The Idealized Slab Plasma approach for the study of WDM

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Outline

- **What is the Idealized Slab Plasma approach?**
- **Isochoric Laser Heating as an ISP platform**
  - **Electrical conductivities**
  - **Solid-plasma transition**

Shock Compression another ISP Platform

Phys. Rev. E 59, 1024 (1999)

Laser & Particle Beams 23, 527 (2005)

ISP approach is a means to achieve single-state measurements

- **An ISP is a planar plasma that can be considered as a single uniform state in which any residual non-uniformities impose negligible impact on the measurement of its uniform properties**

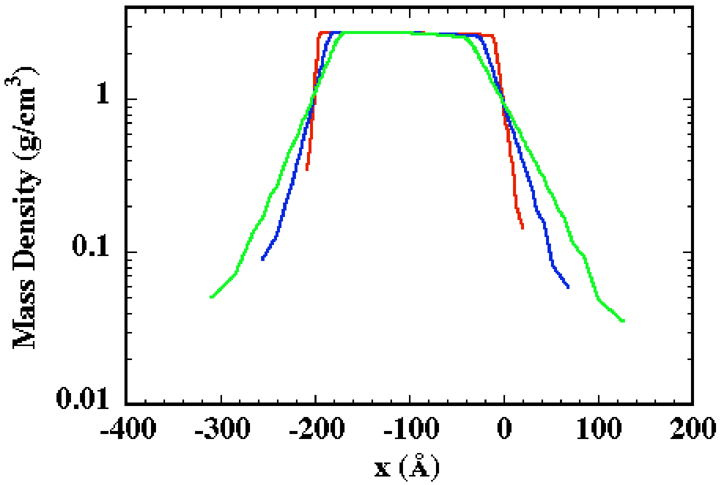
- **The state is characterized by direct measurements**

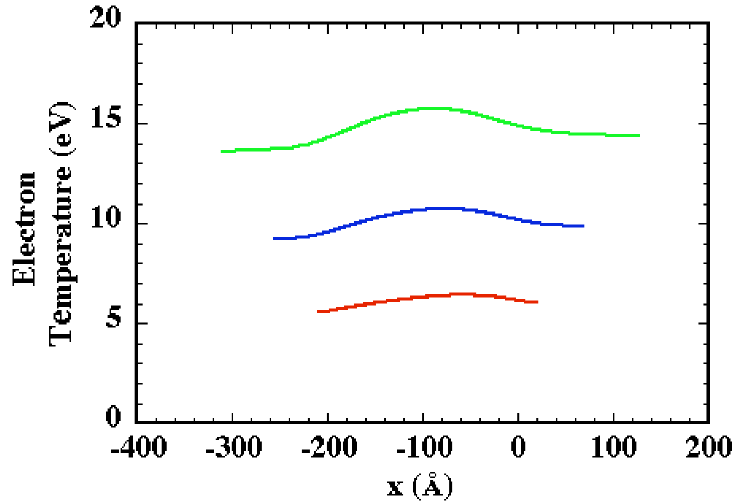
Phys. Rev. E 58, R1248 (1998)

The ISP is first illustrated in simulations of isochoric laser heating of a solid

- **Heating in the *fs* time scale mitigates hydro expansion to yield isochoric condition**
- **Matching sample thickness to range of heating source or conduction scale length yields isothermal condition**

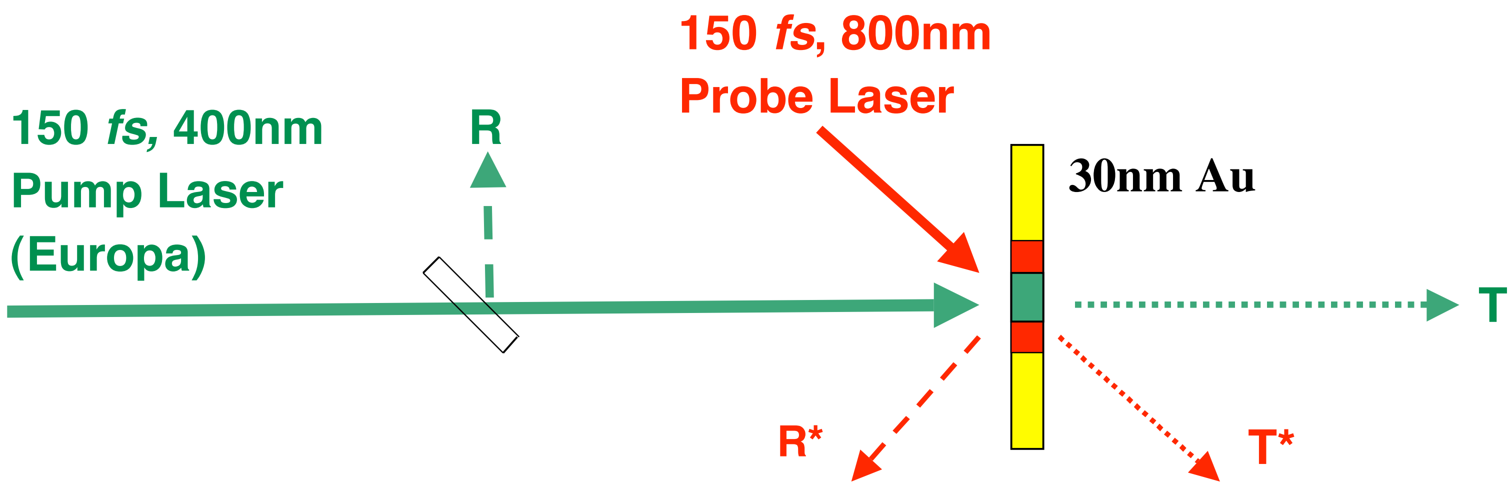
20nm Al heated with a 100fs, 400nm laser pulse





Approach scalable with X-rays, electrons, protons or ions

An ISP platform based on Isochoric Laser Heating has been realized



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

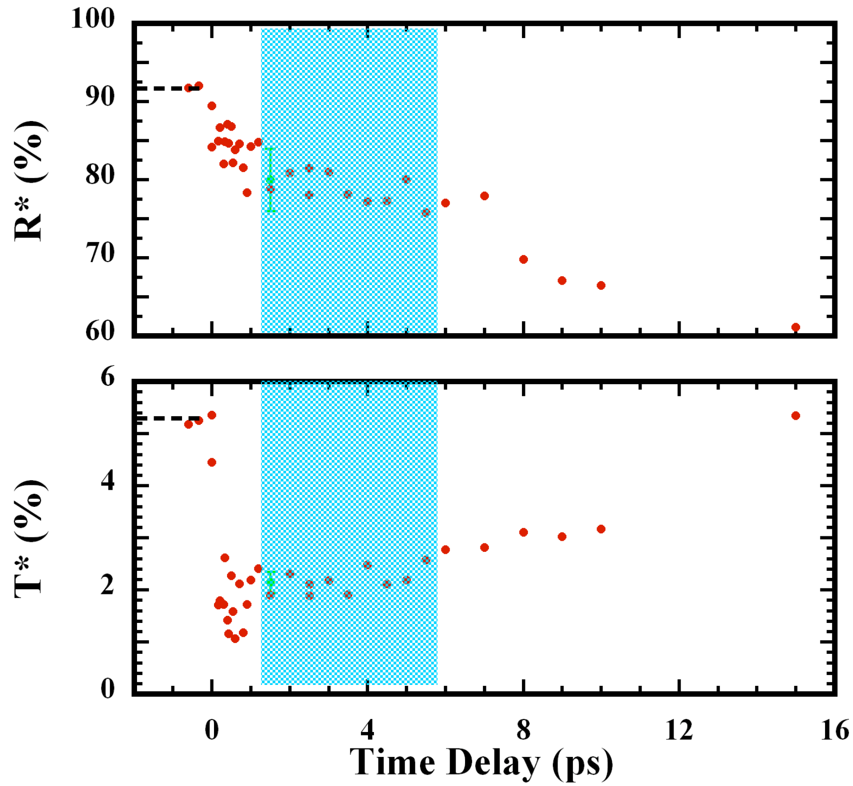
WDM state characterized by ρ_0 and $\Delta\varepsilon$

– $\Delta\varepsilon$ determined directly from {R, T} of pump laser

WDM optical properties measured with probe R*, T*

Measurements of S-pol {R*, T*} reveal interesting temporal behavior

- Three distinct stages are observed
  - An initial transient
  - Quasi steady state
  - Hydrodynamic expansion



***S-pol* probe**

$\Delta\varepsilon$ =(3.5±1.0)x10^6 J/kg

Quasi-steady-state behavior unexpected

- **Hydrodynamic simulations suggest disassembly of the foil in ~1ps after heating when the lattice reaches melting temperature**
  - **Expansion gives rise to a plasma gradient on the surface of the foil; the gradient scale length will continue to increase with time**
  - **To maintain constant probe R* and T*, it would require dielectric properties of the non-uniform system to evolve in a manner that precisely mitigates gradient effects at all times :**
    This is improbable

Condensed matter effects absent in hydro code

Quasi-steady-state behavior has an important consequence

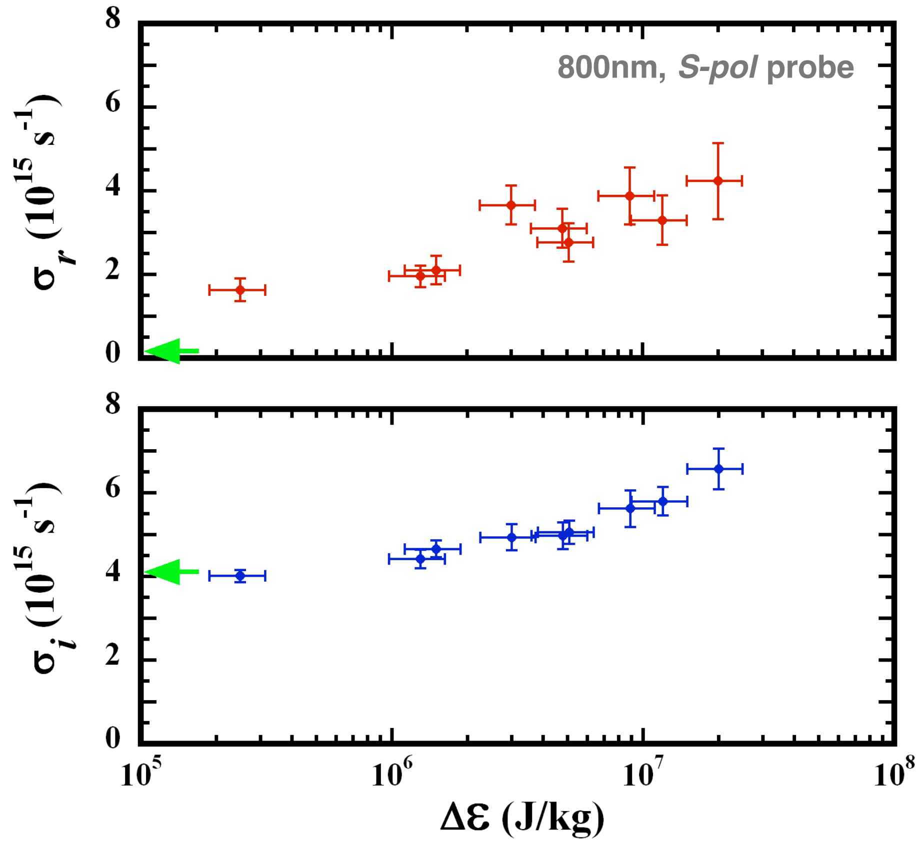
- **It suggests the absence of significant hydrodynamic expansion, preserving the uniform, slab structure of the heated foil at its initial solid density (the essence of isochoric heating).**

- **It yields an uniform state that is characterized by the direct observables of mass density ρ_o and excitation energy density $\Delta\varepsilon$**

This ensures the realization of the ISP approach

It affirms our ability to obtain single-state measurements of AC conductivity

- **We use probe {R*,T*} at the end of the initial transient to solve Helmholtz equs. for EM wave propagation through a uniform dielectric slab**
- **This yields $\sigma_\omega(\rho_o, \Delta\varepsilon)$ to provide a direct test of theory**



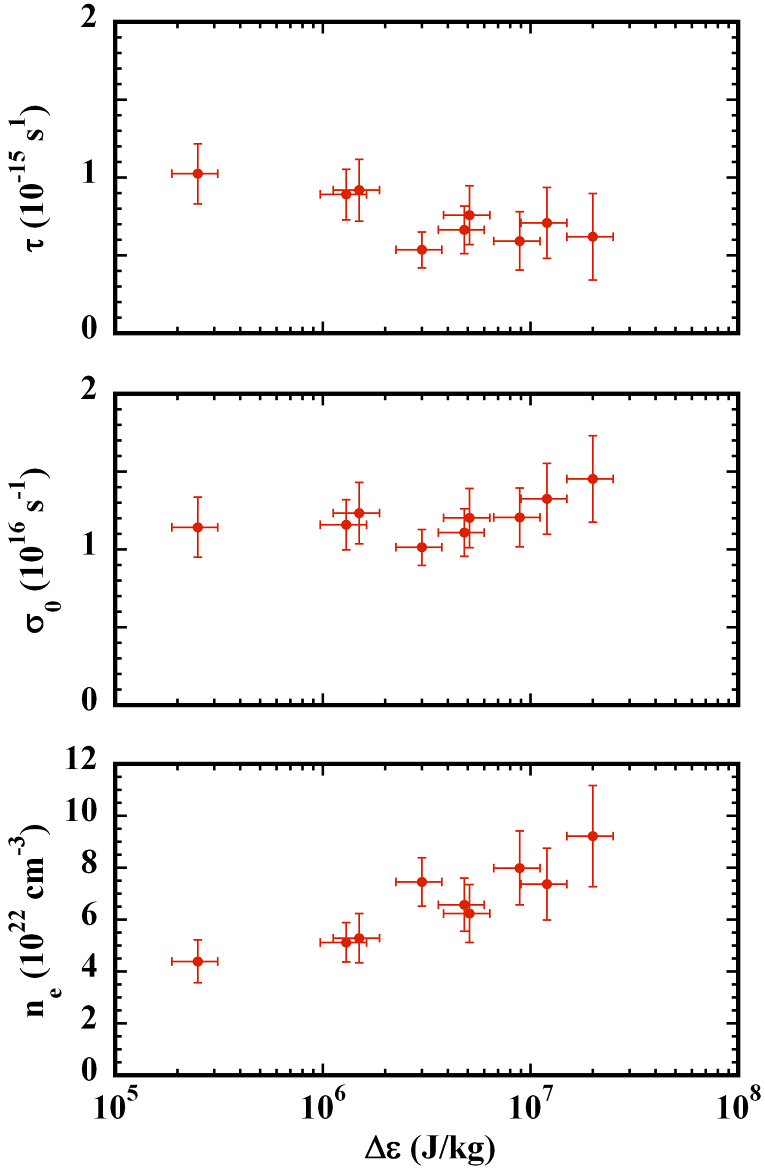
We can learn more if we assume nearly free electron behavior

- **Nearly free electron behavior is expected**
  - **Absence of interband transition at 800 nm**
  - **Conductivity effected by electrons near Fermi surface**

- **Drude :** $$\sigma(\omega) = \sigma_r + i\sigma_i = \frac{\sigma_o}{1+\omega^2\tau^2}(1+i\omega\tau),$$

$$\tau = \frac{\sigma_i}{\sigma_r}\frac{1}{\omega}, \qquad \sigma_o = \sigma_r(1+\omega^2\tau^2), \qquad n_e = \frac{m_e\sigma_o}{e^2\tau}$$

This extends our single-state data to include τ, σ_o and <Z>



At normal conditions:

$\sigma_0 = 4.1 \times 10^{17}\ s^{-1}$

$n_e = 3.8 \times 10^{22}\ cm^{-3}$

PRL 92, 125002 (2004)

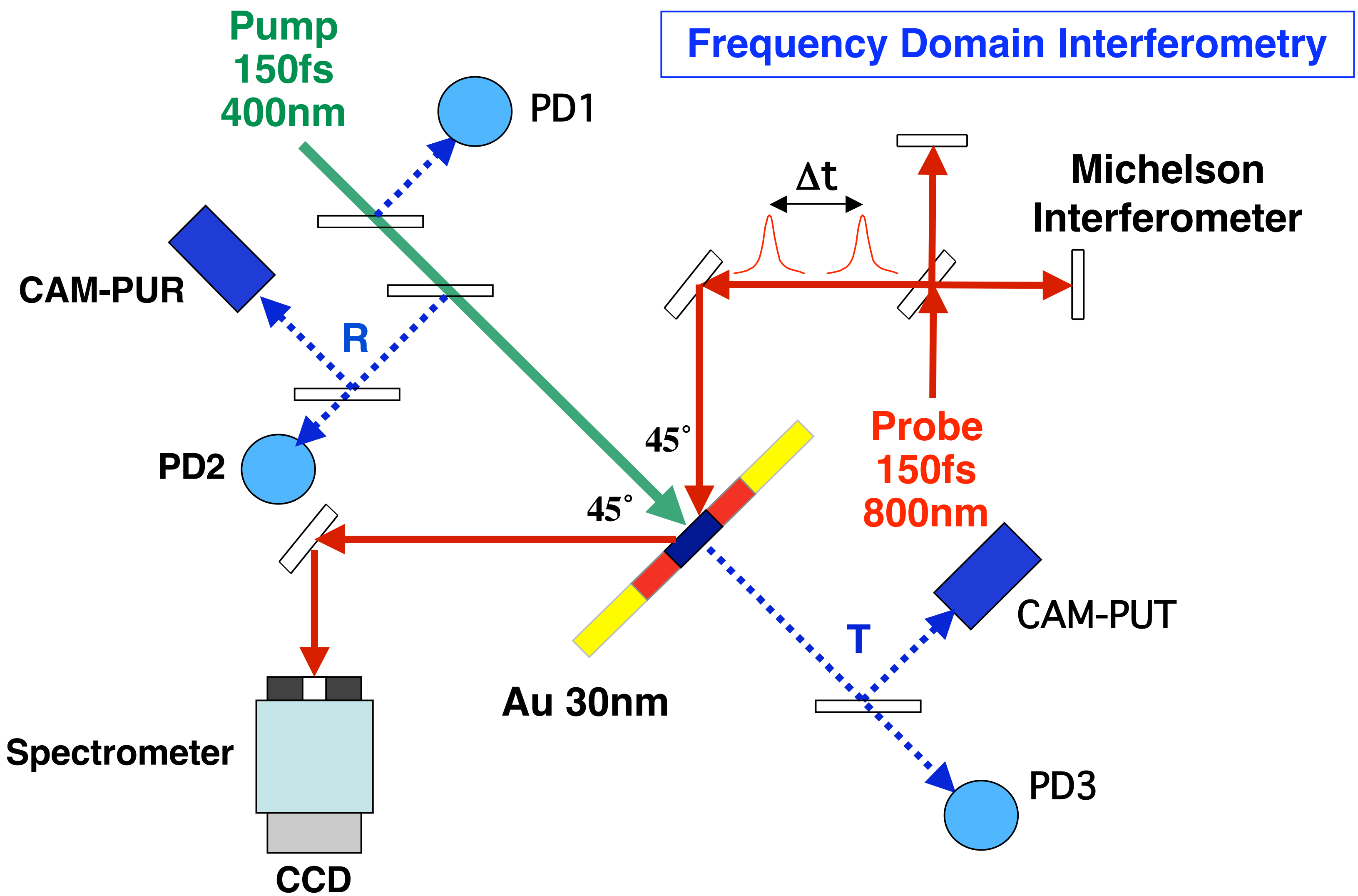
Drude-like optical properties at 800nm has been confirmed

The next critical question is the phase of the quasi-steady state

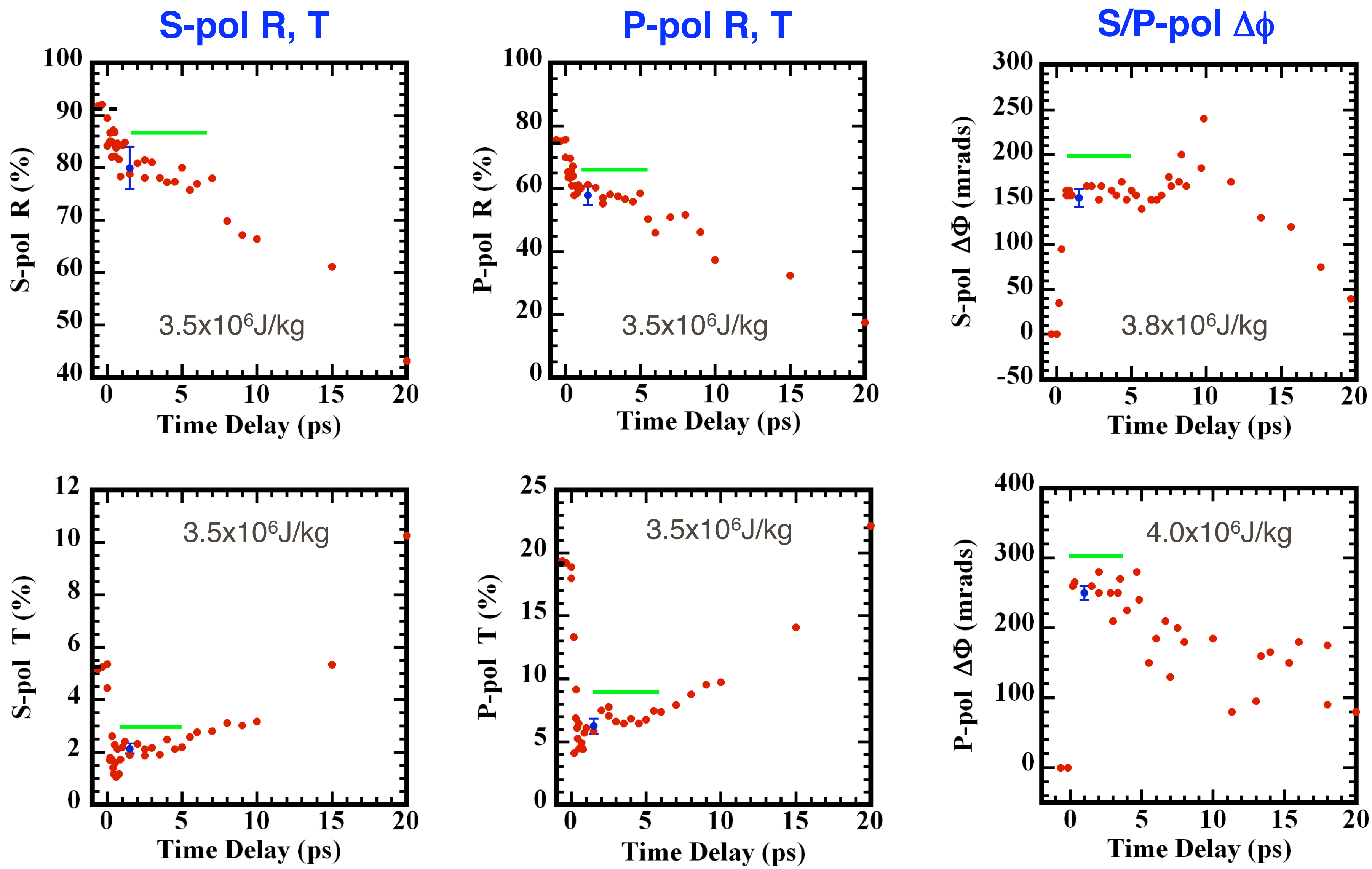
- Calculations of transport properties require phase information, solid versus liquid, to determine the structure factor of the state

- The identity of the quasi-steady state is also key to understanding non-equilibrium phase transitions induced by ultrafast excitation

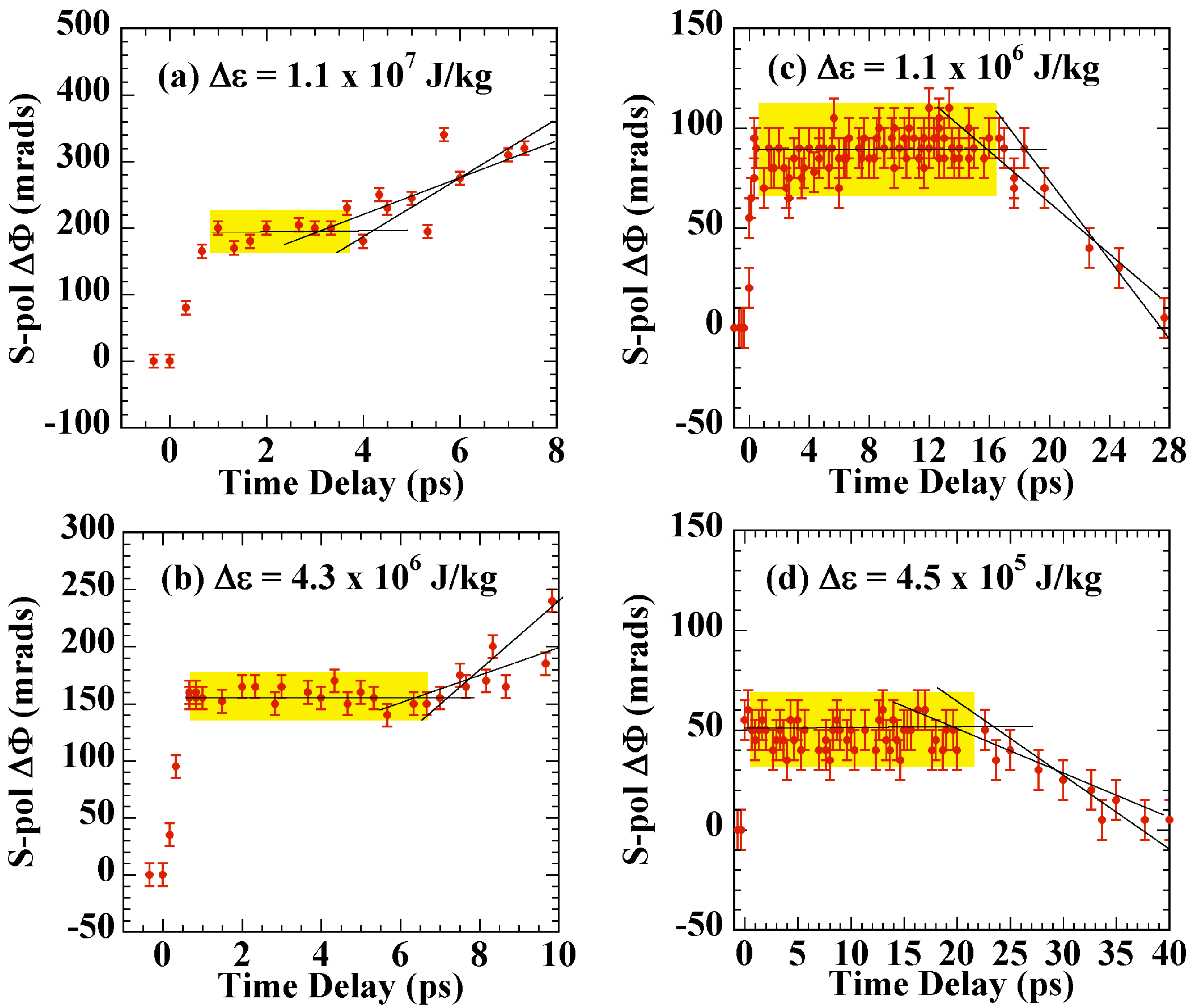
To monitor hydro expansion, we use the more sensitive P-pol R/T & S/P-pol $\Delta\phi$



Quasi-steady state is confirmed in six different measurements

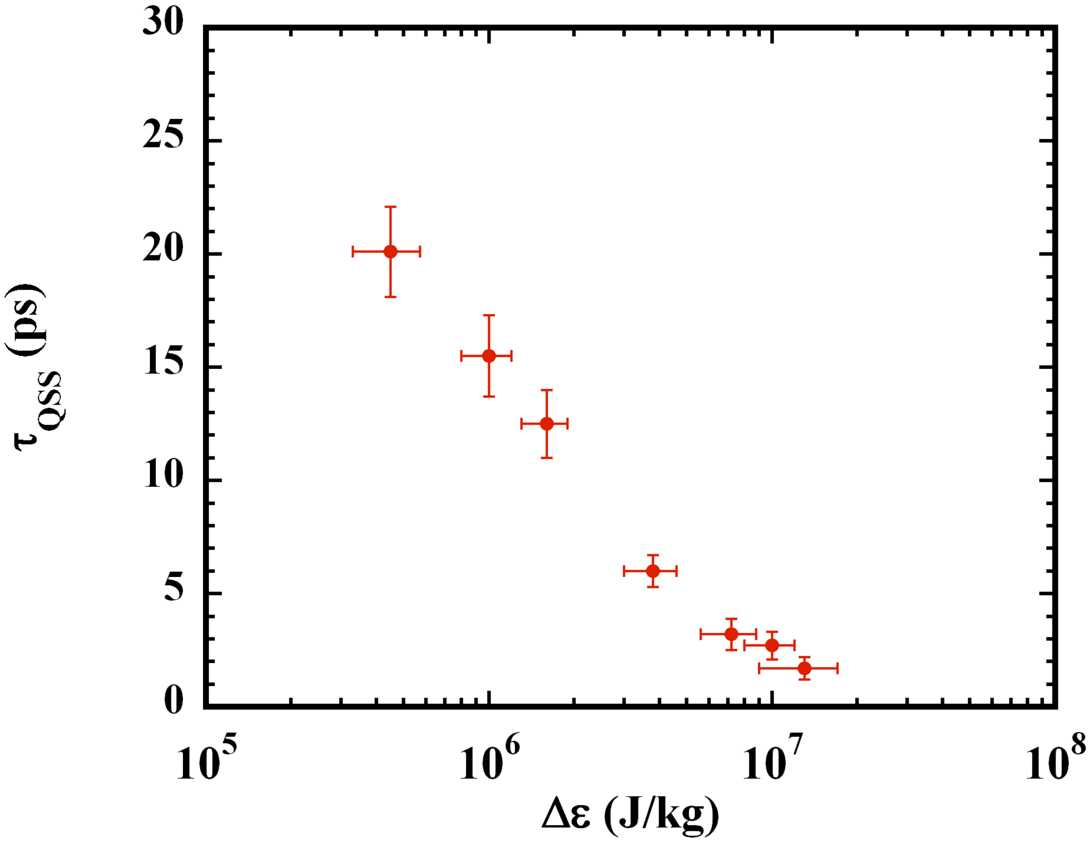


To quantify quasi-steady-state duration, we use an extensive set of S-pol FDI data



Quasi-steady-state duration shows a clear dependence on excitation energy density

- **The range of τ_{QSS} from 2-20ps is substantial**



Dynamical behavior of the heated foil is governed by various processes

- **Laser heating of *s/p* electrons and photo excitation of *d*-electrons**
- **Electron-hole recombination**
- **Electron-electron thermalization**
- **Escape of heated electrons forming a surface sheath; sheath thickness is limited by space charge field**

- **Lattice heating effected by electron-phonon coupling**
- **Melting of the lattice**
  - **Ultrafast, non-thermal melting?**
  - **Thermal melting to meta-stable liquid?**
  - **Superheating prior to melt transition?**
- **Disassembly of the liquid metal into a plasma**

To describe lattice heating, we use a modified Two-Temperature Model

TTM: $$C_e(T_e)\frac{dT_e(t)}{dt} = -g\left[T_e(t) - \varepsilon_l(t)\frac{\rho_{Au}}{C_l}\right] + S(t)$$

$$\rho_{Au}\frac{d(\varepsilon_l(t))}{dt} = g\left[T_e(t) - \varepsilon_l(t)\frac{\rho_{Au}}{C_l}\right] , \qquad \varepsilon_l(t) = \frac{C_l T_l(t)}{\rho_{Au}}$$

Electron-phonon coupling: g = (2.2±0.3)x10^{16} W/m$^3\cdot$K*

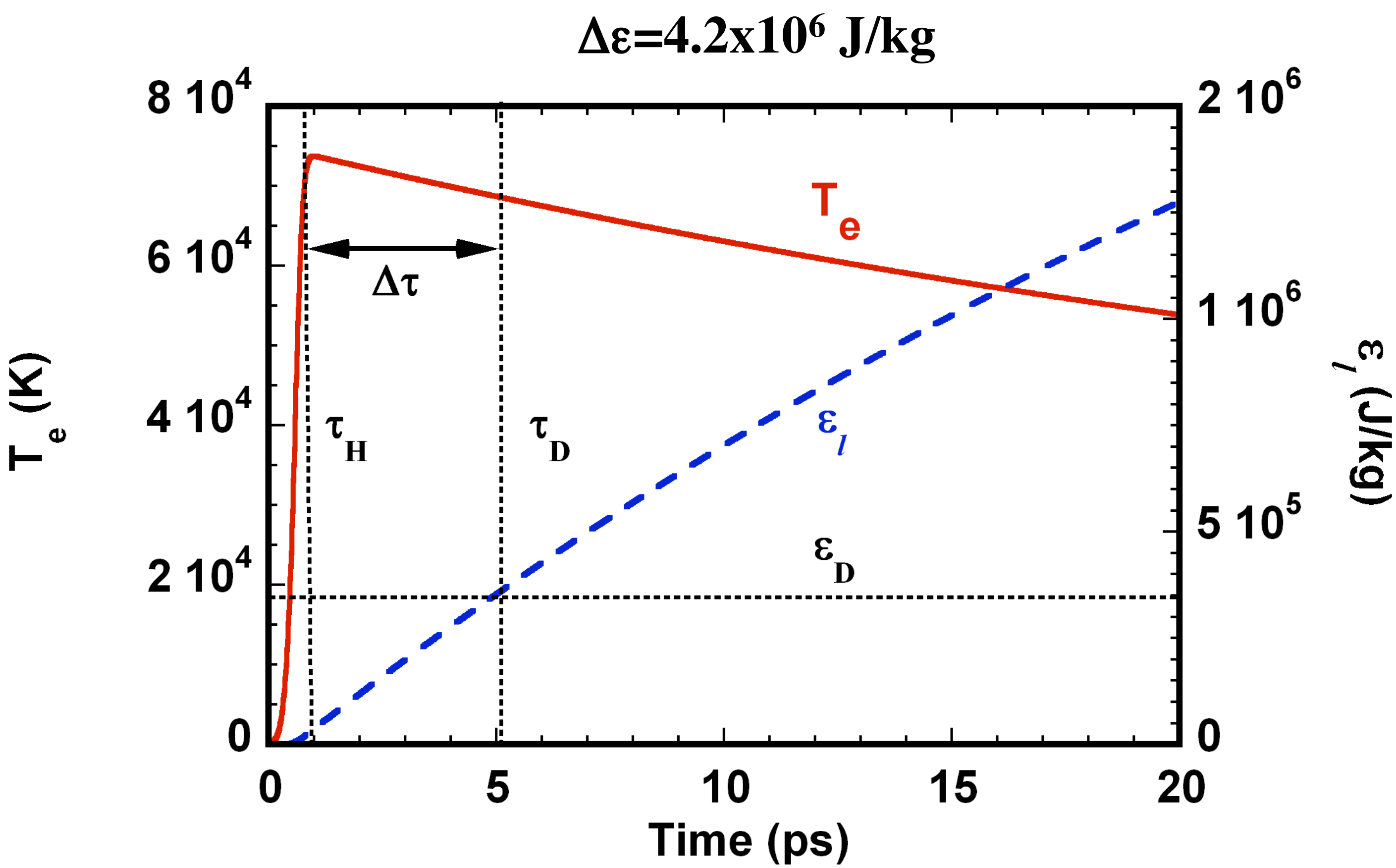
Heat capacities: $C_e(T_e) = \frac{\partial U_e(T_e)}{\partial T_e}$, C_l=2.5x10^6 J/m$^3\cdot$K†

Laser energy deposition: $$S(t) = \frac{\Delta\varepsilon\rho_{Au}}{\tau_P\sqrt{\pi}}\exp\left(-\frac{t^2}{\tau_P^2}\right)$$

*Hohlfeld *et al*. Chem. Phys. 251, 237 (2000)
†Maxmillian's Chemical and Physical Data, Maxmillian Press, London, 1992

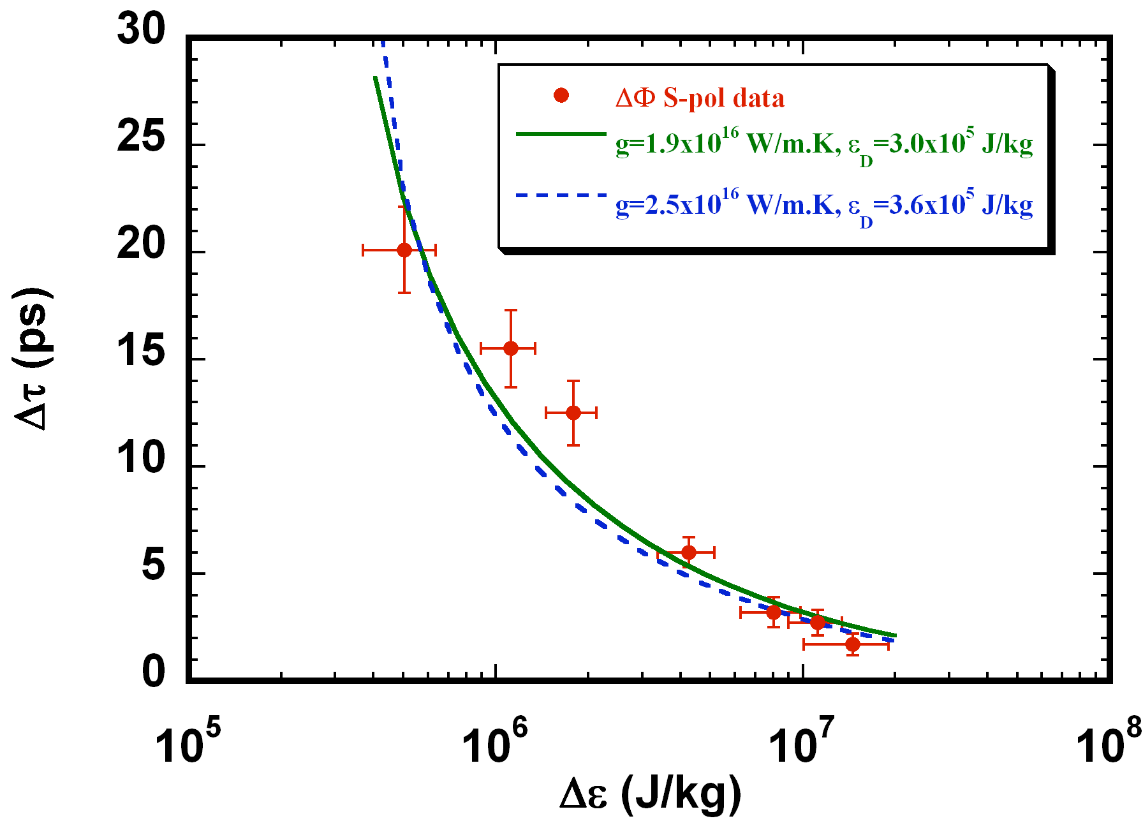
We postulate that disassembly is a rate-independent critical phenomenon

- **Quasi-steady-state duration $\Delta\tau$ is determined by a critical value ε_D that is independent of heating rate (or $\Delta\varepsilon$)**



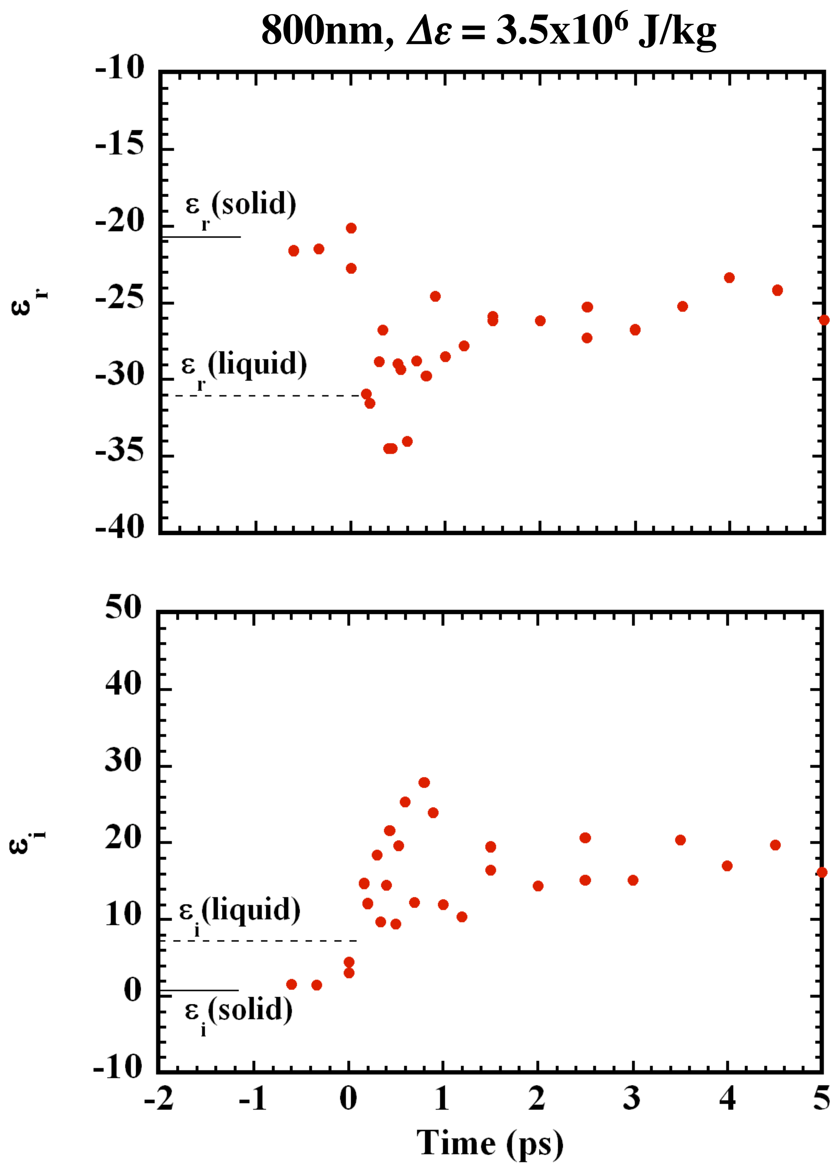
The model shows good agreement with observation

- **This yields the first measurement of the critical lattice energy ε_D=(3.3±0.3)x10^5 J/kg needed for solid-plasma transition under ultarfast laser excitation**



Phys. Rev. Lett. 96, 055001(2006)

Dielectric function appears to indicate ultrafast, non-thermal melting



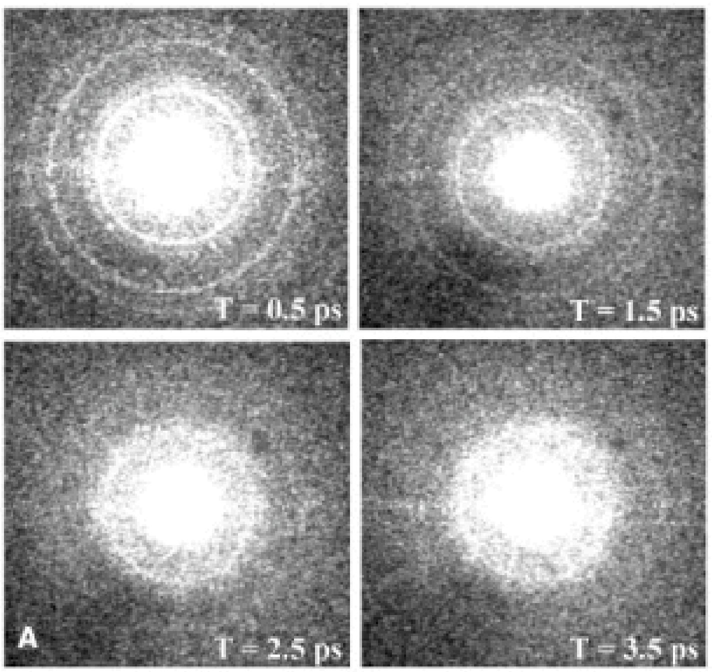
- **Following the non-thermal melting of Al interpretation by Guo *et. al.* [PRL, 2000], ε(t) suggests a solid-liquid transition within ~200fs**
- **The quasi-steady state would then be a meta-stable liquid**

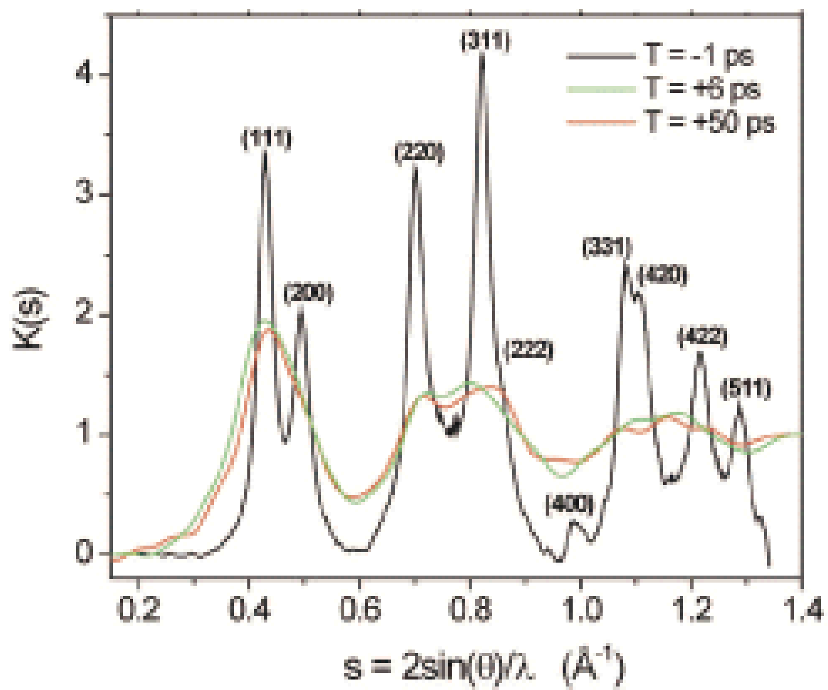
Caveat: comparison with ε for an equilibrium liquid might be inappropriate

UED shows thermal melting followed by a meta-stable liquid phase

Siwick *et al.*, Science (2002)

- Disordering to a liquid occurs in ~ 3.5 ps
- Liquid structure appears unchanged to ~50 ps





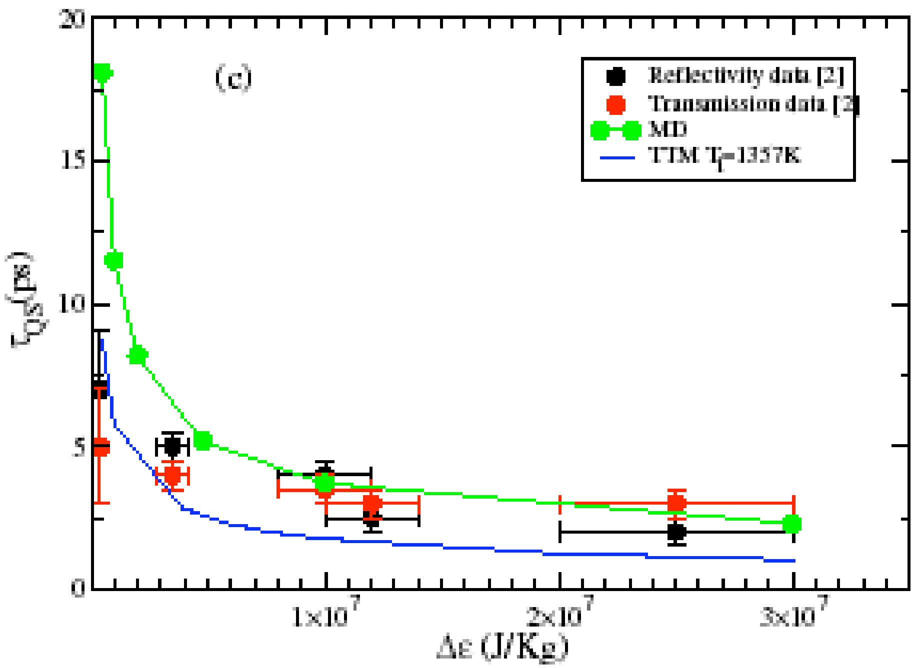
Caution: Observations are for Al at lower energy densities

Recently, our FDI data led to another conclusion in MD simulations

- **FDI measurement presented in LANL, September 2004 and data provided to Mazevet**
- **Using an *e-i* coupling term in the ion equation of motion [Ivanov *et al*., PRB 2003] and assuming melting occurs when $\langle r^2 \rangle = 0.5 \text{Å}^2$ ($\langle r^2 \rangle = 0.58 \text{Å}^2$ for fcc lattice, Shapiro, PRB 1970), MD simulations yielded quasi-steady state durations that appear to be consistent with our FDI data**

Mazevet *et al*., PRL 85, 085002 (2005)

Suggested that the quasi-steady state is a superheated solid



Conclusions

- **The ISP approach has been realized in isochoric laser heating, enabling the measurement of single-state properties**
  - $\sigma(\omega)$, σ_0, τ_{ei}, n_e
  - **Critical energy density for solid-plasma transition**

- **The structural phase of the intermediate, quasi-steady state in the solid-plasma transition induced by ultrafast laser excitation remains an open question**
  - **This is to be resolved in UED measurements**

- **It is important to understand in isochoric heating the processes pertinent to the different energy sources**
  - **The microscopic states of WDM with the same energy density may be quite different**

1996 International Seminar on HED Matter, Vancouver, Canada

- **Strongly coupled plasma**

2000 International Workshop on WDM, Vancouver, Canada

- **Plasma, condensed matter, shock, geophysics, chemistry**

2002 International Conference on WDM, Hamburg, Germany

- **Plasma, condensed matter, XFEL**

2005 International Workshop on WDM, Vancouver, Canada

- **Transport and EOS properties**
- **Experiment and *ab initio* theory**

2007 (M. Koenig, LULI)

Physics & Advanced Technologies

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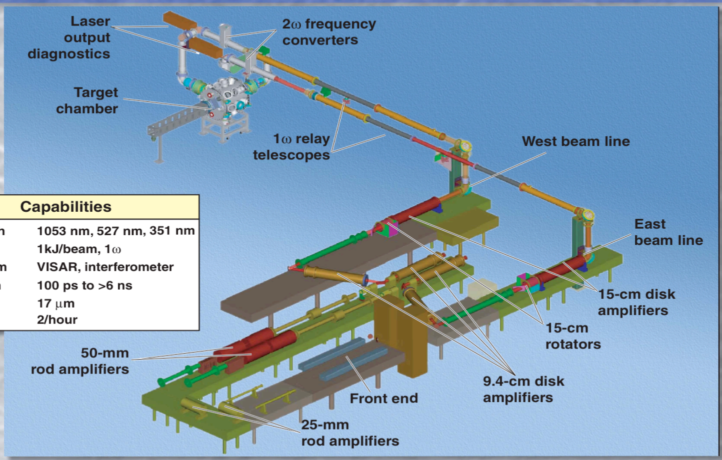
Jupiter Laser Facility

Janus • Titan • Callisto • Europa • COMET

Lawrence Livermore National Laboratory

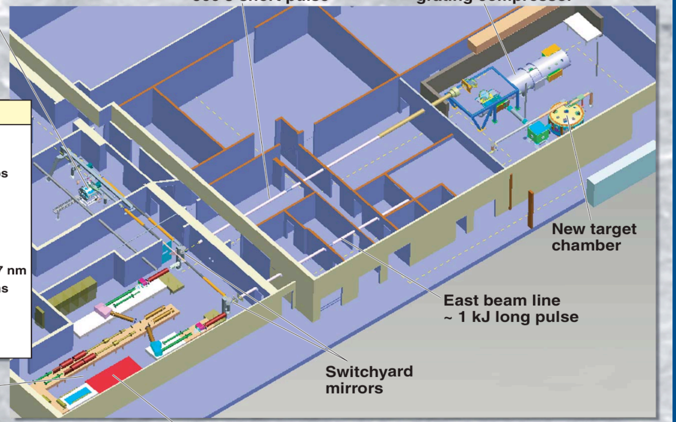
Janus is a 2-beam, 1 kJ/beam (1ω) Nd:glass laser used for target physics and diagnostics



Capabilities

Wavelength	1053 nm, 527 nm, 351 nm
2 beams	1kJ/beam, 1ω
Probe beam	VISAR, interferometer
Pulsewidth	100 ps to >6 ns
Spot size	17 μm
Rep Rate	2/hour

Titan will enable experiments combining short-pulse petawatt-class, and long-pulse kJ beams

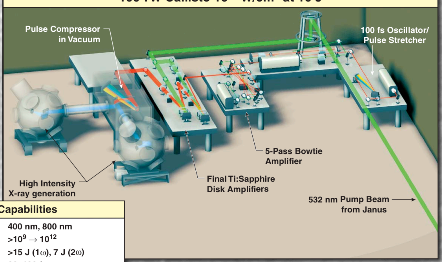


Capabilities

Short Pulse	
Wavelength	1054 nm
Pulsewidth	400 fs - 10 ps
Pulse Energy	350J - 530J
Spot Size	8 μm
Rep Rate	2/hour
Long Pulse	
Wavelength	1053 nm, 527 nm
Pulsewidth	100 ps - >6 ns
Pulse Energy	1 kJ
Spot Size	17 μm
Rep Rate	2/hour

Callisto is a test-bed for HEPW science

100 TW Callisto 10^{21} W/cm^2 at 10 J

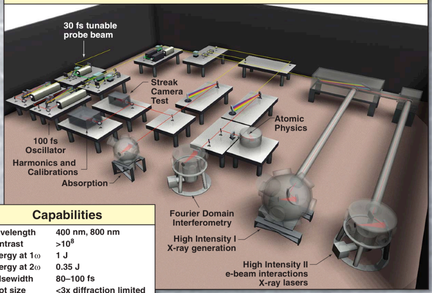


Capabilities

Wavelength	400 nm, 800 nm
Contrast	$>10^9 \rightarrow 10^{12}$
Energy	>15 J (1ω), 7 J (2ω)
Pulsewidth	80–100 fs
Spot size	<2x diffraction limited
Intensity	$>10^{21}$ W/cm^2
Rep Rate	3/hour

Europa is a high-repetition-rate ultra-short-pulse facility

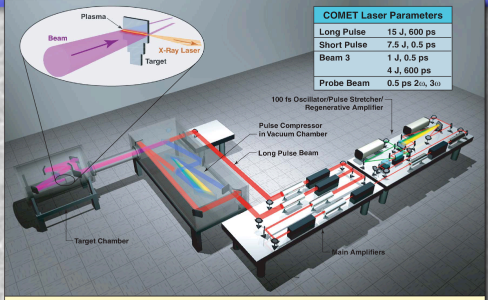
10 TW Europa



Capabilities

Wavelength	400 nm, 800 nm
Contrast	$>10^8$
Energy at 1ω	1 J
Energy at 2ω	0.35 J
Pulsewidth	80–100 fs
Spot size	<3x diffraction limited
Intensity	5 x 10^{19} W/cm^2
Rep Rate	20/hour, 10/second

COMET is a unique table-top X-ray laser user facility



COMET Laser Parameters

Long Pulse	15 J, 600 ps
Short Pulse	7.5 J, 0.5 ps
Beam 3	1 J, 0.5 ps
	4 J, 600 ps
Probe Beam	0.5 ps 2ω, 3ω

XRL is part of C&MS S&T strategy for *in-situ* materials dynamics

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