Plasma physics with ultrafast x-rays

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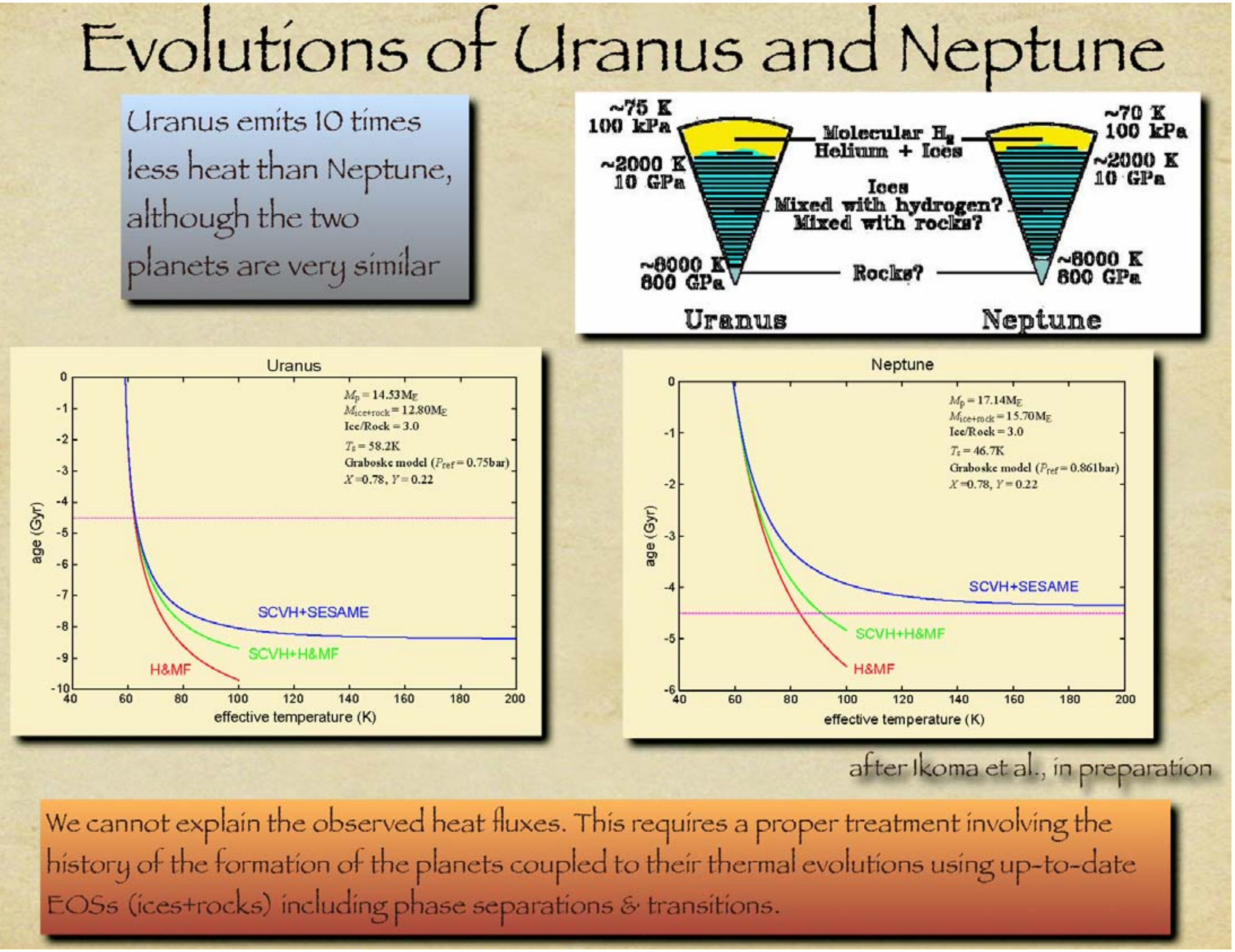
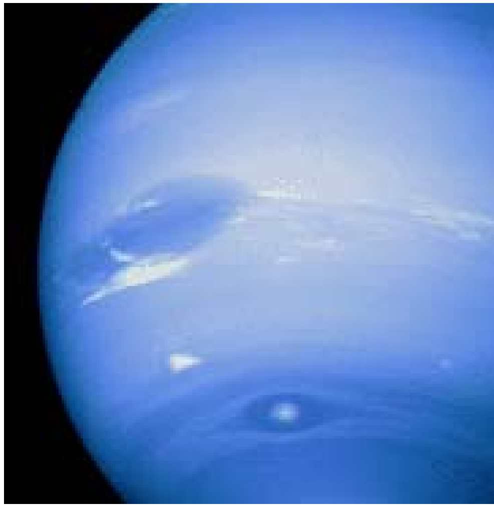
A.Zholents, P. Heimann, M. Zolotorev, J. Byrd, "Generation of subpicosecond X-ray pulses using RF orbit deflection," NIM A **425**, 385, (1999).

- Introduction: optical probing, Thomson scattering, High Pressure phenomena .
- X-ray absorption of Warm Dense Matter at the ALS
- X-ray μ-focusing at FLASH

Motivation for x-ray studies of plasma physics

- From T. Guillot WDM Workshop 2007





- Neptune from Voyager 2

- Other applications: fusion energy, defense

A list of nice experiments related to plasmas

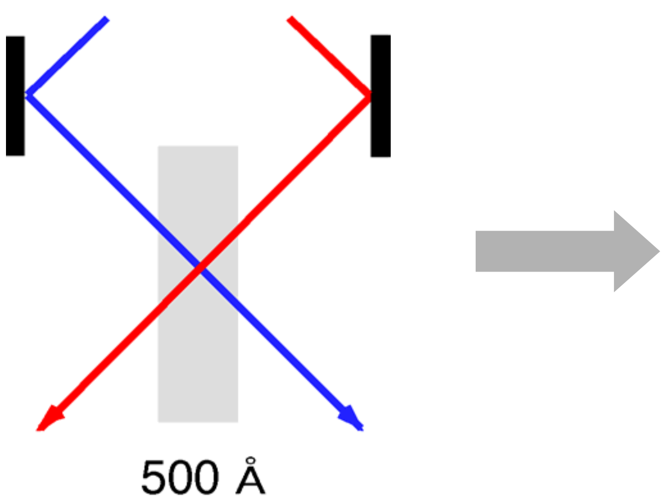
- From peak brightness collaboration at FLASH

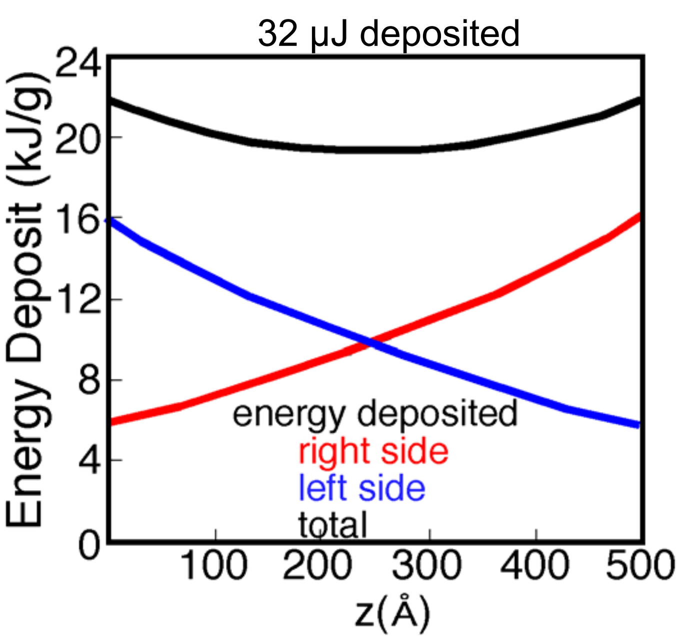
	Experiment	Brief Description
Condensed Matter	Warm Dense Matter Creation	Using x-rays to uniformly warm solid density samples
	EOS Measurements	Use an optical laser to heat a sample and x-rays to provide a diagnostic of the bulk
	Near Edge Absorption	Use an optical laser to heat a solid and x-rays to probe the structural changes
	Femtosecond Ablation	Probe the nature of the ablation process on the sub-ps time scale
Plasma	Trapped, High Γ Plasmas	Use EBIT/laser-cooled trap and probe highly-charged strongly-coupled Coulomb systems
	Diagnostic Development	Develop diagnostics for Thomson scattering, interferometry, and radiographic imaging
	X-ray /Gas-Jet Interaction	Create exotic, long-lived highly perturbed electron distribution functions in dense plasmas
	X-ray / Solid Interactions	Use x-rays directly to create extreme states of matter at high T and ρ
	Plasma-Spectroscopic Studies	Use x-rays as a pump to move bound state populations and study radiation redistribution
Bio-related	Coulomb Explosion	Study Coulomb Explosion process with emphasis on biological imaging problems
	Optics Damage	Study structural changes & disintegration processes of solids under x-ray irradiation

Creating a plasma, difficulties

- Isochoric heating
  - Uniformly heat 50 nm Al foil using the 200 fs x-rays at 60 Å
    - $\frac{E}{V} = \frac{3}{2} n_e T_e + \sum_i n_i I_P^i \Rightarrow$ 3/2 (1.7x10^{23}) x 10 eV
    - Volume = Area x 50 nm ⇒ Area = 50 µm spot
- Isentropic expansion
  - An optical Fourier Domain Interferomery probe measures the isentropic expansion

X-ray or optical beams

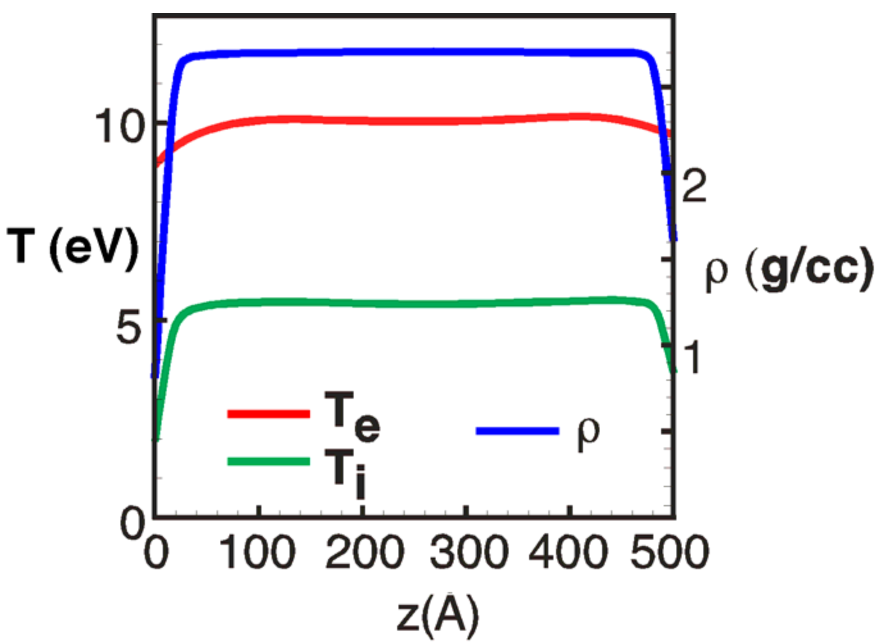


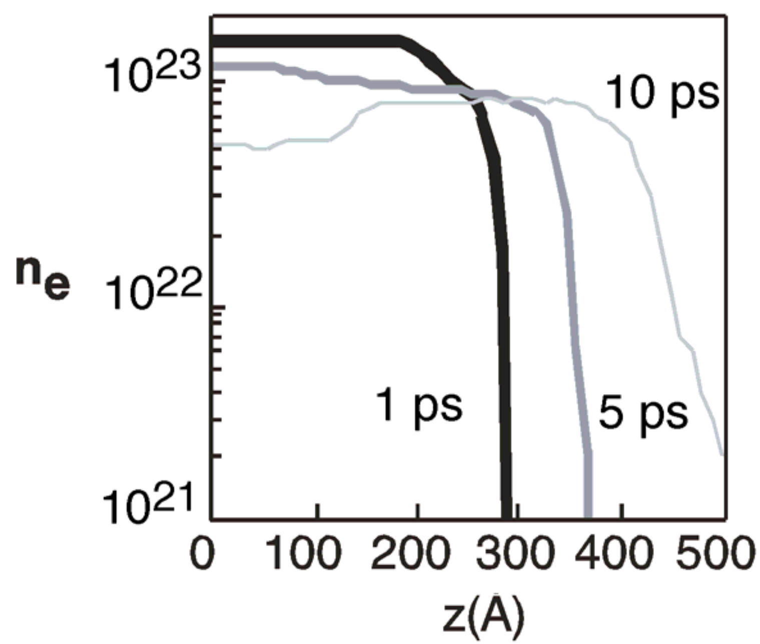


Simulations indicate that the Al sample stays uniform for ~ 1 ps

- For 50 μm spot the sample T_e reaches ~ 10 eV
  - T_i reaches only 1/2 of T_e and equilibrates in > 500 fs
- Sample uniformity is excellent for up to 1 ps
  - Sample tamping, e.g., 10 nm CH, would mitigate gradients in Al

At 1 ps

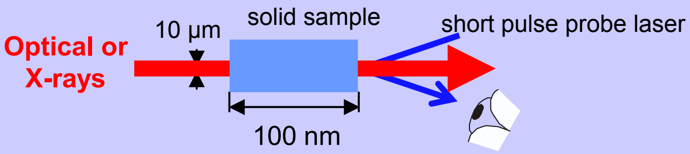




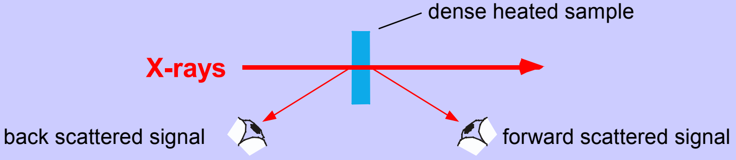
- *1-2 ps is an appropriate time resolution.*

3 classes of plasma experiments, where x-rays can have an impact

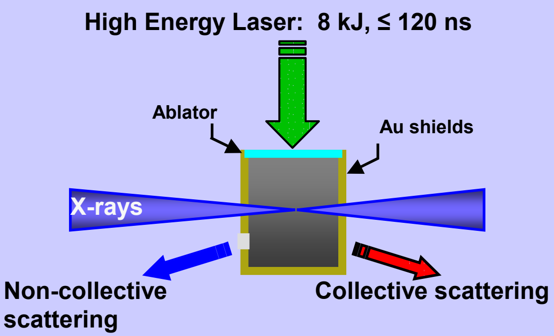
- **Probing Warm Dense Matter**
  - Generate ~ 1 eV solid density matter
  - Measure the equation of state and optical properties



- **Probing a plasma with Thomson Scattering**
  - Perform scattering from solid density plasmas
  - Measure n_e, T_e, <Z>, $f(v)$



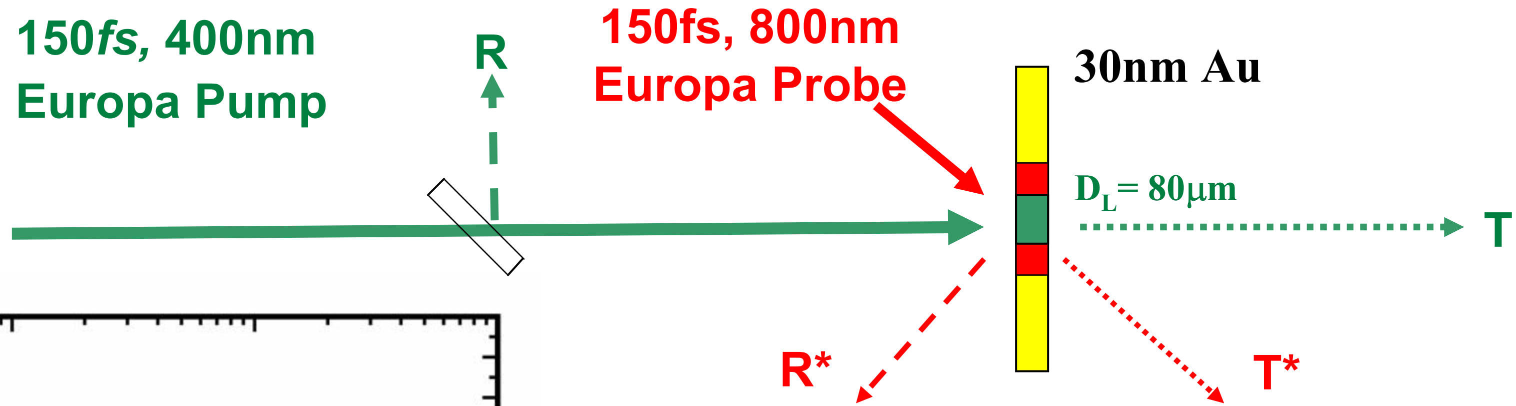
- **Probing High Pressure phenomena**
  - Use high energy laser to create steady high pressures
  - Produce shocks *and* shockless high pressure systems
  - Study high pressure matter on time scales < 1 ps
  - Diagnostics: Diffraction, SAXS, Diffuse scattering, and Thomson scattering

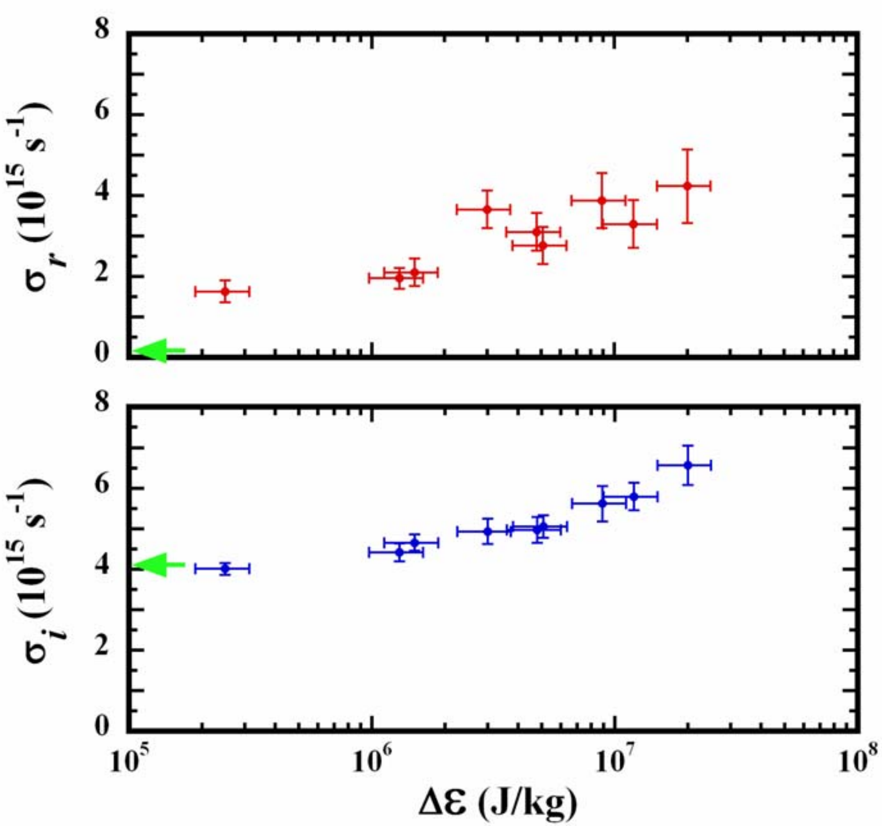


Probing Warm Dense Matter*

- From A. Ng WDM Workshop 2007

*Warm Dense Matter: the phase between plasmas and condensed matter.





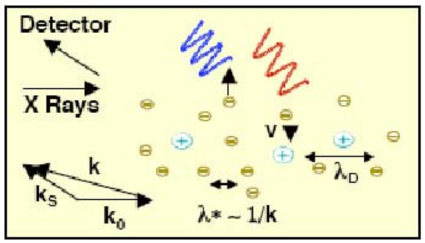
- **Isothermal heating produced by laser skin-depth deposition and ballistic electron transport**
- **Isochoric condition maintained by material strength & inertia**

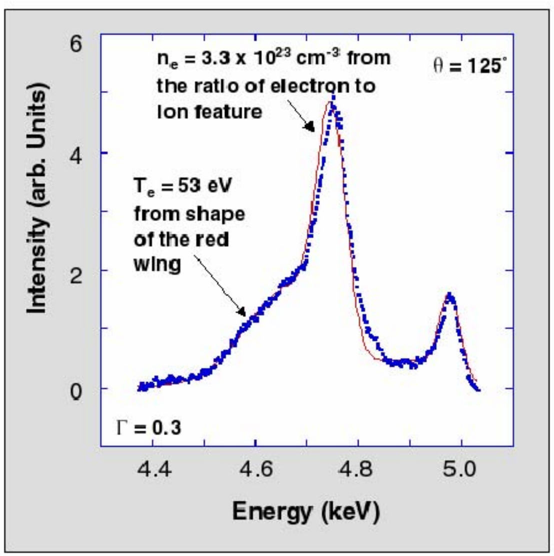
Probing dense matter with Thomson Scattering

- From G. Gregori WDM Workshop 2007
- **At Omega laser (22kJ)**

➔ **Probe individual particle motion**

large k: non collective scattering

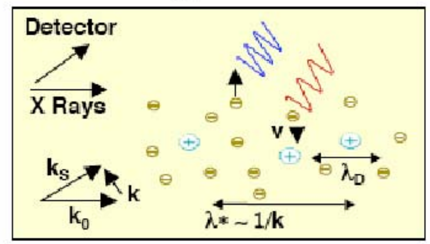


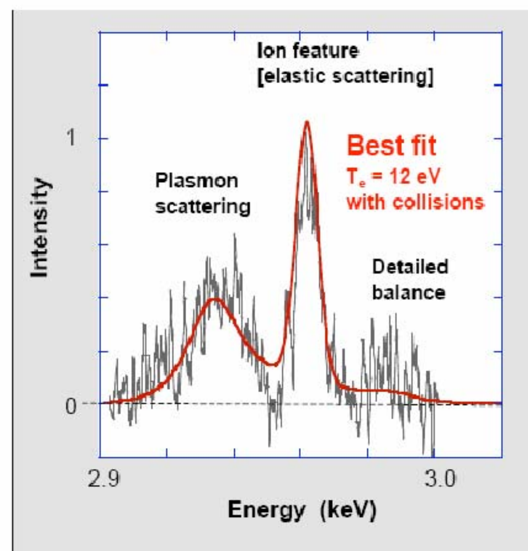


Gregori et al., PRE (2003)
Glenzer, Gregori et al., PRL (2003)
Gregori et al., PoP (2004)

➔ **Probe plasma waves (plasmons)**

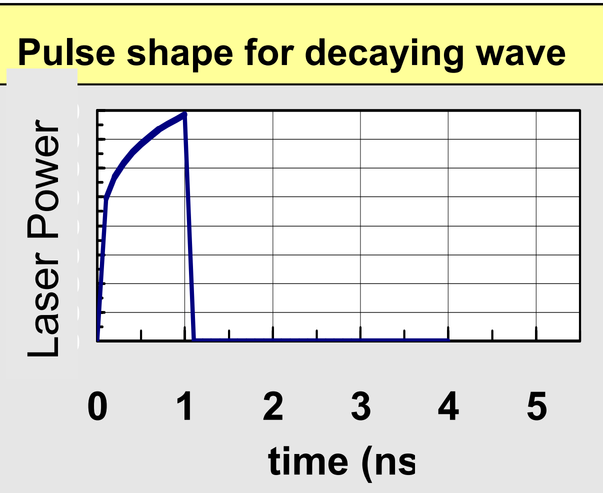
small k: collective scattering

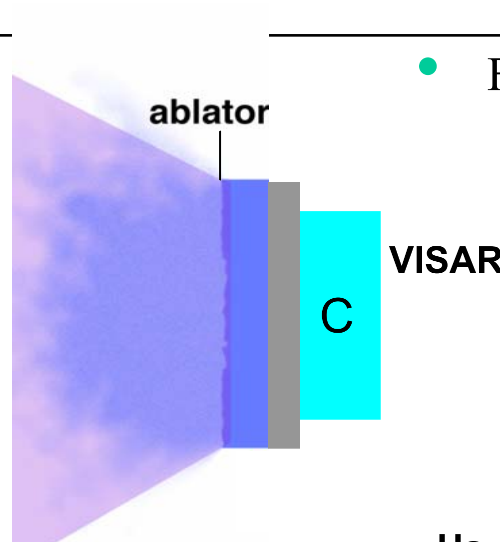




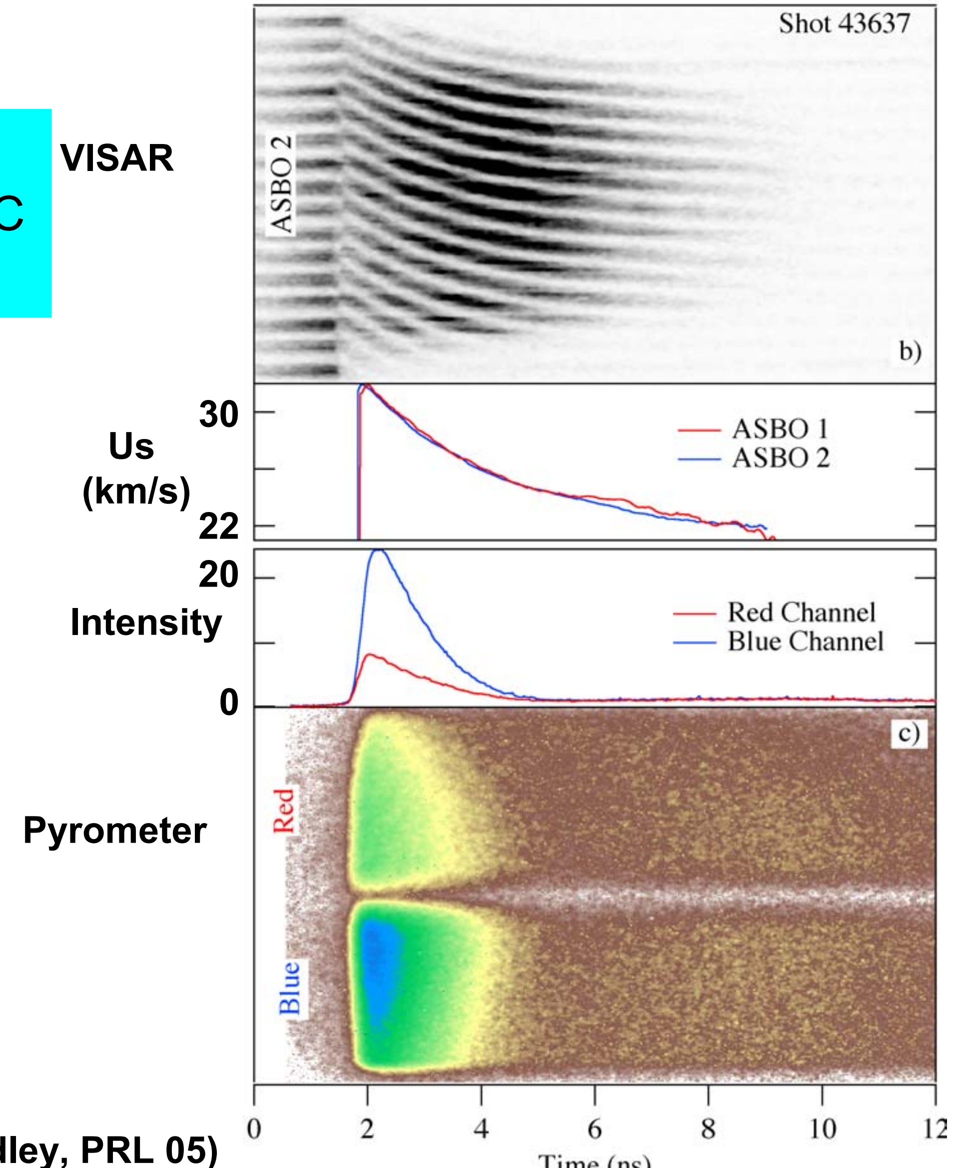
Glenzer, Gregori et al., PRL (2007)
Gregori et al., PRE (2007)
Gregori et al., HEDP (2007)

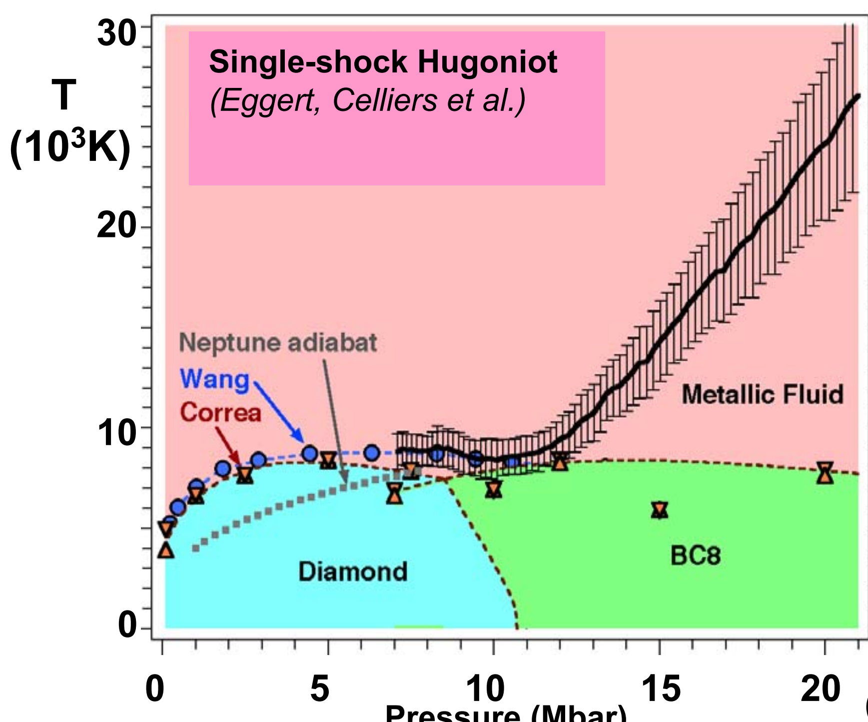
Probing High Pressure phenomena





- From G. Collins WDM Workshop 2007

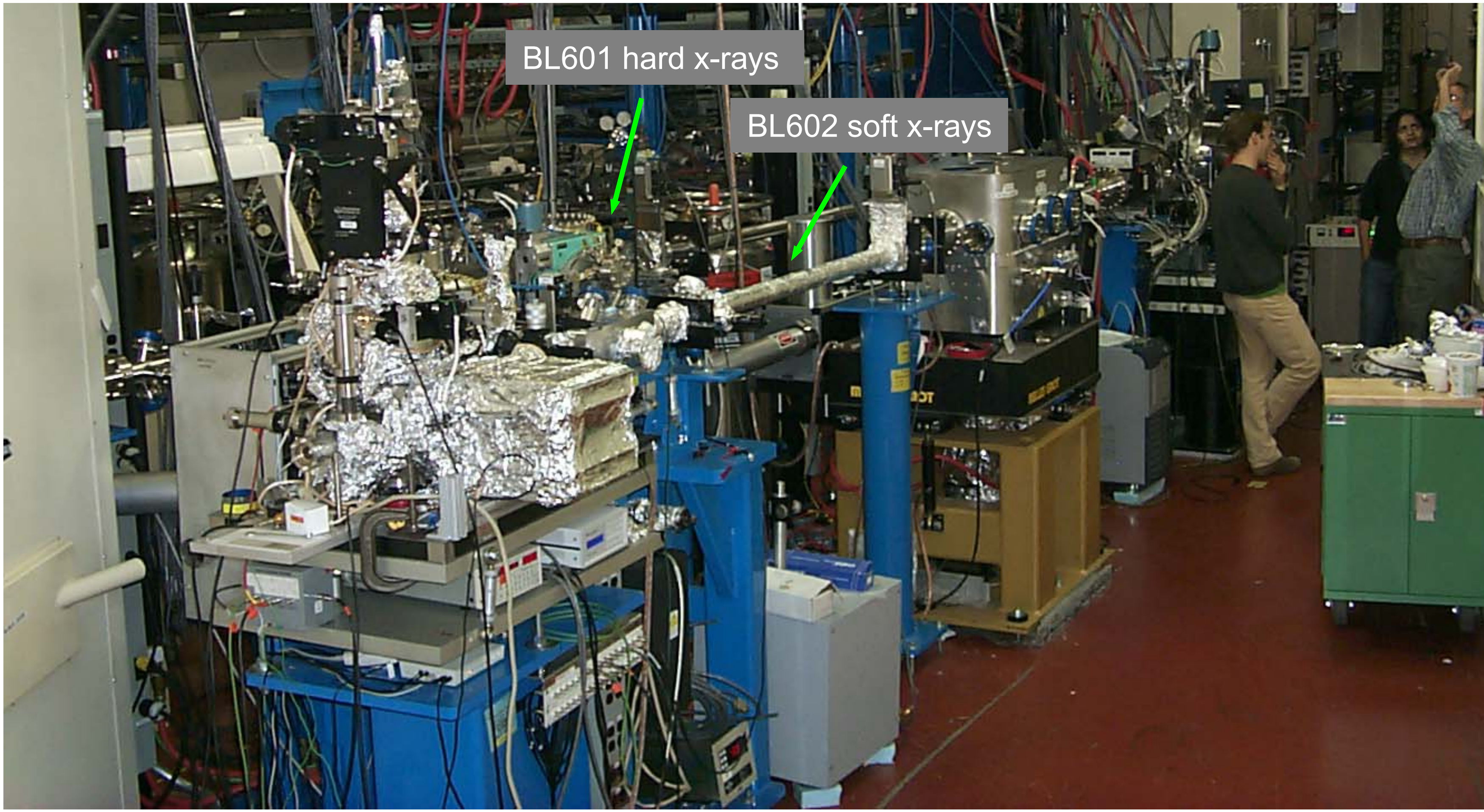




(Bradley, PRL 05)

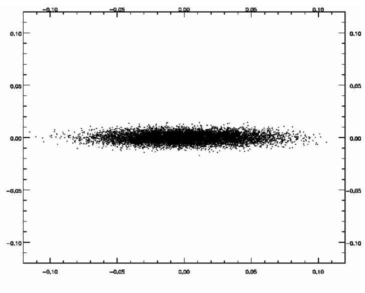
X-ray absorption of Warm Dense Matter at the ALS

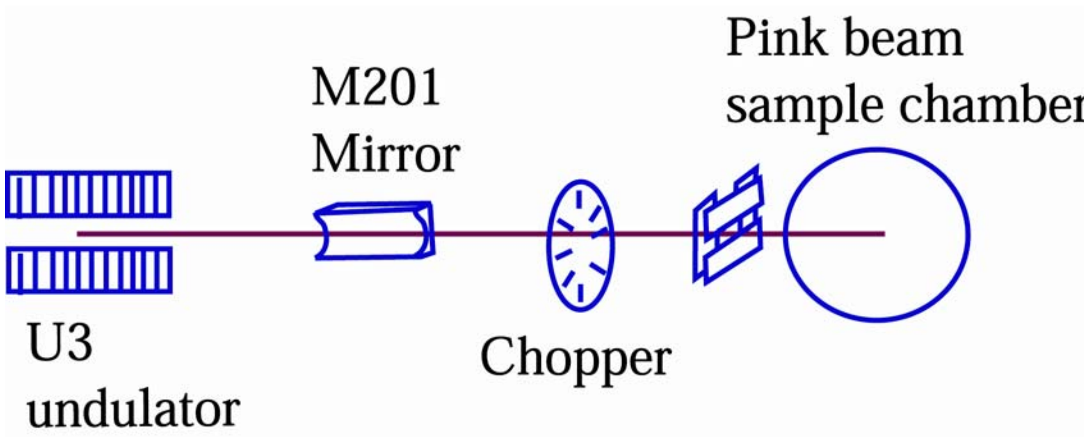
- Slicing undulator beamline on ALS floor



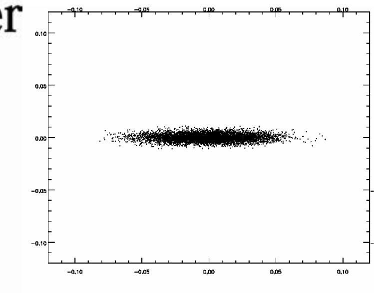
Sample in pink beam focus

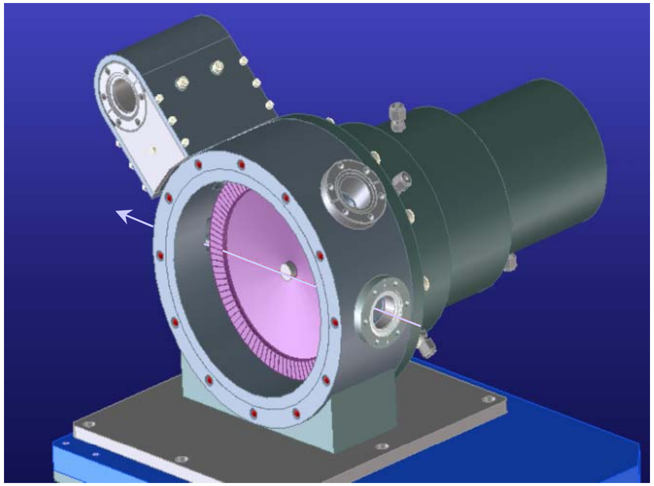
- ALS source





- Pink beam focus:
  560 (h) x 80 µm (v)

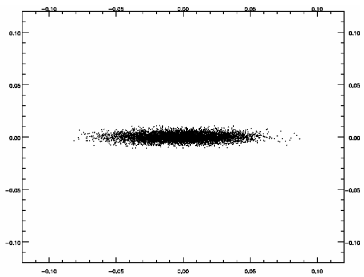


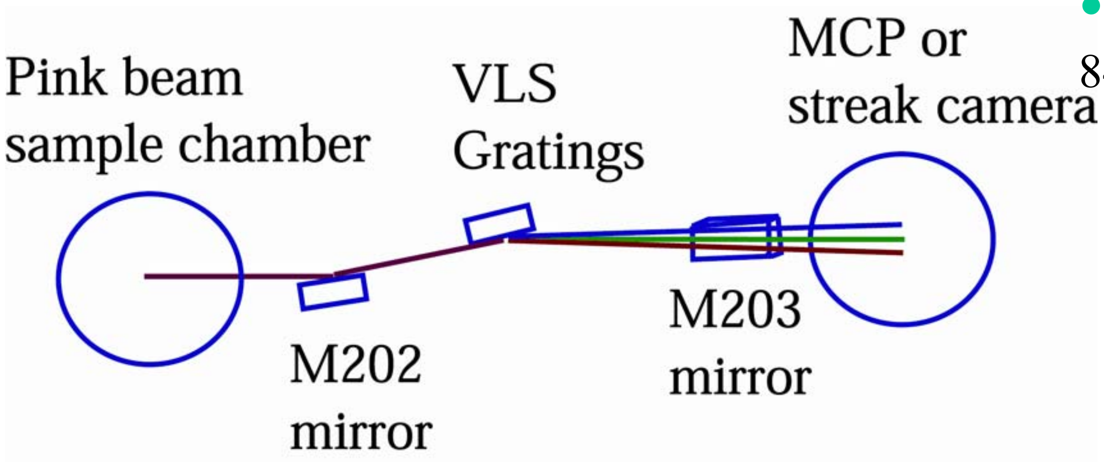


- X-ray chopper reduces power on the samples in pink beam.

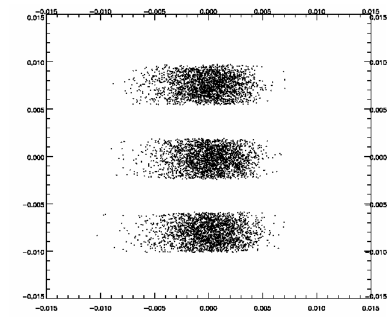
Grating spectrograph and detectors

- Pink beam focus

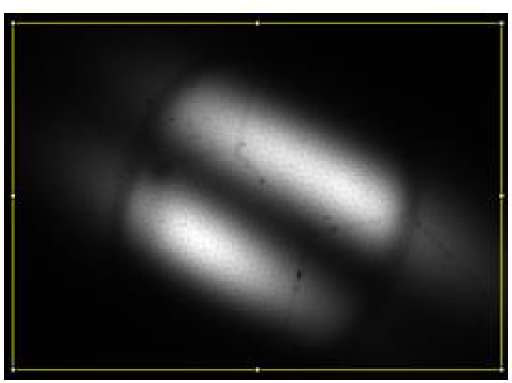


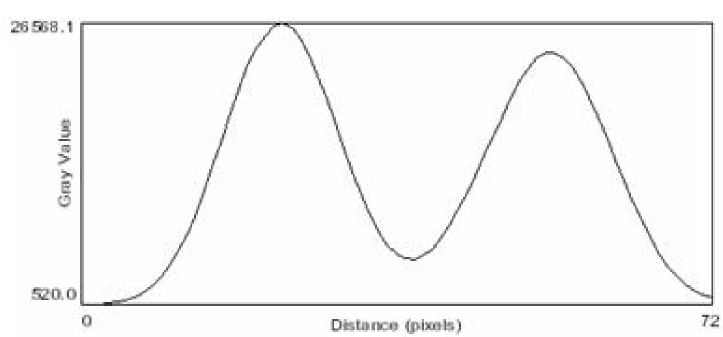


- At the detector 849, 850, and 851 eV



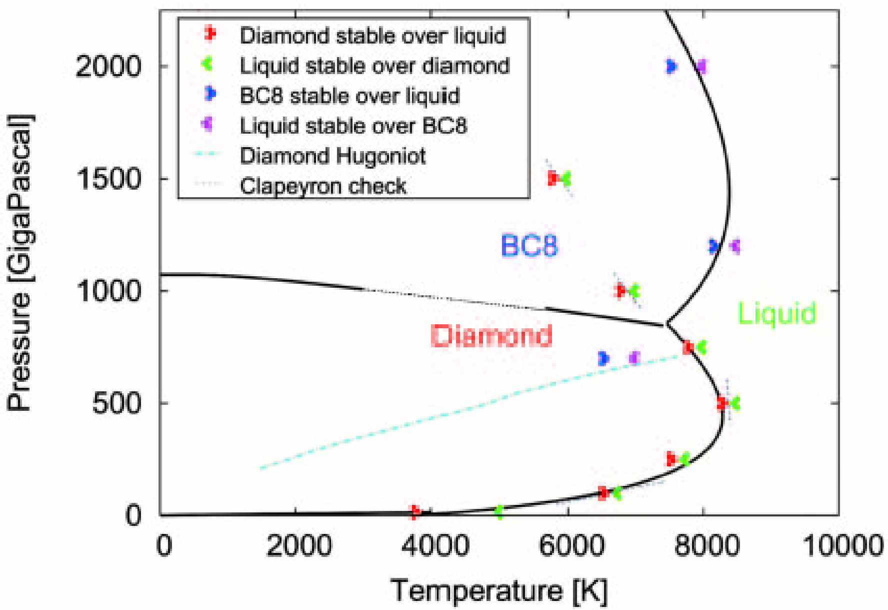
- Following data taken with gated MCP detector.
- June beamtime with streak camera.
- Streak camera with UV pulses, $\Delta t = 2.4$ ps – $\Delta t = 1.5$ ps has been demonstrated with x-rays by J. Feng.



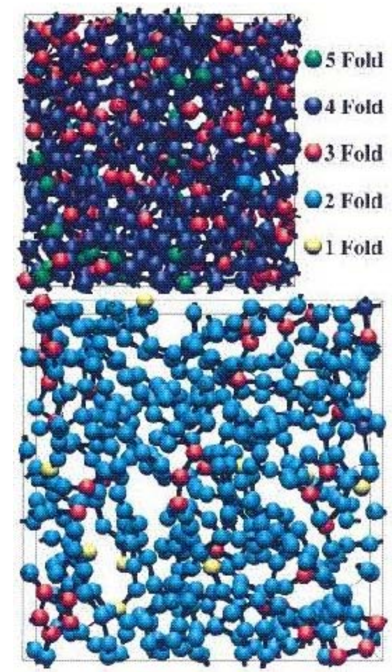


X-ray absorption of liquid carbon

- Liquid carbon not stable at ambient pressure.
- Molecular dynamics calculations: High density ρ liquid predominantly sp^3 coordination, low ρ liquid mainly sp, Glosli and Ree, PRL **82**, 4659 (1999), Wu et al., PRL **89**, 135701 (2002), Correa, Bonev, Galli, PNAS **103**, 1204 (2006)



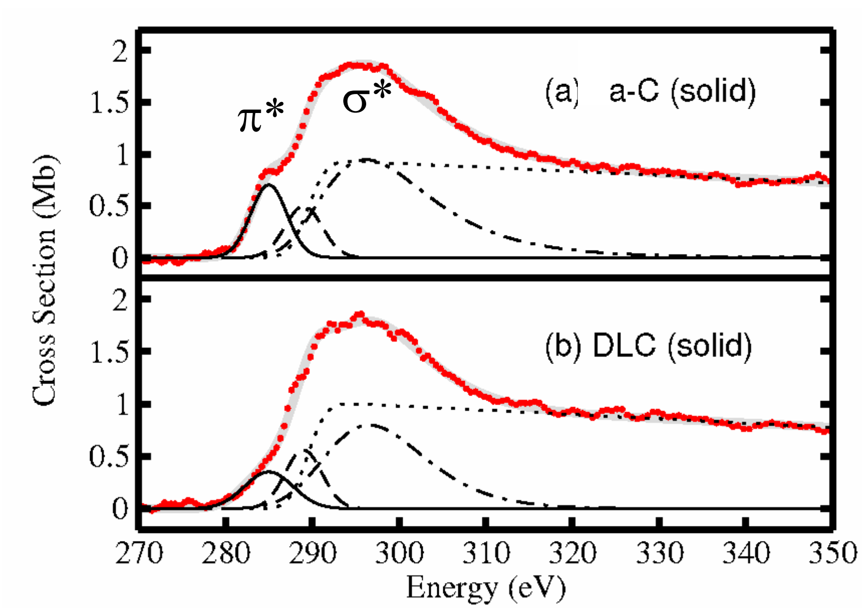
Correa et al.

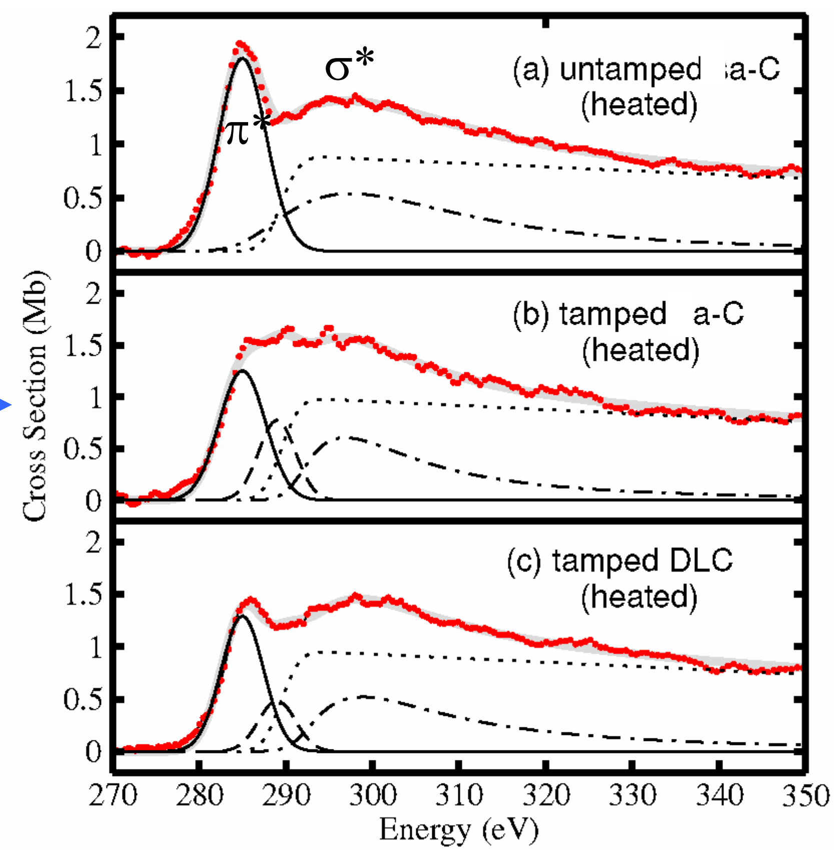


Liquid carbon K-edge spectra

- Johnson, Heimann et al., PRL **94**, 57407 (2005)

- Initial samples: a-C ρ 2.0 g/cm^3, DLC ρ 2.6 g/cm^3, ~2 J/cm^2.
- Isochoric heating: tamp carbon with LiF so that pressure wave requires 100 ps to reach surface and return to carbon sample.
- Heated spectrum shows increase in π* resonance, shift of σ* resonance to higher energy.



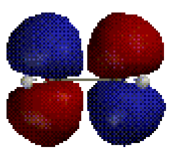


Analysis of liquid carbon spectra: π^* resonance

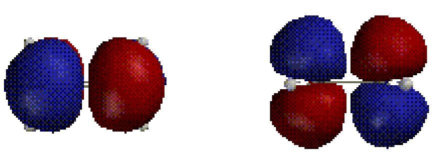
Unoccupied π orbitals

Ethane sp^3
None

Ethylene sp^2



Acetylene sp

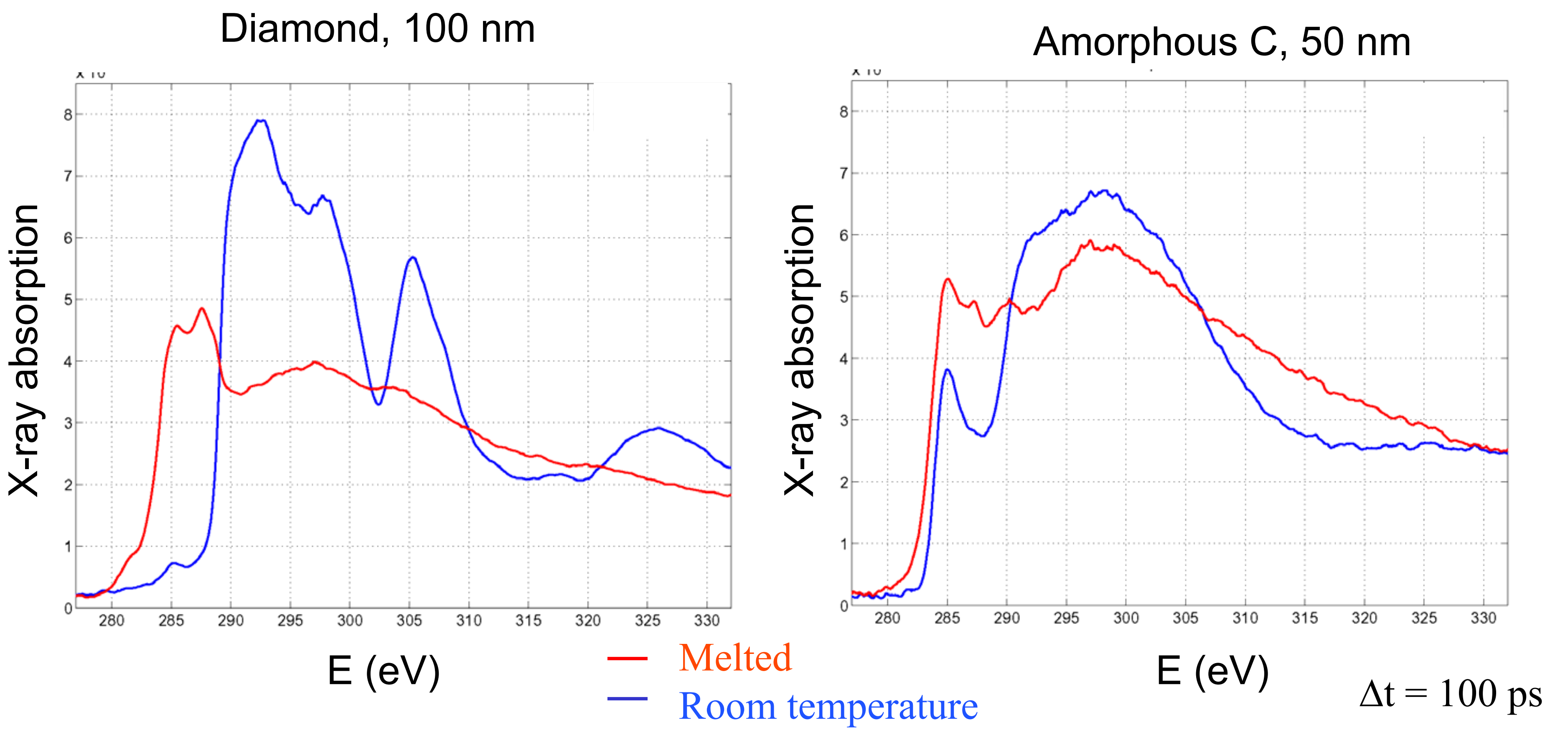


Material	π^* area	π^* states/site	π^* states/site calculation[1]
a-C	3.6	0.7 $\pm$0.2	
DLC	2.1	0.4 $\pm$0.2	
untamped liquid	12.4	2.1 $\pm$0.3	
2.0 g/cc liquid	8.3	1.5 $\pm$0.3	1.5
2.6 g/cc liquid	7.9	1.4 $\pm$0.3	1.2

[1]Morris et al., Phys. Rev. B **52** 4138 (1995) at 6000K

- Normalized to C_{60} with sp^2 bonding – 1 π^* state/site.
- At low density (untamped), liquid C is sp bonded.
- At higher density, liquid C has mixture of different bonding sp, sp^2 and sp^3, agrees with calculations.

Materials under extreme conditions: Carbon

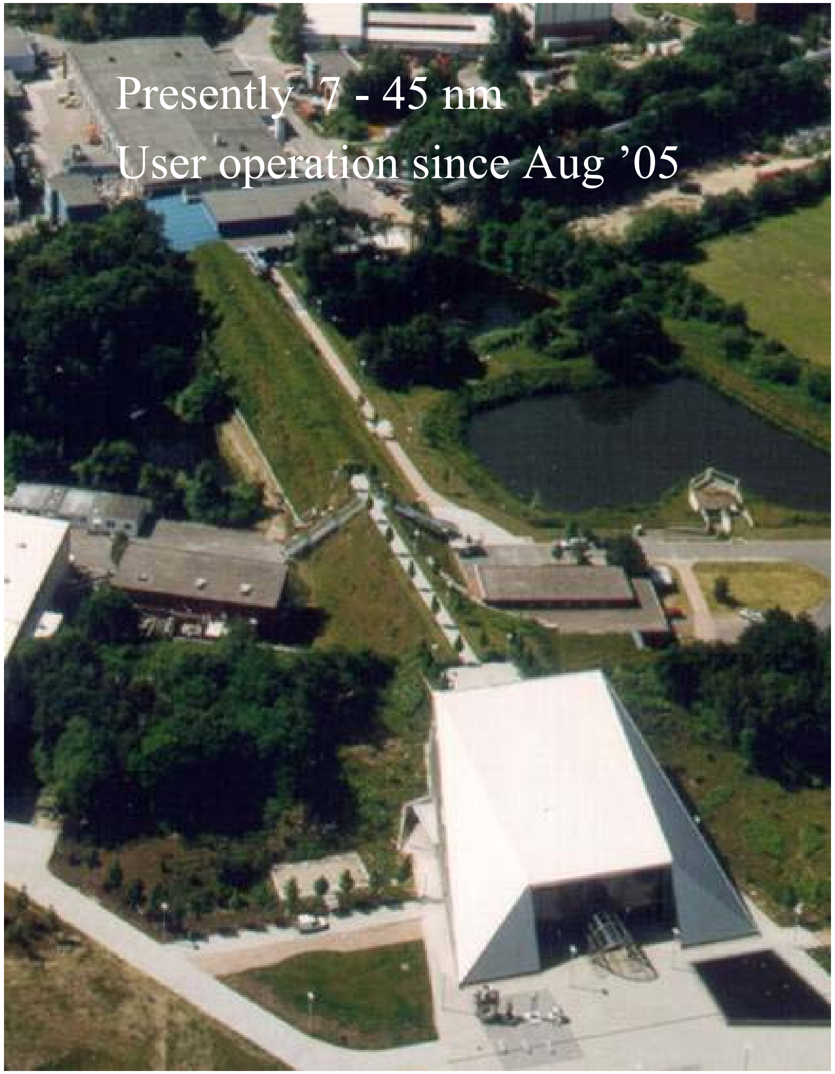


- Liquid spectra exhibit previously unobserved features:
  - Both densities show double-peak structure at π* resonance.
  - In high-density liquid structure above the edge may result from persistent local order.
- Streak camera is next, Δt ~ 2 ps.

FLASH μ-focusing

FLASH FEL parameters

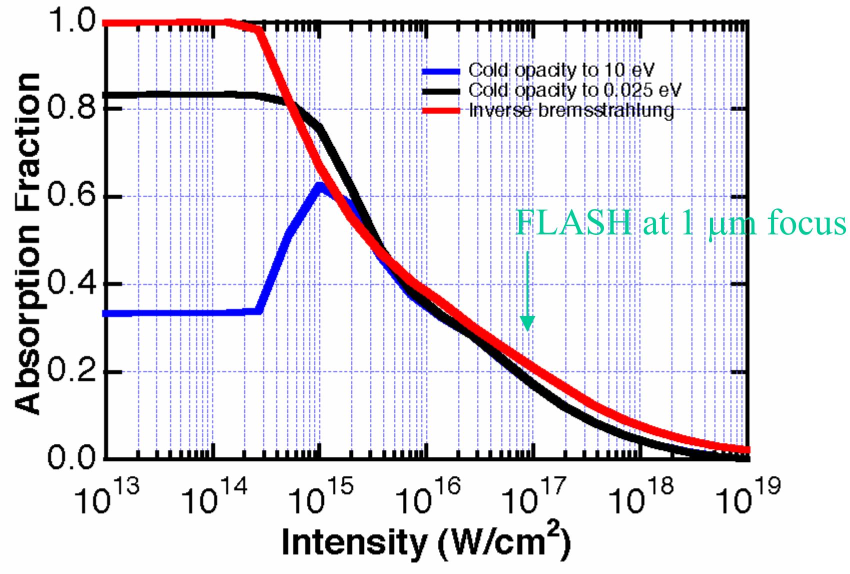
Wavelength	13.5 nm
Photon energy	92 eV
Photon beam size (FWHM)	90 μm
Photon beam divergence (FWHM)	150 μrad
Pulse duration	25 fs
Photons (1/pulse 0.9% bw)	3×10^{12}
Pulse energy	40 μJ
Power density (1 μm spot)	1×10^{17} W/cm^2

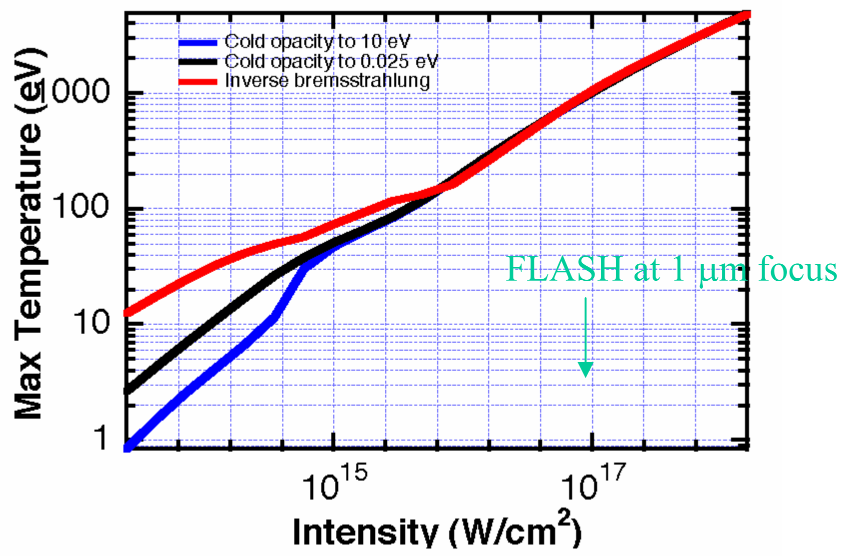


The focused FLASH x-ray pulse can make a plasma.

Calculations of the x-ray absorption of Si_3N_4

- From Dick Lee

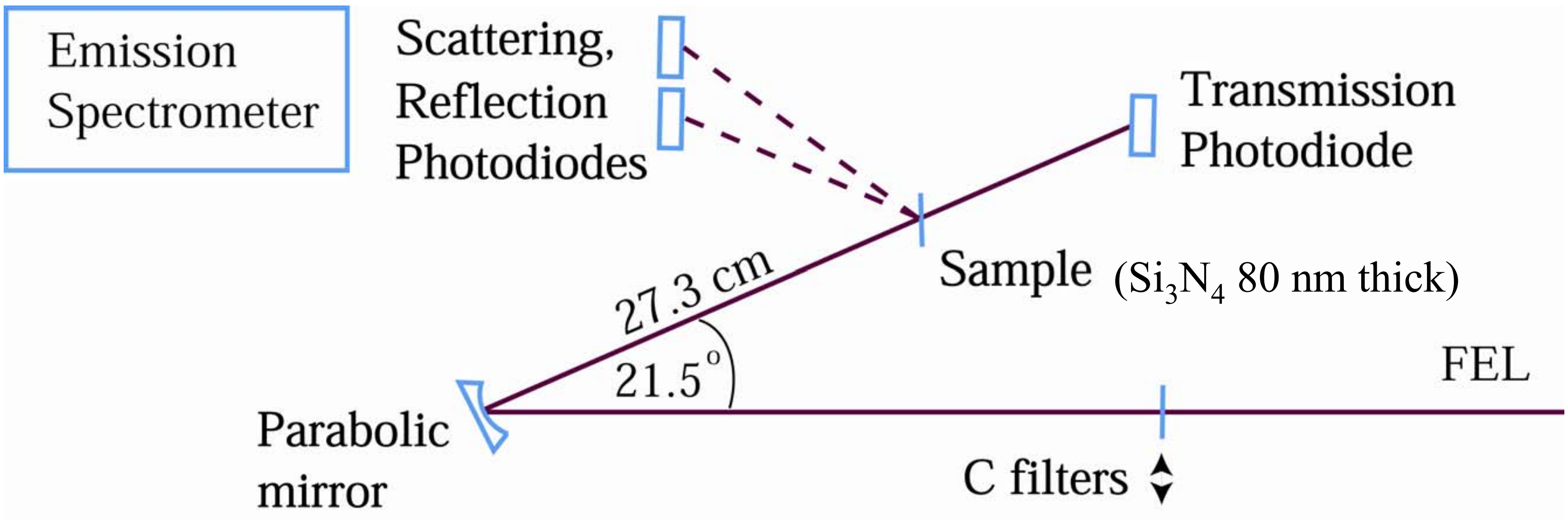


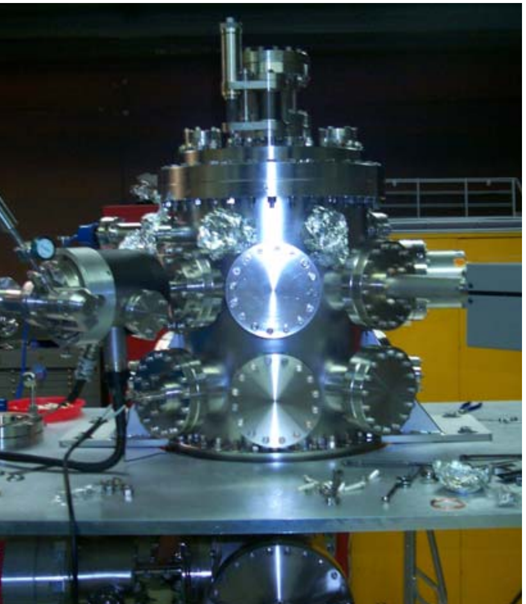


- At low intensity x-ray absorption is dominated by photoionization.
- At high intensity x-ray absorption is dominated by inverse bremsstrahlung.
- At intermediate intensity, ~10^{15} W/cm^2, different calculations disagree.

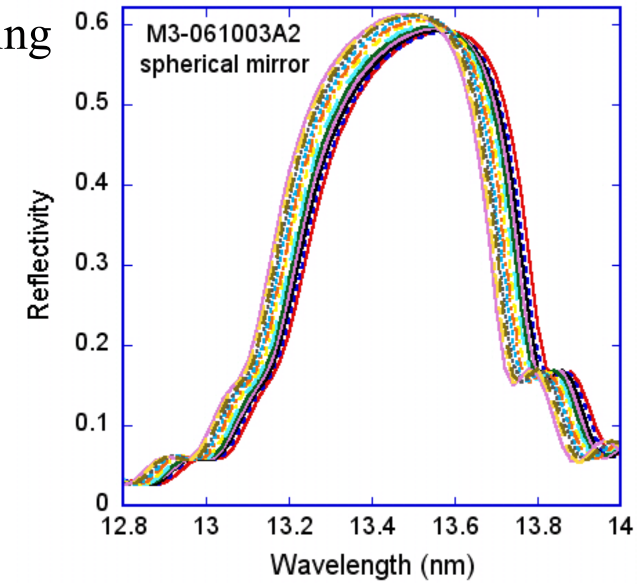
- The goal is to understand the mechanism of x-ray absorption.

Experimental Layout





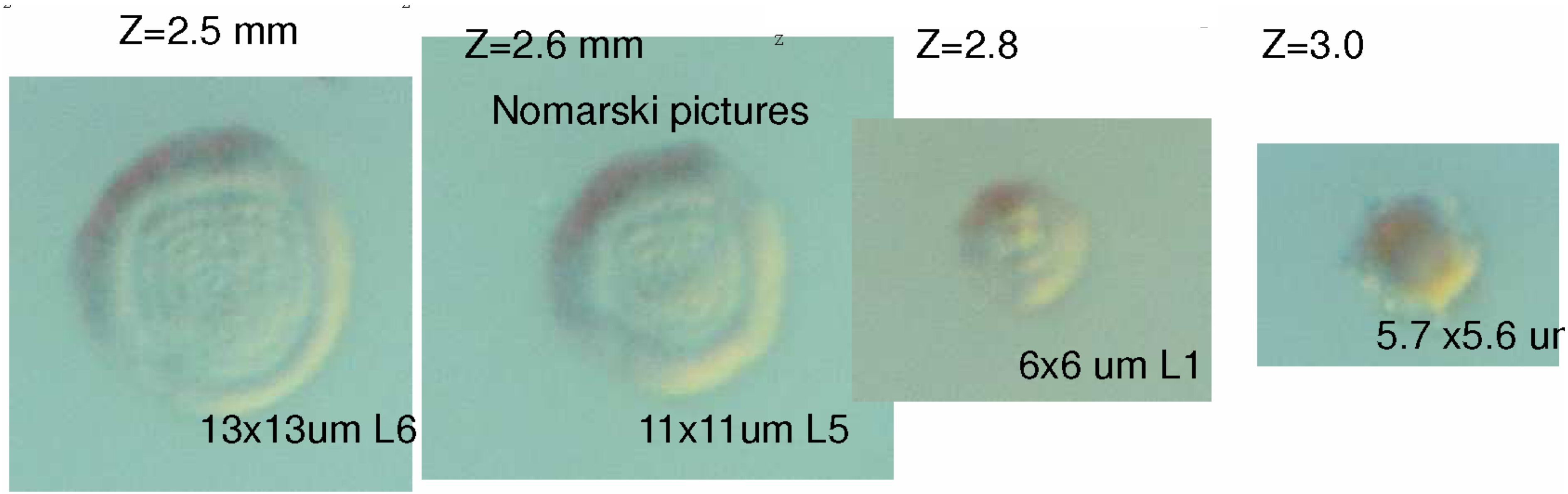
- Mo/Si multilayer mirror coating



- Experimental chamber version 1

Focus of parabolic mirror

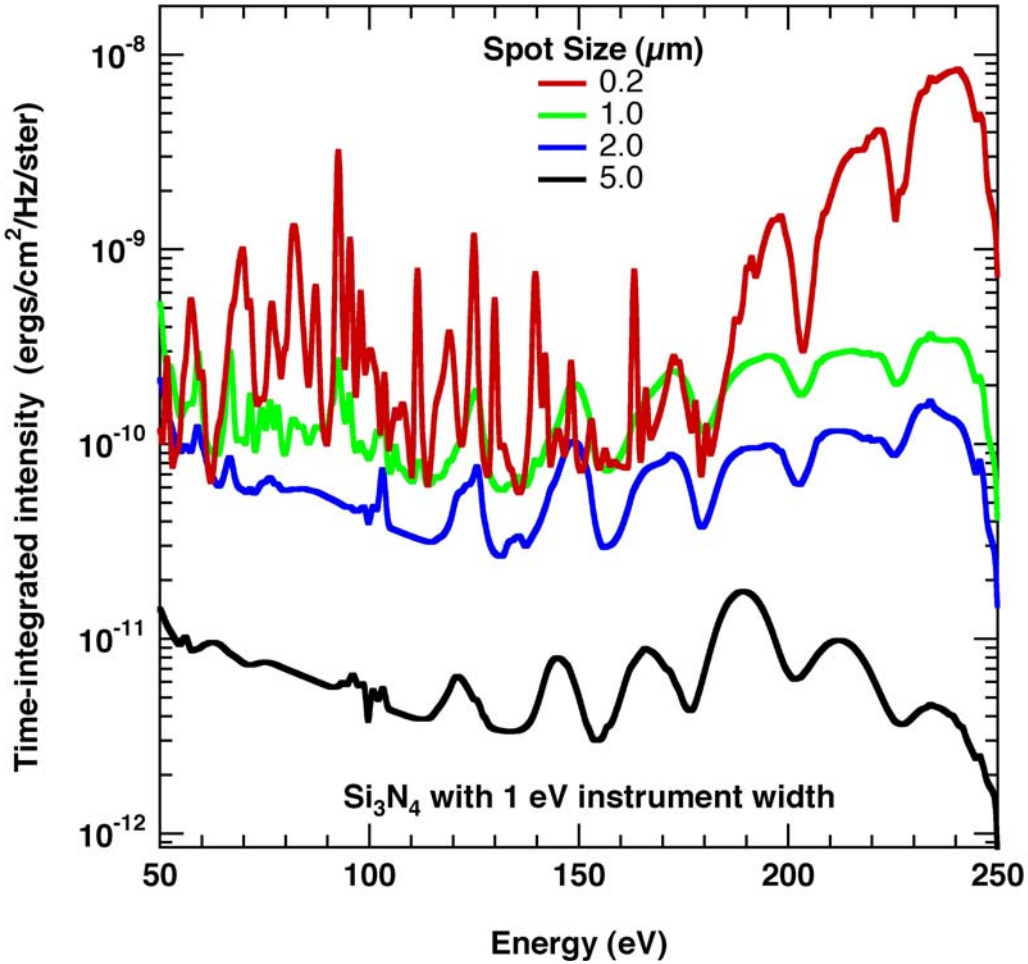
- April 24, 2008
- L. Juha et al., JESRP 144-147, 9292 (2005).



- X-ray focus exposed in PMMA, measured ex-situ by Nomarski microscope.
- Precise focus measured by AFM.

Consistent with Focus ~1 μm^2.

Calculated plasma emission



- From Hyun-Kyung Chung & Dick Lee

- Time integrated emission from plasma.
- At tight focus, there is emission from different ionization states of the Si_3N_4.
- We now have preliminary data for x-ray absorption and emission.

Acknowledgements

ALS x-ray absorption

- Chris Weber, Paul Davis, Roger Falcone (UC Berkeley, LBNL)
- Adam Mann, Jun Feng (ALS, LBNL)
- Dick Lee (LLNL)

FLASH μ-focusing

- Dick Lee, Art Nelson (LLNL)
- Sven Toleikis, Thomas Tschentscher, Roland Faustlin, Henry Chapman (DESY)
- Bob Nagler, Tom Whitcher, Justin Wark (Oxford)
- Dave Riley (Belfast)
- Libor Juha (PALS)
- Pascal Mercere (Soleil)
- Ryszard Sobierajski, Jacek Krzywinski (Warsaw)

High Pressure x-ray diffraction at the SPX

- Laser system:
  - Need > 1 J/cm^2,
  - Suppose 10 μm x-ray focus or 10 μJ optical pulses,
  - Consistent with kHz laser system.
- Sample damages with each laser pulse:
  - Translation of the sample ~ 1 mm/s,
  - Consistent with 10 Hz repetition rate.
- Need 10^{11} photons (Clark and Jeanloz, JSR **12**, 632 2005)
  - Implies 3 hours (at 10^{-2} bandwidth) for 1 diffraction pattern!
- These types of plasma experiments are being done with intense short pulse lasers, high energy long pulse lasers, large pulse power machines, and ion beam accelerators …

- Amorphous Carbon from Clark et al.