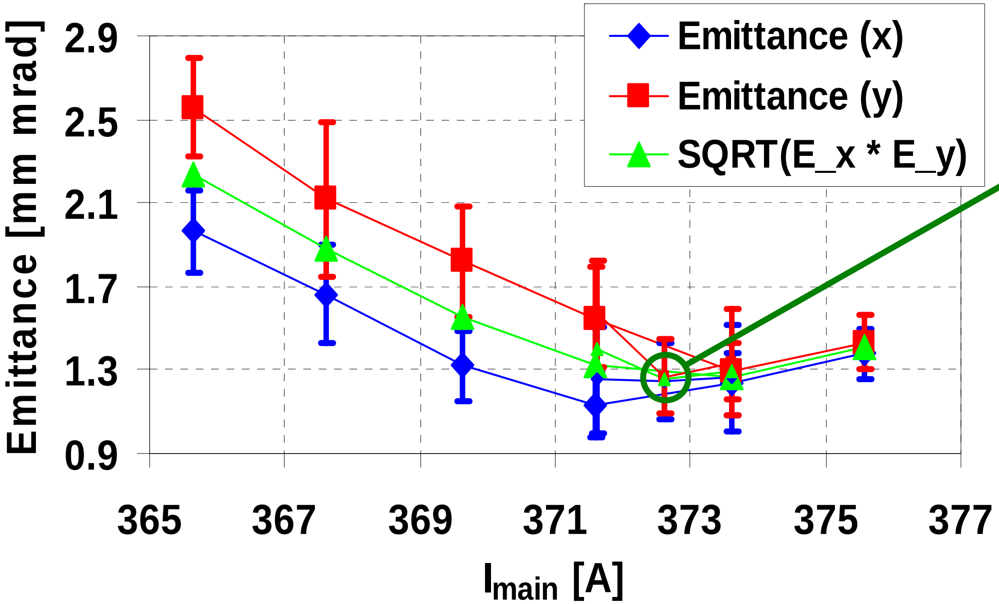
PITZ experimental highlights

Schematics of PITZ setup in 2007:



Transverse Projected Emittance Measurements

(summer 2007)



Cathode: # 90.1
Gun gradient: ~60 MV/m
Gun phase: $\Phi^{gun} = \Phi^{gun}_{ref}$
Momentum from gun: ~6.44 MeV/c

Booster phase: $\Phi^{booster} = \Phi^{booster}_{ref}$
Total beam momentum: 14.5 MeV/c

→ for **~60 MV/m** we obtained

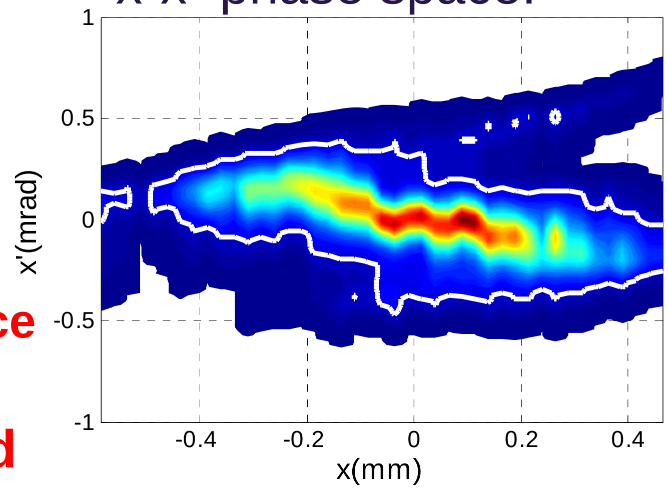
$\varepsilon_{x,n} = 1.25 \pm 0.19$ mm mrad
$\varepsilon_{y,n} = 1.27 \pm 0.18$ mm mrad

@1nC

for 100 % RMS emittance !

→ in good agreement with prediction from ASTRA

x-x´ phase space:



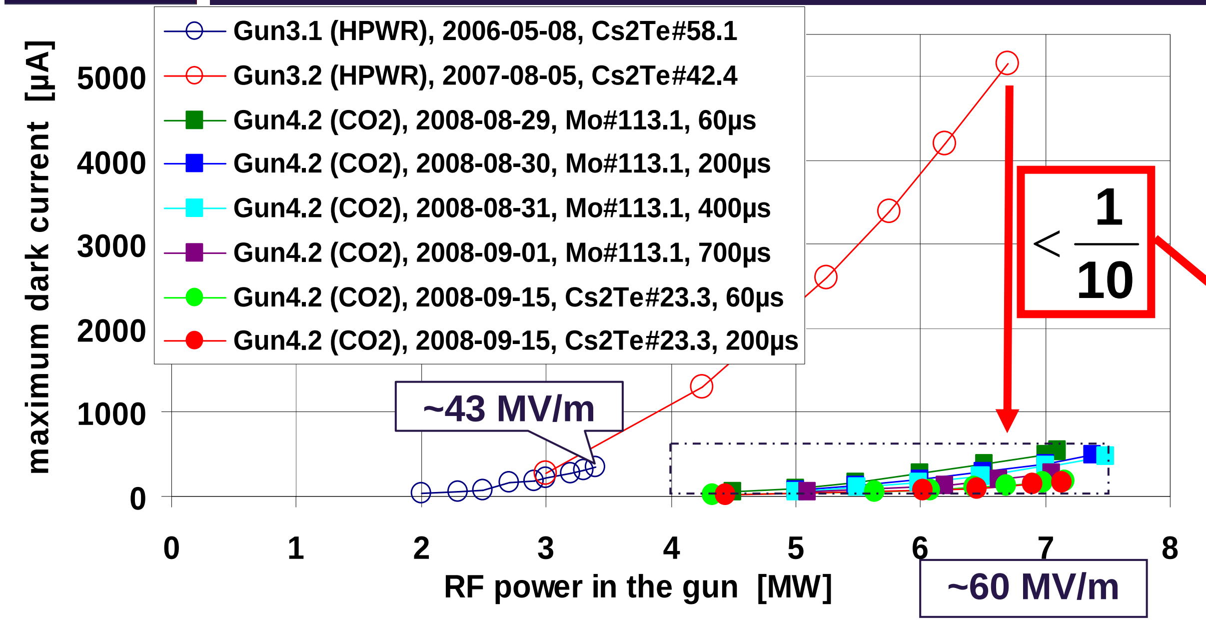
With a 10 % charge cut in the tails of the **phase space distribution** (~ remove non-lasing electrons)

→ normalized projected emittance = **~0.9 mm mrad**

→ first demonstration of beam quality required for European XFEL

Surface Cleaning ↔ Dark Current, High Average Power

(2008)

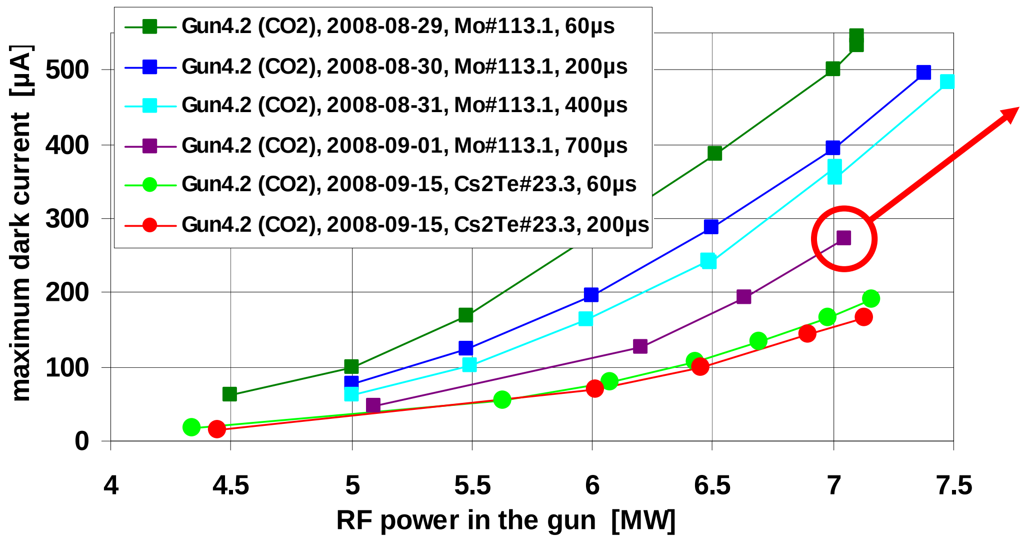


Surface cleaning techniques:

- HPWR: high-pressure water rinsing
- CO2: dry-ice cleaning

Major reduction of dark current by CO2 snow cleaning

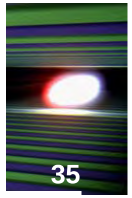
zoom:

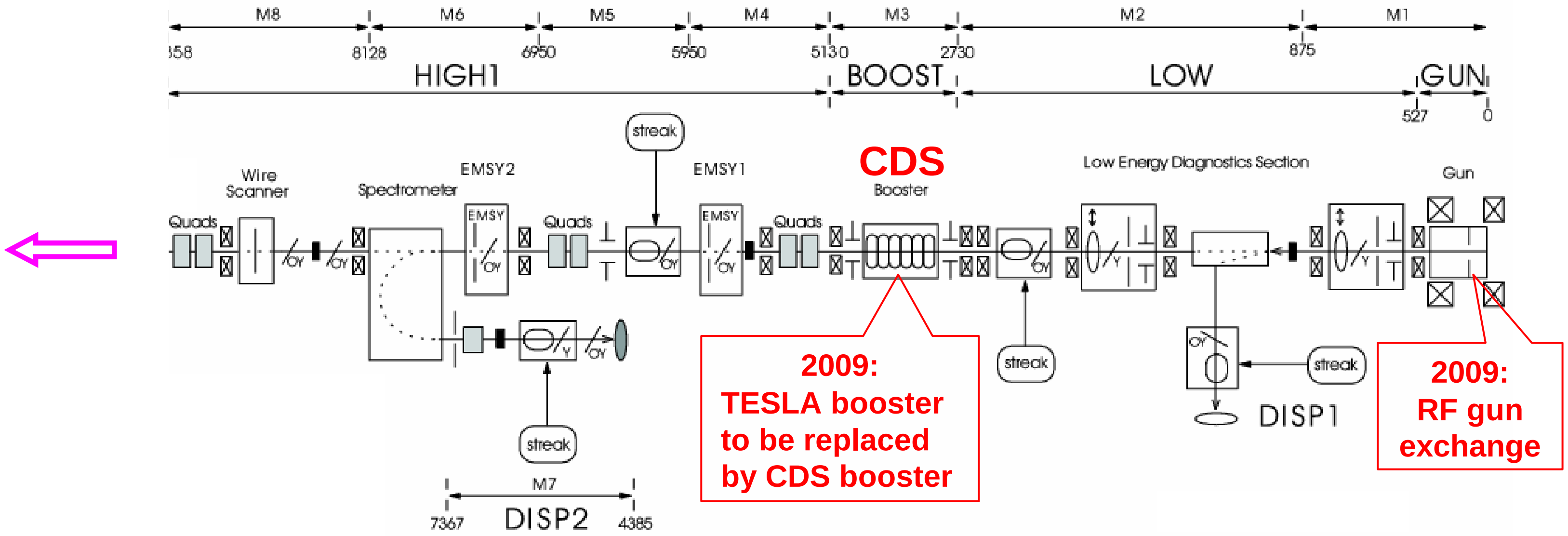


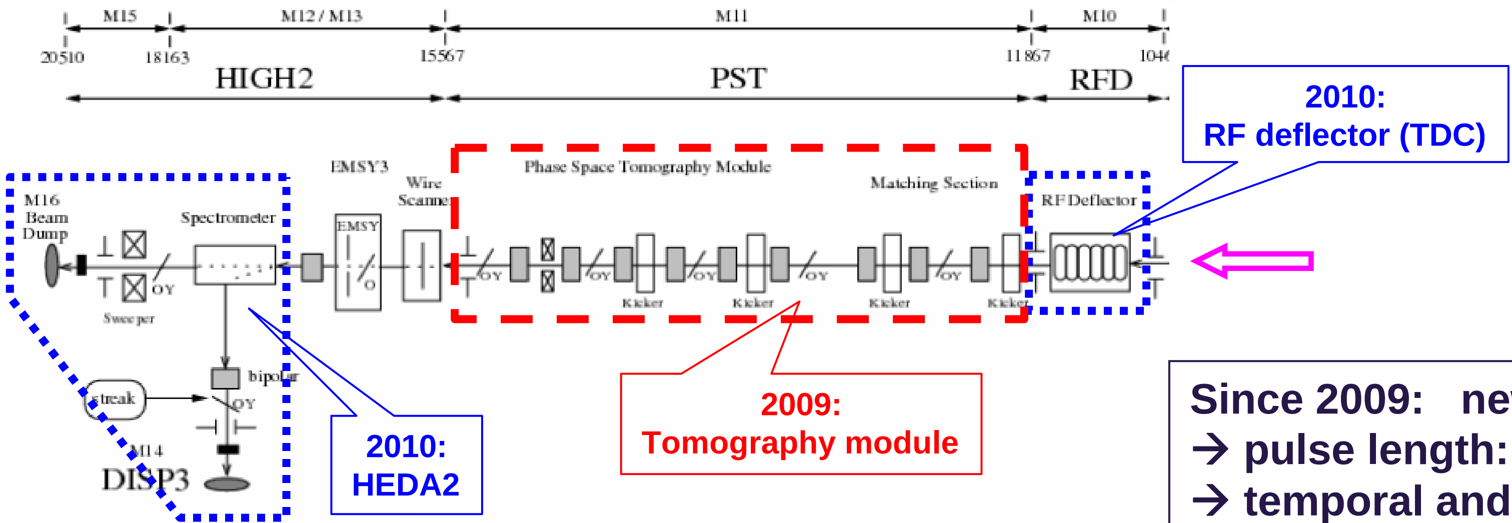
demonstrated operation with 50 kW average RF power
→ fulfills XFEL average RF power specs !

→ allows high brightness, high average current operation:
1–5 mA in 700 μs,
7–35 μA long term average

PITZ beamline: Status and Future







Since 2009: new laser system
→ pulse length: 2-24 ps (FWHM)
→ temporal and transverse laser shaping

Summary

- **European X-ray Free Electron Laser (XFEL)**
  - a next generation light source
  - will allow unprecedented experiments with **atomic** resolution on **femtosecond** time scales with ultra-high peak and average **brilliance** photon beams of transverse spatial **coherence**
  - construction **started**

- **Free electron LASer in Hamburg (FLASH):**
  - precursor for XFEL (testbed for XFEL and ILC)
  - user facility since 2005, **producing unique scientific results**

- **Photo Injector Test facility at DESY, Zeuthen site (PITZ):**
  - develops key component for XFEL → high brightness **electron source**
  - very low **emittance** and high **average power** operation demonstrated
  - R&D ongoing → further improvements, new operation modes

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