The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1936-3

Advanced School on Synchrotron and Free Electron Laser Sources and their Multidisciplinary Applications

7 - 25 April 2008

The European X-ray Free-Electron Laser Project in Hamburg

Jasper Plaisier

MCX beamline –Elettra Trieste

Massimo Altarelli

European XFEL Project Team Leader
c/o DESY
Hamburg - Germany

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European XFEL Project Team Leader

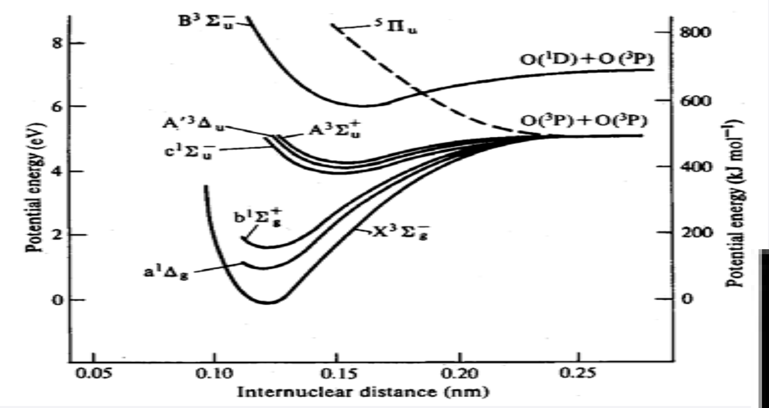
c/o DESY, Hamburg

SUMMARY

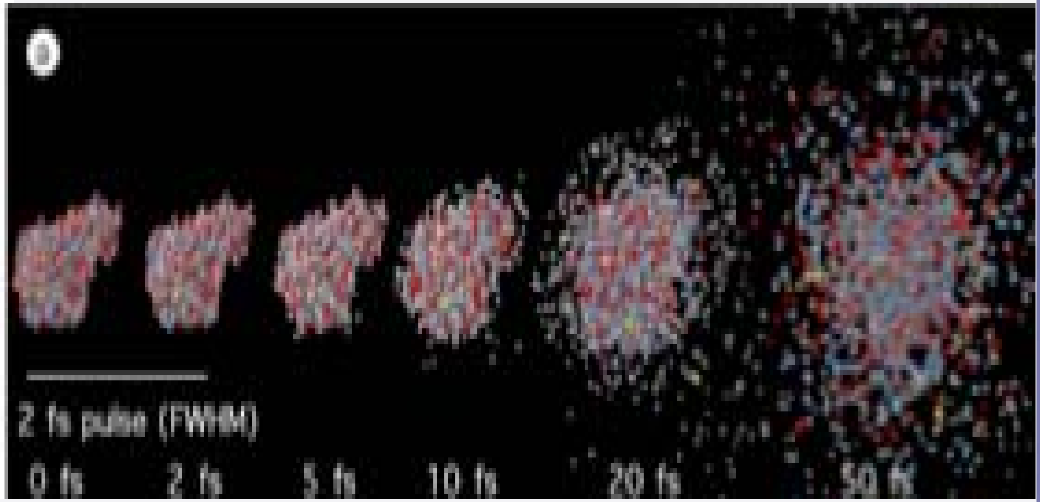
1. **Introduction**
2. **Description and objectives of the European XFEL**
3. **Status of the Project**
4. **Conclusion**

Wanted…A more brilliant X-ray source, with:

wavelength ~ 0.1 nm ==> *atomic-scale resolution*



ultrashort (<1 ps) pulses
==> "molecular movies"

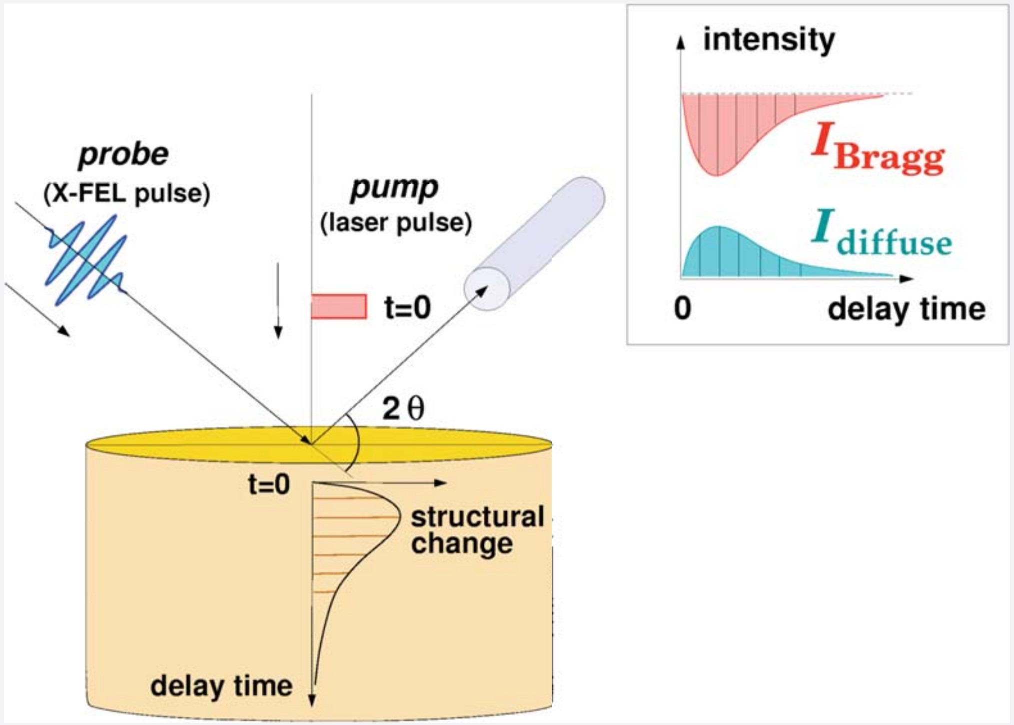


ultra-high peak brightness
==>investigation of matter under extreme conditions…

transverse spatial coherence
==> imaging of single nanoscale objects, possibly down to individual macromolecules (no crystals)

Today: study (structure and) dynamics on a ns to ps timescale

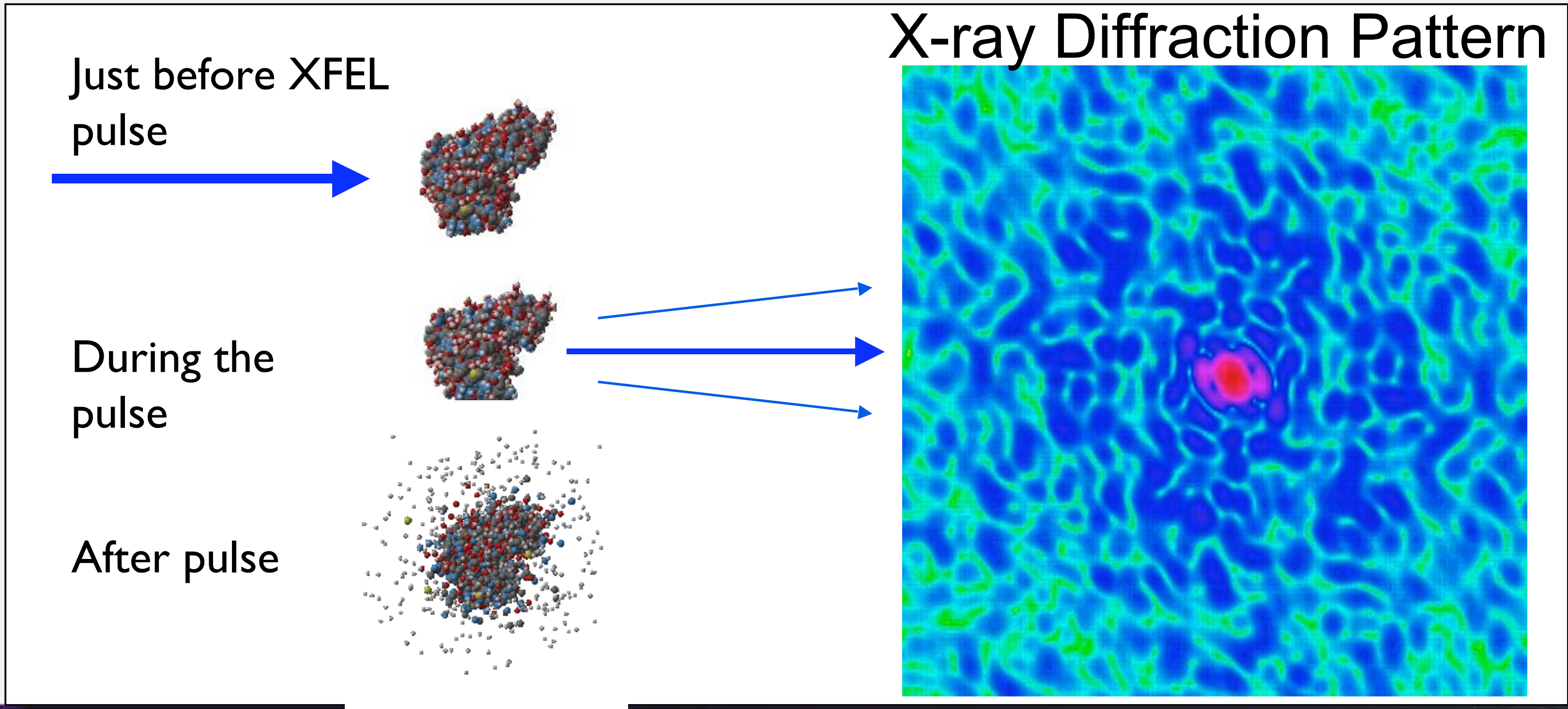
XFEL: study (structure and) dynamics on a ps and fs timescale



HIGH-RESOLUTION IMAGING OF MOLECULES WITH X-RAY Free-Electron Lasers (FEL's)

Henry Chapman,
DESY, U. of Hamburg

Janos Hajdu,
Uppsala University and Stanford



XFEL pump, XFEL probe

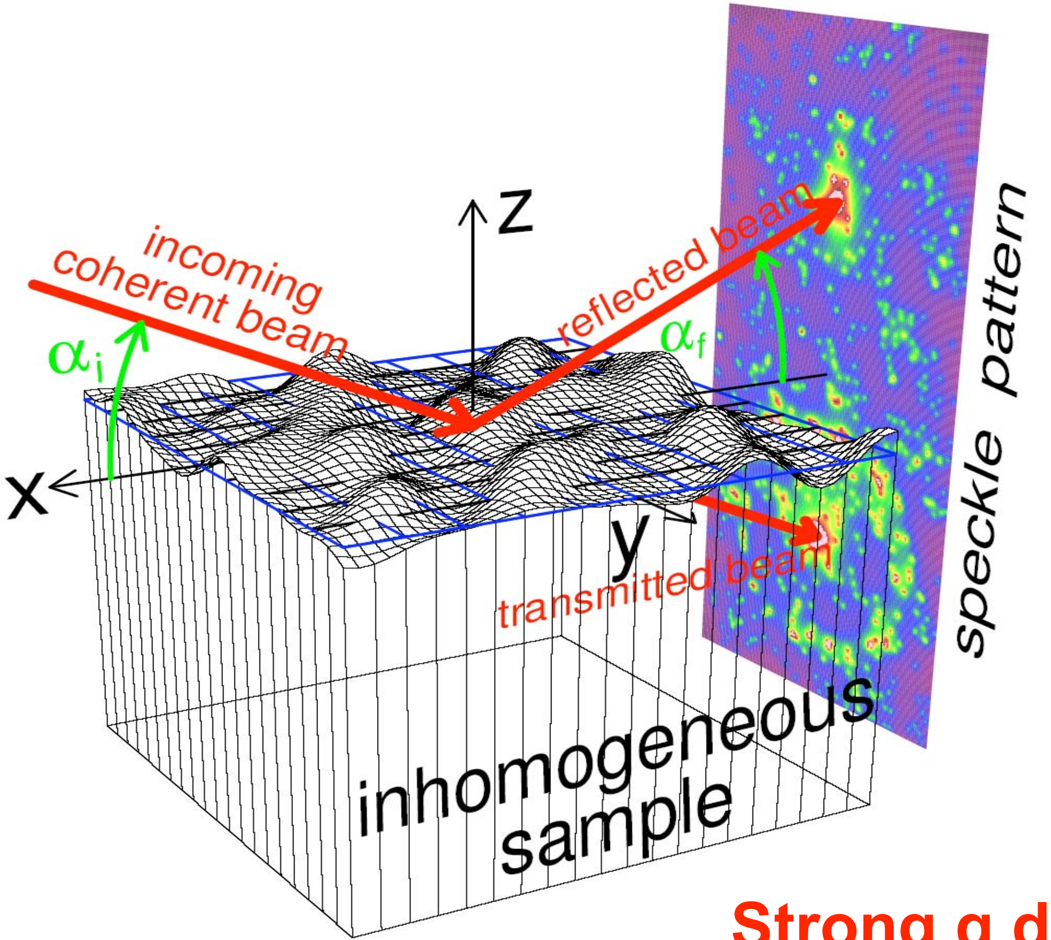
1. **X-ray Photon Correlation Spectroscopy**

   ==> Study dynamics of correlations in matter

   Light coherence length larger than correlation length in sample

2. **High Energy-Density Physics, Plasma Physics**

X-Ray Photon Correlation Spectroscopy

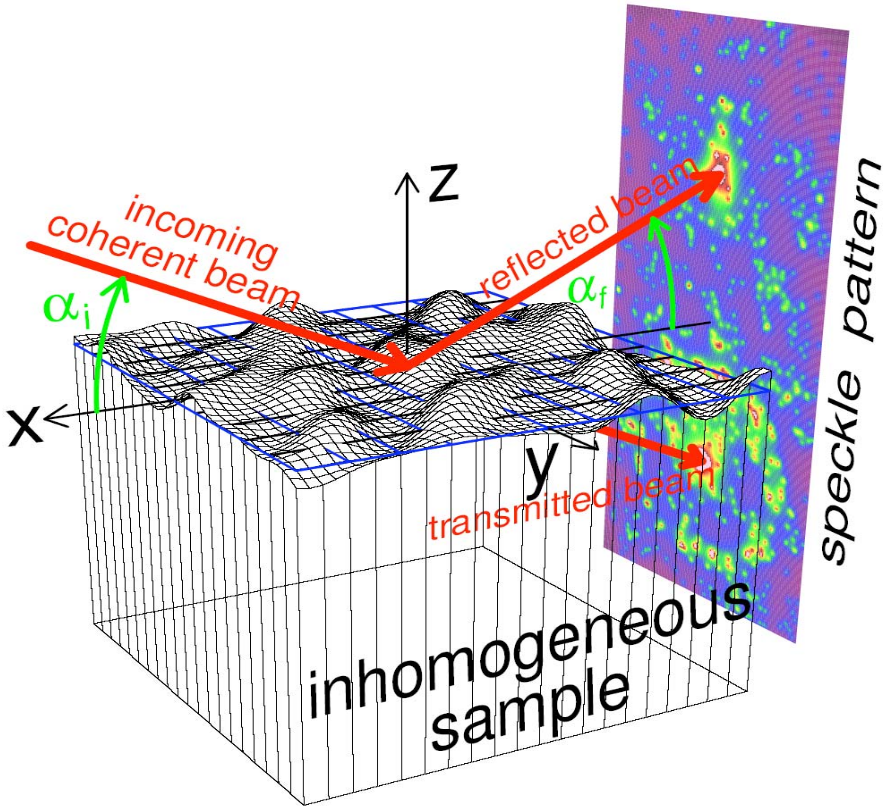


Fluctuating Surface = Fluctuating Speckles

Strong q dependence of intensity

X-Ray Photon Correlation Spectroscopy

Coherent beam case: coherence length of light at sample >> correlation length of domains:



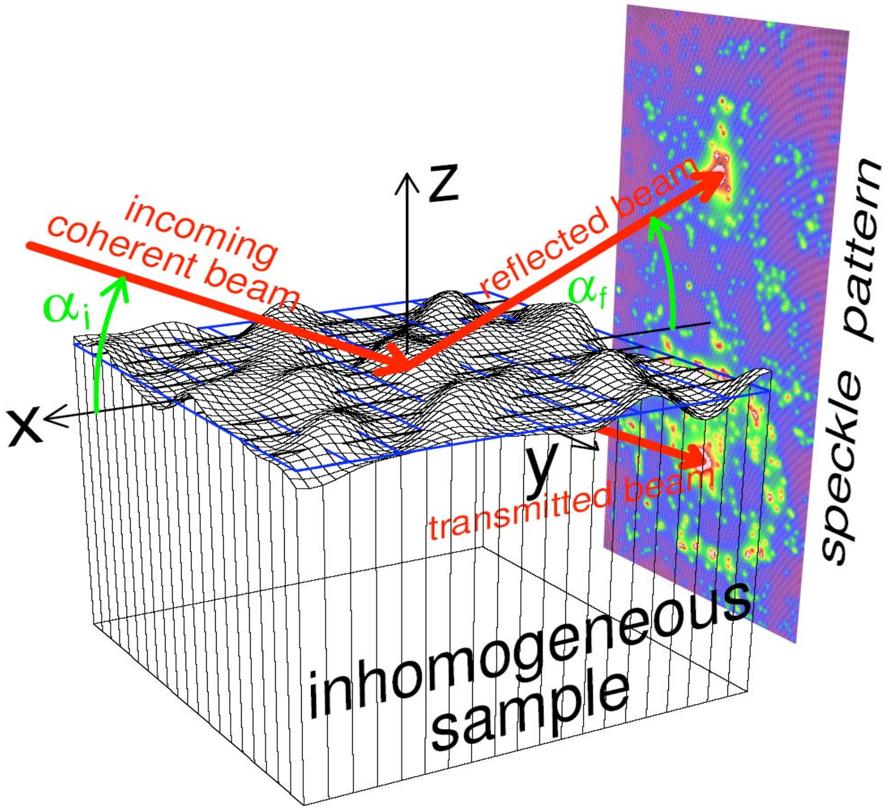
$$I(\mathbf{q}) = \left| \sum_{i=\,domains} e^{i\mathbf{q}\cdot\mathbf{R}_i} f_i \right|^2$$

Fluctuating Intensity :

$$g_2(\tau) = \frac{\langle I(t+\tau)I(t)\rangle_t}{\langle I(t)\rangle_t^2}$$

X-Ray Photon Correlation Spectroscopy

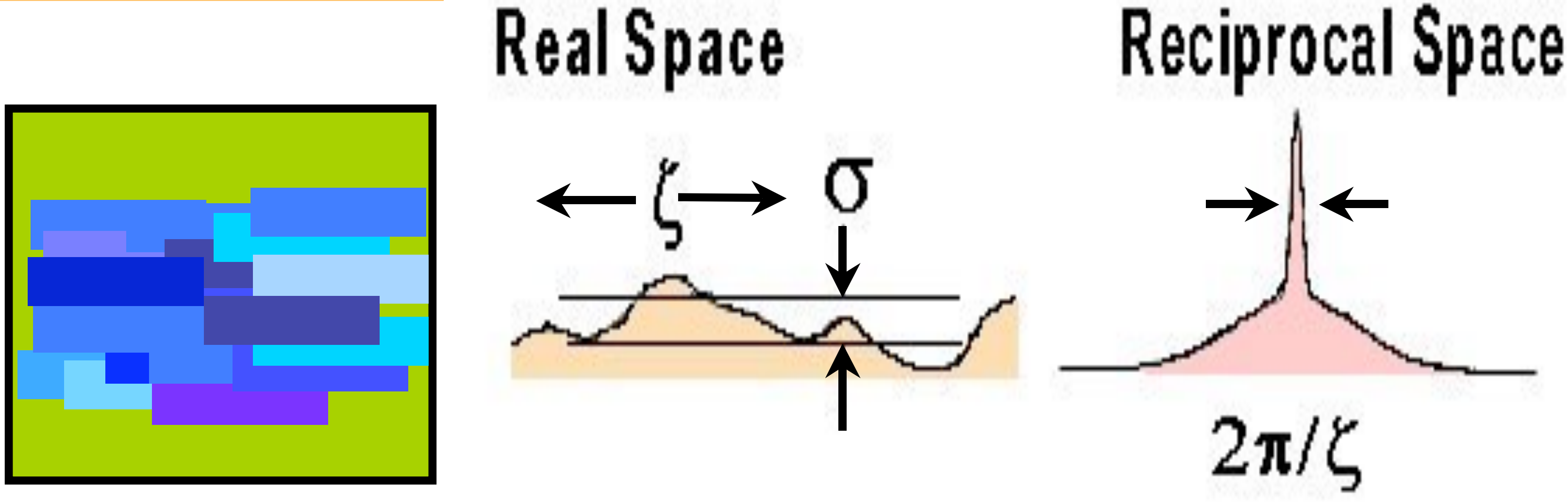
Incoherent beam case: coherence length of light at sample < correlation length of domains:



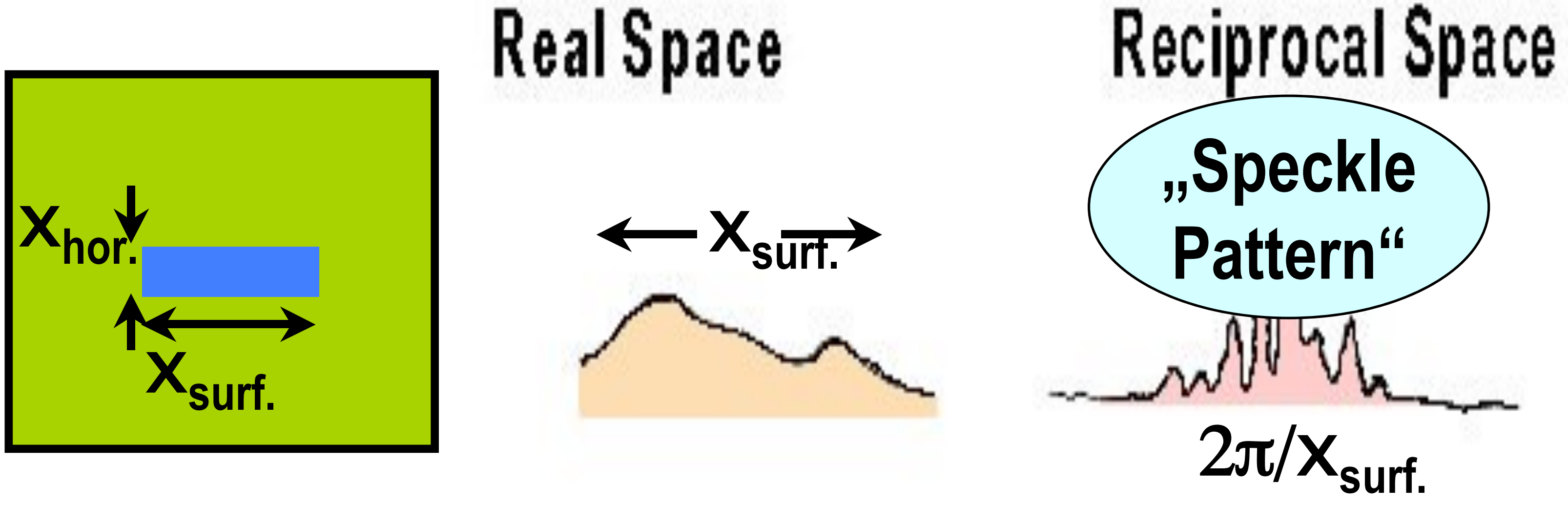
$$I(\mathbf{q}) = \sum_{i=domains} \left| e^{i\mathbf{q}\cdot\mathbf{R}_i} f_i \right|^2$$

Incoherent vs. Coherent Scattering

MANY Coherence Volumes

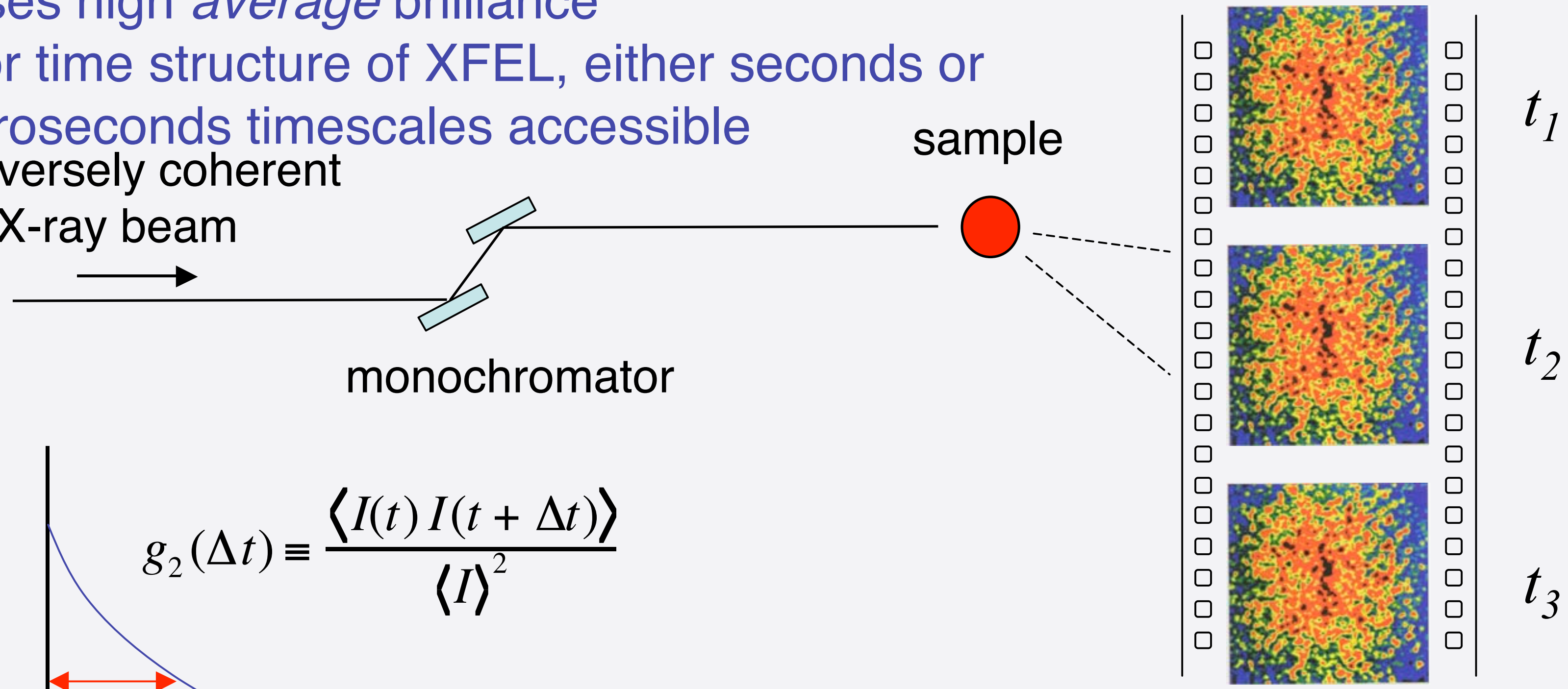


Only ONE Coherence Volume

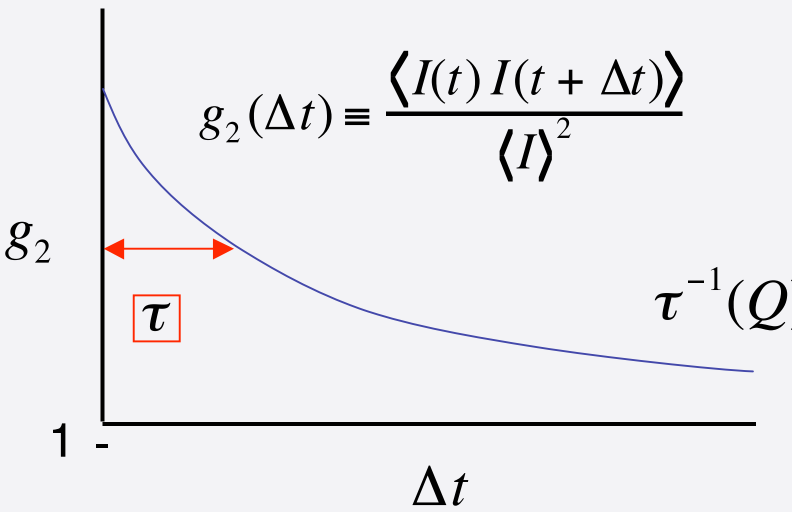


XPCS using ‘Sequential’ Mode

- Time resolution determined by detector
- Uses high *average* brilliance
- For time structure of XFEL, either seconds or microseconds timescales accessible

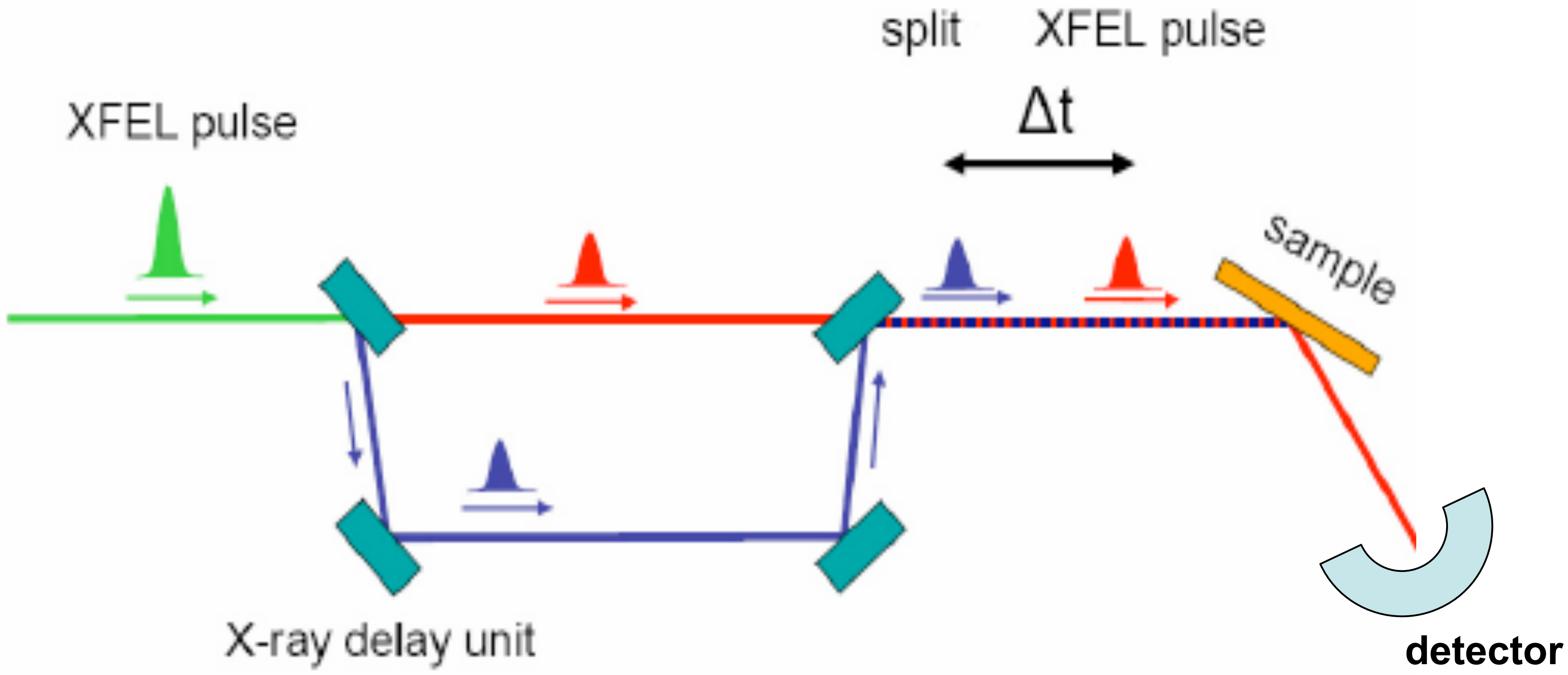


$$g_2(\Delta t) \equiv \frac{\langle I(t)\, I(t+\Delta t)\rangle}{\langle I\rangle^2}$$



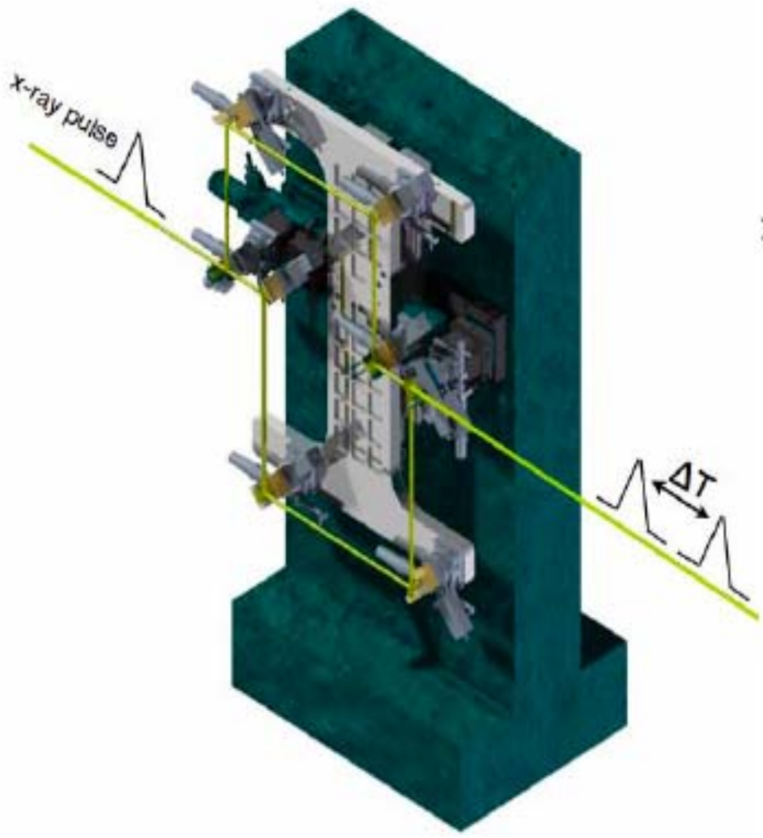
$$\tau^{-1}(Q) = Rate(Q)$$

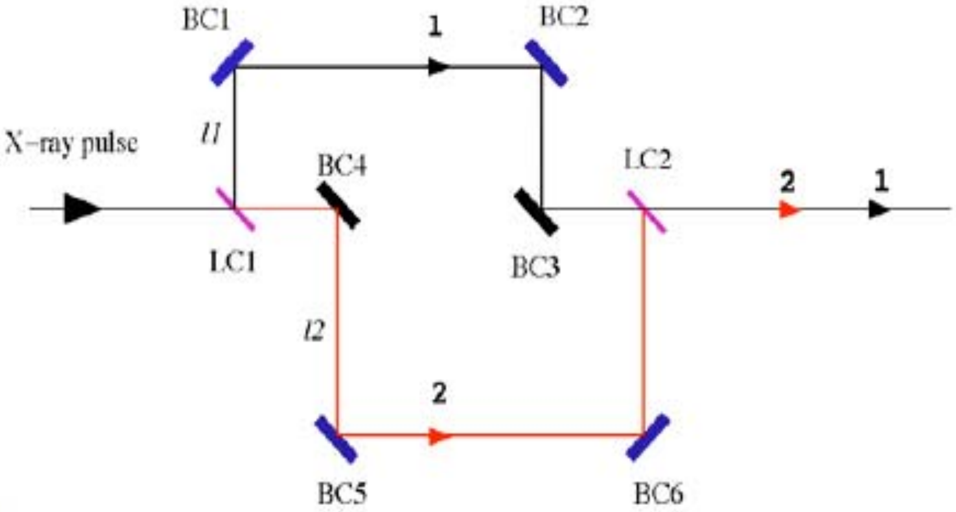
Delay Line splitting of pulses (Roseker, Grübel et al.)



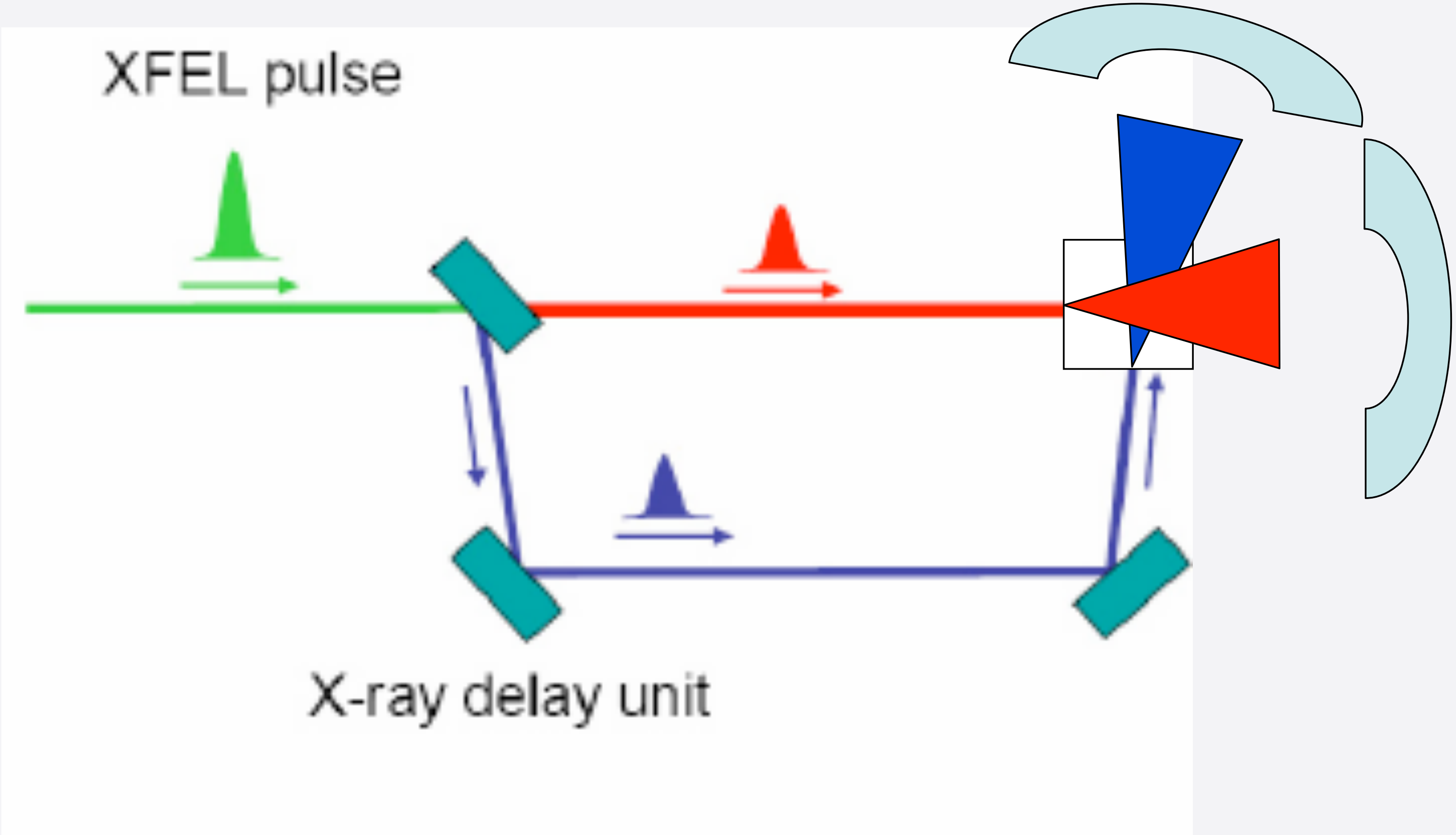
Delays from ~ 500 fs to ns scale conceivable

Delay Line splitting of pulses (Roseker, Grübel et al.)





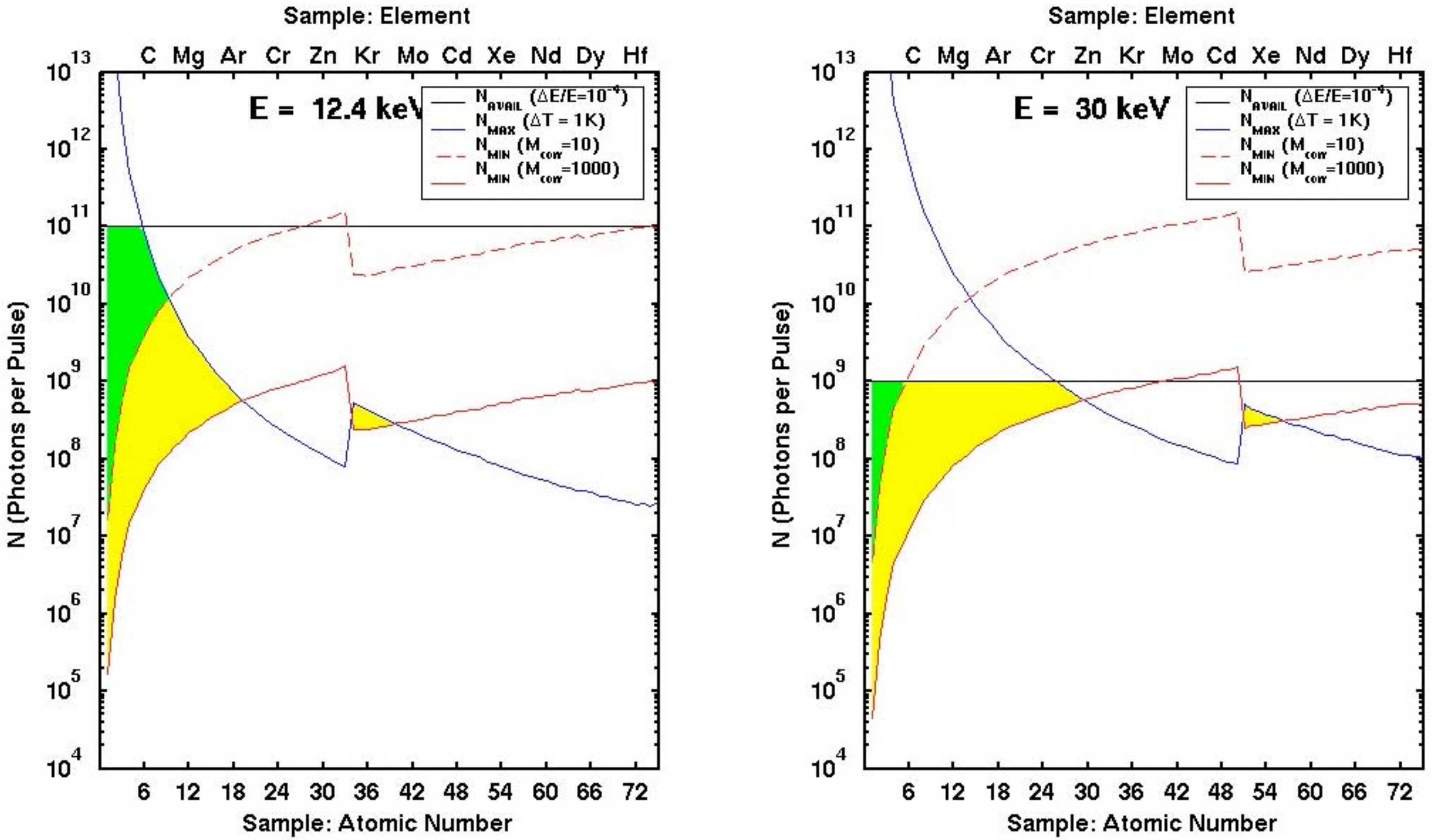
Speckle Scattering: Time Evolution of 2-dim. Patterns



Heating and XPCS Signal from Single Pulse

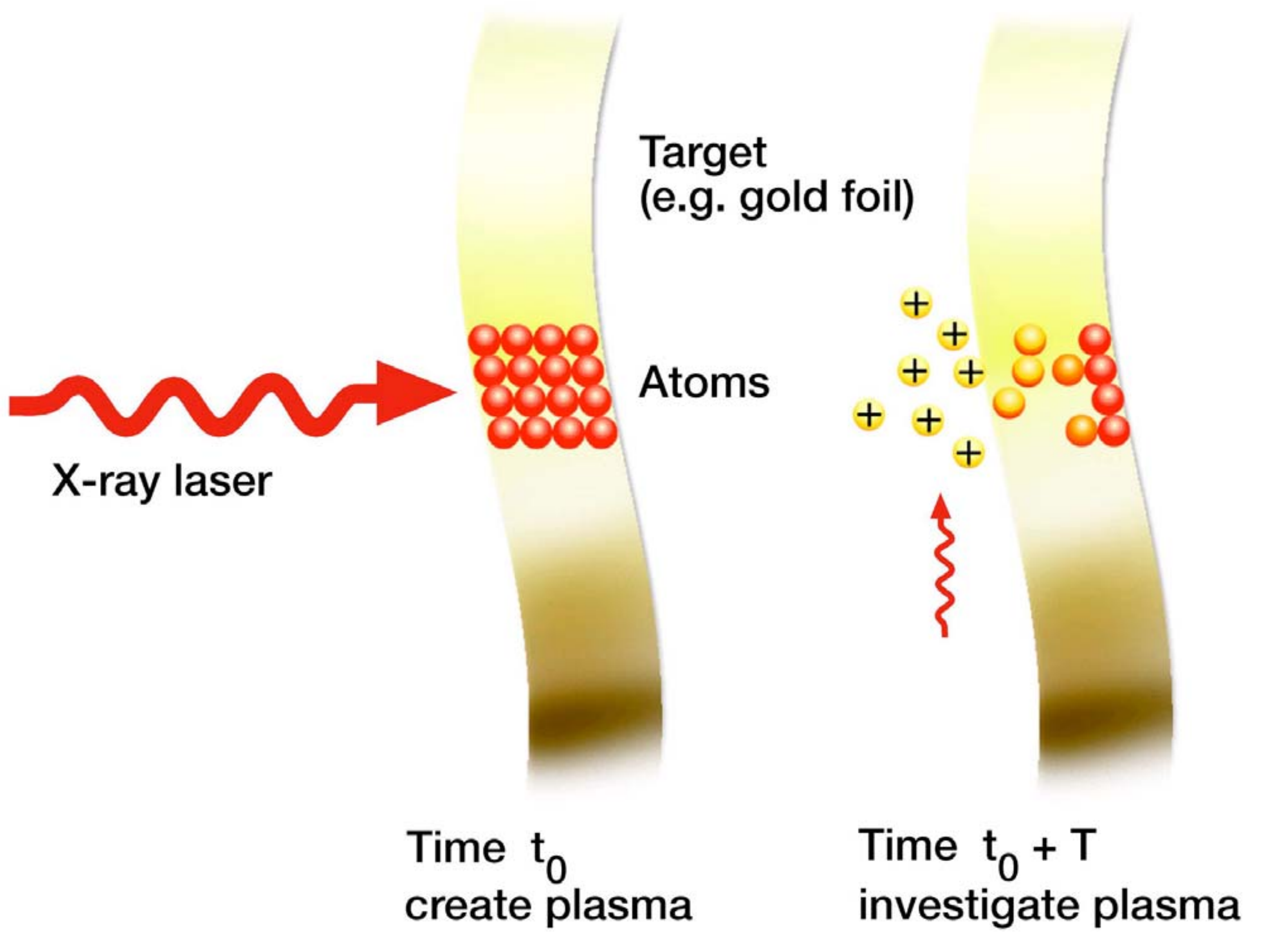
Focused to 100 μm diam.

See analysis in LCLS: The First Experiments

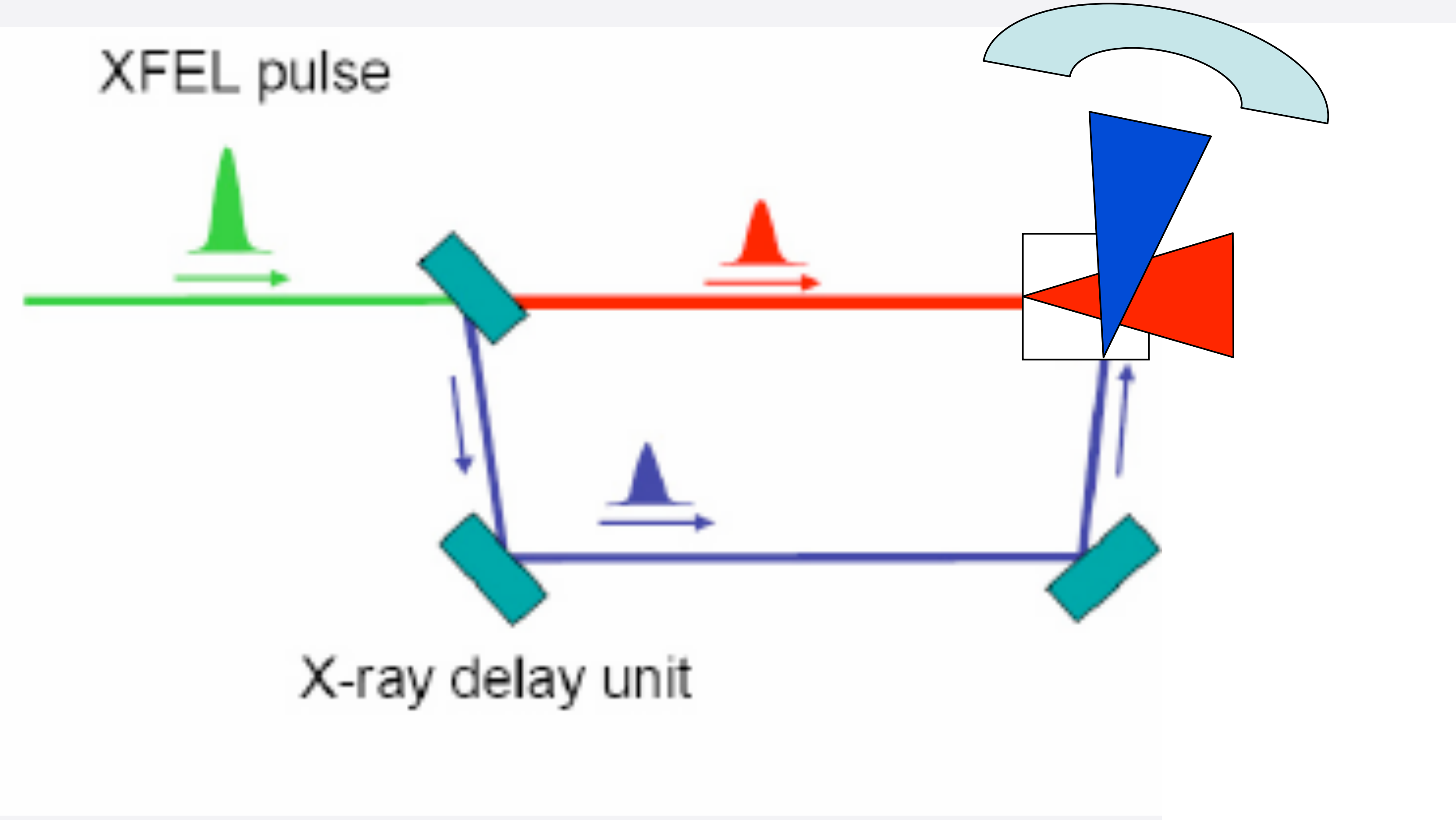


Shaded areas show feasibility regions e.g. for liquid or glass (green) or nanoscale cluster (yellow)

Plasma States by Pump-Probe Techniques



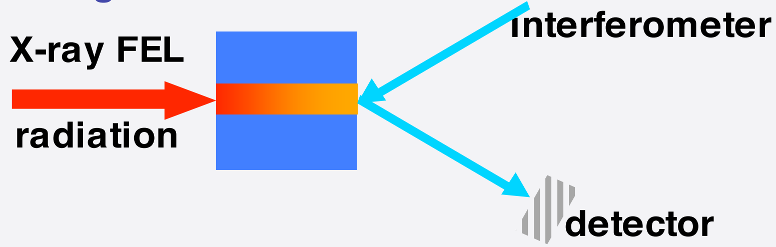
XFEL pump - XFEL probe: non collinear geometry

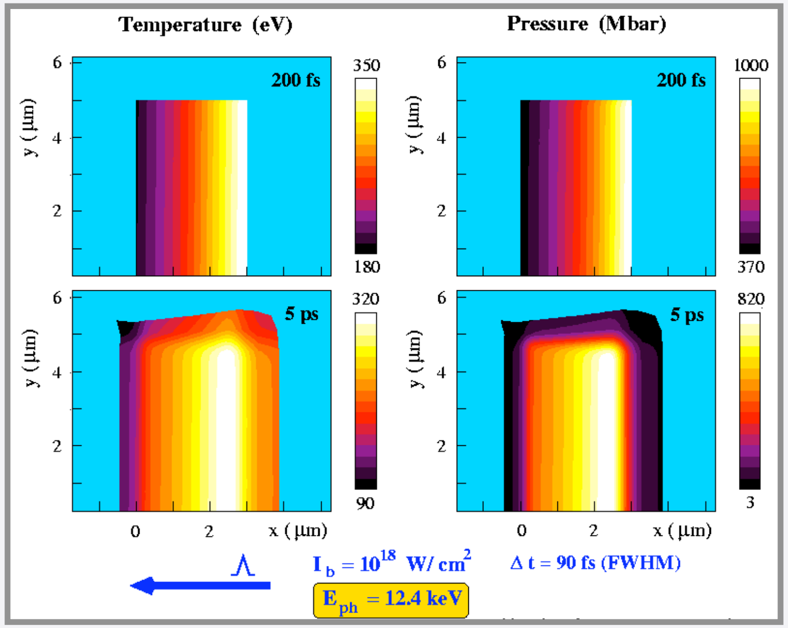


Isochoric heating of plasmas

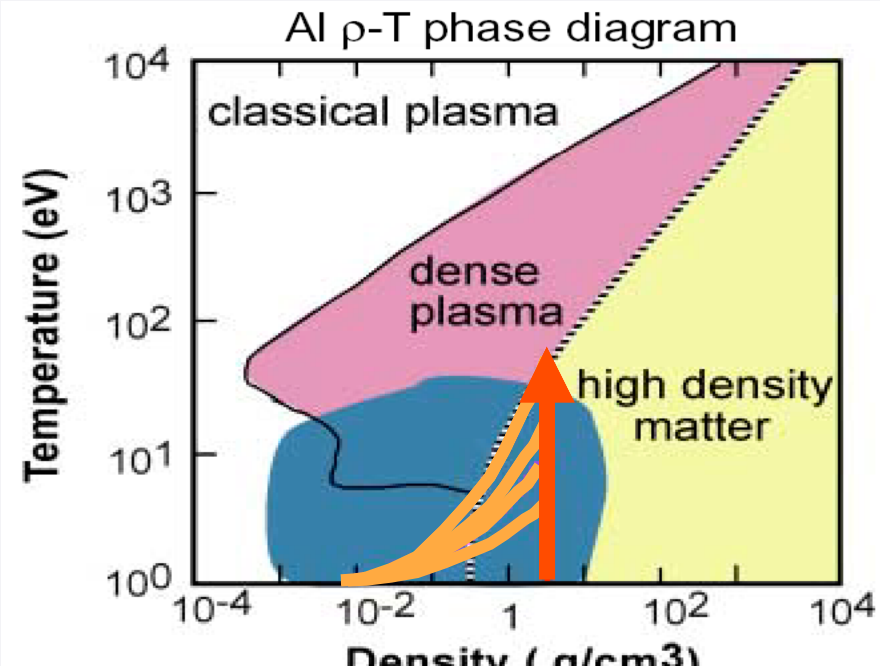
- **Solid density plasmas**
- **T_e up to few 100 eV**
- **Warme dense matter**
- **Pressure up to Gbar**
- **Plasma phase transitions**

Plasma generation





Schlegel et al., (2000)

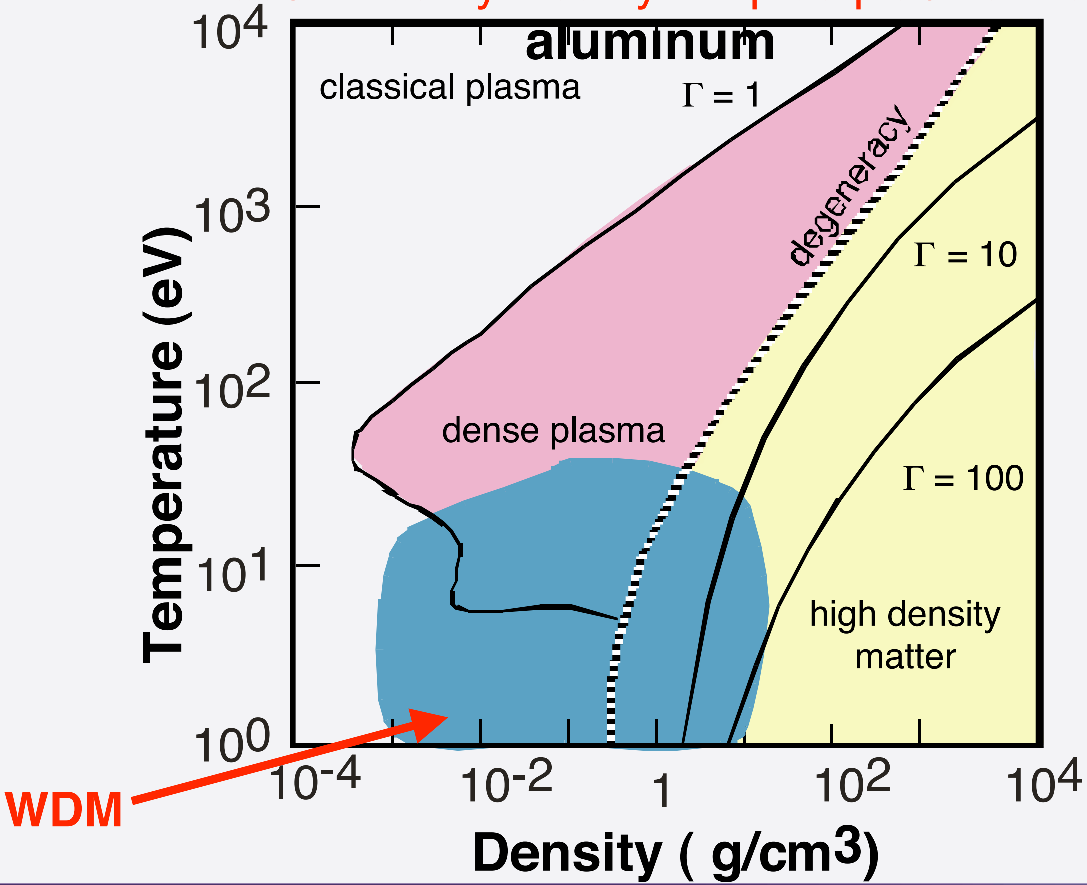


R.W. Lee & coworkers

Warm Dense Matter (courtesy R.W. Lee)

WDM is that region in temperature-density space that is:

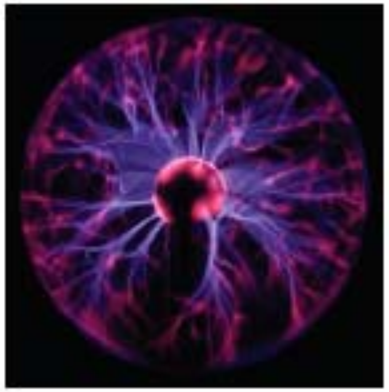
- Not described as normal condensed matter, i.e., T ~ 0
- Not described by weakly coupled plasma theory



- Γ is the strong coupling parameter, the ratio of the interaction energy between the particles, V_{ii}, to the kinetic energy, T
- $$\Gamma = \frac{V_{ii}}{T} = \frac{Z^2 e^2}{r_o T}$$

where $r_o \propto \frac{1}{\rho^{1/3}}$

Tools for ultrafast structural dynamics: x-rays



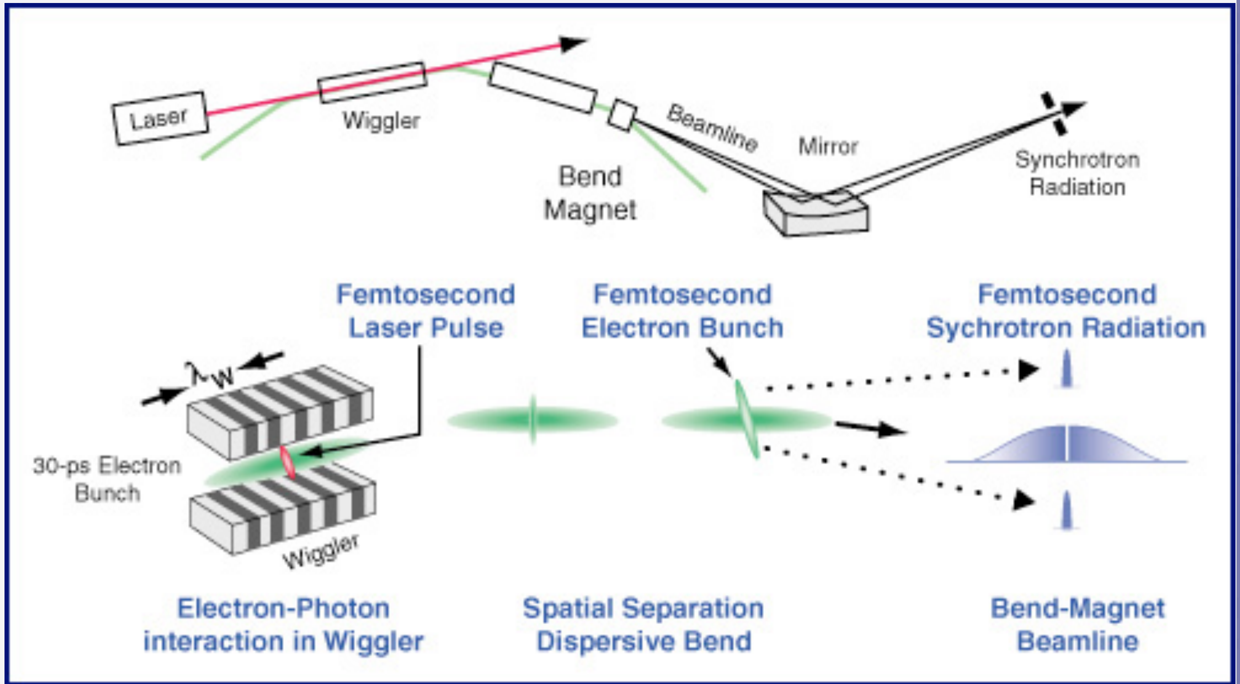
Laser-based: **laser-plasma, plasma-wiggler, HHG,…**

Accelerator-based:

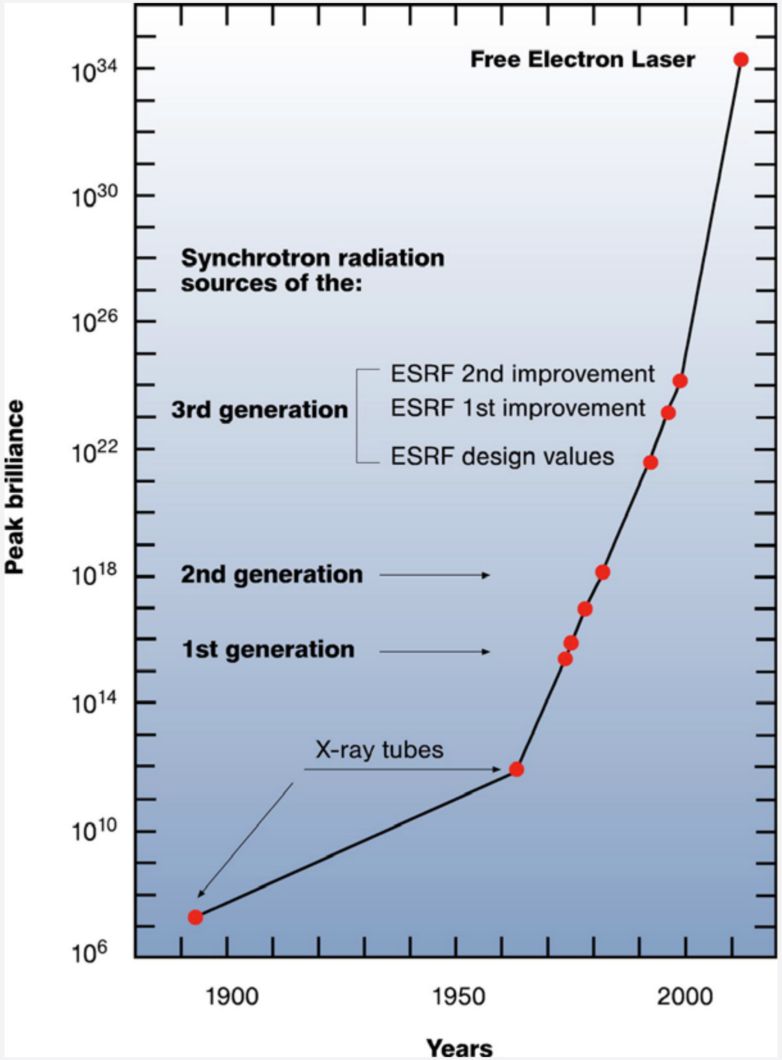
Storage rings:

bunch-slicing,

bunch-rotation



Peak brilliance of X-ray Sources vs. time



Free Electron Lasers:

-Based on Linear Accelerators

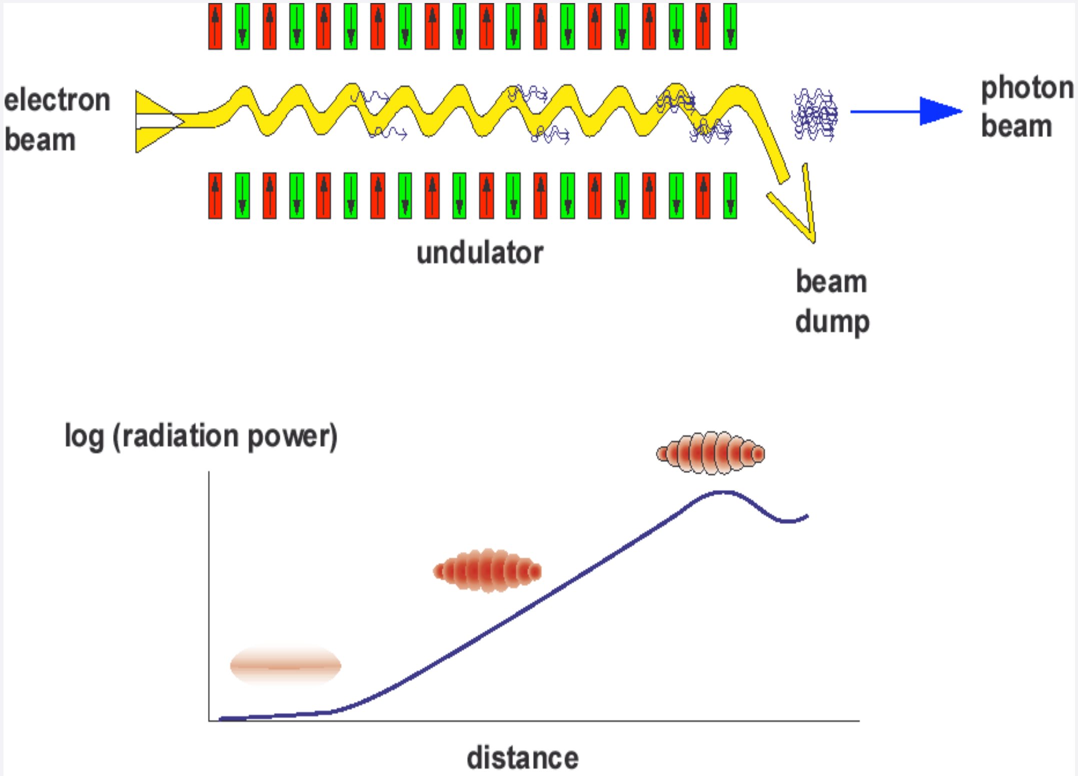
-Deliver ultrashort pulses

(100 fs = 0.1 ps= 10^{-13} s or less)

- (Transversely) Spatially coherent (laser-like) radiation

SASE Process

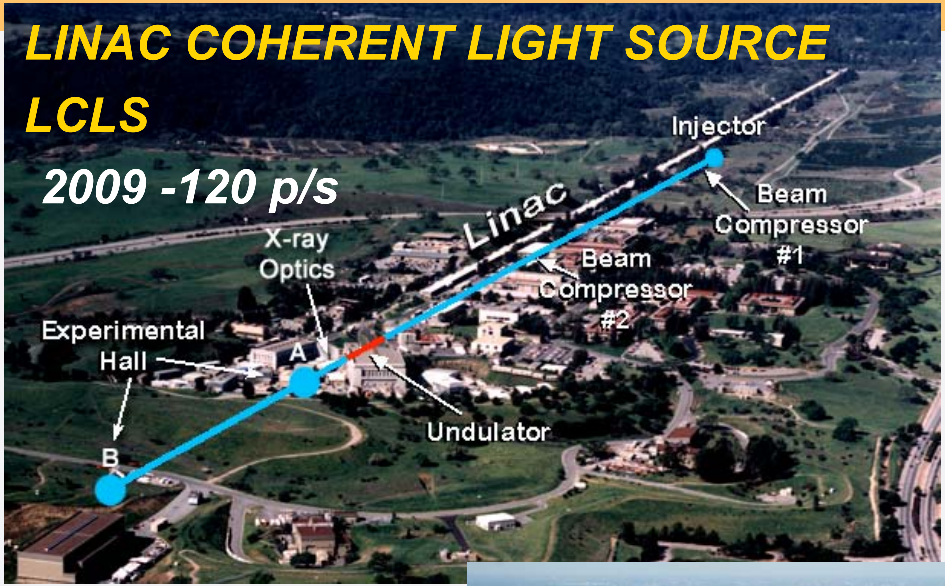
Tightly collimated (low emittance) electron beam in a long undulator: coherent emission results from microbunching, produced by amplification of shot-noise density fluctuations at the resonant wavelength by the radiation, as it progresses through the bunch.



Peak Power:

~ 10 GW

The European XFEL in the International Context



The XFEL TDR - Delivered July 15, 2006

Almost 600 pages,

27 Editors,

over 270 Authors,

from 69 Institutions

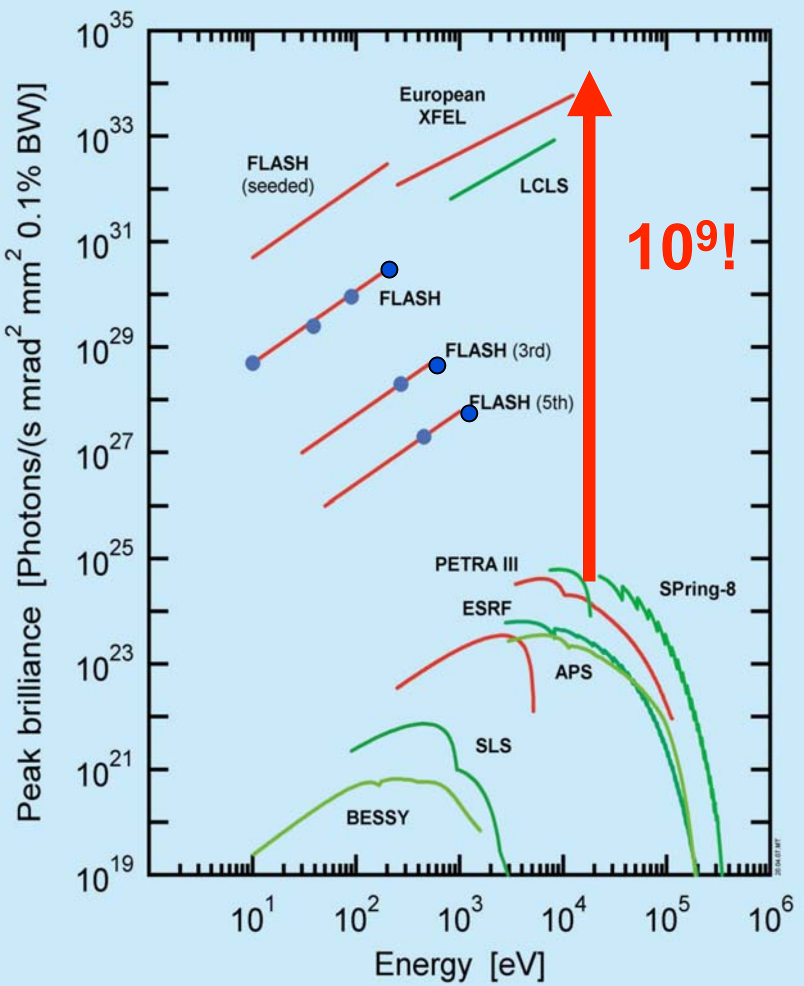
in Europe (57)

America (10)

Asia (2)

http://xfel.desy.de/tdr/index_eng.html

The European XFEL Project essentials…



Construction Phase officially launched June 5, 2007

Civil construction tenders out

First Beam, 2013

Complete Operation with up to 10 Experimental Stations, 2015

SUMMARY

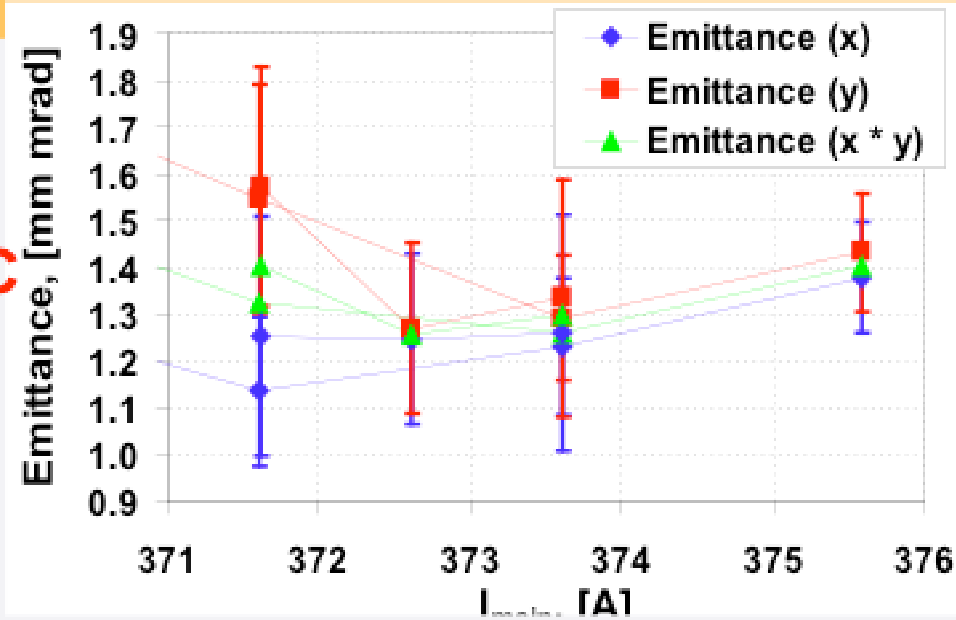
1. Introduction
2. Description and objectives of the European XFEL
3. Status of the Project
4. Conclusion

Overall layout of the European XFEL

HELMHOLTZ GEMEINSCHAFT DESY

Lot 3 - Injector Building

Low-emittance gun (FEL Conf. Novosibirsk)



August 2007:

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

@1nC

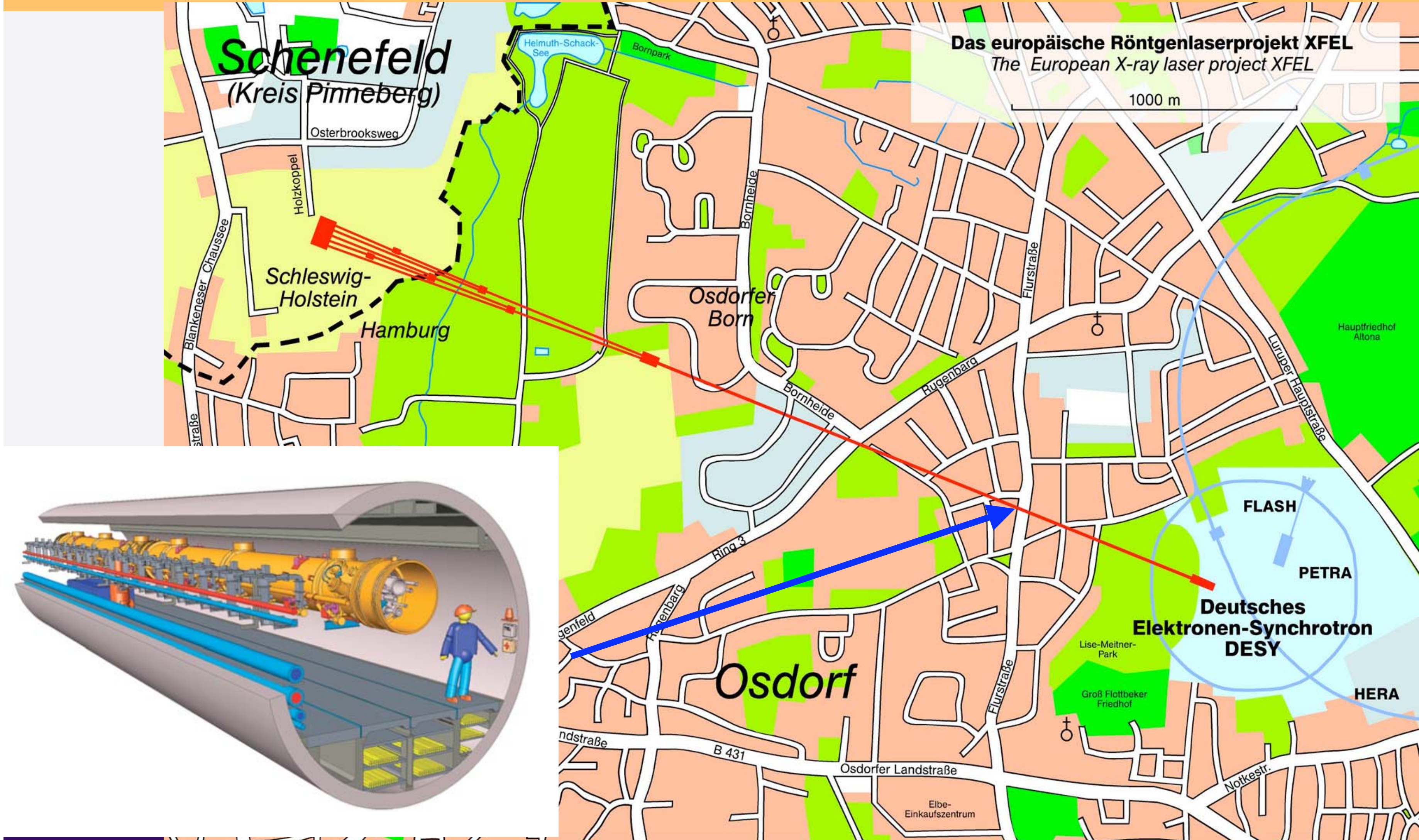
for 100 % RMS emittance !

Cut of large-amplitude tails:

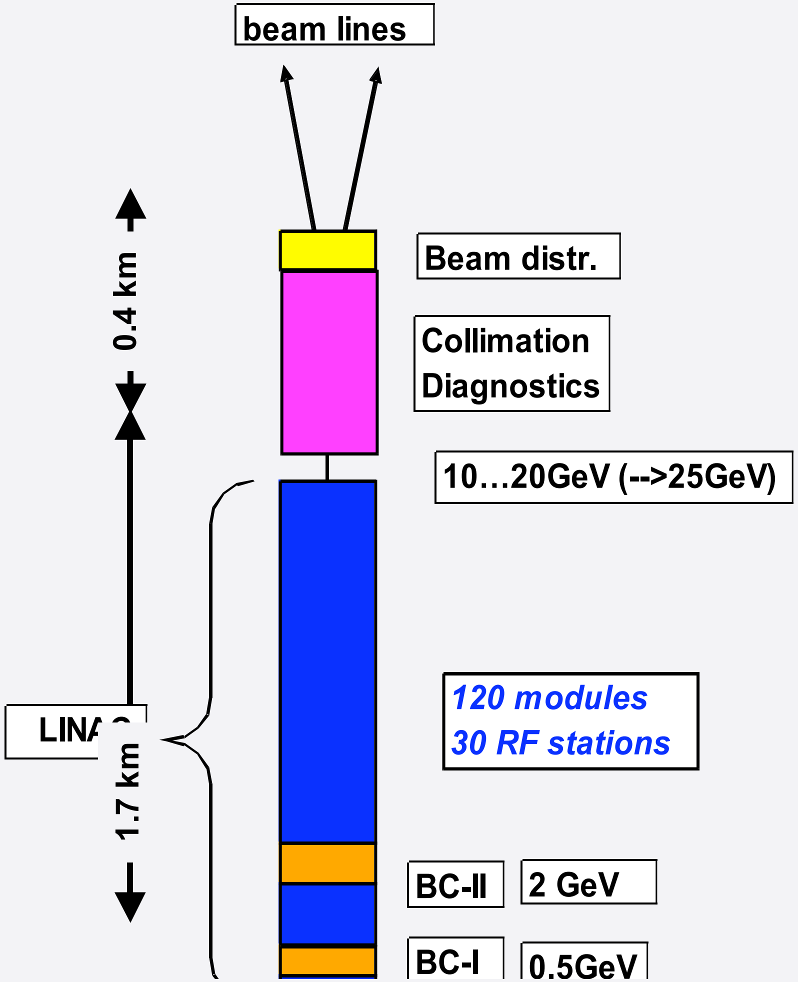
For 95% RMS ➔ $\varepsilon_{xy,n} \cong 0.8 mm \times mrad$

XFEL design values is 0.9 mm mrad from the gun and 1.4 mm mrad in the undulators for FEL saturation at 0.1nm wavelength

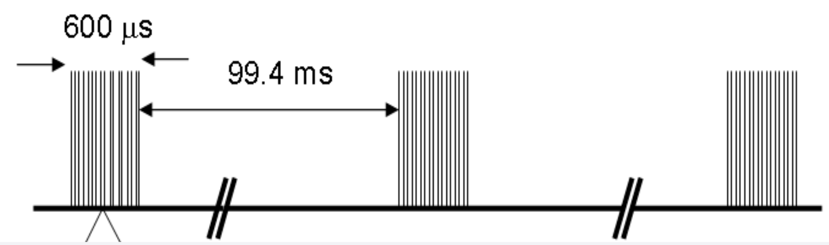
Site near DESY laboratory



The super-conducting electron accelerator

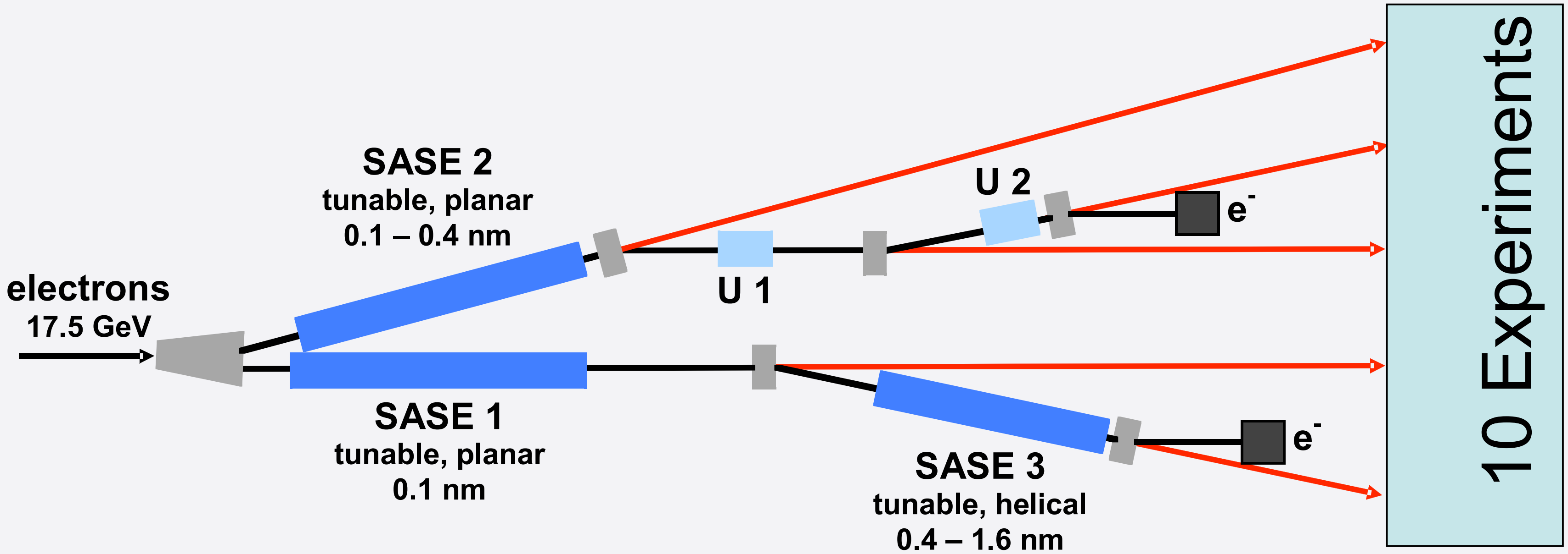


Parameter	Unit	Value
Electron energy for 0.1 nm FEL radiation	GeV	17.5
Accelerating gradient	MeV/m	22.9
Bunch charge	nC	1
RF pulse repetition rate	Hz	10
Electron bunch repetition rate during RF pulse	MHz	5
Max. number of electron bunches per RF pulse		3000
Duration of electron bunchtrain	μs	600
Average electron beam power	kW	570
Normalized slice emittance (rms)	mm mrad	1.4
Electron energy spread (rms)	MeV	< 1



Beam Distribution System

Layout of the European XFEL User Facility



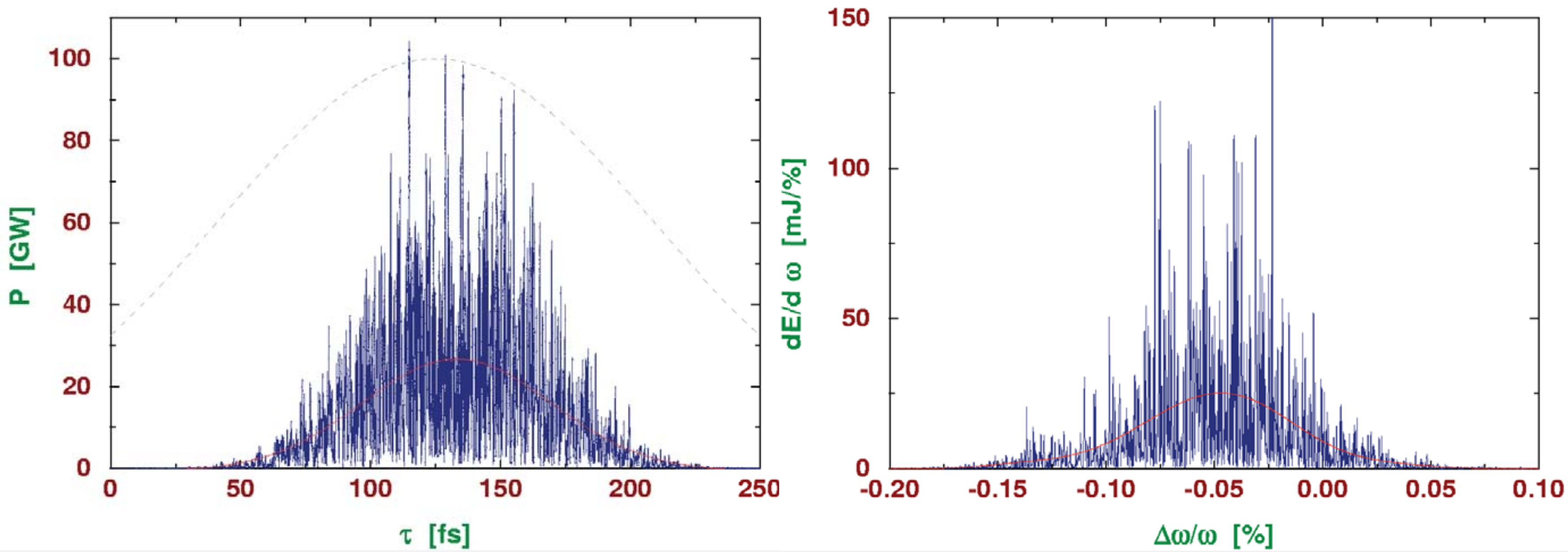
Baseline design

- 2 SASE FELs for hard x-ray FEL radiation
- 1 SASE FEL for soft/medium x-ray FEL radiation
- 2 undulators for spontaneously emitted synchrotron radiation (optionally replace U 1 by additional SASE FEL for soft X-ray range)
- Use spent beam for soft x-ray FEL and spontaneous radiation undulators

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}

SASE process in the hard x-ray range: pulse structure

XFEL: 0.1 nm (Δt = 100 fs FWHM; ≈ 0.1% bw)



≈ 10^{12} ph/bunch

» 300 modes

Experimental Hall Building

Advantages of Superconducting RF Technology for FEL's

Possibility to accelerate 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;

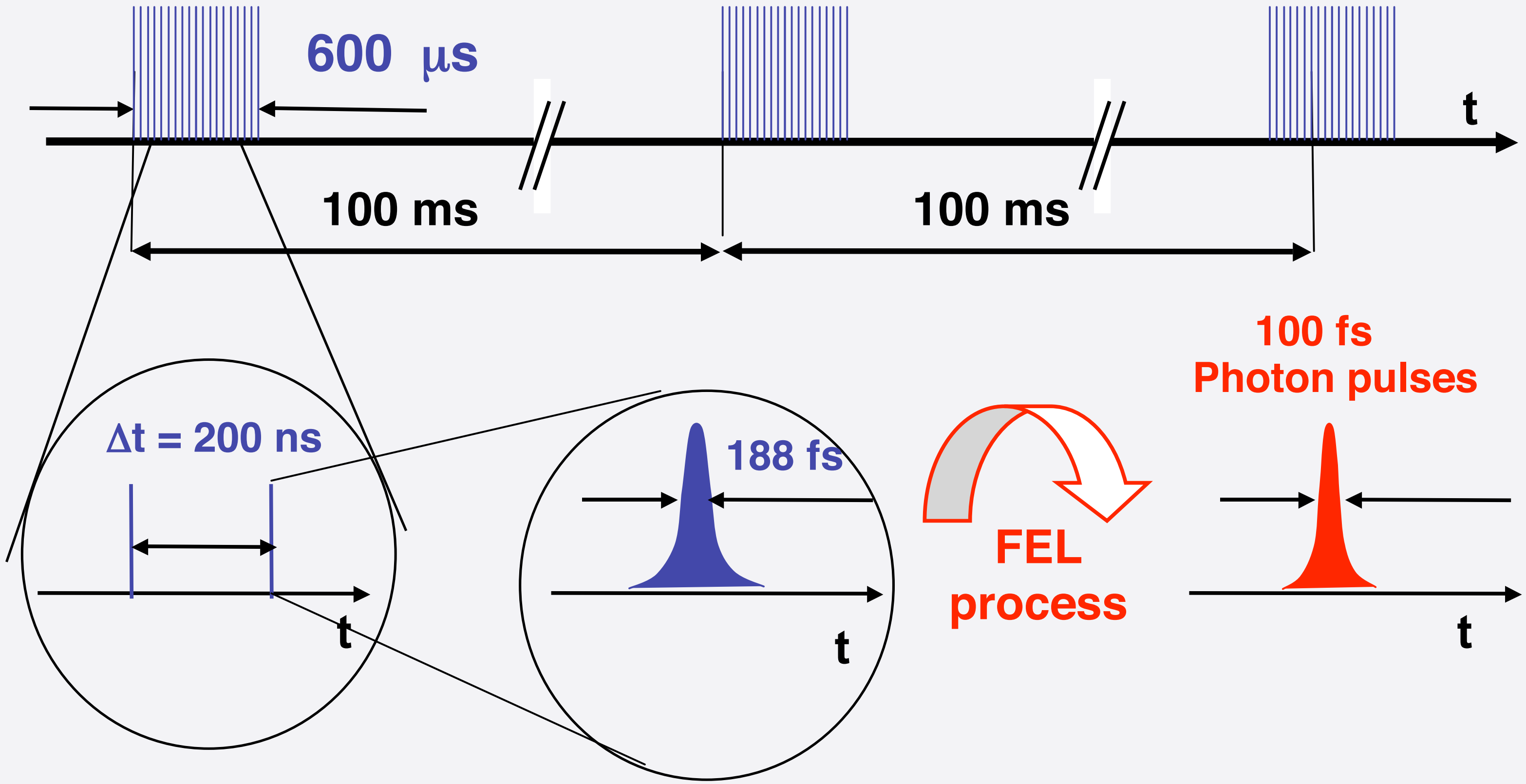
Operational flexibility of time and energy structure.

Comparison of the X-ray FEL Projects

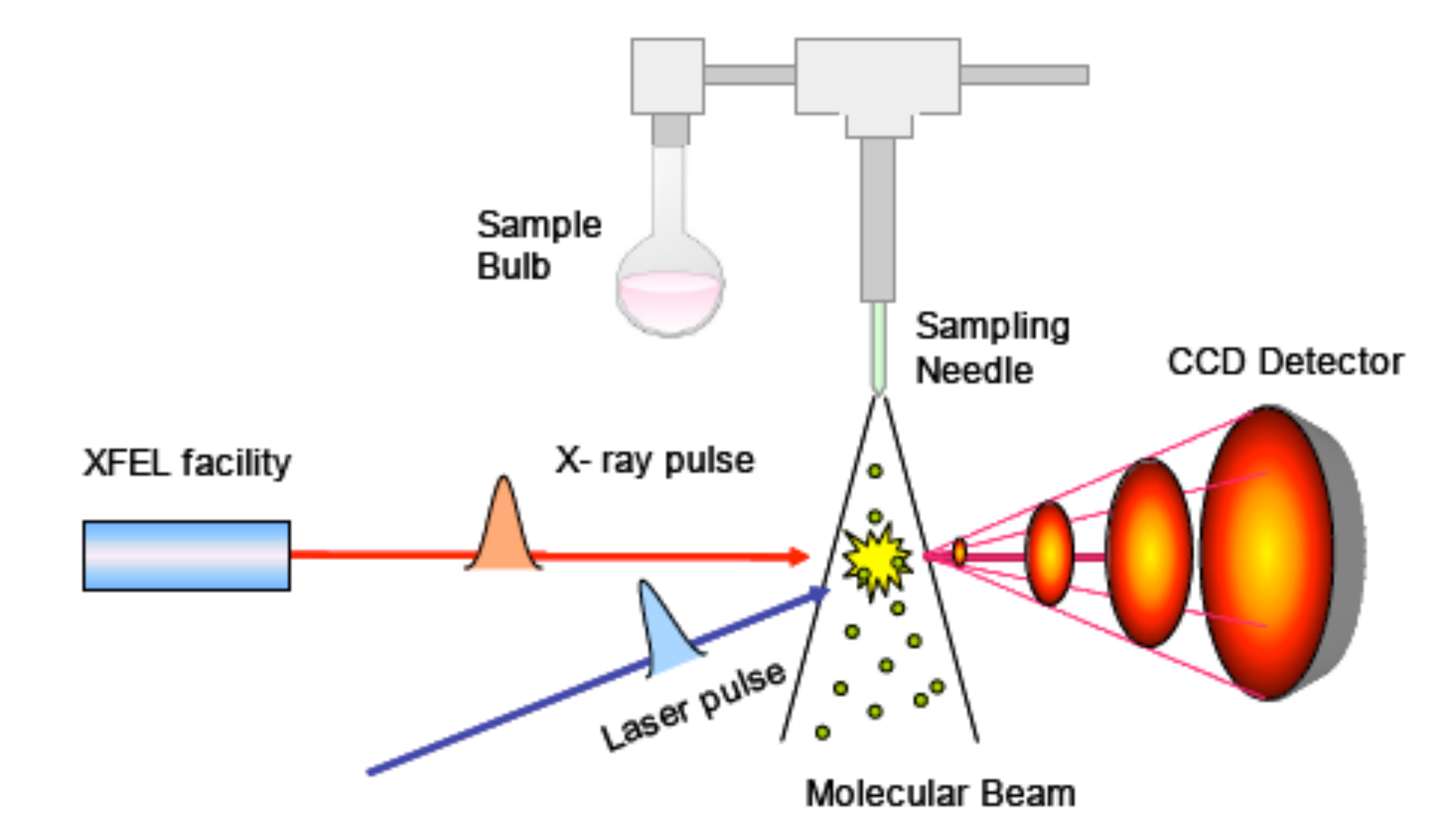
	LCLS (USA)	SCSS (JAPAN)	EUROPEAN XFEL (SASE1)
Minimum Wavelength(nm)	0.15	0.1	0.1
Peak Brilliance	8.5 10^32	5 10^33	5 10^33
Average Brilliance	2.4 10^22	1.5 10^23	1.6 10^25
Pulses/s	120	60	30 000
Pulse duration (fs)	230	500	100
First Beam	2009-2010	2010	2013

TIME STRUCTURE

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



Average Brilliance: Single-Particle Imaging



Orientation, superposition, reconstruction

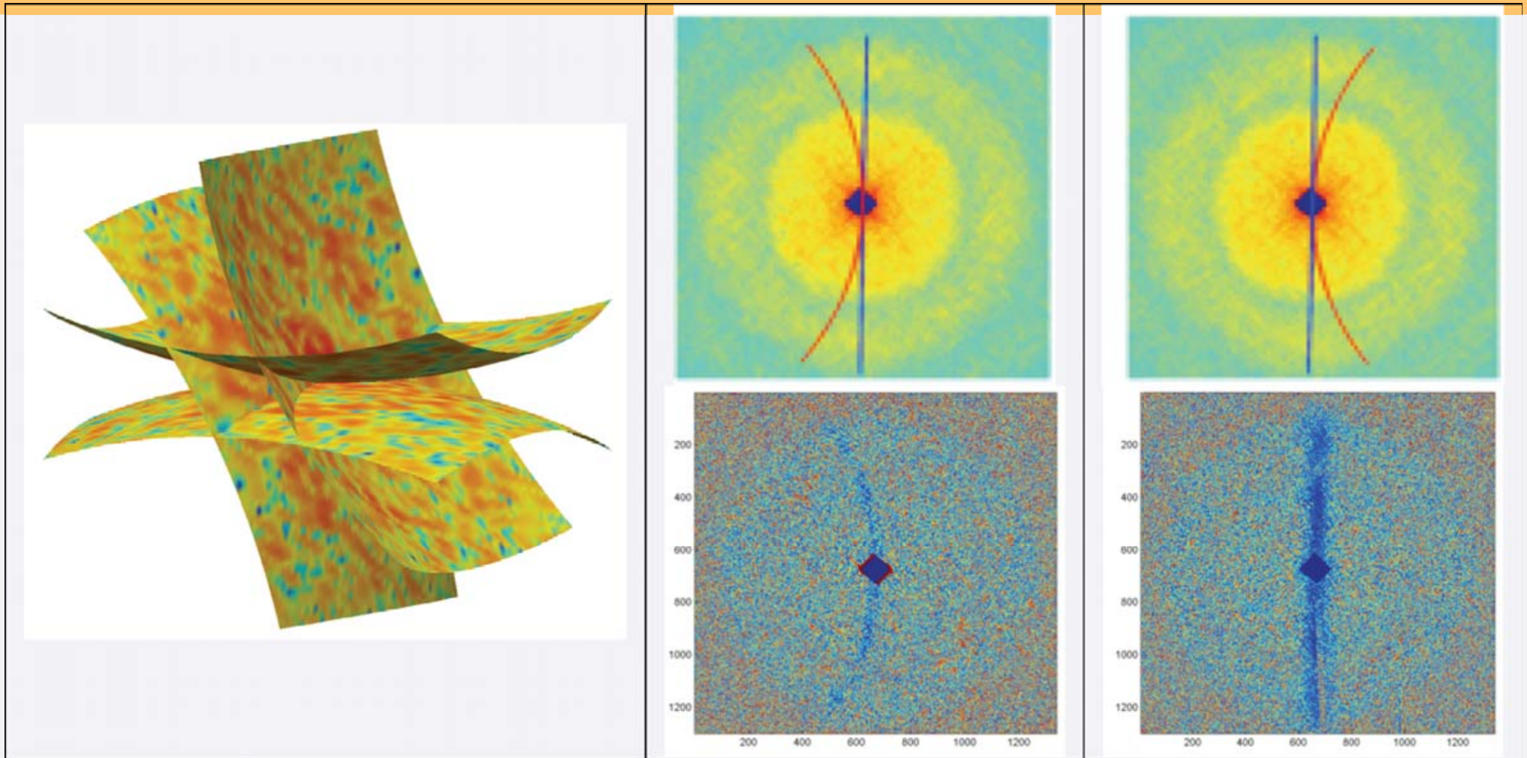


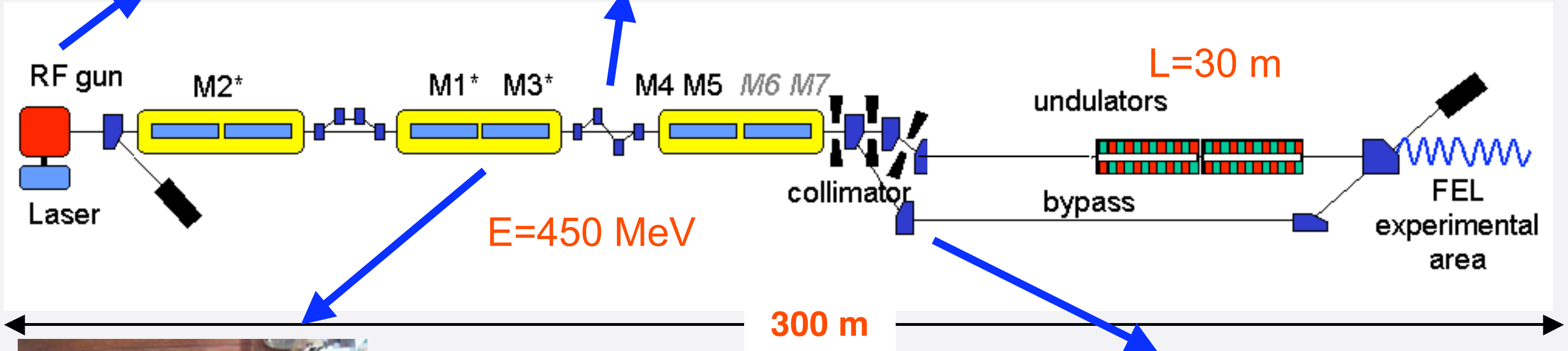
Fig. 6.4.67:	**Intersection of two Ewald spheres with their centrosymmetric opposites.** Centrosymmetry gives an extra intersect as there are *two* common arcs of intersection in *each* diffraction pattern (upper row). The images in the middle show the expected arcs of intersections in two diffraction patterns from the experimental pyramid x-ray diffraction data set from Figure 6.4.668. Images in the bottom row show t hese very lines of intersections when the experimentally obtained patterns are subtracted from e ach other pair wise [38].

How do we know it will work?

FLASH, at DESY

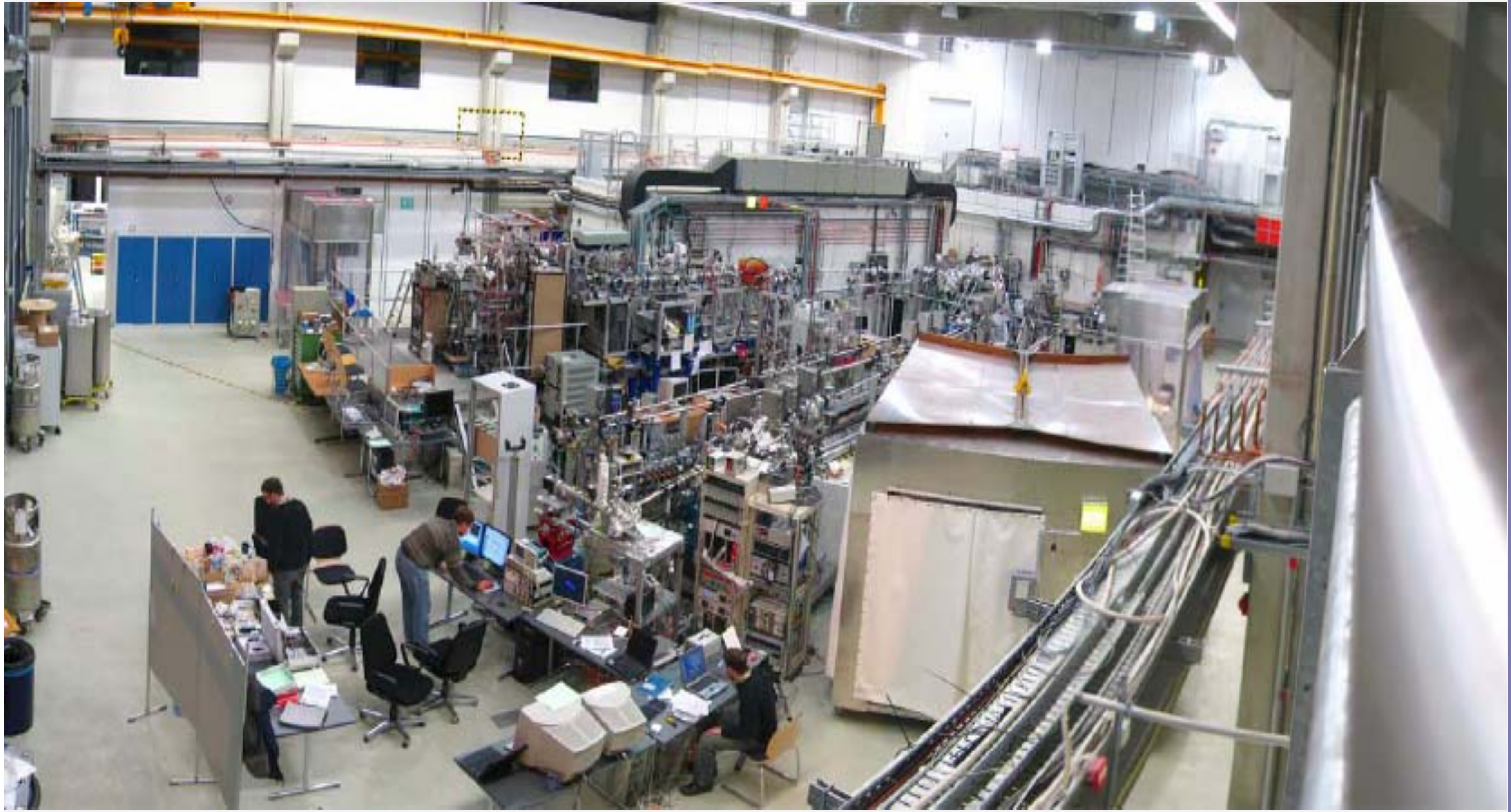
Presently operating down to ~ 6.5 nm (+ 3rd, 5th harmonic)

FLASH vs XFEL:
- **Validation of main components**
- **Operation experience**



Jan 2005: first lasing at 32 nm
Aug 2005: first user exper.

FLASH Experimental Hall

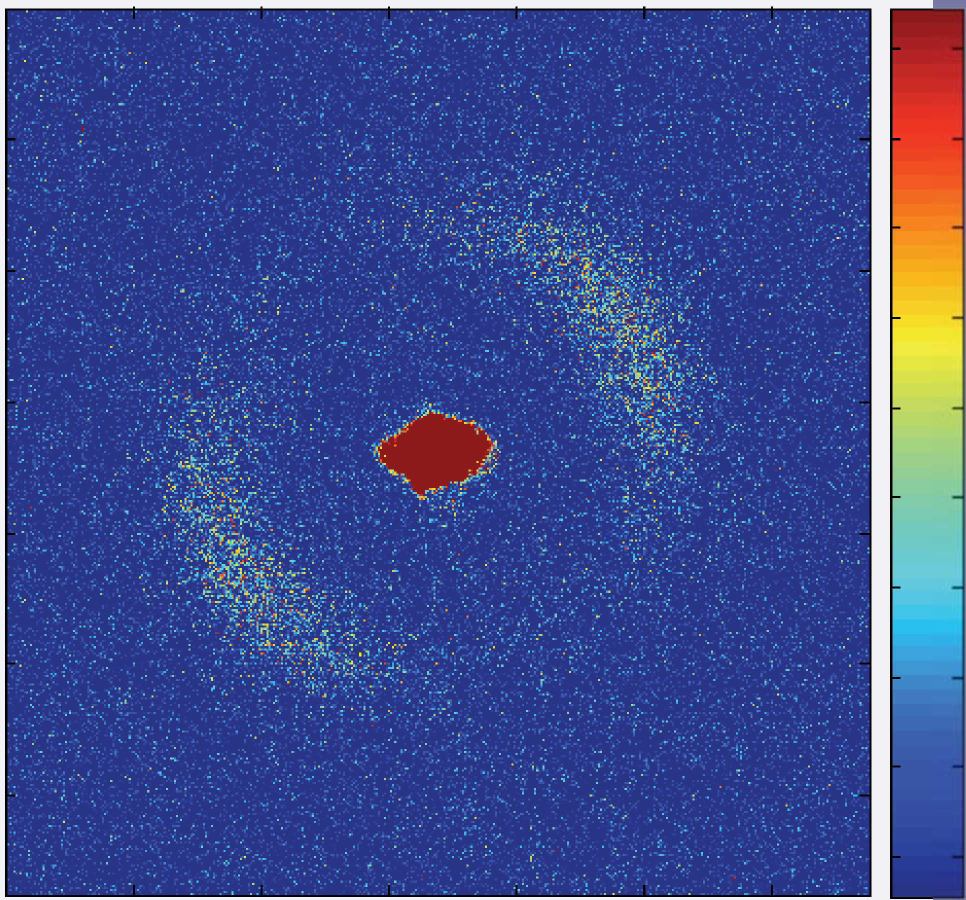


Resonant scattering at the Co L_3 edge

FLASH

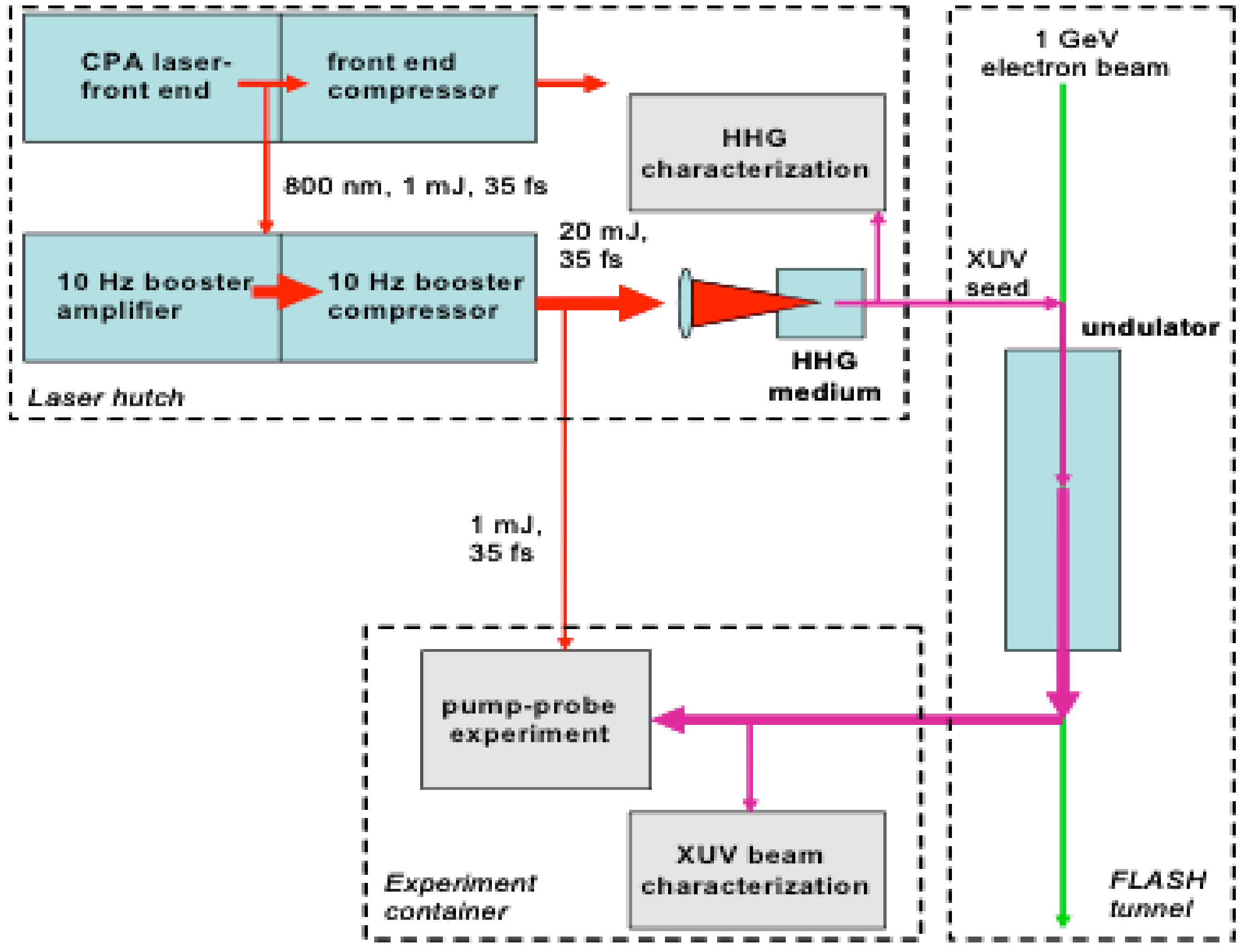
fundamental @ 155,62 eV
5th harmonic @ 778,1 eV (1,59 nm)
> 10^7 photons/ pulse (~25 fs)
50 [Co(4Å) / Pt(7Å)]
sputtered on 20nm Pt layer
on Si3N4 membrane,
capped with 2nm Pt

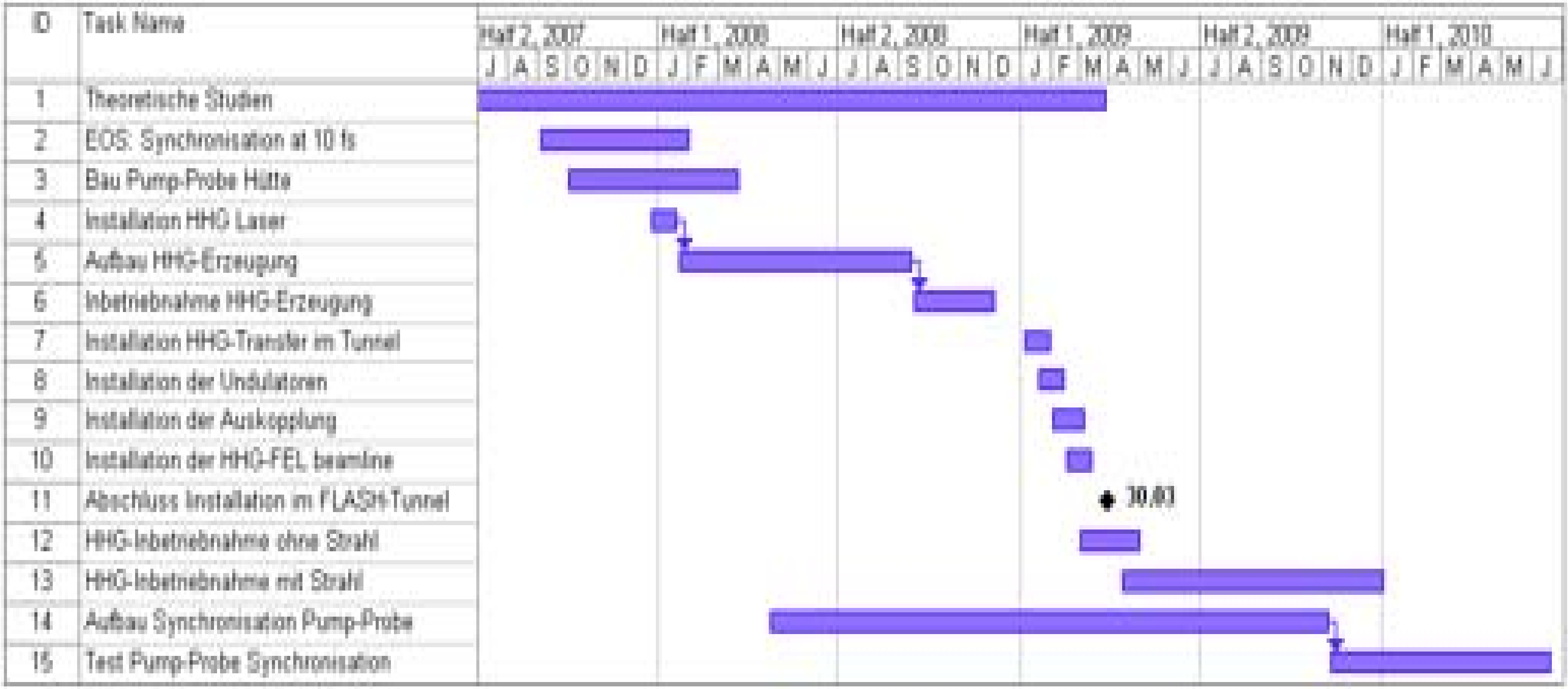
L.-M. Stadler, S. Streit-Nierobisch, C. Gutt, A. Mancuso, A. Schropp, J. Gulden, I. Vartaniants, E. Weckert, B. Pfau, C.M. Günther, R. Könnecke, S. Eisebitt, O. Hellwig, F. Staier, A. Rosenhahn, T. Wilhein, D. Stickler, H. Stillrich, R. Frömter, H.P. Oepen, R. Treusch, N. Guerassimova, M. Martins, K. Honkavaara, B. Faatz, S. Schreiber, M.V. Yurkov, E.A. Schneidmiller, A. Brenger, G. Grübel



S-FLASH: Seeding FLASH by HHG at 30 nm

Project to generate 30 nm harmonics of Ti:Sa ultrafast laser to use as “seed” for FLASH operation.


CPA laser-
front end
front end
compressor
800 nm, 1 mJ, 35 fs
HHG
characterization
20 mJ,
35 fs
10 Hz booster
amplifier
10 Hz booster
compressor
HHG
medium
Laser hutch
1 GeV
electron beam
XUV
seed
undulator
1 mJ,
35 fs
pump-probe
experiment
XUV beam
characterization
Experiment
container
FLASH
tunnel


ID
Task Name
Half 2, 2007
Half 1, 2008
Half 2, 2008
Half 1, 2009
Half 2, 2009
Half 1, 2010
J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J
1 Theoretische Studien
2 EOS: Synchronisation at 10 fs
3 Bau Pump-Probe Hütte
4 Installation HHG Laser
5 Aufbau HHG-Erzeugung
6 Inbetriebnahme HHG-Erzeugung
7 Installation HHG-Transfer im Tunnel
8 Installation der Undulatoren
9 Installation der Auskopplung
10 Installation der HHG-FEL beamline
11 Abschluss Installation im FLASH-Tunnel
12 HHG-Inbetriebnahme ohne Strahl
13 HHG-Inbetriebnahme mit Strahl
14 Aufbau Synchronisation Pump-Probe
15 Test Pump-Probe Synchronisation
30.03

Decision: project realization in stages

Realization of full TDR facility in stages.

Initial ("Start-up") stage:

-Give up accelerator capabilities beyond 17.5 GeV

-Install fewer undulators and fewer stations

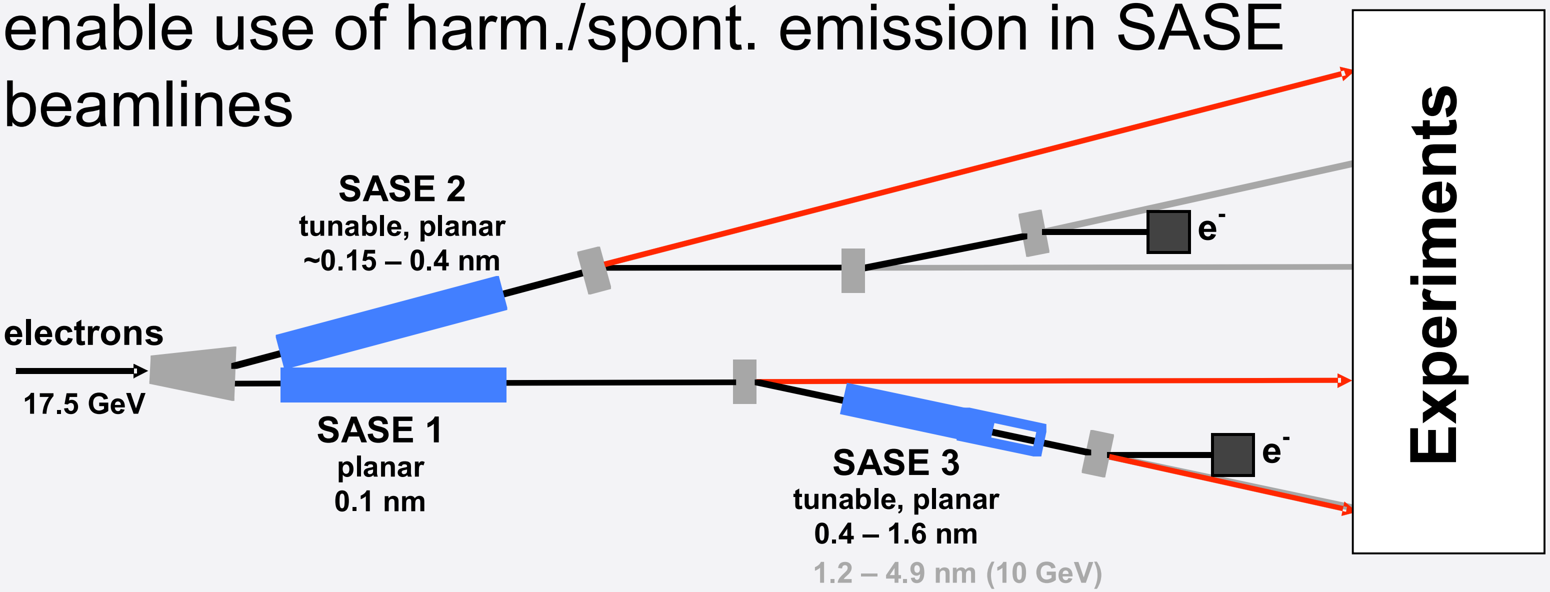
NB: Upgrade to full TDR possible as soon as

more € 's fly in!

First undulators and beamlines

Concentrate on SASE radiation

- provide as large as possible photon energy range
- reduce number of segments
- for soft X-rays start with linear polarization
- enable use of harm./spont. emission in SASE beamlines



Characteristics of initial sources

SASE 1 as described in TDR (2006)

- designed for reaching saturation at 12.4 keV (closed gap)

SASE 2

- magnetic length now 185 m
- saturation length (12.4 keV, 19 mm gap) ~174 m
  - photon energy for saturated FEL rad. might reduce
- verification of tunability range (~4) on-going

SASE 3 planar device for linear polarization

- 'conventional device'
  - higher reliability for commissioning & operation
- magnetic length 105 m, saturation (3.1 keV, 19 mm) ~88 m
- R&D on possible upgrade scenarios has started

Selection of first instruments

Hard X-rays

Soft X-rays

Instrument	Brief description of the instrument
SPB	Ultrafast Coherent Diffraction Imaging of Single Particles, Clusters, and Biomolecules – **Structure determination of single particles: atomic clusters, bio-molecules, virus particles, cells.**
MID	Materials Imaging & Dynamics –**Structure determination of nano-devices and dynamics at the nanoscale.**
FDE	Femtosecond Diffraction Experiments – **Time-resolved investigations of the dynamics of solids, liquids, gases**
HED	High Energy Density Matter – **Investigation of matter under extreme conditions using hard x-rays, e.g. probing dense plasmas.**
SQS	Small Quantum Systems – **Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena.**
SCS	Soft x-ray Coherent Scattering –**Structure and dynamics of nano-systems and of non-reproducible biological objects using soft X-rays.**

SASE 1 scientific instruments

SPB : Ultrafast Coherent Diffraction Imaging of Single Particles, Clusters, and Biomolecules

- Dilute samples (particles/clusters/bio-molecules) in vacuum
- Structure determination by coherent forward diffraction
- Requires extreme peak power (focus, time, intensity)

MID : Materials Imaging & Dynamics

- Solid/liquid/soft matter samples on manipulator
- Structure by coherent diffraction (large angles, few m) and dynamics by speckle spectroscopy (forward; 20 m)
- Requires small bandwidth and tight focus
- Enables use of spontaneous emission radiation

SASE 2 scientific instruments

FDE : Femtosecond Diffraction Experiments

- Solid/liquid/gaseous samples
- Enables various scattering techniques: diffraction, inelastic scattering, XAS
- Uses special preparation of incident beam (bw, intensity)
- Enables use of spontaneous emission radiation

HED : High Energy Density Matter

- Matter under extreme conditions of pressure, temperature or density (prepared by external means of FEL pulse)
- Scattering, diffraction, XAS, optical methods
- Requires extreme peak power (focus, intensity(, time))

SASE 3 scientific instruments

SQS : Small Quantum Systems

- Gaseous and very dilute samples
- Particle detection & scattering
- Requires extreme peak power (focus, intensity, time)

SCS : Soft X-ray Coherent Scattering

- Solids/Soft matter samples in ultra-high vacuum
- Forward scattering, diffraction, speckle spectroscopy
- Requires variable bandwidth & focus

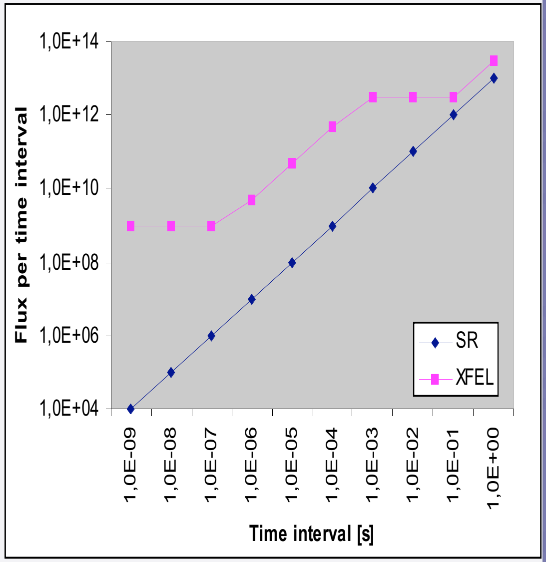
Spontaneous emission radiation by FEL undulators

Use odd harmonics of fundamental line at 12,4 keV

- 3rd: 37,2 keV; 5th: 62 keV; 7th: 86,8 keV

Propagation in beam transport

- optimize angular acceptance (> 9×9 μrad^2)
  - photons/pulse ~10^9
  - relative bandwidth ~3 – 7×10^{-3}
- separation from FEL radiation
  A. Undulator in 'non-lasing mode'
  B. Monochromator set to higher E
  C. Deflect FEL line (e.g. thin crystal)



SUMMARY

1. Introduction
2. Description and objectives of the European XFEL
3. Status of the Project
4. Conclusion

June 5, 2007: Official Launch of the Project!

Before the foundation of the European XFEL some activities are in full swing…

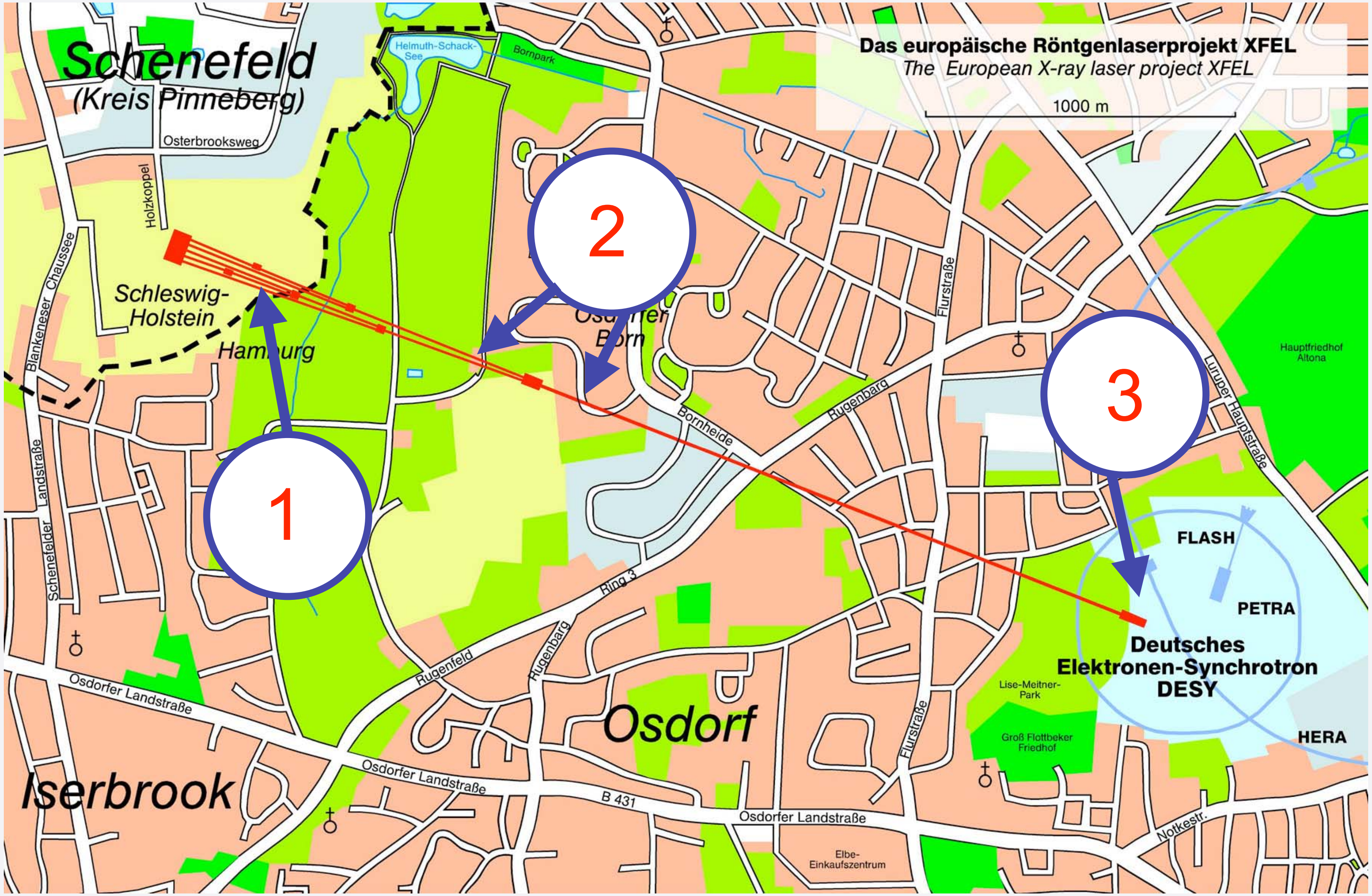
Call for Tenders for Civil Engineering launched, June 07

Accelerator Consortium activities have been going on under the DESY coordination for a long time

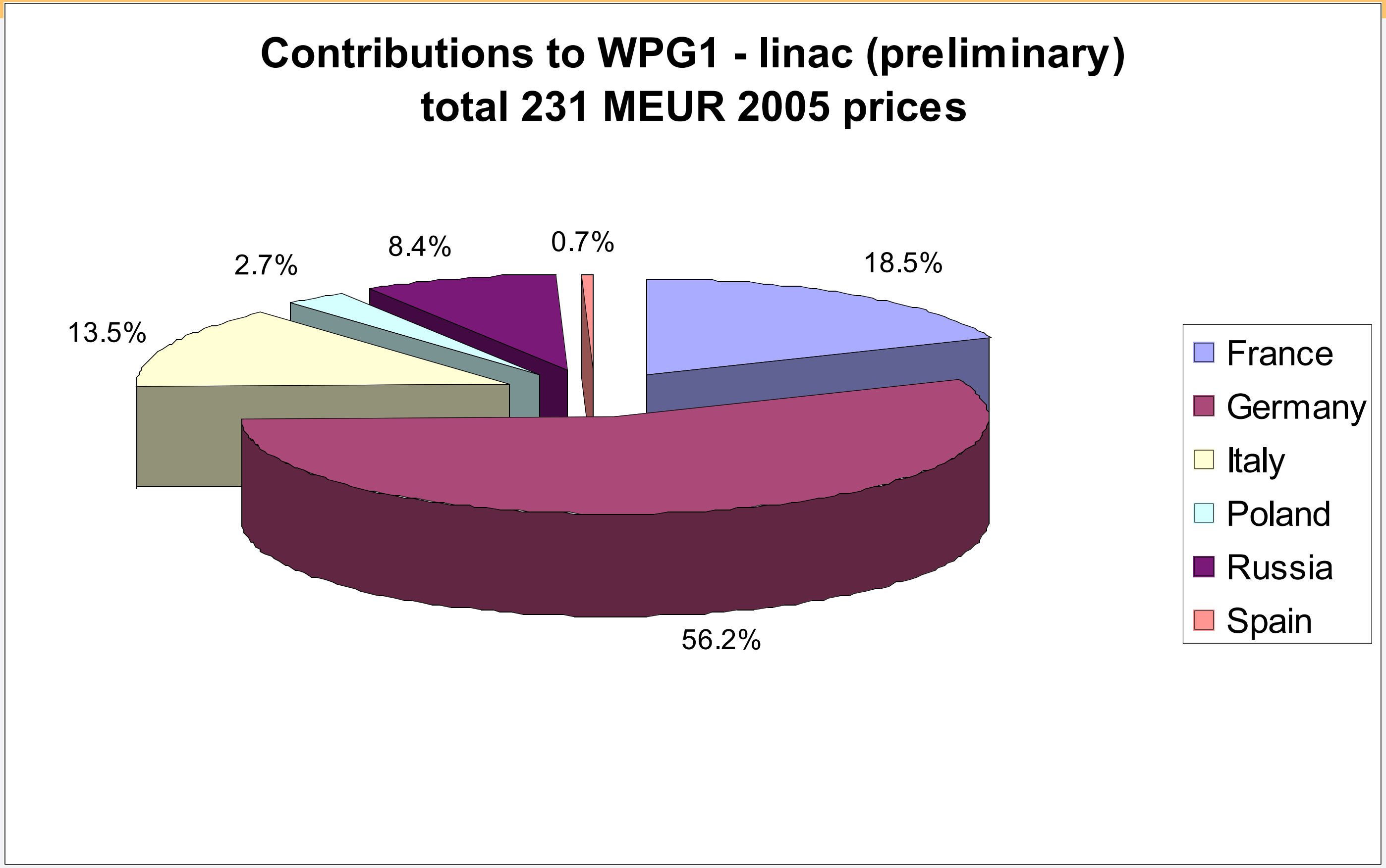
European Contract in the Framework Program 7 (FP7) providing 5 M€ for:

- 3 Users' Meetings and 9 Users' Workshops in 2008-2011
- Early recruitment of staff
- Temporary Accommodation of staff

Calls for Tender for lots 1,2,3 of Civil Engineering



WPG1 Linac – contributions to the consortium



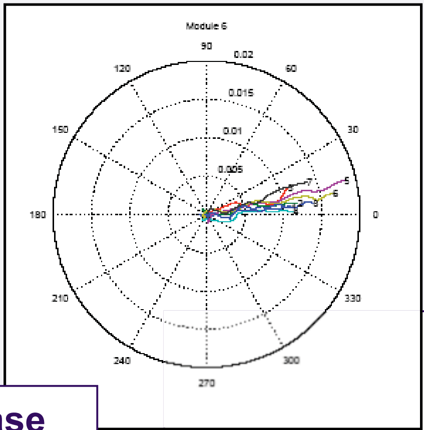
Possible contribution from China under discussion

Operation of CMTB *(cryo module test bench)*

- Three modules tested on CMTB → FLASH
- Positive experience for later series tests:
  - Fast conditioning of RF-power coupler
  - Hardly any additional conditioning in FLASH linac necessary
- Good performance of the modules → **design beam energy reached in FLASH**

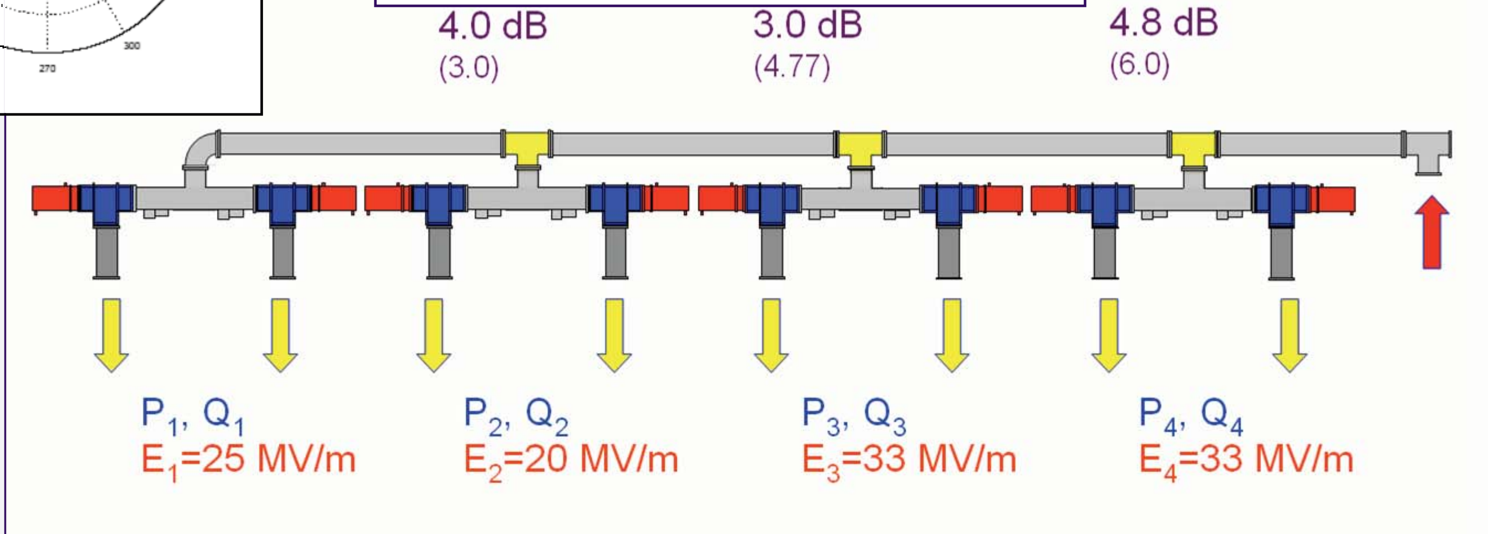
New pre-adjusted waveguide system tested at FLASH/ACC6

Power distribution and phase distribution for the individual cavities almost perfect



Initial phase distribution

Waveguide distribution ACC6



Tunnel mock-up completed and installations ongoing

Transport/installation vehicle under construction

Cavity string & module assembly

Using experience gained at DESY and results of industrial studies, the assembly facility for all 100 XFEL modules will be set up at the CEA-Saclay site

Action plan for instruments

2007 Priority for undulators and instruments is determined

2008+ Formation of user groups for first instruments
- Requirements for beam transport
- Scientific scope and layout instruments
- Infrastructure needs for instruments

2009+ Establish and review conceptual designs
- X-ray Optics & Beam Transport
- Scientific Instruments

2010+ Establish and review technical designs

2011+ Construction and commissioning

2014 Involve Users in early experimental program

Challenges

- Take advantage of repetition rate
- Pump-and probe experiments: synchronization, pulse characterization (arrival time, profile,…)

Consequences of time structure for 2D detectors

- Experiments should profit from high luminosity (30 000 shots/sec).
- Either: < 10Hz or > 1.5 kHz; best 5 MHz
- All photons arrive in 100 fsec → integrating detectors.

Second European XFEL Users' Meeting

January 23-24, 2008 at DESY, Hamburg

Purpose: **Information**
Mobilization
Enlargement
of the scientific community

Feedback on planned scientific programs

Supported by the EC grant as part of Work Package 2: Bursaries for young people

252 Registered Participants

Hamburg	88
Germany	43
United Kingdom	19
Sweden	14
Denmark	12
Slovakia	10
Switzerland	8
Italy	7
France	7
USA	6
Japan	6
Russia	5
Poland	4
China	2
….	

Recruitment in progress

The European
XFEL
X-Ray Free-Electron Laser

Are you interested in working in an international environment for the world's brightest X-ray source?

Launched on June 5, 2007, the European XFEL project now starts hiring scientific, engineering and administrative staff.

The European XFEL facility will provide X-ray radiation with extraordinary, laser-like properties enabling research in a wide range of scientific domains (e.g. physics, chemistry, life sciences, materials research). Commissioning of this brand-new international facility located in Hamburg and Schleswig-Holstein, Germany, will start in 2013. The corresponding research organization, the European XFEL GmbH (company with limited liability) will be founded in 2008.

The XFEL is supported by a "preparatory project" of the European Commission funded until June 2011. This EC project is based on a network of 18 institutions in 12 countries.
We are now looking for:

Scientists

for research, development and construction of undulator systems, X-ray beam systems, scientific instruments and X-ray detectors.

Engineers/Technicians

specialized in physical engineering or mechanics, with experience in either finite-element simulation or development and installation of control systems.

Administrative staff

to provide assistance in legal, financial, procurement, human resources and secretarial matters.

If you are interested in joining the international XFEL team, then have a look at our website for information about vacant positions, and on how to apply: **www.xfel.eu/jobs**

We expressly encourage women to apply. Applications from handicapped individuals with equal qualification will be given preference.

For further information, please address **recruitment@xfel.eu**

European XFEL Project Team c/o DESY
Notkestr. 85, D-22607 Hamburg, Germany

Look on

www.xfel.eu/jobs:

Leading Scientist

positions

for the first instruments

Thanks to:

Reinhard Brinkmann

Andreas Schwarz

Thomas Tschentscher