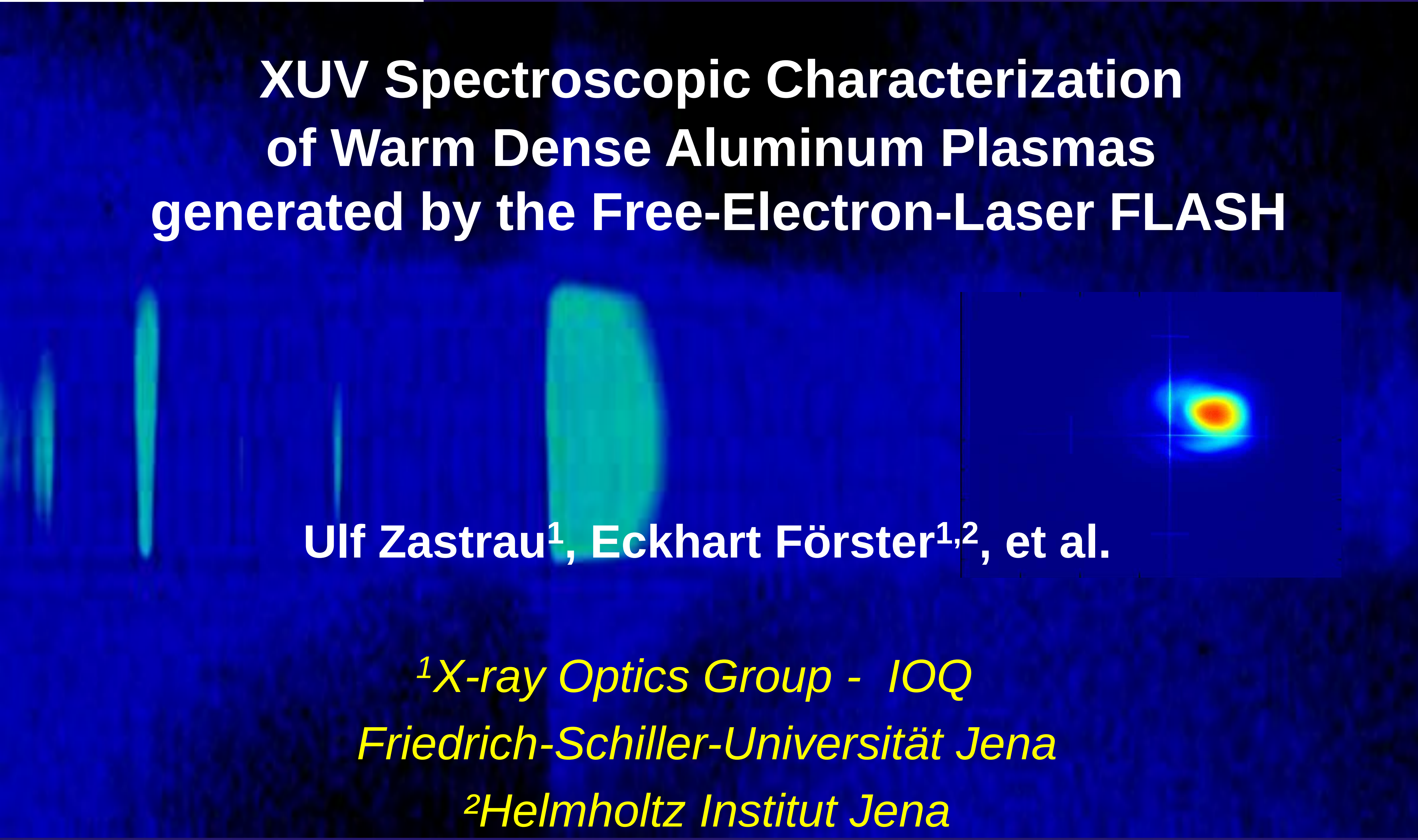
4th EMMI Workshop Darmstadt, May 2-4, 2011



XUV Spectroscopic Characterization of Warm Dense Aluminum Plasmas generated by the Free-Electron-Laser FLASH

Ulf Zastrau[1], Eckhart Förster[1,2], et al.

[1]X-ray Optics Group - IOQ
Friedrich-Schiller-Universität Jena
[2]Helmholtz Institut Jena

Peak Brightness Collaboration

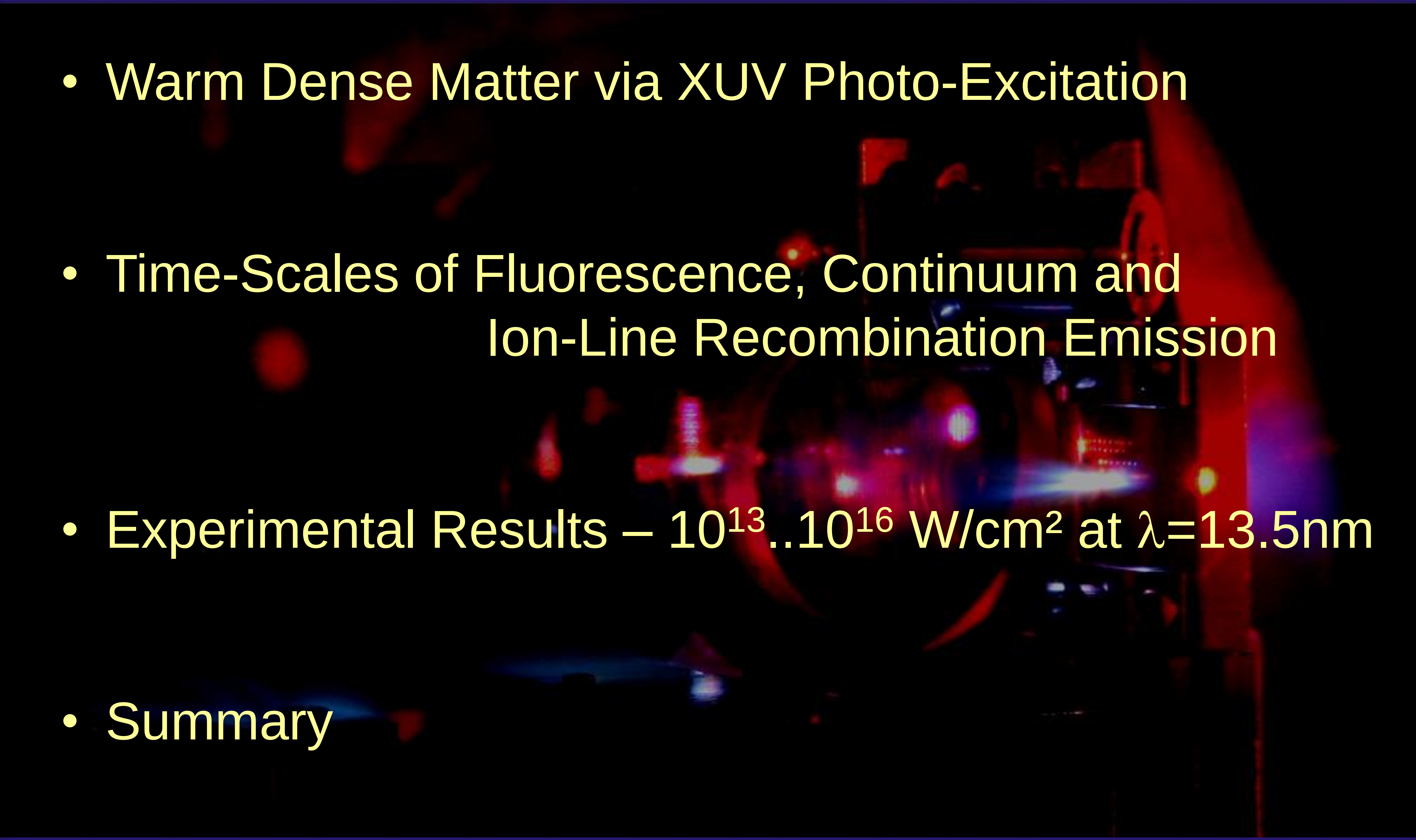
BMBF
FSP 301
“FLASH”

Subdivision „PBC Plasma“
…contribunting to the presented results

J. Andreasson, S. Bajt, T. Burian, J. Chalupsky, H.N. Chapman, J. Cihelka, D. Doria, T. Doppner, S. Dusterer, T. Dzelzainis, R.R. Faustlin, C. Fortmann, E. Forster, E. Galtier, S.H. Glenzer, S. Gode, G. Gregori, J. Hajdu, V. Hajkova, P.A. Heimann, R. Irsig, L. Juha, M. Jurek, J. Krzywinski, T. Laarmann, H.J. Lee, R.W. Lee, B. Li, S. Mazevet, K.-H. Meiwes-Broer, J.P. Mithen, B. Nagler, A.J. Nelson, A. Przystawik, R. Redmer, D. Riley, F. Rosmej, R. Sobierajski, F. Tavella, R. Thiele, J. Tiggesbaumker, S. Toleikis, T. Tschentscher, L. Vysin, J.S. Wark, T.J. Whitcher, S. White, U. Zastrau

+ subsequent talk: N. Medvedev, CFEL

Outline



- Warm Dense Matter via XUV Photo-Excitation
- Time-Scales of Fluorescence, Continuum and Ion-Line Recombination Emission
- Experimental Results – $10^{13}..10^{16}$ W/cm² at λ=13.5nm
- Summary

Warm Dense Matter

Condensed Matter <> ***Warm Dense Matter*** <> Hot Dense Matter

$E_{therm} \sim E_{Fermi}$

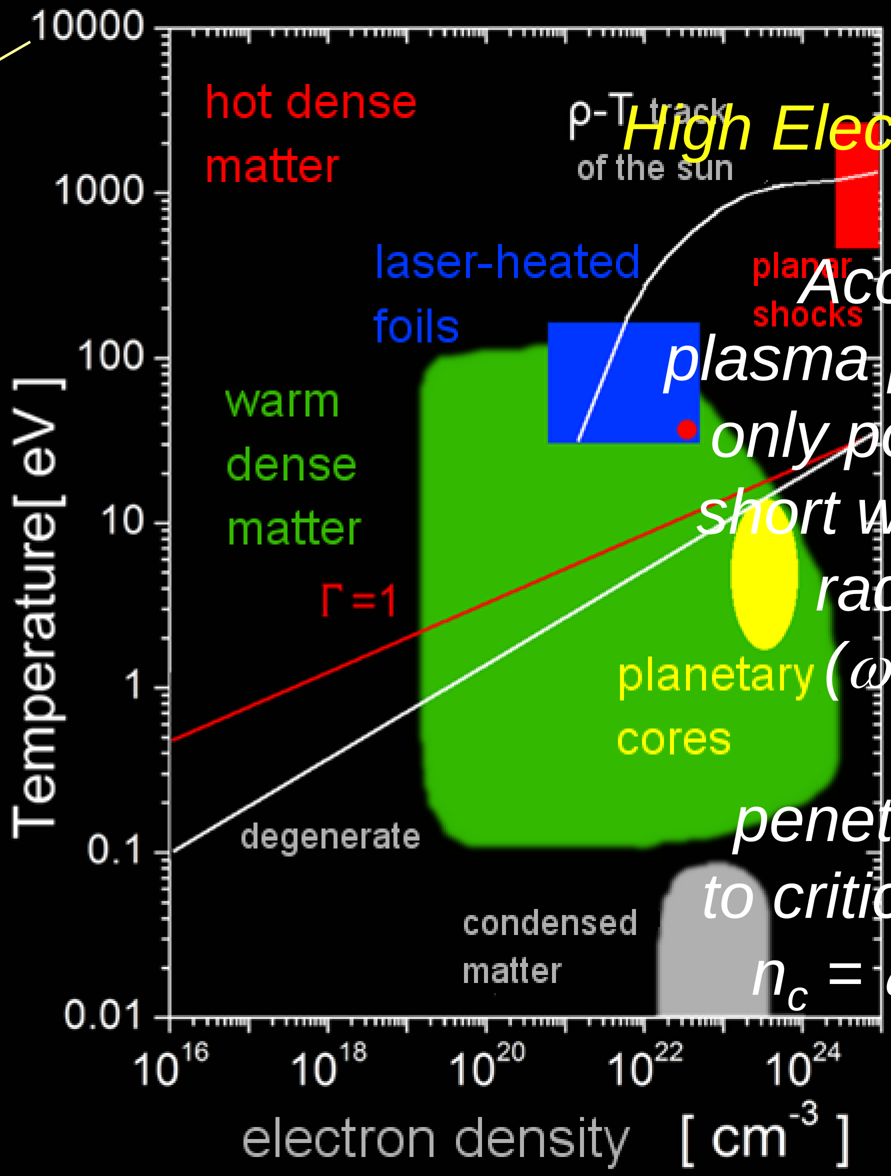
1..100 eV

$\rho_{WDM} \approx \rho_{solid}$

strong coupling

$\Gamma \geq 1$

$E_{coulomb} \sim E_{therm}$



High Electron Density:

Access of plasma parameters only possible by short wavelength radiation $(\omega > \omega_P)$

penetration up to critical density $n_c = \omega^2 \varepsilon_0 m/e^2$

after R.W. Lee, Livermore

FLASH User facility in Hamburg

Wavelength range of the fundamental	13 - 47 nm (from fall 2007: 6.5 nm)
Average pulse energy	up to 100 μJ
Pulse duration	10 - 50 fs

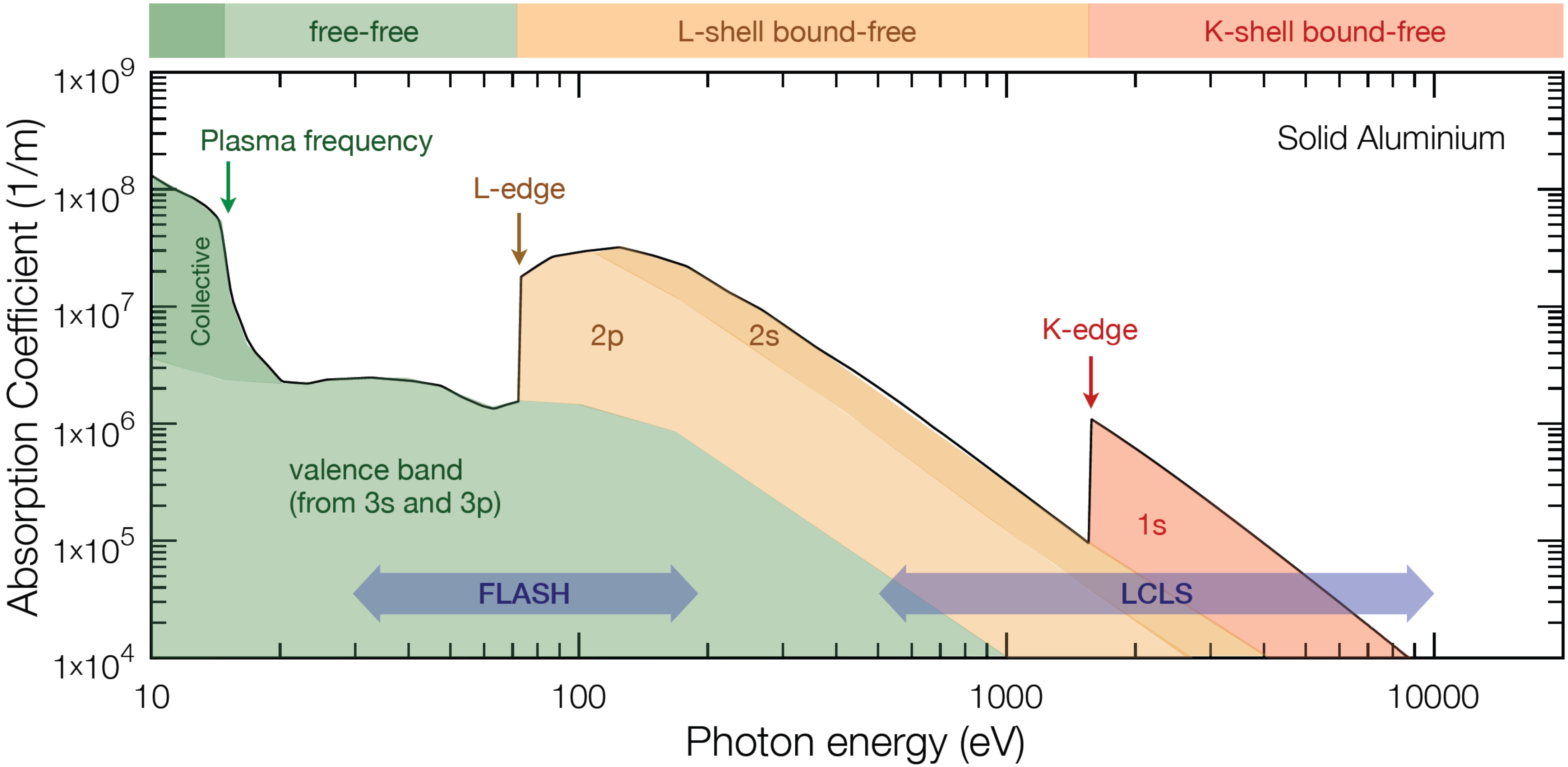
W. Ackermann *et al.*, Nature Photonics 1, 336 (2007)

4th generation light source

Experimental Hall

since 2005

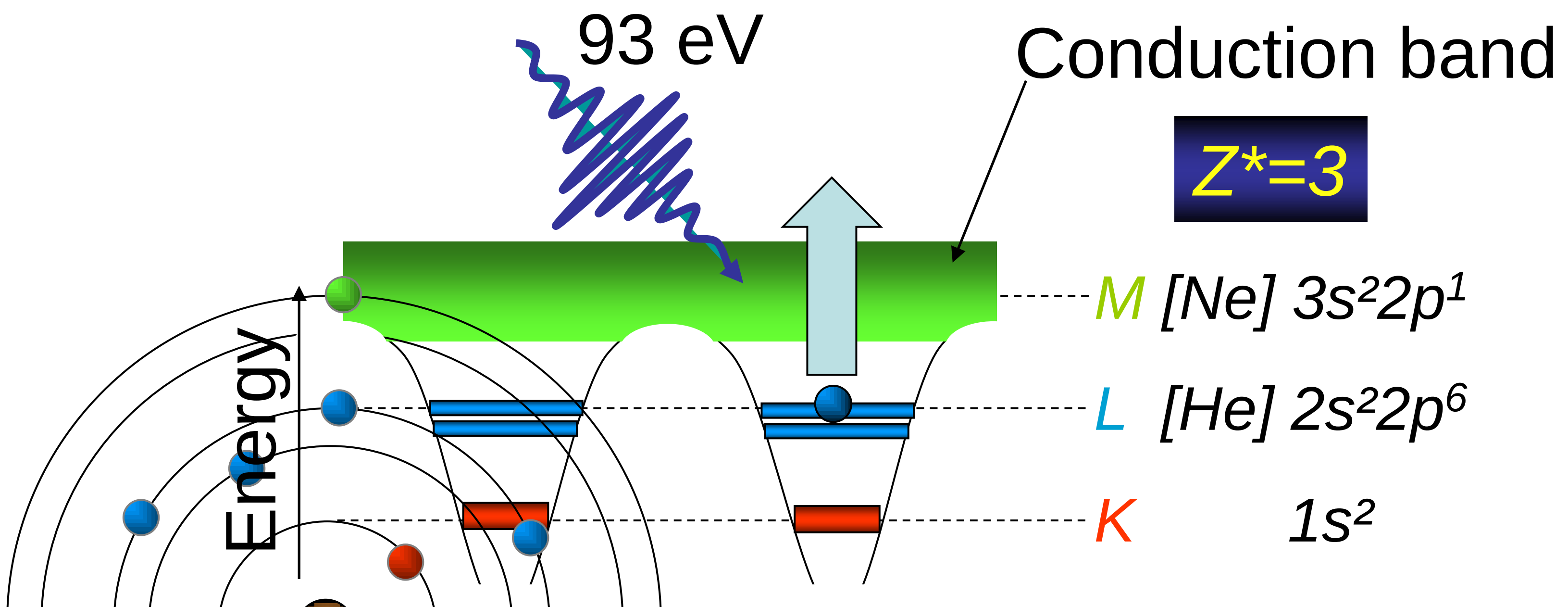
Aluminum excitation by FELs

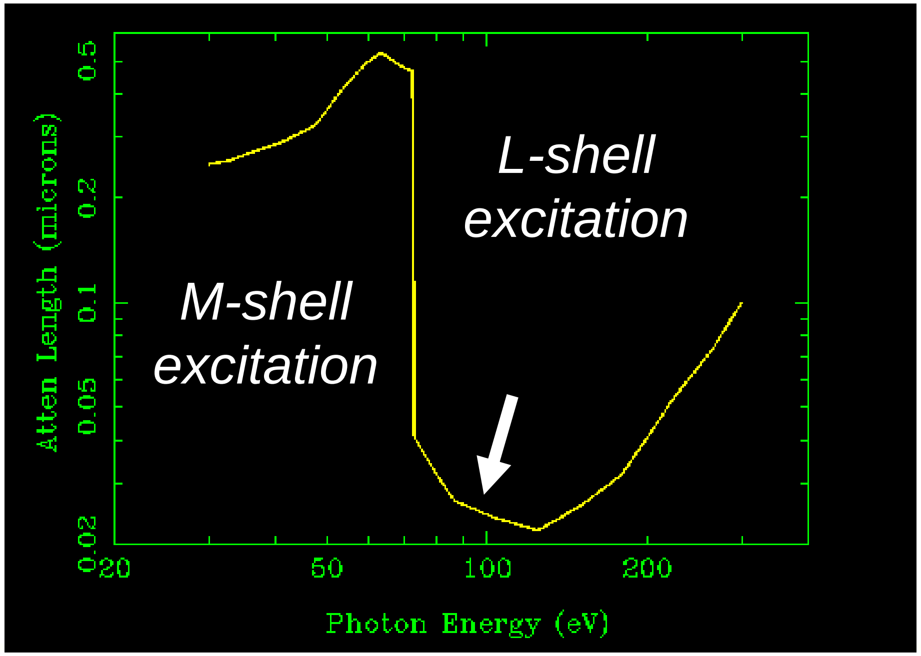


Courtesy of S.M. Vinko (Master Thesis, Oxford 2011)

XUV photo absorption $E > E_{L\text{-edge}}$

Aluminum

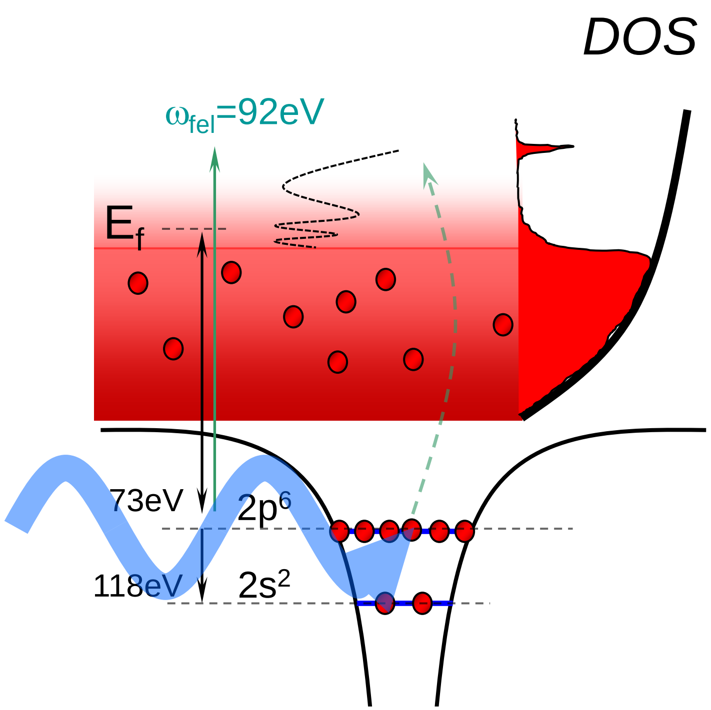




Absorption coefficient above L-edge (72 eV):
μ (L) / μ (M) ~ 10

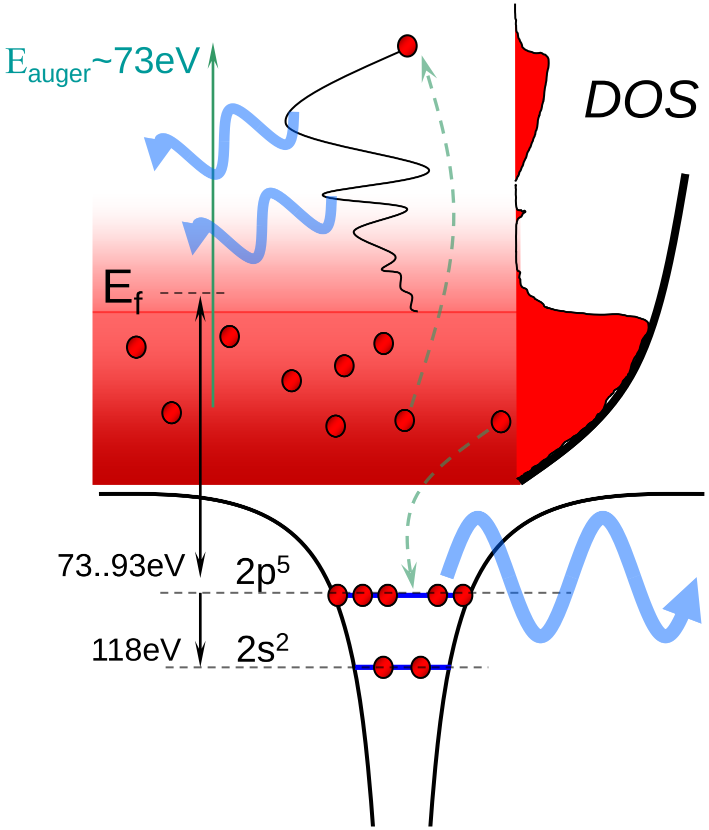
Al plasma excitation processes

t = 0..10 fs
XUV Photo-ionization



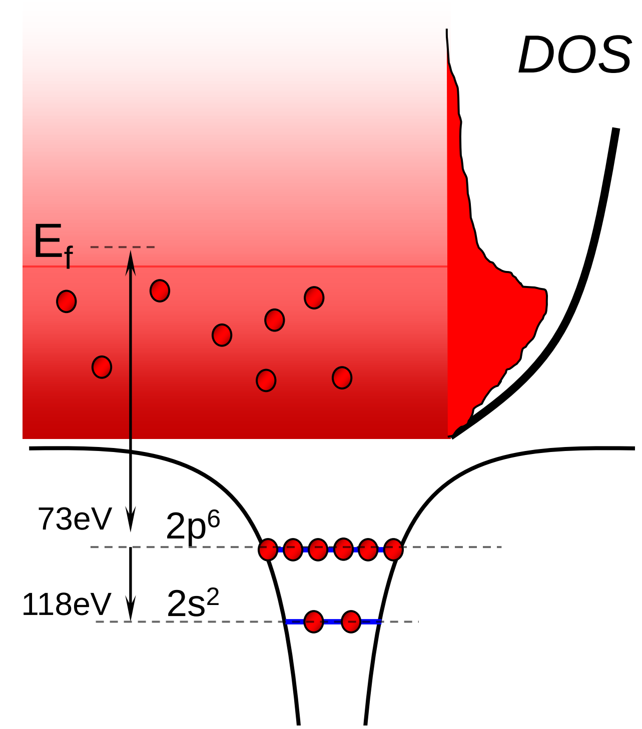
Free excited electrons have
~ 20 eV above E_f
→ Conduction band
is slightly heated ~ 1 eV

t = 0..60 fs
L-hole recombination



Auger & radiative decay
→ fast Auger electrons &
bremsstrahlung ($j \sim n_e^2$)

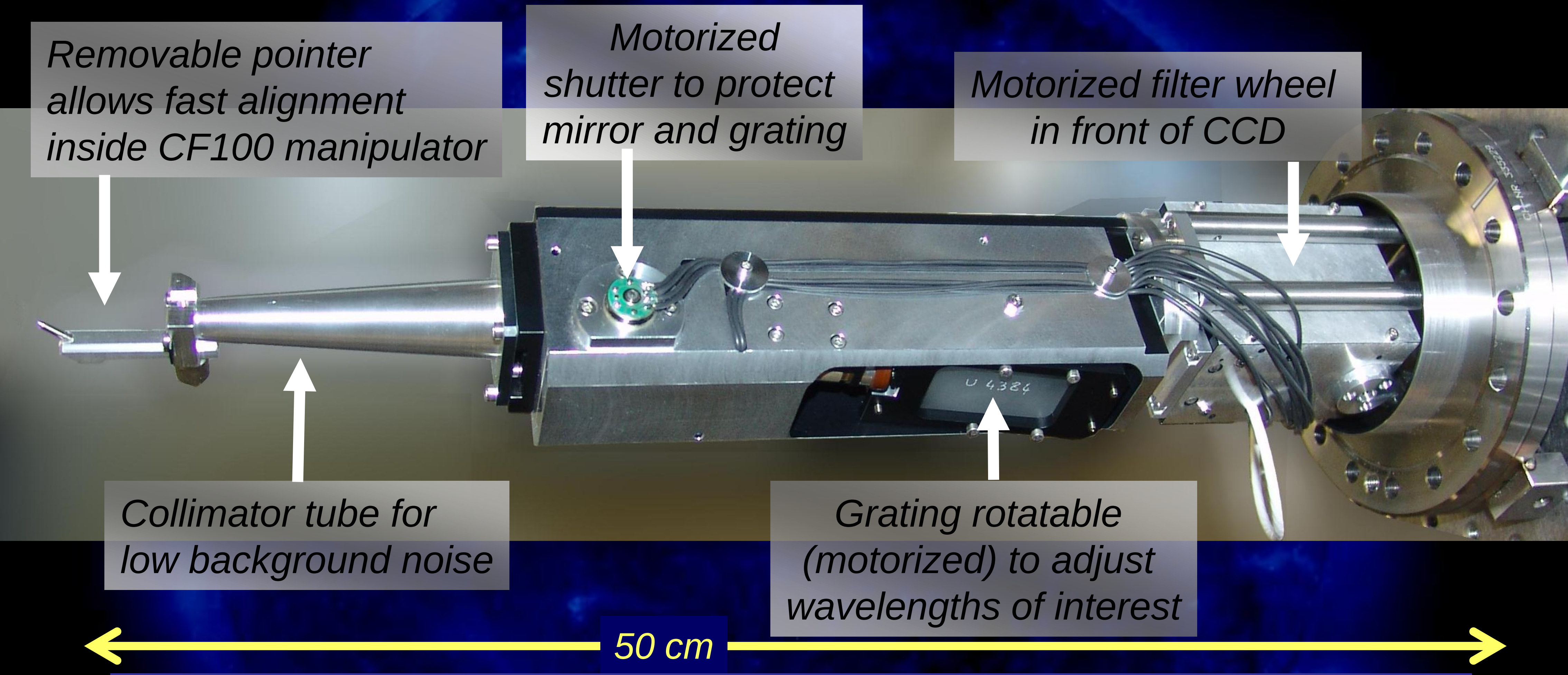
t ~ *ps*
Lattice thermalization



e^--gas in equilibrium:
thermal ionization,
hydrodynamic expansion,
ion-line emission

Reflexion Grating Spectrograph *HiTRaX* -

High Transmission & Resolution Spectrograph of XUV light



Removable pointer allows fast alignment inside CF100 manipulator

Motorized shutter to protect mirror and grating

Motorized filter wheel in front of CCD

Collimator tube for low background noise

Grating rotatable (motorized) to adjust wavelengths of interest

50 cm

Instrument Dispersion: 0.0186 nm per pixel

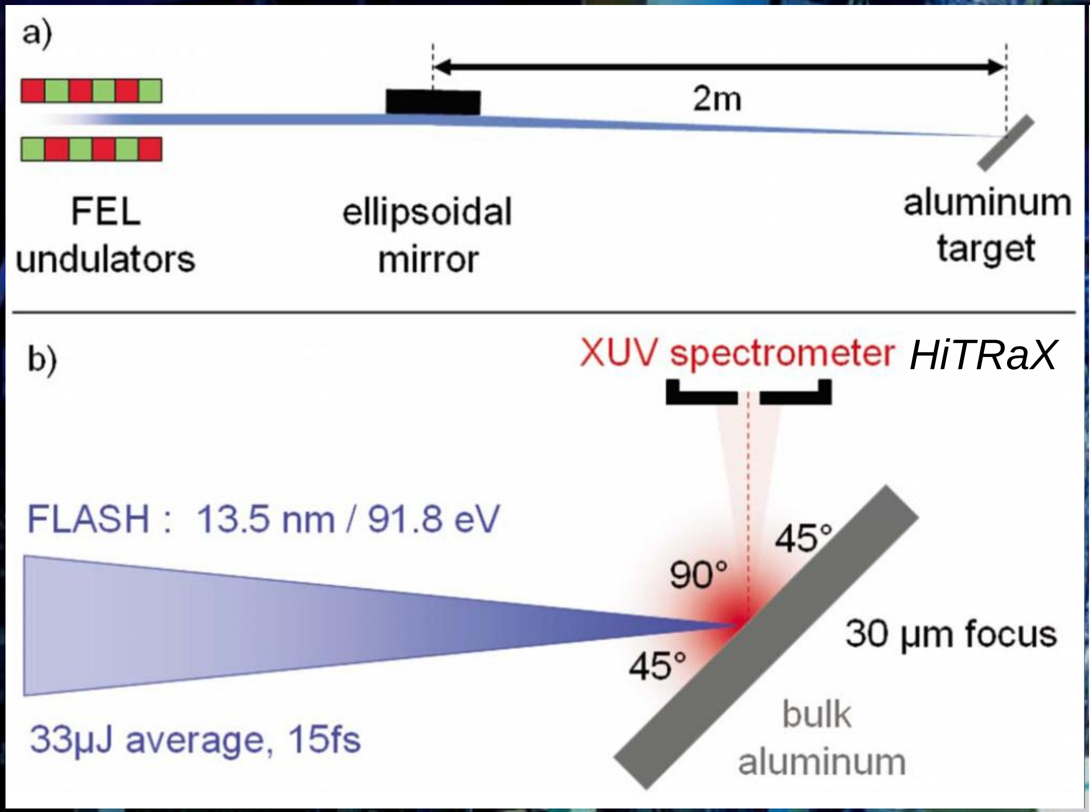
Covered Wavelength Region (1^{st} order) : 6 to 36nm

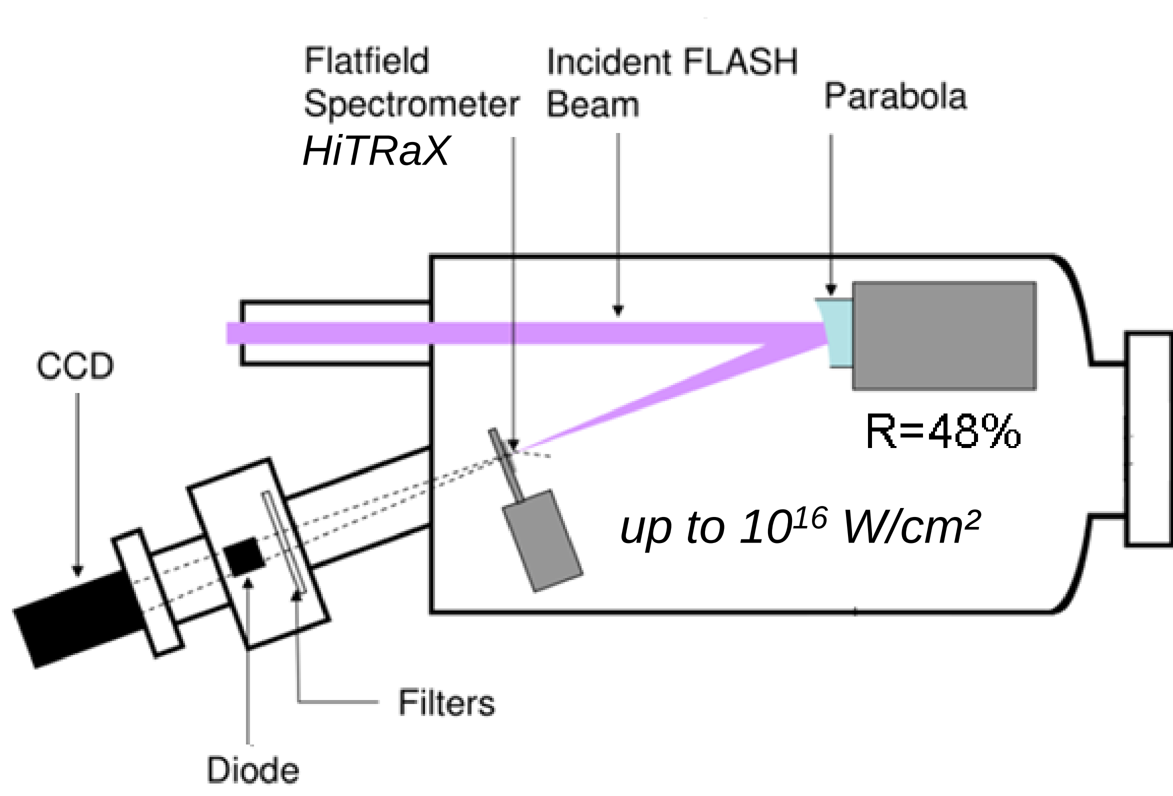
Measured Resolution : $\lambda / \Delta\lambda \approx 300$ (width of plasma line at 21 nm)

Solid Angle of Detection: $1.9*10^{-3}$ sr

RR. Fäustlin, U.Zastrau, E. Förster, et al., J. Instr. 5 , p02004 (2010)

Experimental Setups





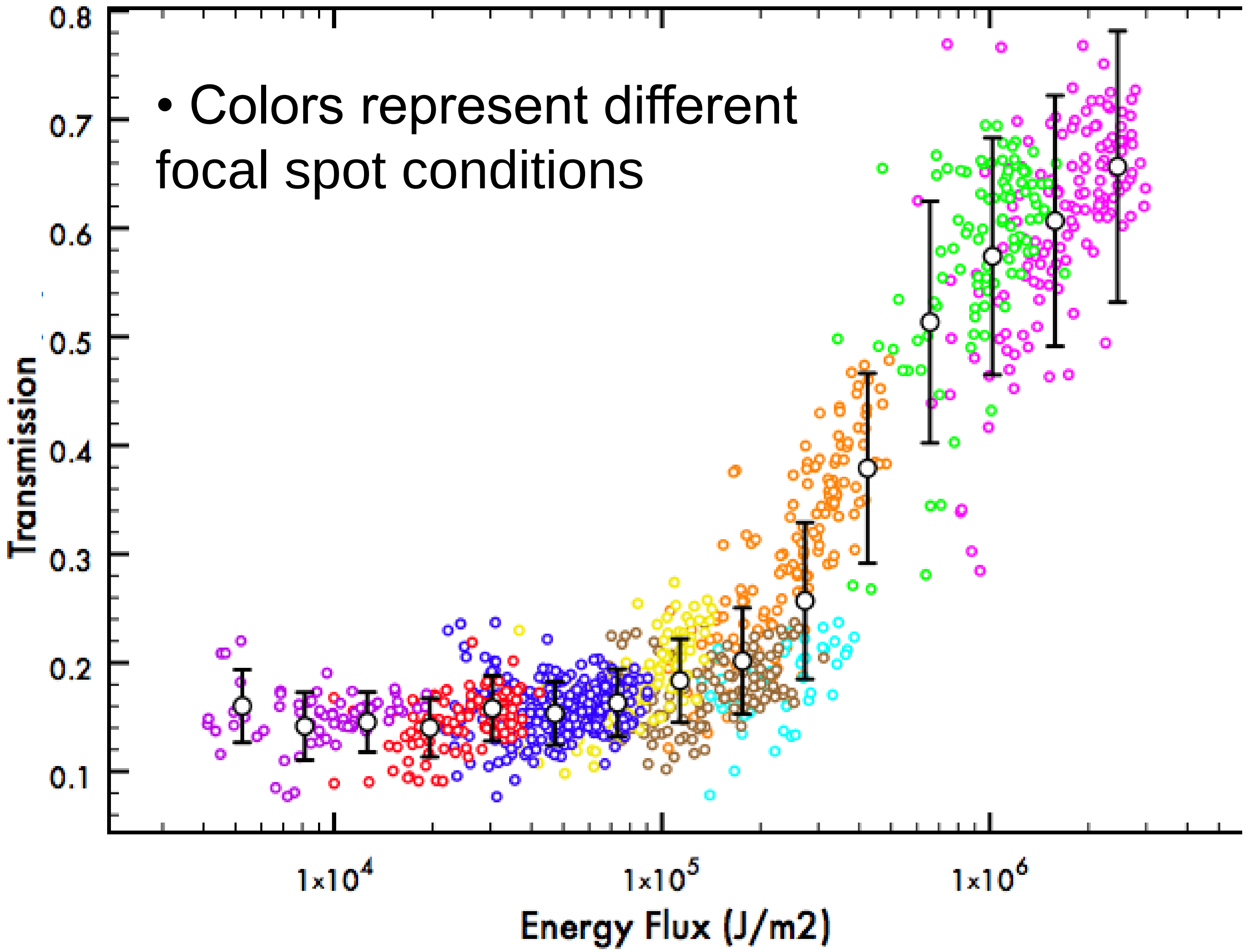
Zastrau, Fortmann, Fäustlin, *et al.*,
Phys. Rev. E 78 (2008), 066406

T.W.J. Dzelzainis et al. / High Energy Density Physics 6 (2010) 109–112
S. Bajt, et al., Proc. SPIE 7361, 18 (2009)
Nagler, Zastrau et al., Nature Physics 5, 693 - 696 (2009)

$n_{crit} = 6 \cdot 10^{24} \mathrm{cm}^{-3} \sim 60\ n_{solid}$

→ direct energy transfer into the bulk → absorption length ~ 40nm *[Henke]*

Transmission of 92 eV FEL fs-pulses through a 53 nm Al foil



Nagler, Zastrau, Fäustlin, Vinko, et al., Nature Physics* 5*, 693 - 696 (2009)

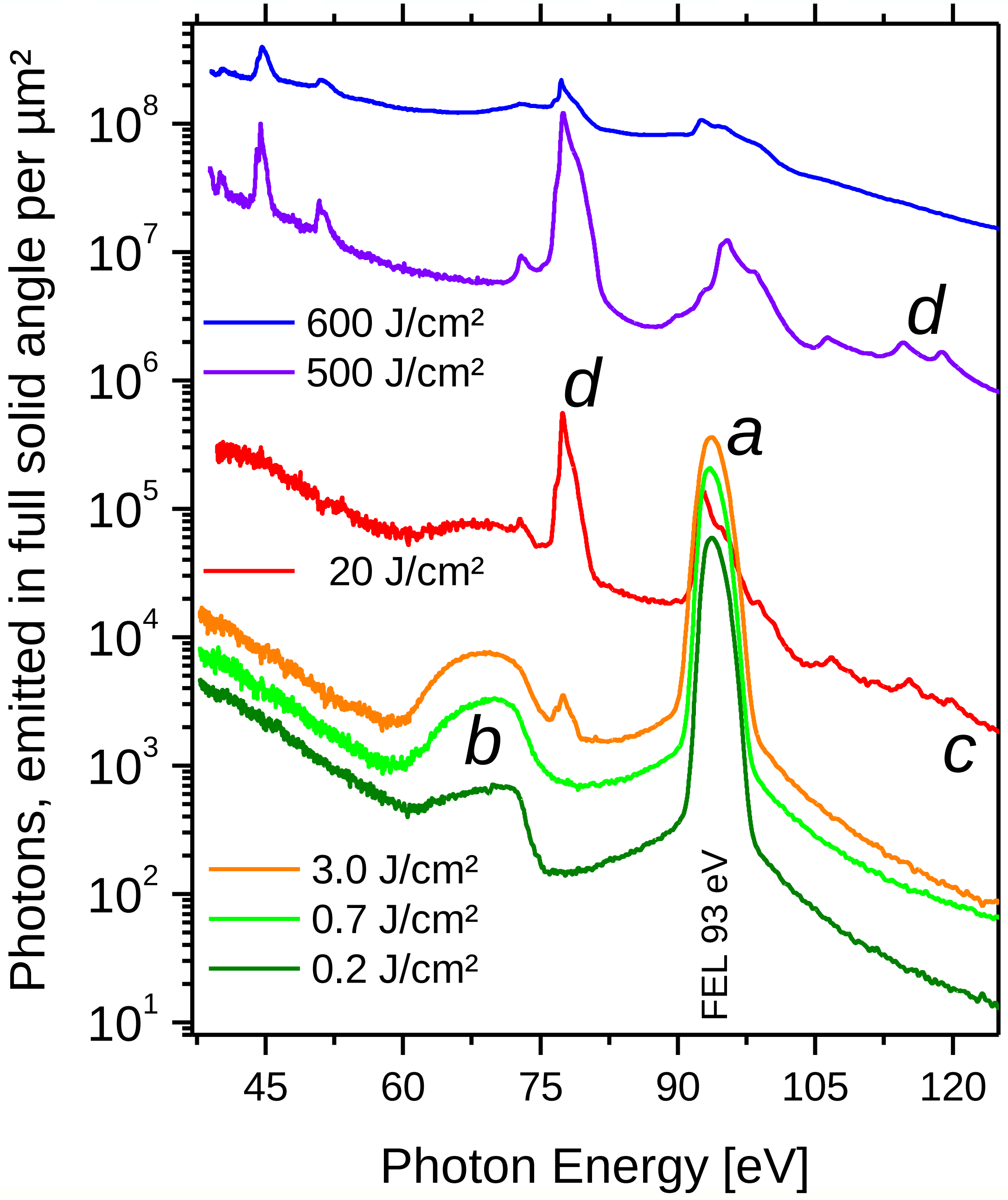
a photon energy of E_{ph} > 93.5 eV is needed to sequentially ionize a further $2p^5$ electron

→ saturable absorption
→ increased absorption length

the energy is still in the electron system, but not in the lattice

the matter is still crystalline.

Analysis of XUV Emission Spectra



d) Ion Lines
→ several 10s of ps

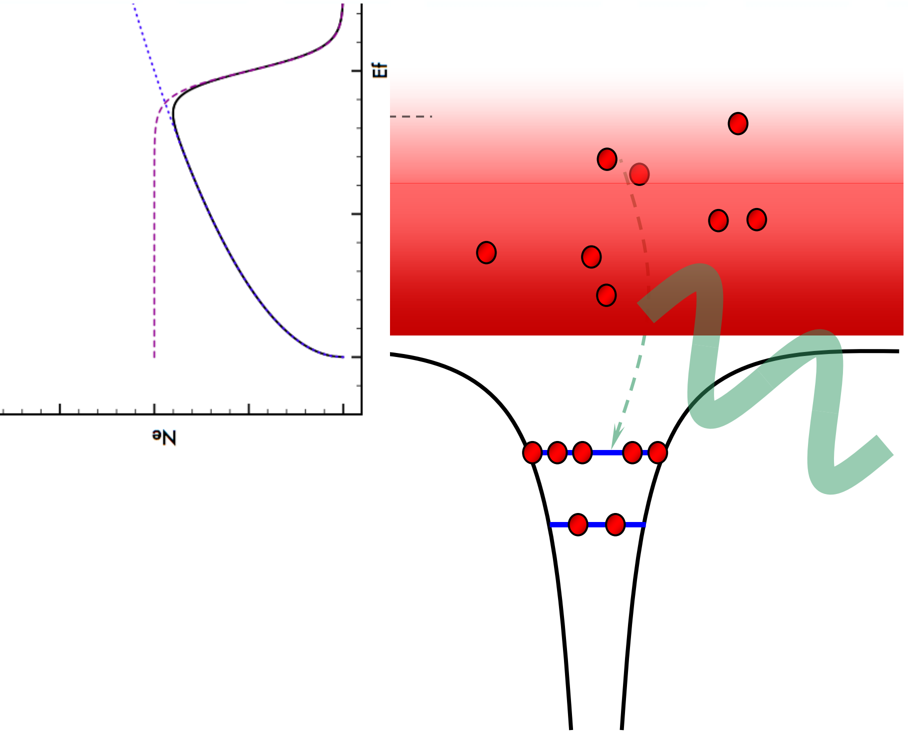
c) Bremsstrahlung
→ first 200 fs

b) Fluorescence
→first 60 fs

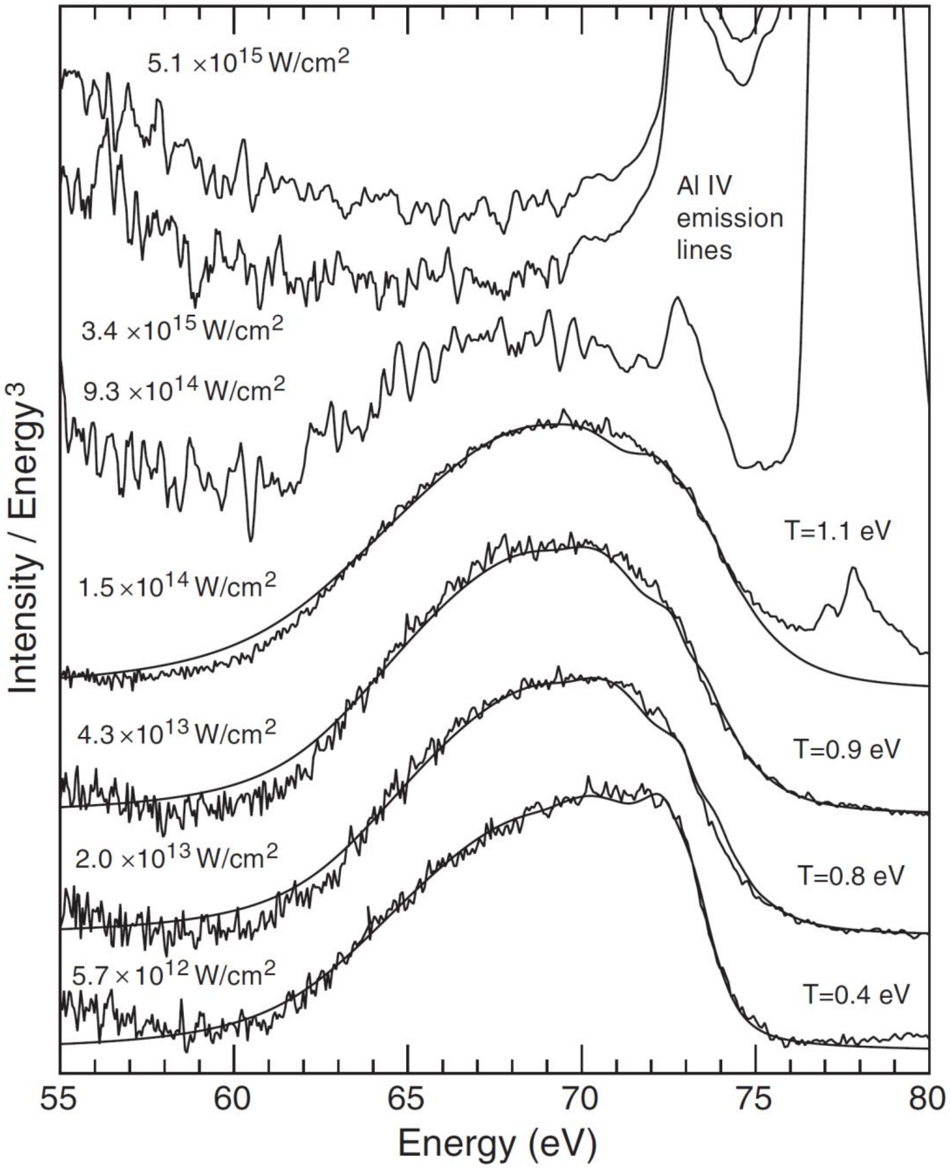
a) FEL scattering
→ within pulse duration

U. Zastrau at al., LPB (2011), in preparation

Process b: Recombination Time and Conduction-Band Temperature



Recombination time ~ 40..60fs, dominated by Auger time-scale.
→ observe fluorescence before the lattice moves



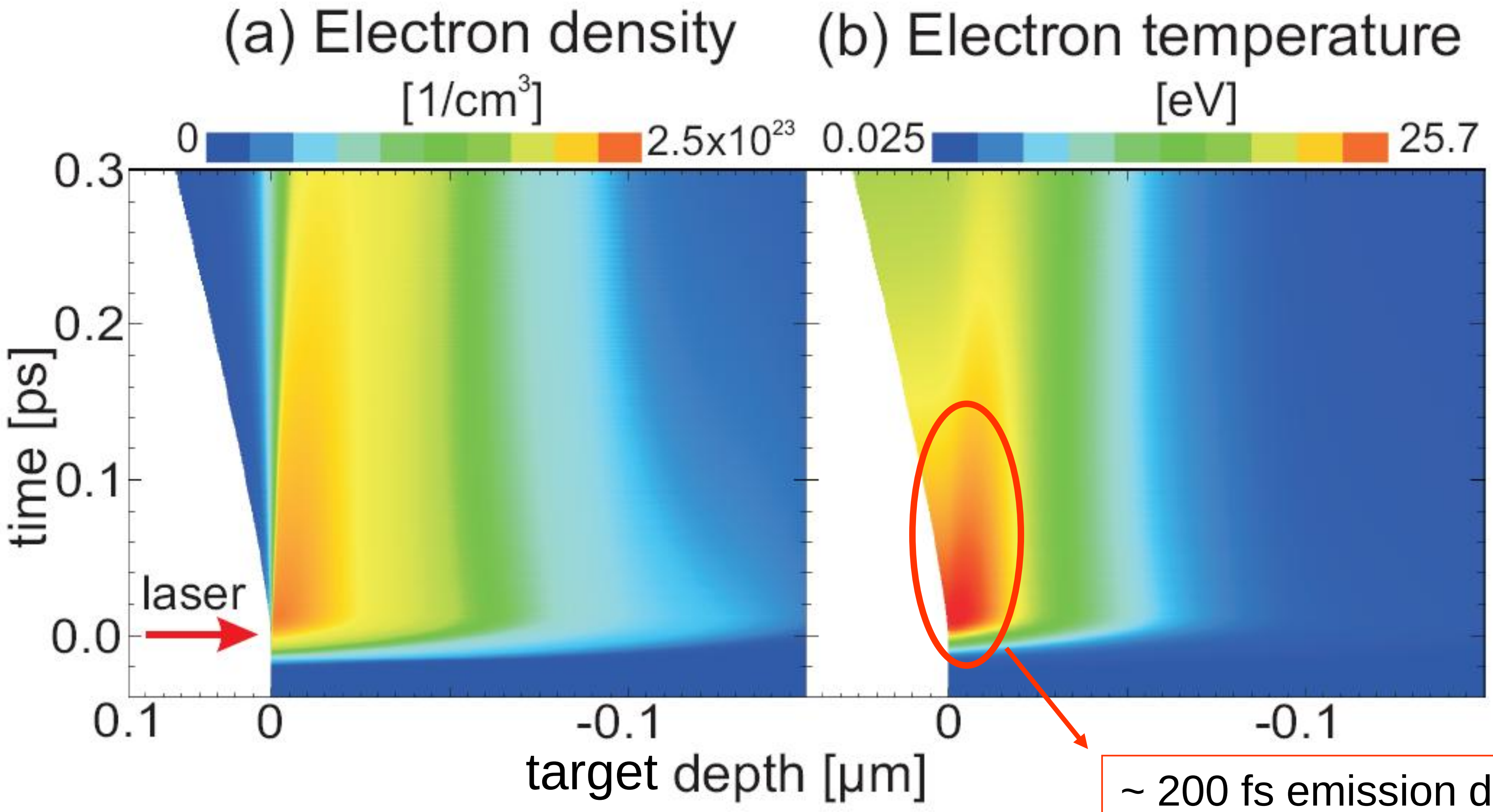
Simple: fluorescence proportional to ω^3 *g(E)f(E,T)*
B. Nagler, U. Zastrau, et al., Nature Physics 5, *693 - 696 (2009)*

Sophisticated: MD-DFT modeling of local DOS
S. Vinko, U. Zastrau, et al., Phys. Rev. Lett. 104, 225001 (2010)

Time Scale of Bremsstrahlung Emission

provided by R. Fäustlin

HELIOS includes absorption via bound-free and inverse Bremsstrahlung, uses same FEL parameters as in the experiment (10^{14} W/cm²)



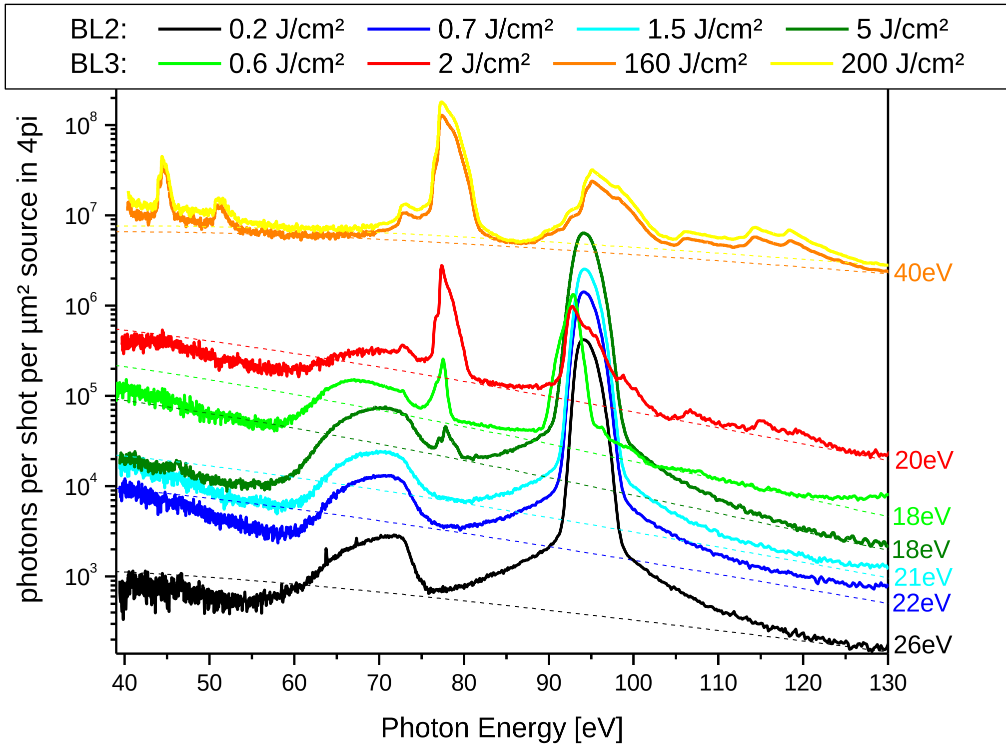
~ 200 fs emission duration

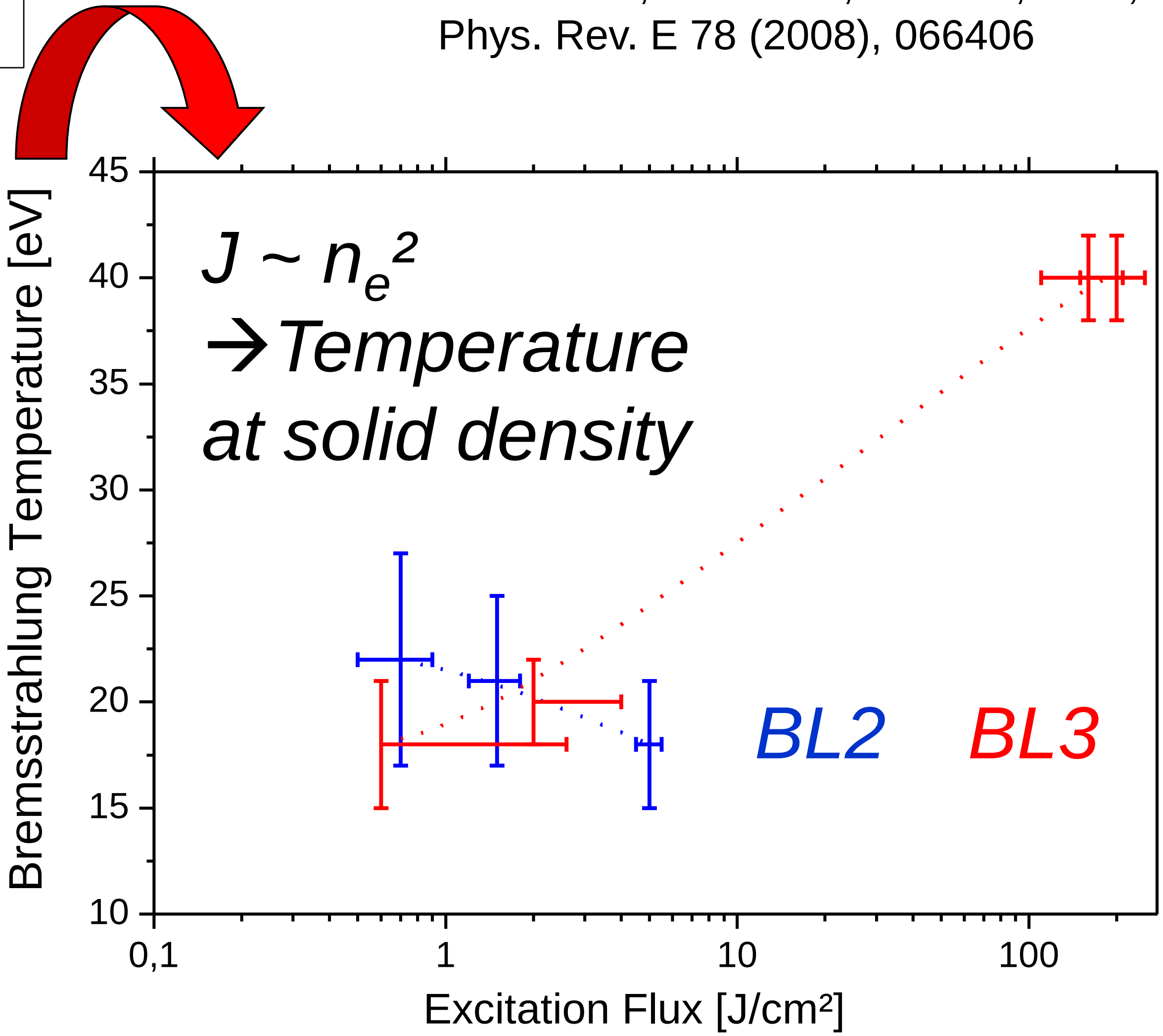
$J \sim n_e^2 \times T$

U. Zastrau *et al.*, Physical Review E **78** (2008), 066406

Process c: Bremsstrahlung

Method: Zastrau, Fortmann, Fäustlin, *et al.*,
Phys. Rev. E 78 (2008), 066406





Bremsstrahlung

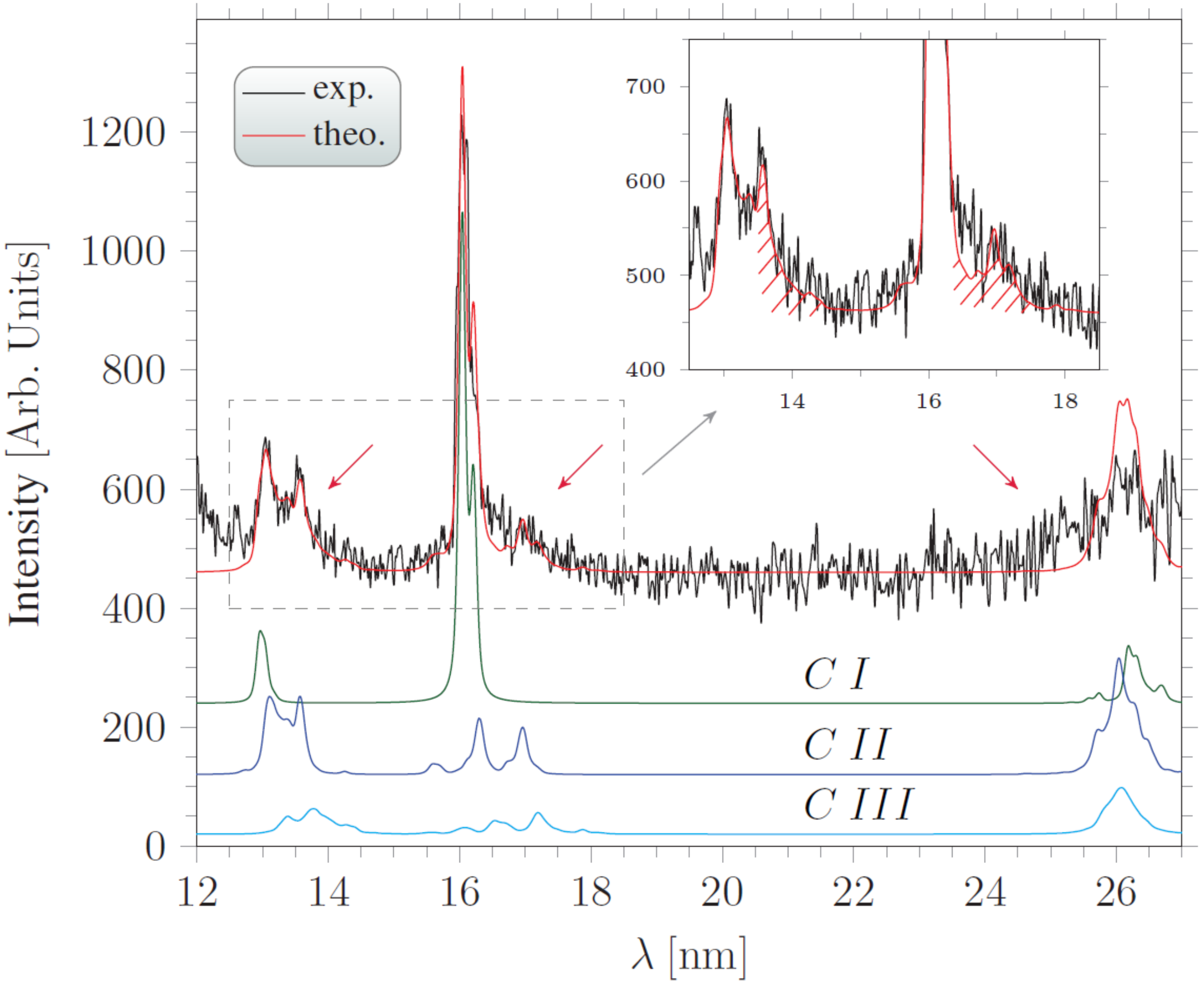
Kramer's Law:

Z : Ion Charge, n_e : free electron density

$$j_{\mathrm{ff}}(\lambda) = \left(\frac{e^2}{4\pi\epsilon_0}\right)^3 \frac{16\pi Z n_{\mathrm{e}}^2 \mathrm{e}^{-2\pi\hbar c/\lambda k_{\mathrm{B}} T_{\mathrm{e}}}}{3 m_{\mathrm{e}} c^2 \lambda^2 \sqrt{6\pi k_{\mathrm{B}} T_{\mathrm{e}} m_{\mathrm{e}}}} g_T(\lambda)$$

We observe a significant
contribution of fast Auger electrons

Process d: Ion lines



E. Galtier, F. Rosmej, et al., Phys. Rev. Lett. **106**, 164801 (2011).

The red curve is the sum

+ of the $K^2L^7M^1$ contribution at T_e = 8 eV

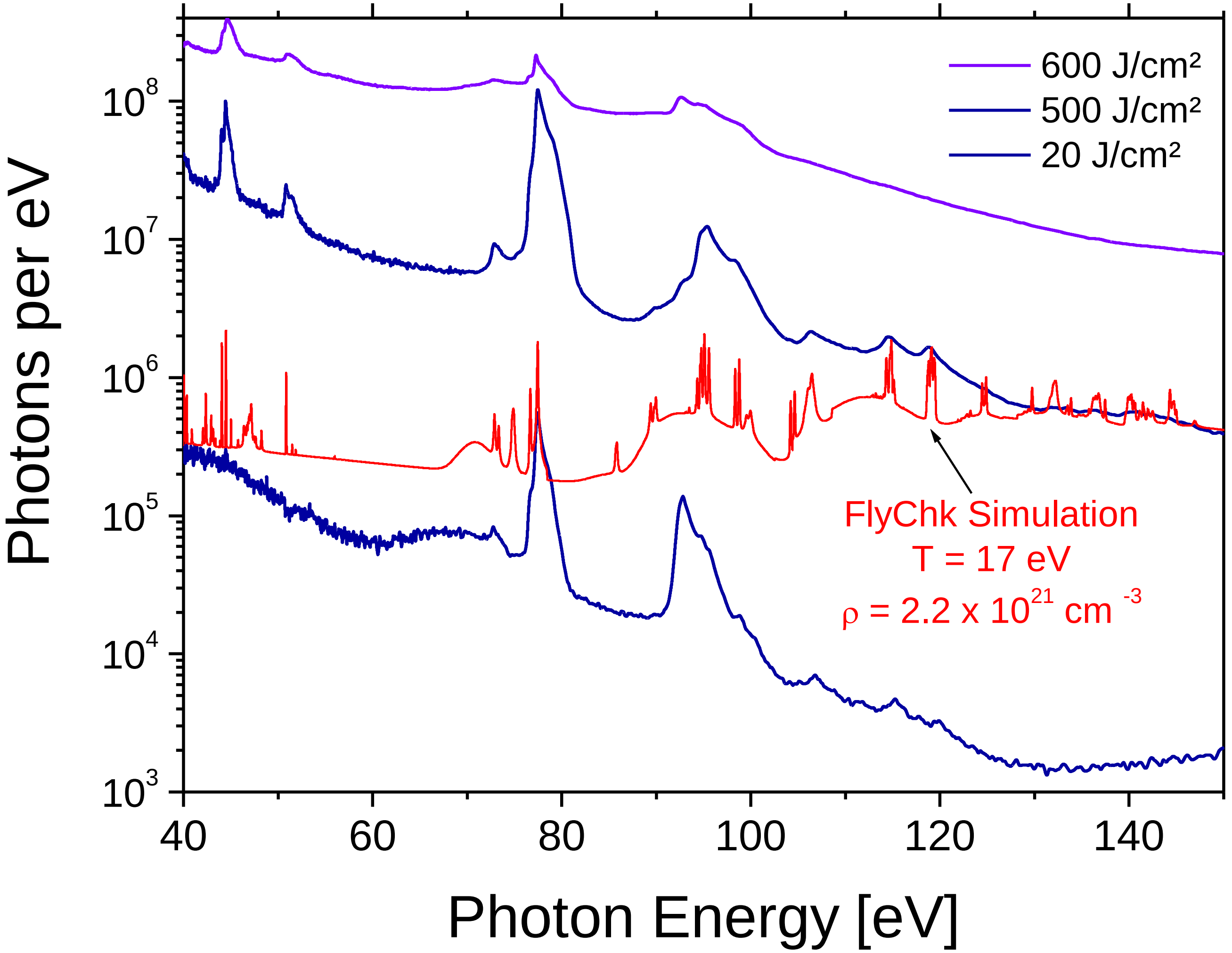
+ and $K^2L^7M^2$ and $K^2L^7M^3$ both at T_e = 25 eV

→25 eV right after the destruction of the Al lattice,
→density ~ 10^{22} /cm³

… refer to talk given by F. Rosmej earlier

Process d: Ion Recombination

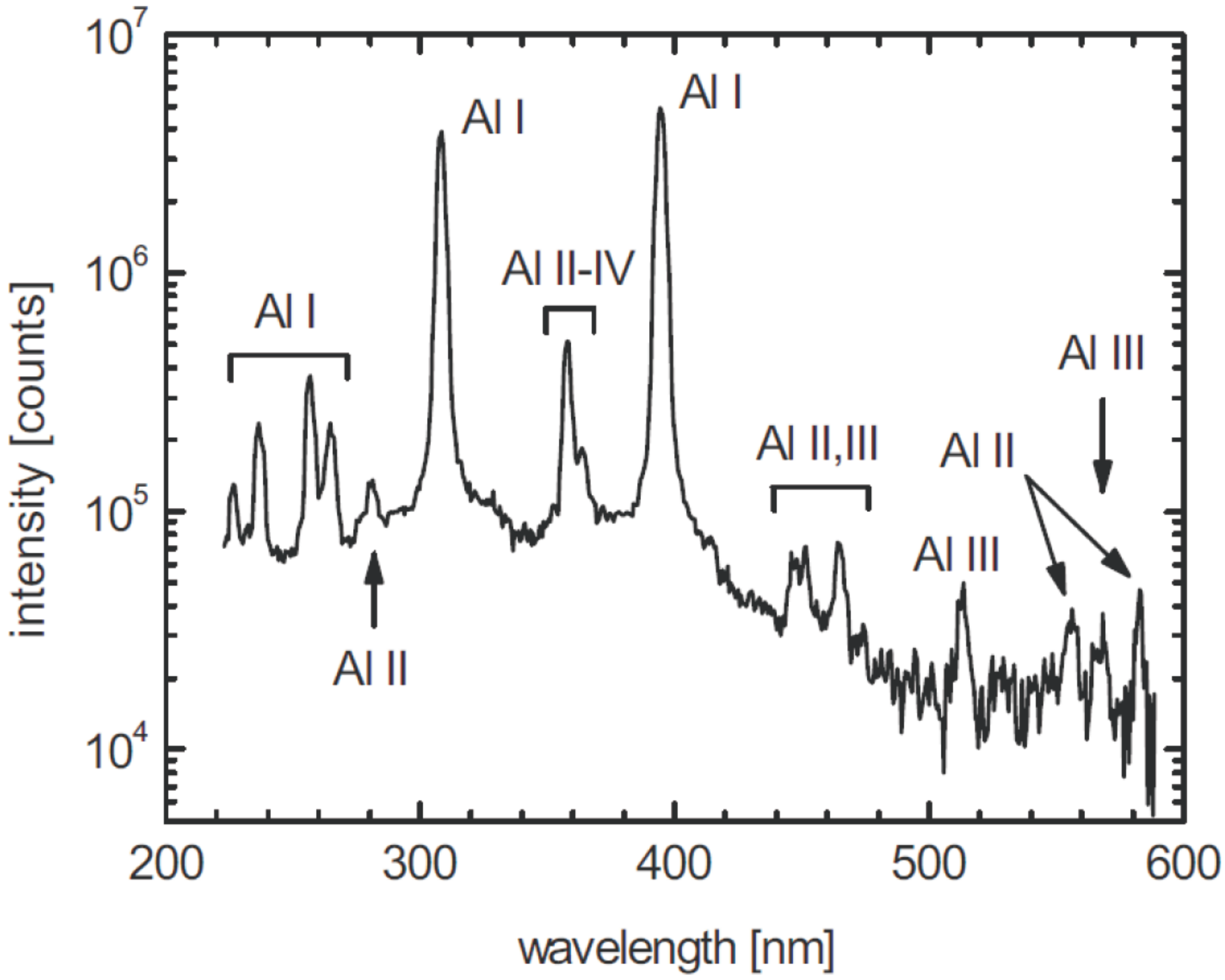
Significant contribution of less dense plasma on ps time-scales
→ Hydro-dynamically inferred density of 2 x 10^{21} cm^{-3} is used.



Theoretical Predictions: Code *FlyChk* *(RW. Lee, LLNL, Y. Ralchenko, NIST)* *High Energy Density Physics v.**1**, p.3 (2005)*

Additional: optical emission

Al irradiation with 13.5 nm at I = 10^{16} W/cm²



J. Cihelka, L. Juha, et al., Proc. SPIE **7361**, 73610P (2009).

Mostly neutral *Al I* emission

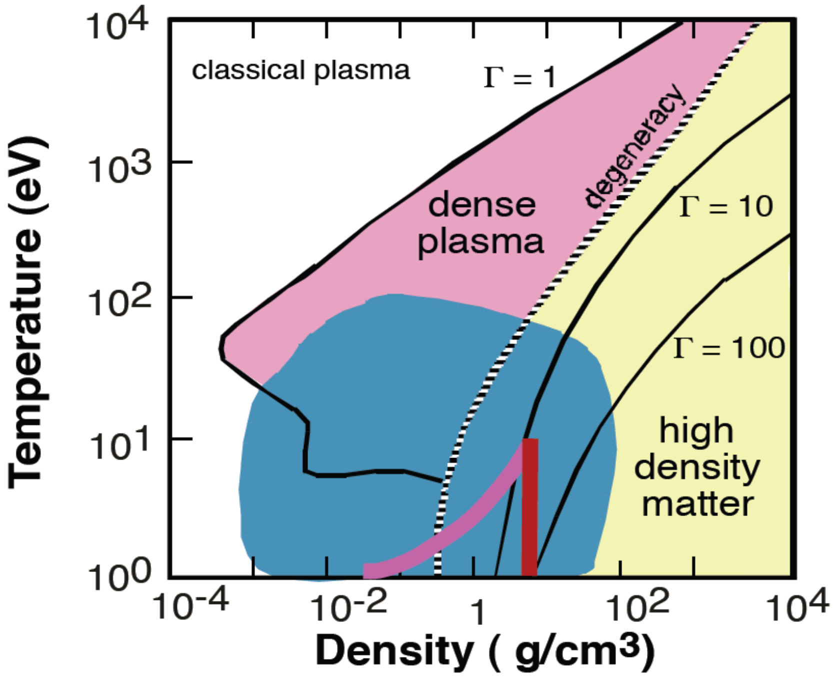
Only 1% of ionic contribution
Originating from Al^+ and Al^{2+}

Fitted with MARIA code:
→ best agreement T_e = 0.5-1 eV

→Expanding plasma plume at late (ns) time scales

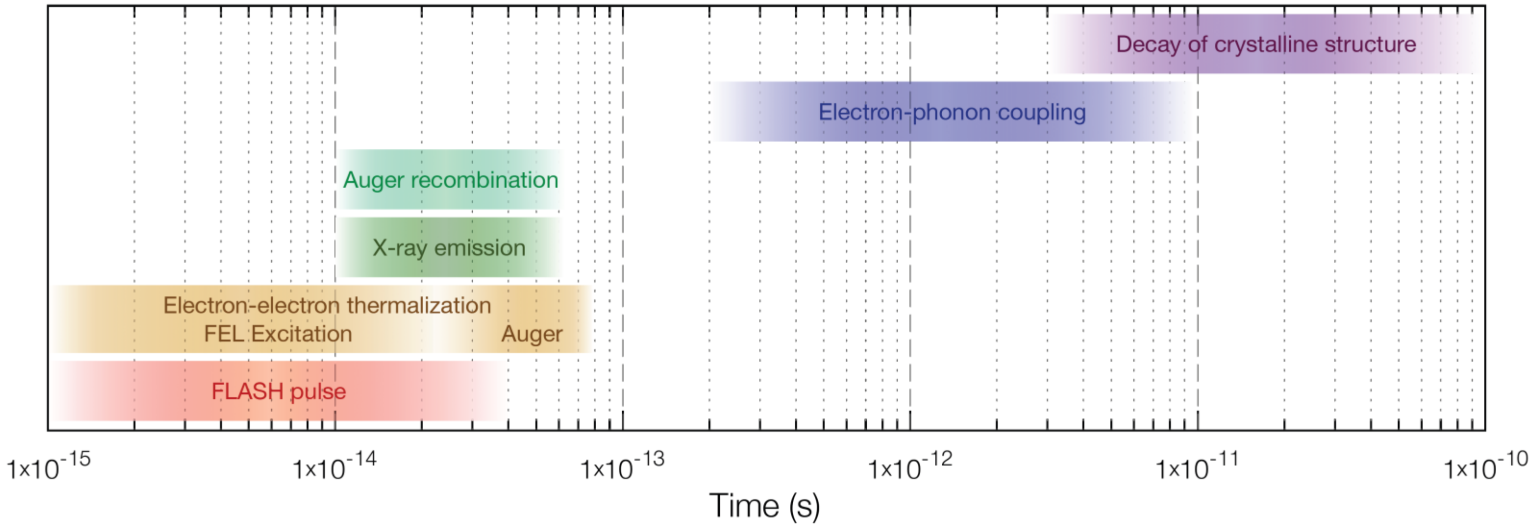
Summary

- **We developed and built the XUV spectrometer *HiTRaX* which has both spectral resolution and detection efficiency.**

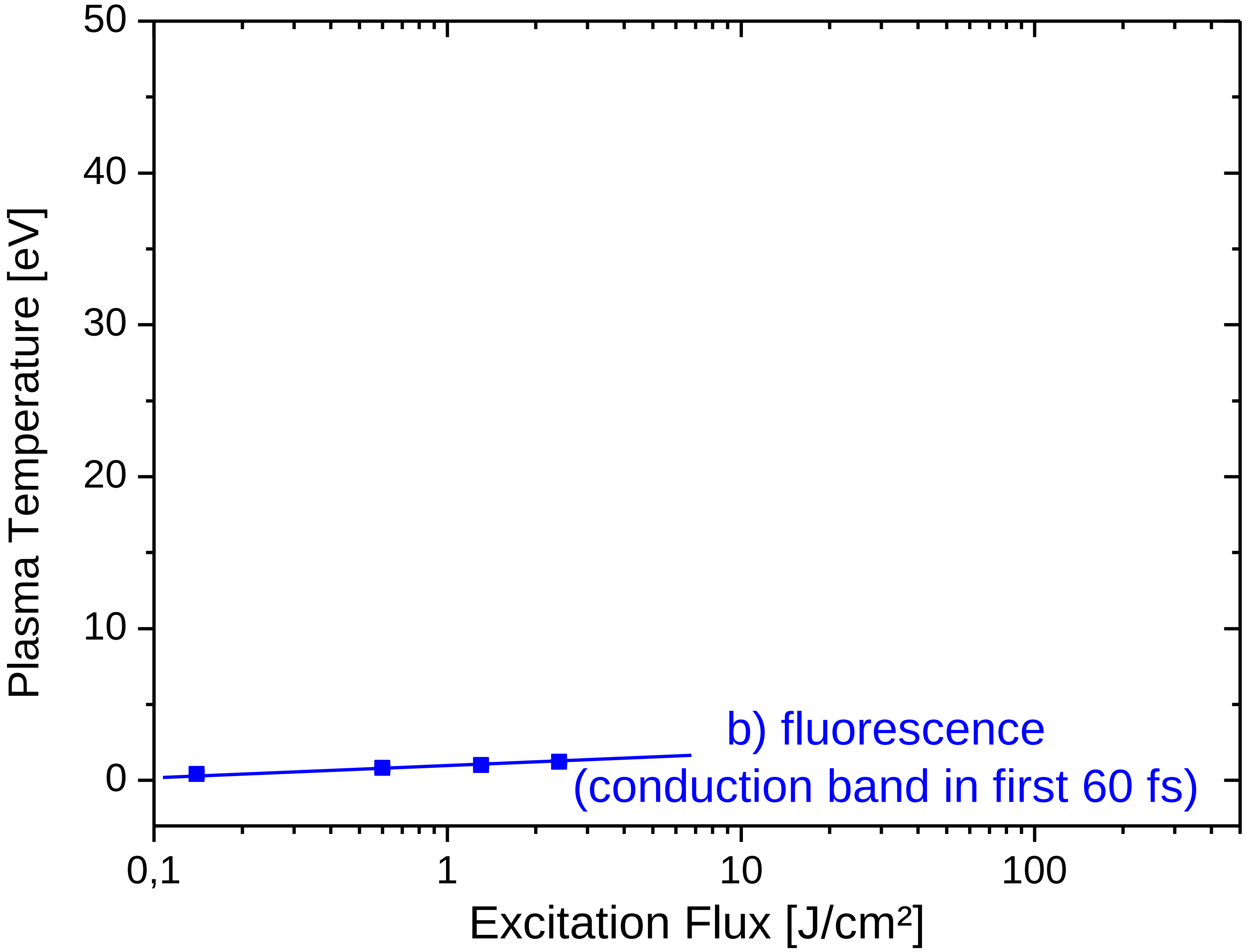


- **We studied excitation mechanisms of Aluminum plasma at an XUV photon energy of E = 92 eV using FLASH from 10^{13} to 10^{16} W/cm².**

- **We made progress in understanding the temporal development of the plasma on various time-scales.**



Time & Temperature Evolution



The assumption of a single density and temperature for the analysis currently limits the precision.