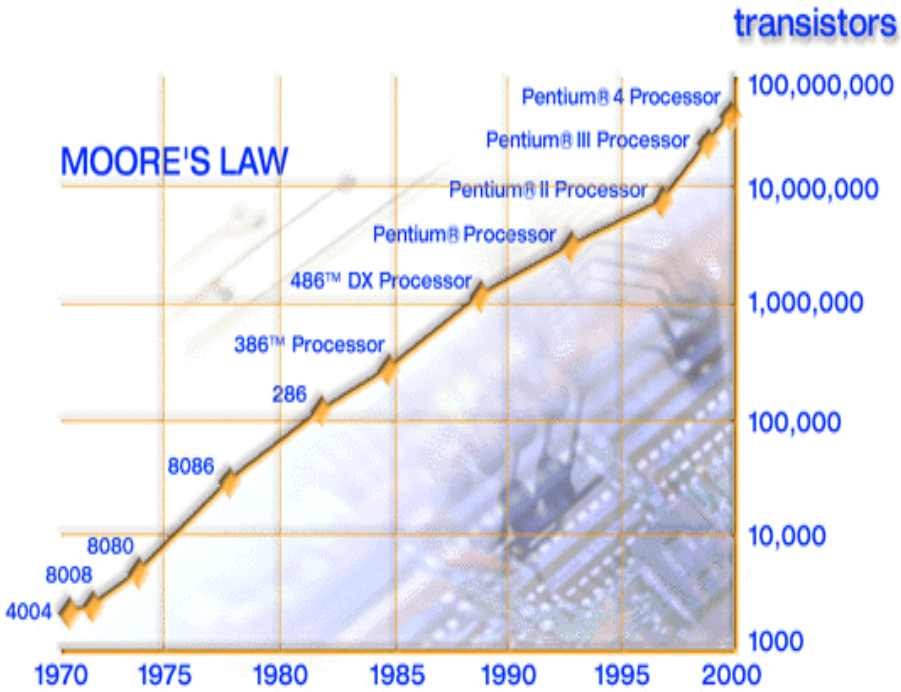
Free-electron lasers at DESY: Status, challenges, and opportunities

Tim Laarmann, DESY

The Free electron LASer in Hamburg:
First FEL user facility for
VUV/soft X-ray radiation in the world

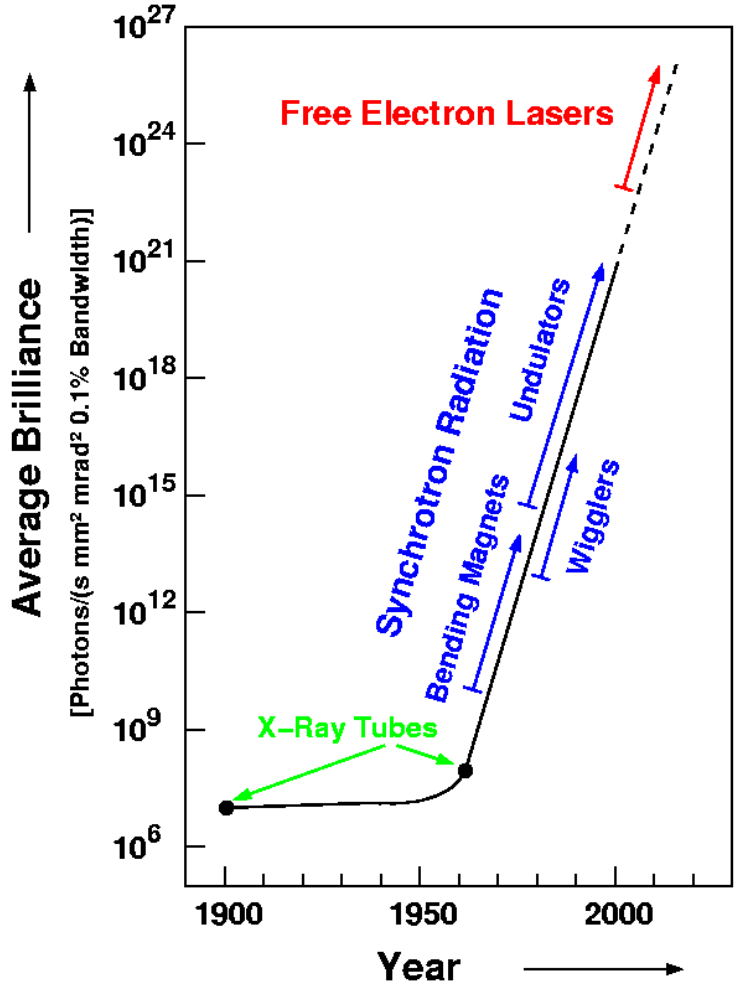
www.xfel.eu

Progress photon source development …



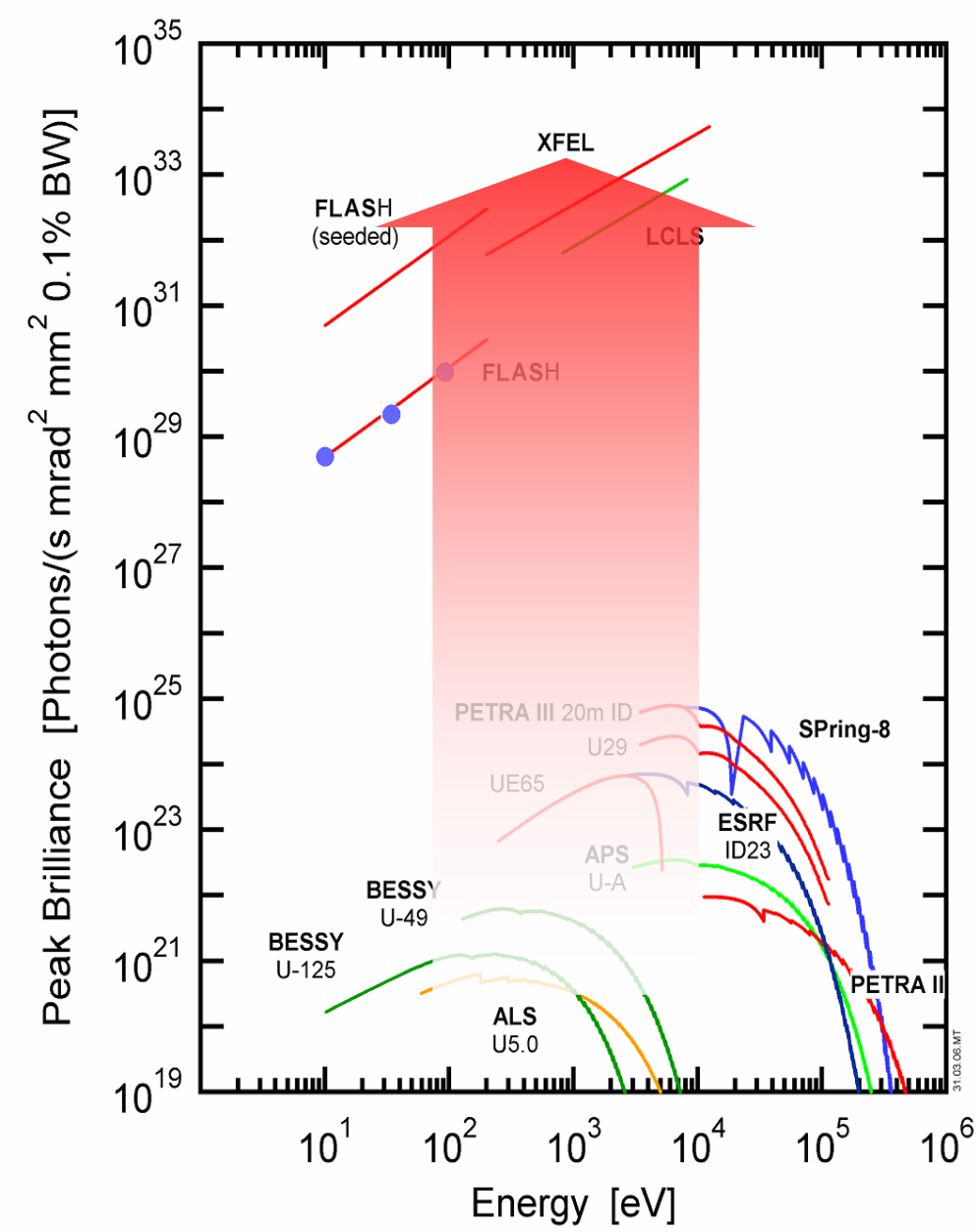
(http://www.intel.com/research/silicon/mooreslaw.htm)

about 30 x more transistors per CPU per decade since 1970



10.000 x more “light” per decade since 1965

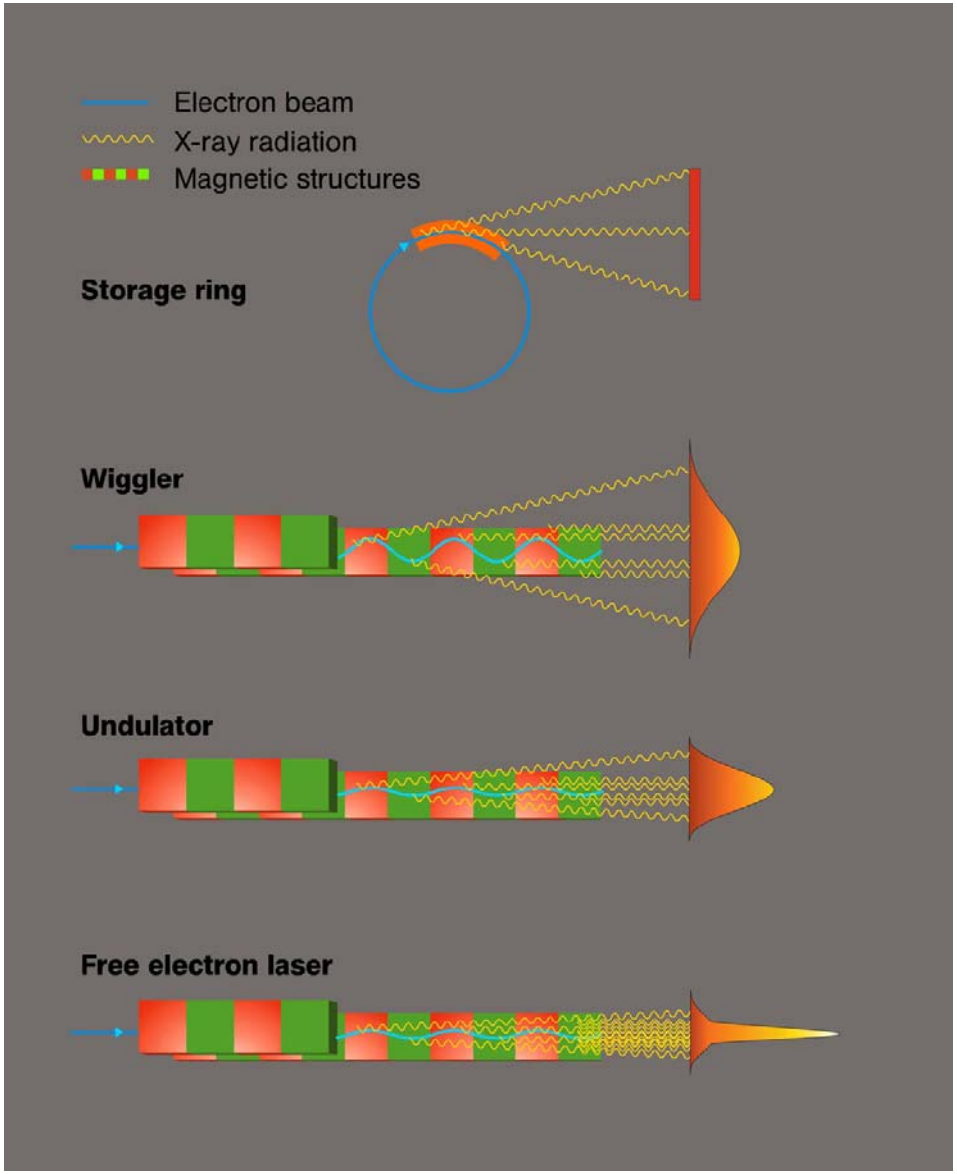
Brilliance


Peak Brilliance [Photons/(s mrad^2 mm^2 0.1% BW)]
10^{35}
10^{33}
10^{31}
10^{29}
10^{27}
10^{25}
10^{23}
10^{21}
10^{19}
10^1
10^2
10^3
10^4
10^5
10^6
Energy [eV]
XFEL
FLASH
(seeded)
LCLS
FLASH
PETRA III 20m ID
U29
UE65
SPring-8
ESRF
ID23
APS
U-A
BESSY
U-49
BESSY
U-125
PETRA II
ALS
U5.0
31.03.06.MT

Obvious questions

- What is an FEL at all ?
- Can you actually do something new with this radiation source ???

Synchrotron Radiation Sources



Photons at the experiment

Bending magnet

$\propto N_W$ x Bending magnet

$\propto N_U^2$ x Bending magnet

$\propto N_U^2$ x N_e x Bending magnet

Current performance of FLASH

Wavelength range (fundamental):
6.5-48 nm

Spectral width (FWHM):
0.5-1 %

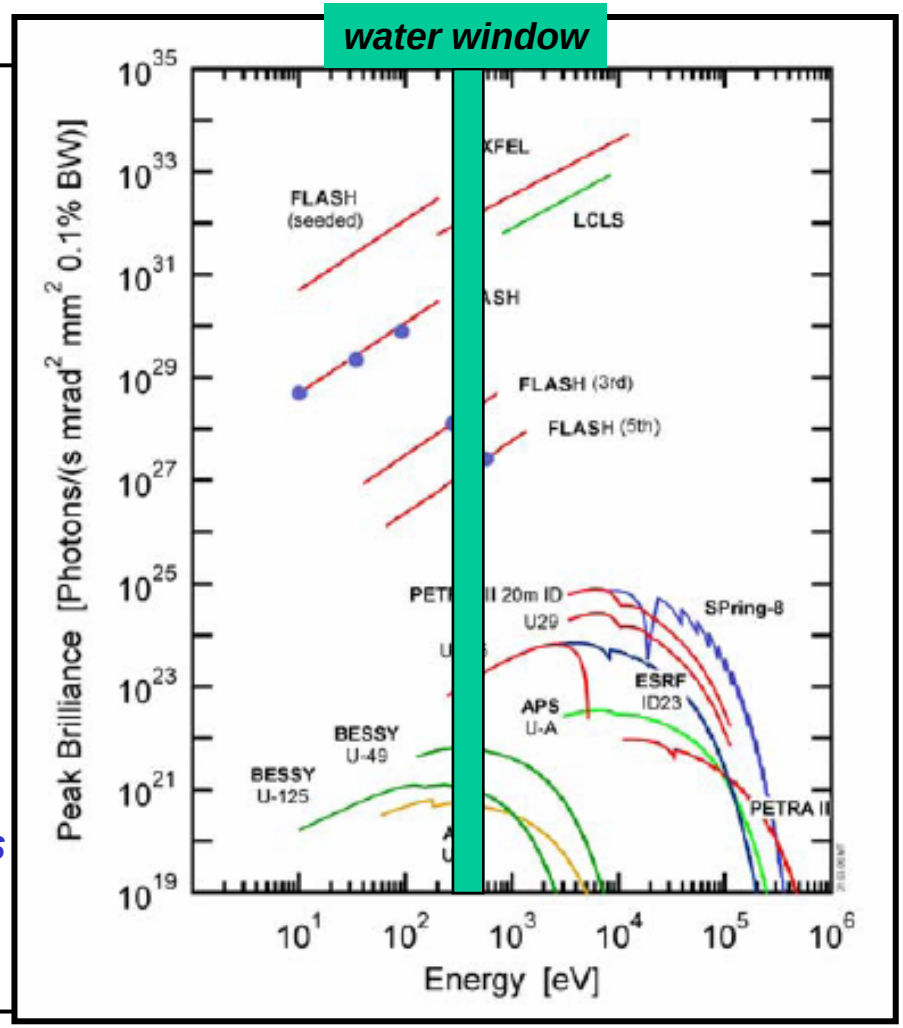
Pulse energy:
up to 100 µJ (average),
200 µJ (peak)

Pulse duration (FWHM):
5-50 fs

Peak power (fundamental):
> 4 GW

Average power (fundamental):
up to 0.1 W (up to 3000 pulses

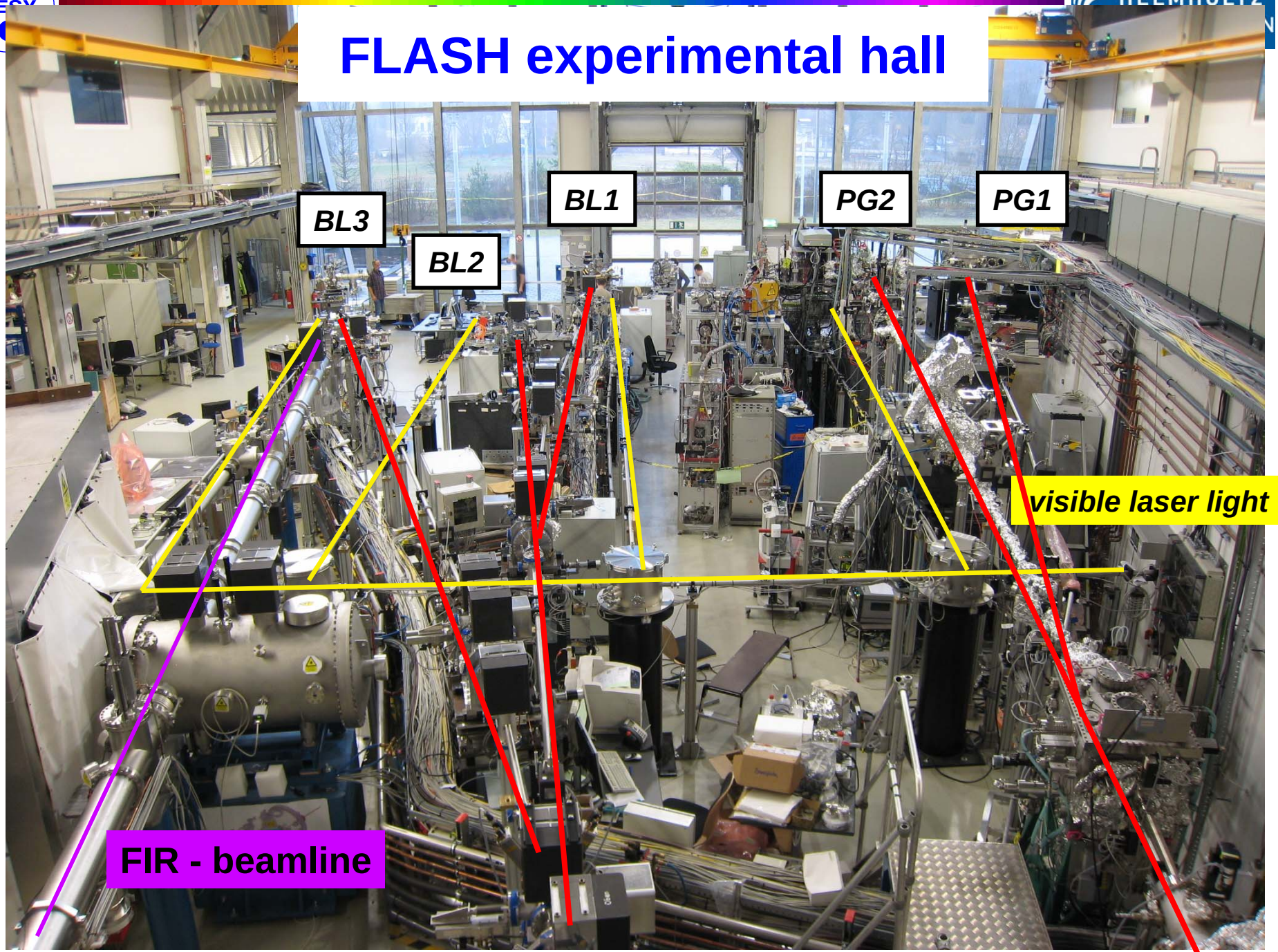
Peak brilliance:
up to 5x10^{29}



peak brilliance

User facility FLASH at DESY

FLASH experimental hall



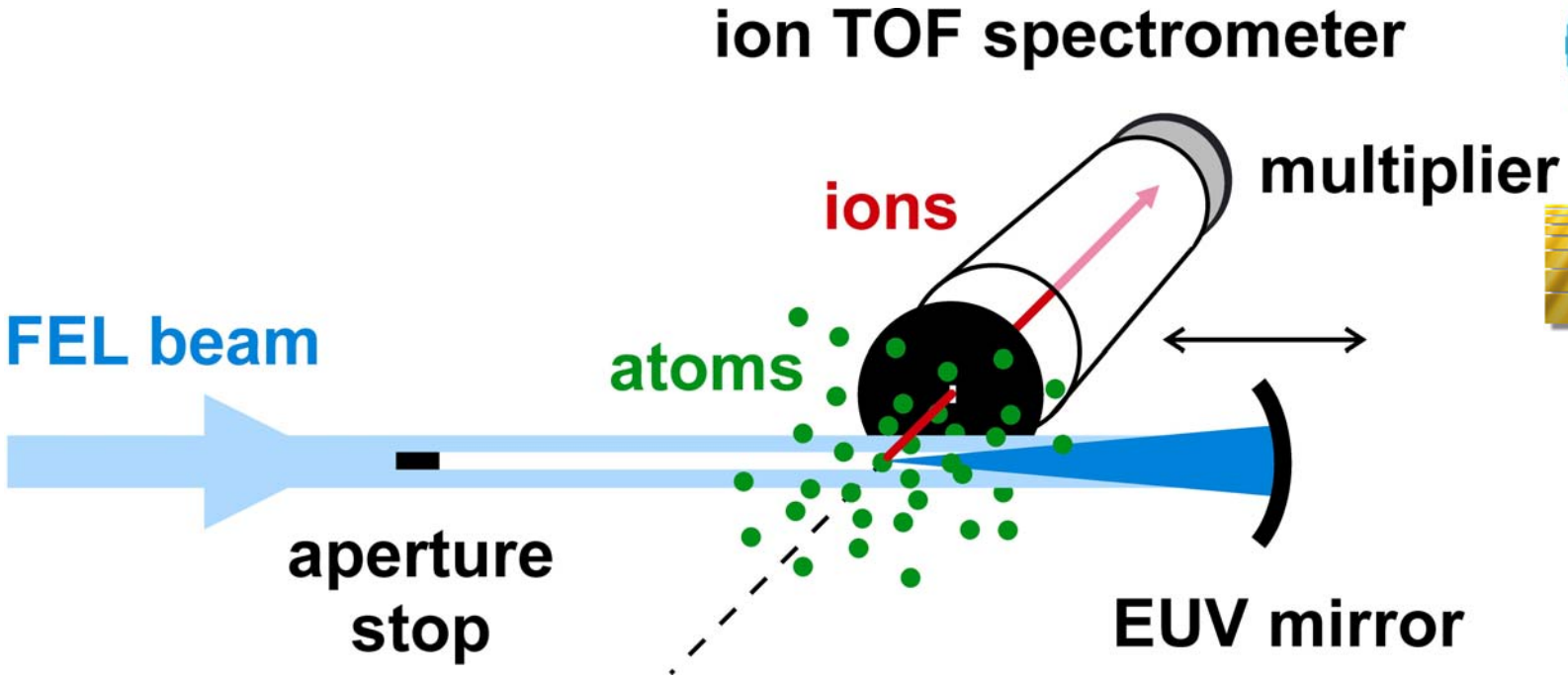
Research Areas

- **Interaction of ultra-intense XUV pulses with matter**
  - multiphoton excitation of atoms, molecules, clusters…
  - creation and characterization of dense plasmas
- **Single-shot Diffraction imaging of (biological) samples**
- **Two-color time-resolved experiments**
  - synchronization FEL - optical laser
  - pump-probe experiments on atoms, molecules and solids

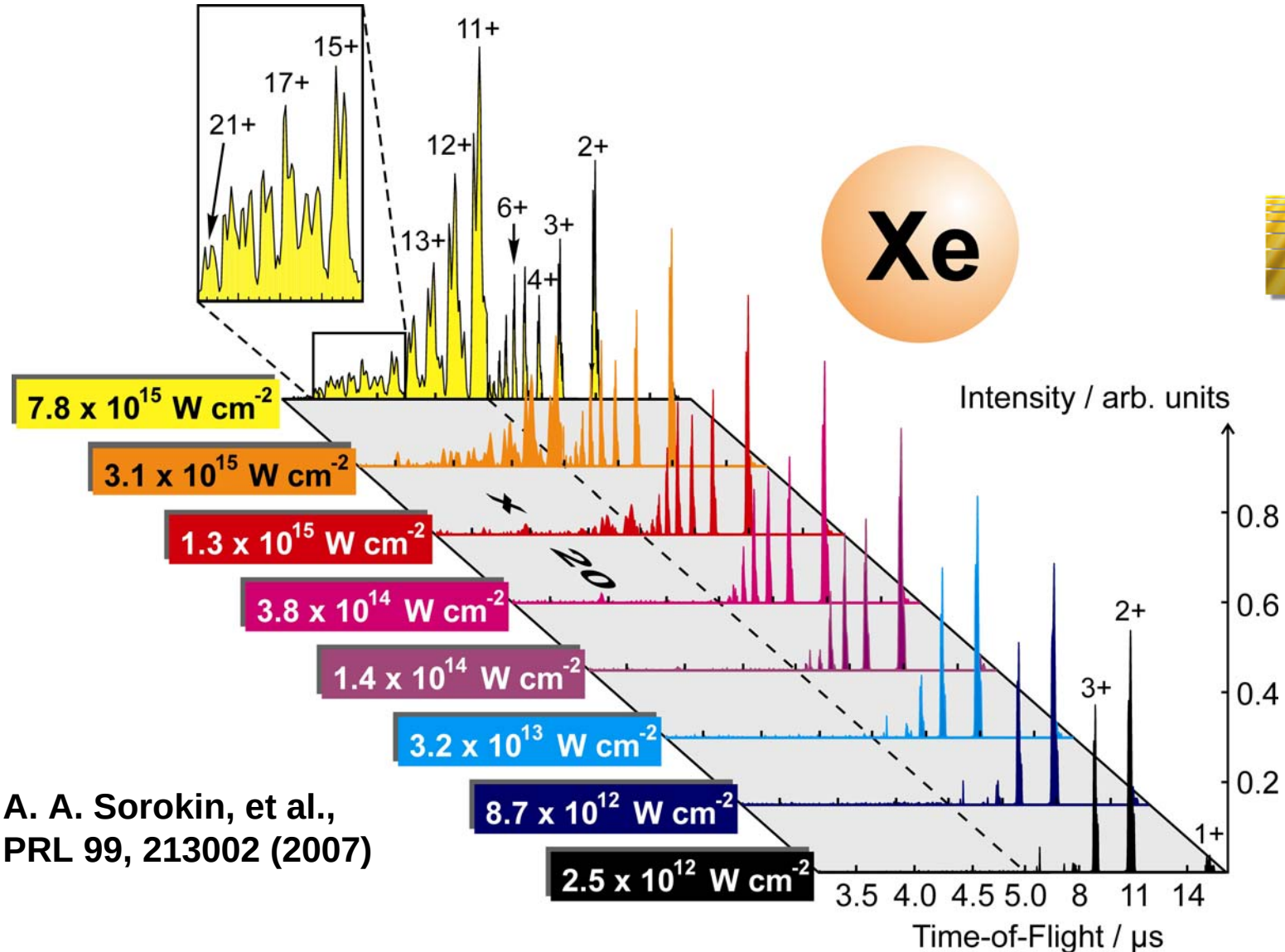
Research Areas

- **Investigation of extremely dilute samples**
  - photodissociation of molecular ions
  - highly charged ions
  - mass selected clusters
- **Investigation of surfaces and solids**
  - surface chemistry and dynamic

Multiple ionization of xenon atoms in the EUV (13.3 nm / 93 eV): ion TOF spectra



Multiple ionization of xenon in the EUV (13.3 nm / 93 eV): ion TOF spectra



A. A. Sorokin, et al.,
PRL 99, 213002 (2007)

Multiphoton multiple ionization of xenon in the EUV

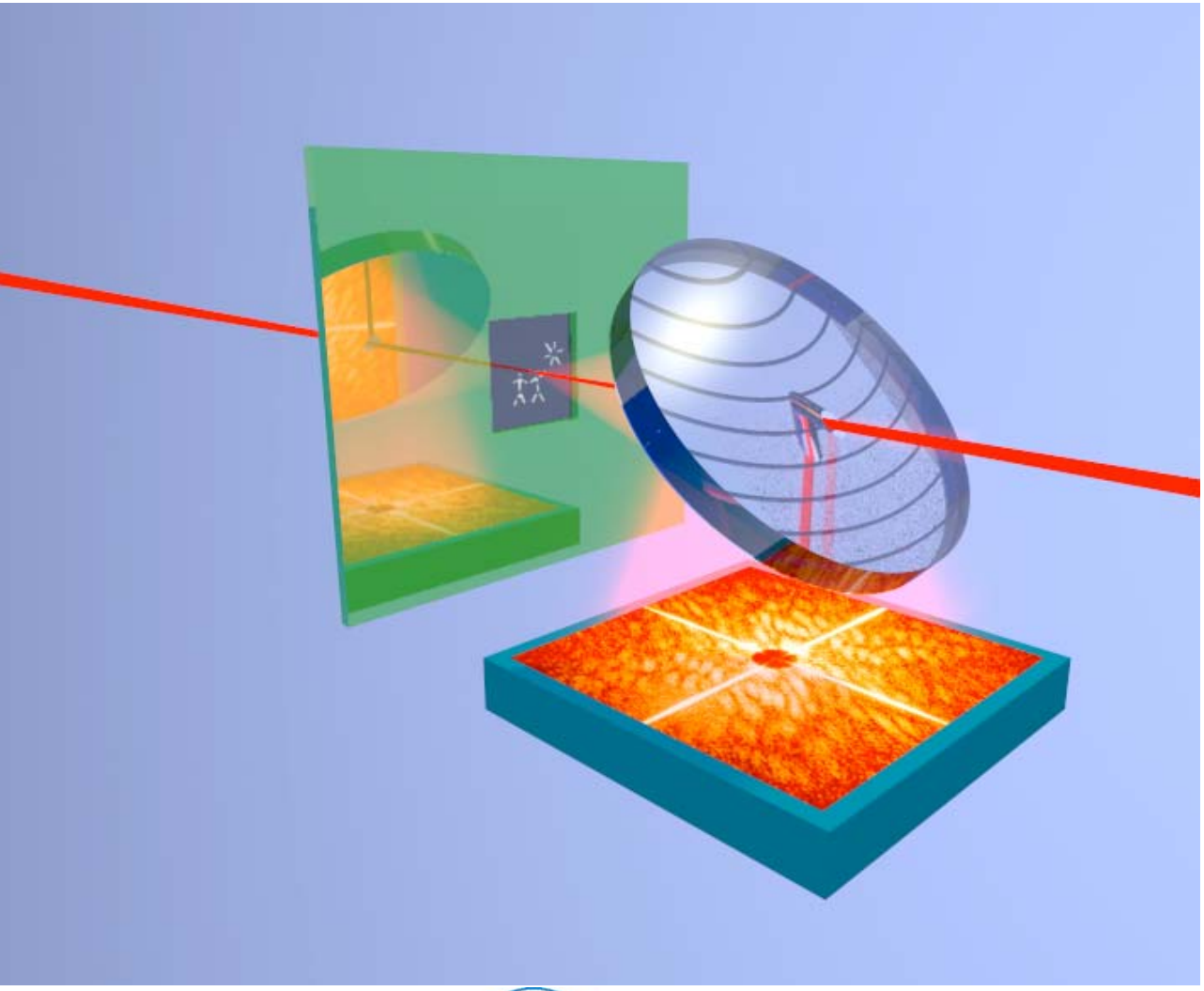
Wavelength:	13.3 nm
Photon energy:	93 eV
Pulse energy:	1 to 10 µJ
Pulse duration:	10 fs
Focus size:	3 µm (FWHM)
Peak irradiance:	8×10^{15} W cm^{-2}
Highest charge state observed:	Xe^{21+}
Energy absorbed per atom and pulse:	> 5 keV
Number of photons absorbed per atom and pulse:	> 57
Number of ionization steps:	≈ 19

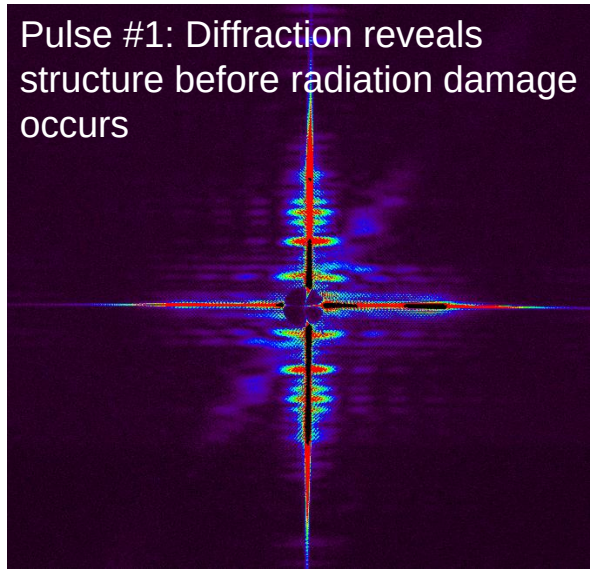
A. A. Sorokin, et al.,
PRL 99, 213002 (2007)

Research Areas

- Interaction of ultra-intense XUV pulses with matter
  - multiphoton excitation of atoms, molecules, clusters…
  - creation and characterization of dense plasmas
- **Single-shot Diffraction imaging**
- Femtosecond time-resolved experiments
  - synchronization FEL - optical laser
  - pump-probe experiments on atoms, molecules and solids

First demonstration of coherent diffraction imaging with a soft-X-ray FEL (J. Hajdu, H. Chapman et al.)





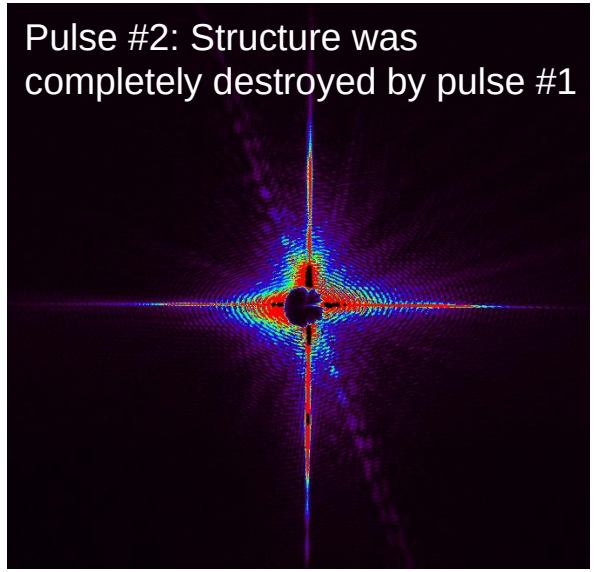
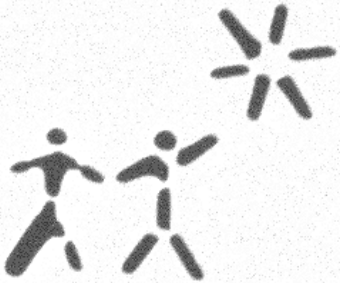
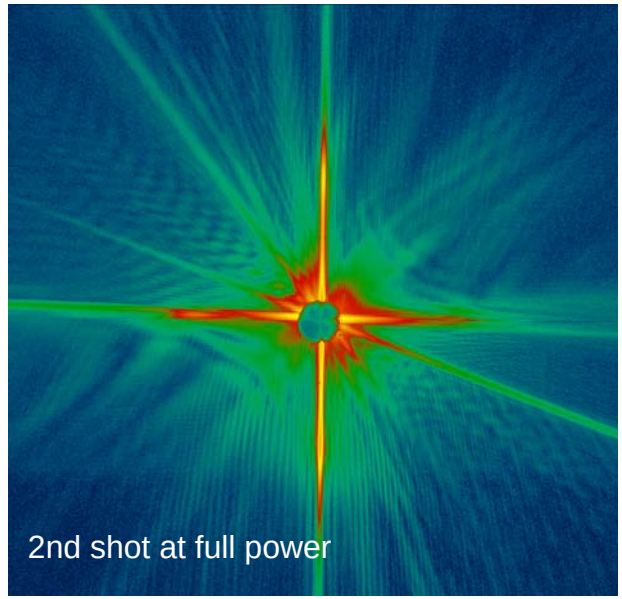


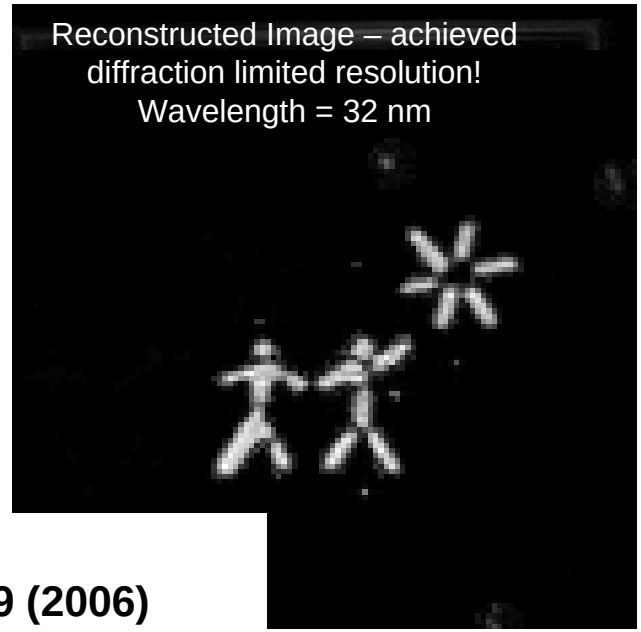
Image reconstruction

1 micron



SEM of structure milled into silicon nitride membrane



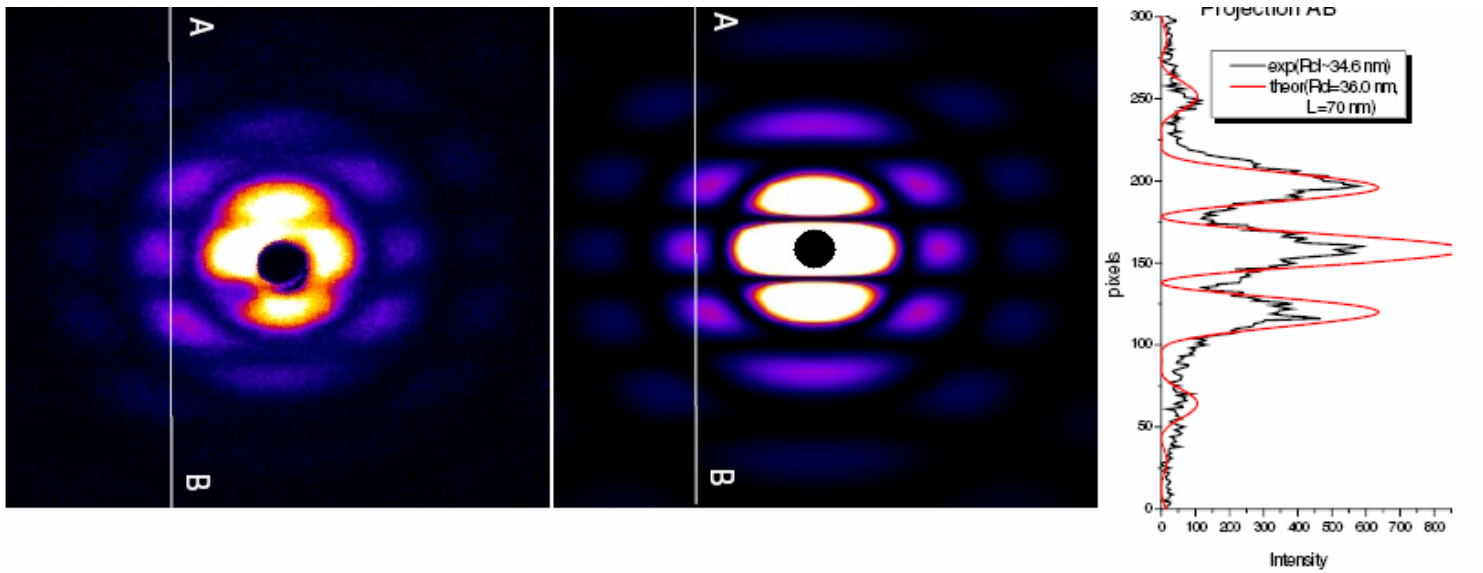


H. N. Chapman et al.,
Nature Physics 2, 839 (2006)

Single-shot imaging by soft-X-ray scattering of single and few nm-gasphase particles (T. Möller et al.)

single shot 2D- scattering patterns of a single twin-cluster
(35 nm radius Xenon cluster, ‘double slit‘ experiment)

experiment **simulation**

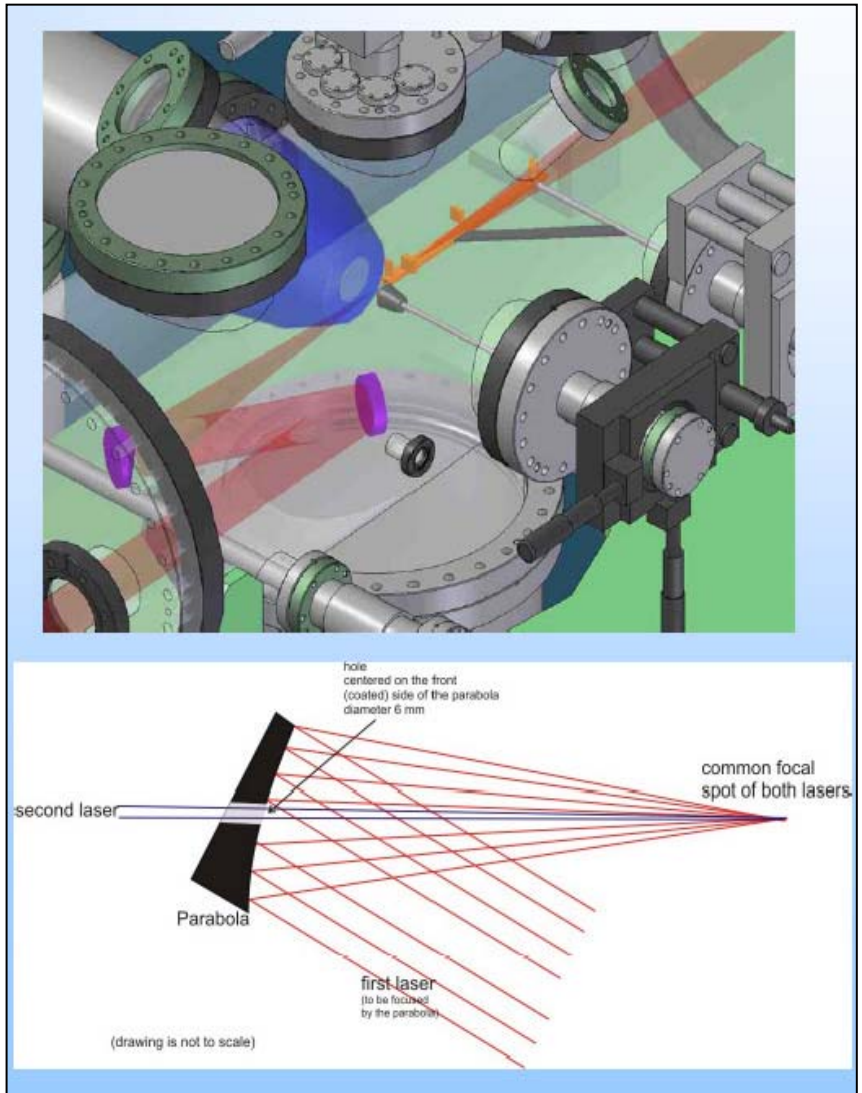


clusters stay intact
during exposure (30 fs)

Research Areas

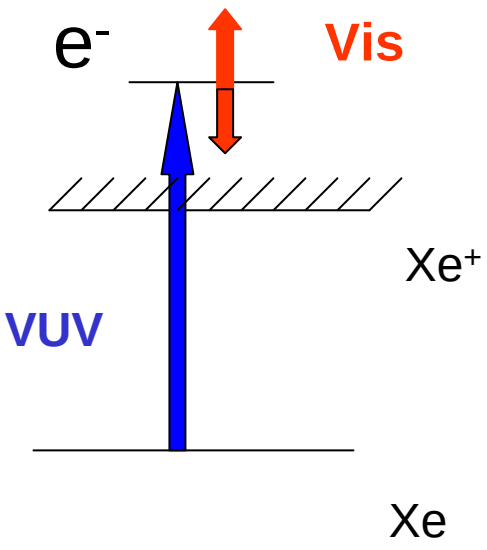
- Interaction of ultra-intense XUV pulses with matter
  - multiphoton excitation of atoms, molecules, clusters…
  - creation and characterization of dense plasmas
- Single-shot Diffraction imaging of (biological) samples
- **Femtosecond time-resolved experiments**
  - synchronization FEL - optical laser
  - **pump-probe experiments on atoms**

2-color photoionization experimental set-up (M. Meyer et al.)

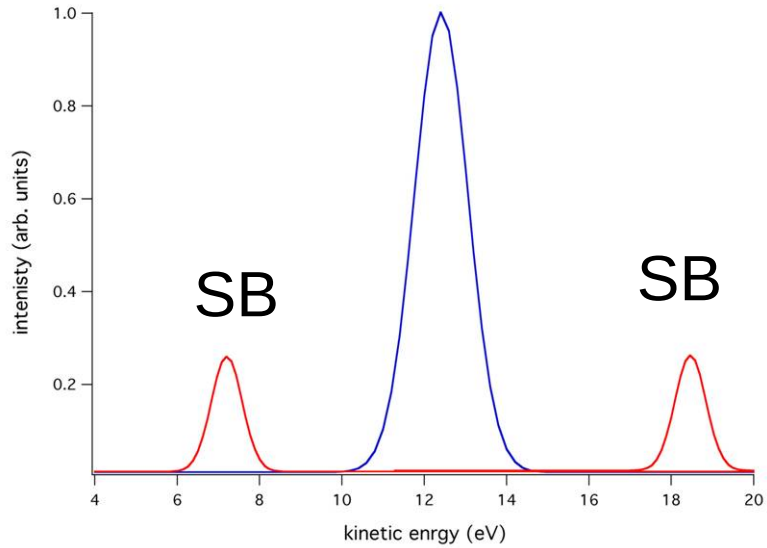


Two-color ionization in a strong optical field

Photoionization of Xe



Photoelectron spectrum



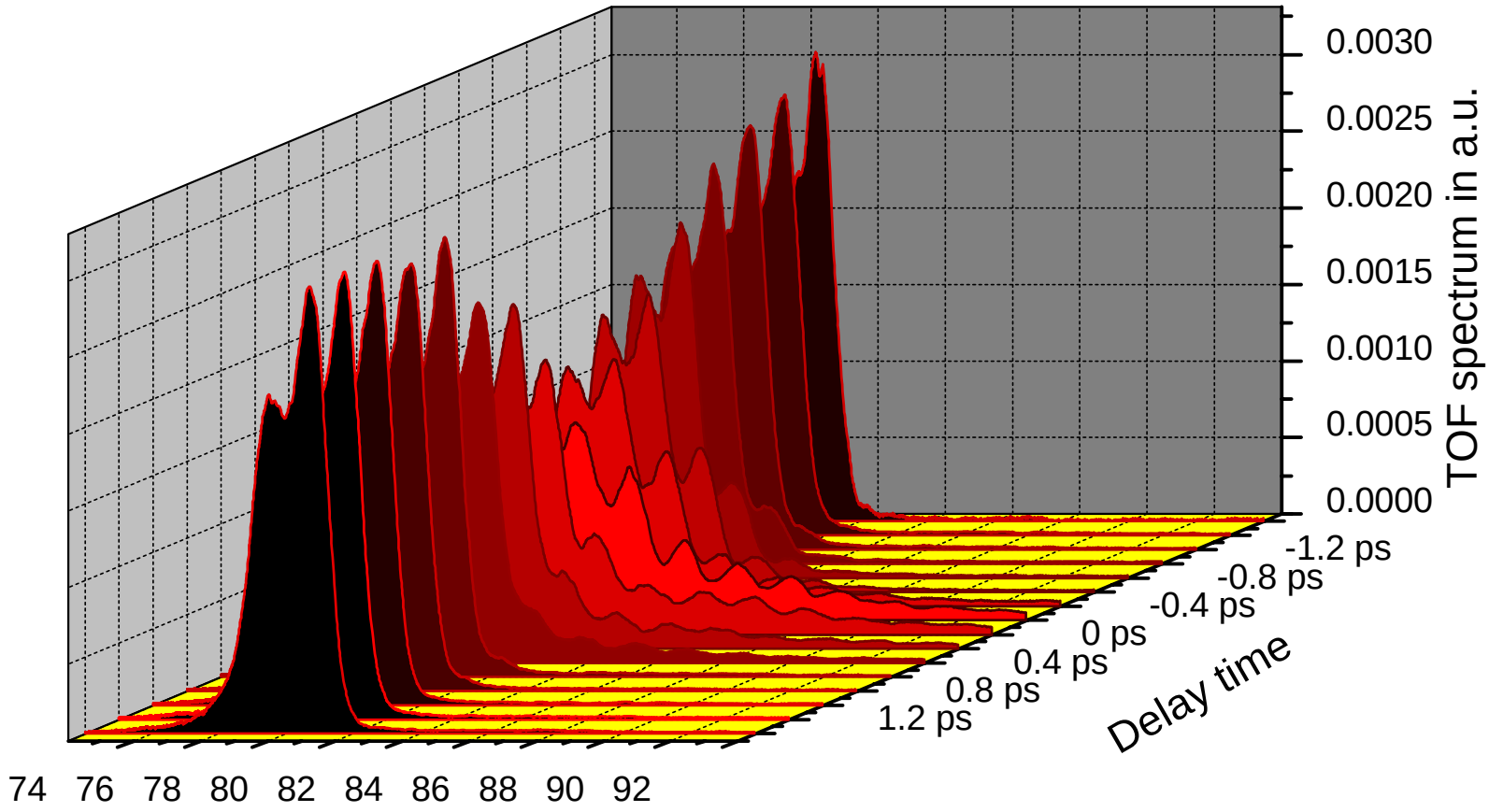
Sideband intensity very sensitive to temporal overlap

E. S. Toma et al., PRA 62, 061801 (2000)

Xe-Sideband scan

optical Laser: 800 nm, ~ 1 10^{14} Wcm^{-2}

FEL : 13.7 nm



M. Meyer et al. PRA 75, 011401 (2006)
Radcliffe et al. APL (2007)
Radcliffe et al. NIM A (2007)

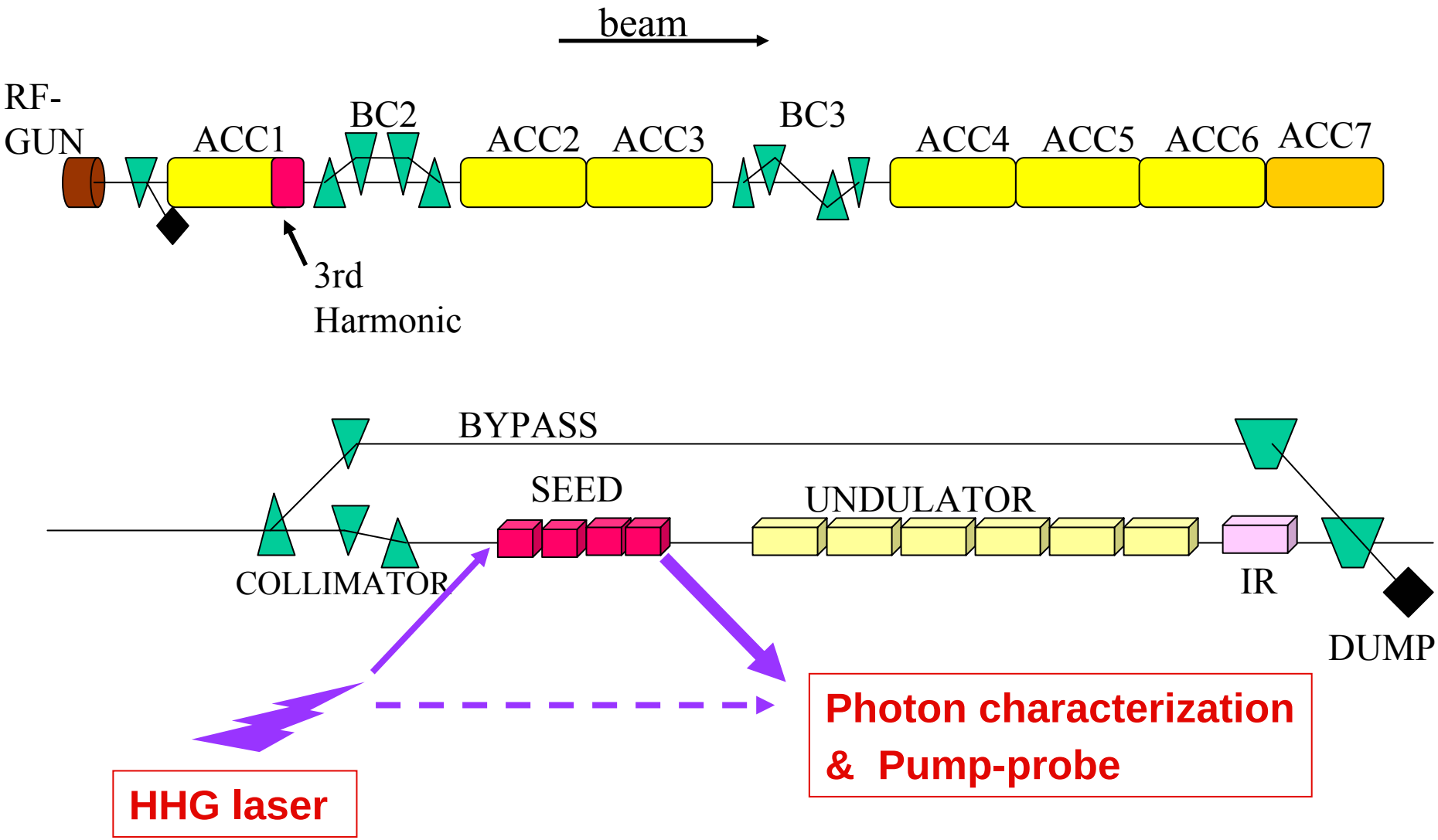
HHG Seeding of FLASH = sFLASH

funded by BMBF 2007-2010

Objectives

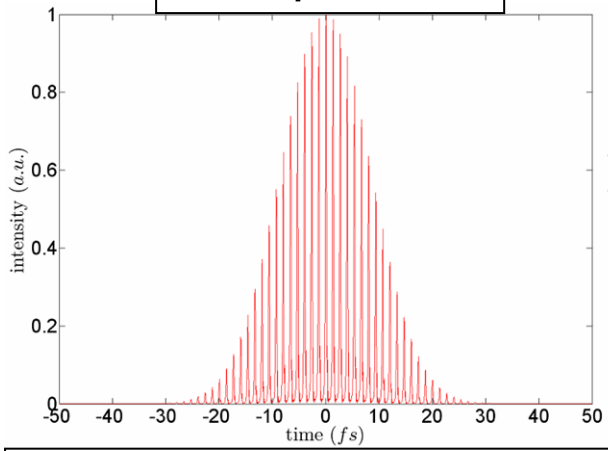
- Seed FEL process with ~20 fs HHG pulses at 13 – 30 nm in a new ~10 m long variable gap undulator
- Demonstrate improved stability of pulse energy
- Set up pilot pump-probe experiment with ~20 fs synchronization
- Do not disturb SASE operation

HHG Seeding of FLASH = sFLASH

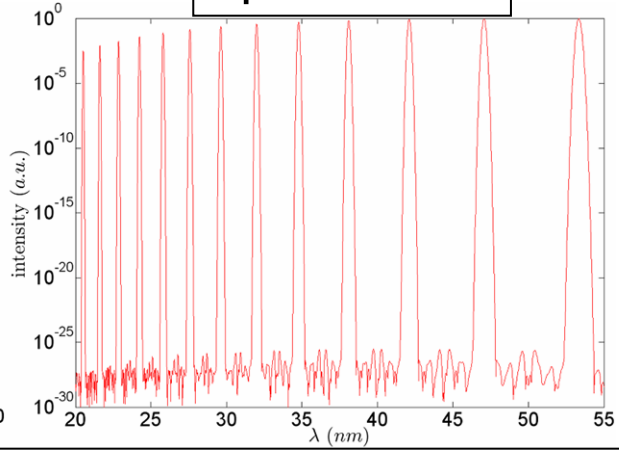


HHG Seeding of FLASH = sFLASH

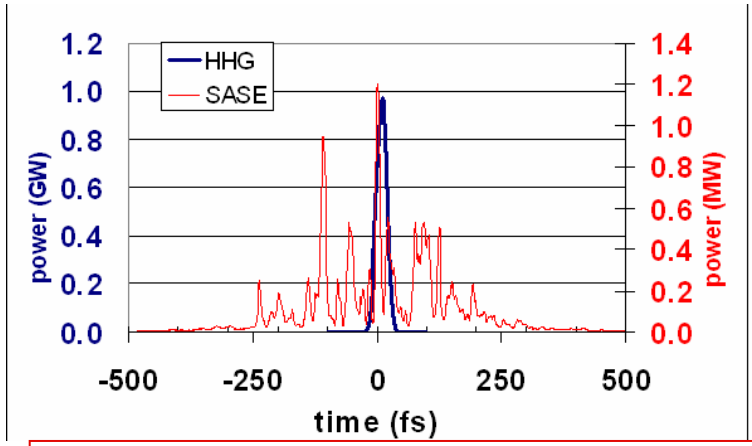
time profile

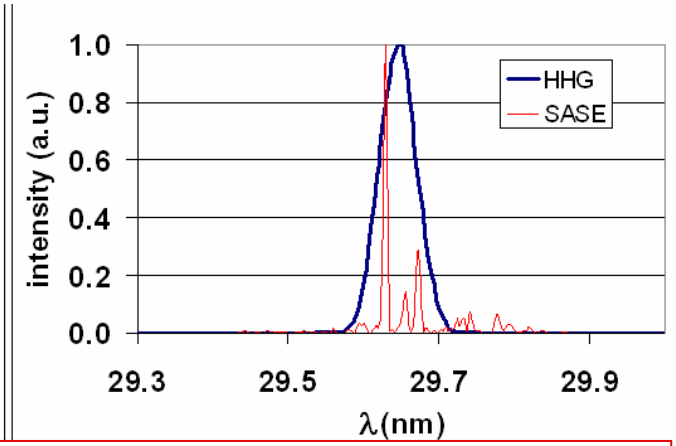


spectrum



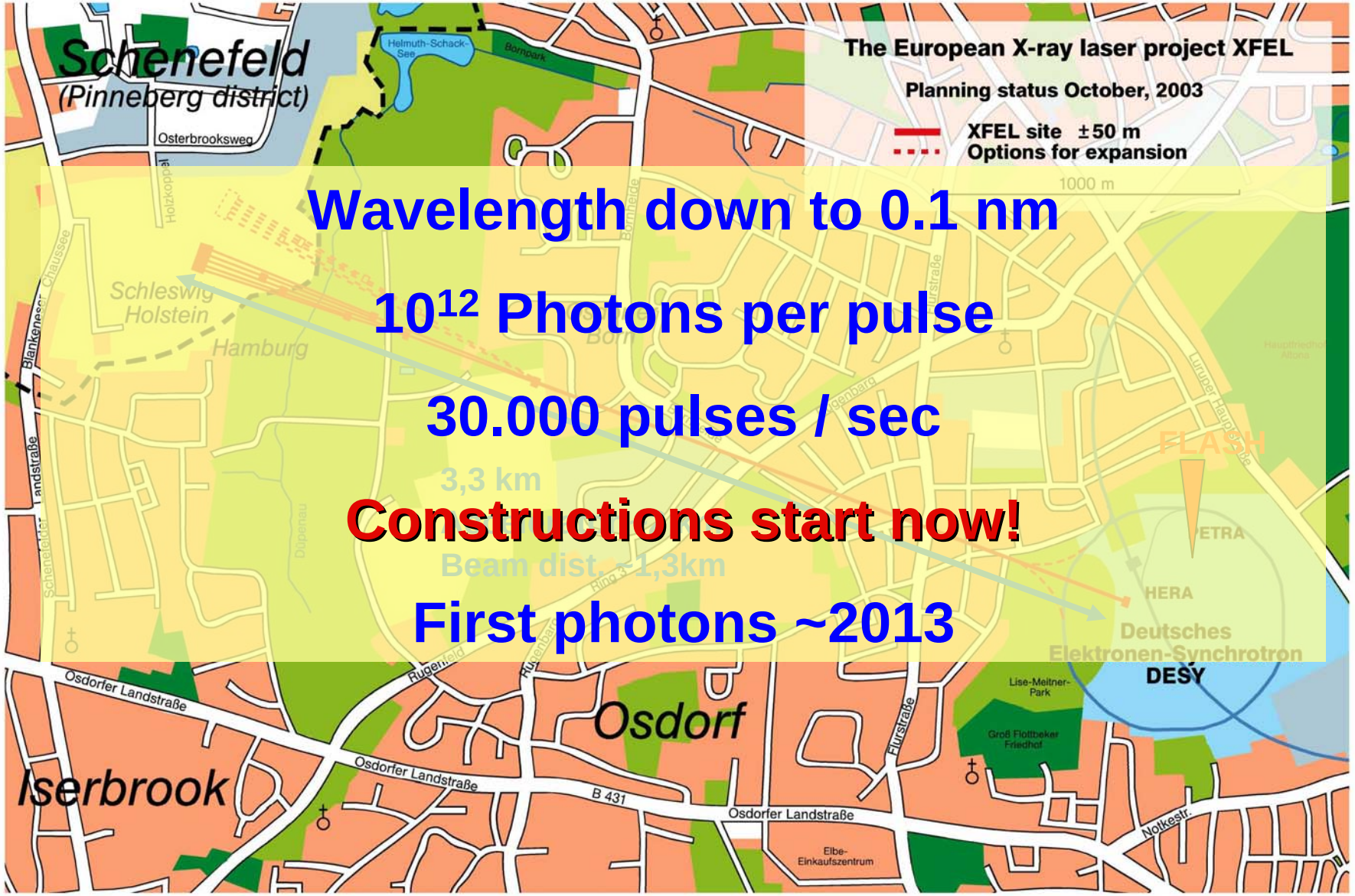
Time profile and spectrum of HHG pulse used for numerical simulation of seeding process (GENESIS)





GENSIS result on seeded FEL pulse after 6 m undulator

European XFEL at the DESY site



Wavelength down to 0.1 nm

10^{12} Photons per pulse

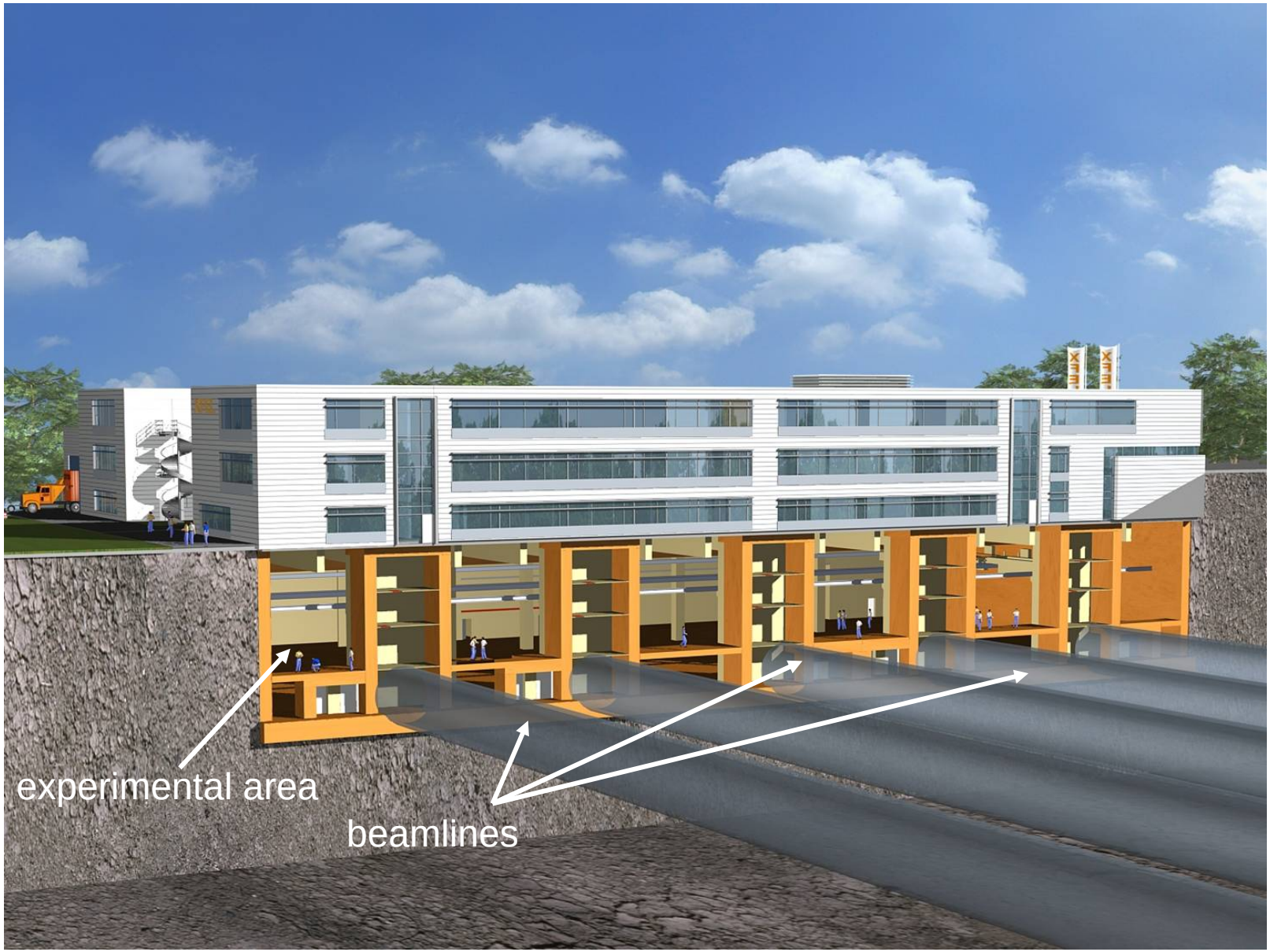
30.000 pulses / sec

Constructions start now!

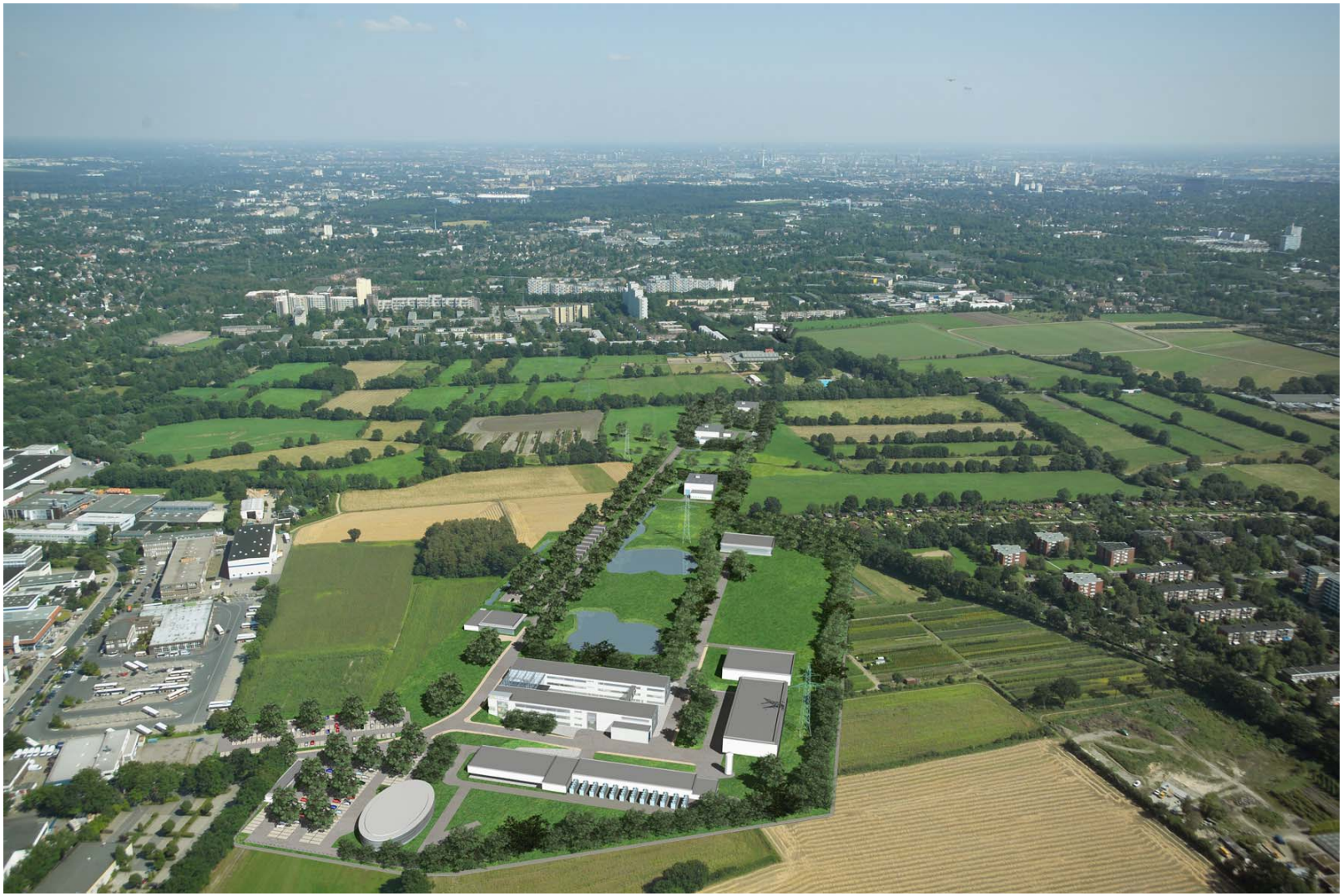
First photons ~2013

Schenefeld

Experimental hall

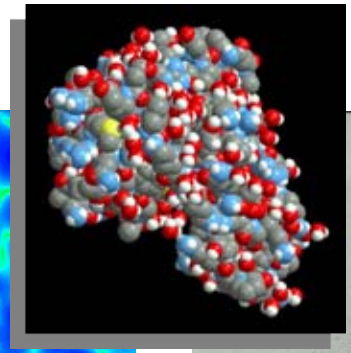


Computer simulation

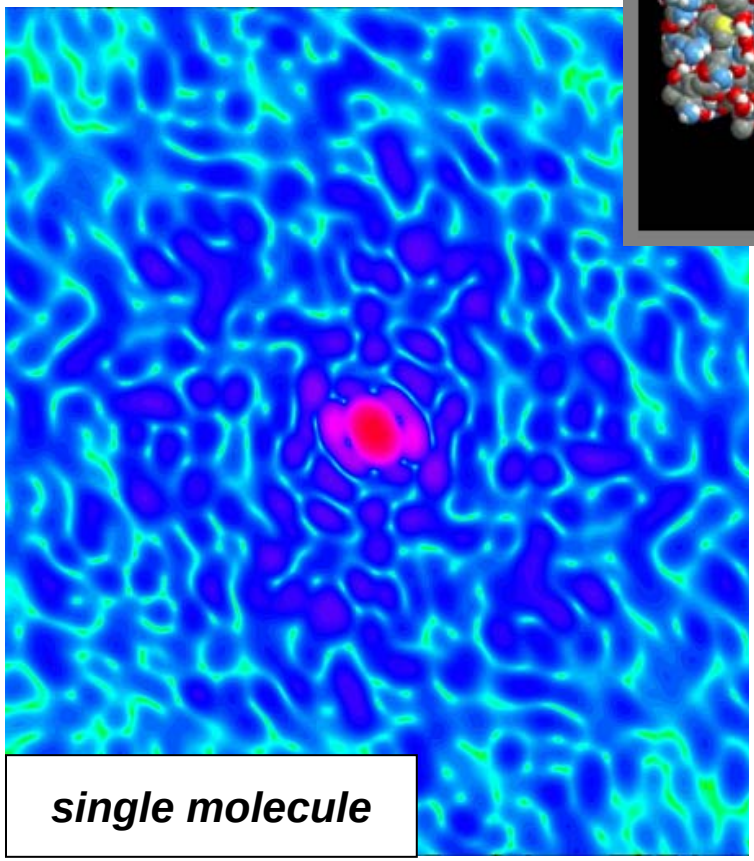


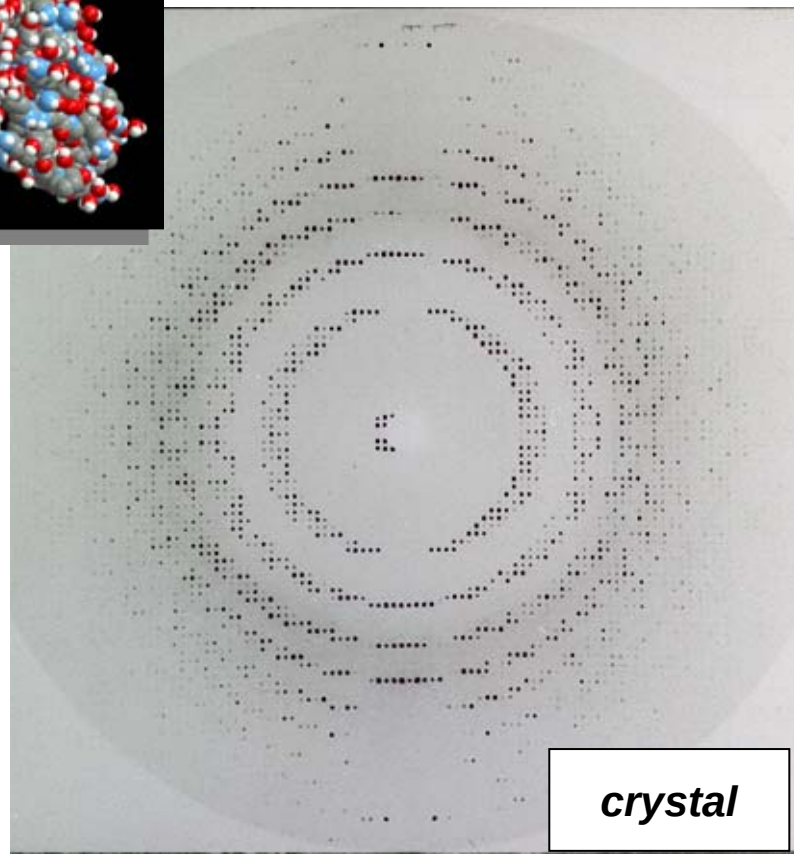
Imaging of a single bio-molecule

with atomic resolution



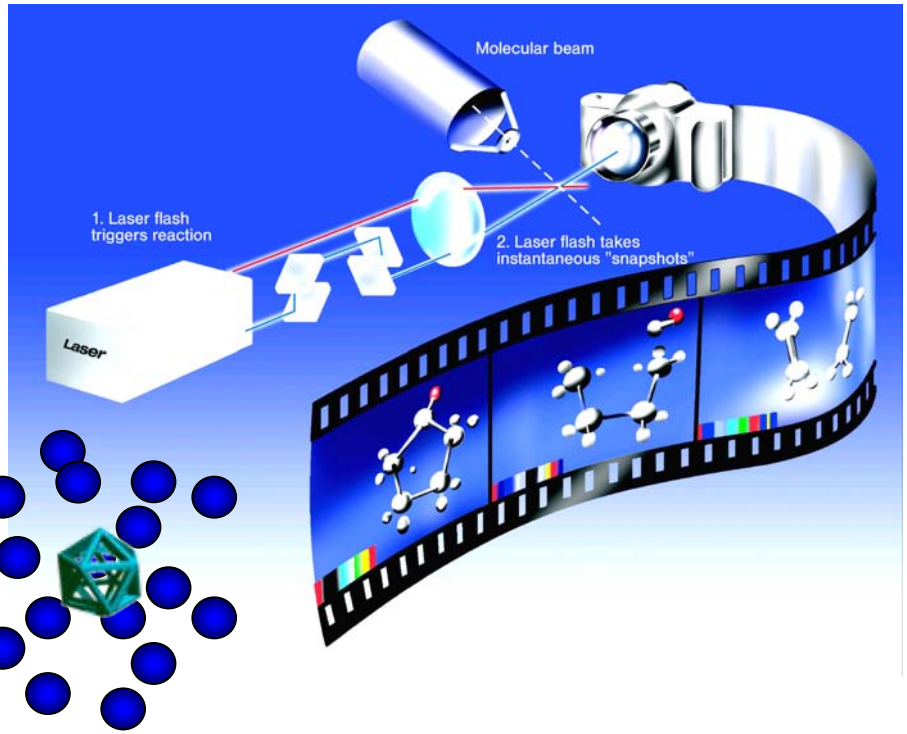
Lysozym





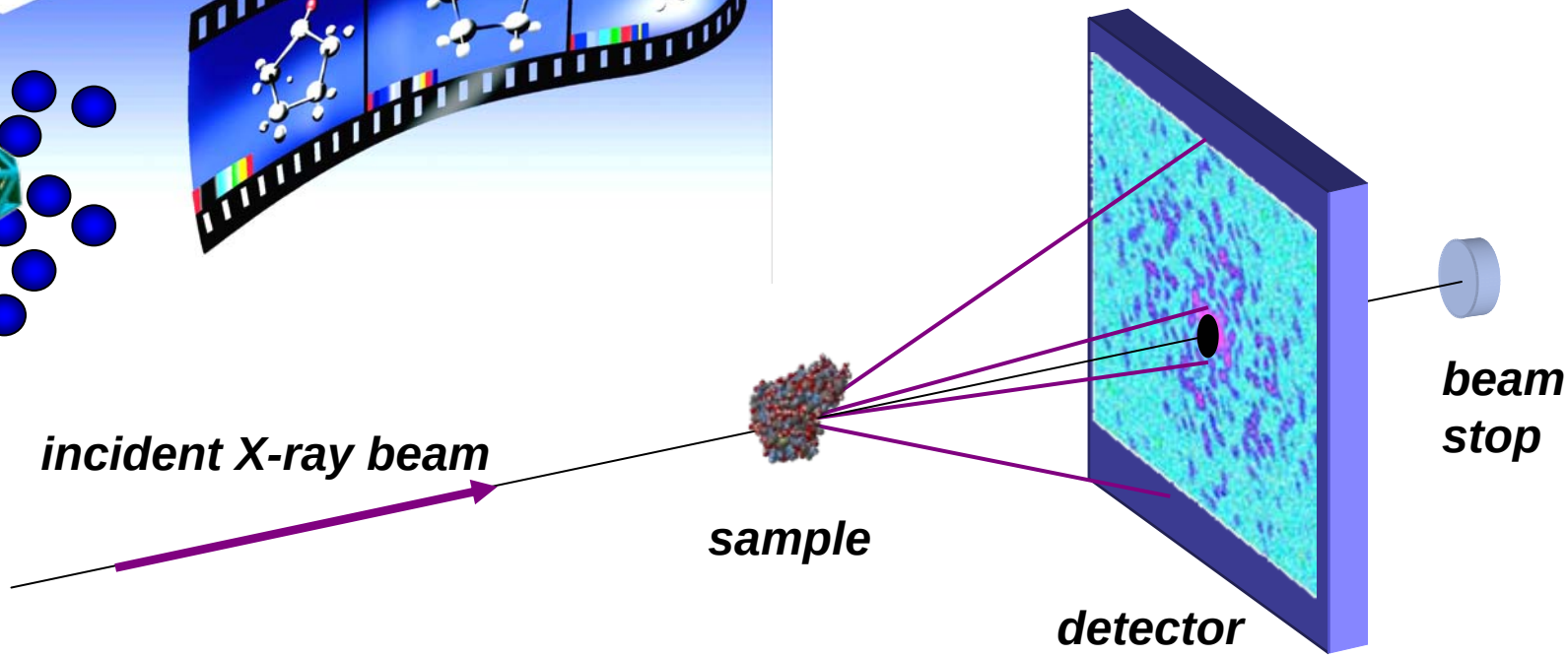
Oversampling: J. Miao, K.O. Hodgson and D. Sayre, PNAS 98 (2001) 6641-6645

Diffraction: From static to dynamics



Realtime holograms of motion of atoms, molecules and electrons

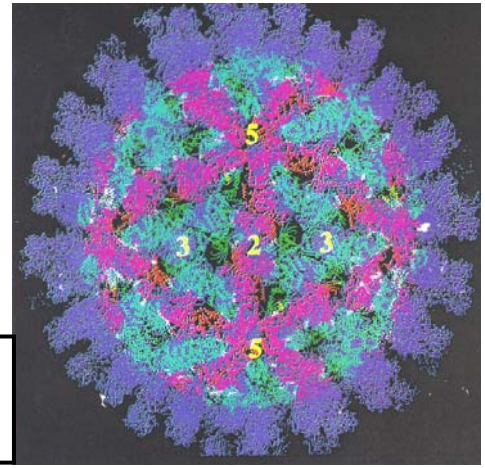
on nature's time scale



Structure of large bio-molecules

30S ribosomal subunit

nucleosome core particle



core particle of the blue-tongue virus

how do they function at work ?

Photon science with FELs at DESY: Present and future

		European XFEL facility			FLASH	
Parameter\Undulator source	Unit	SASE 1	SASE 3	SASE 3	U 1	U 1
Wavelength	nm	0.1	1.6	4.9	6	13
Photons per pulse	#	10^{12}	1.0×10^{14}	3.7×10^{14}	3.0×10^{12}	3.3×10^{12}
Pulse energy	mJ	2	13	15	0.1	0.05
Power density (1 micron spot)	W/cm^2	2.5×10^{18}	1.6×10^{19}	1.9×10^{19}	3.2×10^{17}	1.6×10^{17}
Ponderomotive energy U_p	eV	0.002	3.8	41	1.0	2.4
Keldysh parameter γ (I_p=13.6 eV)		55	1.3	0.4	2.6	1.7

FELs around the world

Location	FEL Name	Wavelength range	Institution, City
America			
USA	DFELL	IR & UV	Duke University, Durham NC
	DUV-FEL & ATF	VUV	NSLS, Brookhaven NY
	Free-Electron Laser Center	IR	Vanderbilt University, Nashville TE
	FEL User Facility	IR	JLab, Newport News VA
	LEUTL	VIS to VUV	ANL, Argonne IL
	LCLS ●	X-rays	SLAC, Stanford CA
	Mark III	IR	University of Hawaii, Manoa
	MIT-Bates X-ray Laser ●	X-rays	MIT-Bates Linear Acc. Center, Middleton MA
	Picosecond FEL	FIR to IR	Stanford CA
	UCSB FEL	MM & FIR	UCSB, Santa Barbara CA
	Neptune, Pegasus, VISA	IR to VIS	UCLA, Westwood CA
Asia and Middle East			
China	BFEL	IR	IHEPA, Bejing
India	FIR-FEL ●	FIR	CAT, Indore
	IPR-FEL	MM	Inst. for Plasma Research, Bhat (Gandhinagar)
Israel	Israeli FEL	MM to FIR	University Tel Aviv
Japan	FEL-SUT	IR	Science University of Tokyo
	iFEL	FIR to UV	University Osaka
	ISIR-FEL	FIR	University Osaka
	JAERI FEL Project	IR	
	LEBRA FEL	IR	Nihon University
	NIJI-IV	VIS to UV	ETL (now AIST), Tsukuba
	SCSS ●	VUV to soft X-rays	SPring-8, Nishi Harima
	UVSOR-FEL	UV	UVSOR, Okazaki

Europe			
France	CLIO	IR	LURE, Orsay
	SUPER-ACO FEL	UV	LURE, Orsay
Germany	BESSY-FEL ●	VUV to X-rays	BESSY, Berlin
	ELBE-FEL	FIR to IR	FZ Rossendorf
	FELICITA I	VIS to UV	DELTA, Dortmund
	IR-FEL	IR	TU Darmstadt
	VUV-FEL	VUV to soft X-rays	DESY, Hamburg
	XFEL ●	X-rays	
Great Britain	4GLS ●	IR, VUV, soft X-rays	Daresbury Laboratory
Italy	ENEA	MM	Frascati
	EUFELE	UV to VUV	ELETTRA, Trieste
	FERMI ●	VUV to soft X-rays	
	SPARC / SPARX ●	VIS to UV / X-rays	CNR, ENEA, INFN, Tor Vergata Univ., INFM-ST, Italy
Russia	PPL mm-FEL	MM	JINR, Dubna
Sweden	IR-FEL & VUV-FEL ●	IR & VUV	MAX-lab, Lund
The Netherlands	FELIX	FIR to IR	FOM, Rijnhuizen
	Fusion FEM	MM	
	TEU-FEL, ...	MM & FIR to IR	University Twente
More Links			
The World Wide Web Virtual Library: Free Electron Laser			
EU Roundtable SR+FEL			

● = under development / proposed project

http://www-hasylab.desy.de/facility/fel/overview/fel_laboratories.htm

Summary

Free-electron lasers at DESY:

- **FLASH:** first and world wide unique soft x-ray FEL
- **European X-FEL:** unprecented experimental oportunities - one of 3 XFEL projects world wide