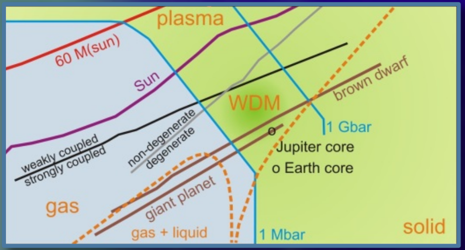
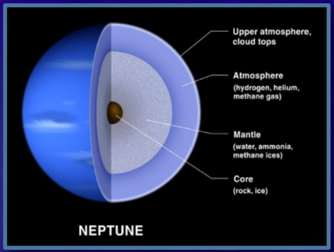
HED science: Experiments using X-ray Heating

Thomas Preston

HED instrument at the European XFEL and
HIBEF user consortium of the HED instrument

XFEL User Meeting, Schenefeld, Germany
22nd January 2018

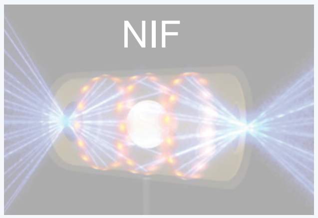


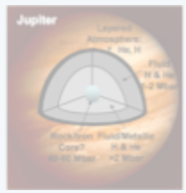


The scientific agenda

Laser Compression

Shock & ramp compression





XRD, IXS, XES

Long-pulse ns lasers

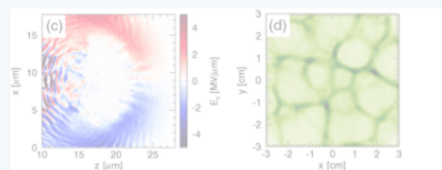
Relativistic Laser-Plasmas

Electron transport,

Instabilities and filamentation,

Particle acceleration,

High EM fields



Multi-100 TW fs lasers

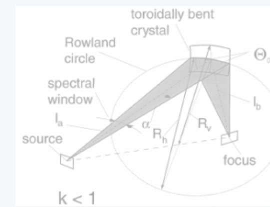
Advanced methods

Spectrometers

Advanced focusing

IXS, SAXS

Phase contrast imaging

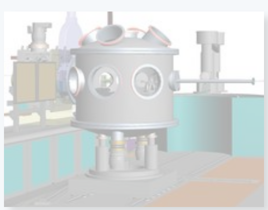


Diamond Anvil Cells

Fast dynamic piezo DAC

Pulsed laser heated DAC

Double-stage DAC

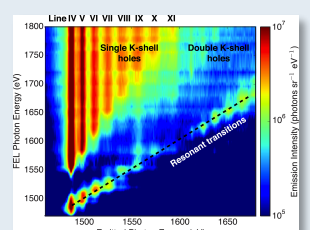


Hard XFELs

Isochoric X-ray excitation

Transport properties,

Hollow atoms, rates



XES, IXS, XRD

Soft and hard XFELs

Further projects

Isobaric heating

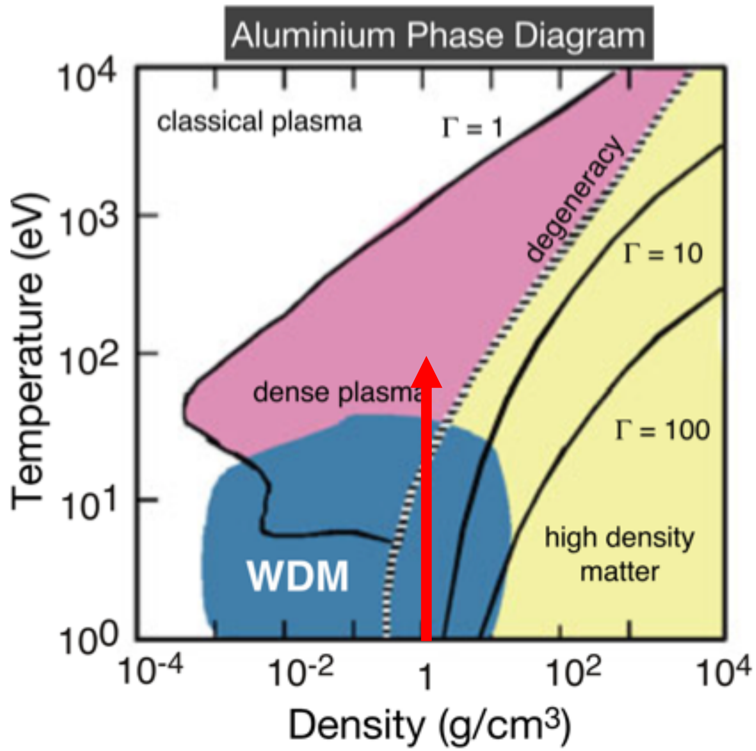
X-ray backlighters

X-ray detectors & EMP

High-purity polarimetry

…

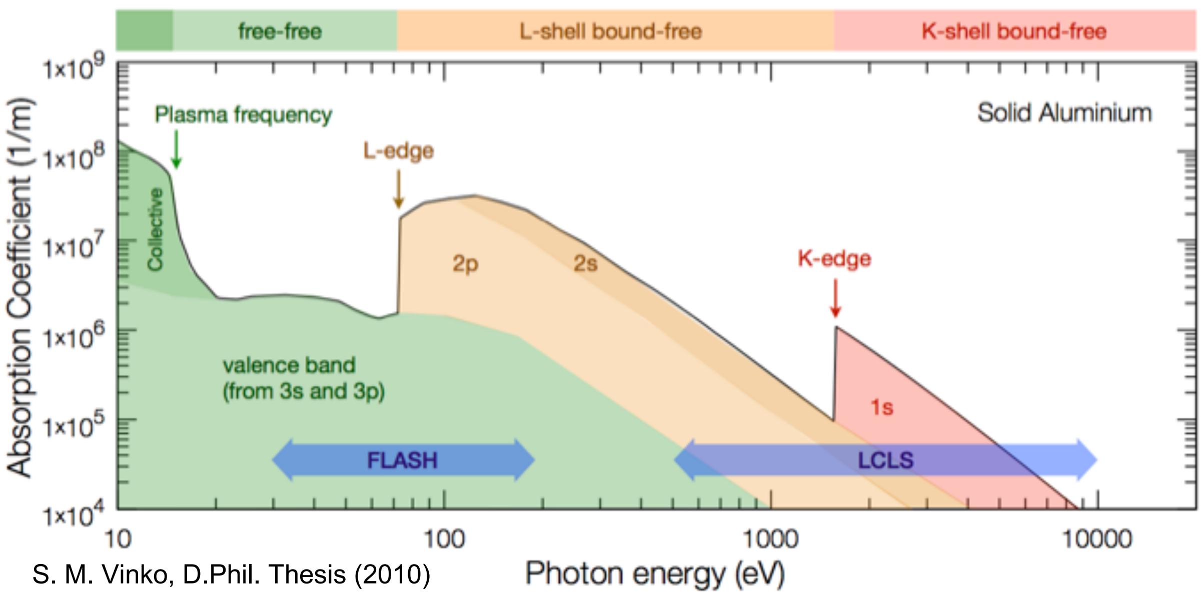
Isochoric heating relies on rapid energy deposition by ultrafast X-rays



S. M. Vinko, J Plasma Physics **81**, 365810501 (2015)

- Energy deposition on timescale of 100fs, faster than hydrodynamic expansion (> 1ps).
- Electron temperatures much higher than ion temperatures.
- Ion density remains constant.
- Can determine electron density from temperature and ionization stage.
- For low-Z elements (Al, Mg, etc.) can heat to over 100eV accessing HDM.
- Create degenerate, highly-coupled plasmas.

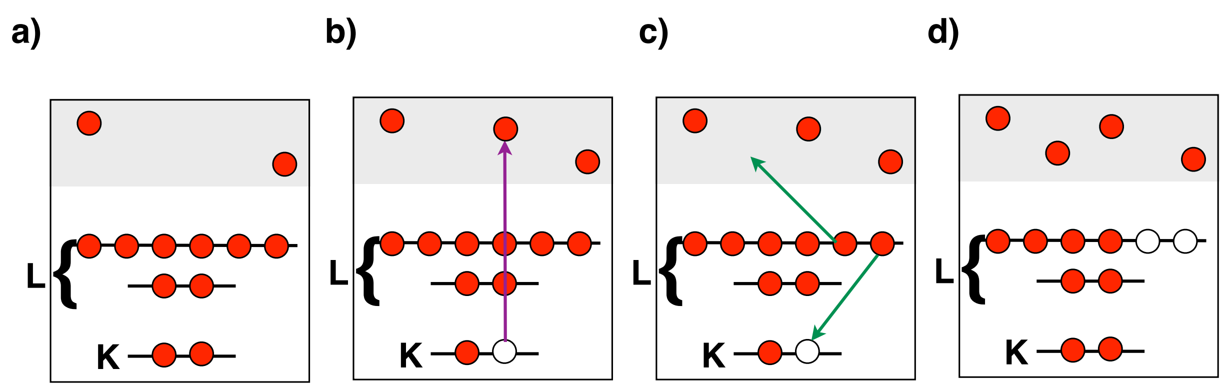
Absorption by focusing X-rays and probing around atomic edges and resonances



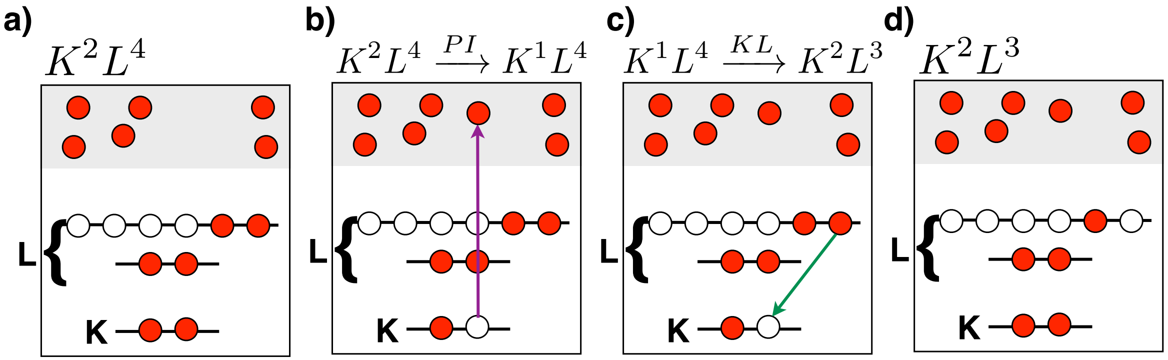
S. M. Vinko, D.Phil. Thesis (2010)

- Higher absorption above edges.
- With small focal spots, ~1um, can absorb many photons per atom.
- Rapid heating is achieved by thermalisation of fast Auger electrons.

Ambient Mg is photoionized from the K-shell.
K-shell hole is then filled by Auger decay.
Two electrons are added to the conduction band.



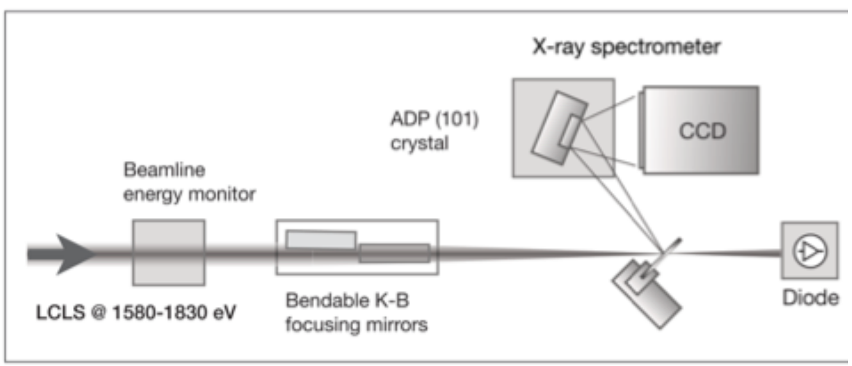
Diagnosis is achieved by using x-ray emission spectroscopy



T. R. Preston, D.Phil. Thesis (2017)

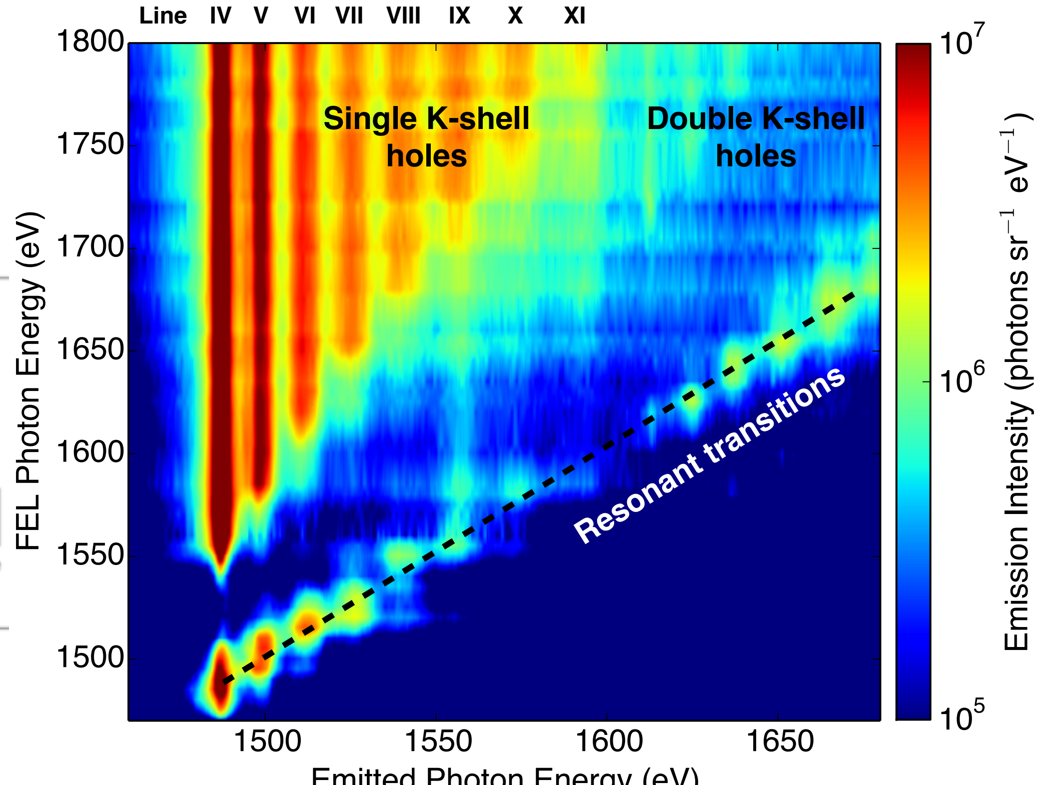
Line VII

Tuning x-ray photon energy through K-edges of successive ionization stages gives higher emission lines.

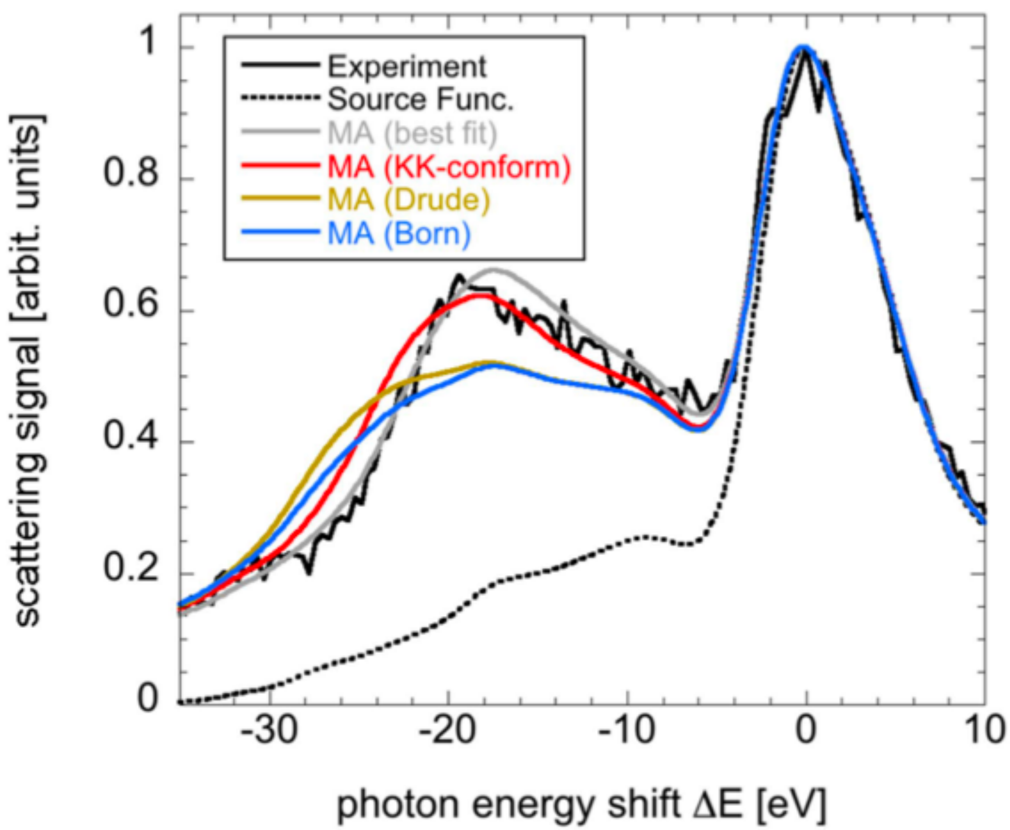


Vinko et al., Nature **482** 59-62 (2012)

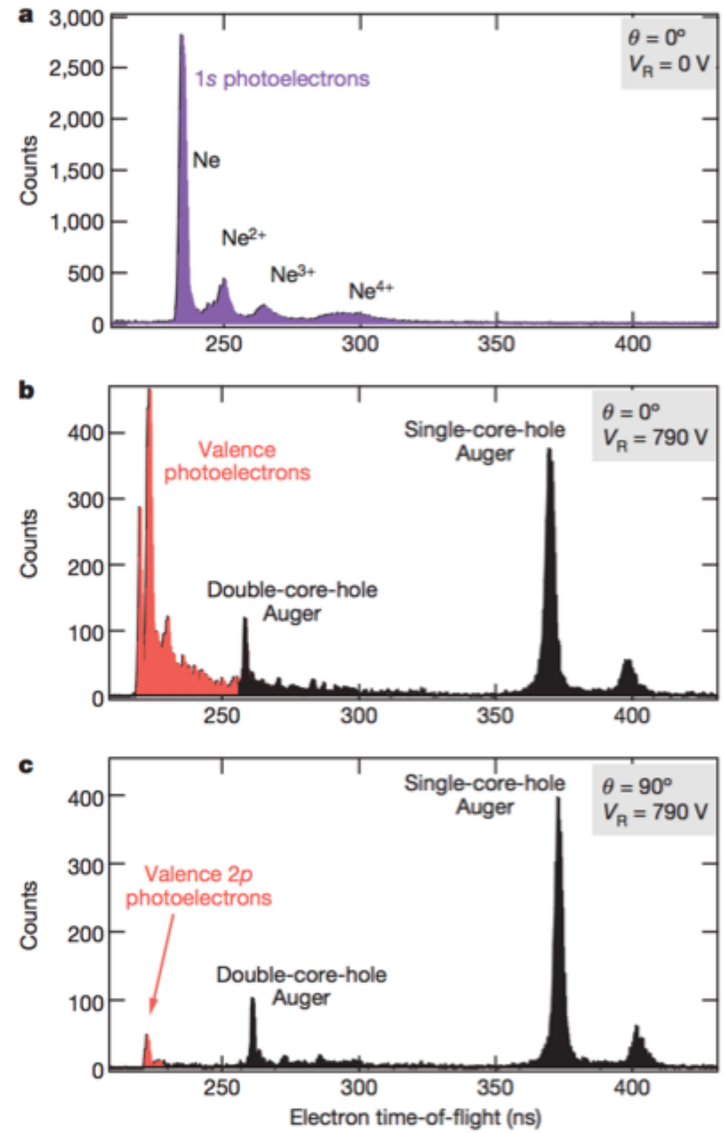
S. M. Vinko, J Plasma Physics **81**, 365810501 (2015)



Disclaimer: other diagnostics are also available…

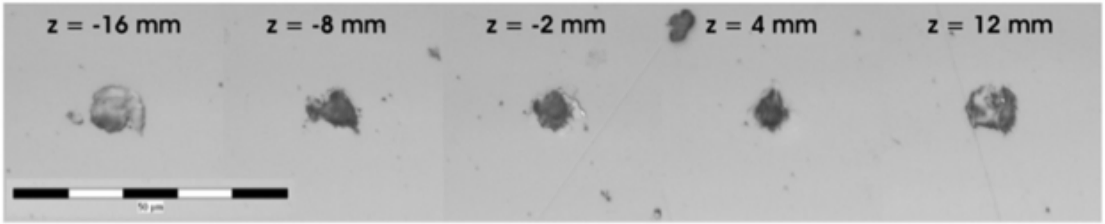


Sperling et al., J. Phys. B.: At. Mol. Opt. Phys. **50**, 134002 (2017)



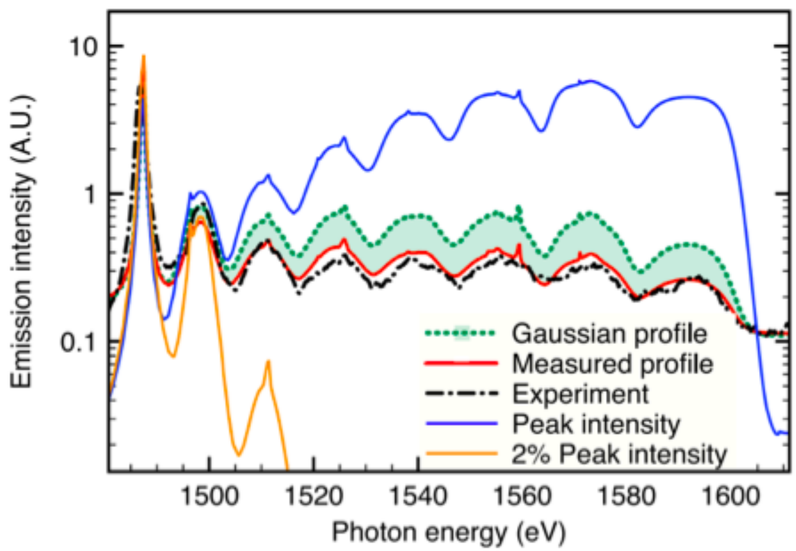
Young et al., Nature **466**, 56-61 (2010)

There are some caveats/considerations when measuring isochorically heated solid density plasmas

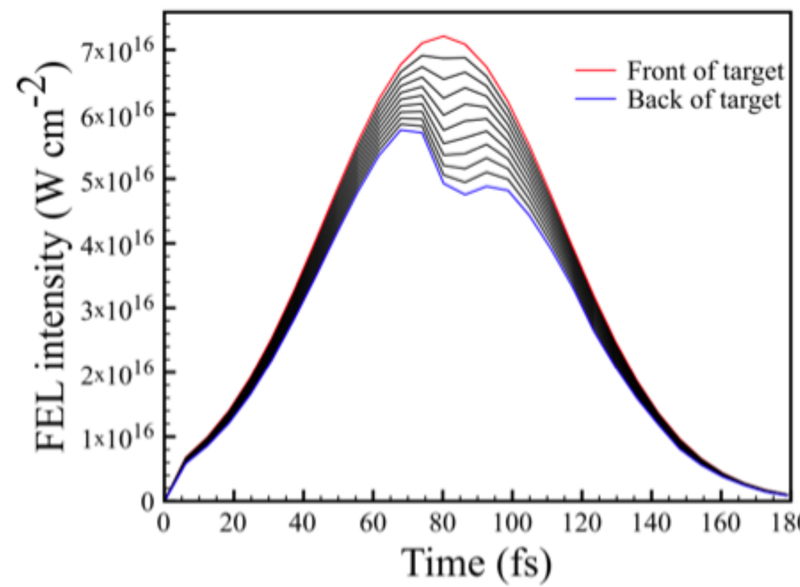


Chalupsky et al., Nucl. Inst. and Meth. in Phys. Res. Sect A, **631**, 130-133 (2011)

- Tightly focused beam has large transverse gradients across focus.
- These must be measured and incorporated into any modelling.
- Longitudinal gradients through target should be considered.



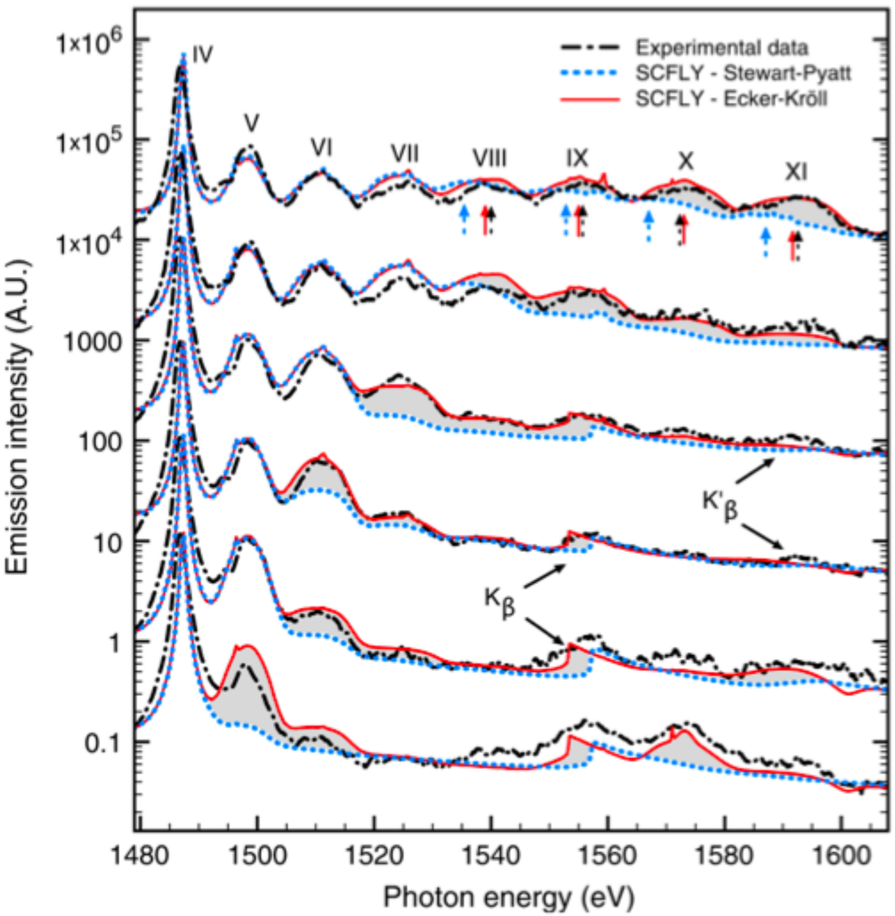
Ciricosta et al., Phys. Plasmas **23**, 022707 (2016)



Rackstraw et al., HEDP **11**, 59-69 (2014)

X-ray heated plasmas provide an important test-bed for many fundamental measurements in plasma physics

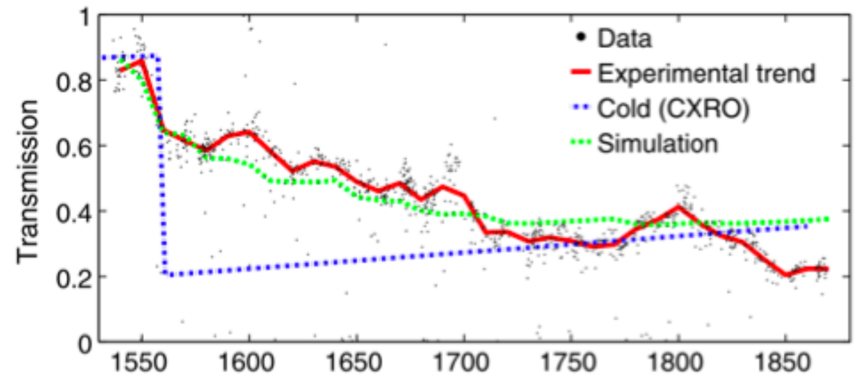
Continuum lowering (IPD)



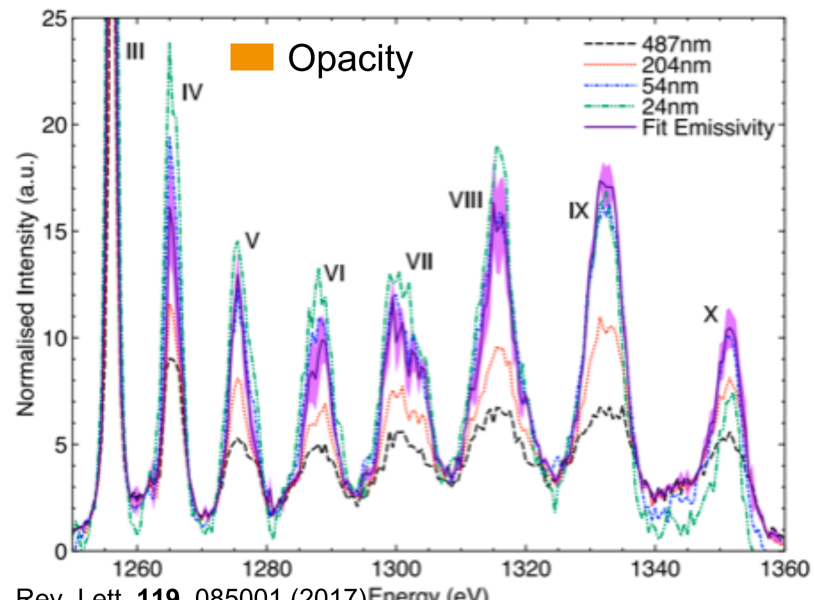
Ciricosta et al., Phys. Rev. Lett. **109**, 065002 (2012)

Saturable absorption

Rackstraw et al., Phys. Rev. Lett. **114**, 015003 (2015)



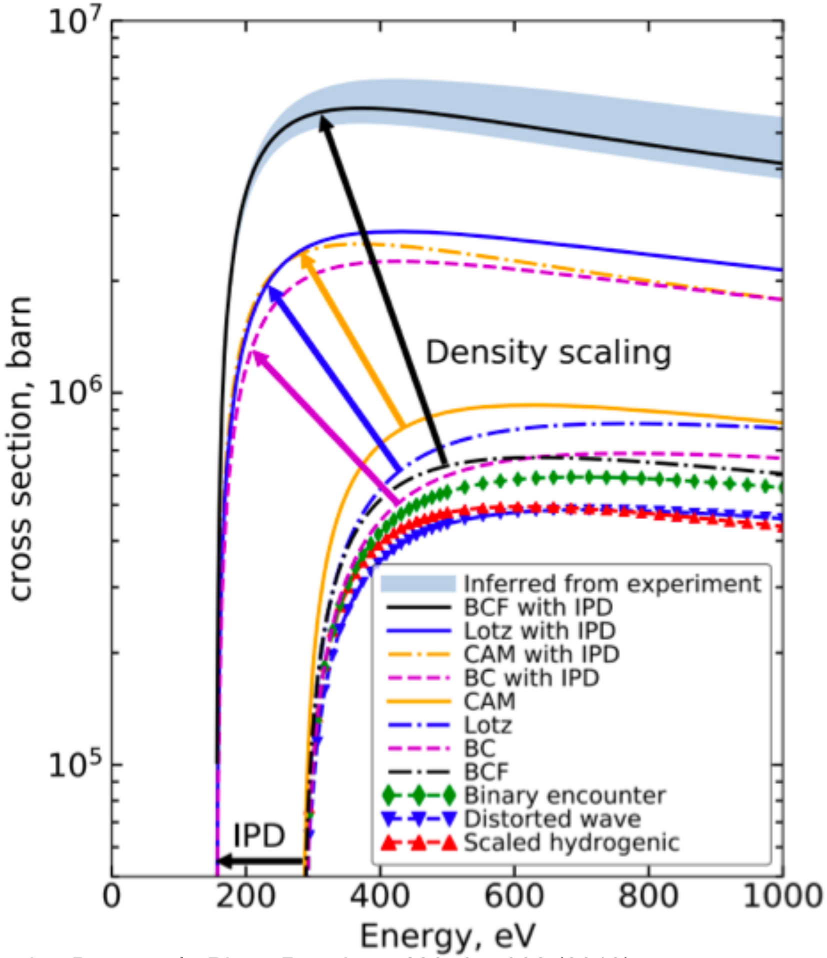
Opacity



Preston et al., Phys. Rev. Lett. **119**, 085001 (2017)

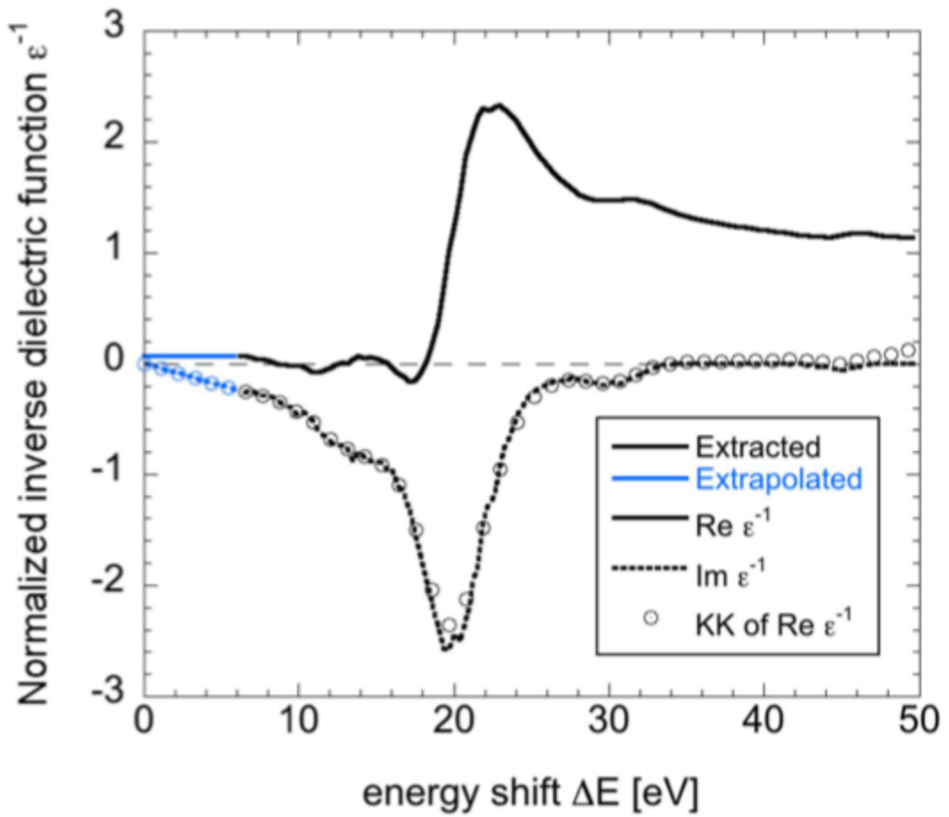
X-ray heated plasmas provide an important test-bed for many fundamental measurements of electronic properties

Collisional Rates



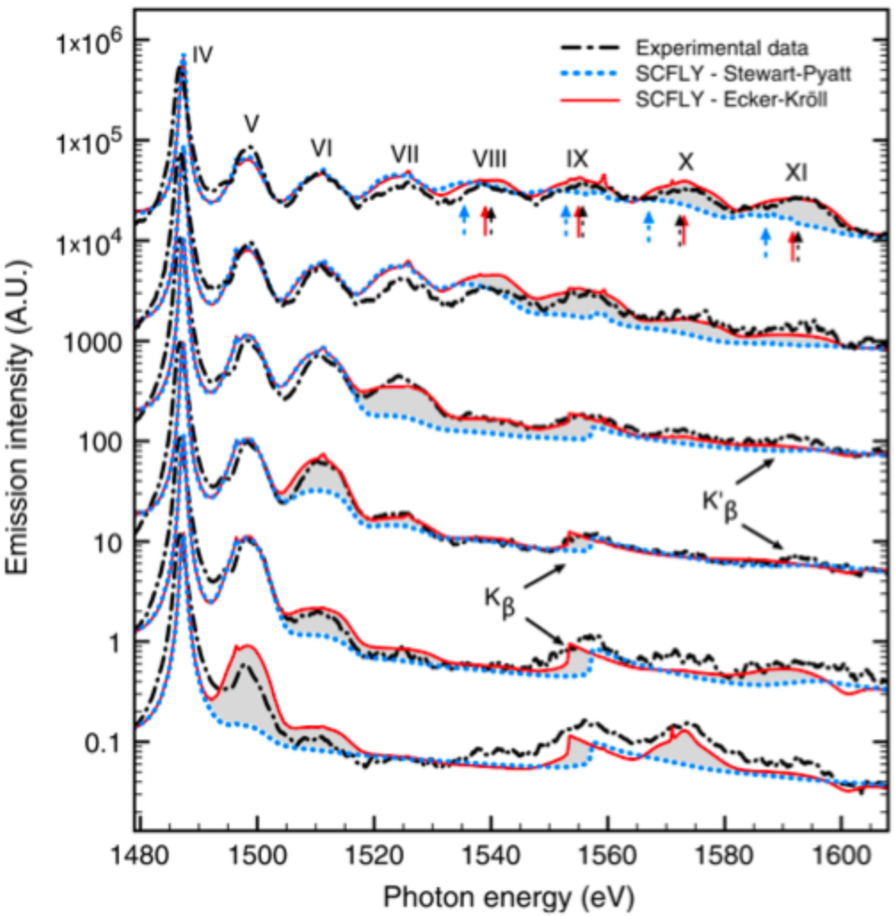
Van den Berg et al., Phys. Rev. Lett. **120**, 055002 (2018)

Dielectric function

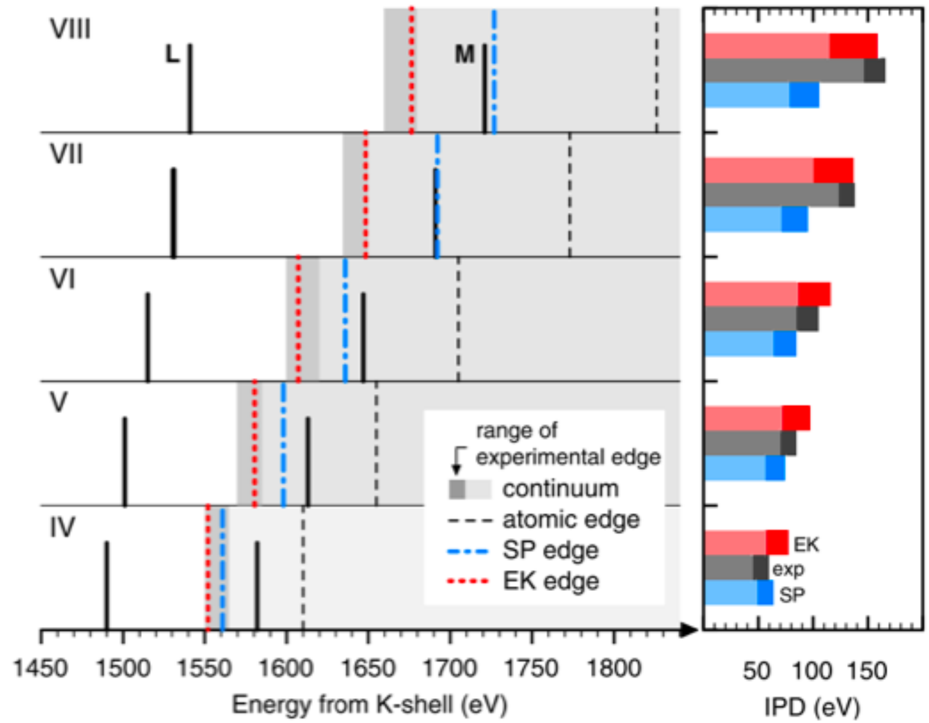


Sperling et al., J. Phys. B.: At. Mol. Opt. Phys. **50**, 134002 (2017)

IPD can be measured by knowing the incoming XFEL photon energy and measuring edge positions

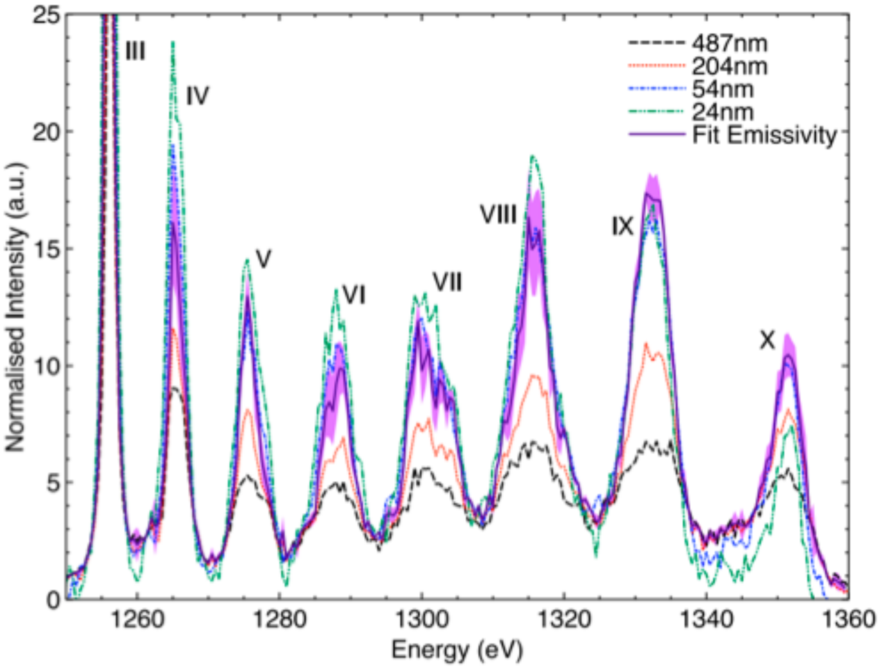


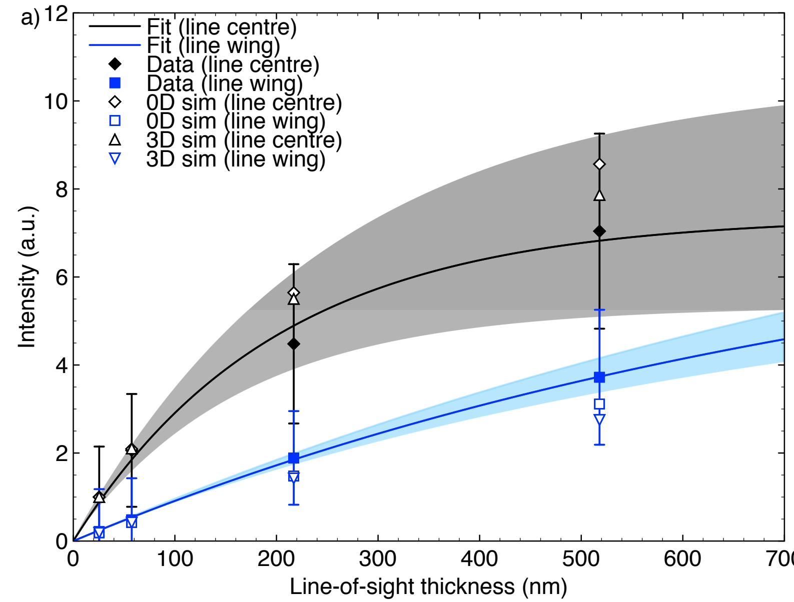
Ciricosta et al., Phys. Rev. Lett. **109**, 065002 (2012)

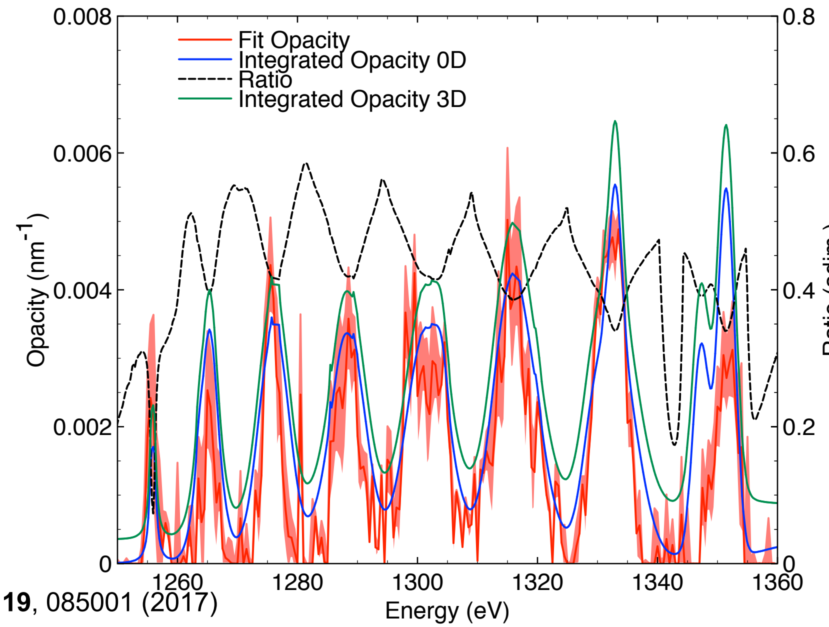


- IPD affected by density and charge state. Different charge states give different electronic screening.
- Isochoric heating gives fixed ion density, and known electron density from charge state.
- Pump photon energy is known and therefore measures edge.

K-shell opacity can be deduced using emission from targets of known thickness



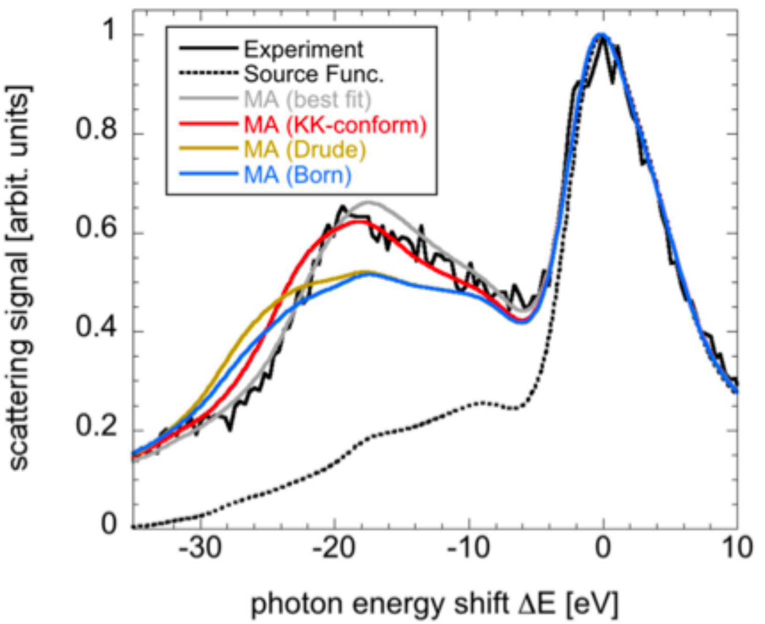


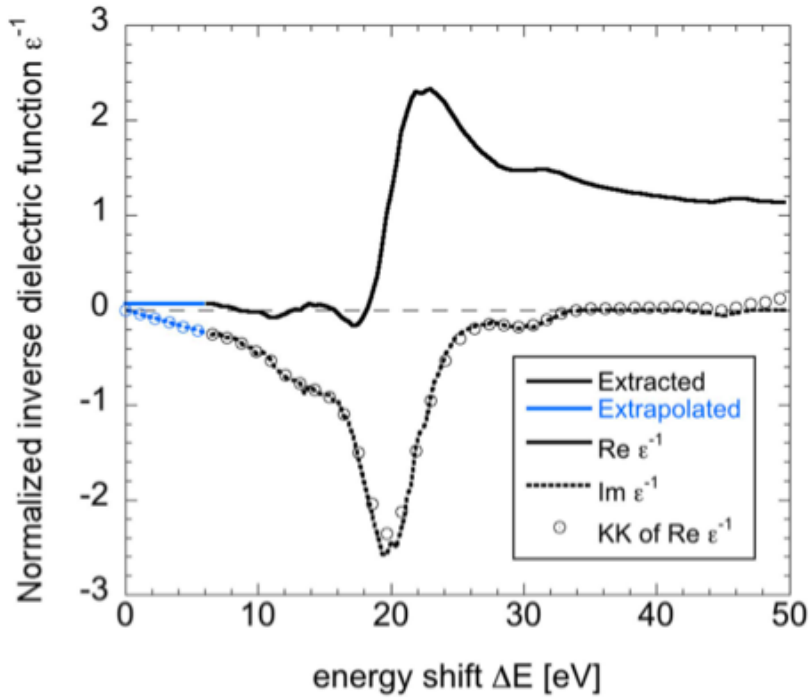


- Fit 1D slab solution to the equation of radiative transfer for a range of thicknesses as a function of emitted photon energy.
- Fit parameters are then the emissivity and opacity.
- Due to constant ion density, and simple absorption process, the electron density and temperature of the measurement are well defined.

Preston et al., Phys. Rev. Lett. **119**, 085001 (2017)

The dielectric function can be extracted from Thomson scattering





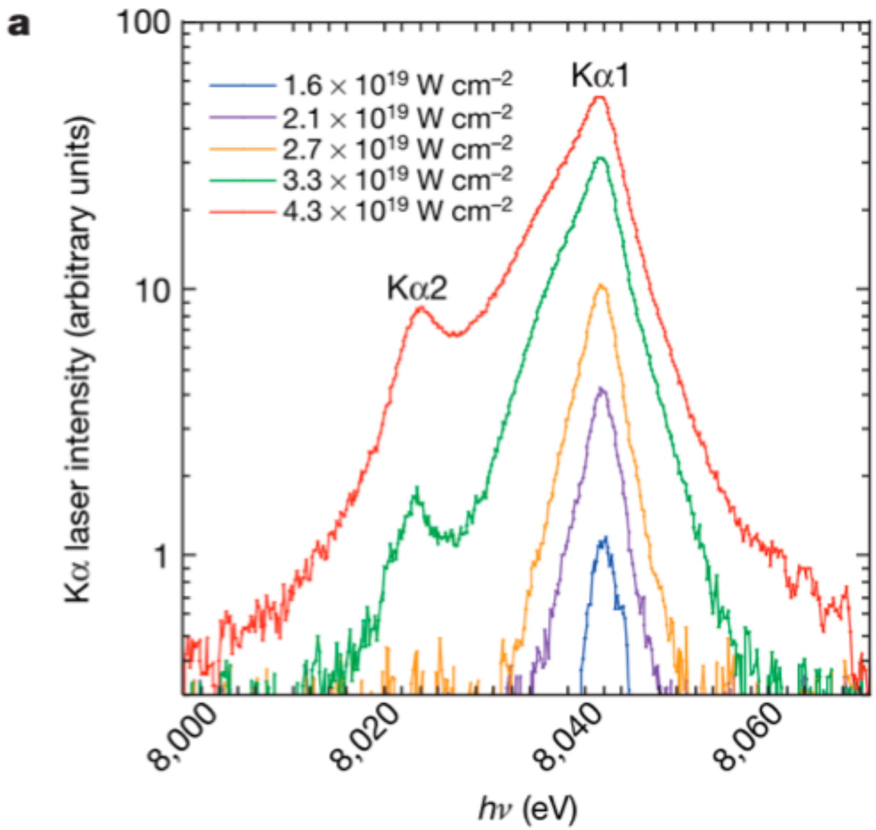
- Plasmon is fitted.
- Deconvolving out the instrument function gives the imaginary part of the dielectric function.
- Kramers-Kronig relation yields the real part of the dielectric function, and the inverse transform is verified to conform with the original Im part.

$$S^0_{ee}(k,\omega) = -\frac{\varepsilon_0 \hbar k^2}{\pi e^2 n_e} \frac{\mathrm{Im}\,\varepsilon_1^{-1}(k,\omega)}{1-\exp\left(\frac{-\hbar\omega}{k_B T_e}\right)}$$

$$\mathrm{Re}\,\varepsilon_1^{-1}(k,\omega) = 1 + 2\mathcal{P}\int_0^\infty \frac{d\omega'}{\pi} \frac{\omega'\,\mathrm{Im}\,\varepsilon_1^{-1}(k,\omega')}{\omega'^2-\omega^2}$$

Sperling et al., J. Phys. B.: At. Mol. Opt. Phys. **50**, 134002 (2017)

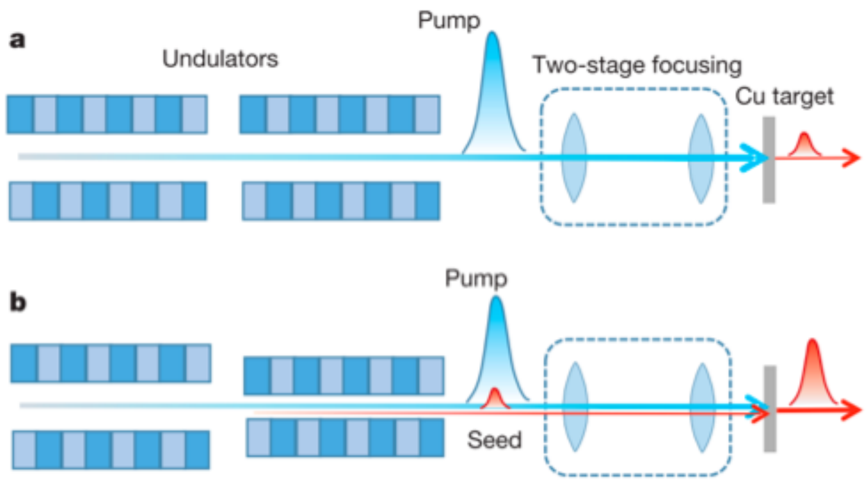
First observations of hard X-ray lasing on atomic transitions



Yoneda et al., Nature **524**, 446-449 (2015)

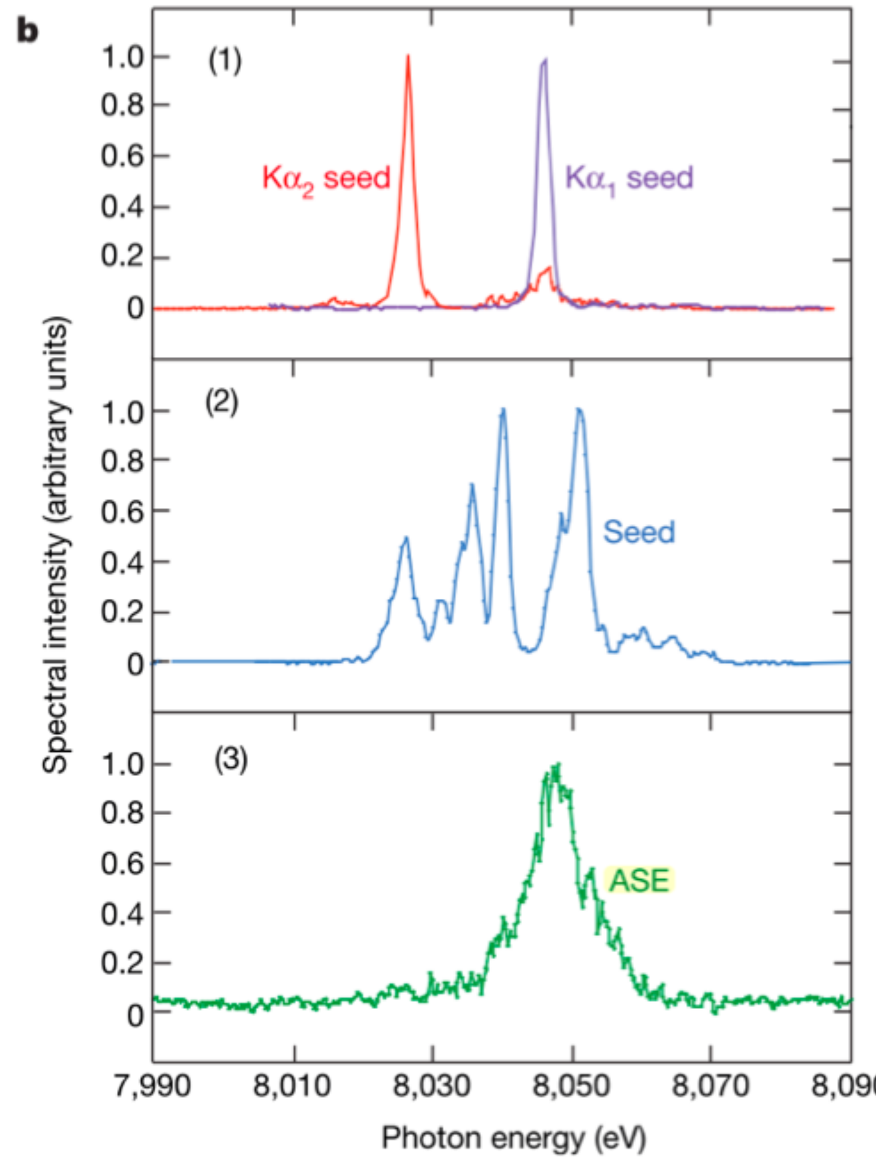
- Cu laser demonstrated at SACLA using both ASE (amplified spontaneous emission) and seeding.
- Left is shown ASE case as pump is increased.
- Lines get broader – more KLL Auger electrons yields more 3d vacancies.
- Line ratio is greater than that for spontaneous emission (2:1).

First observations of hard X-ray lasing on atomic transitions



Yoneda et al., Nature **524**, 446-449 (2015)

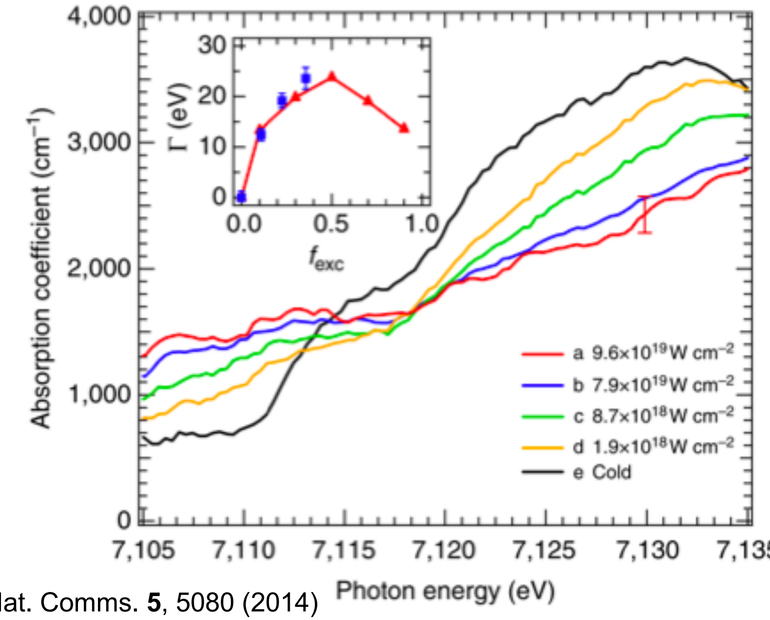
- Seeded case is achieved using variable gap undulators and one bunch. Pump above edge to create K-shell hole, then probe with seed on 1fs timescale.
- Large shot-to-shot variation in seed spectrum.
- Can pump each Kα line individually.
- Lines narrower indicating enhanced lifetime for upper level in laser.



Yoneda et al., Nature **524**, 446-449 (2015)

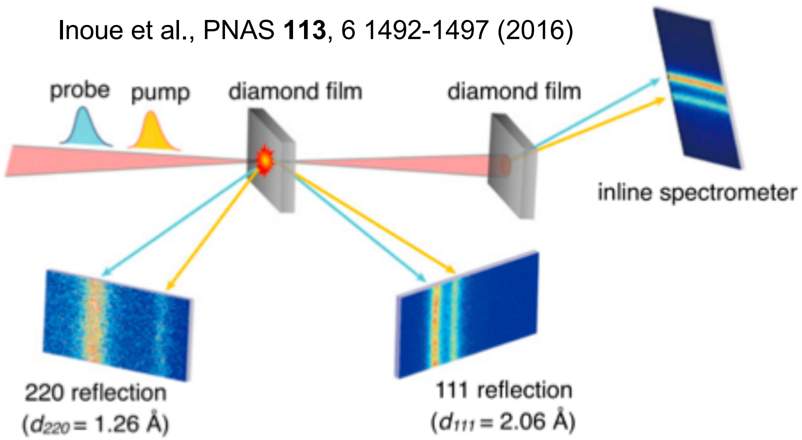
The future of isochoric heating

- Iron was isochorically heated at SACLA with 7keV X-rays and saturable absorption measured. observed.
- Pump-probe heating of diamond with ~6keV allows measurement of femtosecond X-ray damage processes.

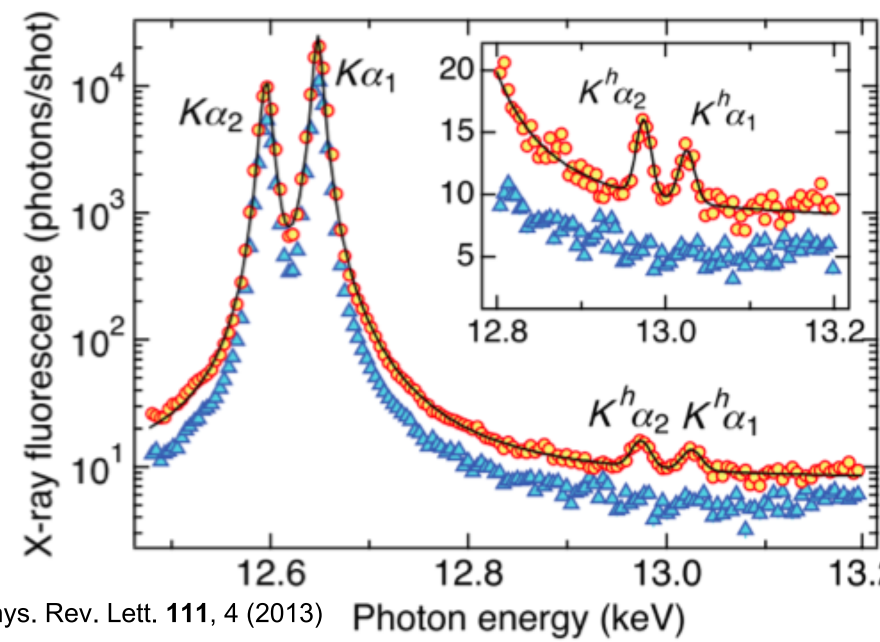


Yoneda et al., Nat. Comms. **5**, 5080 (2014)

Inoue et al., PNAS **113**, 6 1492-1497 (2016)



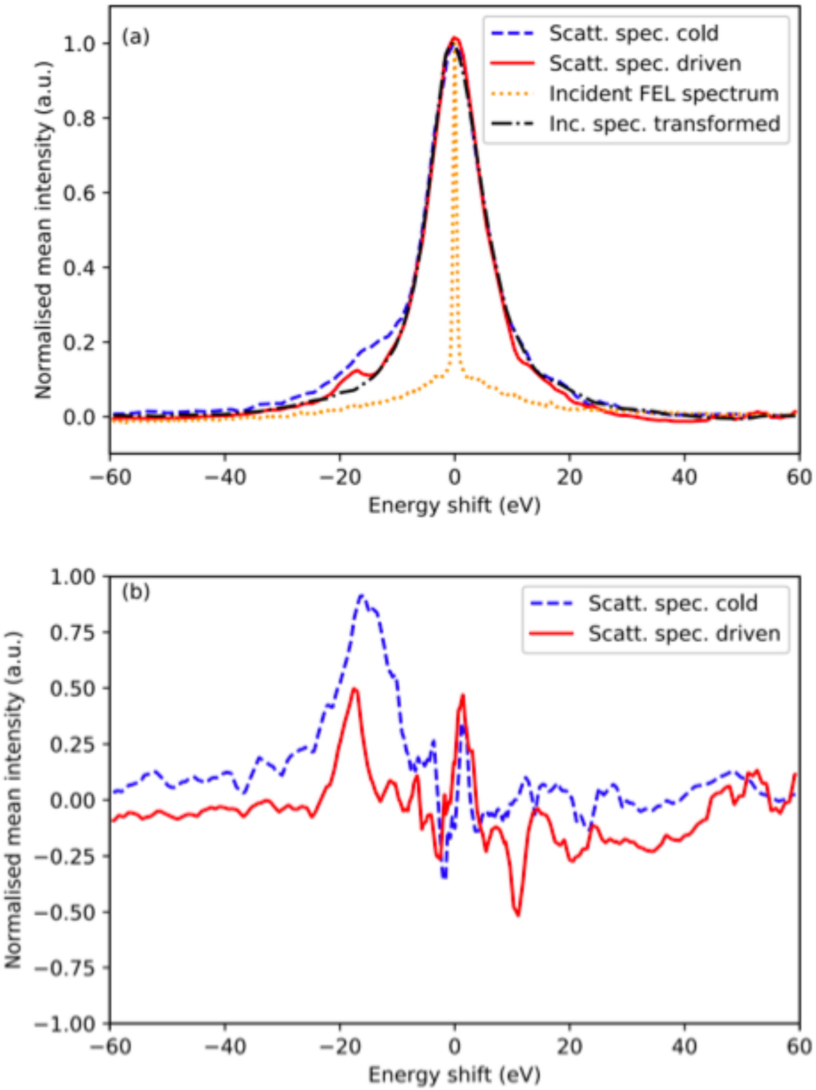
- Double core holes were created in Krypton with 15keV X-rays.
- With European XFEL we can push to harder photon energies (20keV fundamental) and smaller nanometre focal spots.



Tamasaku et al., Phys. Rev. Lett. **111**, 4 (2013)

The future of Thomson scattering with higher repetition rates

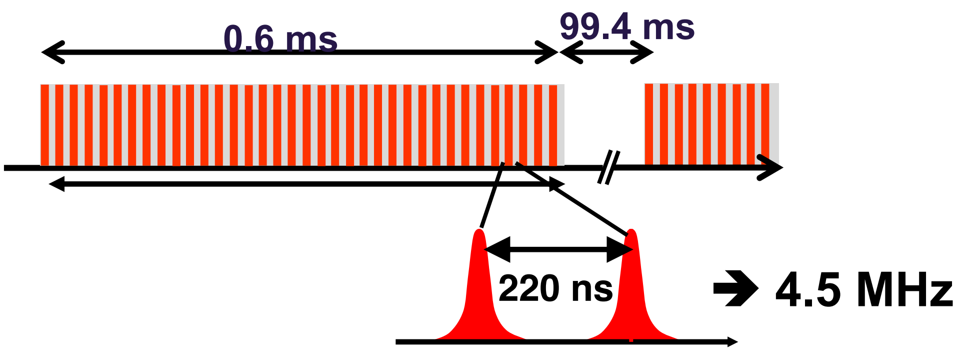
- Example shown is shock-compressed but principle is the same for isochoric heating.
- Measuring incident spectrum upstream allows elastic signal to be subtracted yielding just the plasmon.
- Higher repetition rate at XFEL on X-ray only and isochoric heating experiments will expedite these measurements of the shape of the plasmon.
- Further inferences from plasmons can then be made, such as the dielectric function.



Preston et al., Appl. Phys. Lett. **114**, 014101 (2019)

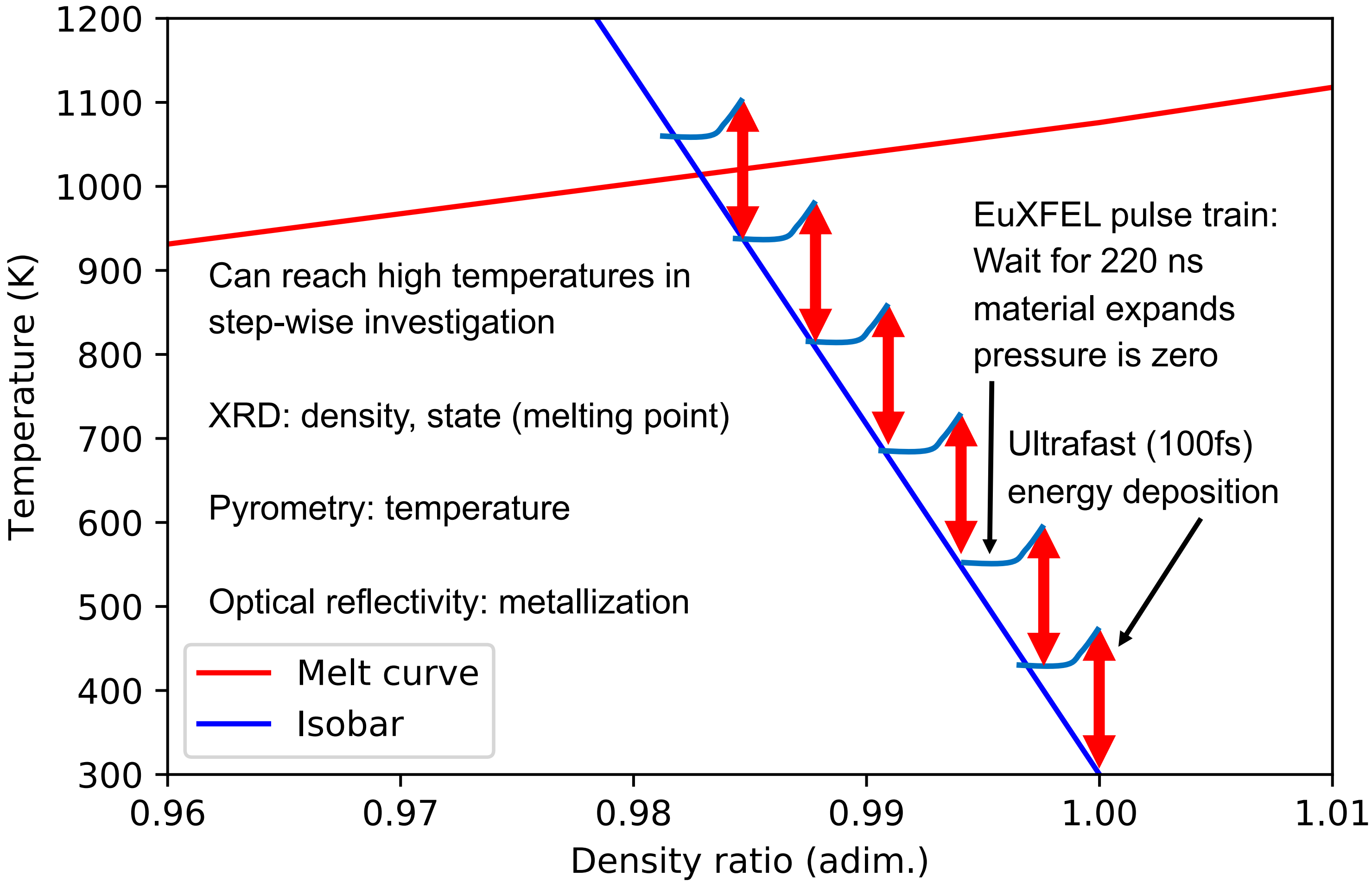
Exploring European XFEL's unique pulse train

0-2700 pulses/bunch



- Dynamic DAC (high P):
  - full structural history (XRD) of a material from 0 to few Mbar in one burst.
  - Strain rate studies (fast, slow ramp), Phase transition hysteresis studies.
  - Single x-ray pulses are ultrashort, no blurring. 1s at synchrotron ~ 1 shot at EuXFEL.
- Pulsed laser heated DAC (high P, T)
  - Temperature history of irradiated spot (pyrometry) correlated with structure (XRD).
  - X-ray emission studies at each pulse (time step).
  - No averaging over time like at synchrotron.
- Isobaric heating (high T)
  - Stepwise heating of sample until melt.
  - Investigation of structure (XRD), temperature (pyrometry), optical properties (R,T, A).
  - Pressure is constant by free expansion in vacuum.

The future with isobaric expansion experiments



Melt curve from:

A. Hänström and P. Lazor, J. Alloys Compd. **305**, 209 (2000)

Isobar assuming linear thermal expansion with $\alpha = 24 \times 10^{-6}\ K^{-1}$

Over a decade of XFEL isochoric heating of dense plasmas

First Spectroscopy of XUV FEL-heated solid density plasma
Zastrau et al., PRE **78** 066406 (2008)

First observation of saturable absorption, “transparent aluminum”
Nagler et al., Nature Physics **5** 693–696 (2009)

Conduction band temperature measurements
Vinko et al., Phys. Rev. Lett. **104** 225001 (2010)
Medvedev et al., Phys. Rev. Lett. **107** 165003 (2011)

First Spectroscopy of LCLS-heated solid density Al plasma
Vinko et al., Nature **482** 59-62 (2012)

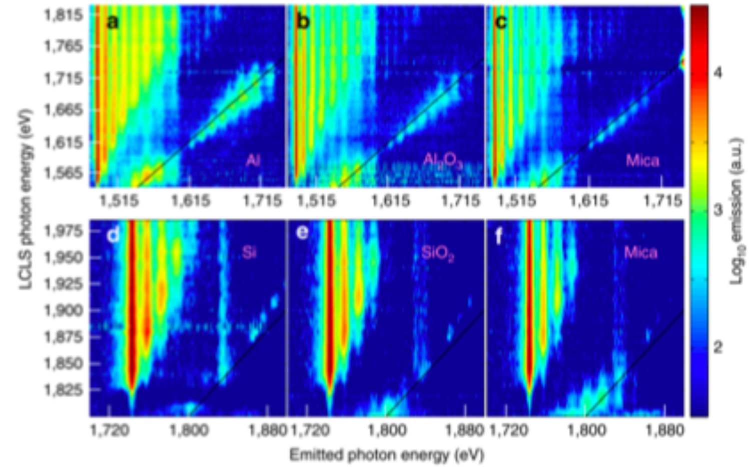
Measurements of ionization potential depression in Al, Mg, Si, and compounds
Ciricosta et al., Phys. Rev. Lett. **109** 065002 (2012)
Ciricosta et al., Nature Comm. **7** 11713 (2016)

First XUV-pump XUV-probe experiment on dense hydrogen plasma
Zastrau et al., Phys. Rev. Lett. **112** (2014)

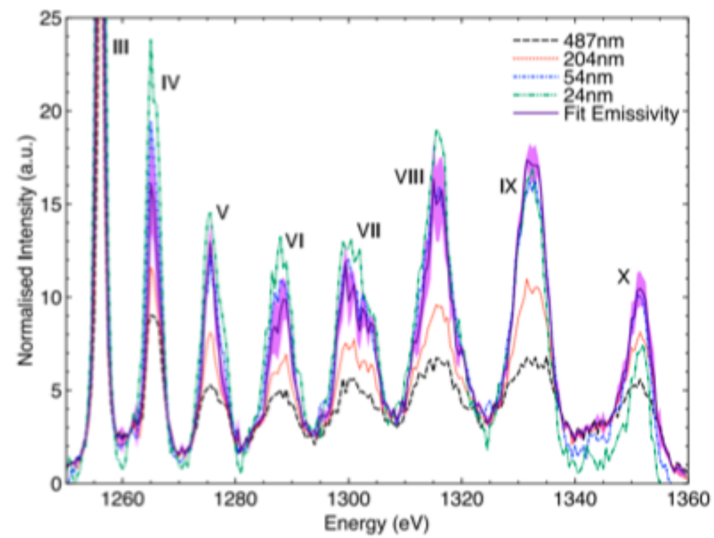
First observations of hard X-ray lasing on atomic transitions
Yoneda et al., Nature 524, 446-449 (2015)

Measurement of unexpectedly high collisional rates
Vinko et al., Nature Communications **6** 6397 (2015)
Van den Berg et al., Phys. Rev. Lett. 120, 055002 (2018)

Measurements of K-shell opacities of solid Mg plasma
Preston et al., Phys. Rev. Lett. **119**, 085001 (2017)



Ciricosta et al., Nature Comm. **7** 11713 (2016)



Preston et al., Phys. Rev. Lett. **119**, 085001 (2017)