Physikalisches Kolloquium
February 12, 2020, DESY, Zeuthen

Study of structure and Transport Properties of Warm Dense Matter using Ultra-Fast X-rayMethods

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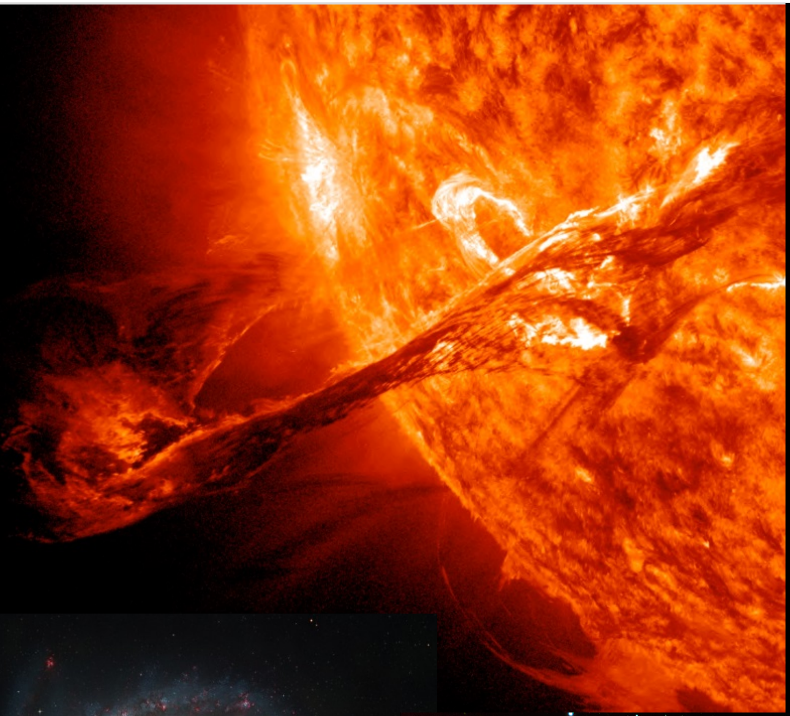
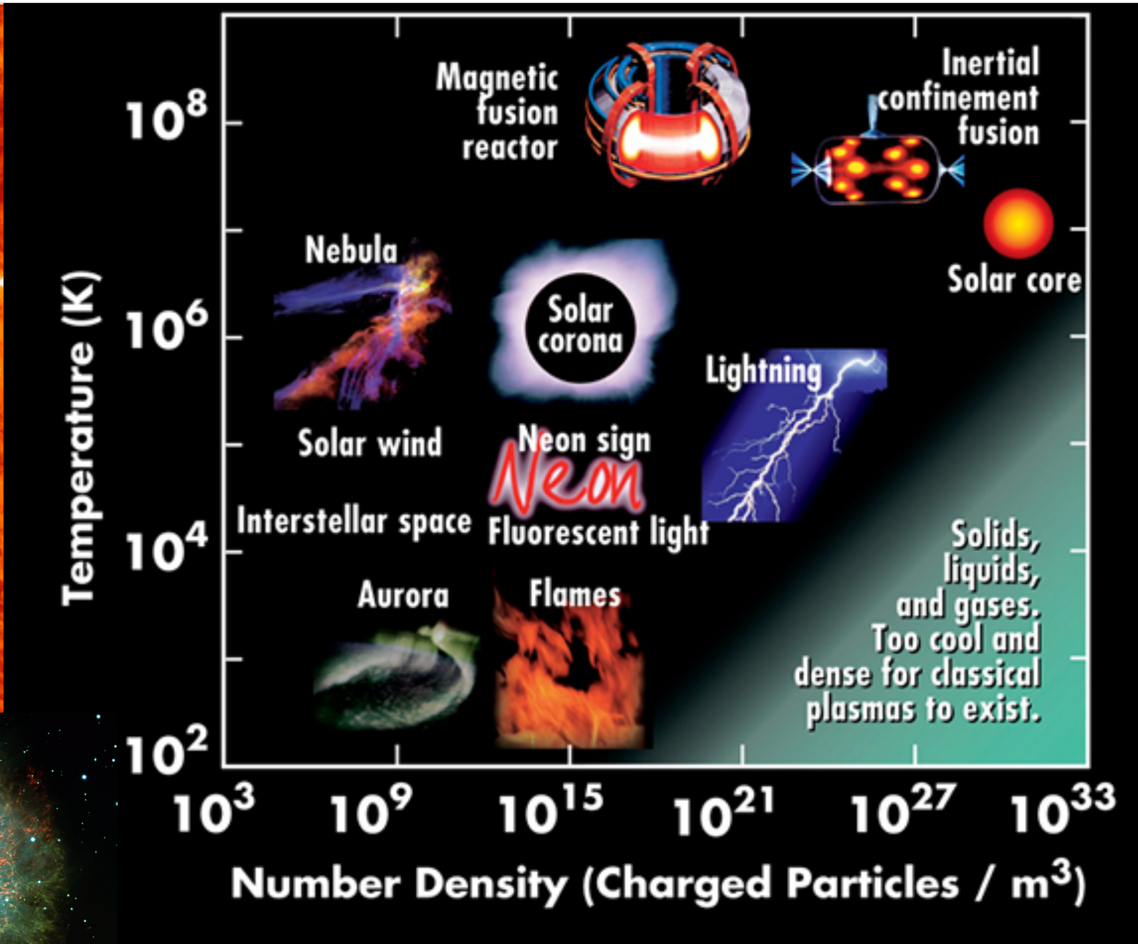
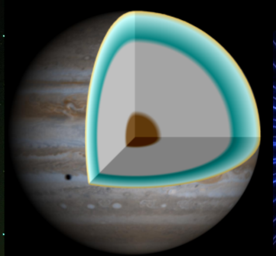
Talk outline

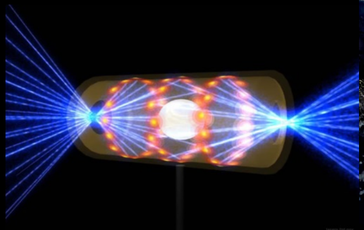
- **Introduction to Plasma Physics**
- **Definition of Warm Dense Matter (WDM)**
- **Applications in Astrophysics**
- **Applications in Inertial Confinement Fusion (ICF)**
- **Experimental methods to study WDM**
- **Introducing large laser facilities**
- **Ultra-fast laser probes and transport properties of WDM**
- **Research projects:**
  - **OMEGA: Warm Dense Matter equation of state and transport**
  - **DRACO: XANES absorption spectroscopy on heated copper**

Plasma Physics → What is “plasma”?









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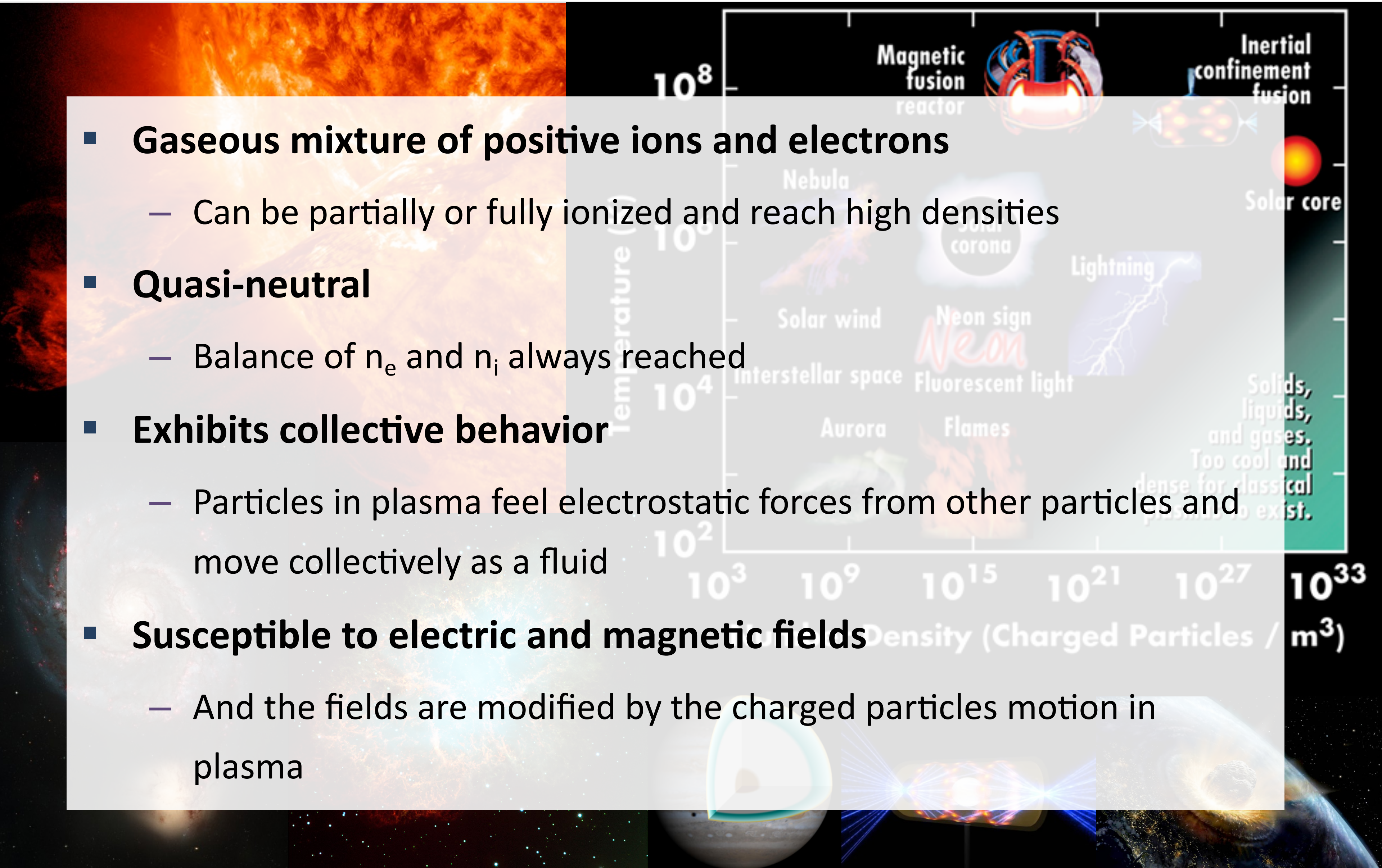
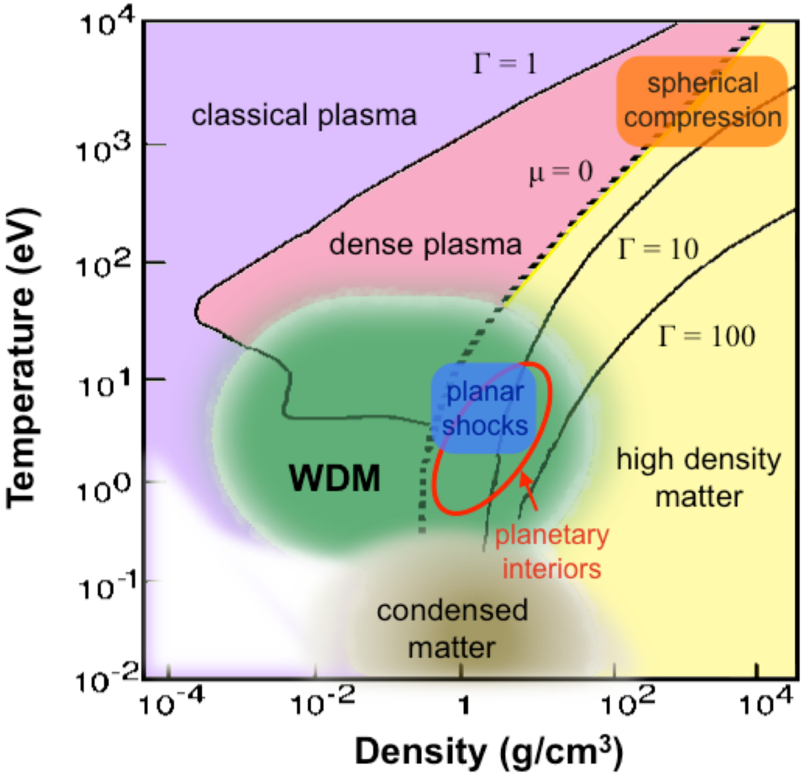
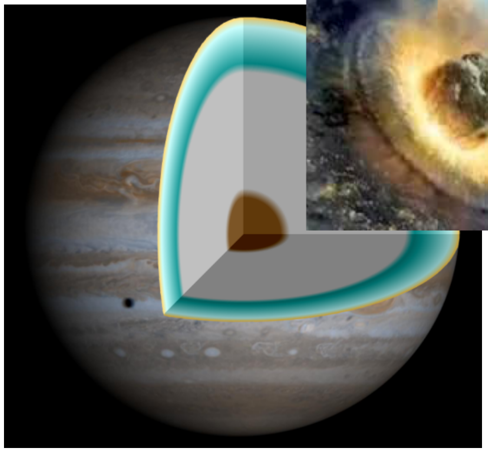


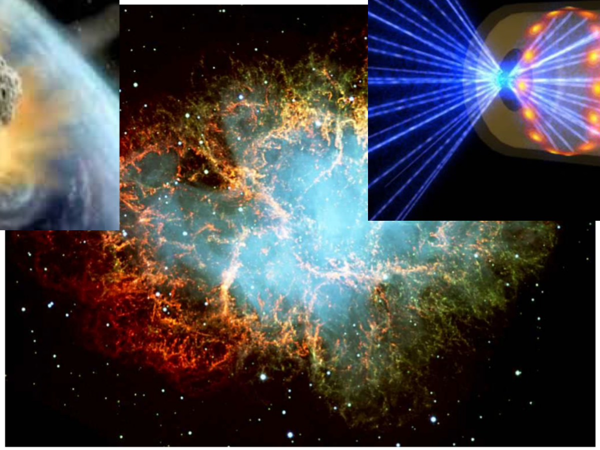
- **Gaseous mixture of positive ions and electrons**
  - Can be partially or fully ionized and reach high densities
- **Quasi-neutral**
  - Balance of n_e and n_i always reached
- **Exhibits collective behavior**
  - Particles in plasma feel electrostatic forces from other particles and move collectively as a fluid
- **Susceptible to electric and magnetic fields**
  - And the fields are modified by the charged particles motion in plasma

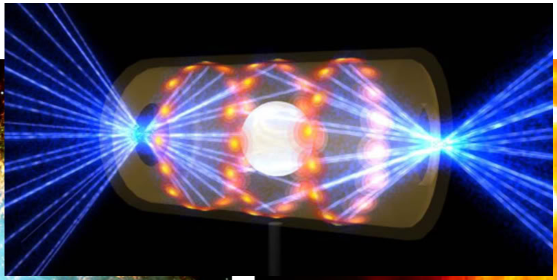
Warm Dense Matter

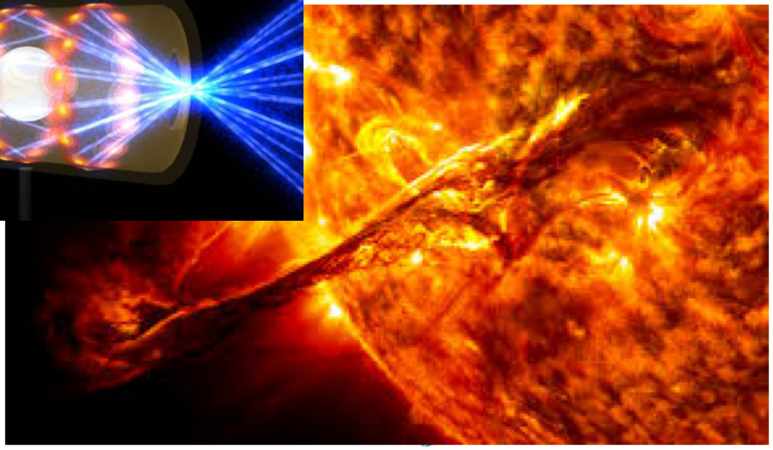
- Solid densities (~1 g/cm^3), moderate temperatures (0.1 – 100 eV)
- Ions strongly coupled and fluid-like, exhibit long-range order
- Electrons fully or partially degenerate
  ➔ quantum effects become important
- Planetary cores/dynamos, white dwarfs, crusts of old stars, supernova explosions, etc.
- Also can be created in a lab by high power lasers, inertial confinement fusion (ICF)
- Equation of state (EOS) structure and transport properties largely unknown











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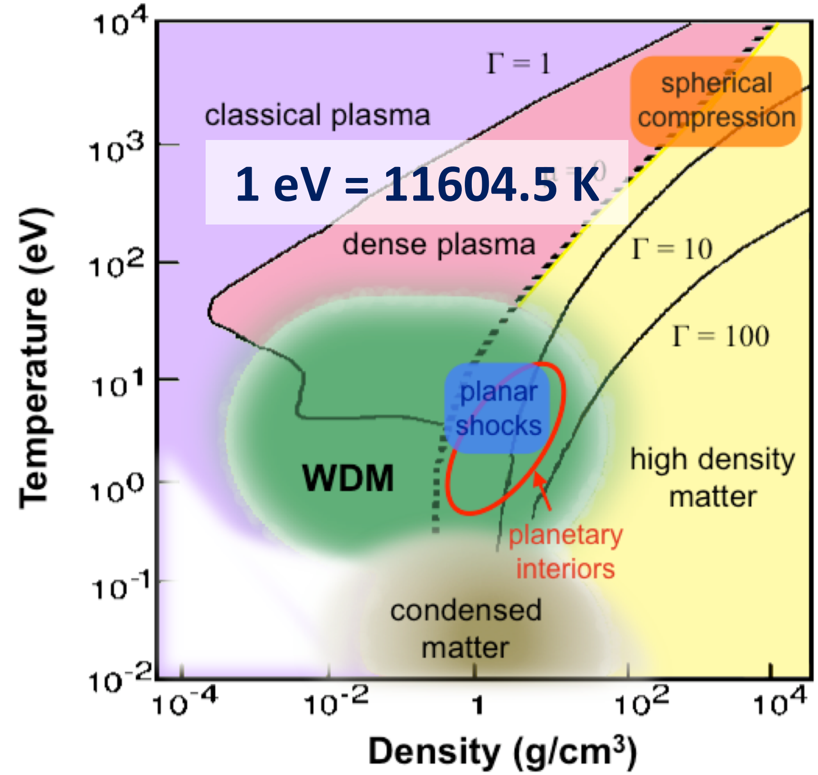


- **Coupling parameter:**
  ratio of Coulomb & thermal energy

$$\Gamma_{\alpha,\beta} = \frac{Z_\alpha Z_\beta e^2}{4\pi\varepsilon_0 a_{\alpha,\beta} k_B T_{\alpha,\beta}}$$

➔ strongly coupled plasma for $\Gamma_{ii} > 1$

- **Degeneracy parameter:**
  ratio of thermal energy & Fermi energy

$$\theta = \frac{k_B T}{E_F}$$

➔ in WDM $\theta < 1$

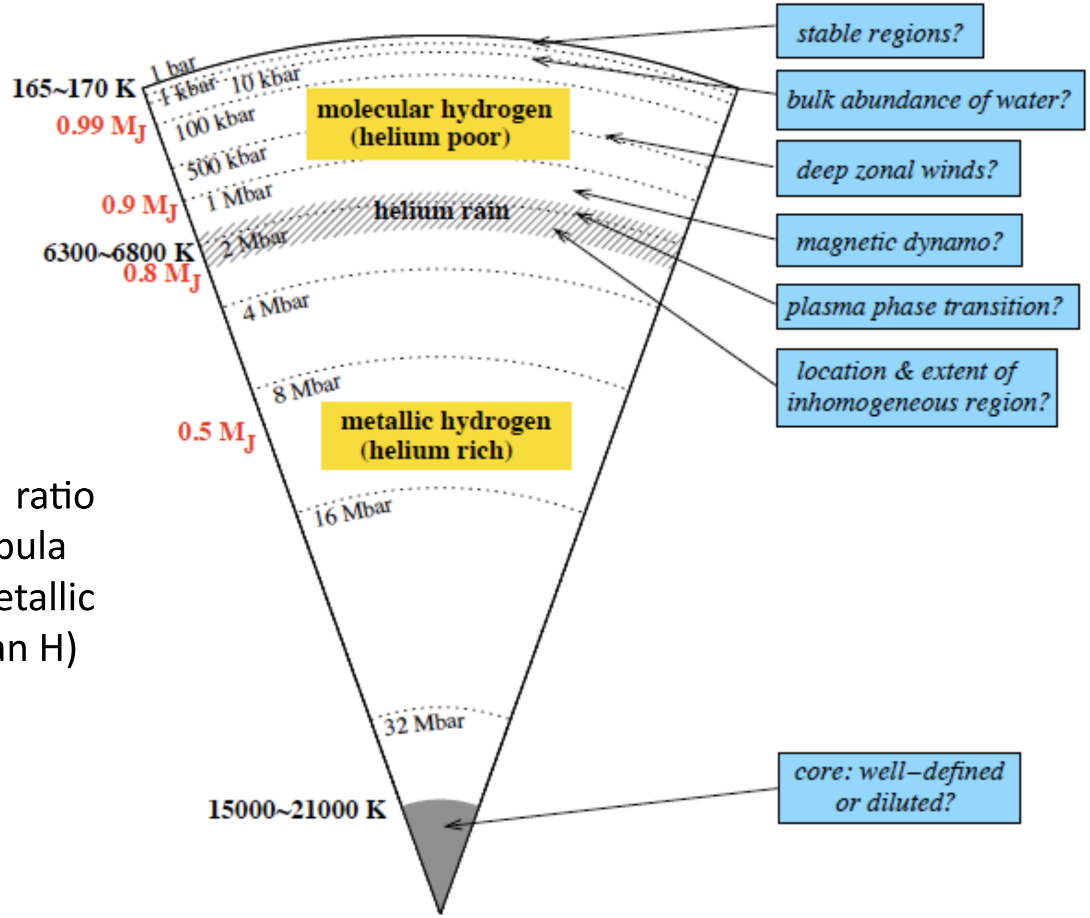
Most electrons populate the states within the Fermi sea and cannot further reduce the distance between them (Pauli exclusion principle).

Motivation for plasma transport & EOS experiments

- Interiors of planets are often in the WDM regime
- Jupiter's magnetic field generated by a dynamo of metallic hydrogen deep inside

Outstanding questions:

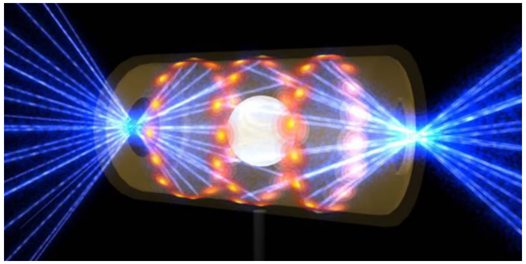
- **Metallization of hydrogen:**
  - What pressure? Temperature?
  - Phase transition continuous
  - or discontinuous? (first/second order)
- **H/He phase separation:**
  - Atmospheric H/He mixing ratio different from protoplanetary nebula
  - Condensation of He in the metallic envelope (He harder to ionize than H)
  - ***Helium rain inside Jupiter?***
- **Diamond rain inside Neptune?**
- **Rock core?**

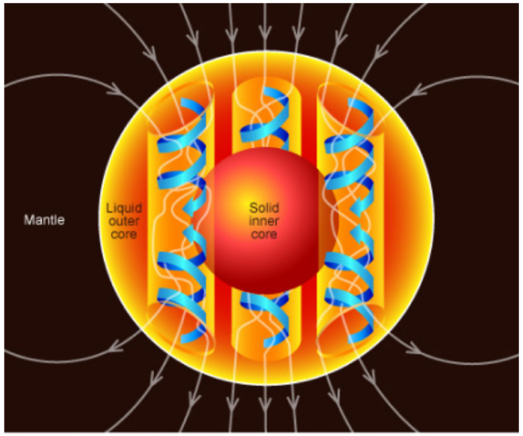


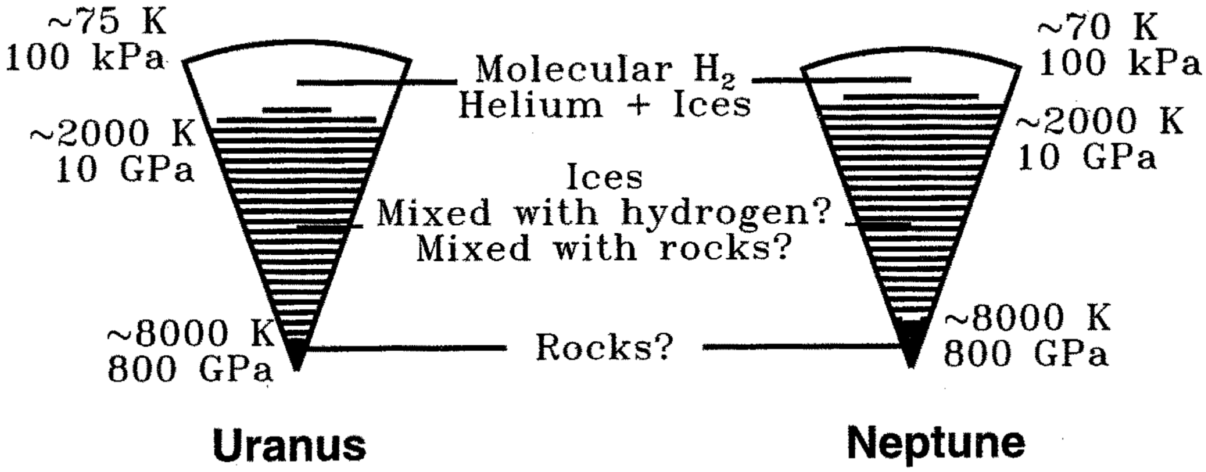
Guillot T., Hubbard W.B., Stevenson D.J. & Saumon D. 2003, *"The Interior of Jupiter"*, in Jupiter (Eds. F. Bagenal *et al.*)

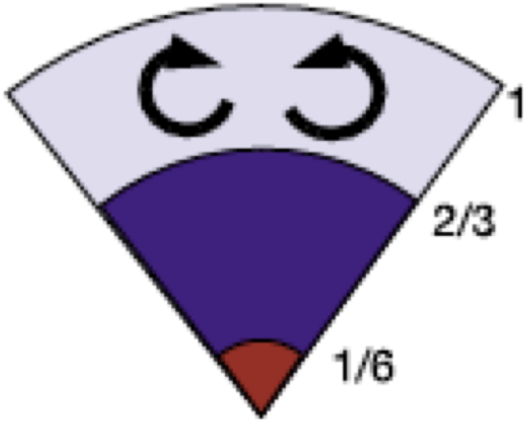
Motivation for plasma transport experiments

- Electric conductivity of plasmas inside planetary dynamos
- Convection inside planets and stars
- Radiation transport in stars and supernovae
- Fuel mix and heating processes in ICF
- Fast electron/proton transport in fast ignition



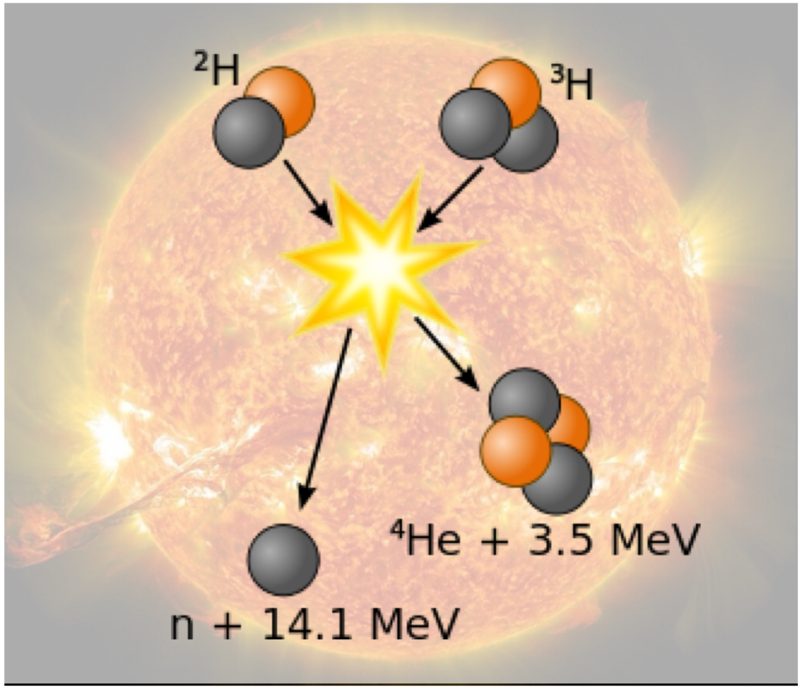


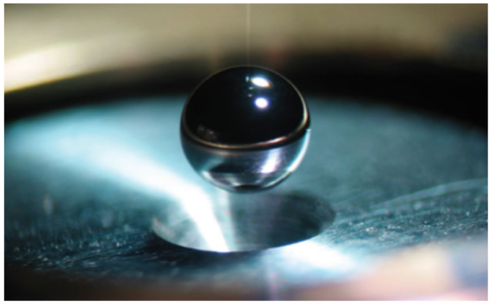


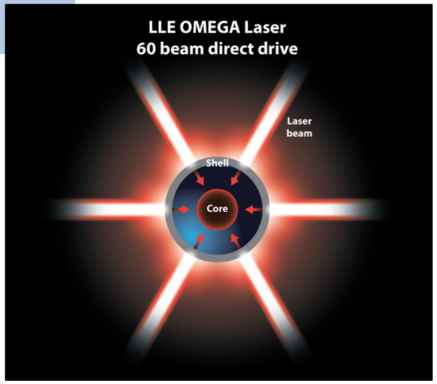


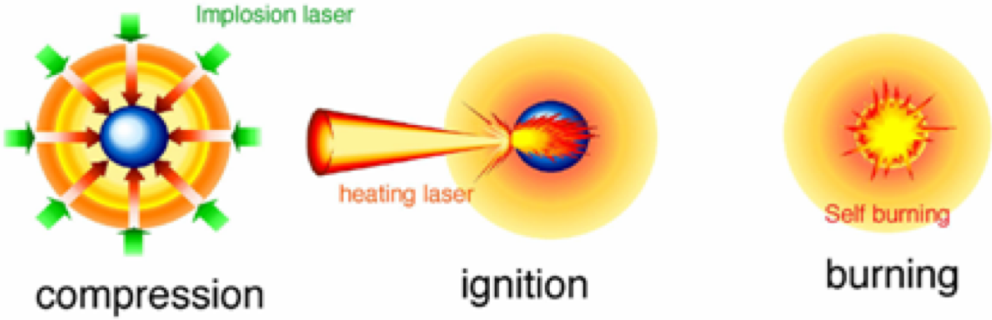
Fusion technology with lasers (ICF)

- **Inertial confinement fusion concept to fusion relies heavily on the knowledge of equation of state and transport properties of WDM**
- 60 – 200 laser beams of combined power of 10^{12} W (TW)
- Fusion reaction of hydrogen atoms to form Helium at extreme temperatures and densities
- Three main laser approaches:
  - Direct drive compression
  - Indirect drive with x-rays
  - Fast ignition fusion



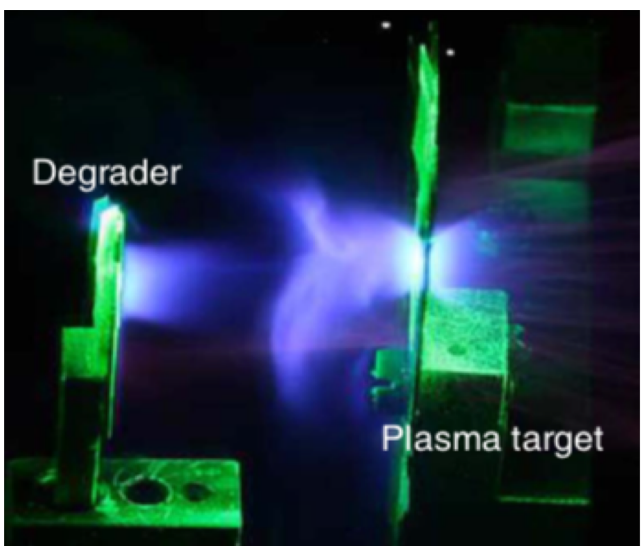


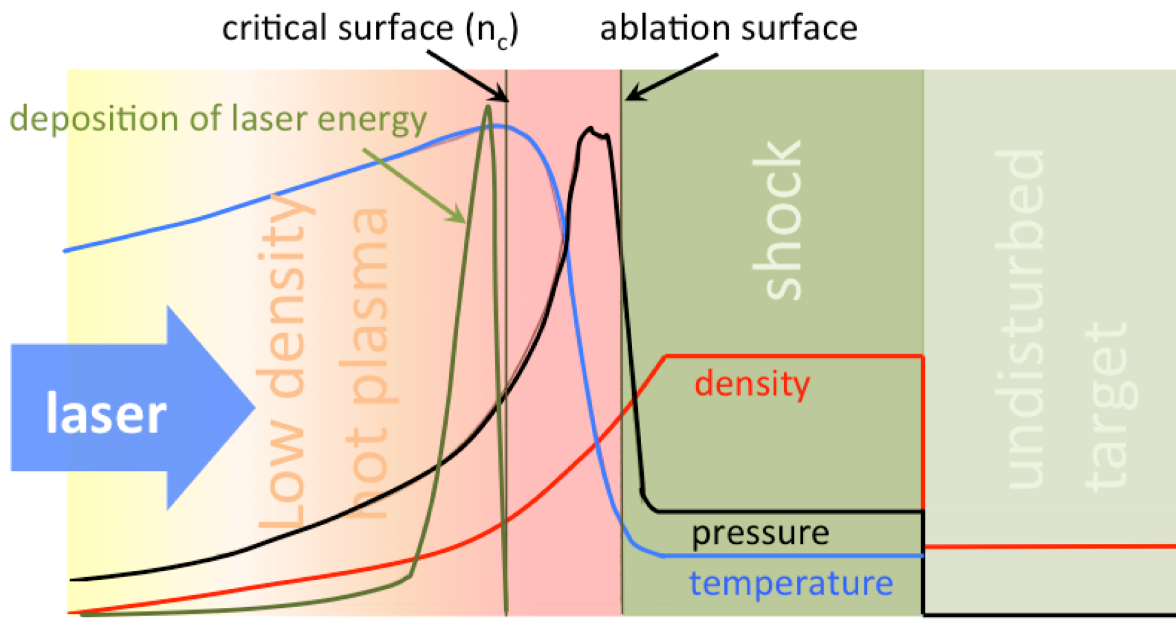




Generating WDM: Dynamic compression

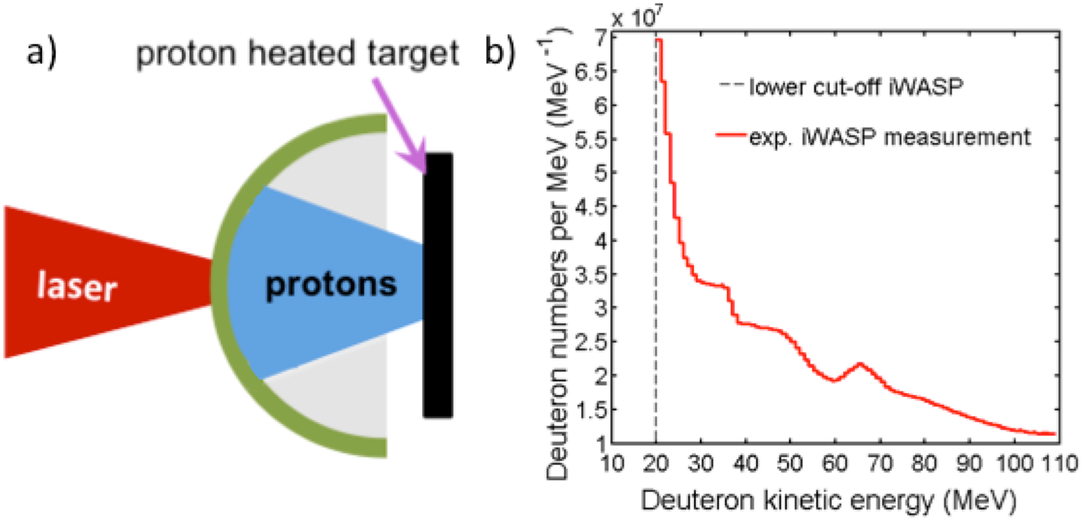
- **Experimental platforms for dynamic compression using lasers**
- **Typical solid/liquid target compression techniques typically used:**
  - Shocks driven directly by laser ablation
  - Shock-and-release ➔ achieve states away from the Hugoniot (few Mbar, 1–100 eV)
- **Main challenges:**
  - Preheat of material before the shock changing initial conditions
  - Shock stability and reproducibility (mainly issue on lasers)
  - Gradients in generated plasma conditions





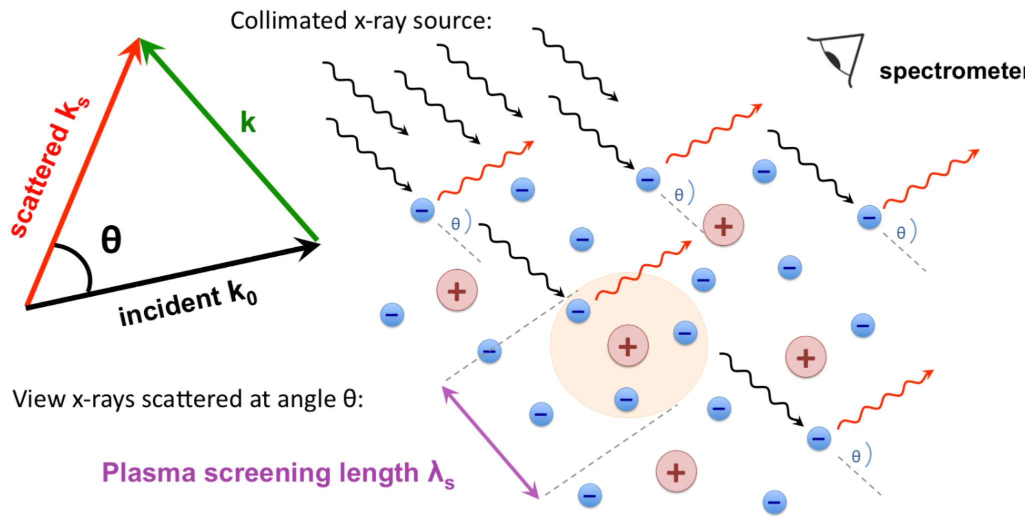
Generating WDM: Isochoric heating

- **Experimental platforms for isochoric heating:**
  - High energy laser facilities
  - Particle accelerators, synchrotrons and free-electron lasers (FEL)
- **Typical heating sources:**
  - X-rays (laser generated, synchrotron or x-ray FEL)
  - Protons (typically laser-acceleration, lower energies than accelerators)
  - Electrons (laser generated)
  - Direct heating with optical lasers also done, but requires very thin targets
- **Allows more homogeneous heating of solid density samples due to better penetration of x-rays or particle sources of dense targets, density is known**
- **Ultrafast and non-thermal processes can be studied with short-pulse heating sources**
- **Main challenges:**
  - Non-uniform plasma blow off
  - Electromagnetic pulses damaging electronics
  - Radiation, nuclear activation



X-ray Thomson scattering

- **Active probes needed for WDM**
  - High density
  - Relatively low temperatures
    - ☛ Optical probes cannot penetrate inside WDM
    - ➔ use x-rays, particles
- **X-ray Thomson scattering**
  - Measurements of temperature, density, ionization state and microscopic structure
  - Requires very strong x-ray sources



Scattering vector:

$$k = (4\pi/\lambda_0)\sin(\theta/2)$$

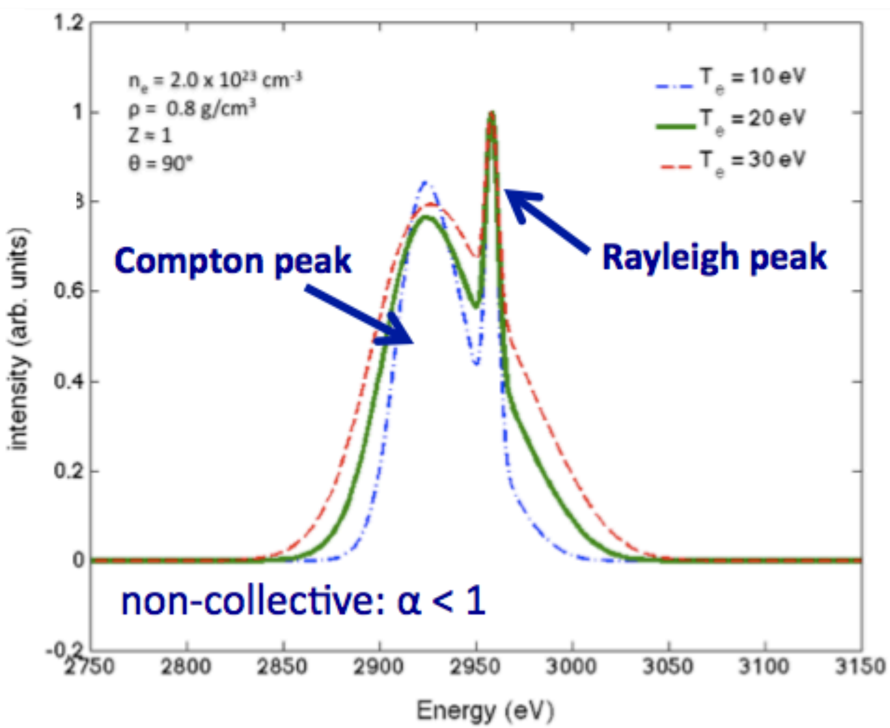
$$\lambda_s = \sqrt{\frac{k_B T_e^{\mathrm{eff}}}{4\pi e^2 n_e}}$$

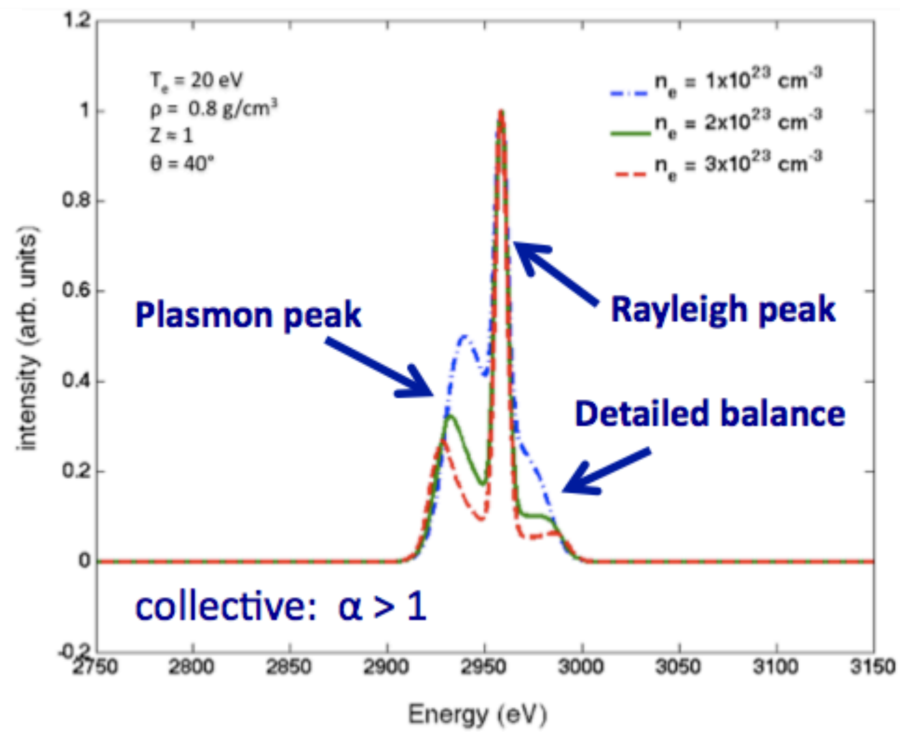
$$S_{ee}^{tot}(k,\omega) = |f_I(k) + q(k)|^2 S_{ii}(k,\omega) + Z_f S_{ee}^0(k,\omega) + Z_c \int \tilde{S}_{ce}(k,\omega-\omega')S_s(k,\omega')d\omega'$$

Bound electrons/following motion of the ions | **Free/delocalized electrons** | **Bound-free transitions**

S. H. Glenzer and R. Redmer, Rev. Mod. Phys. **81**, 1625 (2009)

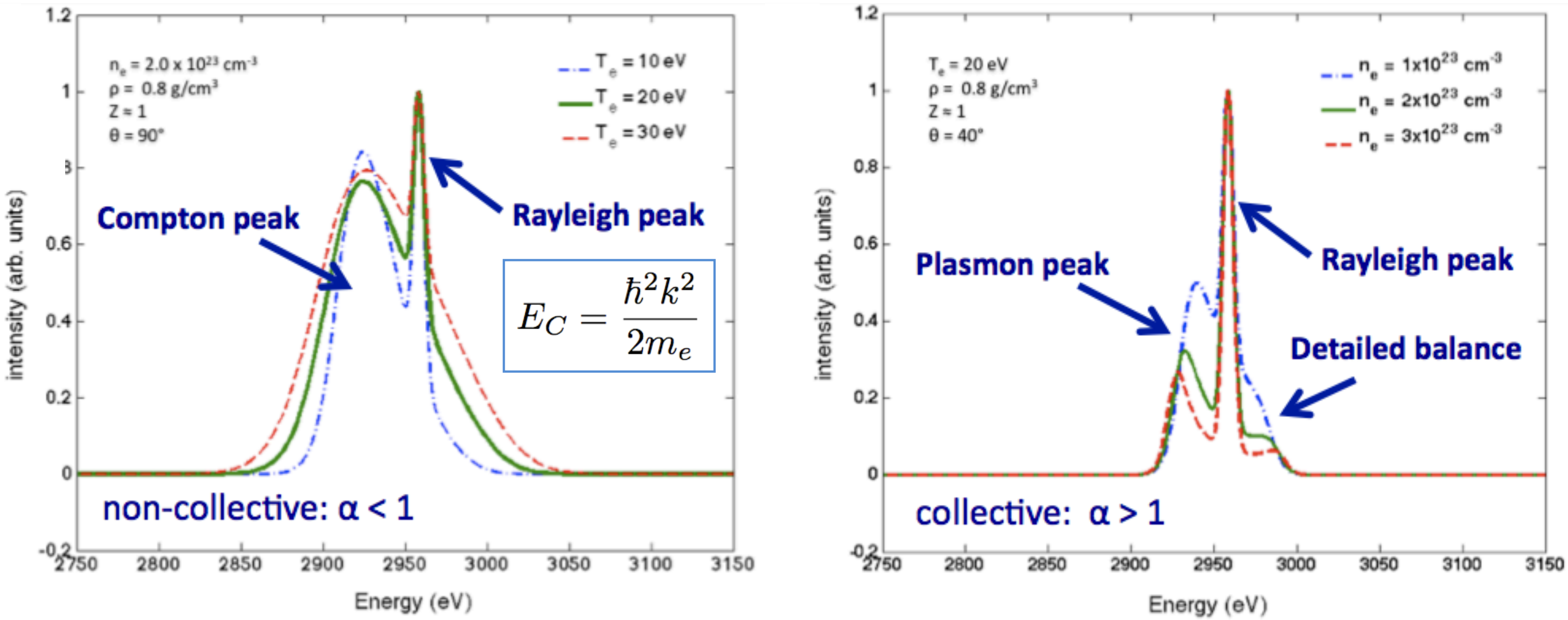
X-ray Thomson scattering





Rayleigh peak: elastic scattering (bound electrons)
Compton peak: inelastic scattering (free/metallic electrons)

X-ray Thomson scattering



$$E_C = \frac{\hbar^2 k^2}{2m_e}$$

Rayleigh peak: elastic scattering (bound electrons)
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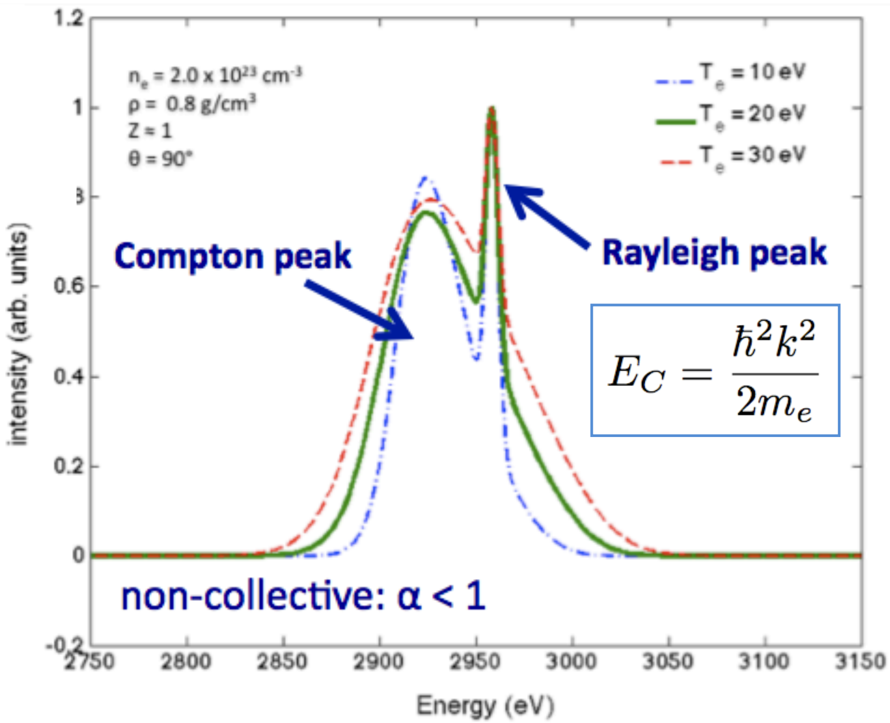
$$\Delta\omega = -\frac{\hbar^2 k^2}{2m_e} \pm \mathbf{k}.\mathbf{v}$$

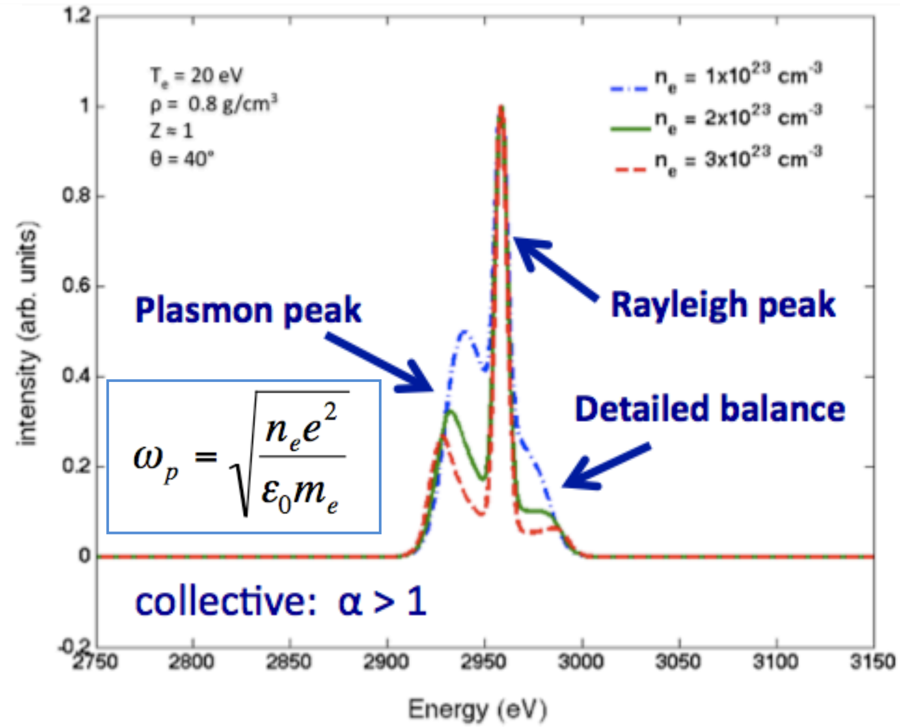
- **Determine the elements of EOS from features of scattering spectra:**
  - Electron temperature (T_e) from width of the inelastic peak (or detailed balance)

$$\frac{S(\mathbf{k},\omega)}{S(-\mathbf{k},-\omega)} = e^{-\frac{\hbar\omega}{k_B T_e}}$$

DRESDEN concept

X-ray Thomson scattering





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DRESDEN concept HZDR

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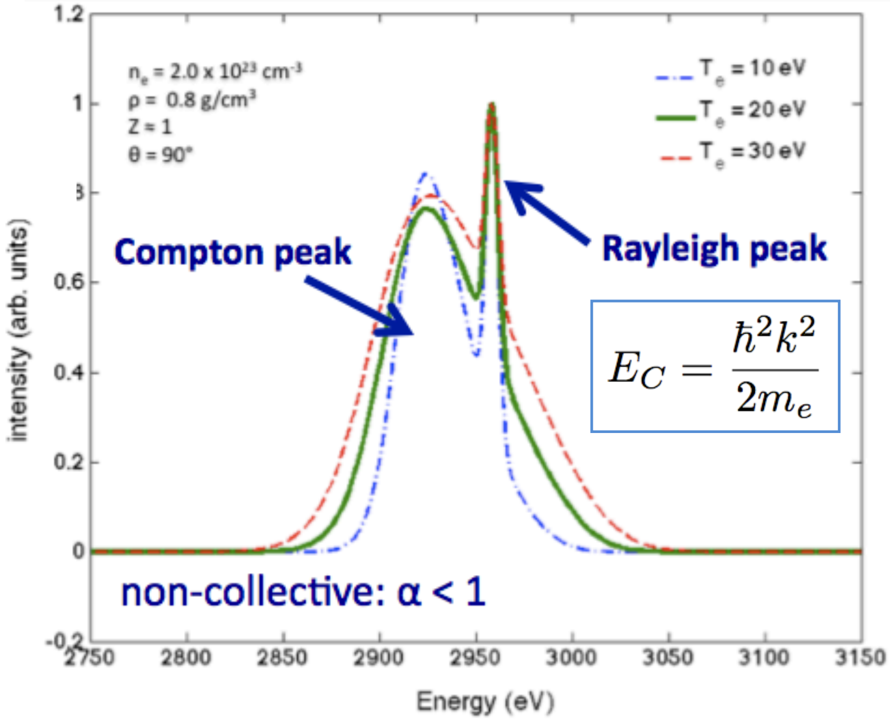

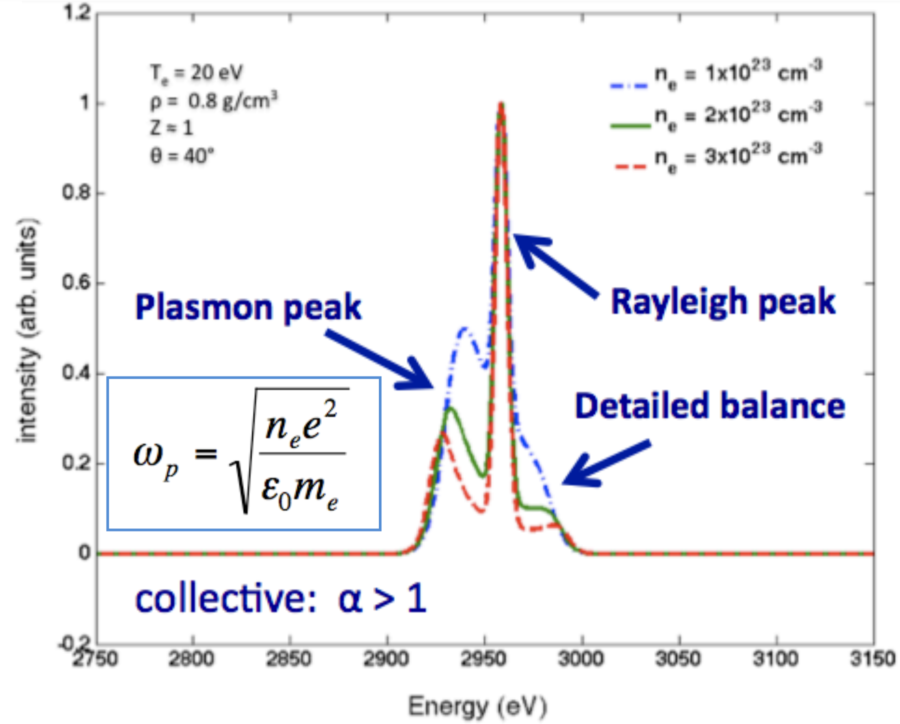

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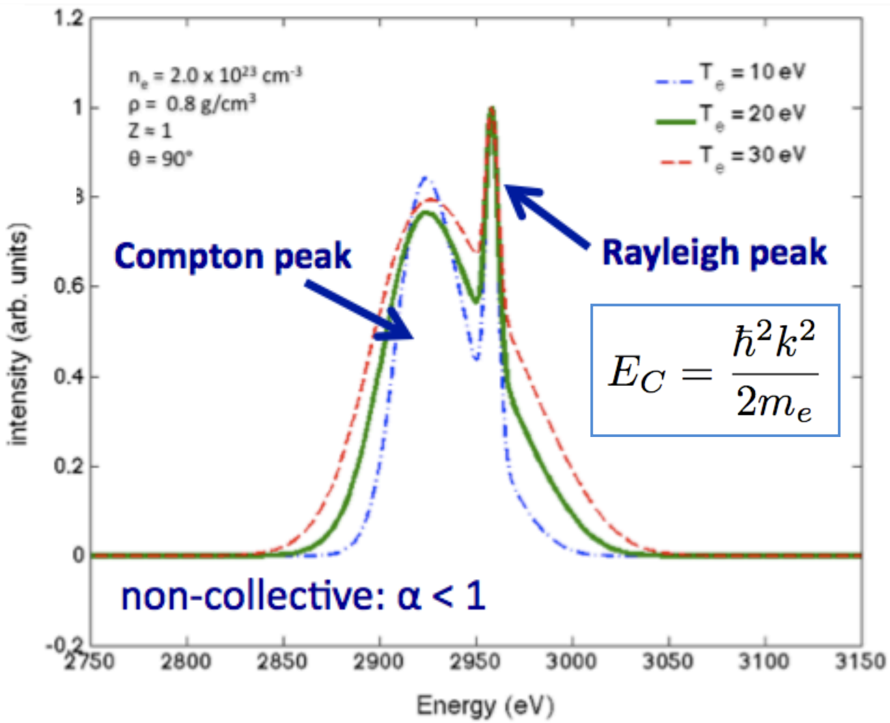

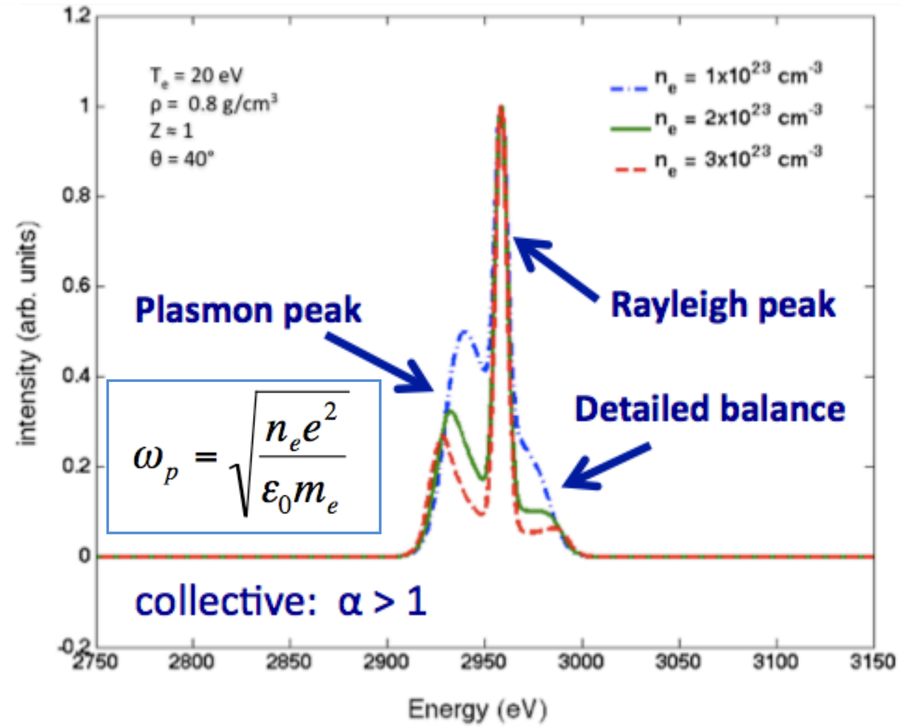

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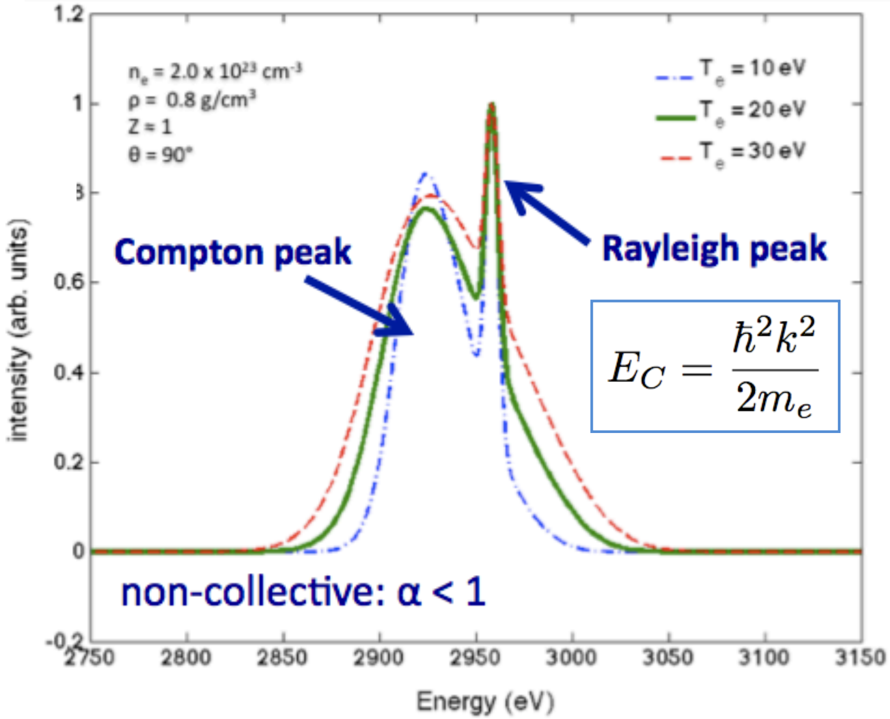
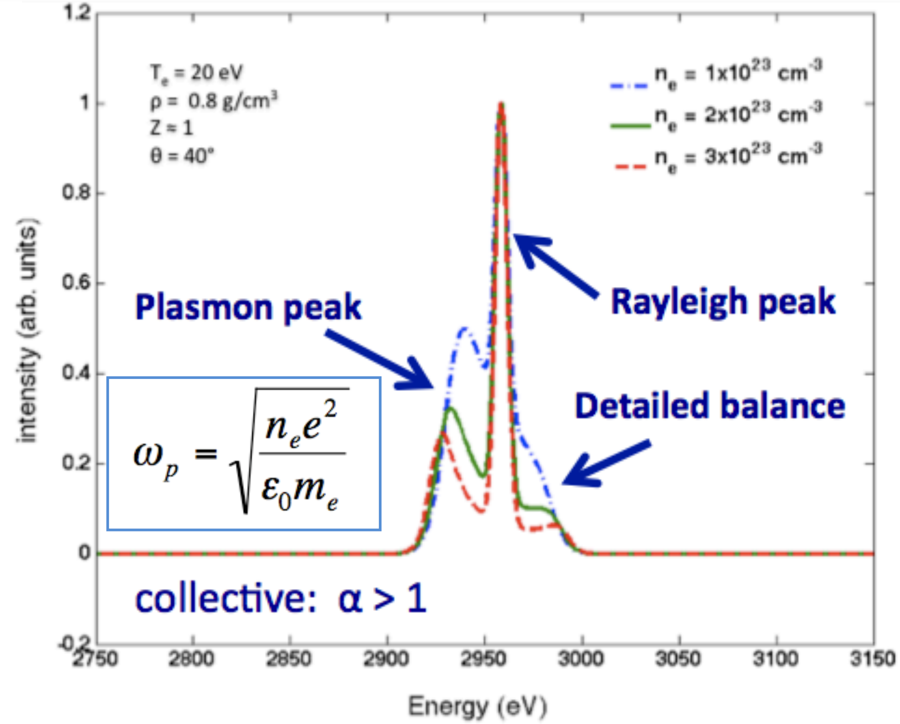
X-ray Thomson scattering





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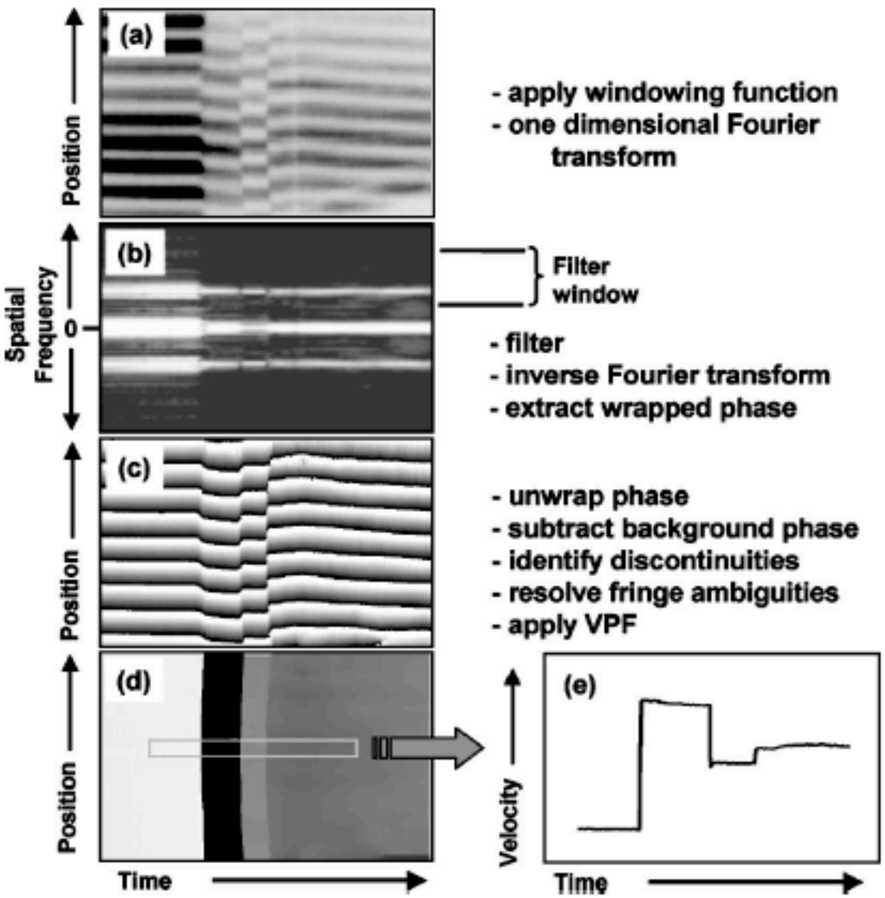
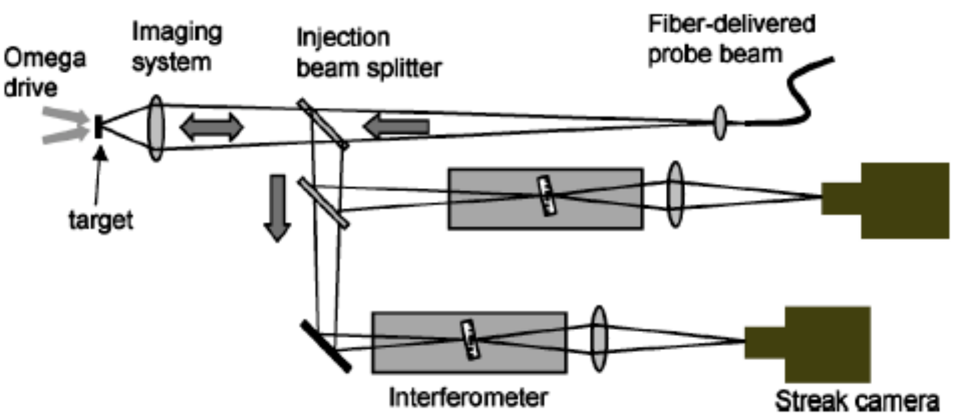
  - Average ionization state (Z) from intensity ratio of the Rayleigh and Compton peaks
  - Atomic structure from bound-free tail contribution

Optical diagnostics for WDM

- **VISAR (Velocity Interferometry of Any Reflector)**
  - Measures velocity of moving shockwave
  - Used to infer pressure and density in shocked material (WDM state)

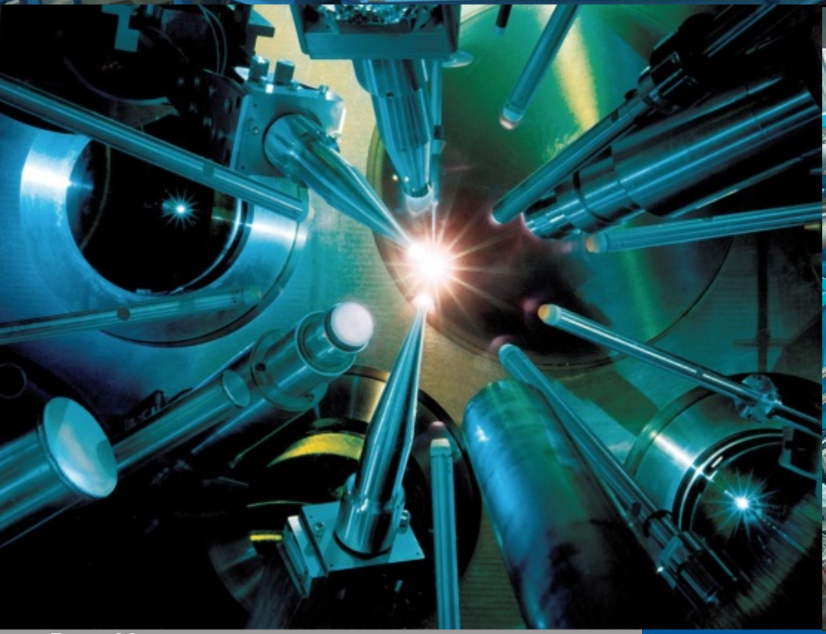
- **SOP (Streaked Optical Pyrometry)**
  - Measures optical emission from shock
  - If calibrated absolute temperature measurement can be extracted from the intensity measurement by comparison with blackbody radiation

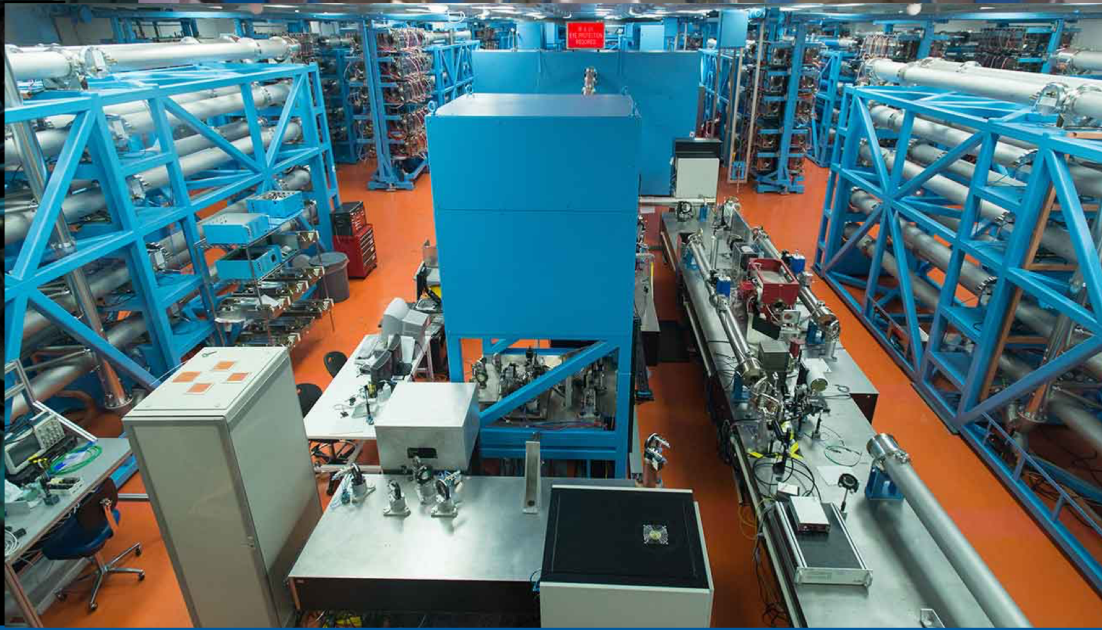




P. M. Celliers *et al*., Rev. Sci. Instrum. **75**, 4916 (2004)
J. E. Miller *et al*., Rev. Sci. Instrum. **78**, 034903 (2007)

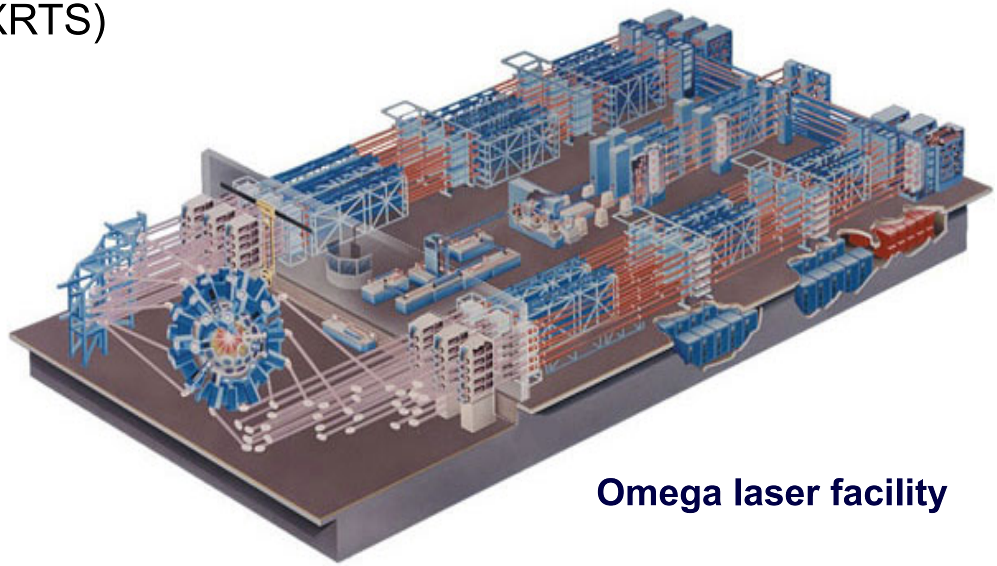
Going to big lasers: OMEGA





Novel experimental platform at OMEGA

- Warm Dense Matter with conditions relevant to ICF and Jovian planets interiors was generated by 14–15 OMEGA beams (University of Rochester) with laser drives of varied pulse duration and intensity: up to 3×10^{15} W/cm^2
- A versatile platform for shock-and-release experiments, classical EOS measurements as well as novel approach to study transport in WDM
- Targets are planar samples of various materials including diamond, graphite, CH foams and aerogels
- WDM/plasma state diagnosed using:
  - Imaging x-ray Thomson scattering (XRTS)
  - X-ray radiography (V backlighter)
  - Velocity interferometry (VISAR)
  - Streaked optical pyrometry (SOP)

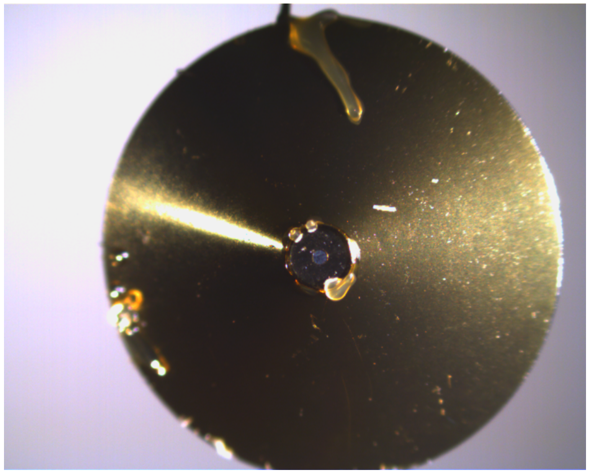


Omega laser facility

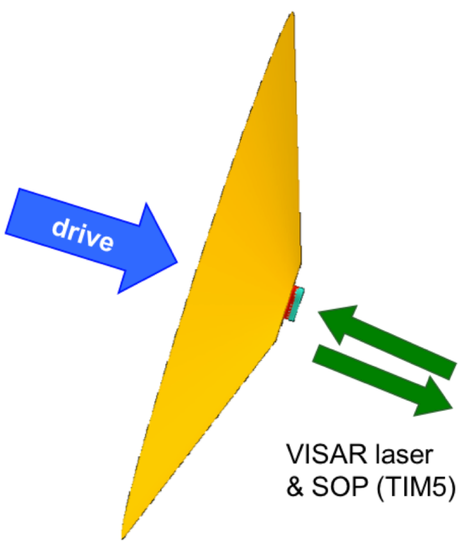
K. Falk *et al*., Phys. Rev. Lett. **112**, 155003 (2014)
K. Falk *et al*., Phys. Plasmas **21**, 056309 (2014)
K. Falk *et al*., Phys. Rev. E **90**, 033107 (2014)
K. Falk *et al*., PPCF **59**, 014050 (2017)
K. Falk *et al*., Phys. Rev. Lett. **120**, 025002 (2018)

Experimental configuration

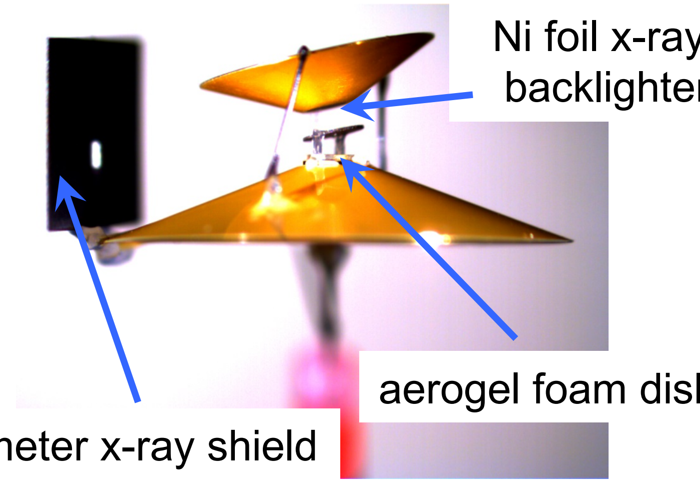
VISAR Target viewed from TIM5

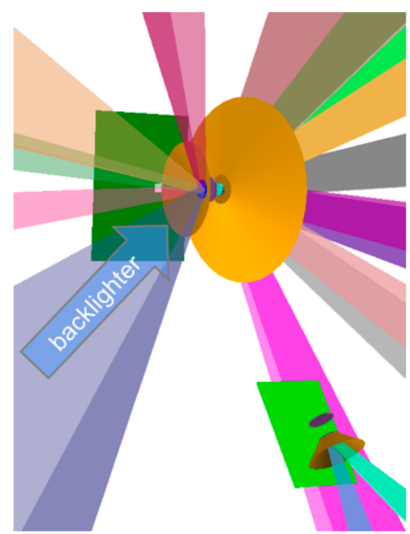


TIM5-ASBO telescope



IXTS Target viewed from top

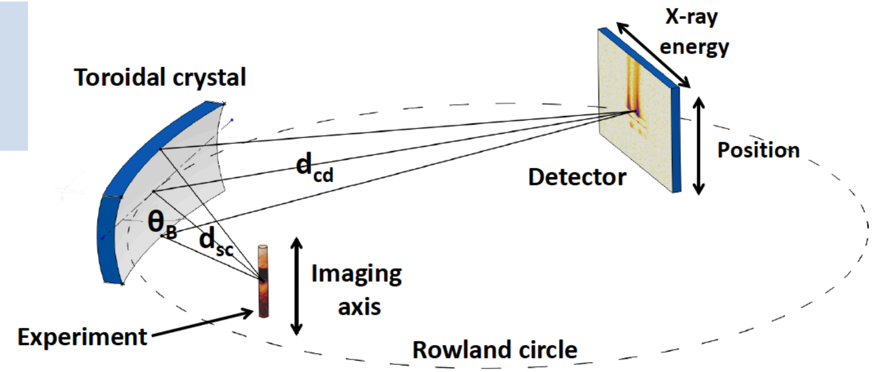


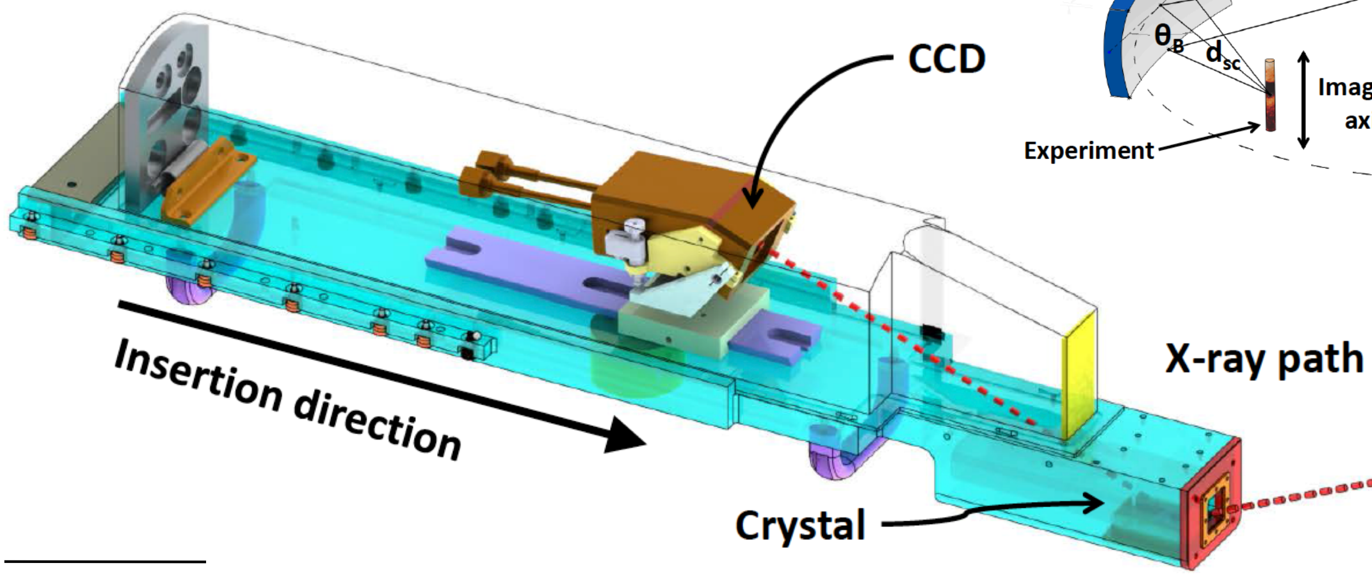


Imaging x-ray Thomson Spectrometer (IXTS)

- **A novel diagnostic particularly suitable for shock-release experiments developed by LANL and the University of Michigan to operate in a standard TIM setup**
- Toroidal Ge crystal used to provide spatial and spectral resolution in the same image

Spatial resolution = 25 µm (<50 µm)
Spectral resolution = 4-5 eV

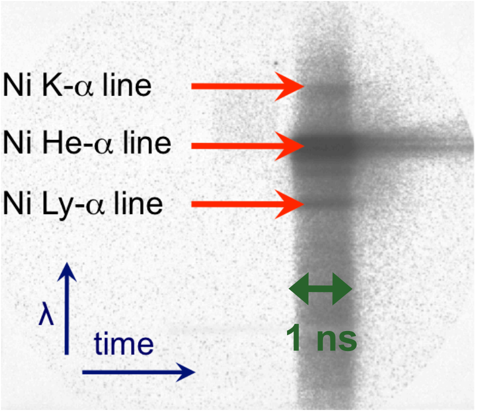


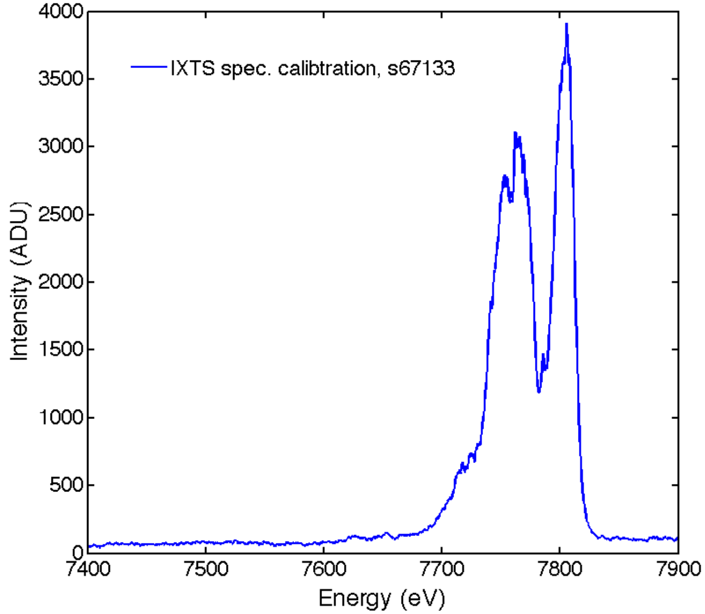


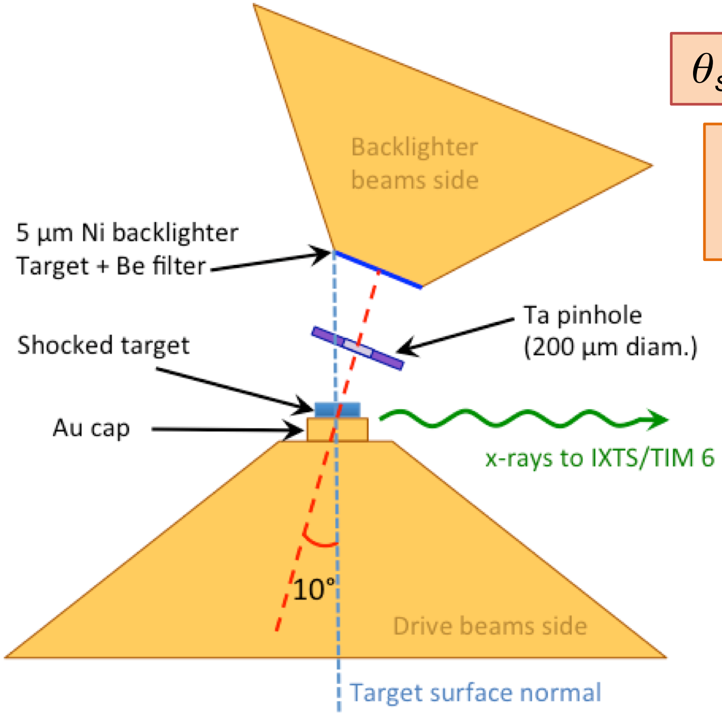
E. J. Gamboa *et al*., JINST **6**, P04004 (2011)
E. J. Gamboa *et al*., Rev. Sci. Instrum. **83**, 10E108 (2012)

X-ray scattering setup

- **Probe x-rays Ni He-alpha @ 7.8 keV**
- Narrow-band Ni He-alpha x-rays created by 10 laser beams incident onto a Ni foil @ 2–3 × 10^{15} W/cm^2
- Collimated by a 200 µm diameter Ta slit, placed 500 µm from the shocked target
- Double line with FWHM ~ 40 eV



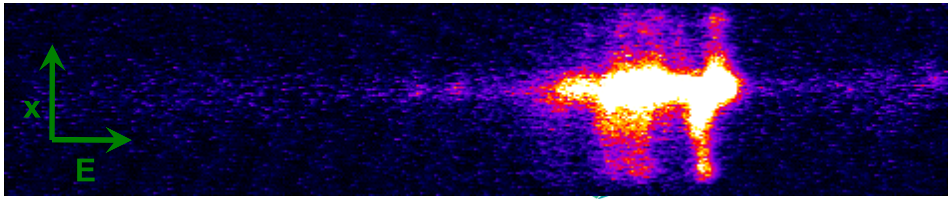




$\theta_{scattering}$ = 95 – 100°

XRTS parameter:
α = 0.3 – 0.35

IXTS measurement of the source spectrum:



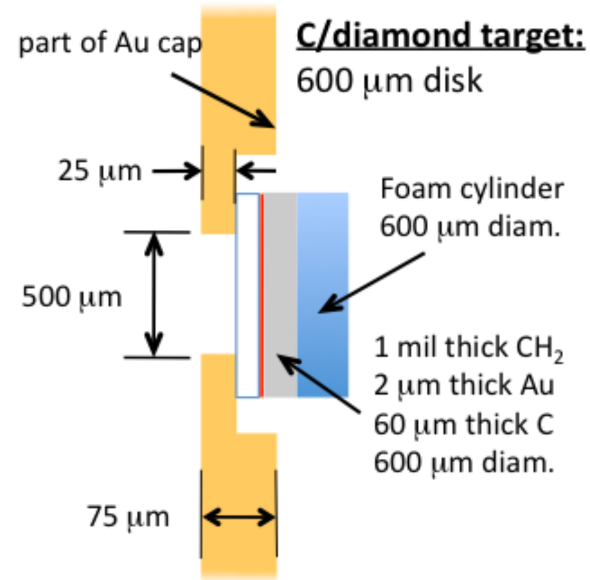
Shock-and-release experiments

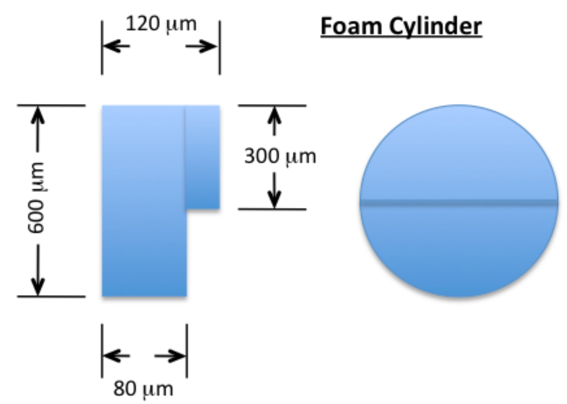
- **Planar targets with diamond and graphite used**
- 0.2 g/cm³ silica aerogel foam was used as a low density pressure standard, i.e. release material with well-known Hugoniot:

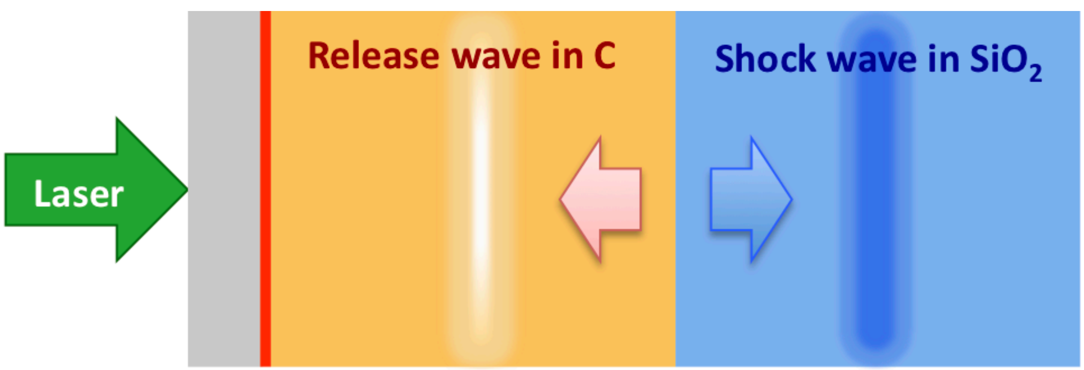
$$\boxed{u_s = 1.2027u_p + 0.507}$$

- 40 μm step on foam used for shock breakout timing
- When shock transits into the foam a release wave travels back through the C sample creating WDM
- **Pressure in diamond/graphite determined from Hugoniot relations:**

$$\boxed{P_{release} = \rho_0 u_s u_p}$$



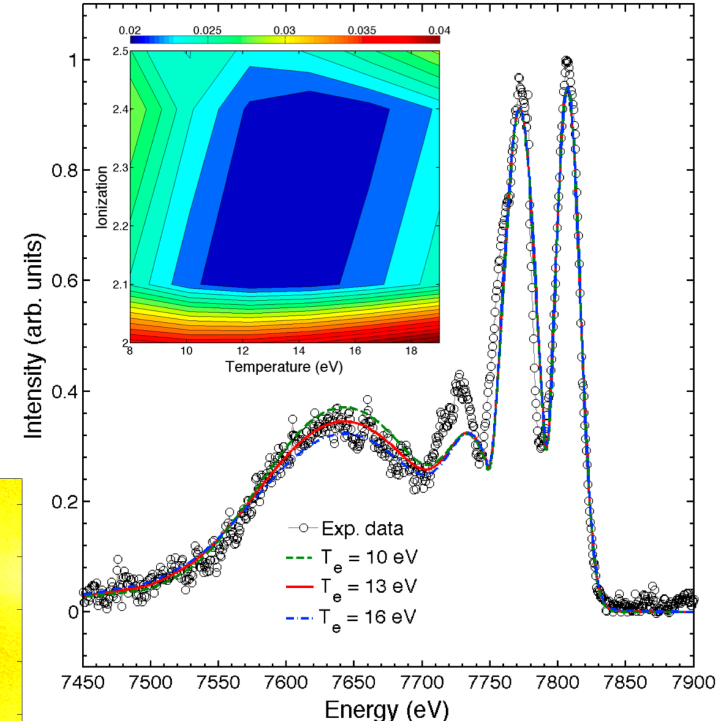


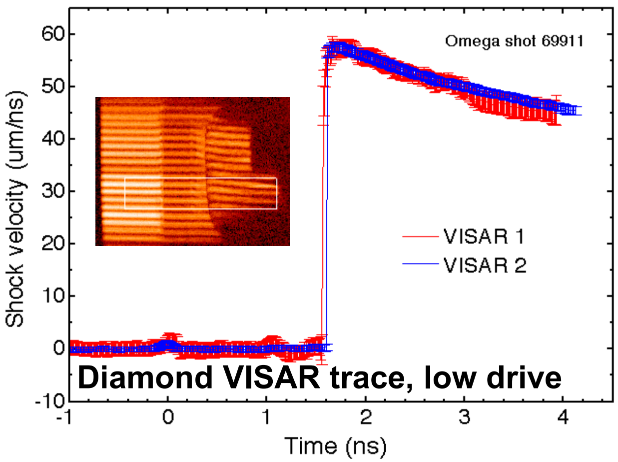


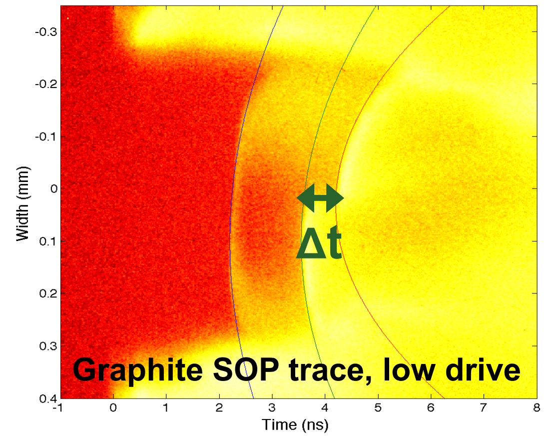
Knudson *et al.*, J. Appl. Phys. **97**, 073514 (2005)

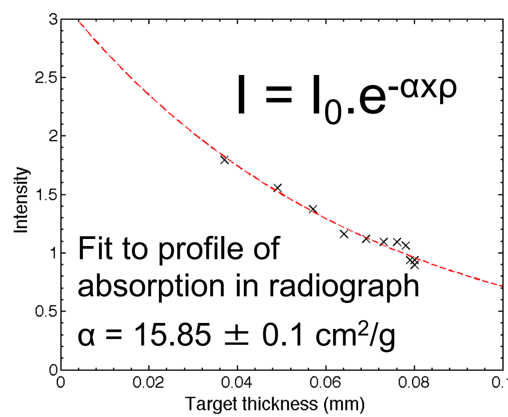
Experimental results

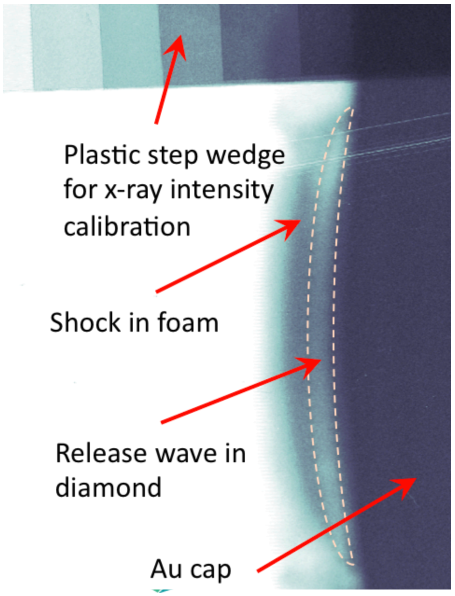
- Radiography measured the release wave density
- Imaging XRTS used for temperature measurement
- VISAR and SOP used to obtain shock velocity
  - Shock velocity was used to calculate the pressure from experimentally determined relationship









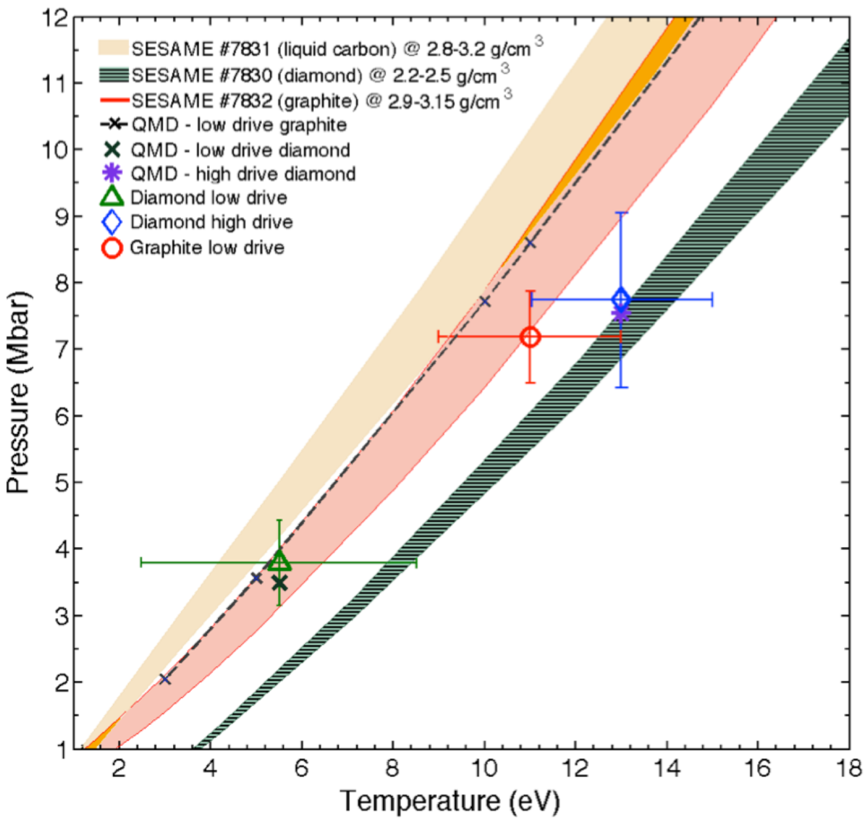


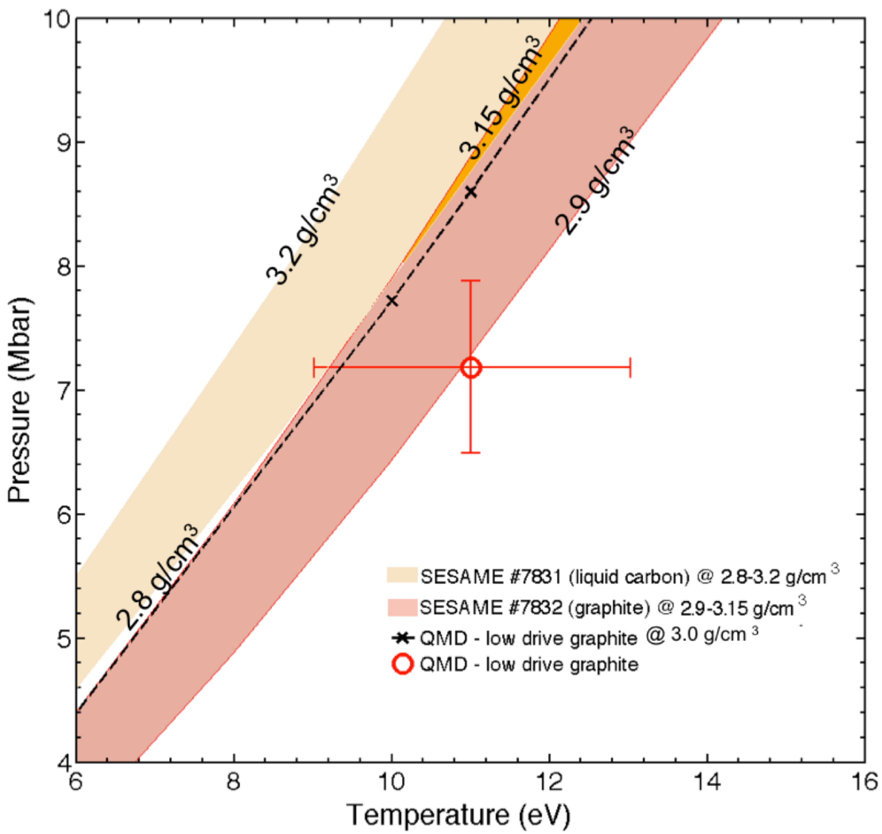
<u>Diamond measurements (high drive):</u>

ρ = 2.3 ± 0.2 g/cm³ (radiography)
P = 7.74 ± 1.31 Mbar (VISAR/SOP)
T_e = 13 ± 2 eV (XRTS)
Z ~ 2.2 ± 0.2 (approximate, XRTS)
n_e = 2.5 ± 0.2 x10²³ cm⁻³ (XRTS)

First model-independent EOS measurement

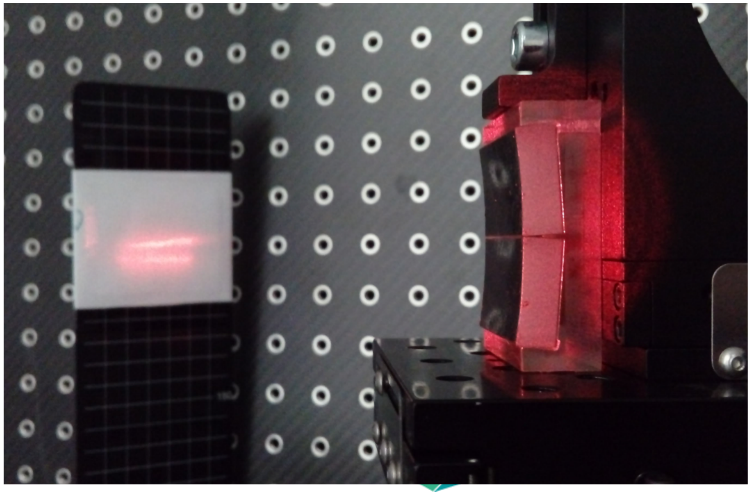
- This was the first model independent full equation of state (EOS) measurement (T, ρ and P) in WDM to date
- Experimental data were compared with SESAME tables:
- Comparison with ab-initio QMD models provided excellent agreement





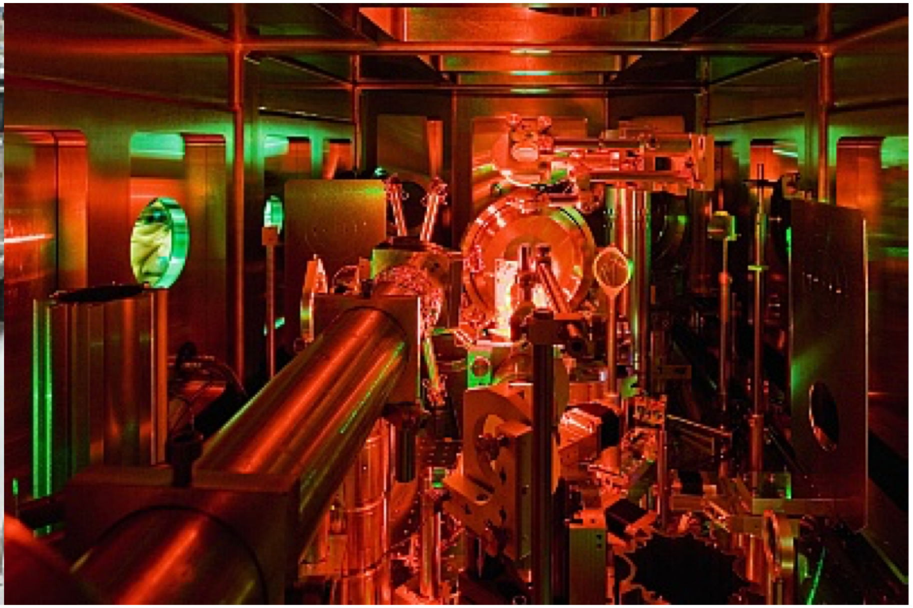
Transport properties with ultrafast probes

- **Transport coefficients in plasma are linked to non-equilibrium/ultra-fast processes**
  - Conductivity, diffusion, mixing of material, particle stopping powers, etc.
  - High temporal resolution (femto- or pico-seconds) is required
- **Ultrafast x-ray/particle sources for heating and probing:**
  - Nano/micro-structured targets for K-alpha production with short-pulse lasers
  - Laser wakefield acceleration
  - Proton acceleration with lasers
- **Multi-beam fs laser facilities**
- **Development of new instruments**



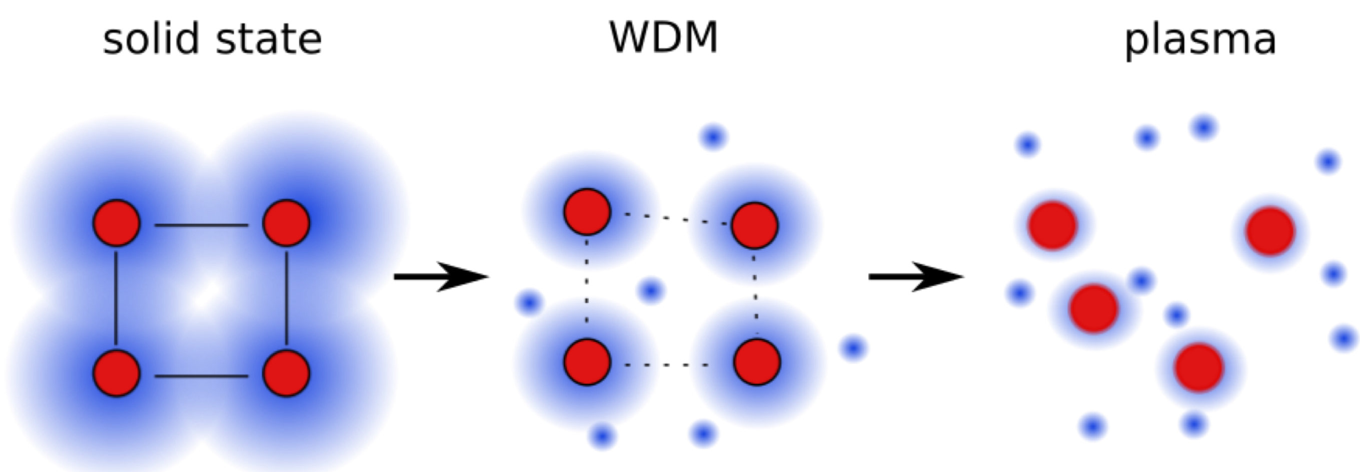
DRACO laser facility and HIBEF

- **HZDR has an on-site multiple beam short-pulse laser facility:**
  - 200 TW (6 J, 30 fs) laser system with reliable betatron setup
  - Additional 1 PW (30 J, 30 fs) laser available since 2017
  - PENELOPE laser system (150 J, 150 fs) under development (expected in 2020)
- **HZDR has direct links to the HIBEF beamline at the European XFEL:**
  - Multi-beam laser facilities, magnetic field generators available, XFEL operational



Ultrafast melting of Warm Dense Cu

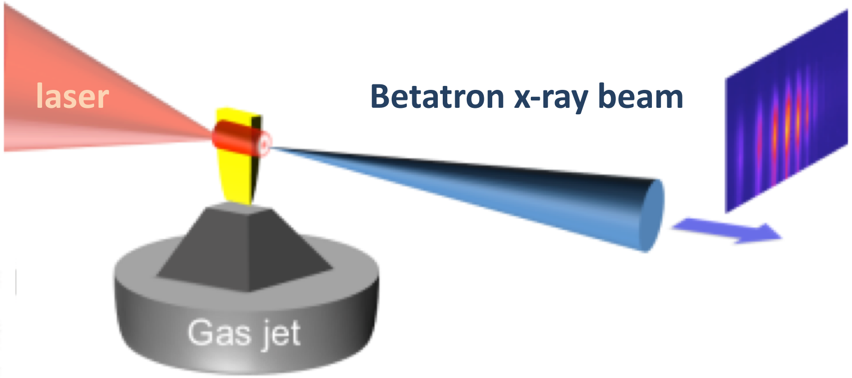
- Study ultrafast structural transformation in WDM
- Non-thermal melting, lattice disordering, bond hardening
- Utilize unique laser-driven x-ray beams
- Develop suitable x-ray spectrometer

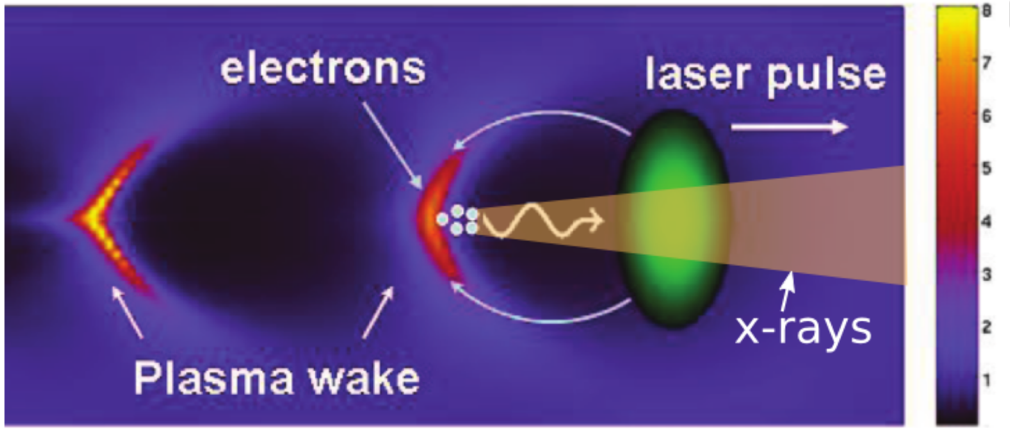


F. C. Kabeer, Phys. Rev. B **89**, 100301 (2014)

Laser wakefield acceleration and betatron sources

- **Laser wakefield acceleration for electron acceleration:**
  - A femtosecond laser pulse drives a plasma wave in a gas target that creates ”bubbles” free of electrons with a strong potential in which injected electrons are accelerated
- **Laser-driven betatron source:**
  - Driven by oscillation of electrons in strong electrostatic fields inside the “bubbles”
  - Oscillatory motion emits bremstrahlung with synchrotron-like “betatron” spectrum
- **Low divergence (tens of mrad)**
- **Short duration (tens of fs)**
- **Broadband spectrum with E_{crit} ~ 1 – 100 keV**





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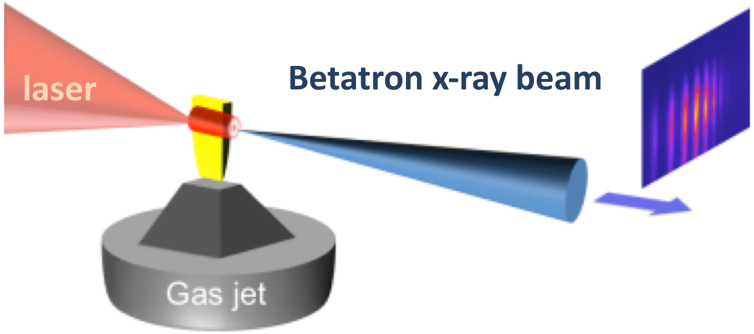

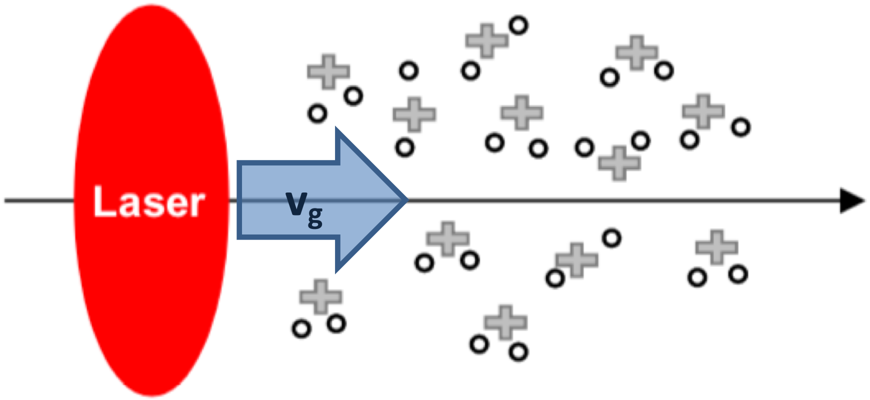

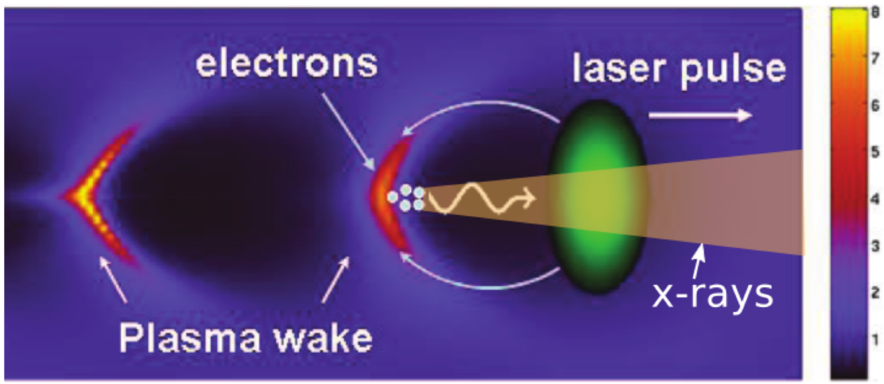

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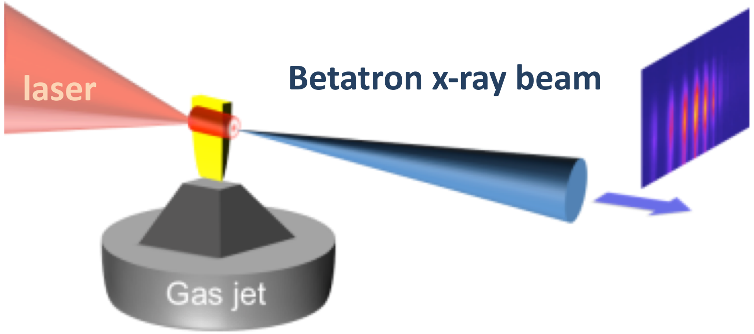

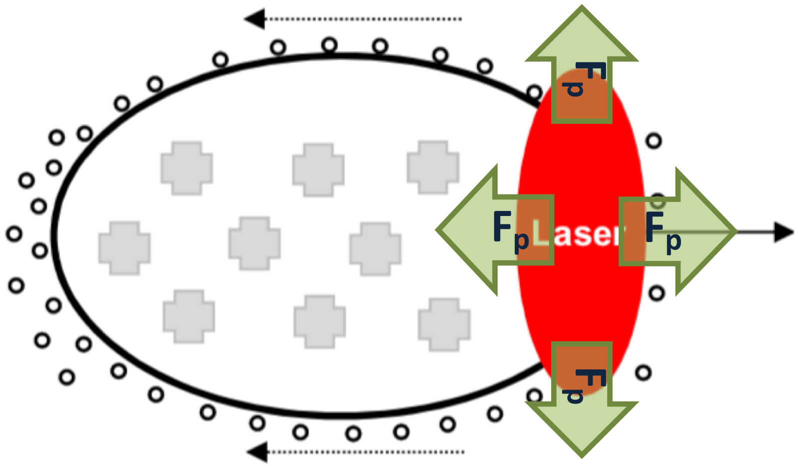

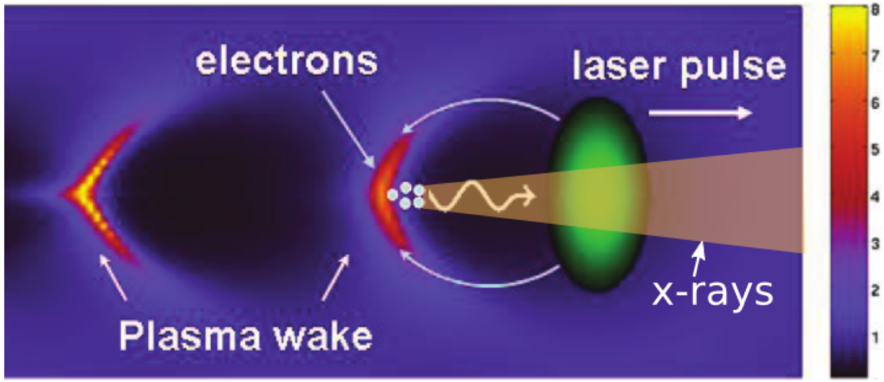

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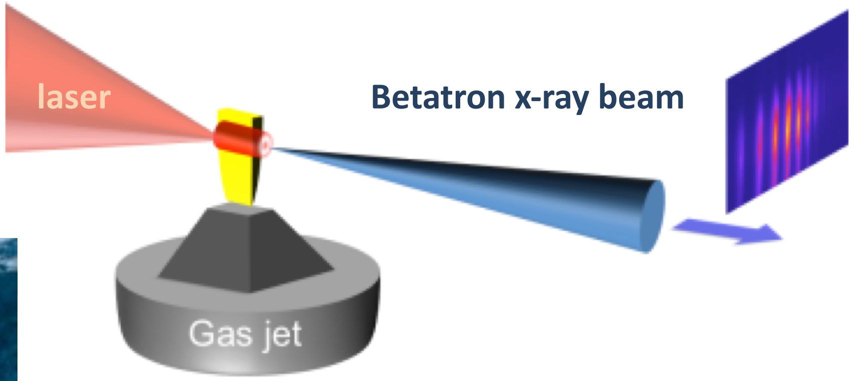

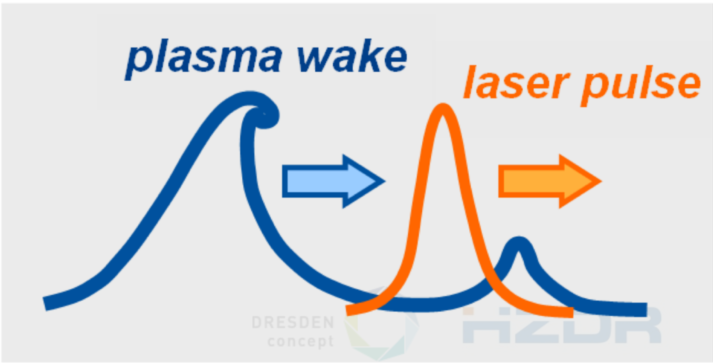

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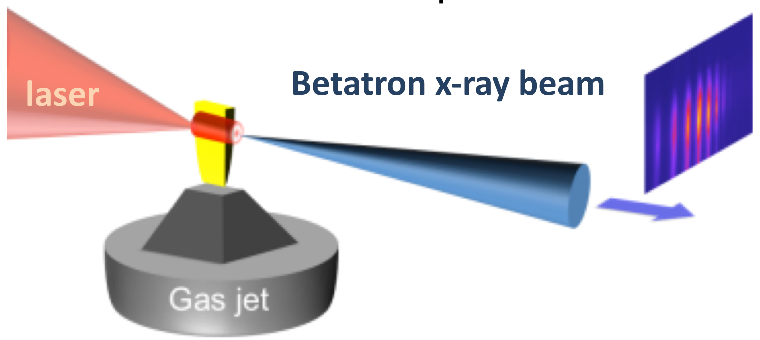

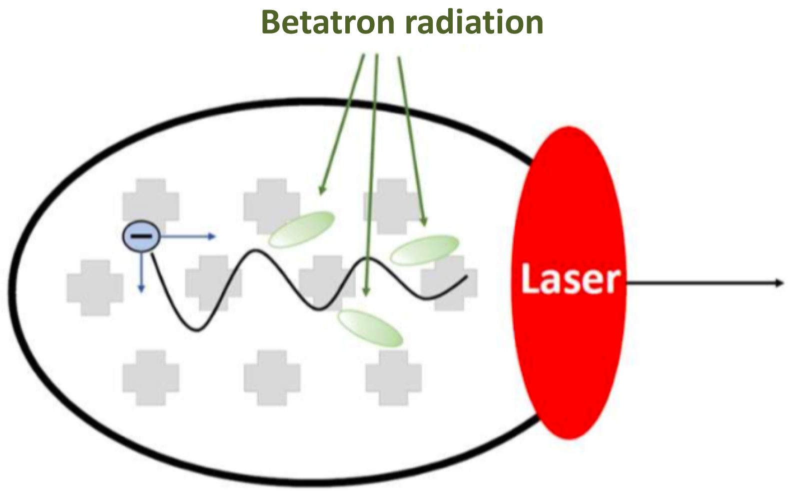

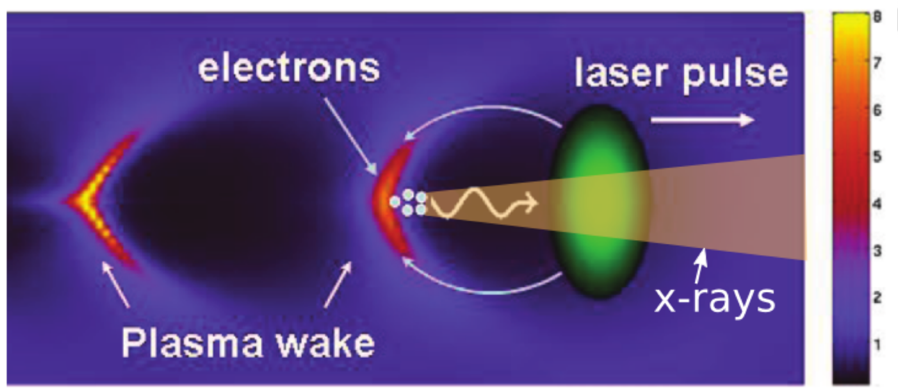

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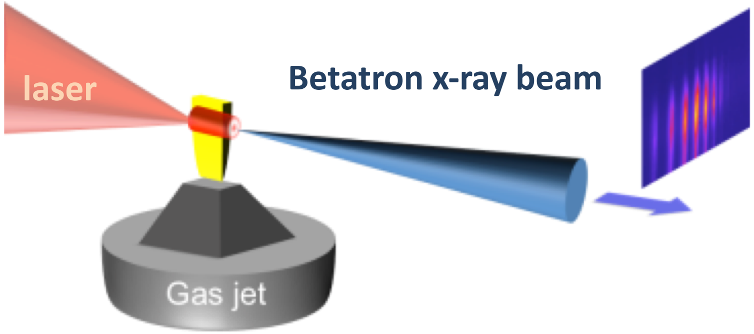
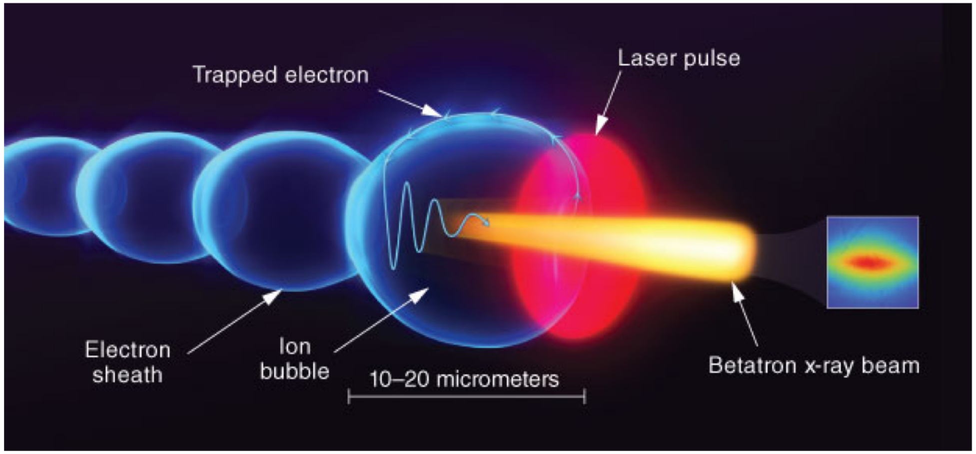
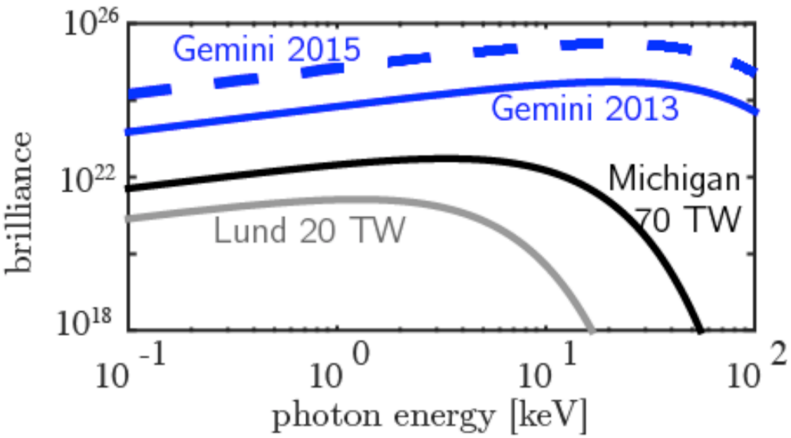


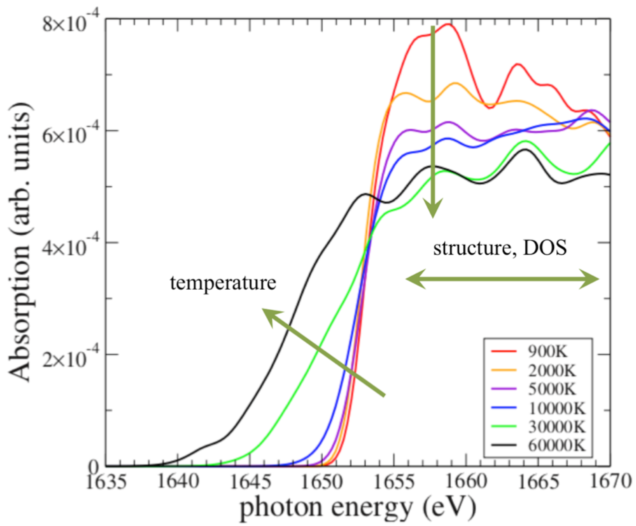


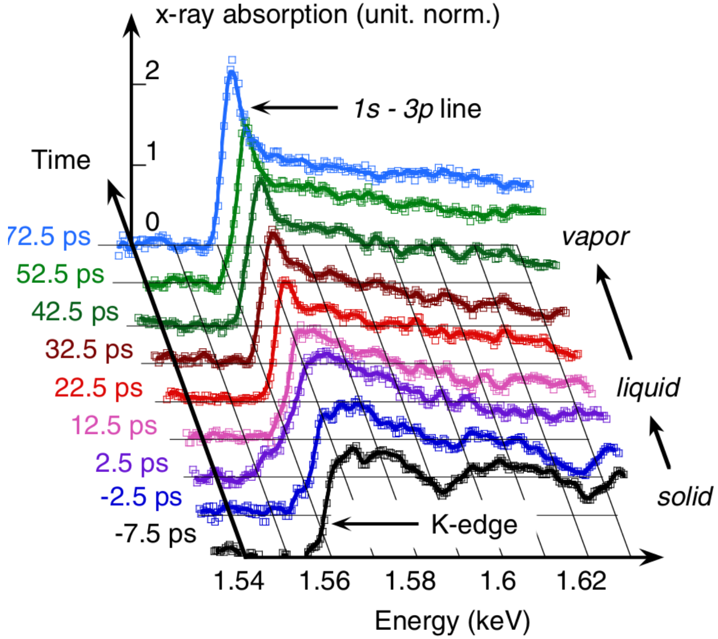


X-ray absorption spectroscopy (XANES)

- X-ray Absorption Near Edge Spectroscopy (XANES)
- Absorption peaks above edges correspond to spatial distribution of ions
- Photoionized electron - ejected into continuum state with low residual energy

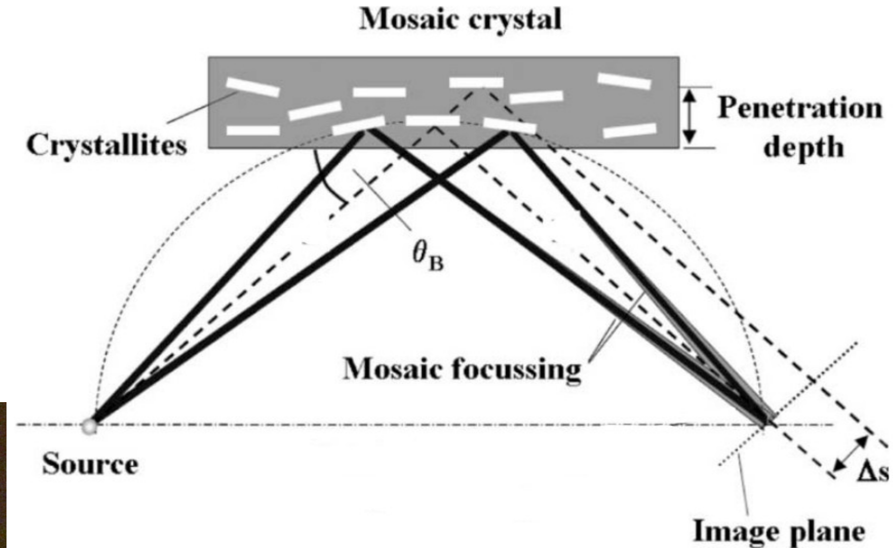
  ⇒ Scattering by the surrounding ions
  ⇒ Absorption cross section reflects the ionic structure of the matter.
- Slope of K-edge corresponds to density of free states ~ temperature.
- Has to be modelled by simulations (e.g. Abinit, DFT-MD)



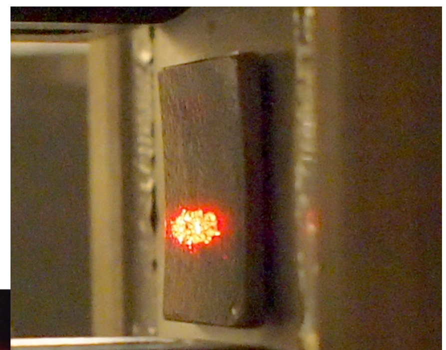


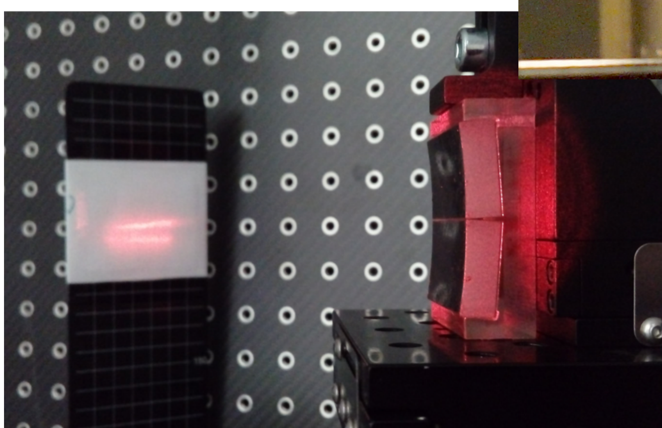
F. Dorchies *et al.*, Phys. Rev. Lett. **107**, 245006 (2011)

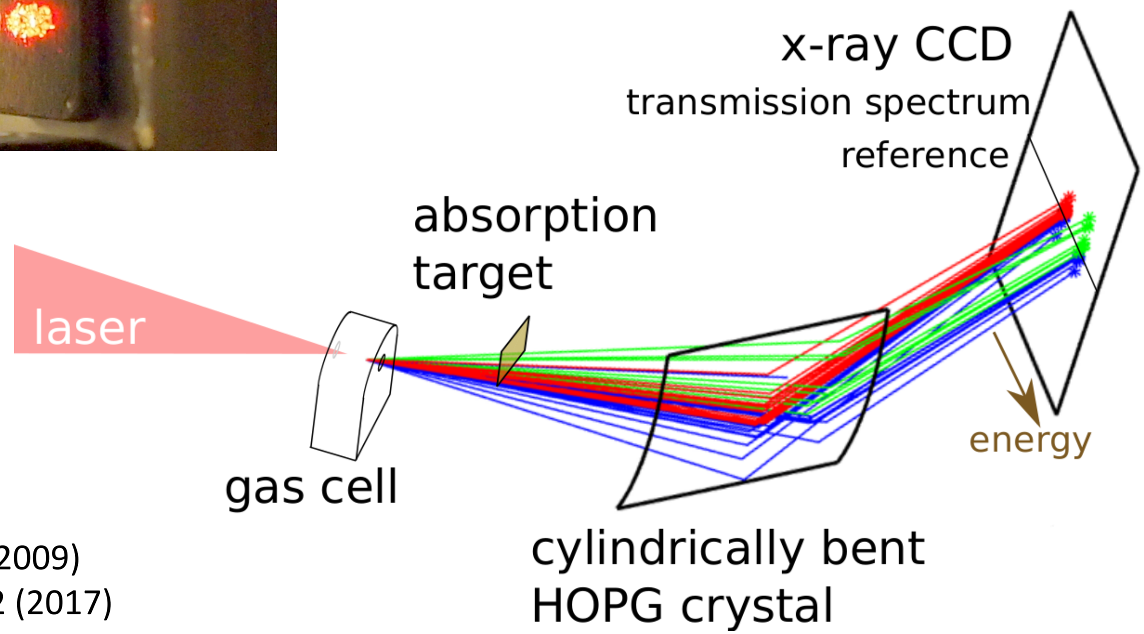
Mosaic HOPG crystal spectrometers



- Bragg reflection, HOPG (graphite) suitable for 4 – 10 keV, 2d = 6.708 Å
- Composed of small crystallites with plane slightly tilted from the surface (~ 0.1 – 1°)
- High reflectivity
- Mosaic focusing
- Angular resolution



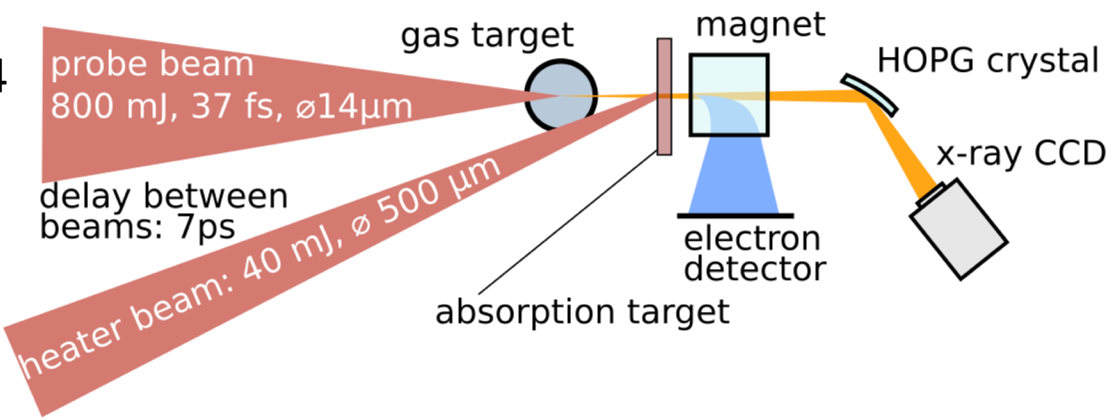


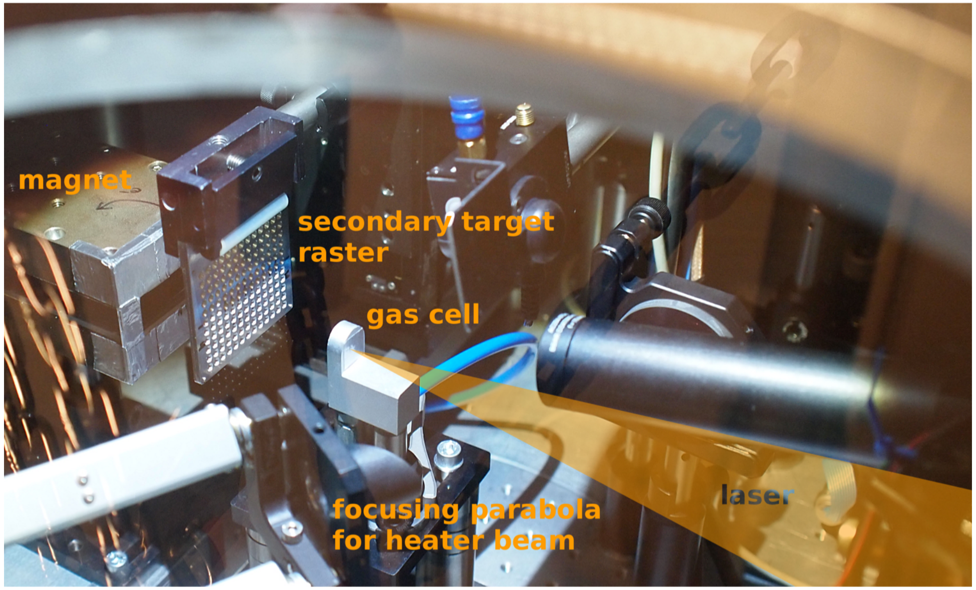


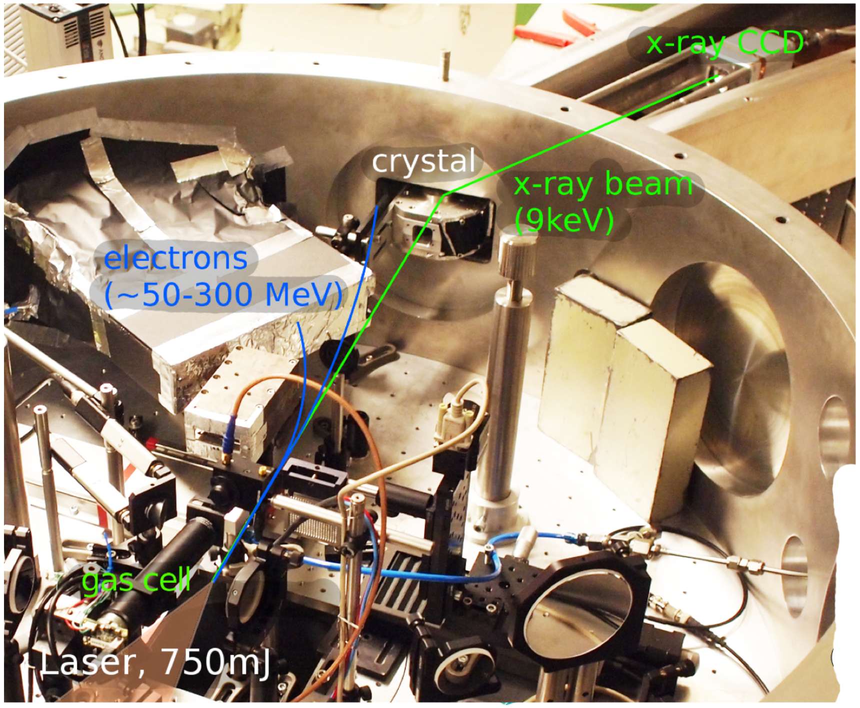
H. Legall *et al.*, J. Appl. Cryst. **42**, 572–579 (2009)
M. Šmíd *et al.*, Rev. Sci. Instrum. **88,** 063102 (2017)

Preliminary experiments in Lund

- Lund Laser Center, Sweden
- Ti:Sapphire, ~ 750 mJ, 37 fs, 14 µm spot, 1.5 µm Cu foil
- Production of 200 MeV electrons
- Detected signal ~ 30000 photons per shot





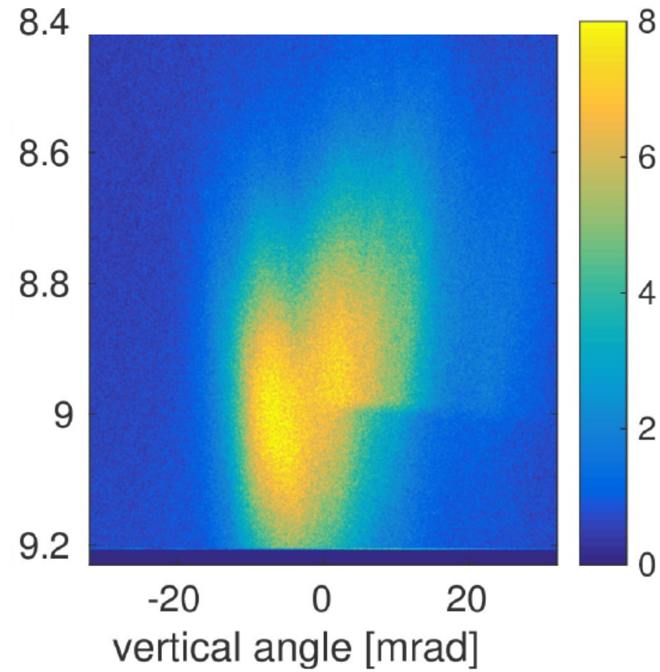


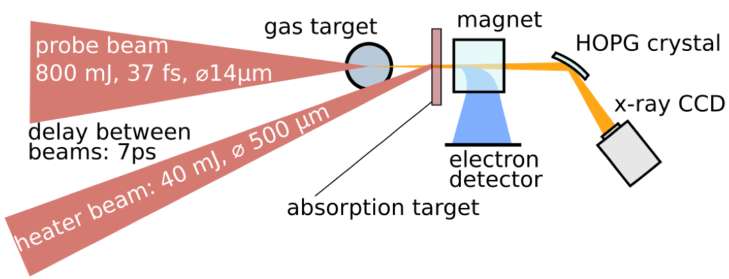
M. Šmíd *et al.*, Rev. Sci. Instrum. **88,** 063102 (2017)

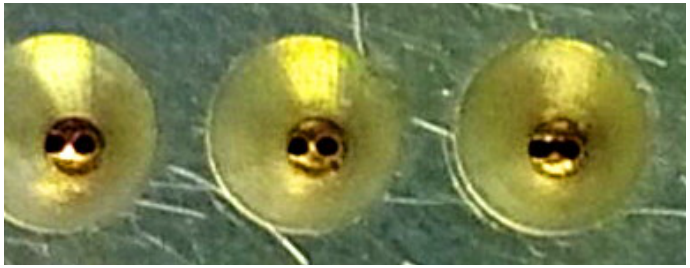
HOPG spectrometer performance

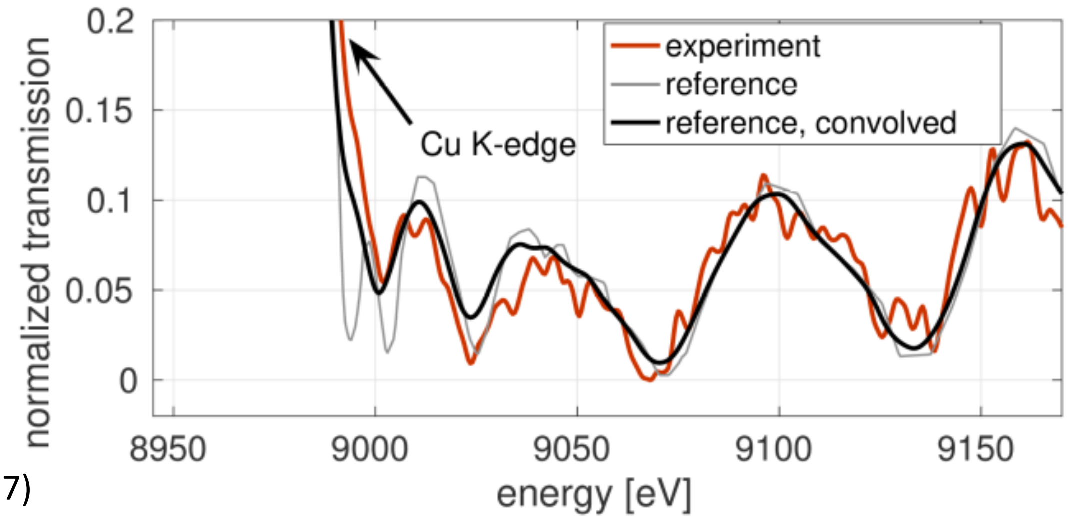
- Crystal spectrometer showed excellent spectral 5.5 eV (E/dE = 1600)
- Single hit analysis
- Angular resolution

⇒ distinguish two parts of target





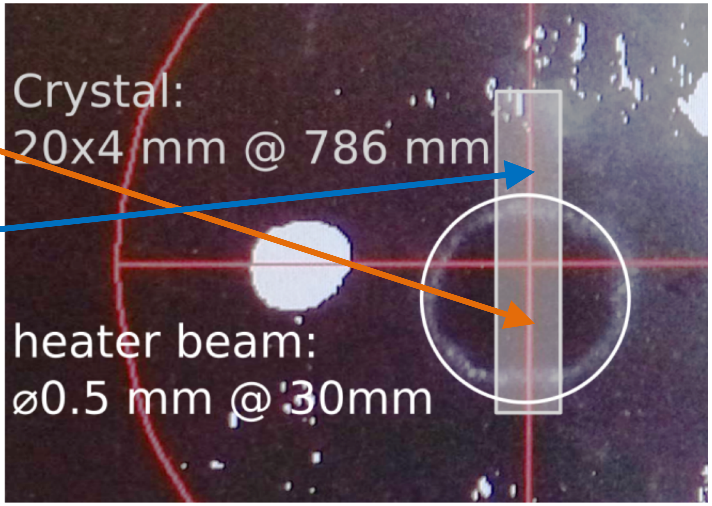


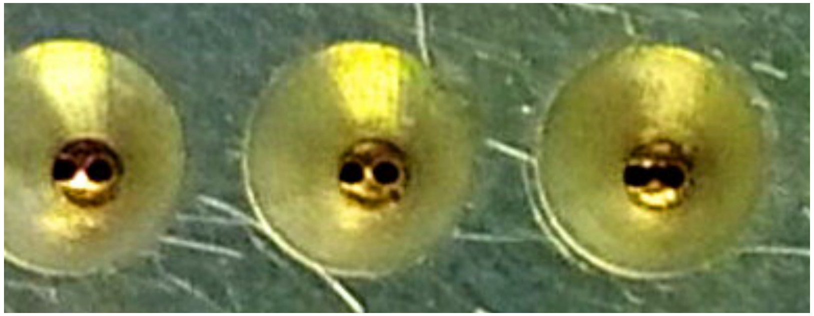


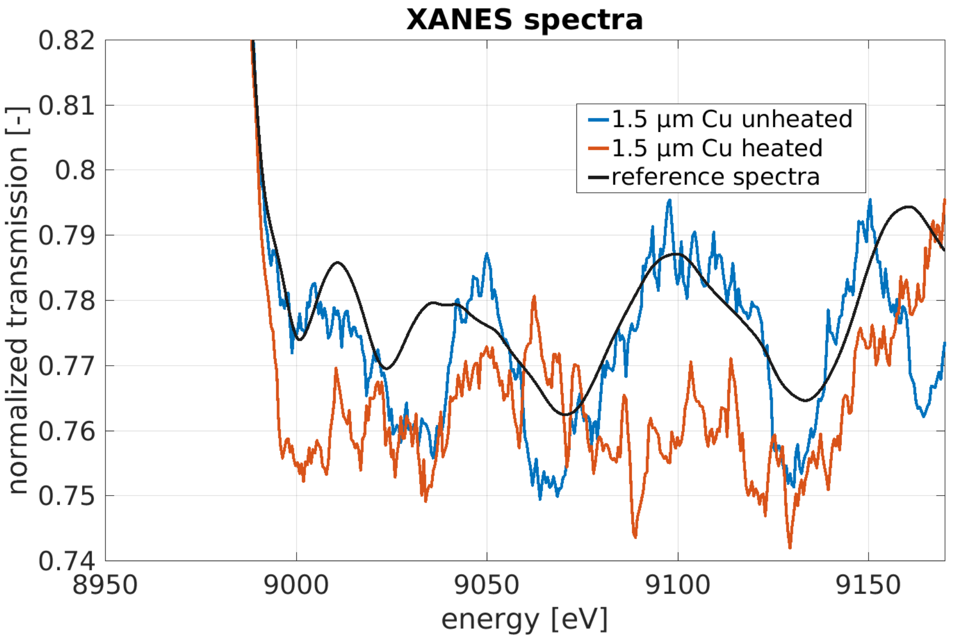
M. Šmíd *et al.*, Rev. Sci. Instrum. **88,** 063102 (2017)

X-ray absorption spectroscopy (XANES)

- 500 µm large spot was directly heated by small part of the laser
- Second part of x-ray beam penetrated unperturbed Cu target
- Signal accumulated over ~ 200 shots
- Statistically significant decrease of XANES features on heated part.
- Experimental proof of ultra-fast Cu melting







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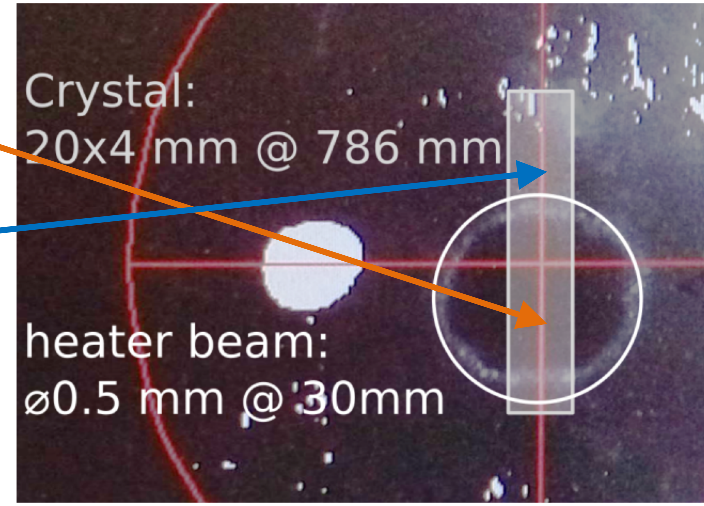
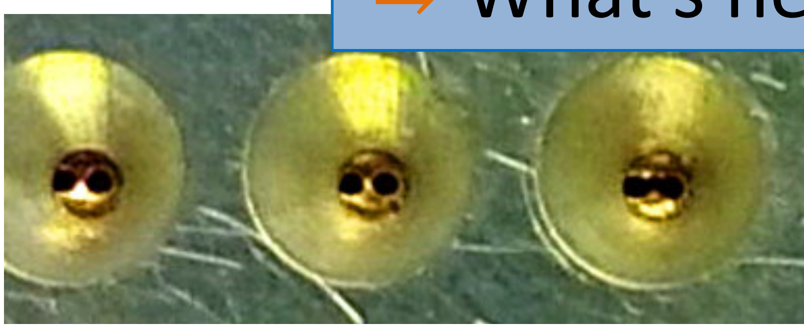
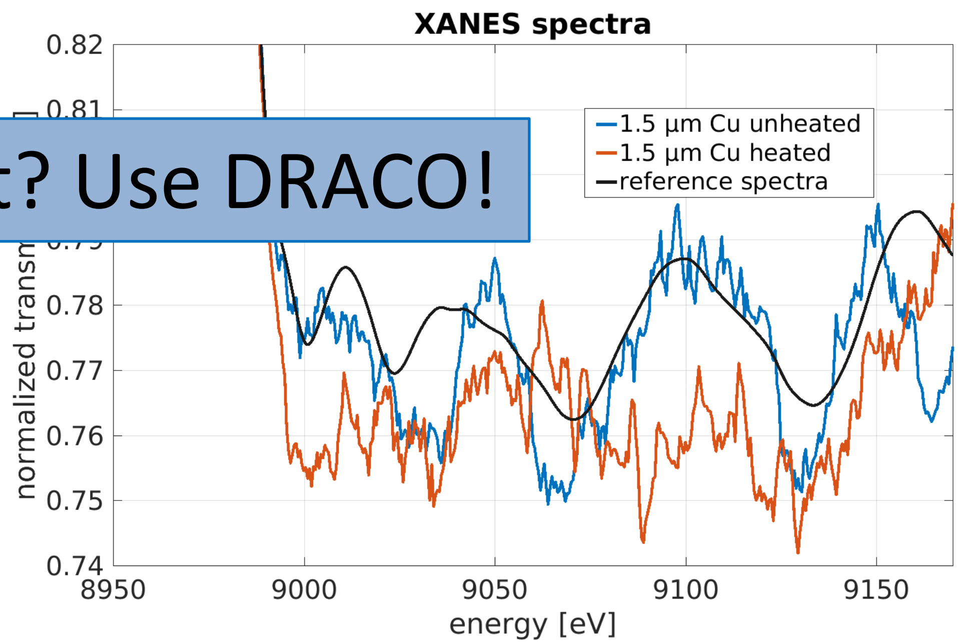


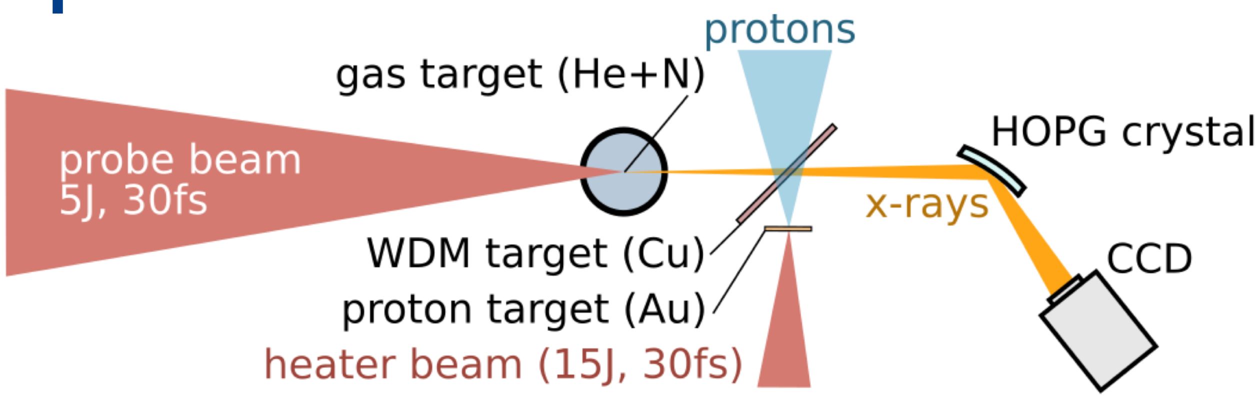
⇒ What's next? Use DRACO!



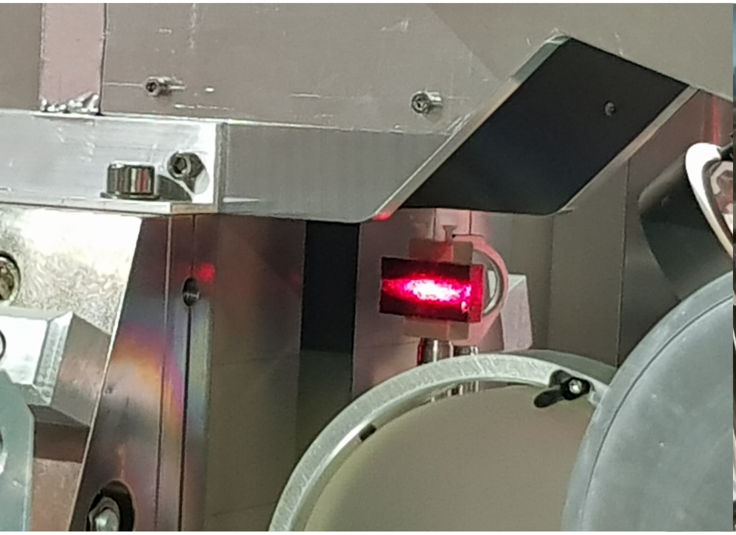


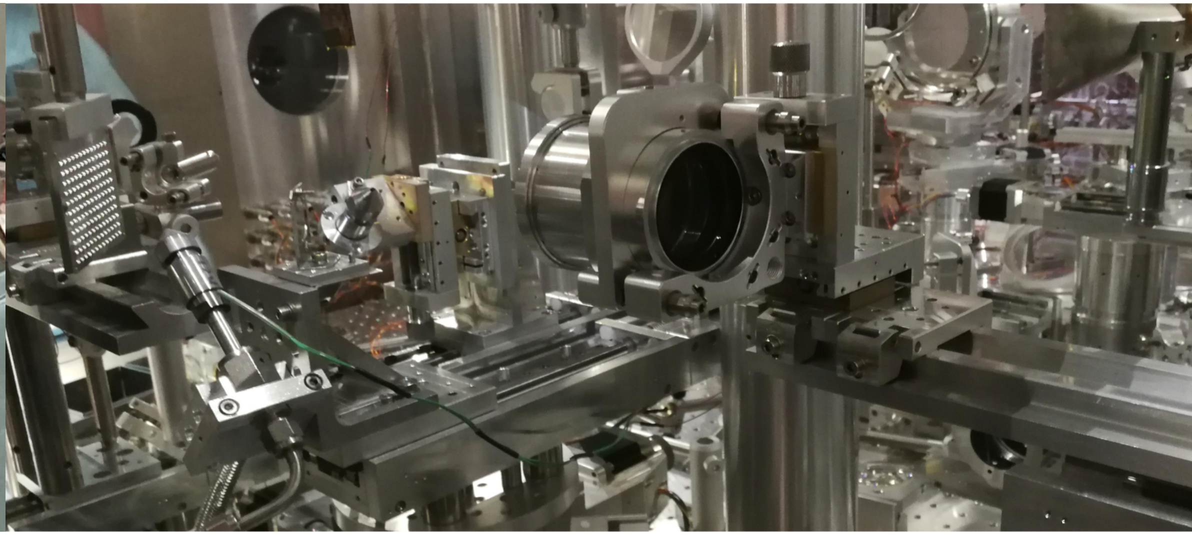
Member of the Helmholtz Association
Dr. Katerina Falk I Institute of Radiation Physics I www.hzdr.de

Permanent setup at HZDR



- DRACO (4-5 J, 30 fs, 150 TW)
- 400 MeV electrons
- Achieve higher energy x-ray spectra and stronger signal
- New permanent setup for WDM studies
- Novel thin HOPG-flex crystal spectrometer for better resolution
- Spring 2020: 1 PW laser for direct laser and isochoric x-ray/proton heating





Summary

- **Warm dense matter (WDM) is a difficult state do describe theoretically**
  - Applications in in ICF, planetary science, materials and theoretical physics
  - Transport properties largely unknown with great current interest
  - Requires active x-ray probing
- **Novel platform for WDM EOS and transport measurement at OMEGA**
  - Imaging X-ray Thomson scattering, VISAR/SOP, X-ray radiography
  - First full model-independent EOS measurement in WDM
- **Experiments with short pulse lasers (DRACO facility)**
  - LWFA betatron radiation source for ultrafast absorption spectroscopy
  - Heating of Cu samples with lasers or x-rays/protons
  - Study non-thermal melting and bond-hardening
  - New instrument design (x-ray spectrometers, detectors)

OMEGA experiment collaboration

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Thank you for your attention!
Any questions?

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