High Energy Density Physics at FLASH.

Sven Toleikis

High Energy Density Physics at FLASH

EMMI Workshop, GSI
7 – 9 June 2010

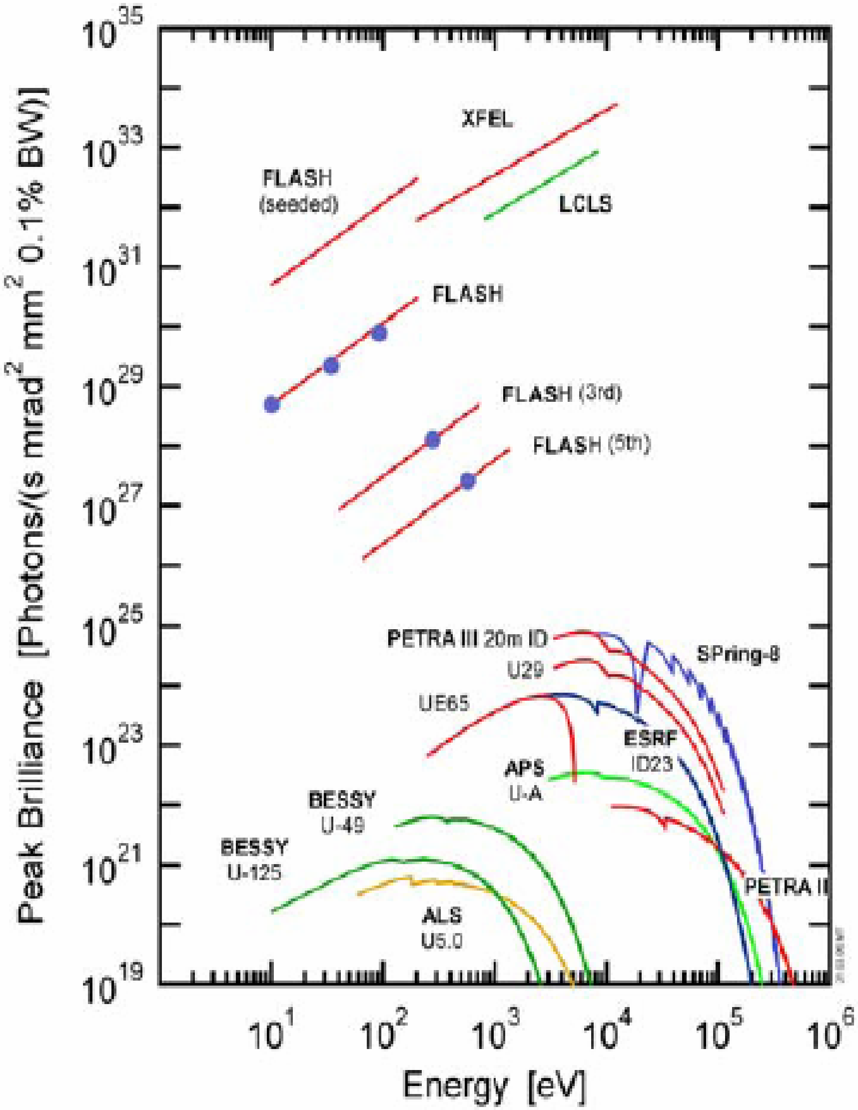
HELMHOLTZ | ASSOCIATION

DESY

Outline

- > FLASH
- > Thomson Scattering on Dense Hydrogen
- > Microfocusing Campaign –> “Transparent” Aluminum
- > Outlook: FLASH II

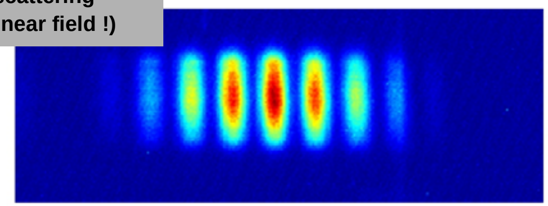
SASE FEL Radiation Properties

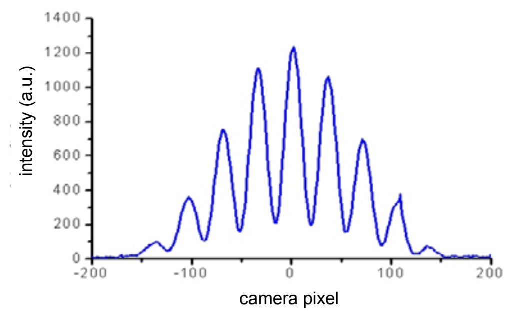


> **Ultra-short pulse duration:**
- **10 - 300 fs**

> **Coherent beam:**
- **full transversal coherence**

FLASH, May '06 at 25 nm, double-slit scattering (detector in near field !)



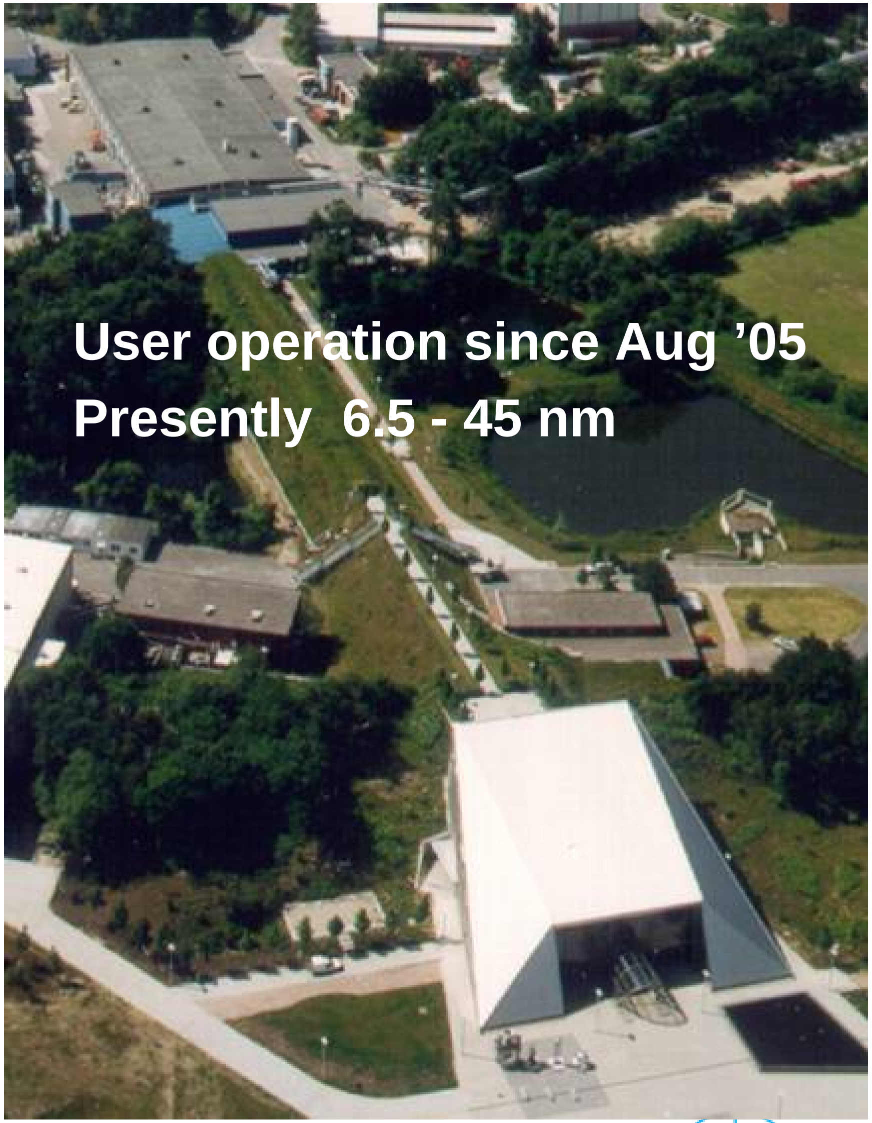


*Singer et al. PRL **101**, 254801 (2008)*

> **GW peak power,**
10^{12} - 10^{13} photons / pulse

The FLASH Facility

- **Free electron LASer in Hamburg**
- **World-first FEL user facility in the short-wavelength domain**
  - **scientific experiments**
  - **testing and validation of concepts for accelerator, diagnostics, beamlines**
  - **experience on timing, synchronization, data acquisition strategies**
  - **extraordinary asset for the European XFEL project**



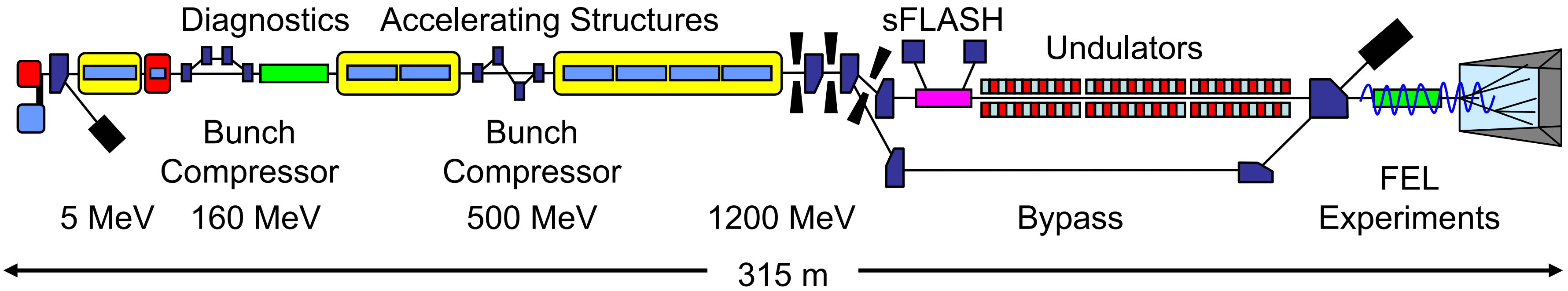
- **SASE FEL properties:**
  - **high intensity (GW peak power)**
  - **coherence**
  - **femtosecond pulses**
  - **narrow bandwidth**
  - **full wavelength tunability!**
  - **down to (soft) X-rays (with 3rd/5th harmonic)!**
  - **But: shot-to-shot fluctuations (w/o seeding)**

FLASH layout – after this upgrade

Installation of modules into the accelerator

sFLASH undulators

Experimental Hall



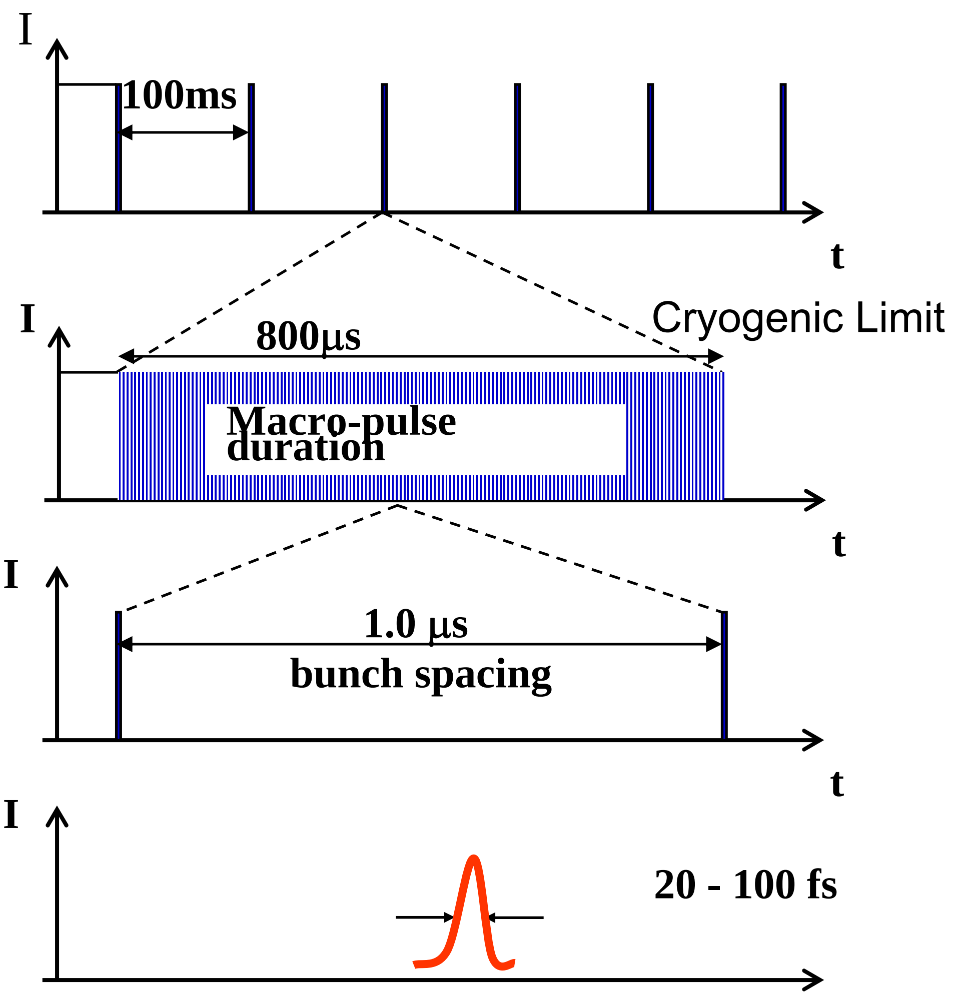
RF electron gun

Bunch compressor

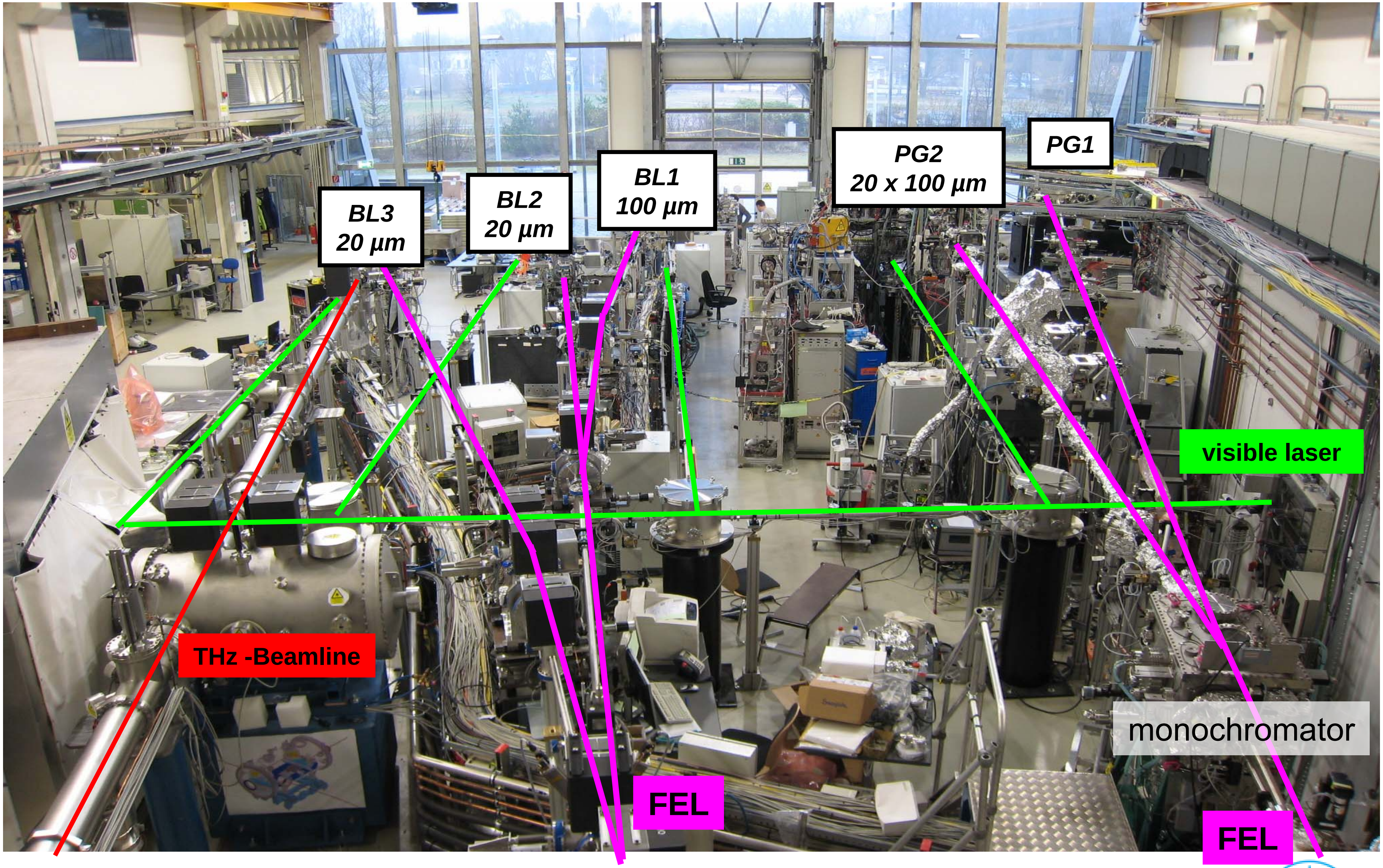
Undulator assembly

FLASH Bunch Structure

- Repetition rate
  upgrade (2010): 10 Hz
- Macro-pulse (bunch train)
  1-30 bunches/train (normal)
  up to 700 bunches/train (tested)
- Bunch spacing is variable:
  1, 2, 4, 5, 10 or 20 μs
- With fast shutter:
  single pulse operation
  (1 bunch/train)



FLASH Experimental Hall



K. Tiedtke et al., New Journal of Physics 11, 023029 (2009)

Peak Brightness Collaboration (at FLASH)

> The production and investigation of very dense finite-temperature matter.

> The production and investigation of more plasma-like states.

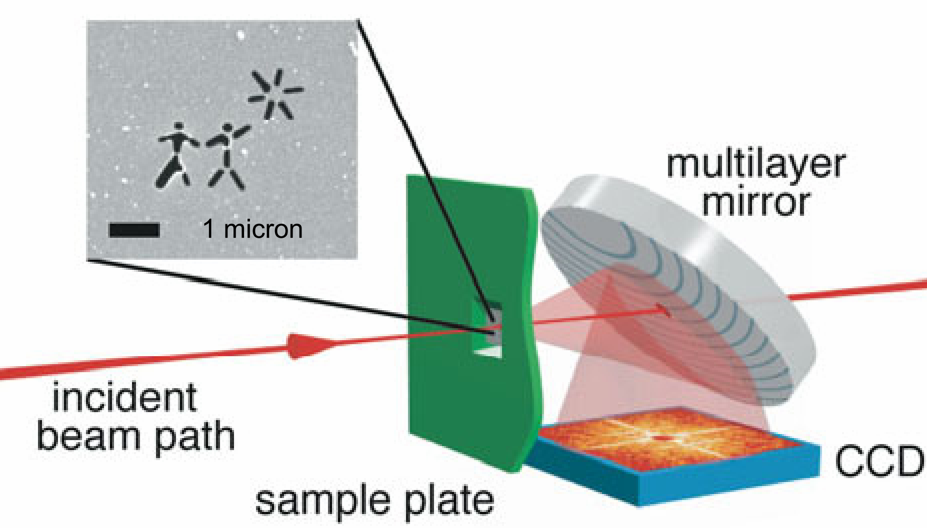
> The investigation of processes which are of importance to the quest for biological imaging.

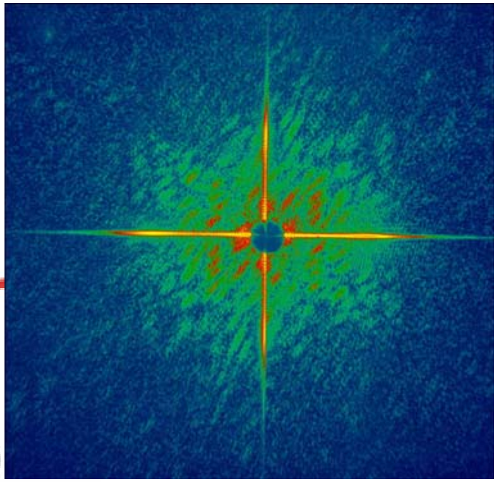
> http://hasylab.desy.de/science/user_collaborations/peak_brightness_collaboration/index_eng.html

> Physical processes:

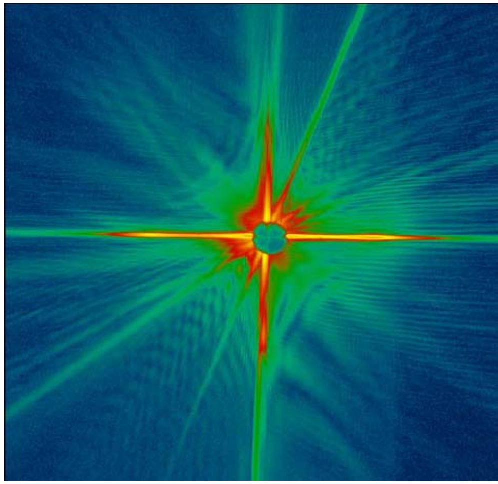
- Creation and characterization of WDM
- Equation of state measurements
- Femtosecond ablation studies
- Near-edge absorption studies
- Strongly coupled plasma studies
- Diagnostic development of Thomson scattering, interferometry, and radiography
- Plasma physics of photo-ionized gases
- FEL solid target interaction
- Plasma spectroscopy
- Investigation of nano-plasmas

First diffraction experiment at FLASH





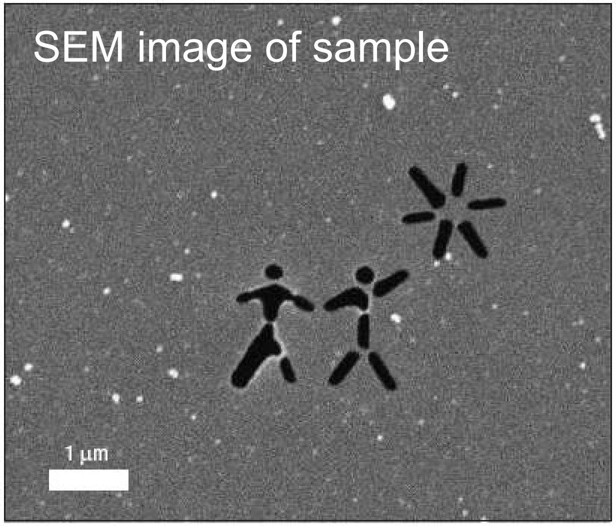
1st shot

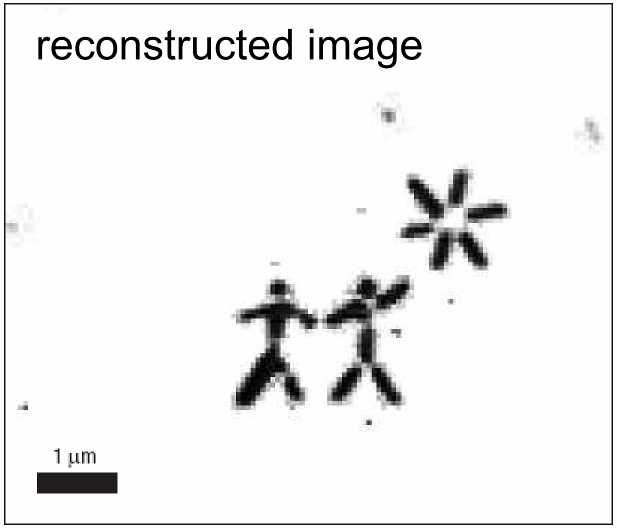


2nd shot

20 µm focus, 30 fs pulse, ~10^{14} W/cm²;

Sample heated to 60 000 K!

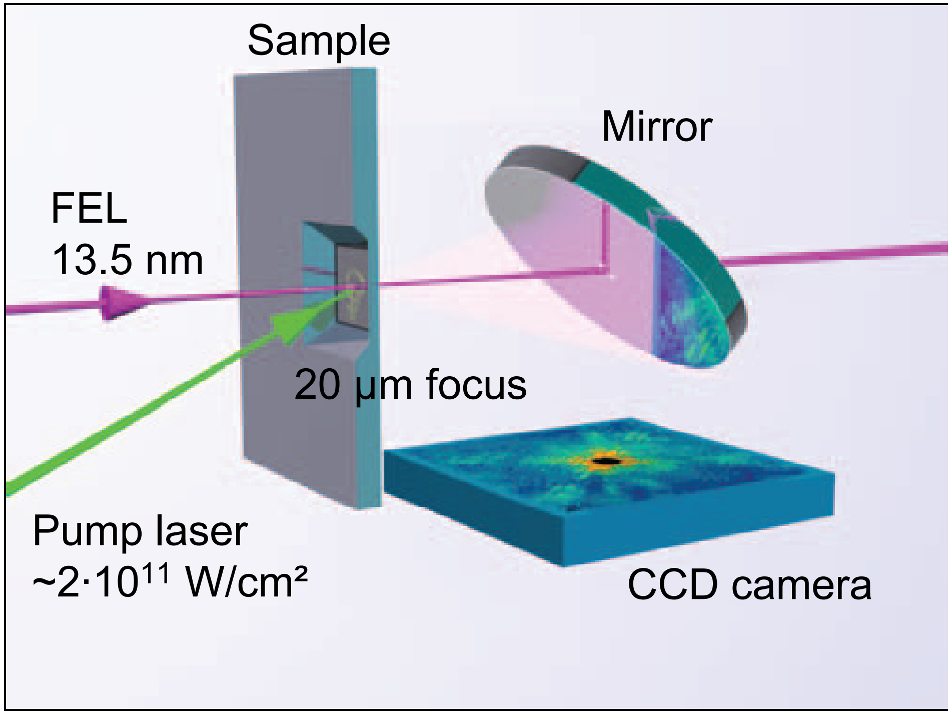


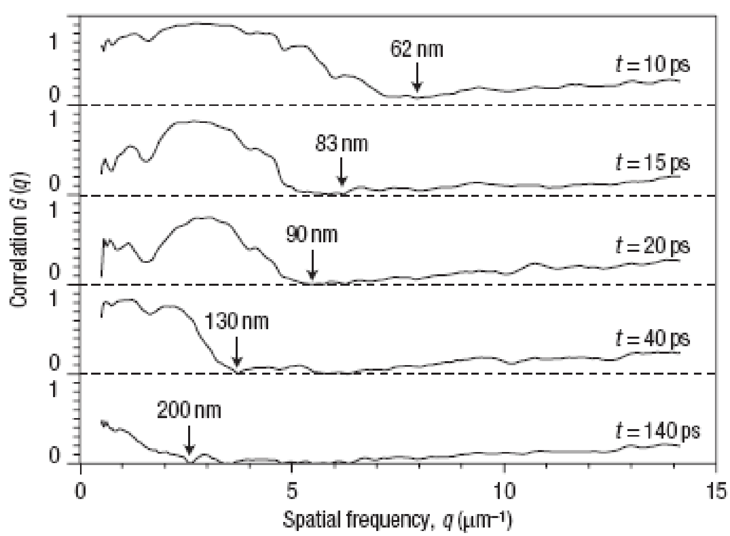


-> diffraction limited resolution at 32 nm wavelength

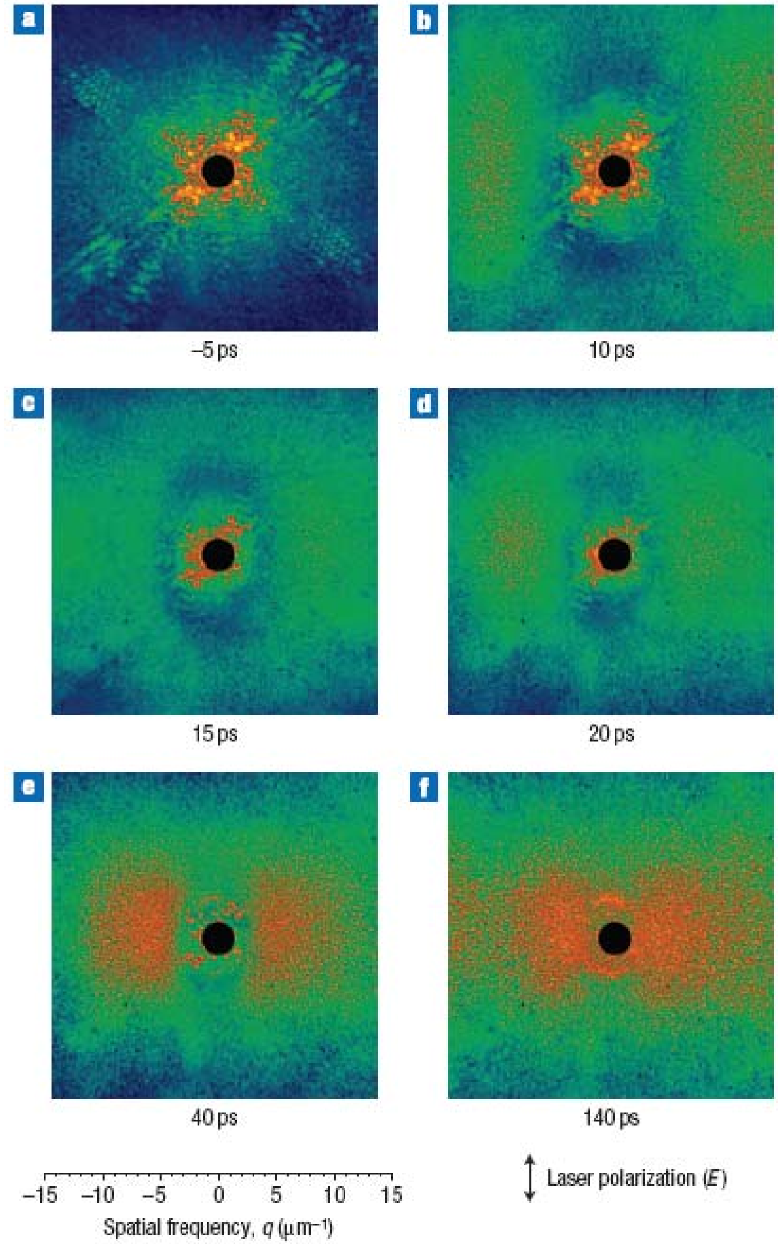
H. Chapman et al., Nature Physics 2, 839 (2006)

Ultrafast single-shot diffraction imaging of nanoscale dynamics

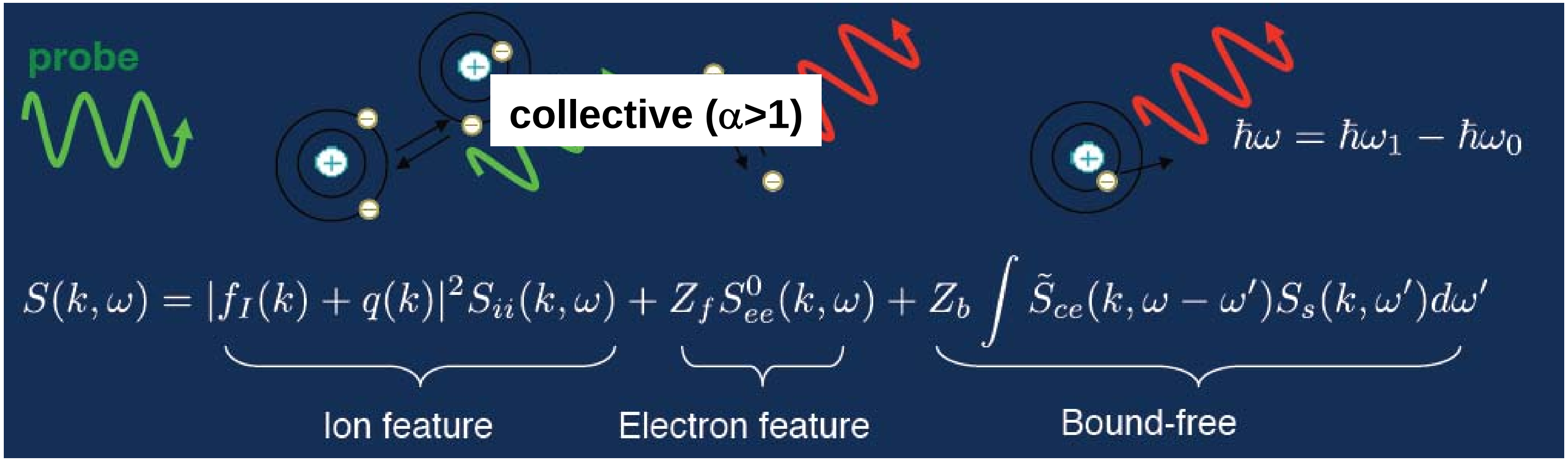




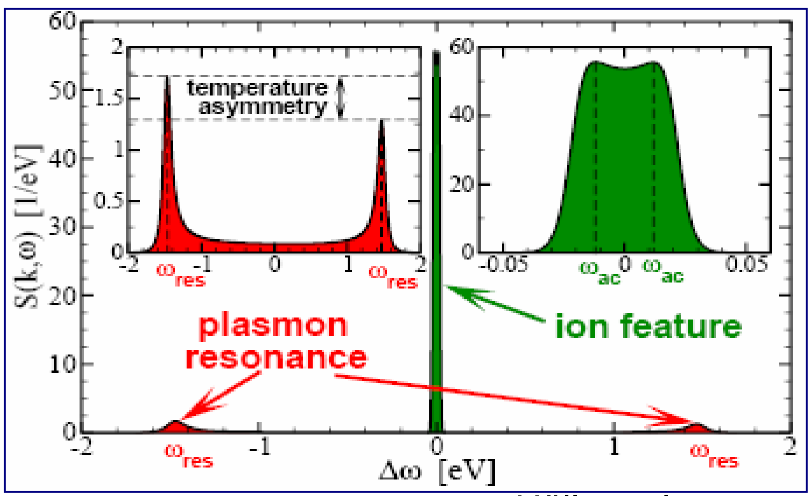
A. Barty et al.,
Nature Photonics 2, 415 (2008)



Scattering Reveals Target Conditions



Courtesy of G. Gregory



Höll, et al.
HEDP 3, 120 (2007)

collective (α>1)

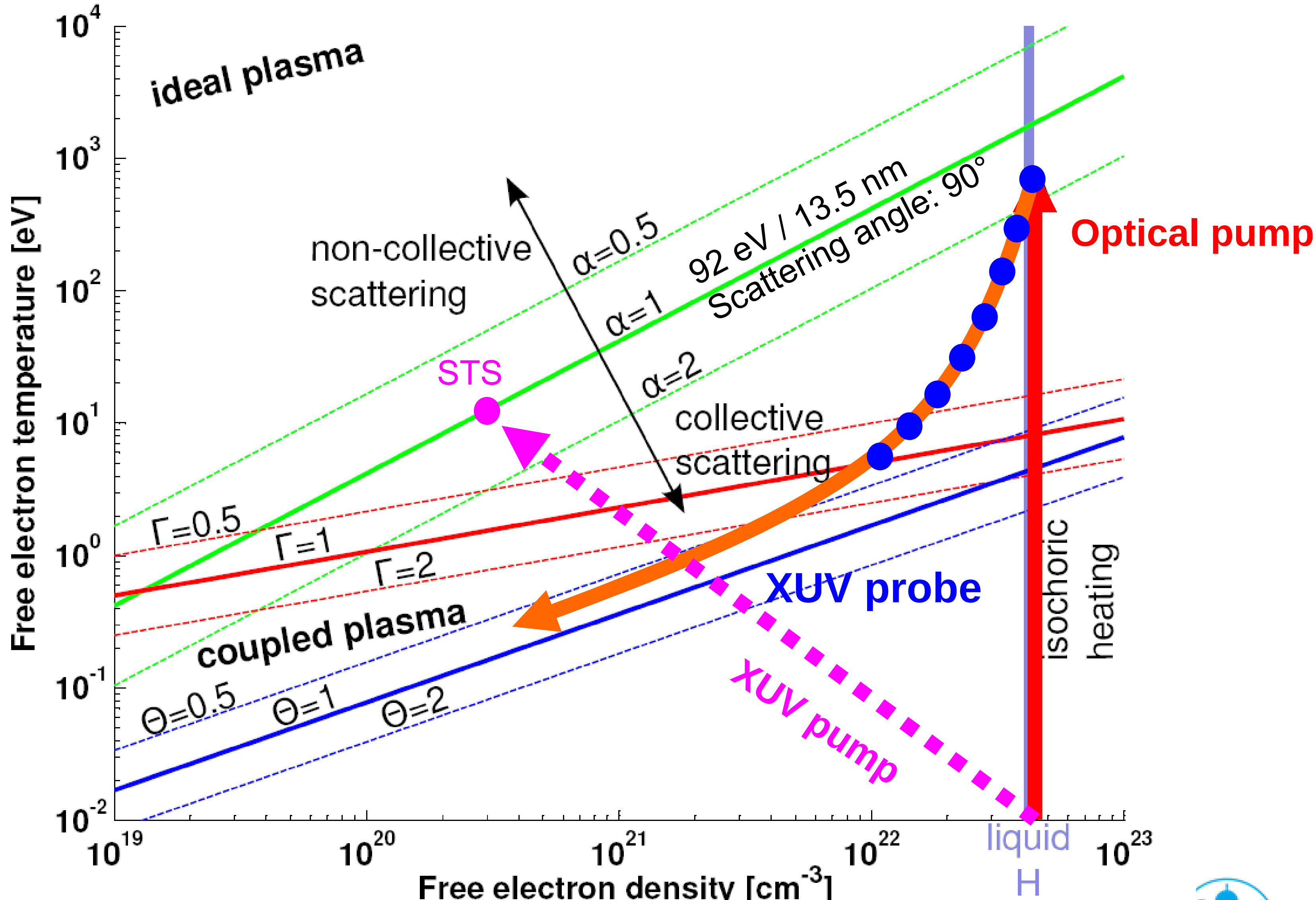
Detailed balance:

$$\frac{S(-k,-\omega)}{S(k,\omega)} = \exp\left(-\frac{\hbar\omega}{k_B T}\right)$$

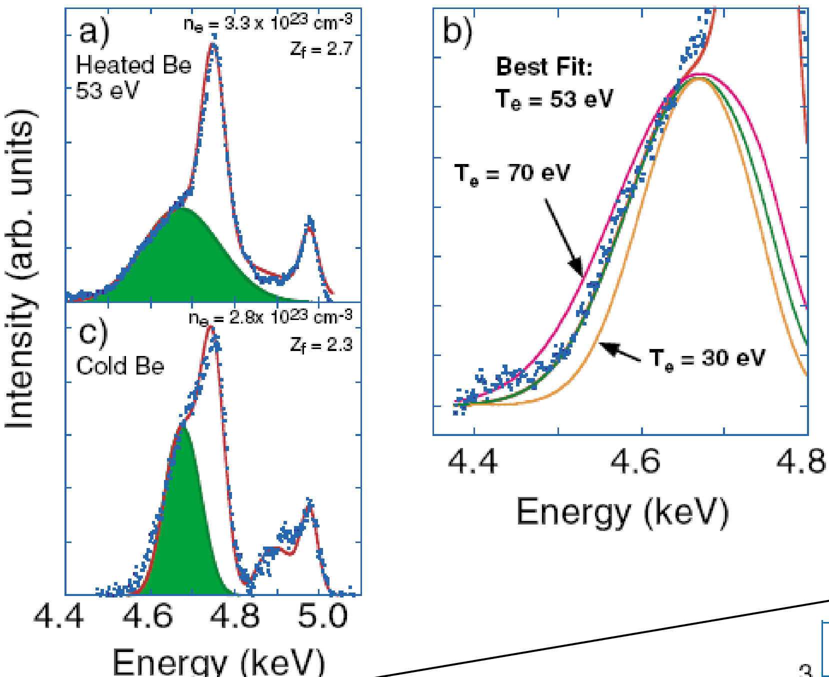
Plasma frequency:

$$\Delta\omega = \omega_{pl} = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}$$

T-n Phase Space Diagram

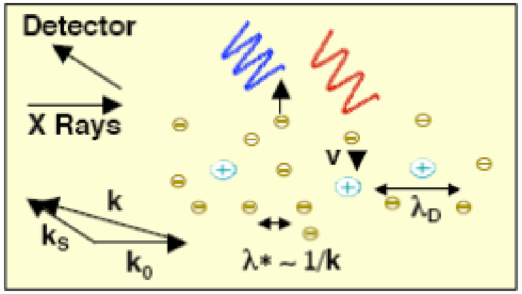


X-ray scattering using laser sources, e.g. Omega laser



> **Probe individual particle motion**

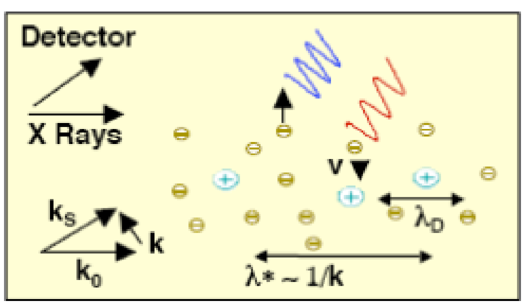
> **large k: non-collective scattering**



*S.H. Glenzer et al., PRL **90**, 175002 (2003)*

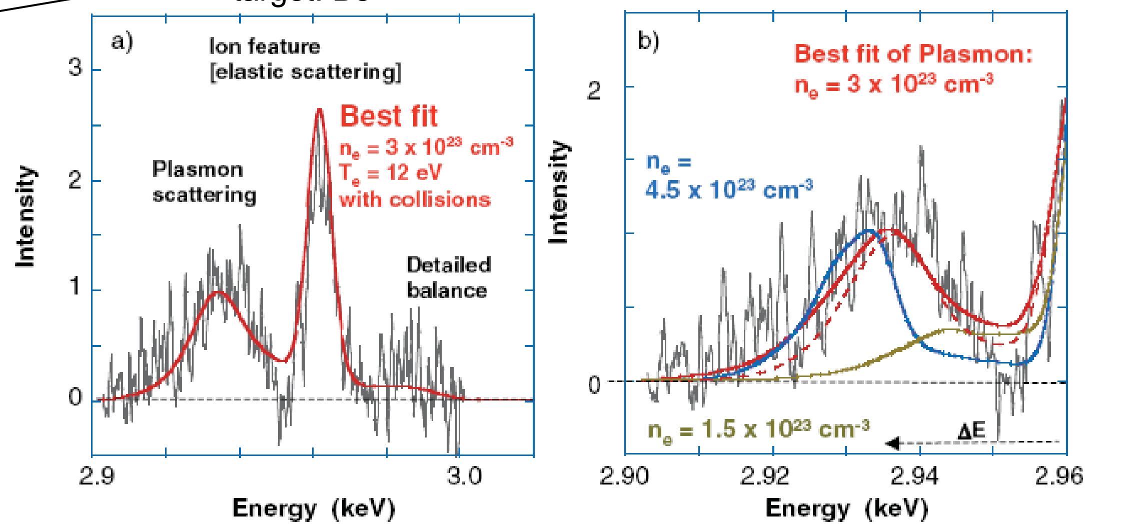
> **Probe plasma waves (plasmons)**

> **small k: collective scattering**



target: Be

*S.H. Glenzer et al., PRL **98**, 065002 (2007)*



The Team

- **CFEL, Hamburg**
  B. Ziaja
- **DESY, Hamburg**
  S. Düsterer, R.R. Fäustlin, M. Harmand, T. Laarmann, F. Tavella, H. Redlin, S. Toleikis
- **EMMI / GSI, Darmstadt; University of Frankfurt**
  P. Neumayer
- **University of Jena**
  E. Förster, I. Uschmann, U. Zastrau
- **LCLS, Stanford**
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- **University of Oxford**
  G. Gregori, B. Li, J. Mithen, C. Murphy, S. Vinko, T. Whitcher
- **University of Rostock**
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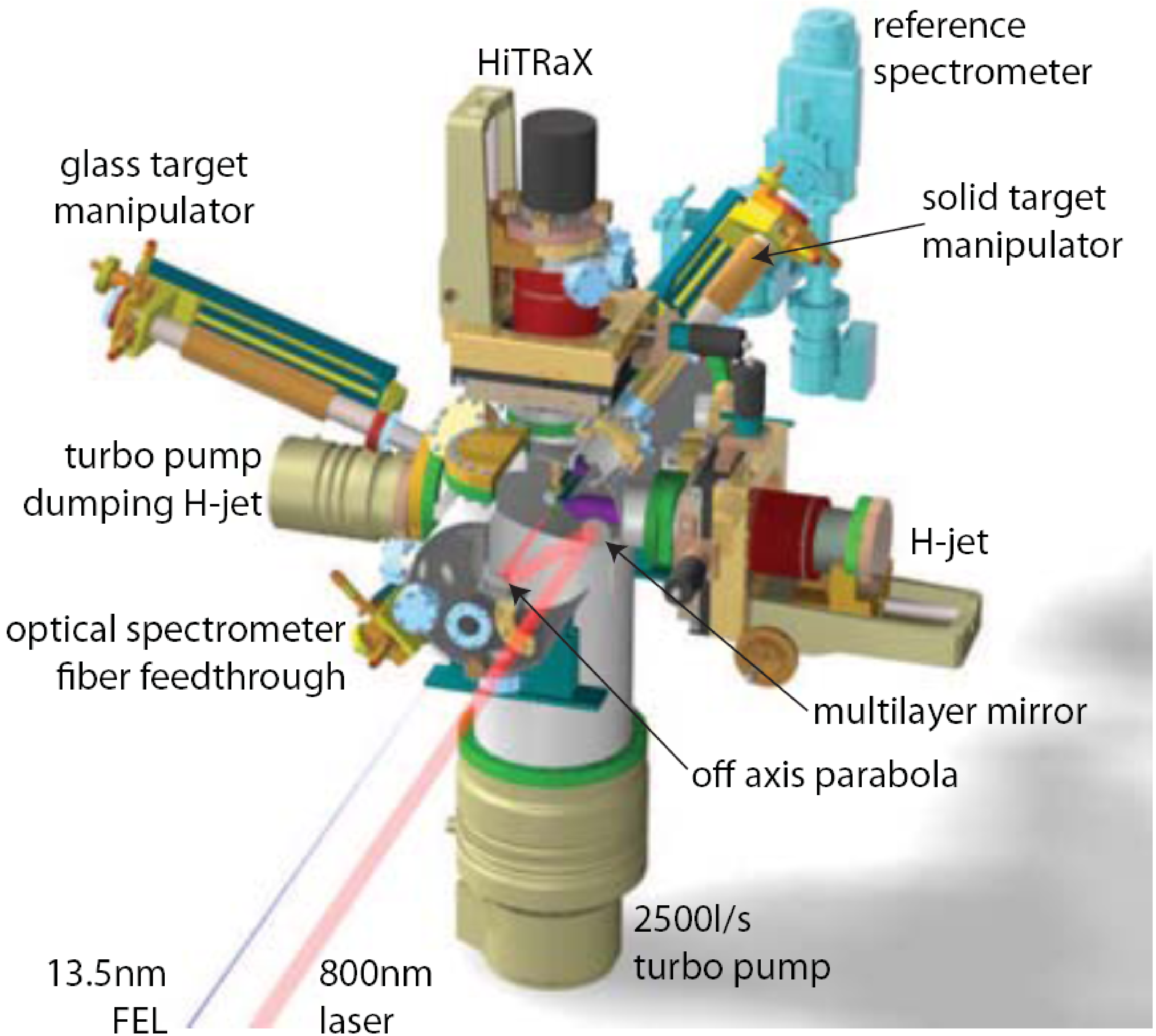
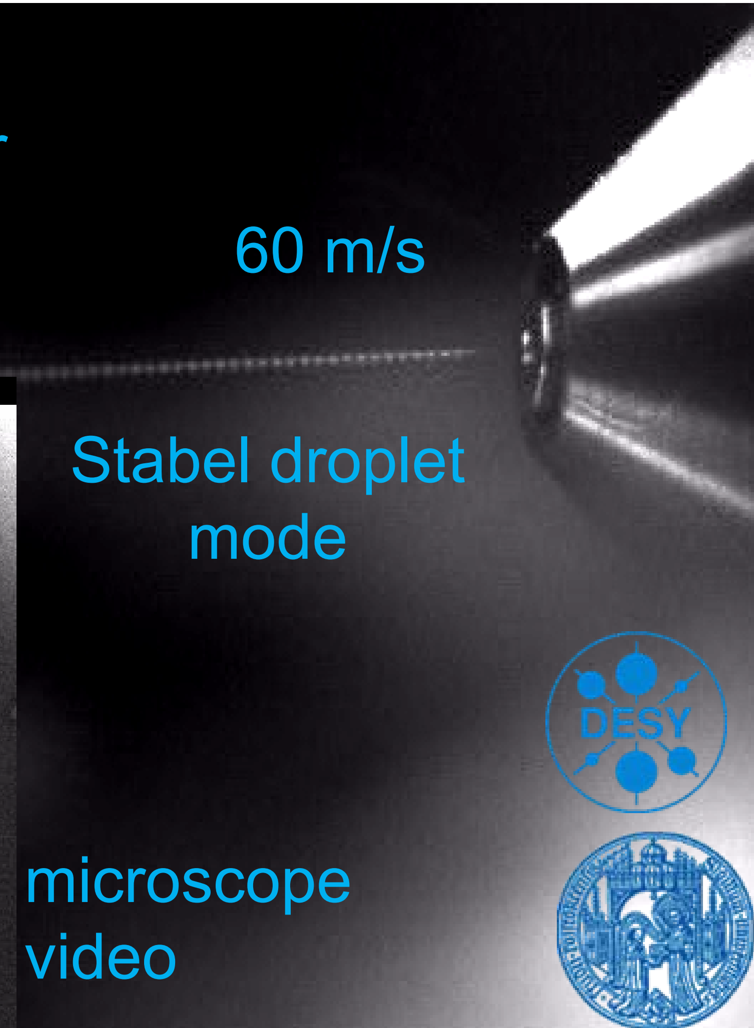
- **European XFEL, Hamburg**
  P. Radcliffe, T. Tschentscher

Experimental Setup at FLASH

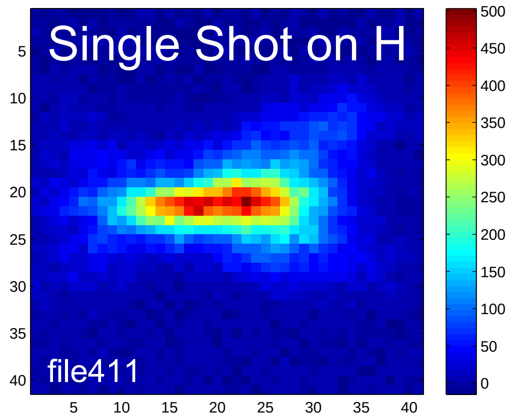


Liquid Hydrogen Beam

- He cooled cryostat
- 20 µm droplets @ 17-22 K, 1 bar
- Solid density: $4.2 \cdot 10^{22}$ /ccm

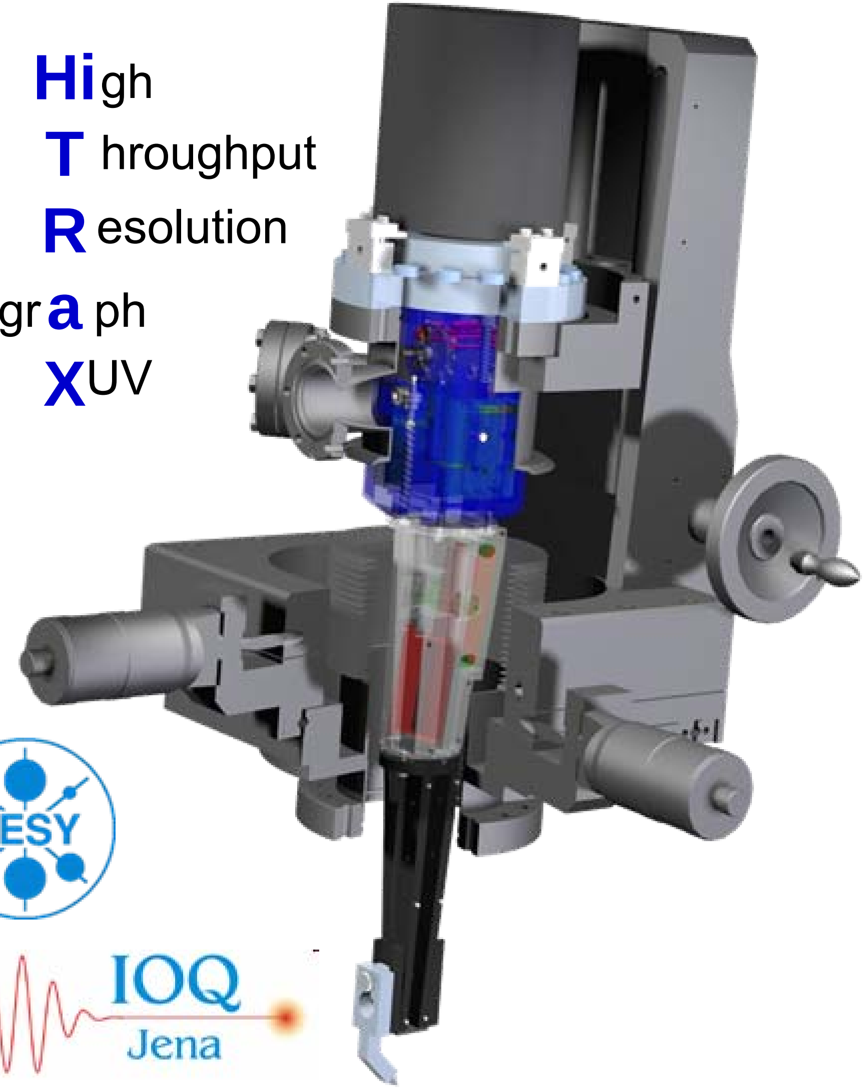


Single Shot Scattering – Yes, HiTRaX can!



- High Collection Optics (1.9E-3 sr, 11% throughput)
- High Resolution (0.05nm)
- Spectral Window 7-31nm
- Versatile, Compact Built
  - Grating Motorized
  - Motorized debris shutter
  - 6 Motorized Filters
- Easy Alignment

High
T hroughput
R esolution
Spectrogr**a**ph
XUV



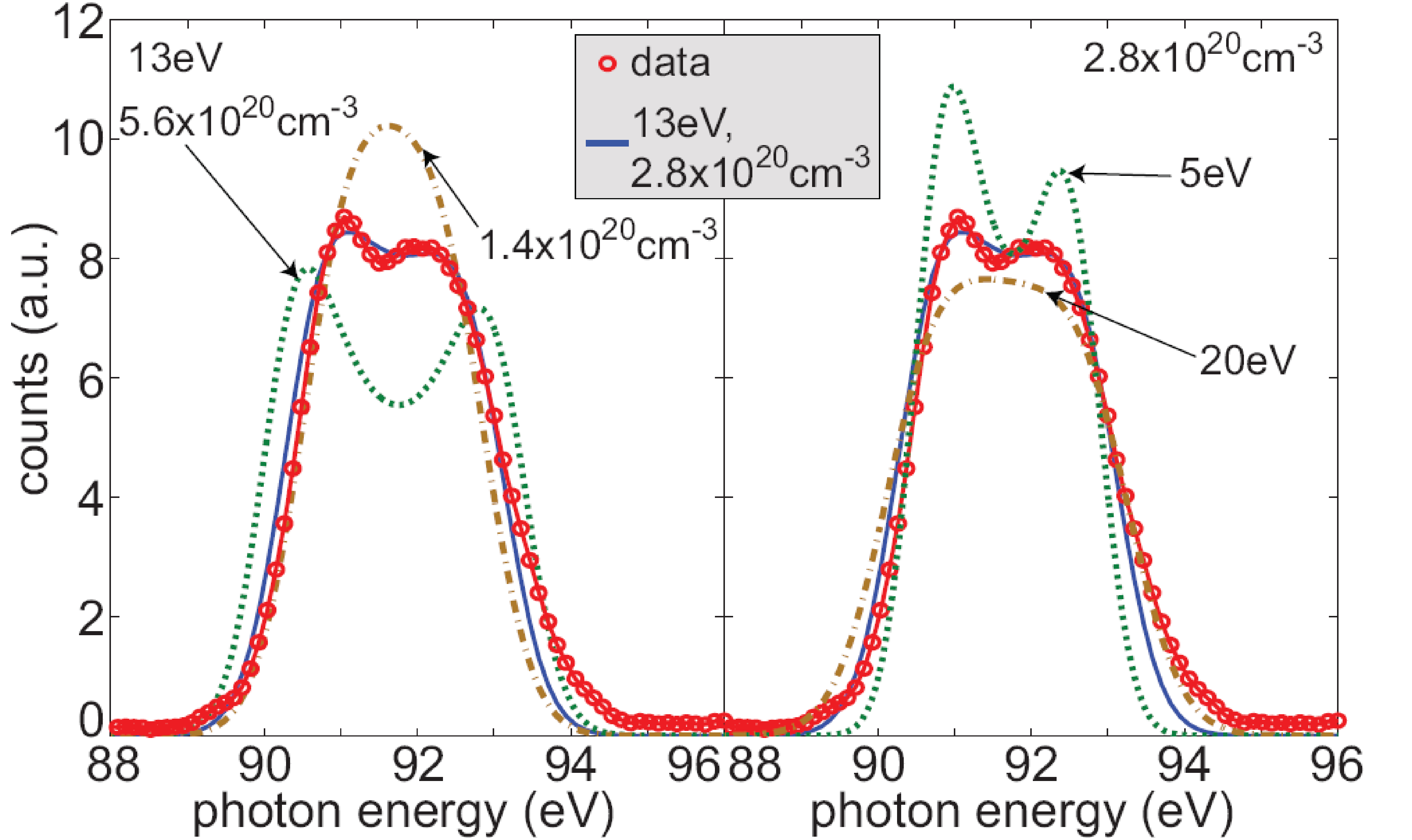
DESY

IOQ Jena

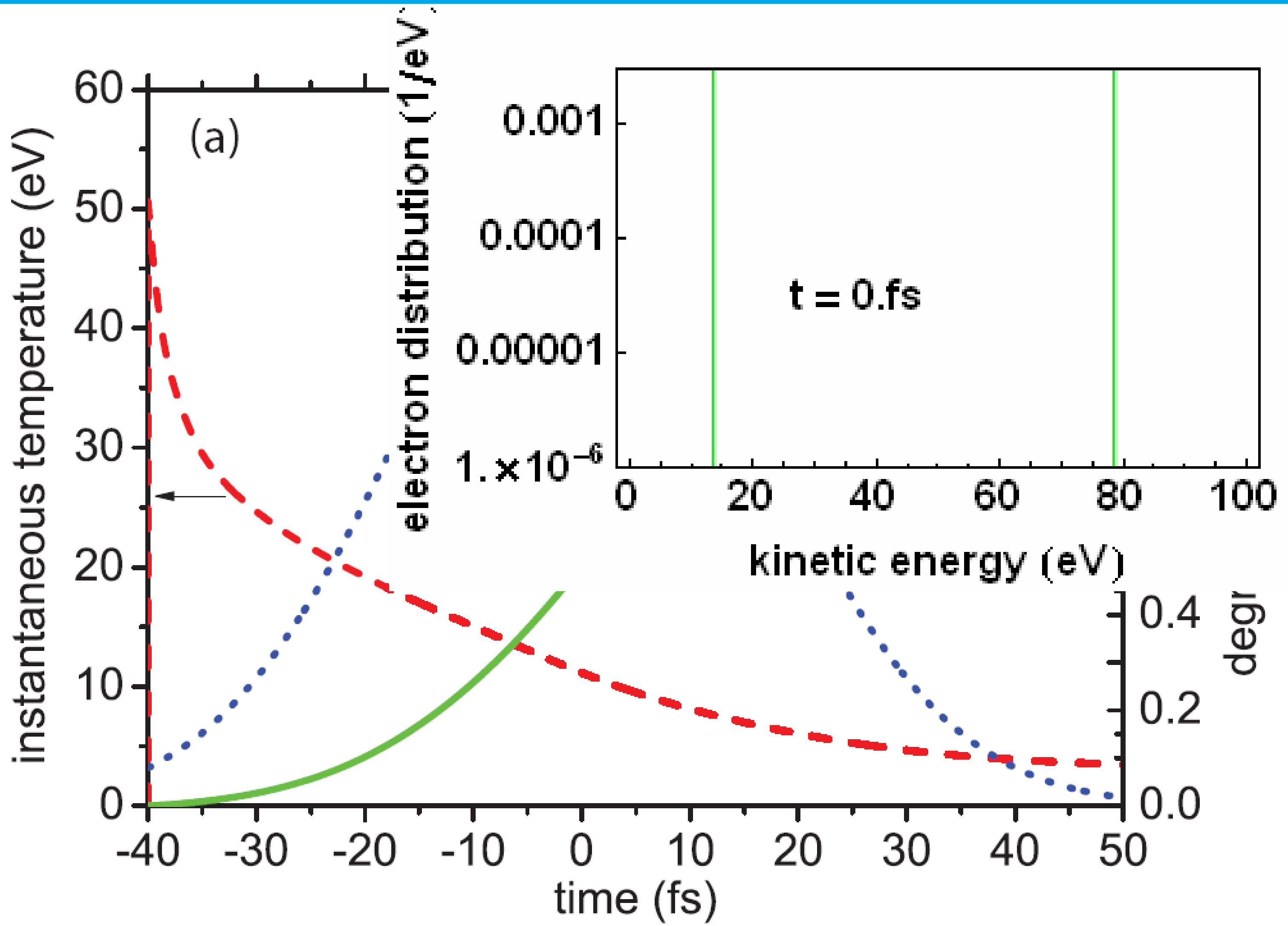
R.R. Fäustlin et al., JINST 5, P02004 (2010)

Recent Results – Self Thomson Scattering

FEL: ~8·10^13 W/cm² heats and scatters during the FEL pulse, integrated over 4500 shots



Self Thomson Scattering probes fs electron thermalization

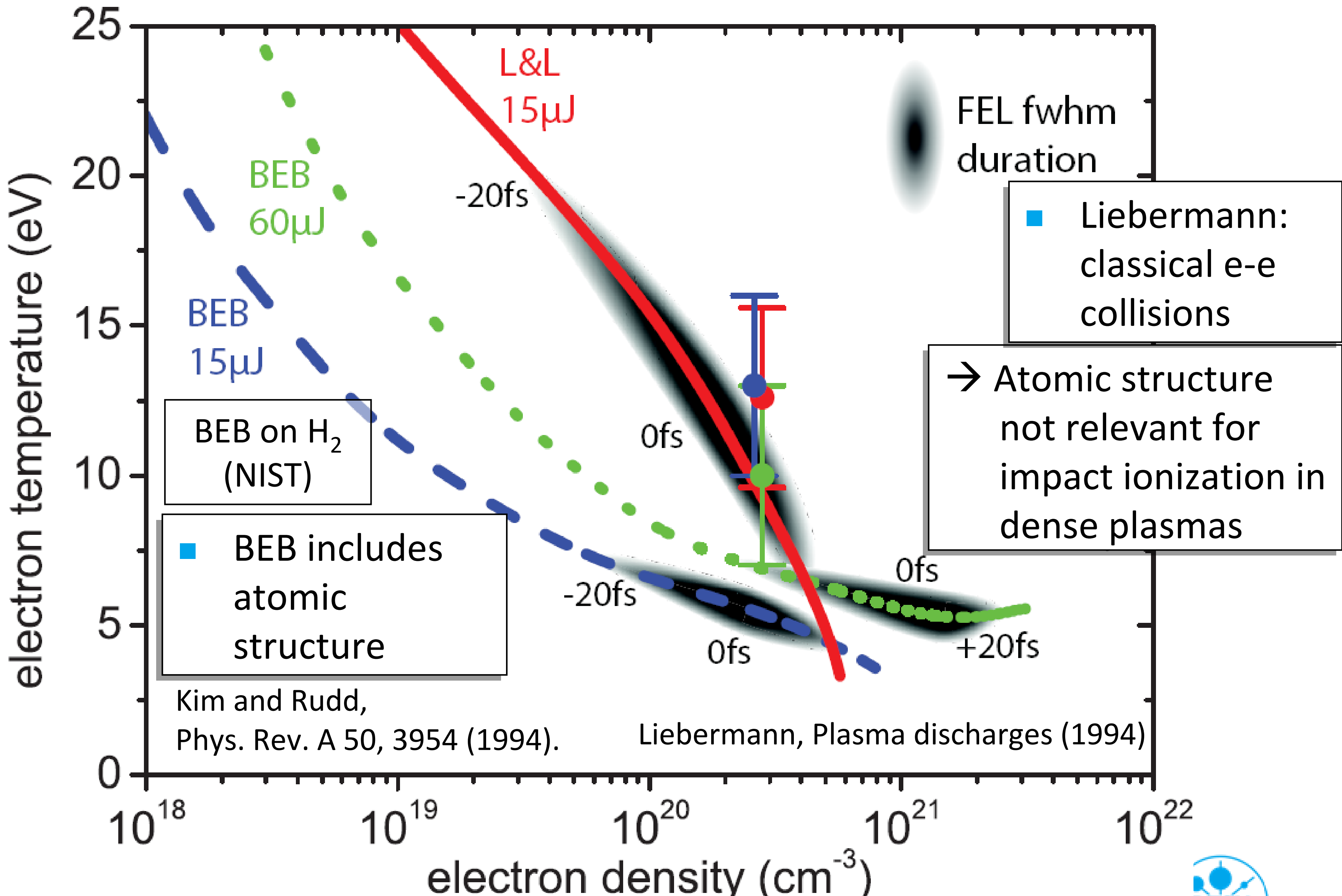


simulation
180 Å box

~10^5 H-atoms

B. Ziaja et al., Eur.Phys.J. D **40** (2006)

Effect on different impact ionization cross sections



R.R. Fäustlin et al., PRL 104, 125002 (2010)

We Observe Non-Equilibrium Plasma

> Reduction of elastic scattering

- Low Z-target: Hydrogen

$$S(k,\omega) = Z_f S_{ee}(k,\omega) + Z^2(1-e^{-2W})S_{ii}(k,\omega)$$

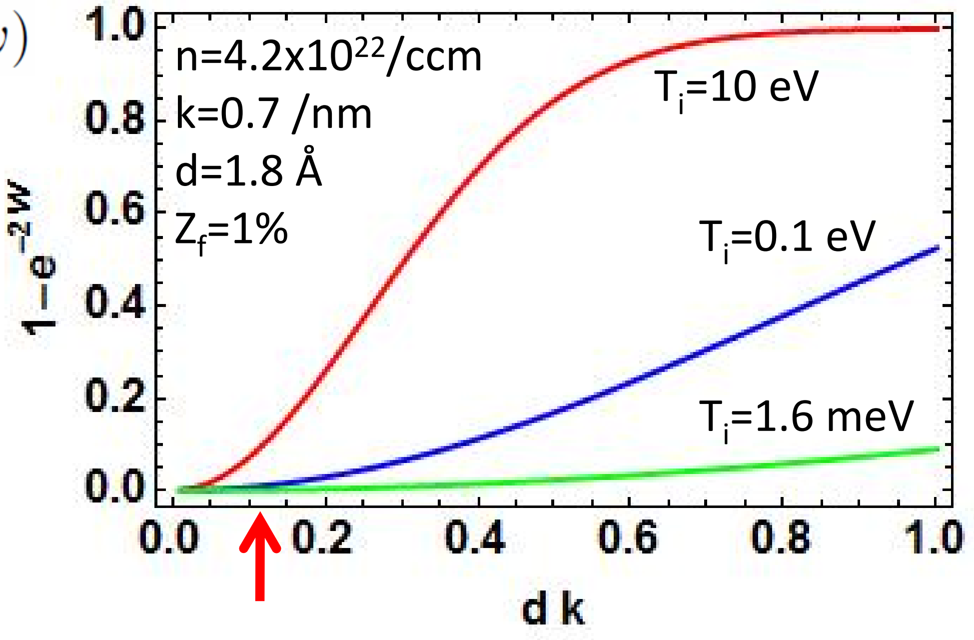
- XUV radiation (k=0.07 /Å)
- Cryogenic Ions (T_i=1.6 meV, 20 K)

> We observe within 40 fs

T_e=13 eV ⟷ T_i<0.1 eV

Debye Waller factor

$$2W = \frac{\pi^2 k^2 \hbar^2}{4Mk_B T_D}\left(\frac{T_i'}{T_D}\right)^2$$



Ravasio et al., PRL **99**, 135006, (2007)
Gregori et al., Phys. Rev. E **74**, 026402, (2006)

People involved (Microfocussing at FLASH)

Bob Nagler[1], Ulf Zastrau[2], Roland R. Fäustlin[3], Sam M. Vinko[1], Thomas Whitcher[1], A. J. Nelson[4], Ryszard Sobierajski[5,6], Jacek Krzywinski[7], Jaromir Chalupsky[8], Elsa Abreu[9], Saša Bajt[3], Thomas Bornath[10], Tomas Burian[8], Henry Chapman[11,12], Jaroslav Cihelka[8], Tilo Döppner[4], Stefan Düsterer[3], Thomas Dzelzainis[13], Marta Fajardo[9], Eckhart Förster[2], Carsten Fortmann[10], Eric Galtier[14], Siegfried H. Glenzer[4], Sebastian Göde[10], Gianluca Gregori[1], Vera Hajkova[8], Phil Heimann[15], Libor Juha[8], Marek Jurek[5], Fida Y. Khattak[16], Ali Reza Khorsand[6], Dorota Klinger[5], Michaela Kozlova[9], Tim Laarmann[3], Hae Ja Lee[17], Richard W. Lee[4], Karl-Heinz Meiwes-Broer[10], Pascal Mercere[18], William J. Murphy[1], Andreas Przystawik[10], Ronald Redmer[10], Heidi Reinholz[10], David Riley[13], Gerd Röpke[10], Frank Rosmej[14], Karel Saksl[19], Romain Schott[14], Robert Thiele[10], Josef Tiggesbäumker[10], Sven Toleikis[3], Thomas Tschentscher[20], Ingo Uschmann[2], Hubert J. Vollmer[4] and Justin S.Wark[1]

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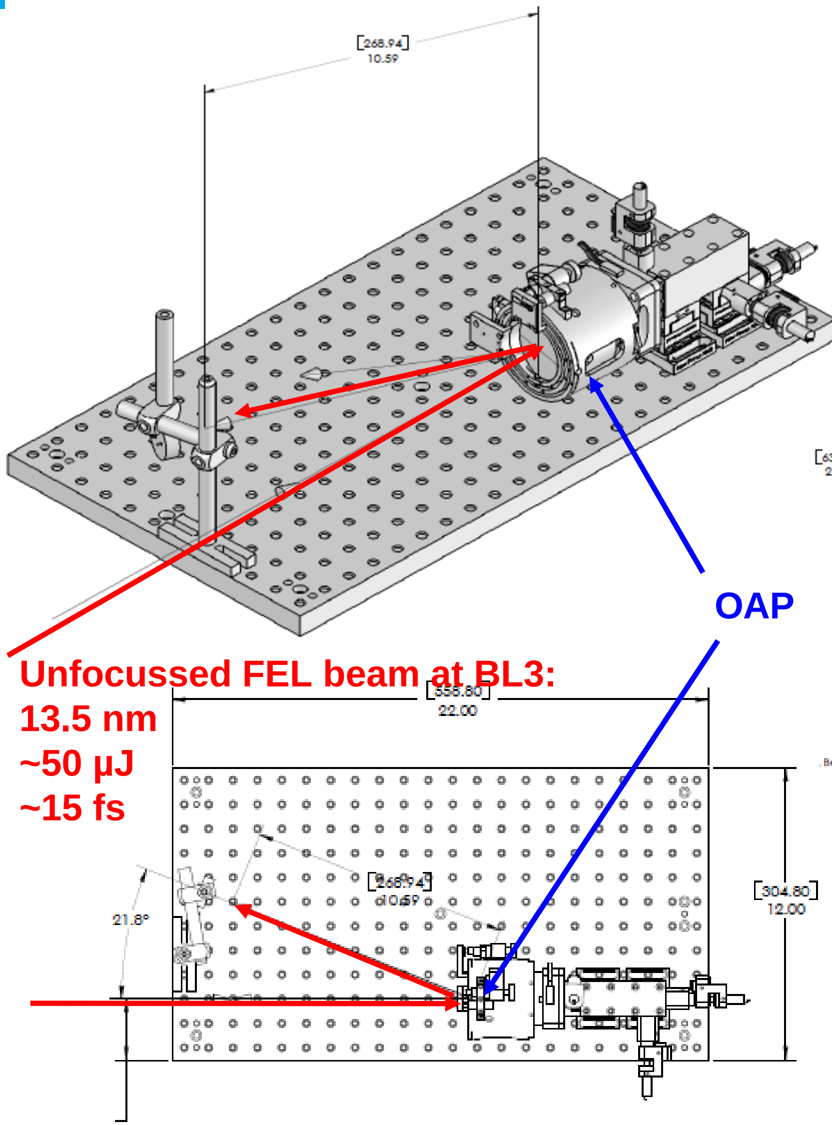
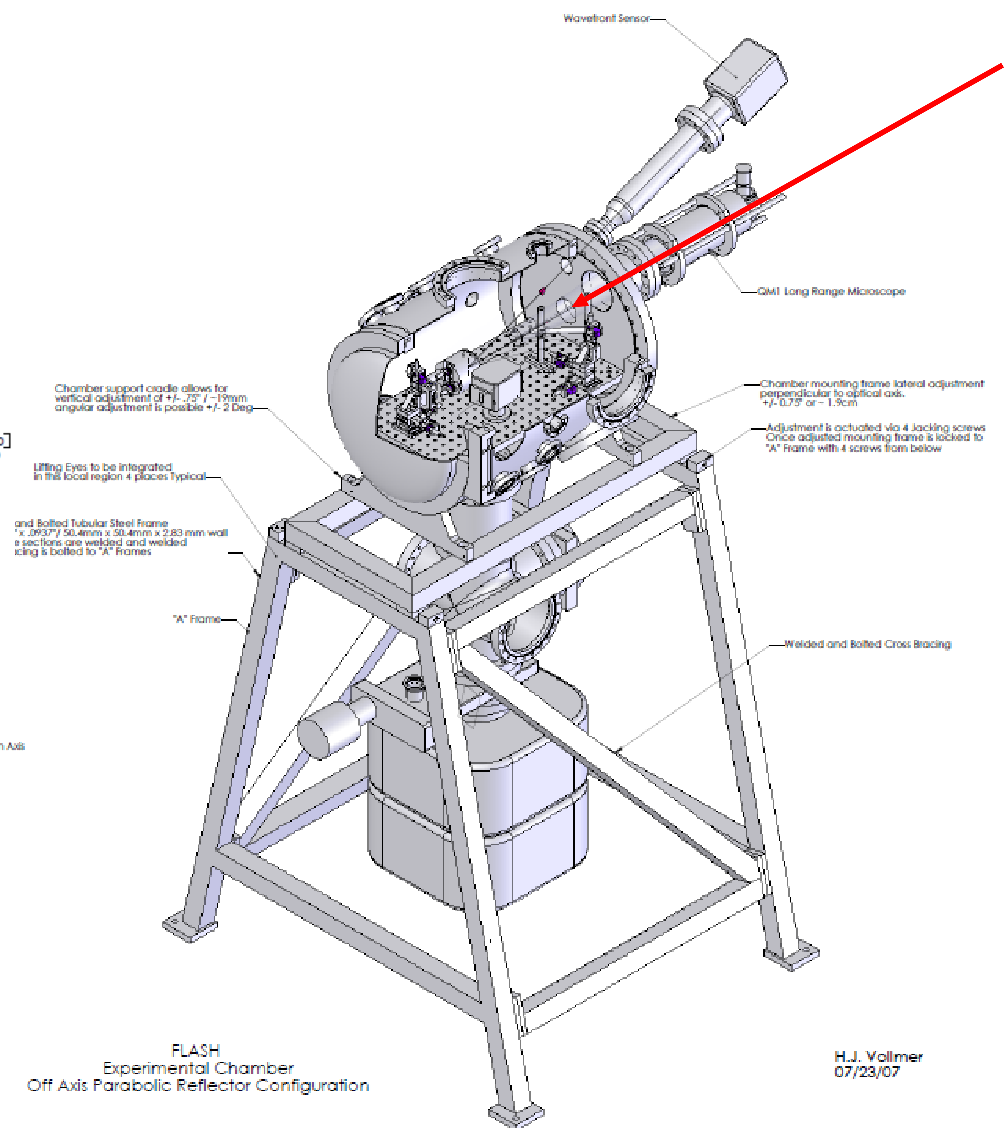
20. European XFEL GmbH, Albert-Einstein-Ring 19, 22761 Hamburg, Germany

Nature Physics 5, 693 (2009)

Microfocusing experiment - Setup



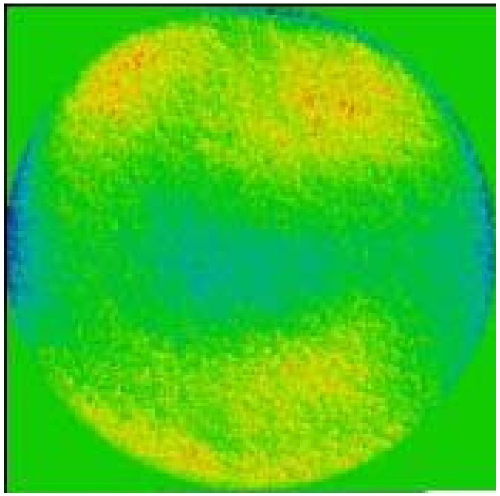


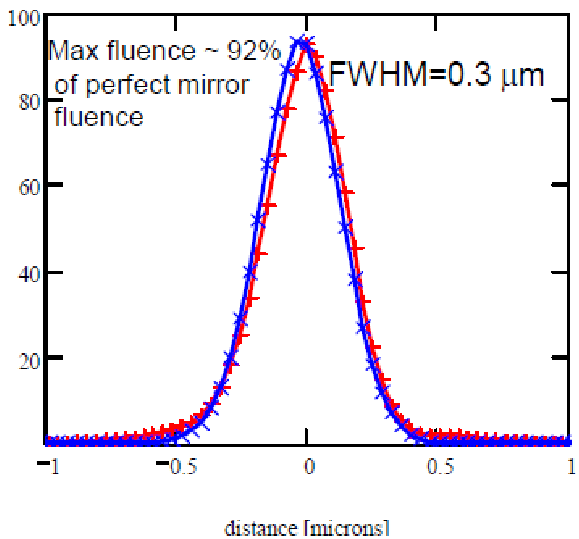
DESY

OAP repolished

Repolished by ASML:

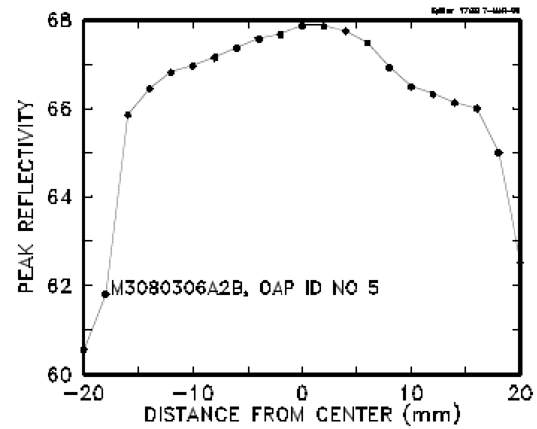
-> now RMS height error is 0.3 nm

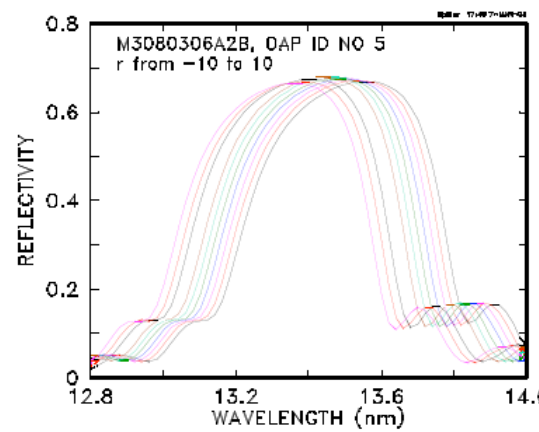




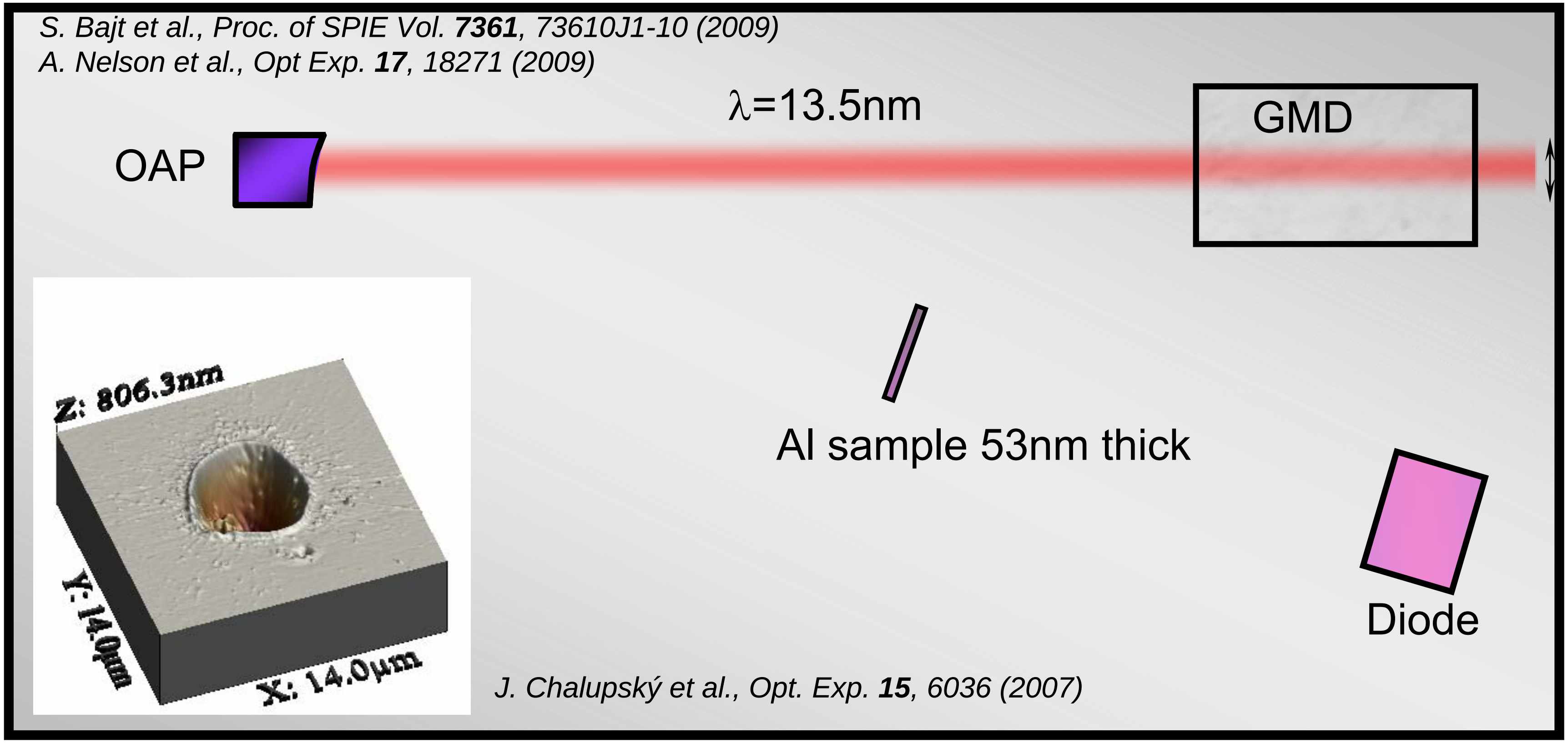
Multilayer coating for 13.5 nm:

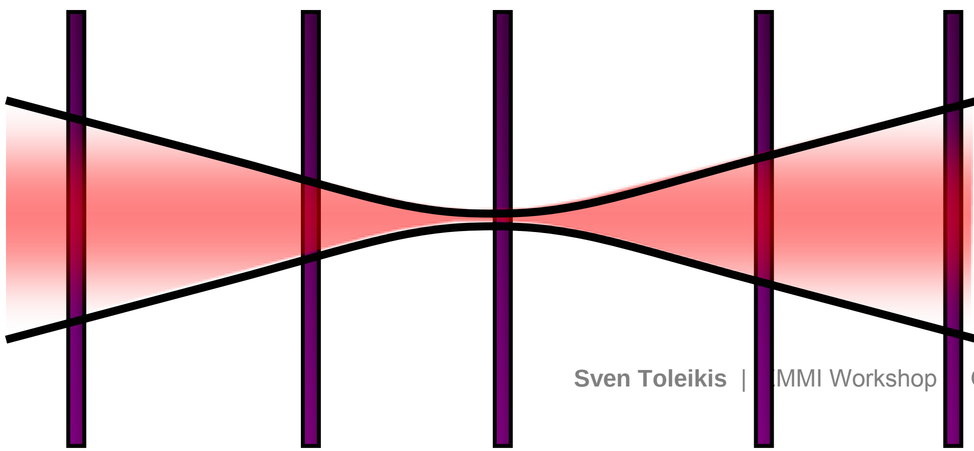
- 50 bilayer period Mo/Si multilayer with a Si capping layer (by LLNL)
- peak reflectivity: 67.9% @ 13.40 nm (measured at ALS, LBNL)





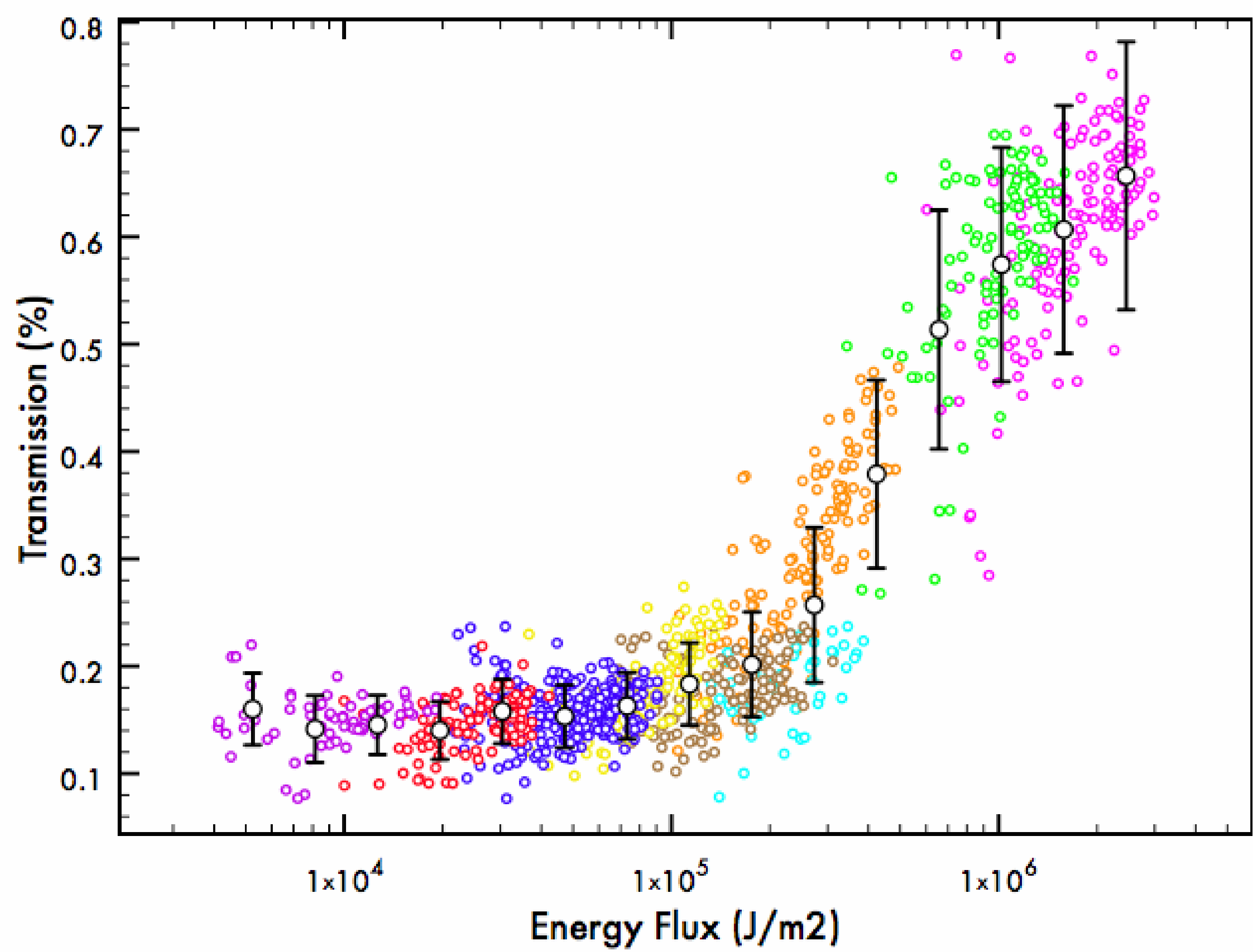
Transparent Aluminium - Experimental Setup @ FLASH





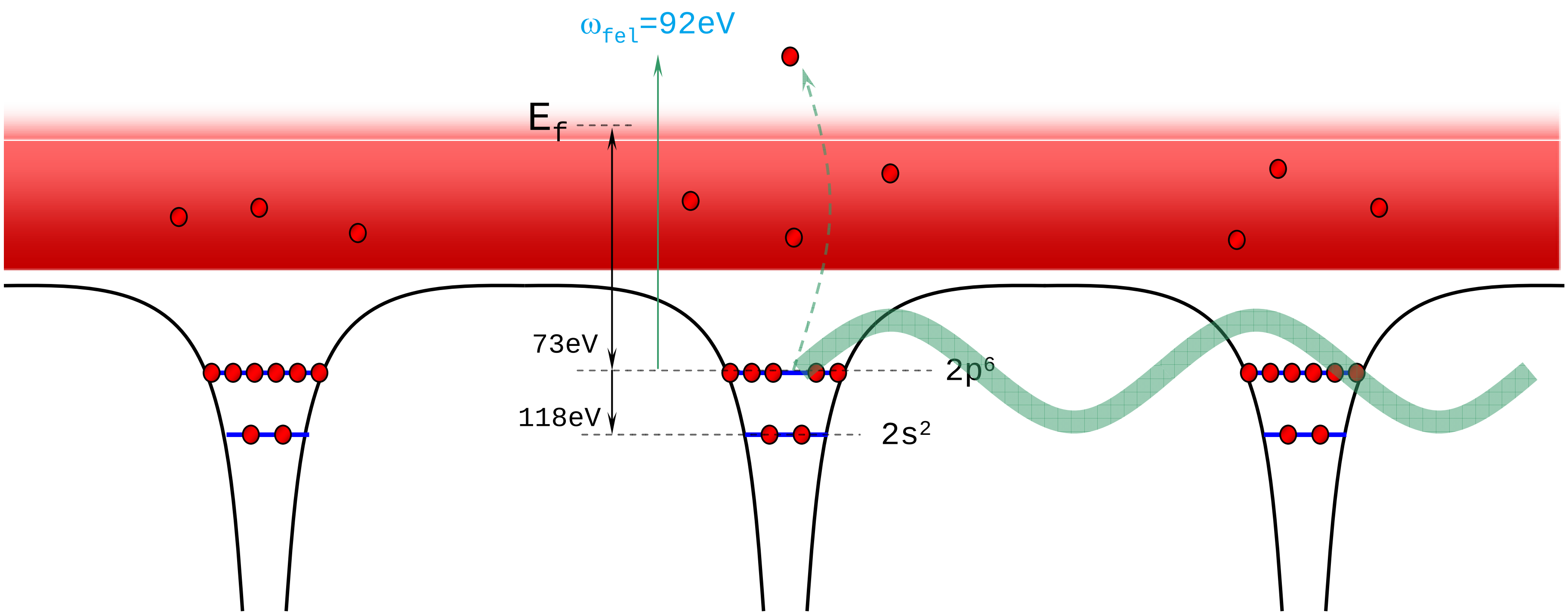
Sample is moved thru focus to vary the intensity from 10^{13}-10^{17} W/cm²

Transmission of FEL at 13.5 nm through 53 nm Al

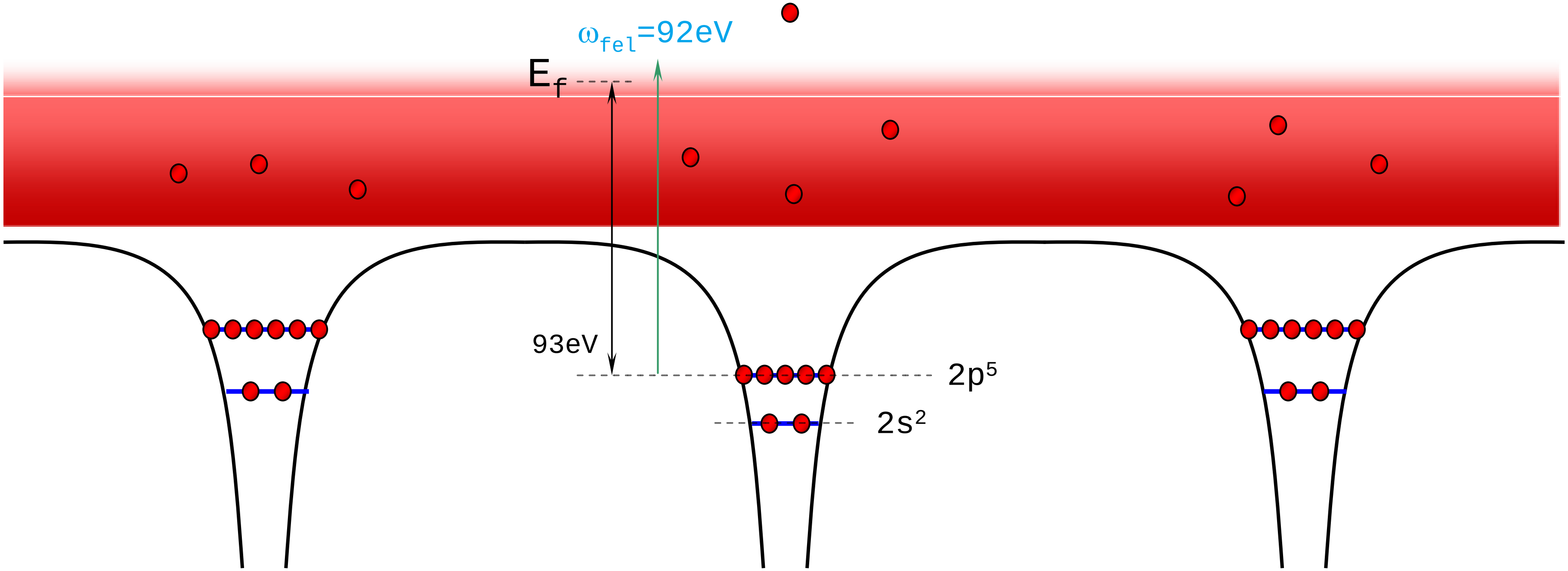


• Colors represent different focal spot conditions

Al after a single photoionization

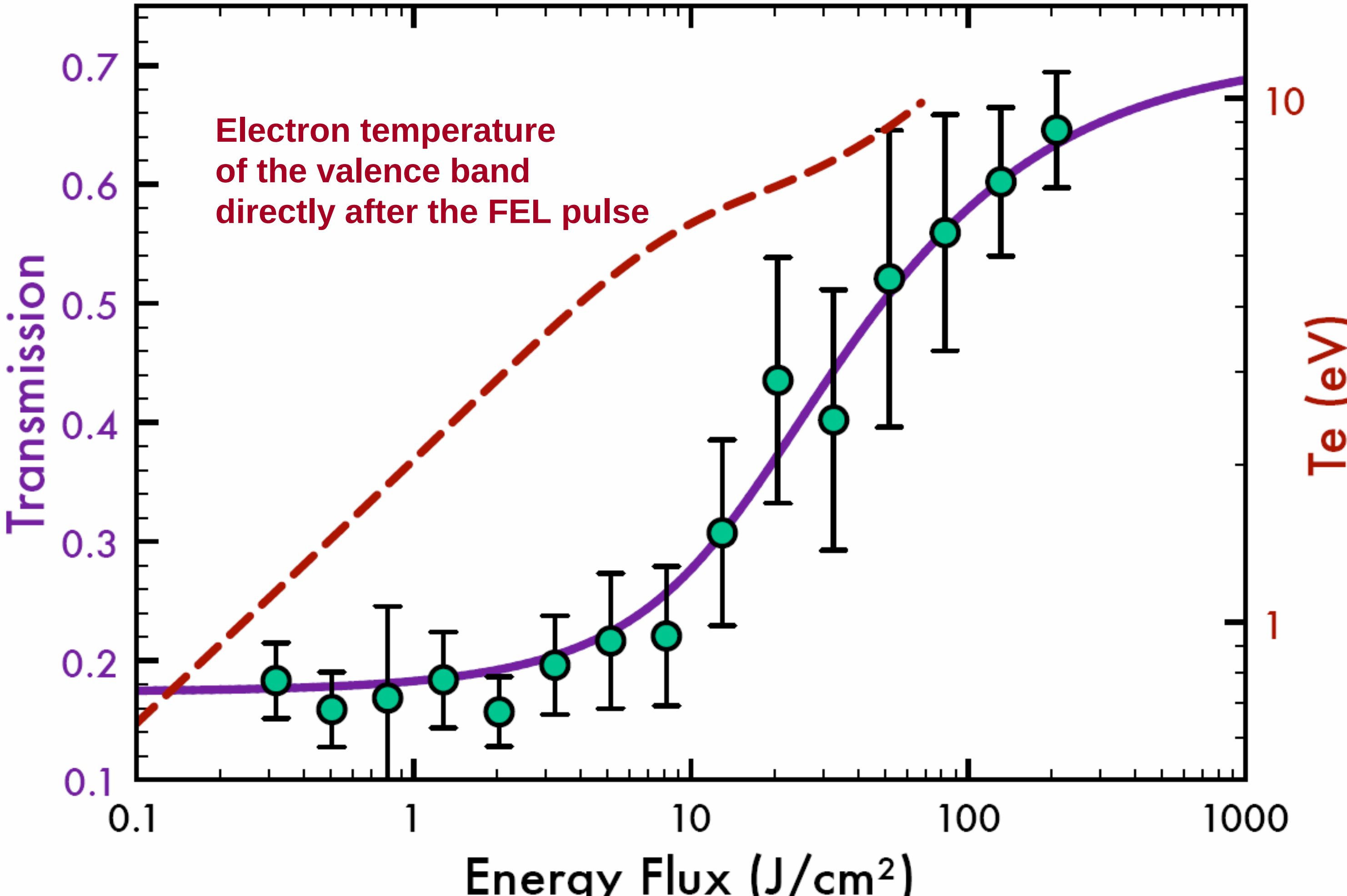


Al L-edge shift after photoionization



- Removal of 1st 2p electron causes shift of n = 2 shell due to loss of the outer screening.
- Further photons cannot ionize the L-shell
- E_f will increase as there are now four electrons in the conduction band (~ 2.4 eV)

Transmission of 53 nm Al including 10 nm oxide layers



(c)

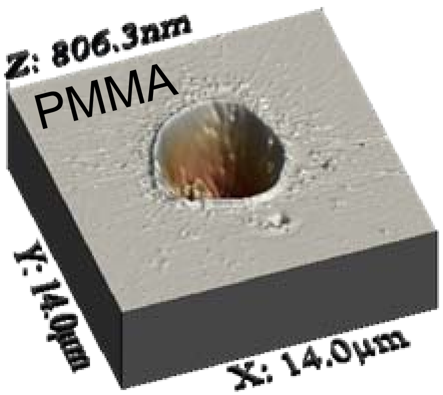
- •Photoionization of L-shell electrons
- •L-shell core hole state
- •L-shell shift
- •Quenching of bound-free absorption
- Recombination time ~40 fs (Auger recombination)
- FEL pulse duration ~30 fs

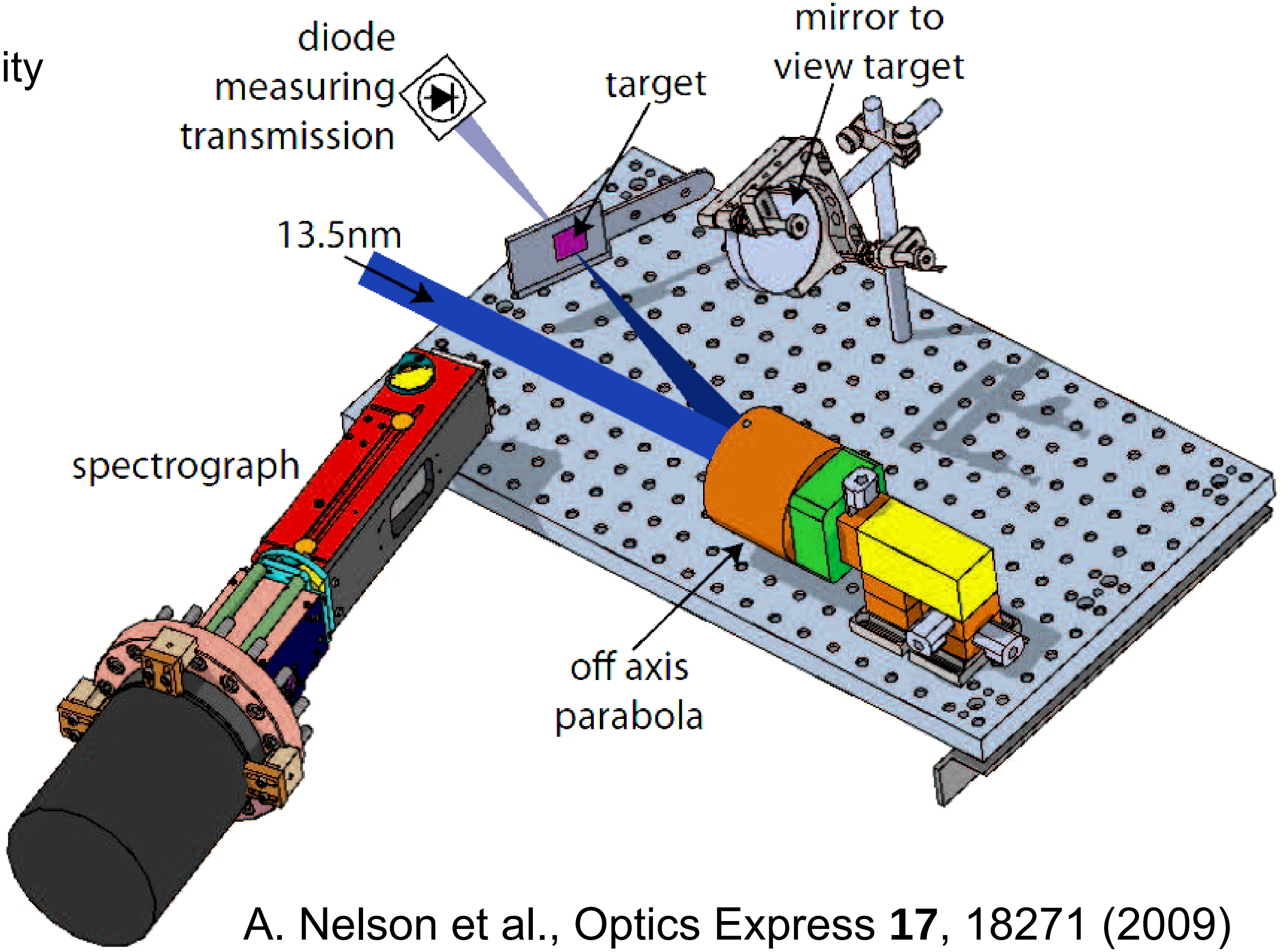
B. Nagler et al., Nature Physics 5, 693 (2009)

Microfocusing FLASH

→ High Energy Density

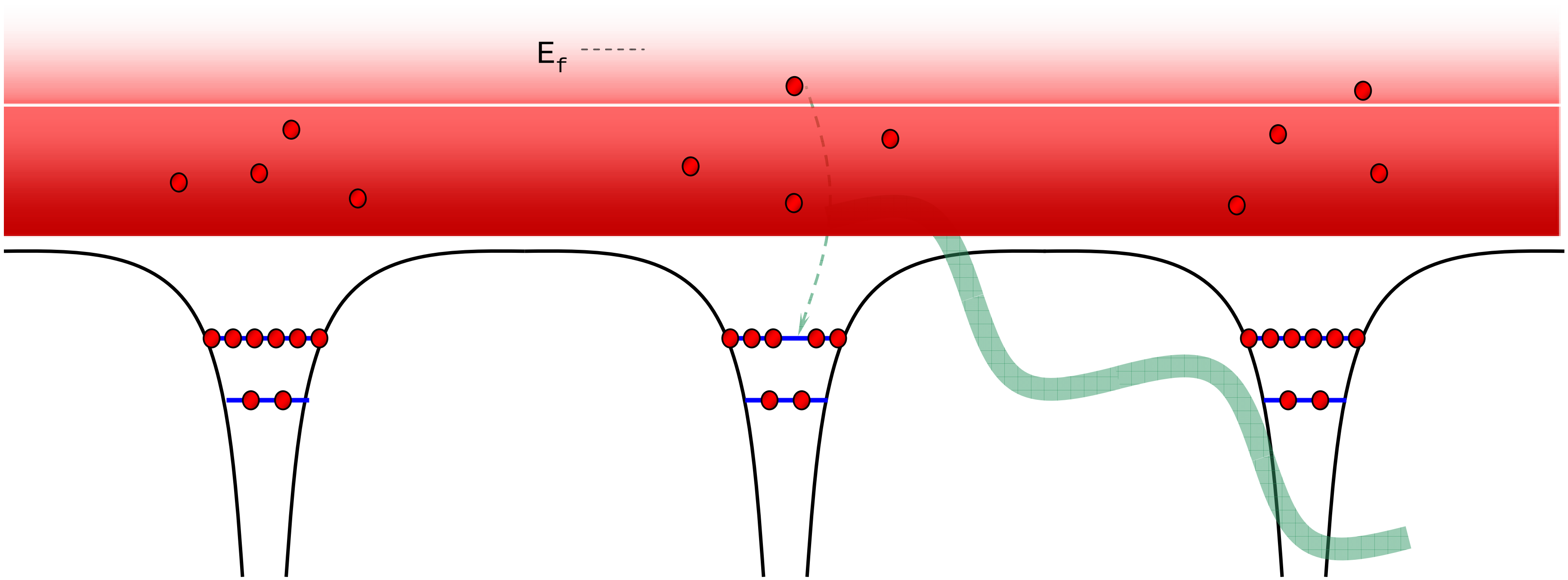
- 10^{17} W/cm^2
- Focus ~0.7 µm





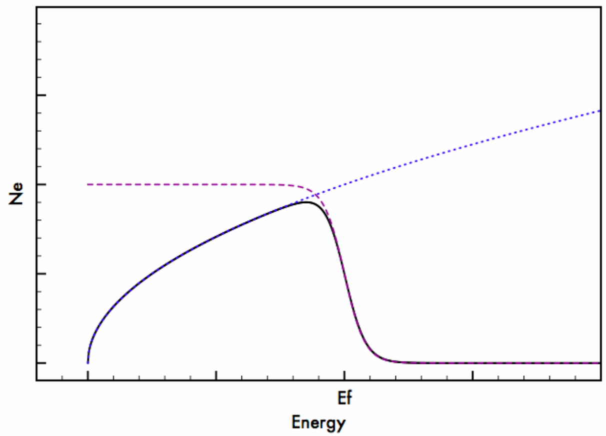
A. Nelson et al., Optics Express **17**, 18271 (2009)

Recombination Time



Recombination time ~40fs

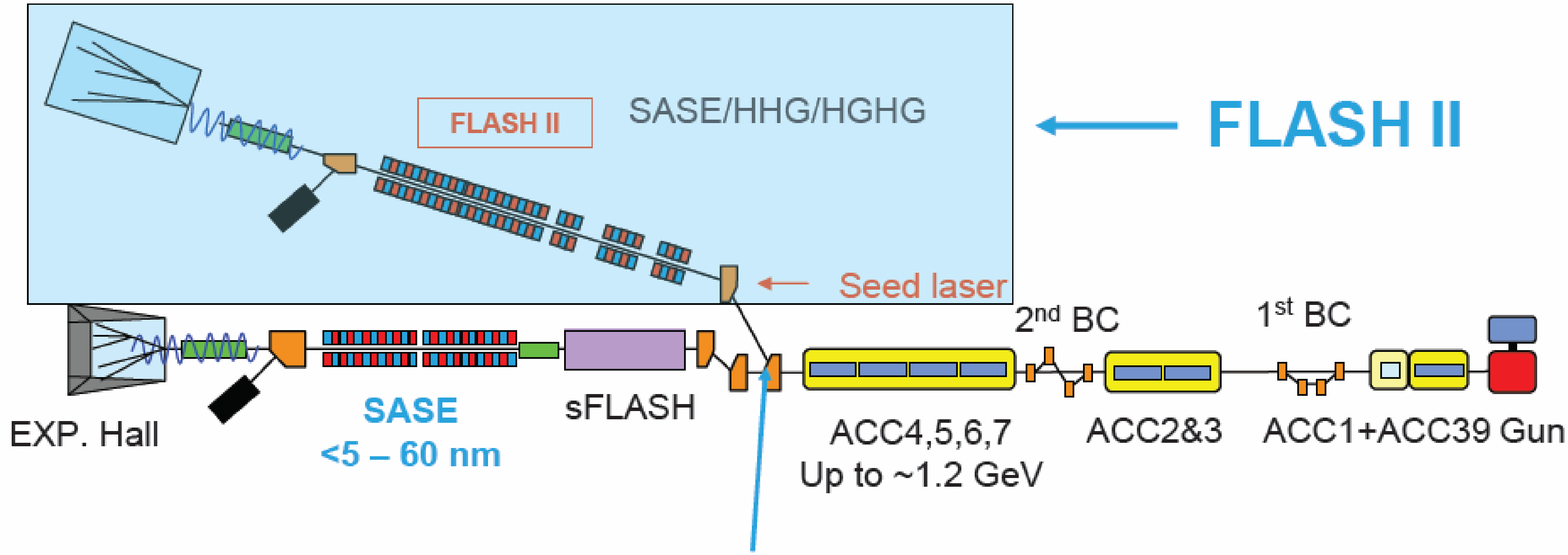
Should see fluorescence before lattice moves.



Fluorescence proportional to ω^3 *g(E)f(E,T)*
(better model under development)

FLASH II

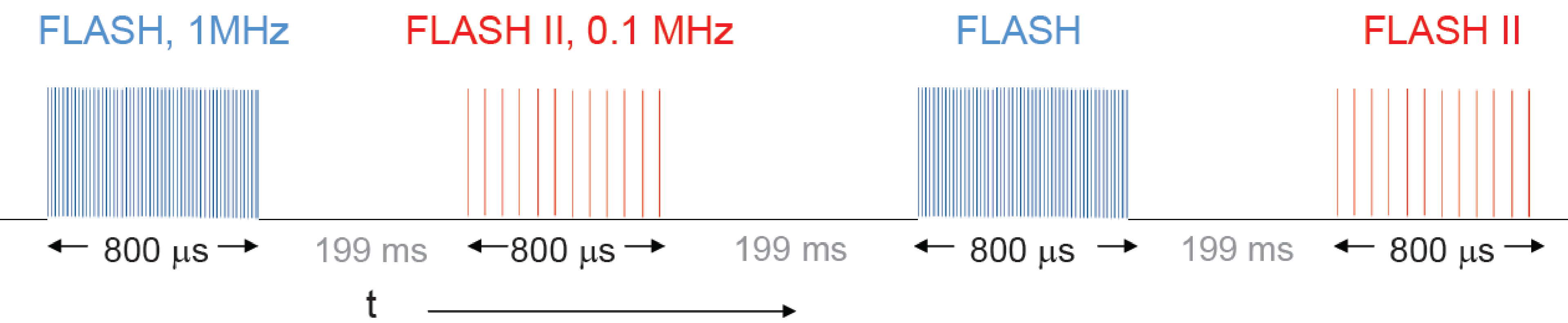
> **Combined DESY/HZB proposal for a 2nd undulator line (FLASH II)**



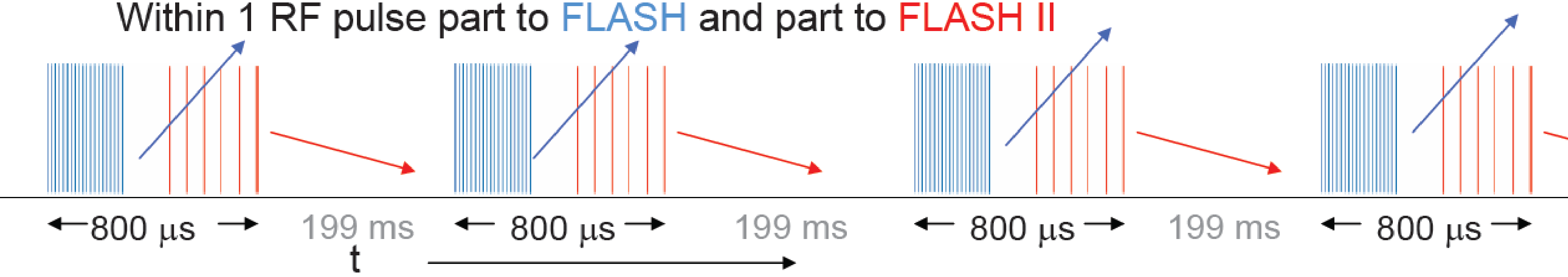
- Separation FLASH and FLASH II behind last accelerator module
- Tunability of FLASH II by undulator gap change
- Extend user capacity with SASE and HHG/HGHG seeding
- Use of existing infrastructure up to last accelerating module
- New undulator tunnel, new experimental Hall
- Decision on Funding in 2010

Beamline switching: FLASH + FLASH II

From pulse to pulse to FLASH or FLASH II



Within 1 RF pulse part to FLASH and part to FLASH II



Expected FLASH performance after upgrade

	with harmonic module					without*
Bunch charge, nC	1	0.5	0.25	0.1	0.02	0.5-1
Wavelength, nm	6.5					6
Beam energy, MeV	1000					1000
Peak current, kA	**2.5**	**2**	**1.7**	**2.6**	**2.5**	1.3-2.2
Slice emmitance,mm-mrad	**1-1.5**	**0.7-1.5**	**0.5-1.2**	**0.5-1**	**0.5-0.7**	1.5-3.5
Saturation length, m	**13-15**					22-32
Energy in the rad. pulse, µJ	700-1200	400	200	30	3	50-150
Radiation pulse duration FWHM, fs	**100-200**	**35-150**	**25-100**	**3-5**	**2-3**	15-50
Averaged peak power, GW	3-5				1	2-4
Spectrum width, %	0.4-0.5			0.3-0.4		0.4-0.6
Coherence time, fs	4-5			-	-	-

*) E.L.Saldin at al, Expected properties of the radiation from VUV-FEL at DESY, TESLA FEL 2004-06, 2004.

S2E simulations (Igor Zagorodnov).

Summary

- We have made transparent aluminum using FLASH – homogenous heating of Al to the warm dense matter state
- The transparency is caused by ionization and depletion of L-shell electrons - further ionization (and absorption) is inhibited by the L-shell increasing in energy above the photon energy, due to reduced shielding
- Plasma spectroscopy is an important tool to get information on different time scales -> future work: time-resolved measurements (w/ X-ray streak camera)
- WDM diagnostic established – Thomson scattering works with unprecedent signal-to-noise ratio
- Investigation of ultrafast non-equilibrium collective dynamics
- Much remains to be understood about the warm dense matter state:
  map complete time evolution from t=0 fs to t=~ns
- More possibilities – upgrades in 2010 (accepted FLASH proposals for 2010/11)
- XFELs: shorter wavelength
  - -> high densities can be explored
  - -> investigation of higher Z elements
  - -> hollow ion creation (K-shell)


Thank you for your attention