High Energy Density Science on FELs

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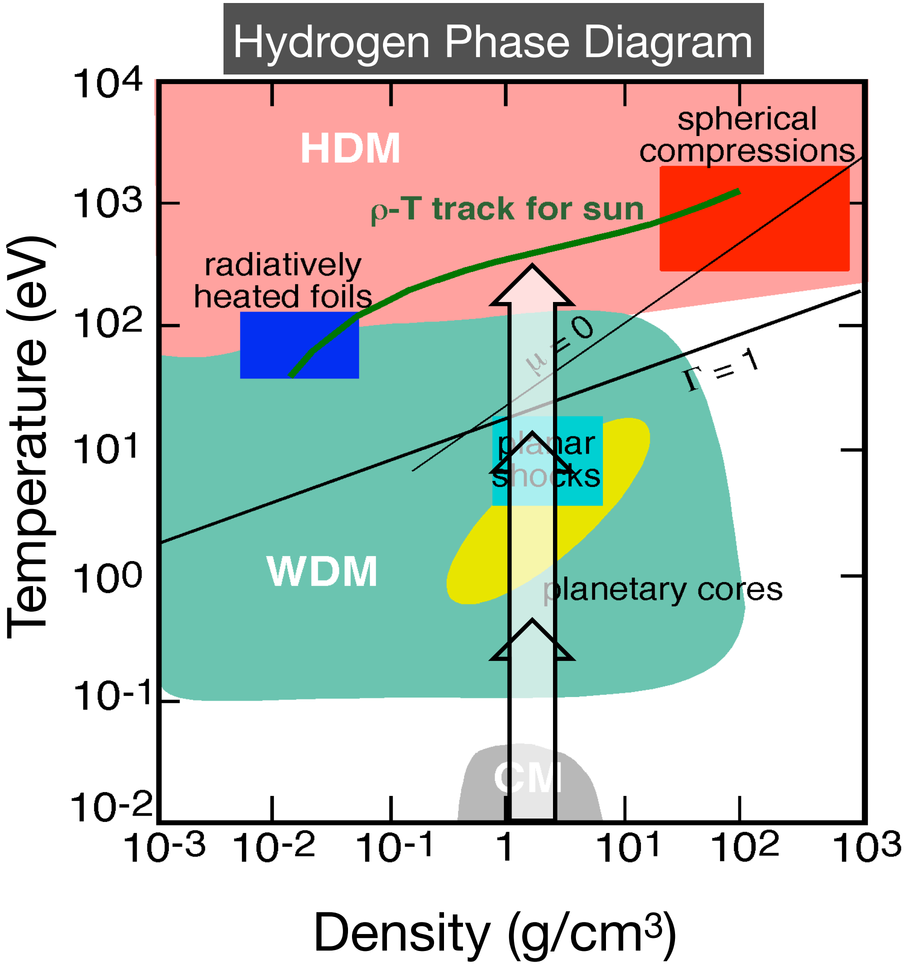
Overview

- FELs provide a unique way to controllably create high energy density systems and probe specific properties in isolation.
  - By HEDS we mean warm/hot dense matter (plasmas), akin to stellar interiors. These can be created by intense x-ray FEL radiation (x-ray only experiments).
  - OR
  - we mean highly compressed solids (or again plasmas) generated by optical lasers:
  - > 100 J nanosecond lasers can produce solid state matter at TPa pressures (exoplanet interiors) by ramp compression along an isentrope, and dense plasmas by shock compression.
  - The community is also interested in using few 100 TW (ideally PW) short pulse lasers to produce even hotter conditions.
  - *For the experiments involving optical lasers your system is only as good as the worst of the optical/x-ray laser - so you must consider the expense of optical drivers. Some science can be performed with 'cheap' (few Million) commercial systems, but in any event the optical aspect should be designed in from the start.*

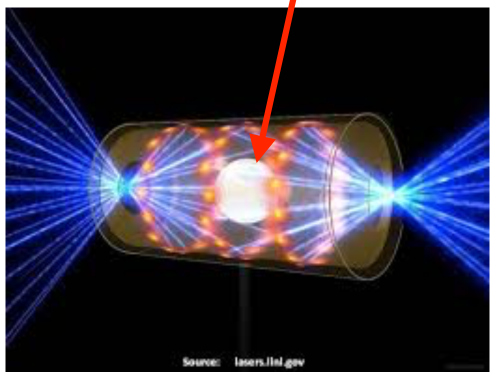
Creating well-controlled HED states is extremely challenging



Isochoric heating with femtosecond, bright X-ray free-electron laser (FEL) sources creates well-defined warm- and hot-dense matter.

We can controllably create plasmas at:

- **temperatures between 1–250 eV (~1keV?)**
- **densities between 10^{23}–10^{25} electrons/cm^3**



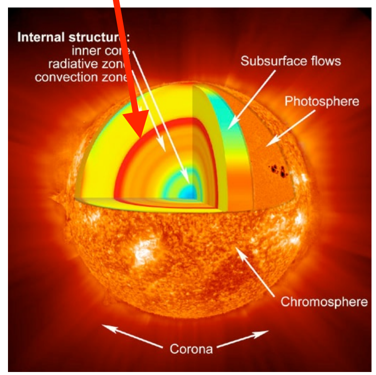
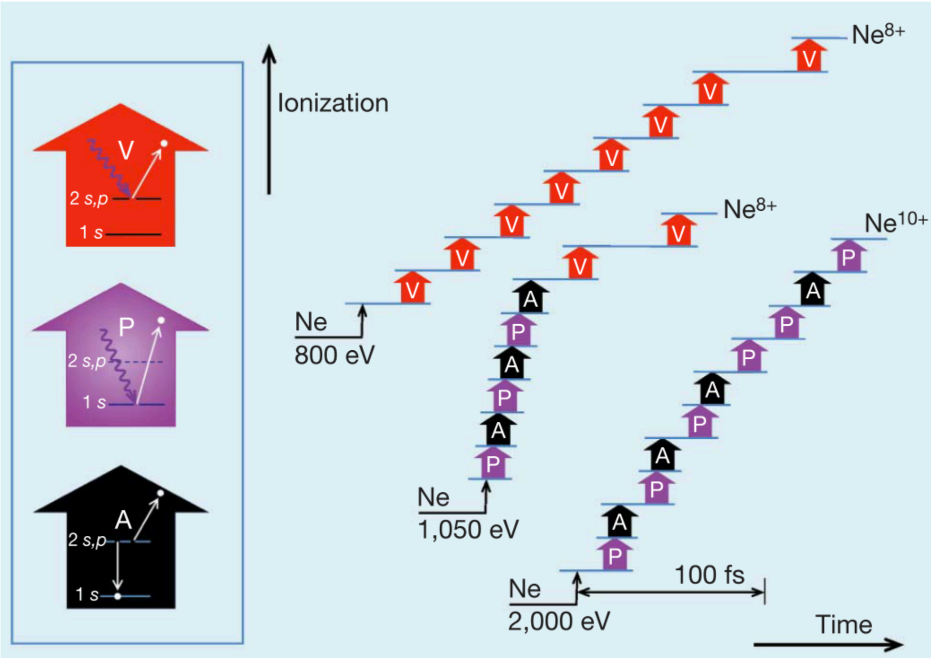
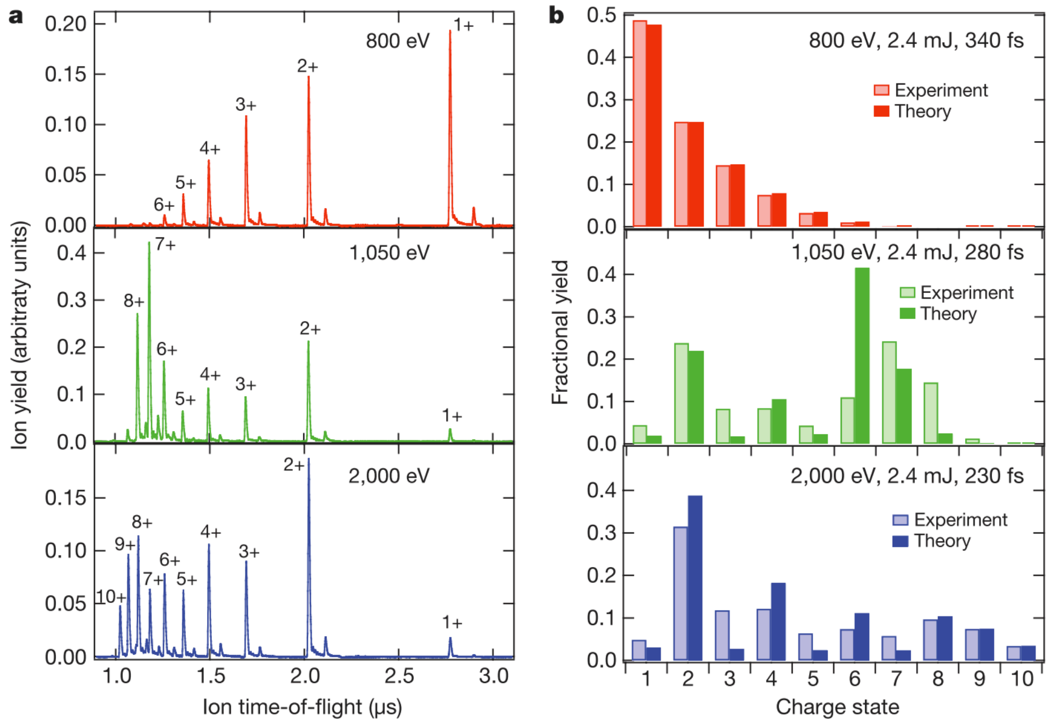


Figure: R.W. Lee et al., J. Opt. Soc. America B 20, 770 (2003).

First experiments at LCLS show dominance of multi-photon ionization

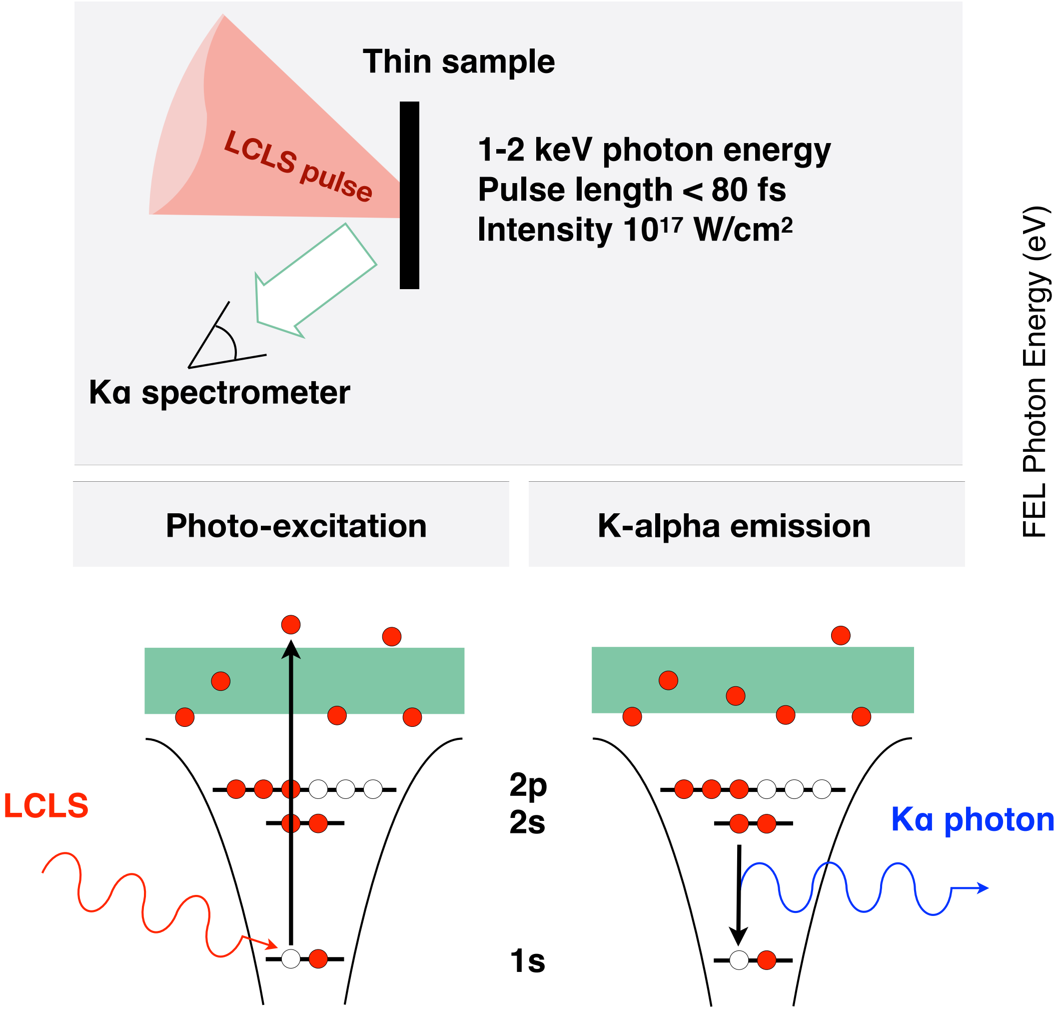
First experiments on Ne at LCLS in 2009 show sequential multi-photon ionization can strip Ne atoms of all their electrons on fs timescales

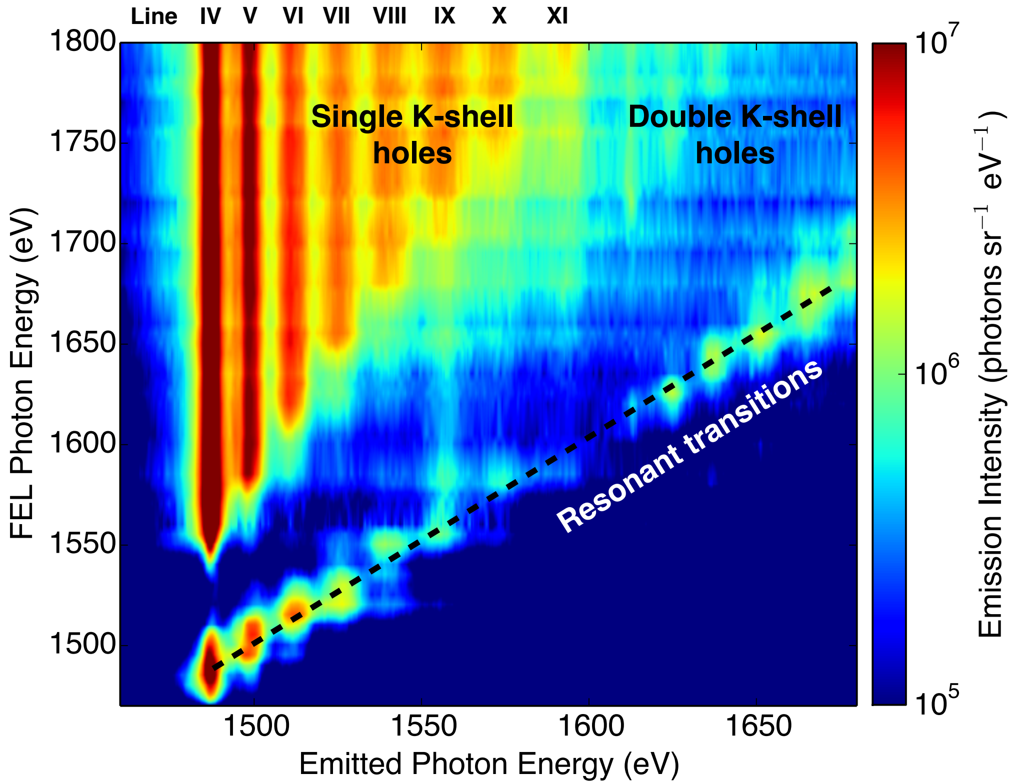




Young et al., Nature 466, 56–61 (2010).

X-ray spectroscopy shows that hot dense plasmas can be created isochorically at solid density



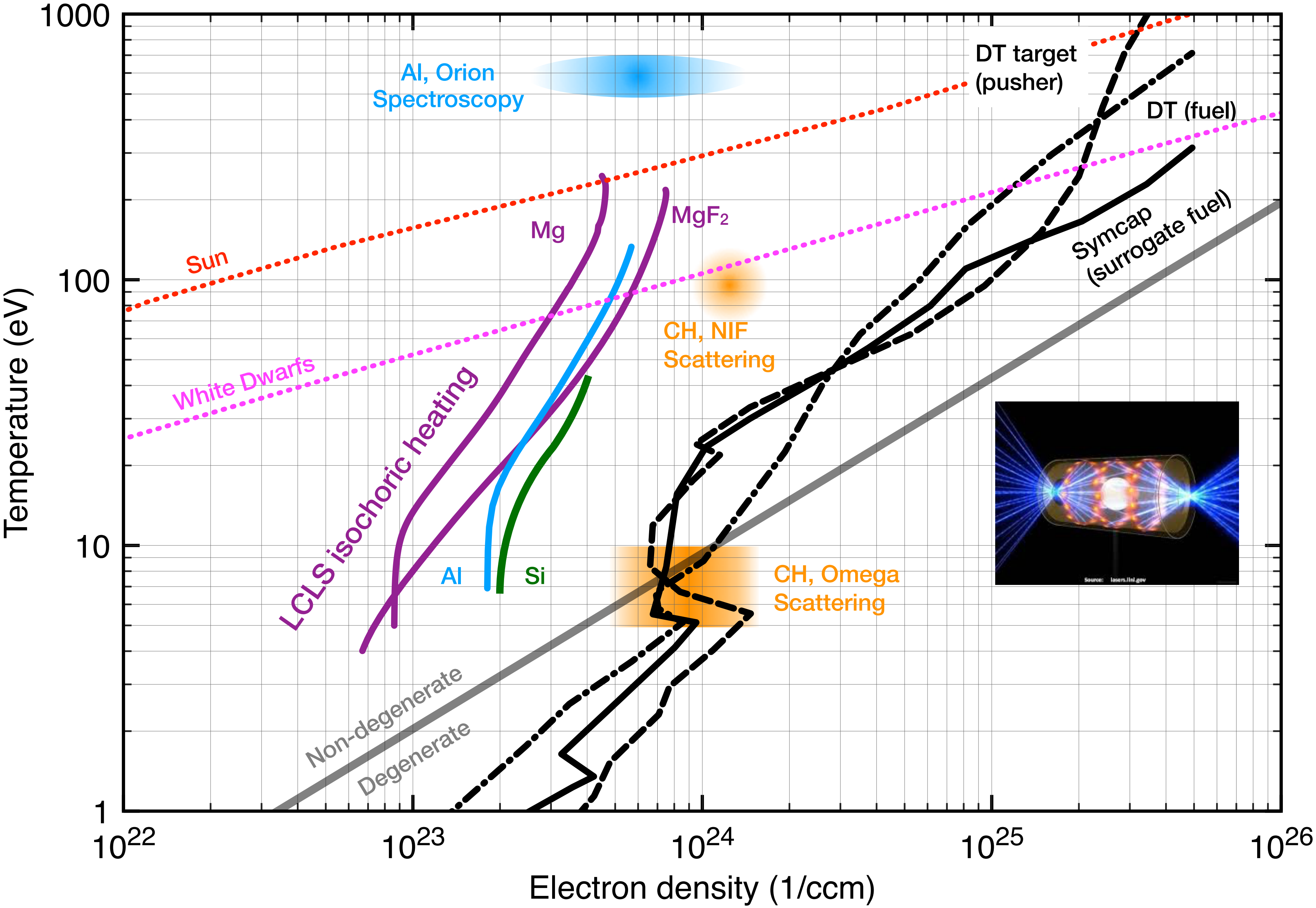


X-ray-driven emission spectroscopy can measure electronic structure of plasmas

Collisions beat photoionization, in contrast to experiments in atoms and clusters.

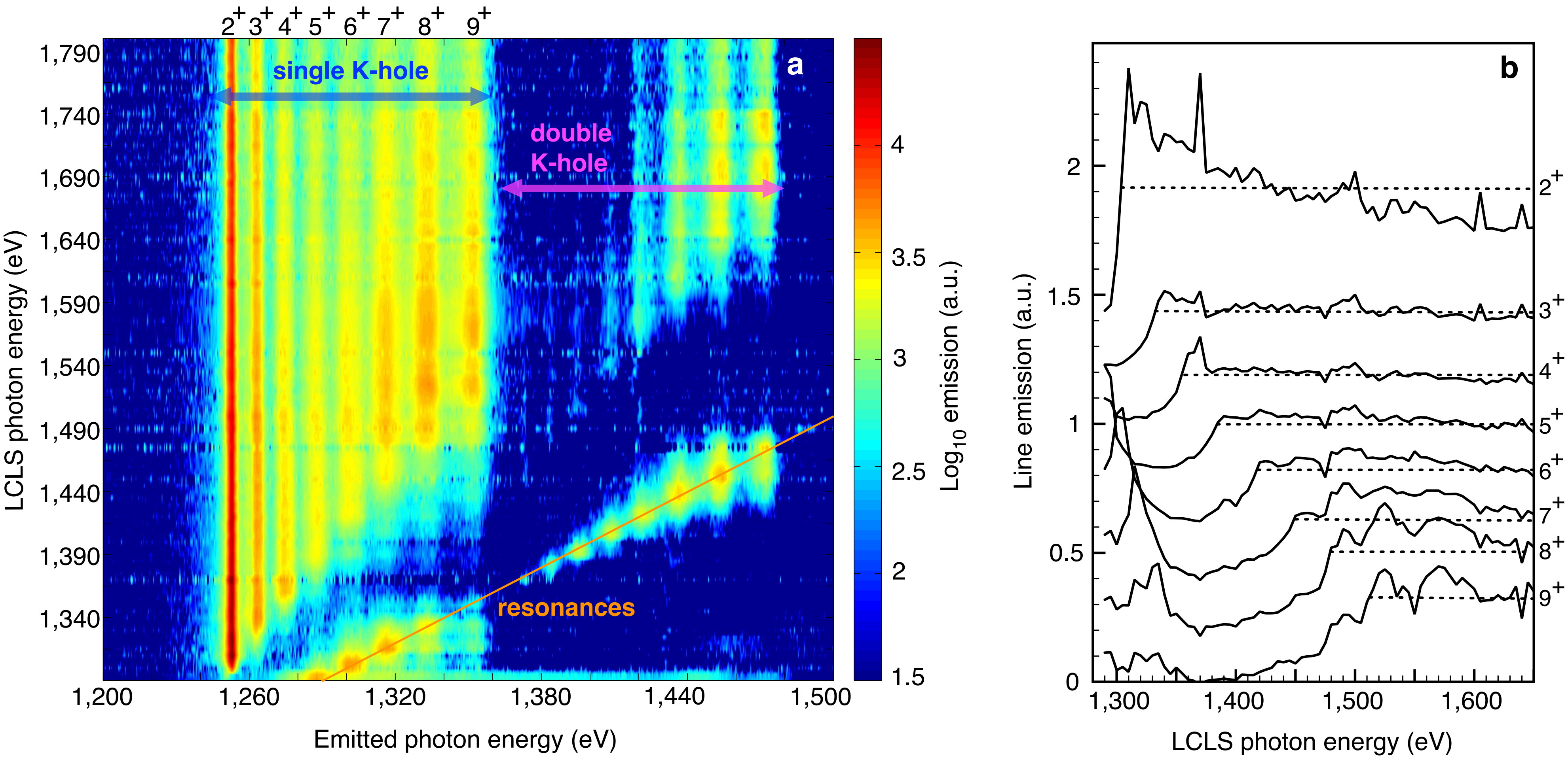
Vinko et al., Nature 482, 59 (2012)
Cho et al., PRL 109, 245003 (2012)

FELs can isochorically create high energy density plasmas



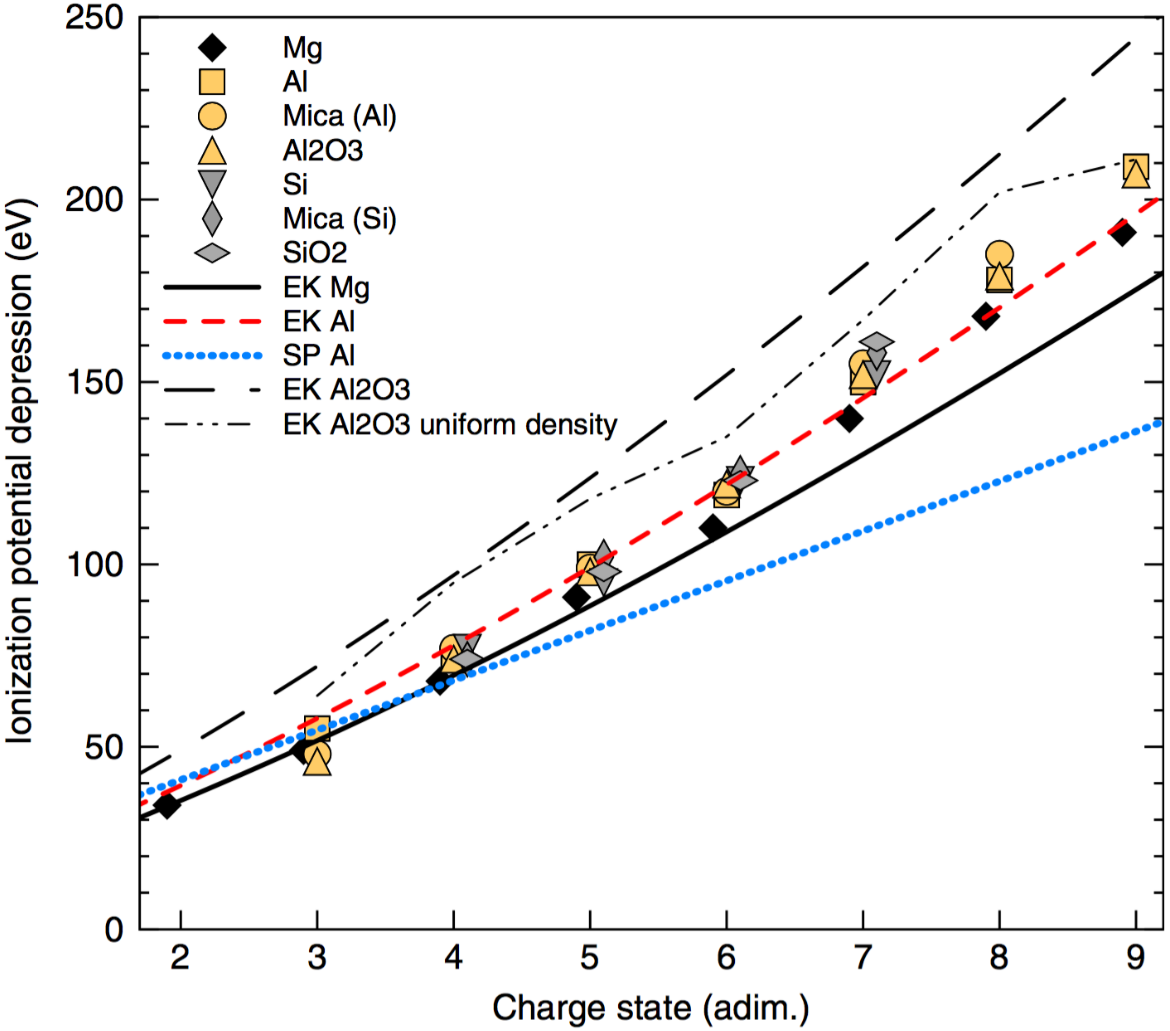
Measurements of electronic structure of Mg plasmas

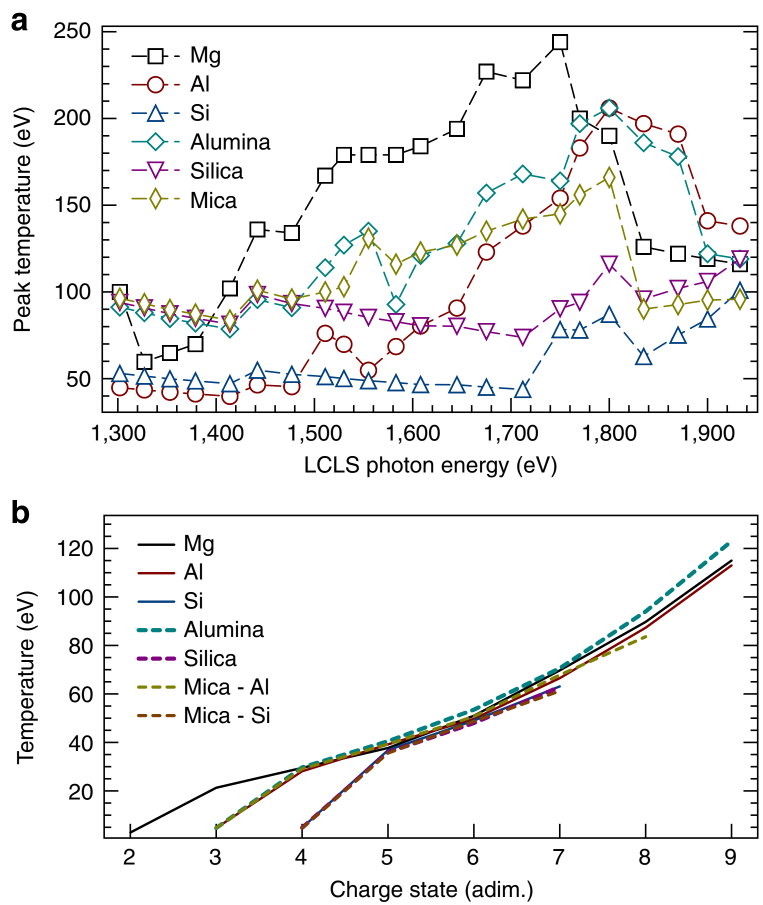
We can map how the plasma environment affects atomic physics via x-ray spectroscopy



Ciricosta et al., PRL 109, 065002 (2012)
Vinko et al, Nat. Commun. 5, 3533 (2014)
Ciricosta et al., Nat. Commun. 7, 11713 (2016)

Ionization potential depression depends on the local density

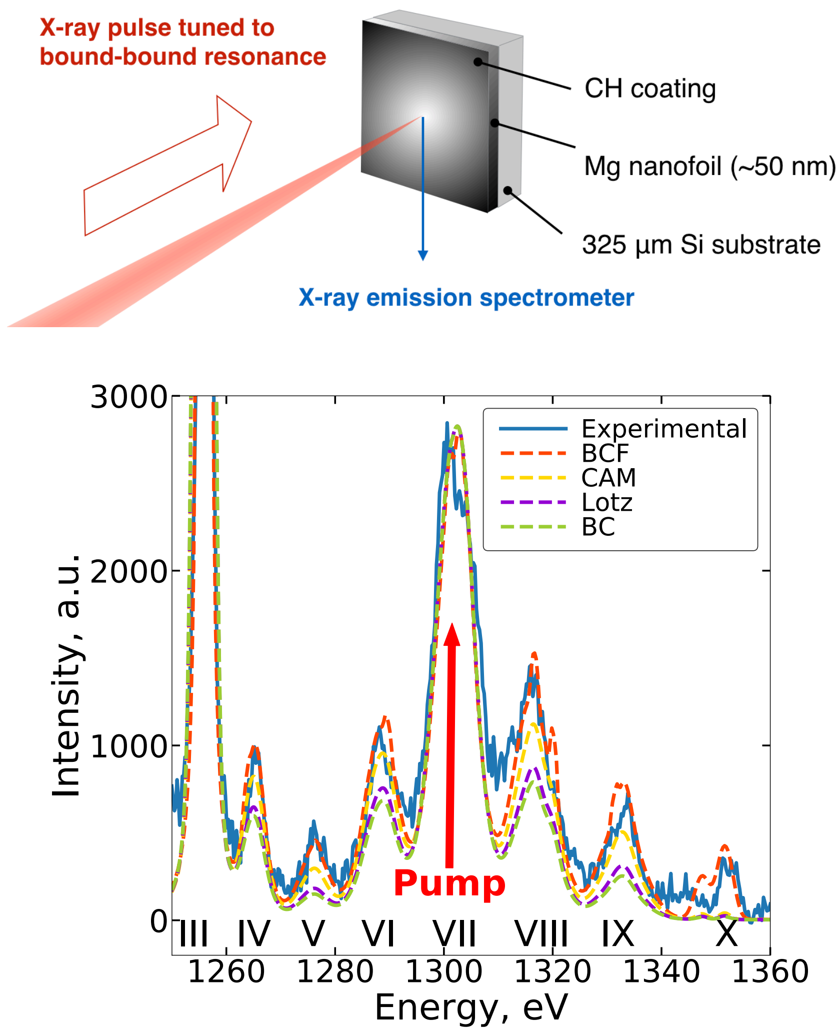




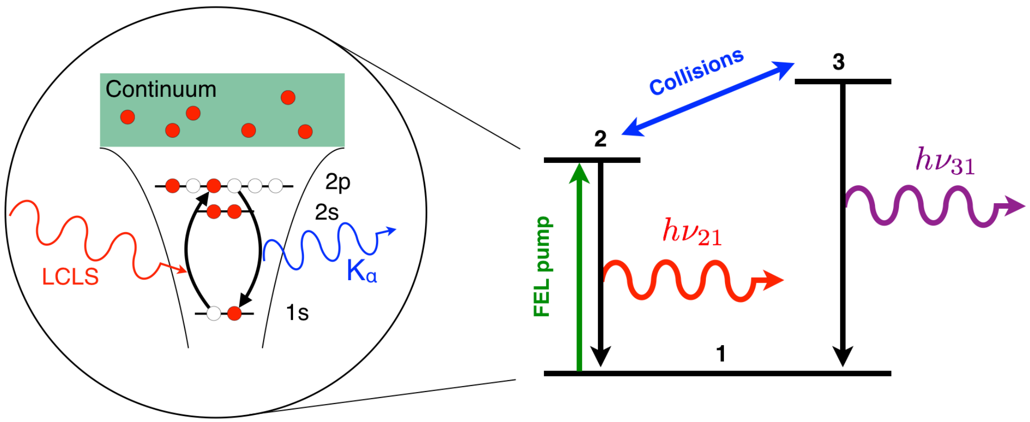
Ciricosta et al., Nat. Commun. 7, 11713 (2016)

XFELs can clock sub-femtosecond electron collisional dynamics

- How quickly does do electrons collisionally ionize in hot-dense plasmas?
- What are the timescales for electron 'damage' in dense systems?



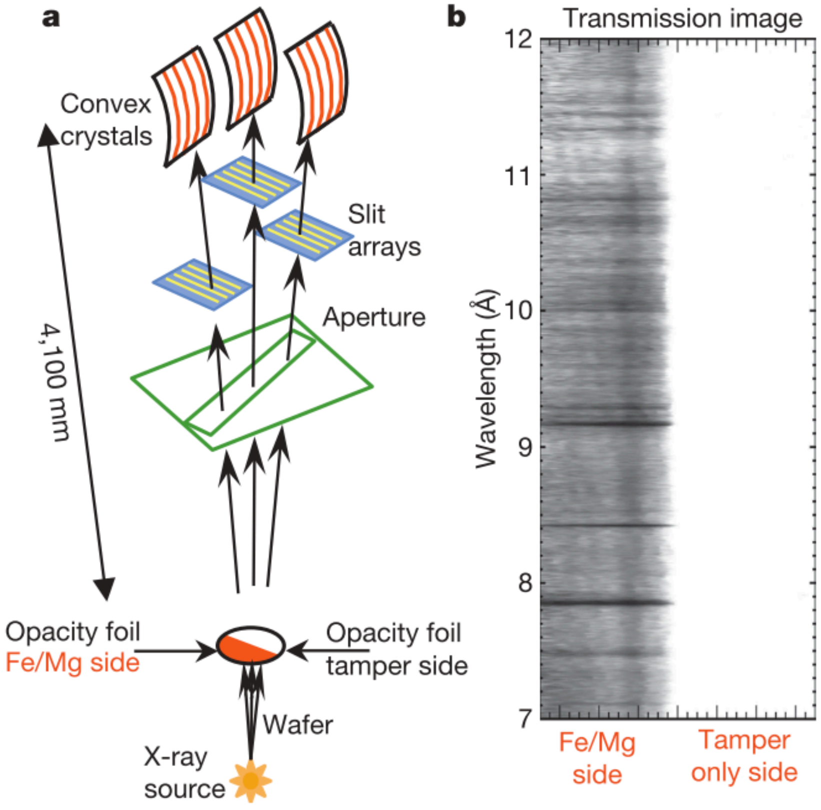
Collisions are 'clocked' by the Auger decay: Auger clock for collisional dynamics.

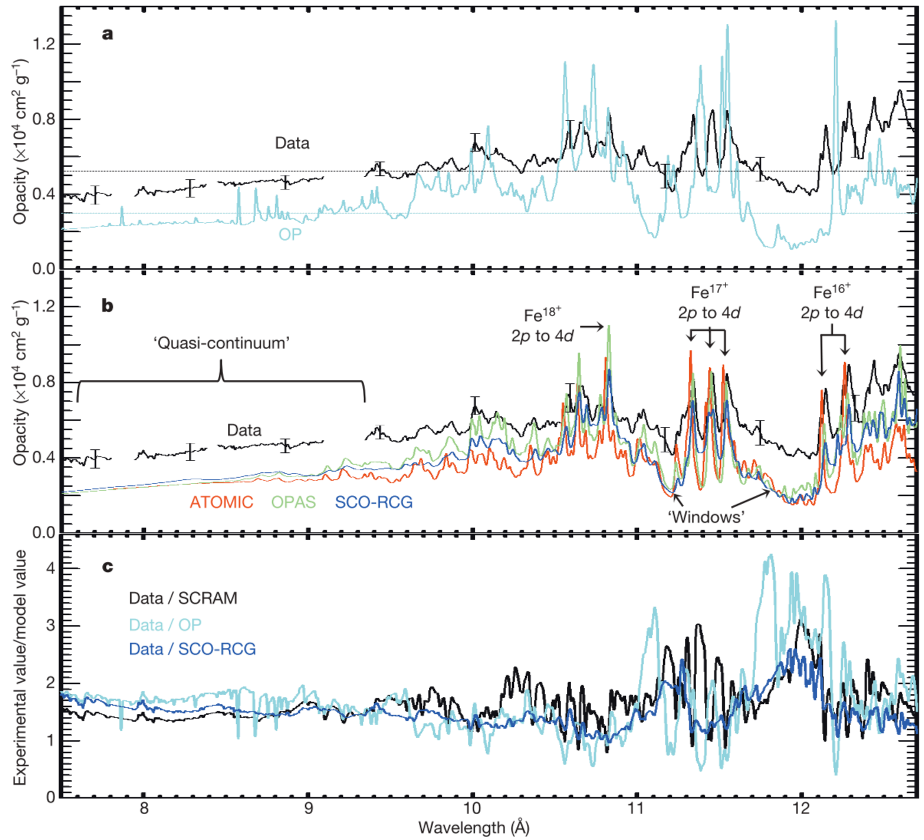


$$R_{\text{Collisions}} = R_{\text{Auger}} \cdot \left[\frac{I(\nu_{21})}{I(\nu_{31})} - 1 \right]^{-1}$$

Vinko et al., Nature Commun. 6, 6397 (2015)
van den Berg et al., PRL 120, 055002 (2018)

Radiation absorption by stellar matter controls the internal temperature profiles within stars





Solar models using elemental abundances from photosphere spectral analysis disagree with helioseismic observations.

Bailey et al., Nature 517, 56, (2015)

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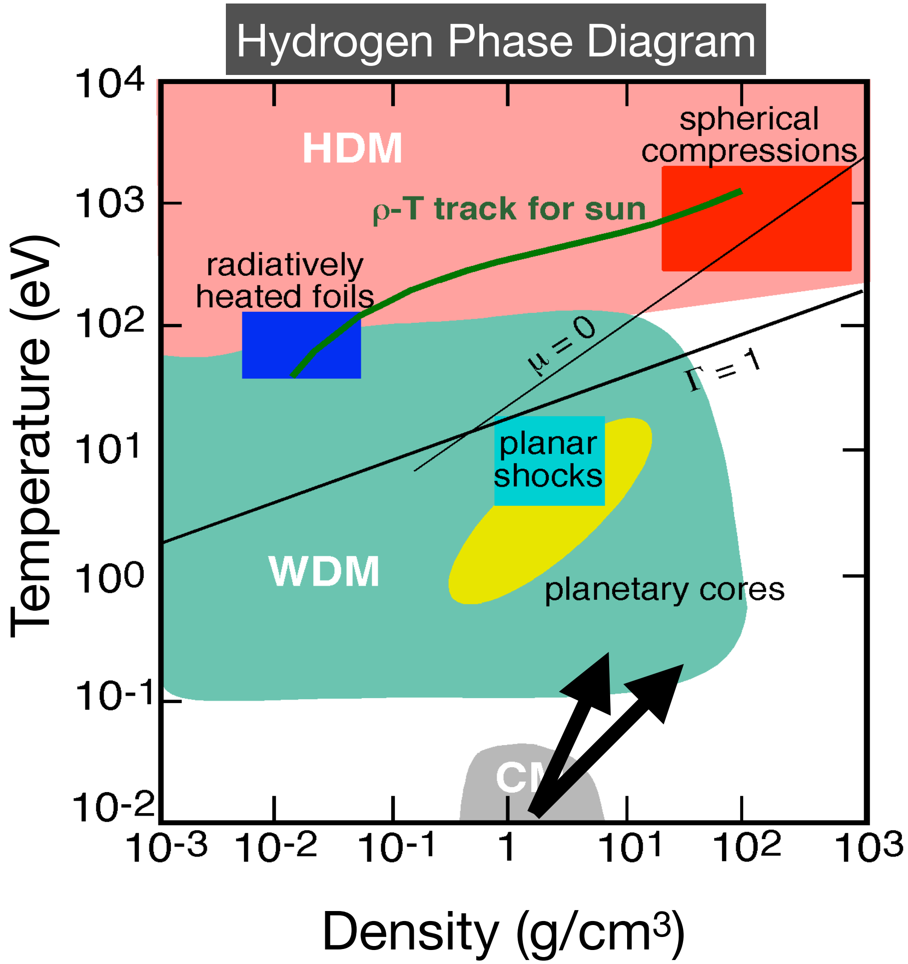
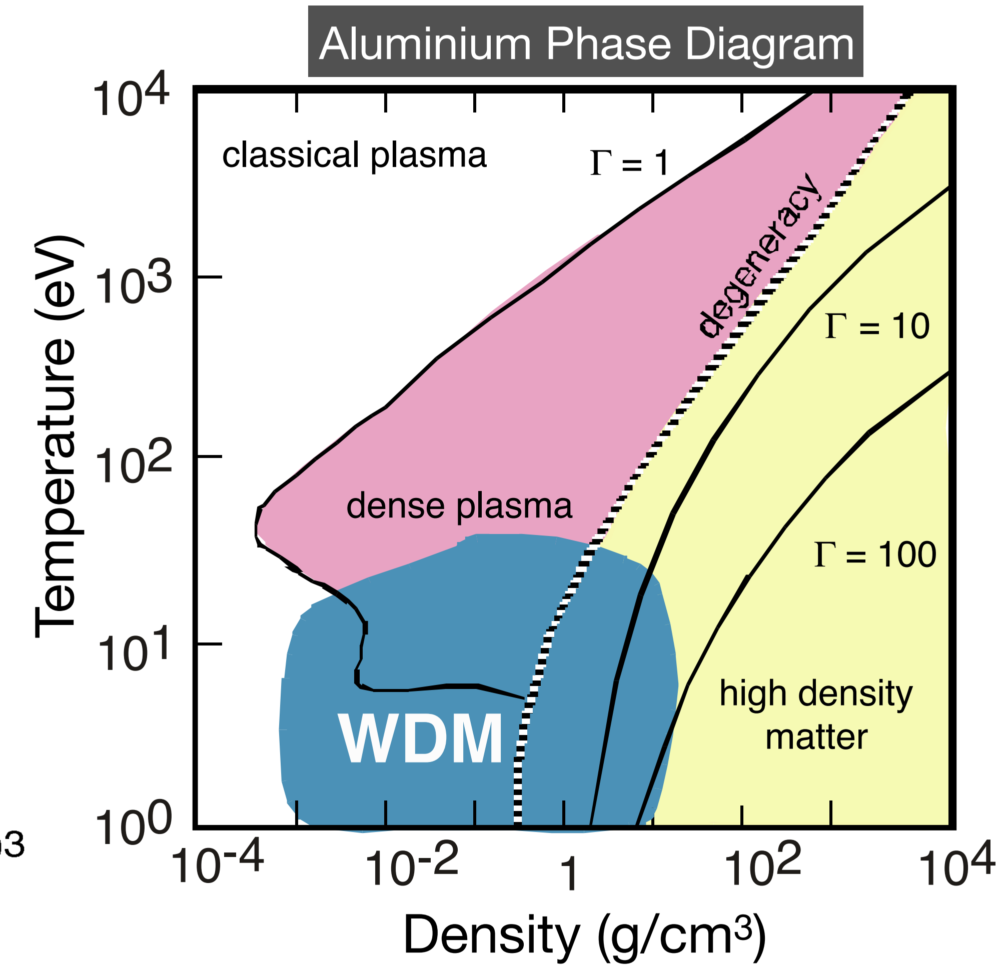
Summary of ‘x-ray only’ wish-list

- FELs provide a unique way to controllably create high energy density systems and probe specific properties in isolation. But we need:
  - high pulse energies - several mJ (single-shot experiments required, stability);
  - broad range of photon energies; capability to pump in soft x-ray regime (1-2 keV) and probing at hard x-rays (~ 8 keV) would be fantastic;
  - pump-probe time delays between 1-2 fs to 100’s of ps (explore collisional physics);
  - short pulses (< 10 fs, < 1fs) with high energy (>2 mJ);
  - resonant processes & scattering techniques would benefit from much smaller bandwidths ($<10^{-4}$), but without sacrificing too many photons.
  - High repetition rate & 2D detectors with single-photon counting capability

Matter in extreme conditions



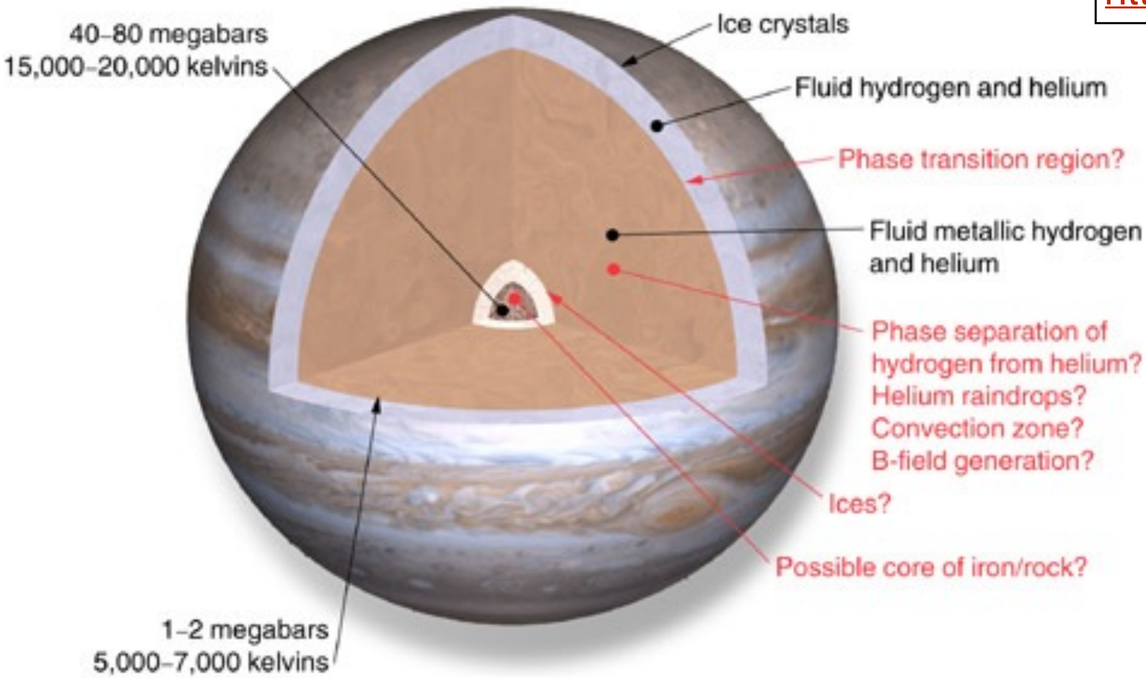


$$\Gamma = \frac{V_{\text{Coulomb}}}{E_{\text{Kinetic}}} \approx 1$$

Figure: R.W. Lee et al., J. Opt. Soc. America B **20**, 770 (2003).

Warm Dense Matter (WDM) occurs widely in nature

Planetary Physics



http://exoplanets.org

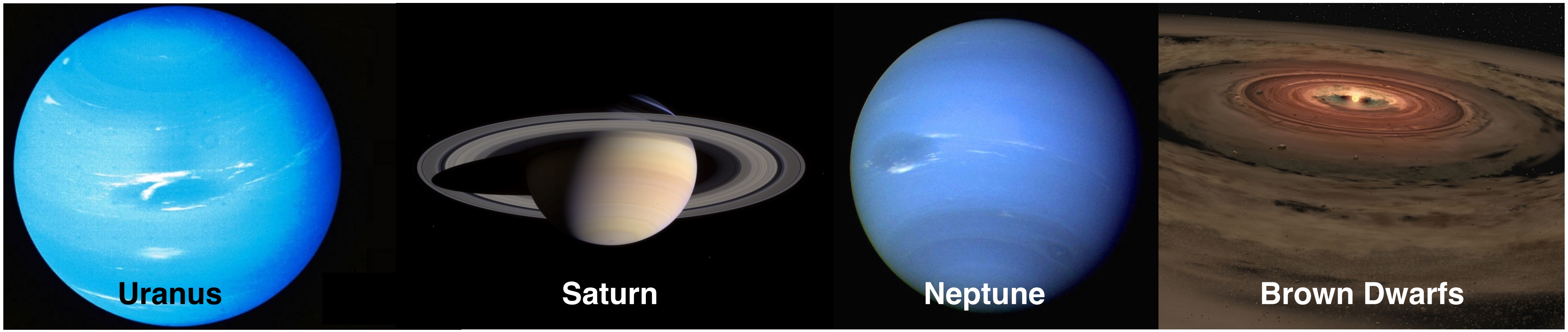
2925 EOD Planets
Planets with good orbits listed in the Exoplanet Orbit Database

25 Other Planets
Including microlensing and imaged planets

2950 Total Confirmed Planets

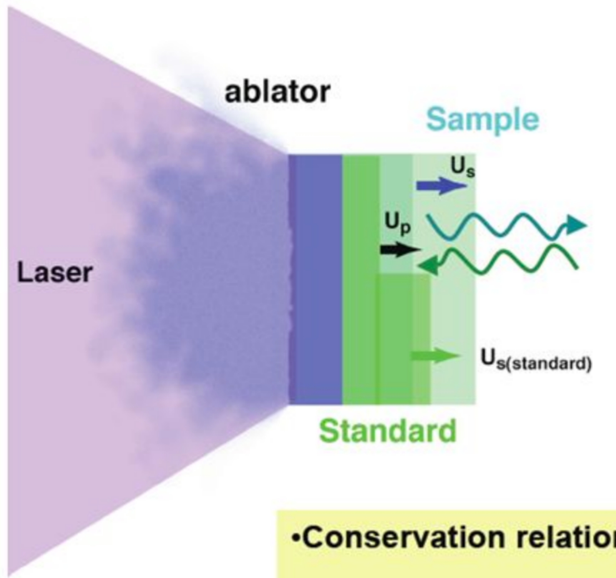
2504 Unconfirmed Kepler Candidates

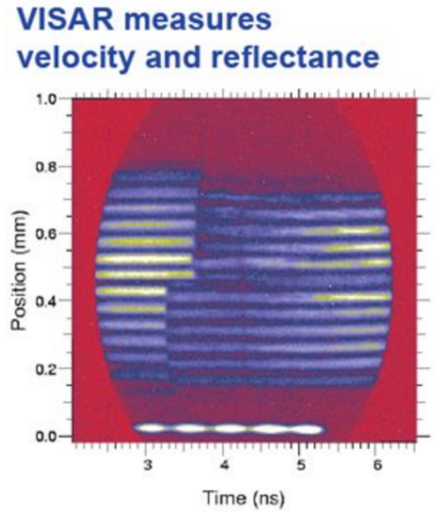
5454 Total Planets
Confirmed planets + Kepler Candidates



Laser Ablation

- Laser irradiates an ablator and launches shock
- VISAR measures the velocities of particles, shock and standard from a stepped sample





•Conservation relations => $P = \rho_0 U_s U_p$

$\rho/\rho_o = 1/(1-U_p/U_s)$

•Temperature needs to be measured separately

Nanosecond lasers can easily induce multi-TPa (1TPa=10Mbar)

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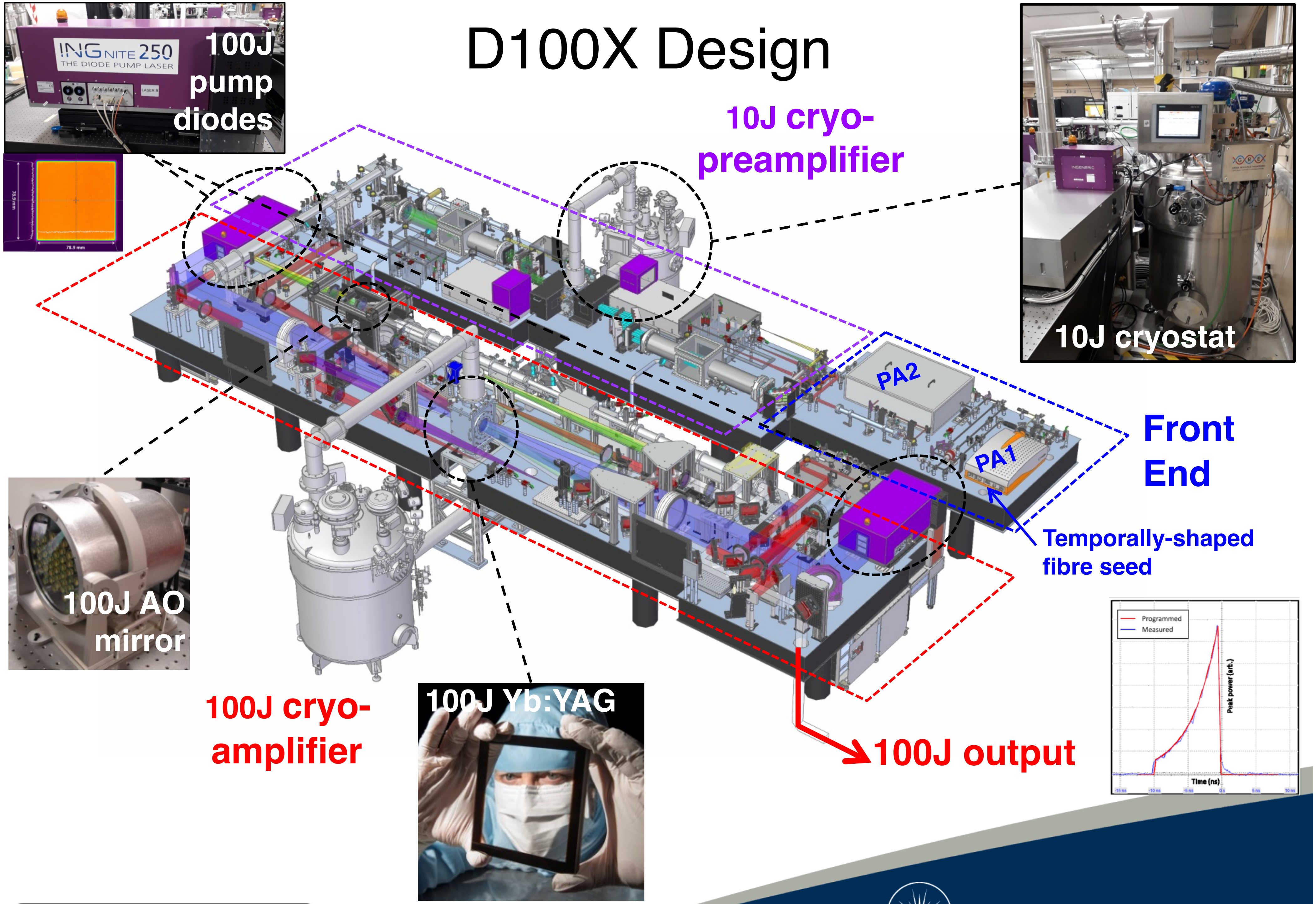
D100X Design

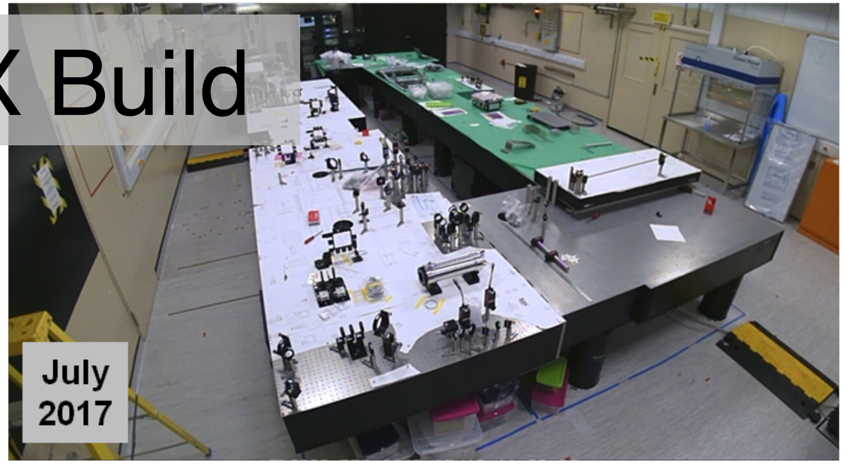


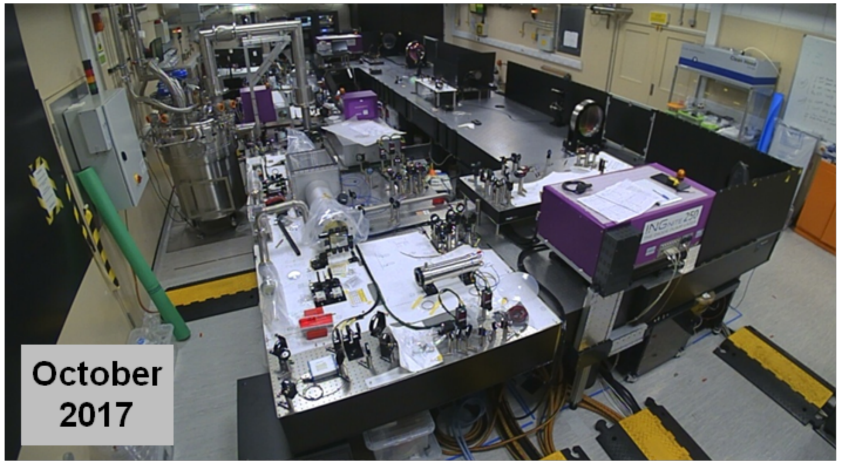
DiPOLE100

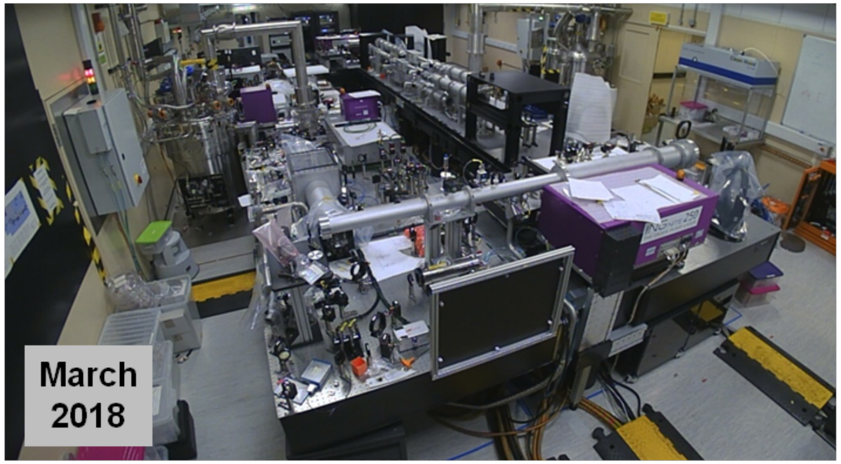
Science & Technology Facilities Council
Central Laser Facility

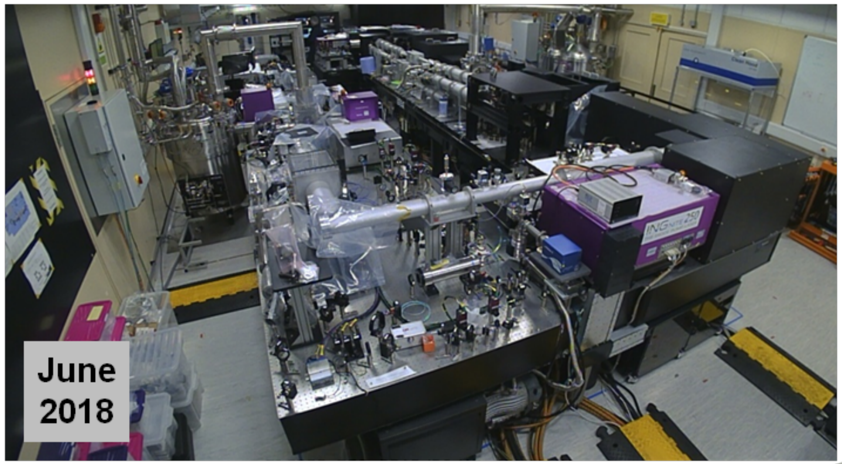
D100X Build

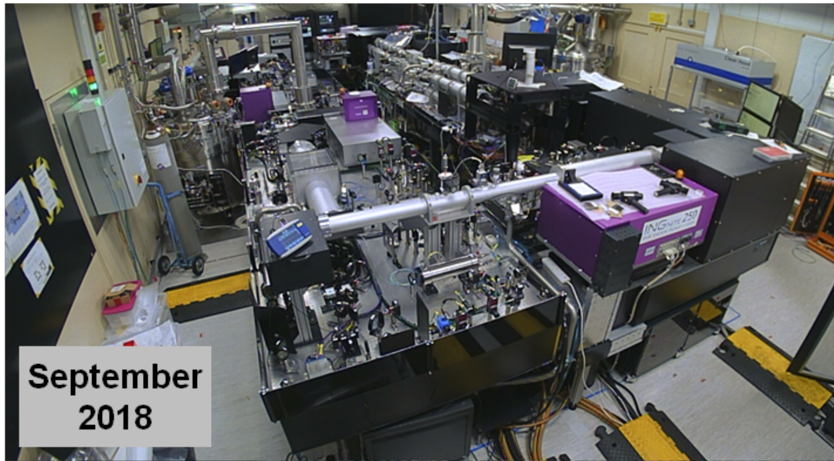

March
2017


July
2017


October
2017

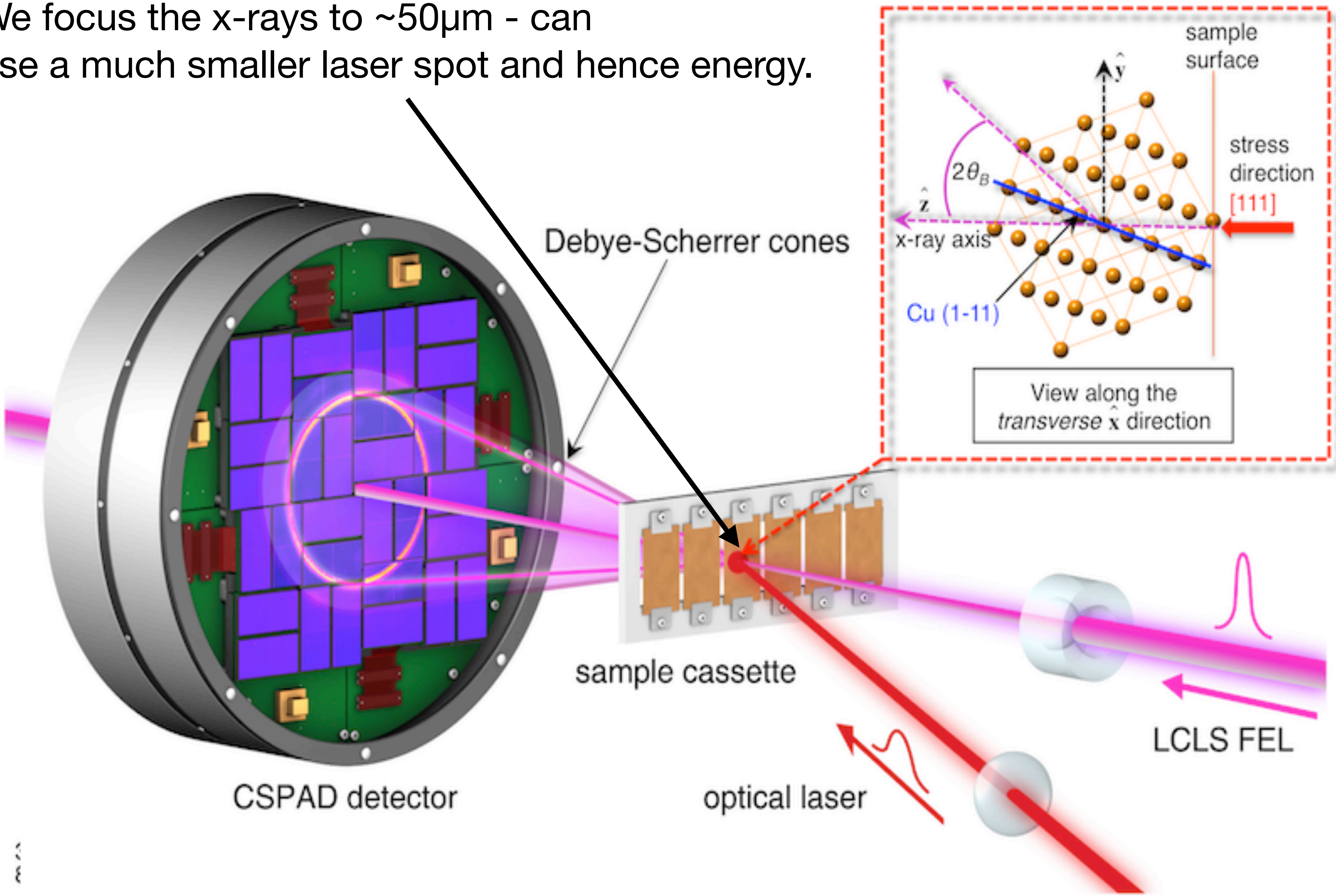

March
2018


June
2018


September
2018

Experimental Set-Up - CXI

We focus the x-rays to ~50μm - can use a much smaller laser spot and hence energy.



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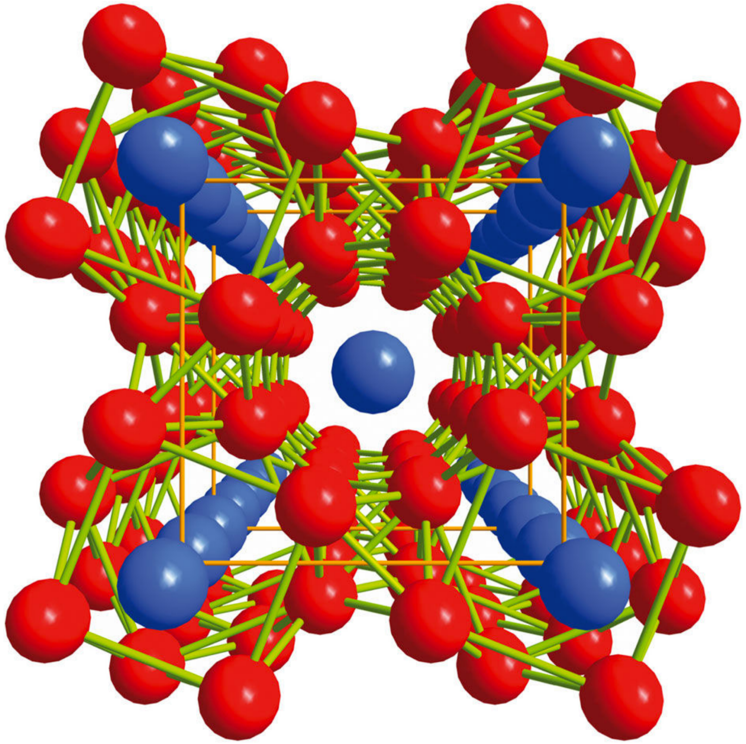
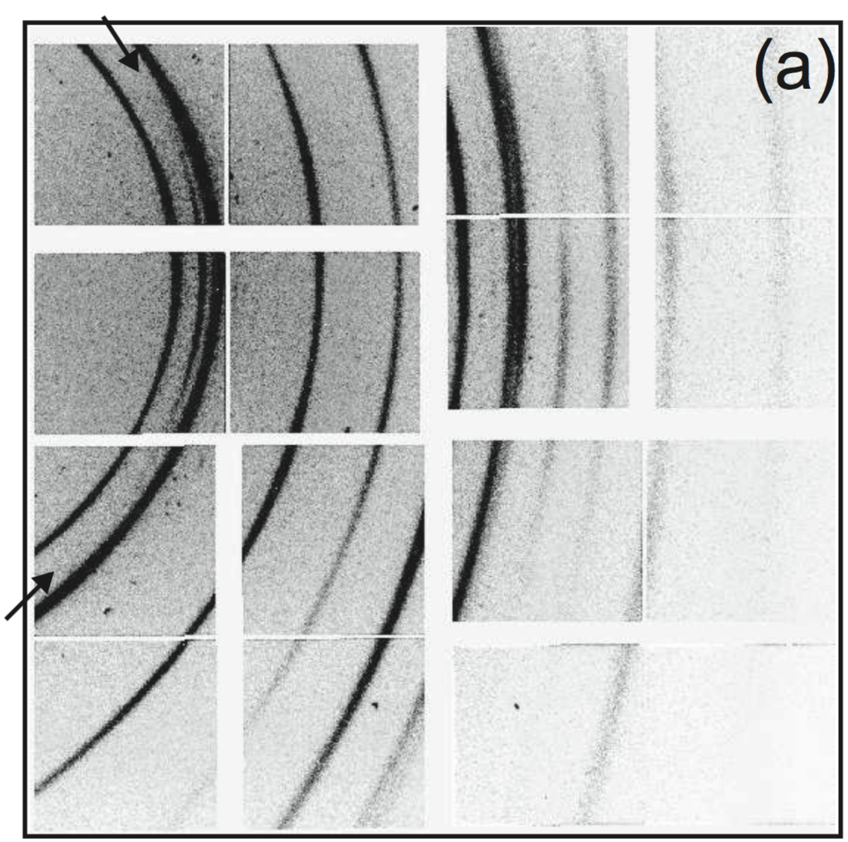
Host Guest Structures

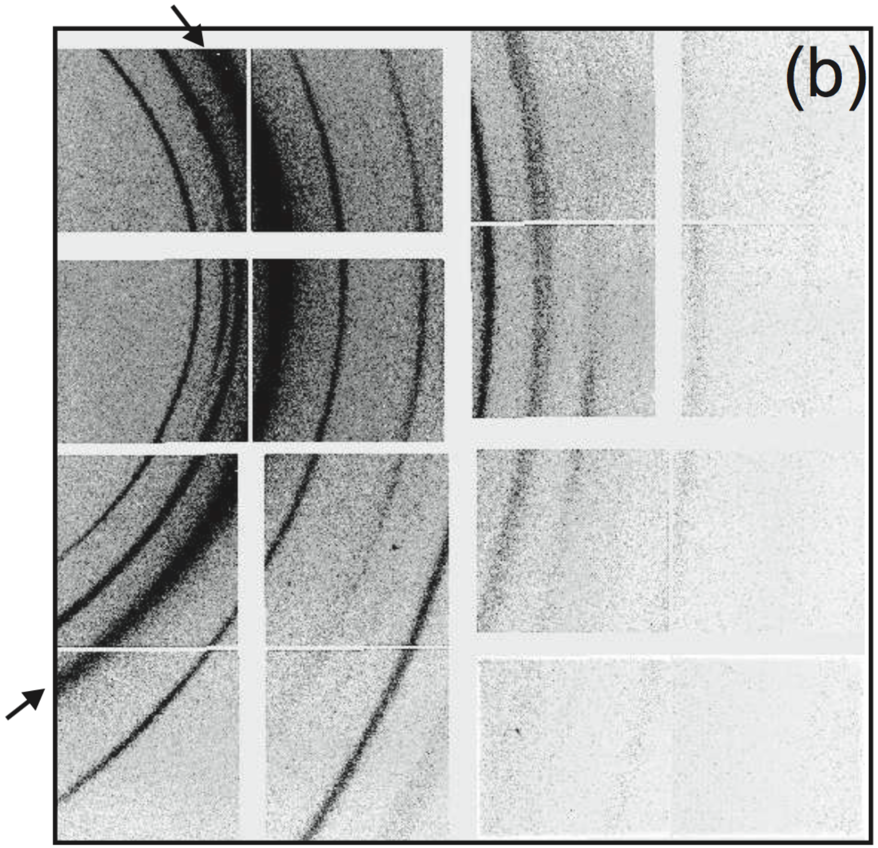


Despite being a very complex structure, under pressure several simple elements take this form - e.g. potassium. Even aluminium is predicted to form a host-guest structure at 30 Mbar

- In a host-guest structure it is as though, for a single element, we have a ‘normal’ crystal structure (the host), and down one axis ‘well-holes’ have been drilled periodically, and a 1-D string of atoms (the guest) runs down those holes. Amazingly, the spacing of the guests is totally incommensurate with the spacing of the host.

Scandium Diffraction



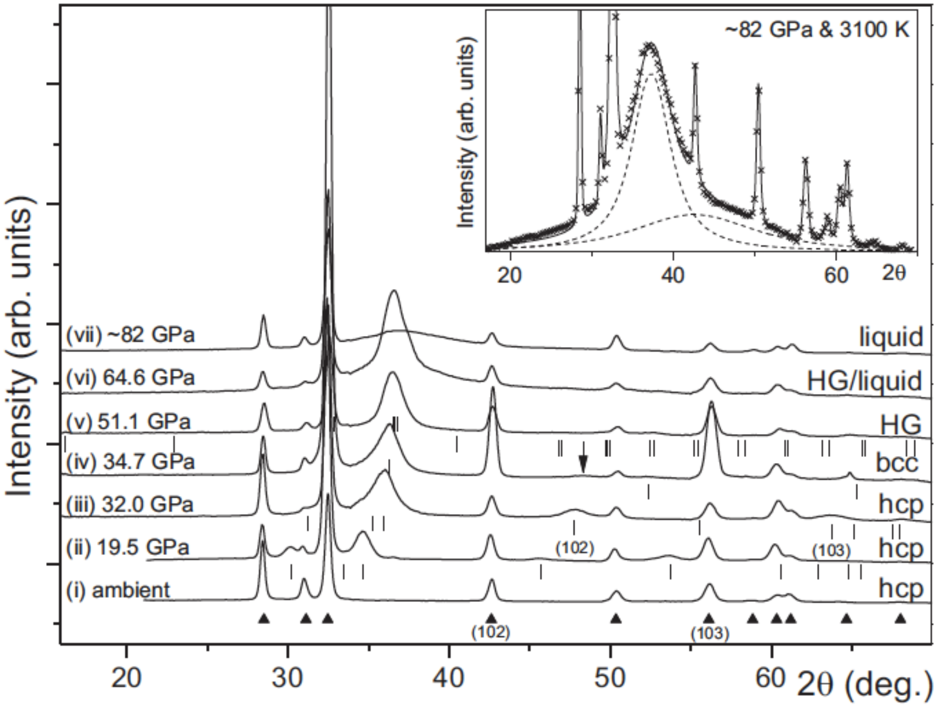


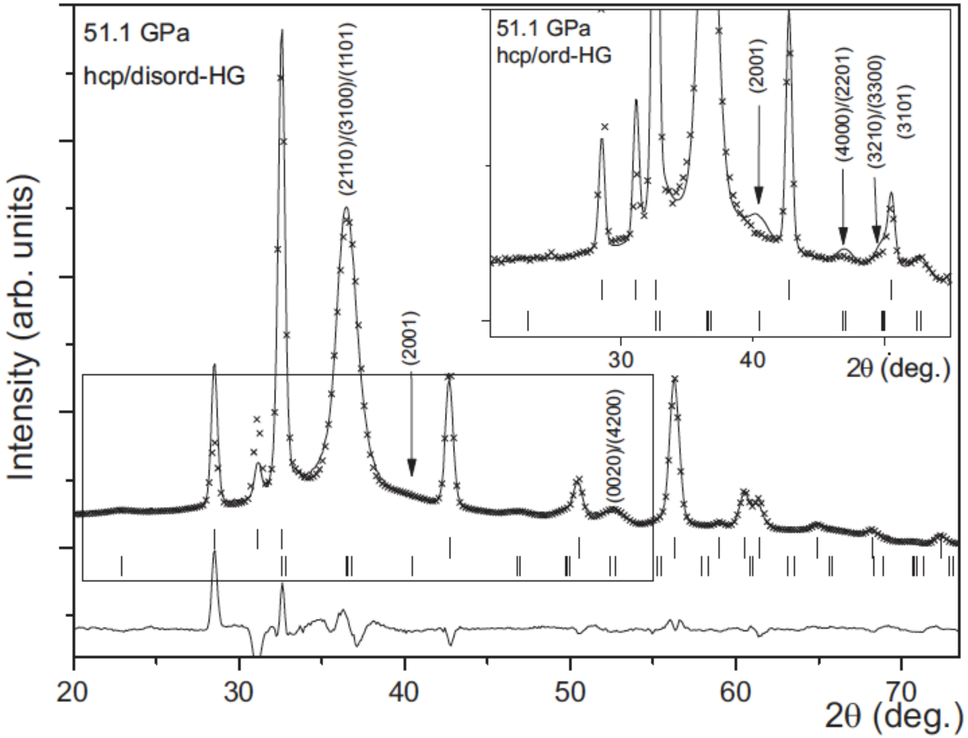
Uncompressed hcp

Compressed to 51.8 GPa

R. Briggs et al, Phys. Rev. Lett., 025501 (2017)

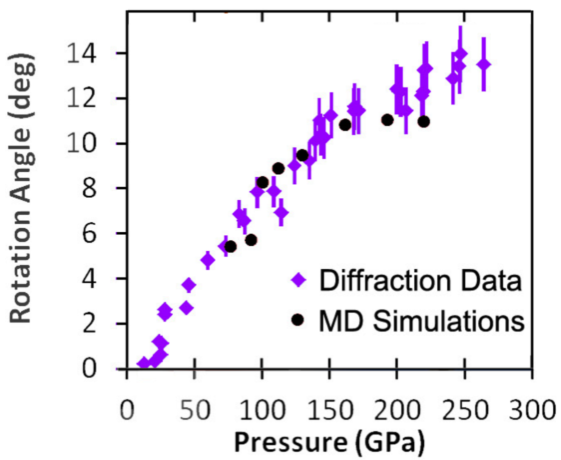
Scandium Diffraction

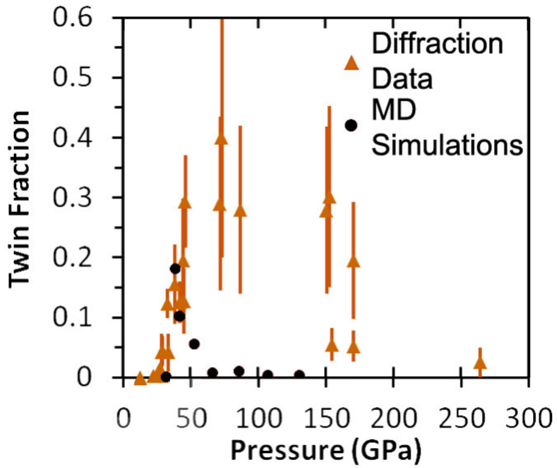


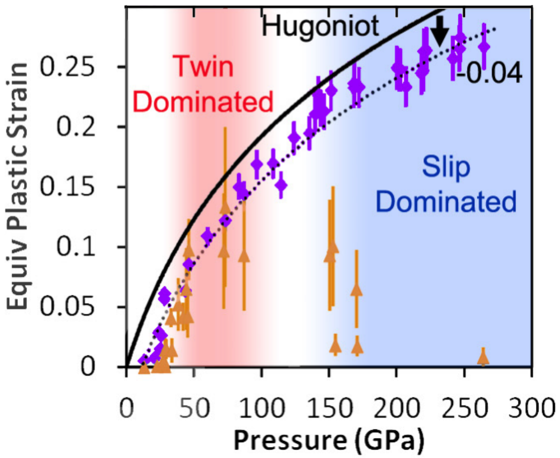


A disordered host-guest structure forms on nanosecond timescales

Results







- We observe increase in rotation angle up to ~14^{o} at 250 GPa.
- This rotation can be used to calculate the total transverse plastic strain, but does not tell us by which mechanism it is relieved.
- By comparing the ration of peaks heights, we can find the twin fraction of the material, and use this to find the plastic strain due to twinning: $\varepsilon_p = f_{twin}/$ sqrt(2)*schmid factor
- At low pressure, the dominant plastic mechanism is twinning, whereas at high pressure appears to be more important.
- Remains BCC up to melt.

*C. Wehrenberg et al., Nature, **550**, 496 (2017)*

Summary of 'ns laser-driver' wish-list

- One would *ideally* need a high repetition rate >100J nsec optical laser alongside the FEL. Overall facility is only as good as the optical laser. Note DIPOLE is a ~£10M system.
- Some good physics can still be done with smaller, commercial, optical lasers, but the scope will be limited.
- Key diagnostic is diffraction. 8 keV is good, but the high energy the better (in general) - e.g. the >20 keV of XFEL.
- Energy per pulse sufficient for single shot diffraction (fraction of mJ).
- Useful to have narrow bandwidth ($<10^{-6}$) monochromated beam for inelastic scattering from phonons (temperature measurement). With current bandwidths and then monochromatic (throwing away photons), single shot temperature measurements will be challenging. Thus seeding (or other ways of getting more energy per bandwidth) is useful.
- Have not had time to discuss short (<1ps) optical physics. LCLS/XFEL will have a few hundred TW systems - again expensive, but again a few TW system is <1M.

Some overall thoughts

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- My understanding is that the project is offering technology to others who may wish to build a compact FEL, but will not be building a FEL itself.
- My view would be that *IF* such a system really is *much cheaper* than a ‘standard’ warm FEL, then someone will wish to build it, and there is no need to agonise over whether this is a University or a national lab.
- However, if building such a standard (few mJ, 100-fsec, 0.5 - 10 or 20 keV) FEL at low cost is your USP, you really need to know what that cost is.
- It is far from clear how costs scale with length. True costs can be better estimated by current FEL providers - to what extent are they involved, and a ‘technology provider’ is not necessarily best placed to make total cost estimates.
- The other question to consider is does the technology provide any other truly unique USP? (This would be nice, but in my view not essential).
- In the presentation yesterday it was stated “*the funding success rate is 10-15% for EU grants and probably the same for national grants. The success rate for beam time applications doesn’t need to be much higher. Hence, the argument that we don’t have enough FEL beam time is weak*”. This is NOT a logical statement. There is not a one-to-one correspondence between the success rate of grants, and the concomitant requirements for beam-time (It could well be that the number of successful grants is such that the required FEL time is greatly exceeded - or indeed the reverse).