Study of Warm Dense Matter Physics with Ultra-Short Pulse Lasers

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U.S.-Japan Workshop on Heavy Ion Fusion and High Energy Density Physics, Academia Hall", Utsunomiya University, Sep. 28-30, 2005

Outline

Ellipsometric pump-probe measurements of WDM

+ Diffuse scattering of probe pulse
+ White-light femtosecond probe beam
  for frequency dependence of AC conductivity
+ Data reconstruction technique to identify surface expansion
  and detect sharp interface inside plasma
+ New EOS calculation and proposal to obtain critical point of metal

*Electron localization in WDM (low conductivity, metal-insulator transition)
*Positive-negative ion plasma in WDM
*Two phase fluid region (gas & liquid)(droplet formation, EOS in 2 phase, ..)
*….

Purpose of this study

Warm dense matter:

Material properties between solids(liquid) and plasmas

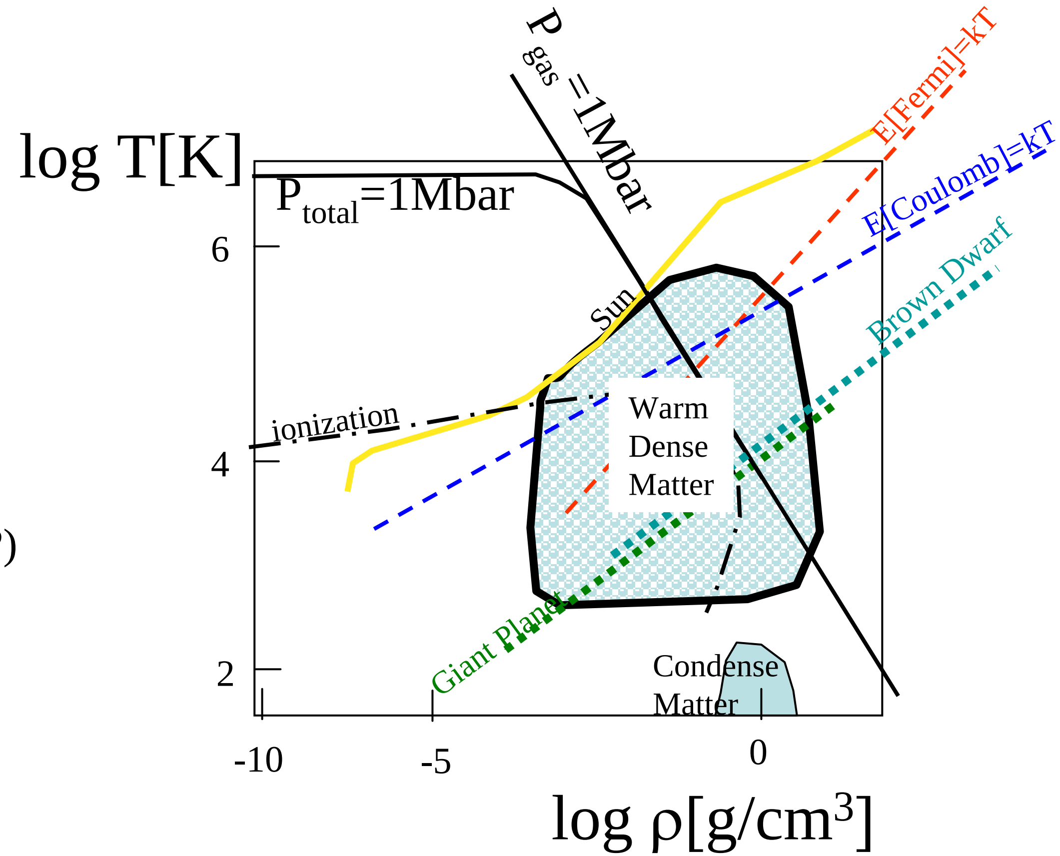
*Chemical force(condensed matter) ~
Coulomb force(ideal plasma)

*Electron degenerated plasma
(Giant planet interior material)

*Strongly coupled plasma

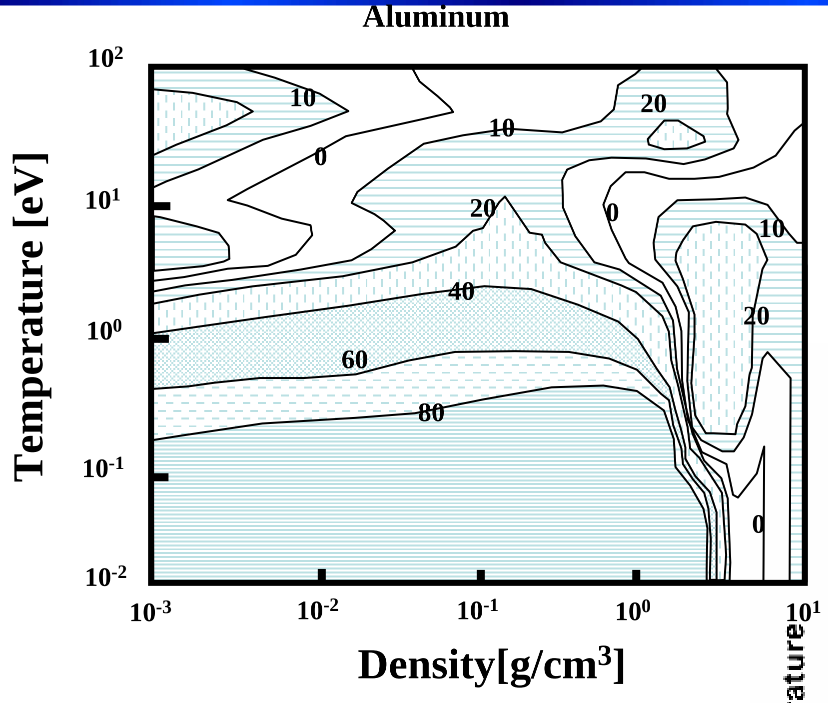
*Metal-insulator transition(minimum conductivity, similar to Anderson transition?)

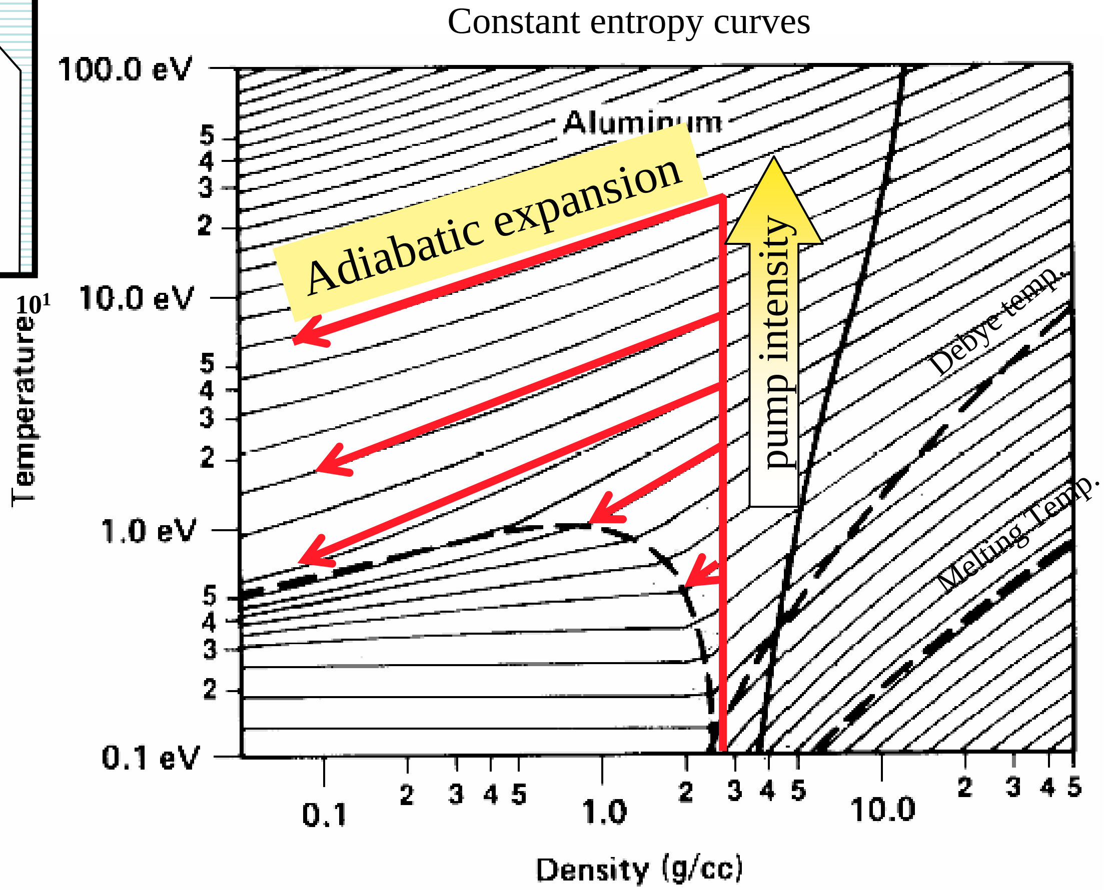
*Two phase region [gas and liquid]
(droplet or debris formation)



There are a lot of new physics and many uncertain phenomena.

How to create WDM



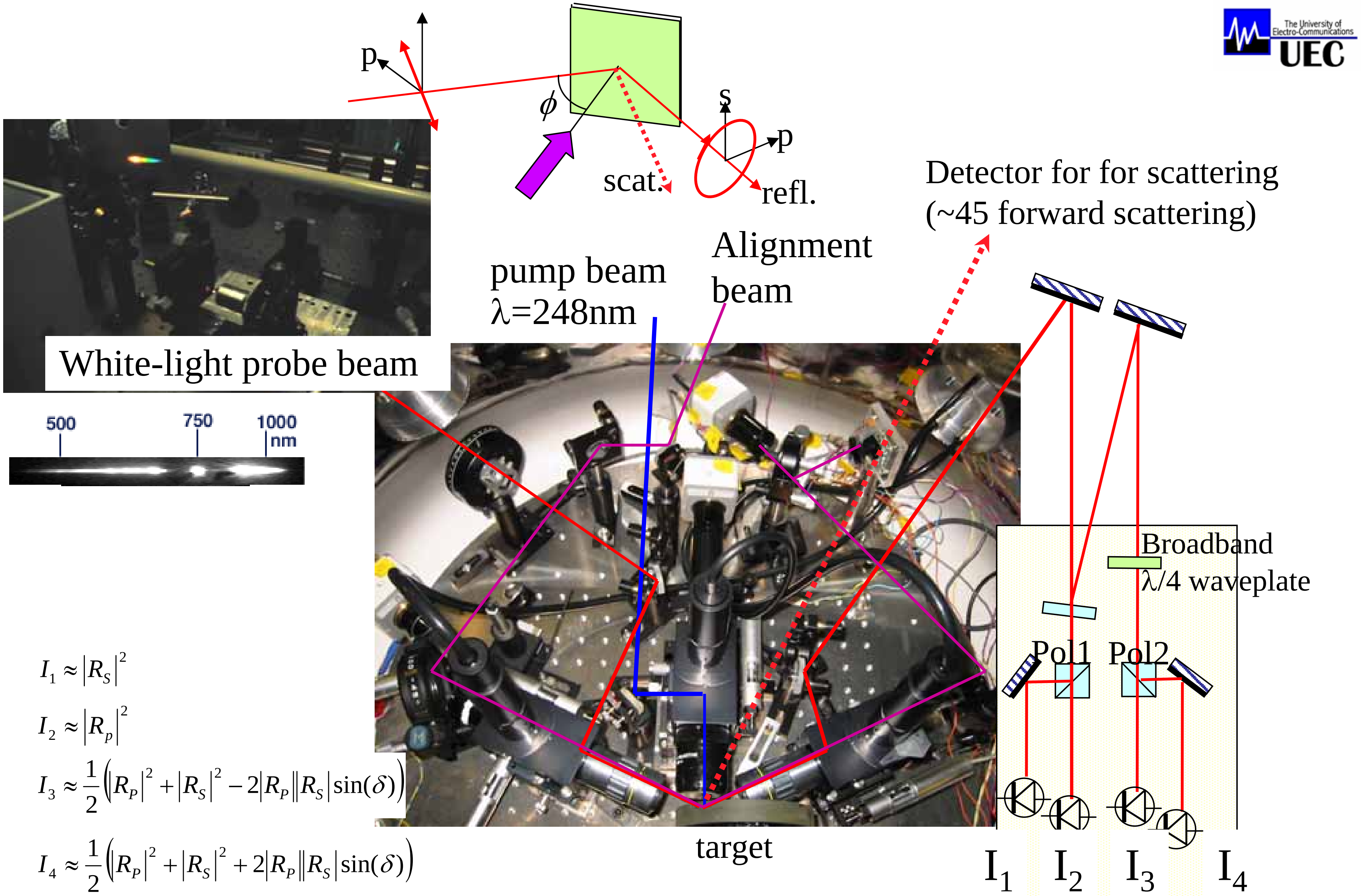


We need
heating faster than expansion, and measurements with high resolution.

Ellipsometric pump-probe measurements in WDM

- X-Y plot (Rp/Rs vs. F(Rp, Rs, δp-s))
- Reconstruction method with Fresnel’s law
- Diffuse scattering measurements

Measurements of ellipsometric parameter and diffuse scattering



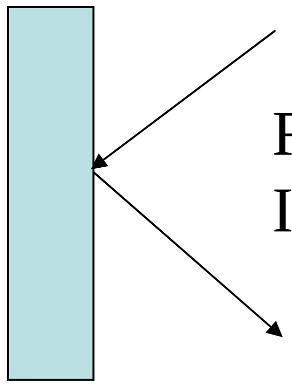
$$I_1 \approx |R_S|^2$$

$$I_2 \approx |R_p|^2$$

$$I_3 \approx \frac{1}{2}\left(|R_P|^2 + |R_S|^2 - 2|R_P||R_S|\sin(\delta)\right)$$

$$I_4 \approx \frac{1}{2}\left(|R_P|^2 + |R_S|^2 + 2|R_P||R_S|\sin(\delta)\right)$$

What optical electromagnetic waves see

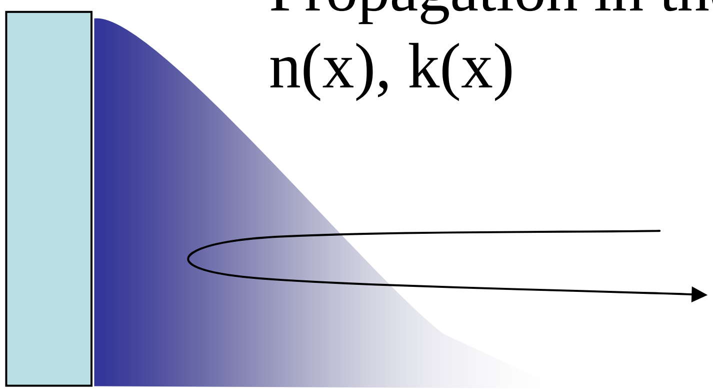


Reflection at sharp boundary
Impedance miss-matching

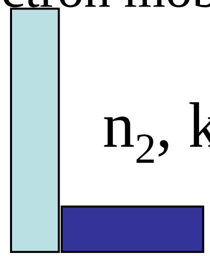
$$r = \frac{(n+ik)-1}{(n+ik)+1} = \frac{\sqrt{\varepsilon_1 + i\varepsilon_2} - 1}{\sqrt{\varepsilon_1 + i\varepsilon_2} + 1}$$

reconstruction method

Propagation in the expanded matter
n(x), k(x)



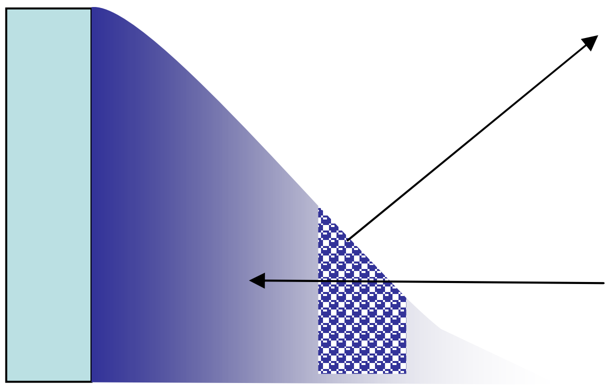
AC conductivity
electron mobility+atomic polarizability



n_2, k_2, d

3 Stokes' Parameters or
Rp, Rs, δp-s

diffuse scattering

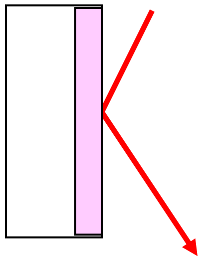
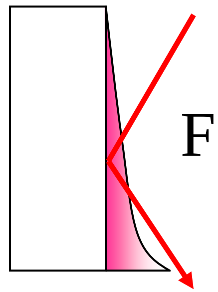


Droplet formation when? how?
Critical point, two fluid region
Conductivity of fluid with droplet

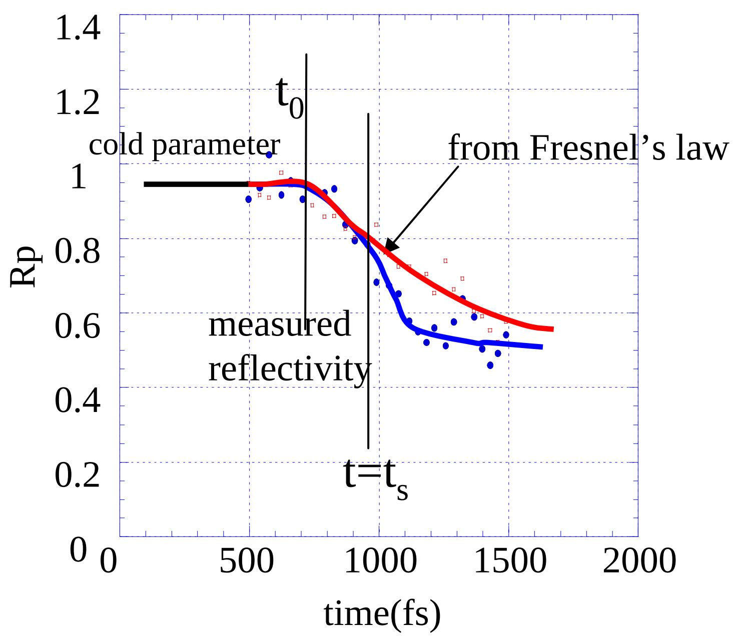
To check starting time when expansion component cannot be neglected.

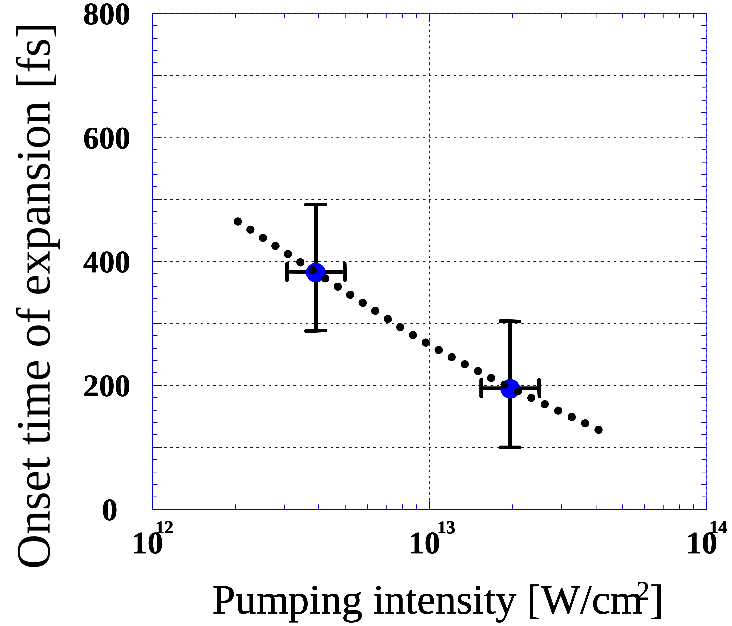
measured parameters

Stokes' parameters
$s_1(t)$, $s_2(t)$, $s_3(t)$,
(s_0)
F=3

time	$t < t_s$	$t_s < t$
plasma	single interface  F=2 $\rho = \tan(\varphi)\exp(i\Delta)$	expanded plasma  F>3
Fresnel's law	available	No

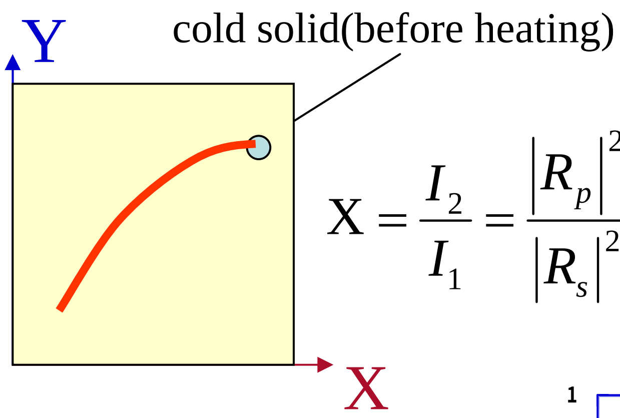
Au shot 021114-4-1 Rp signal



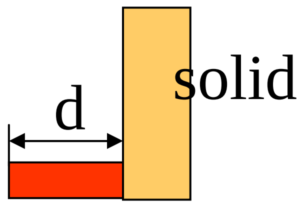


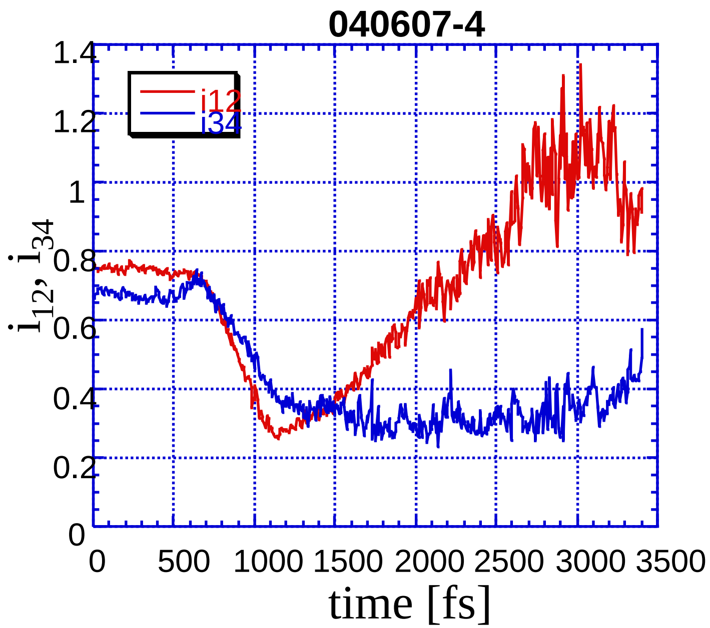
Change of polarization state of probe beam with target heating

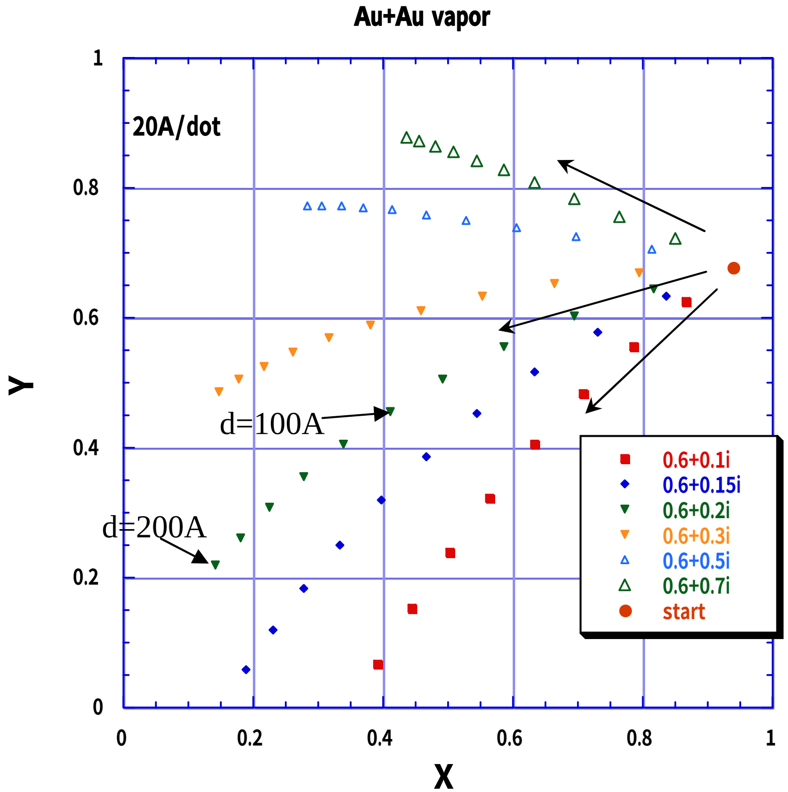
$$Y = \frac{I_3 - I_4}{I_3 + I_4} = \frac{2|R_S||R_P|\sin(\delta)}{|R_S|^2 + |R_P|^2}$$



$$X = \frac{I_2}{I_1} = \frac{|R_p|^2}{|R_s|^2}$$





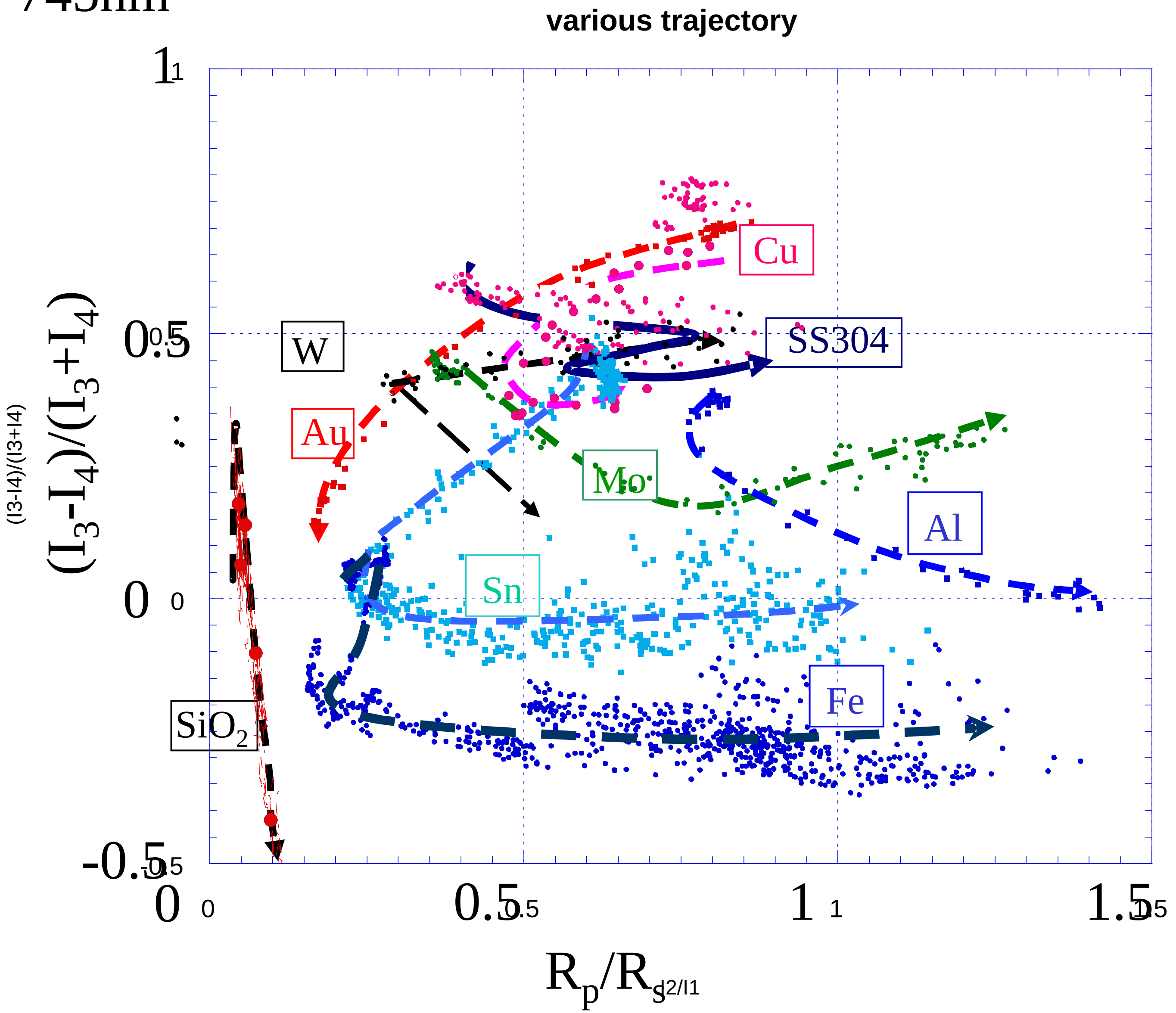


Very sensitive to optical constant and thickness of plasma

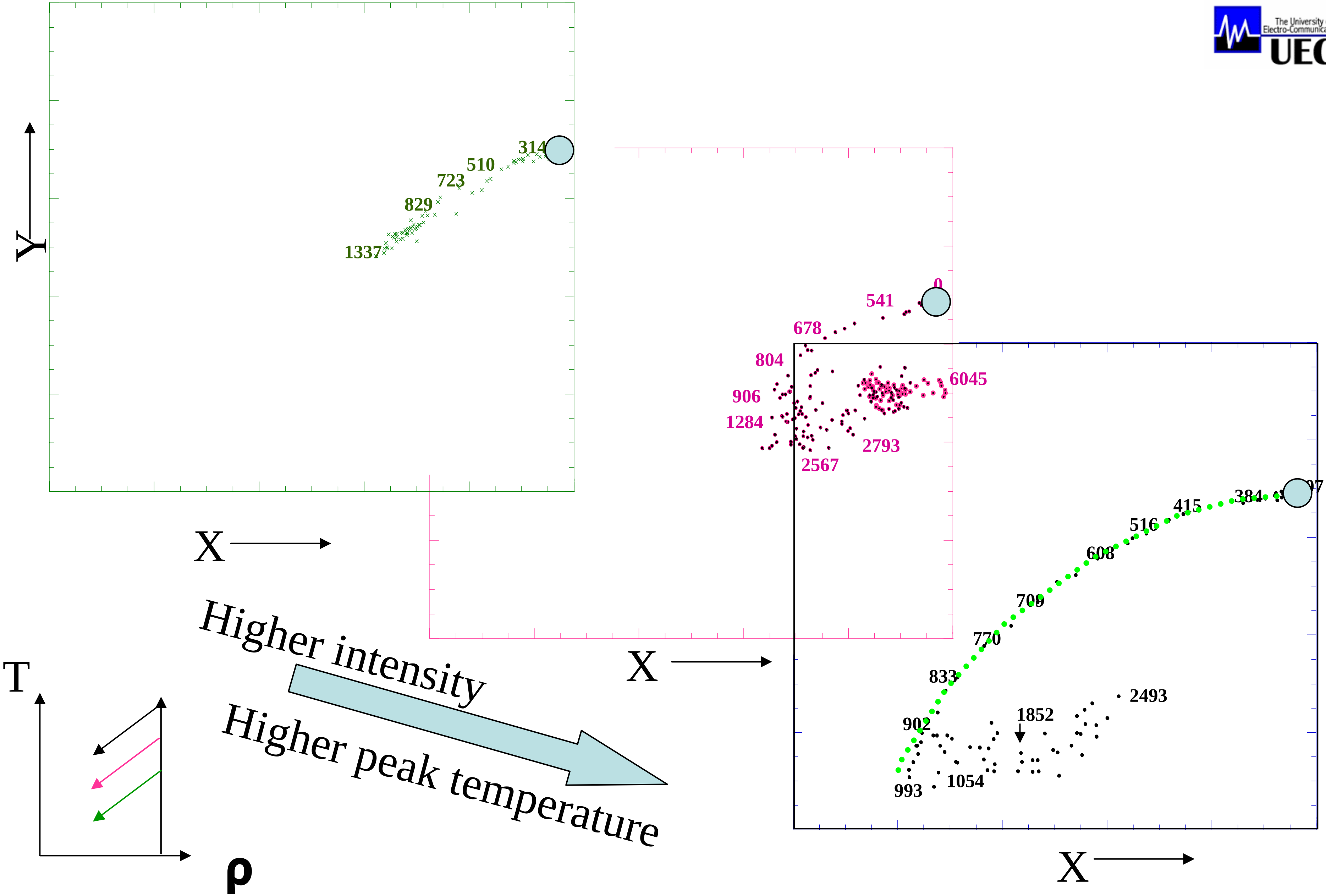
Strong reduction of AC conductivity in Gold

We have measured Au, Cu, Al, W, Mo, Sn, Fe, SS304, SiO_2.

For λ=745nm

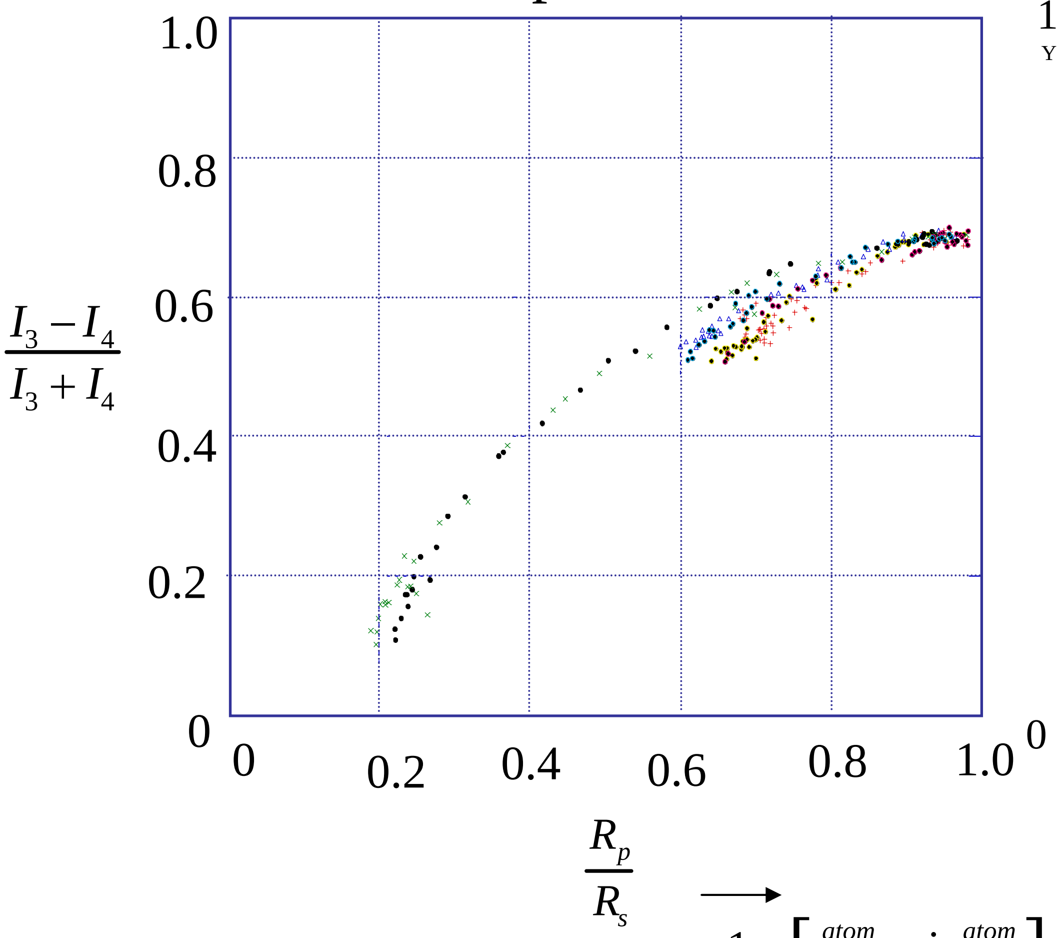


Experimental results (Gold targets)

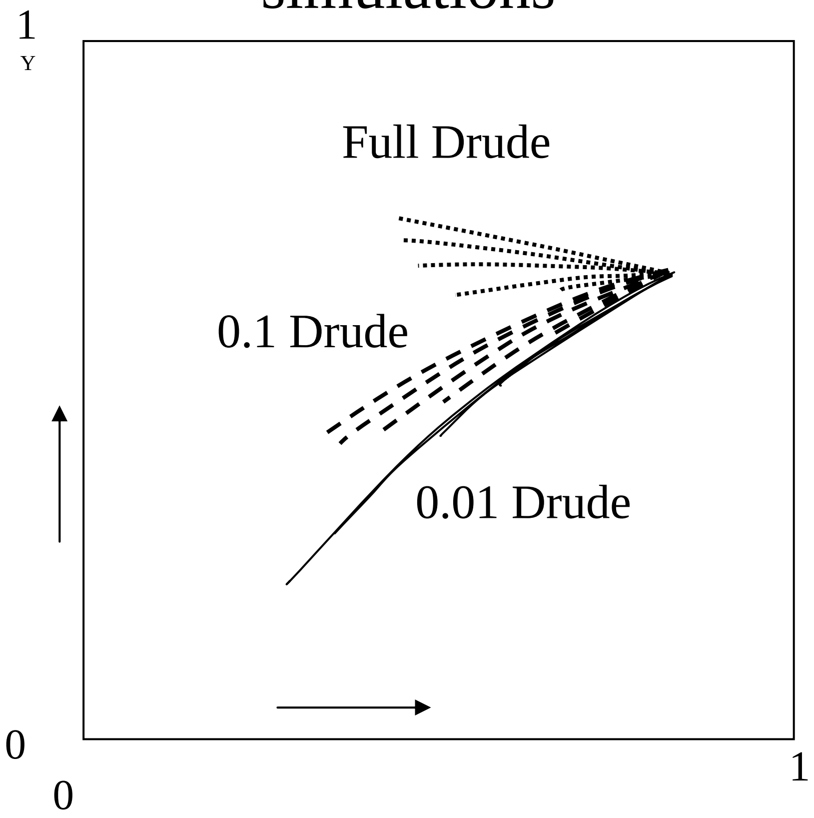


· AC conductivity in Au

experiments



simulations



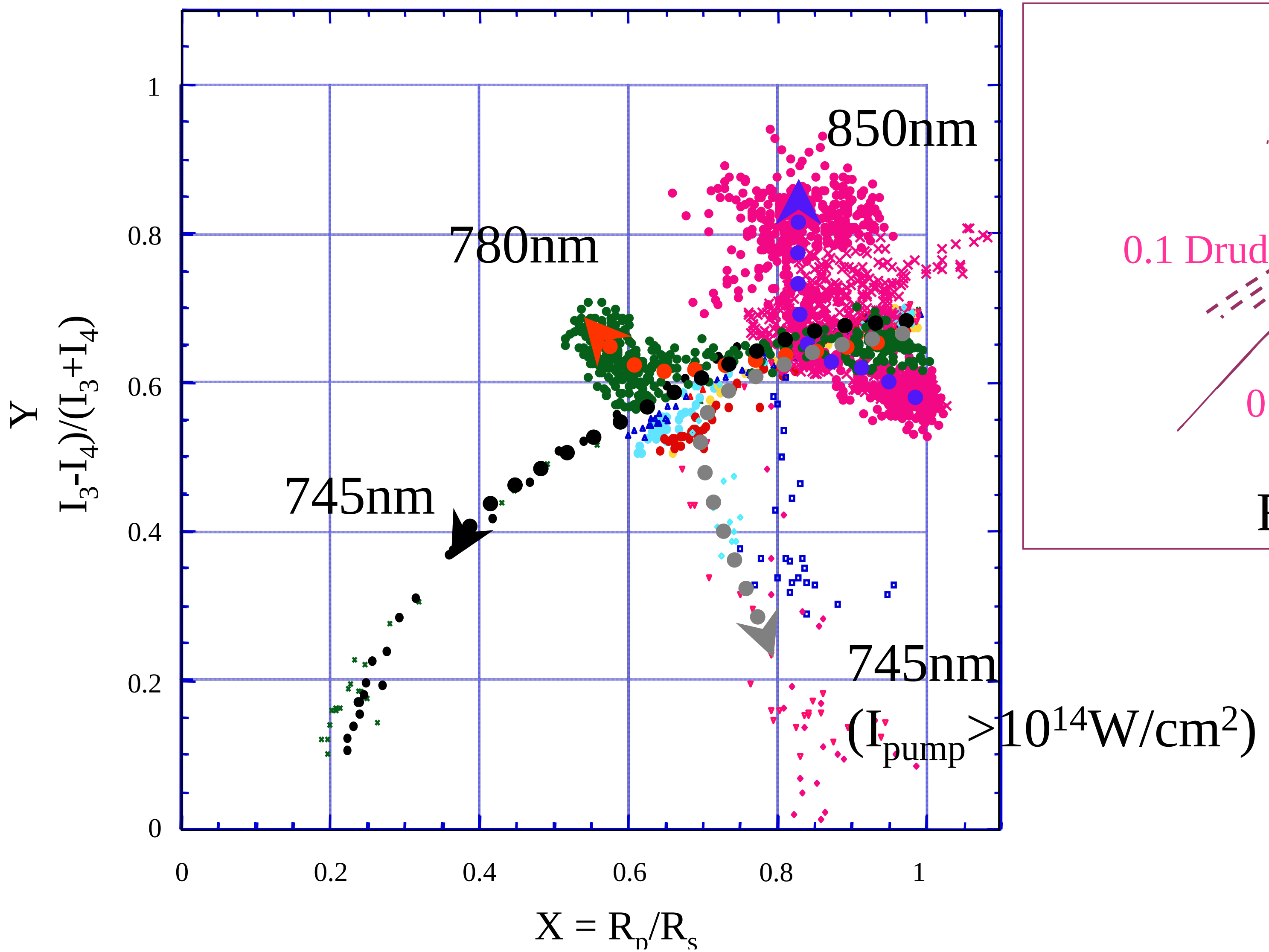
$$\varepsilon = 1 + \left[\varepsilon_r^{atom} + i\,\varepsilon_i^{atom}\right] + \left[-\frac{\omega_p^2}{\omega^2}\frac{(\omega\tau)^2}{1+(\omega\tau)^2} + i\frac{\omega_p^2}{\omega^2}\frac{\omega\tau}{1+(\omega\tau)^2}\right]^{free-electron}$$

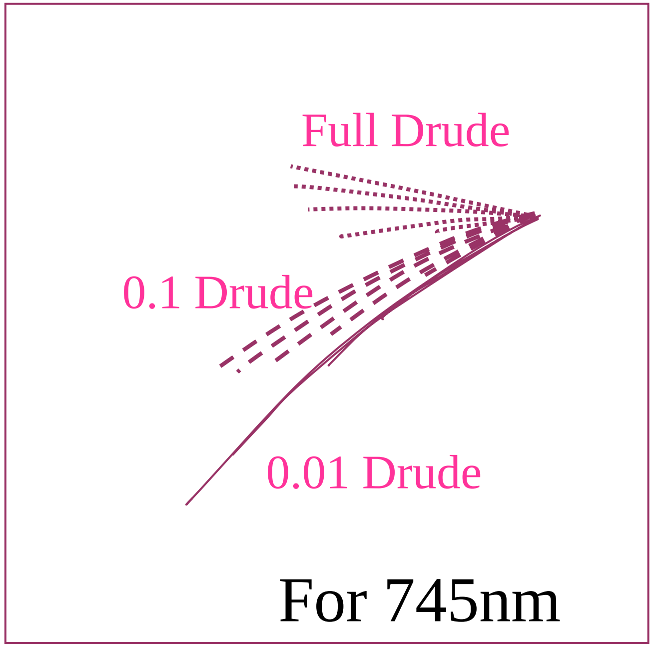
like Lorentz-Lorenz model

like Drude model

Multi frequency probe of warm dense Au plasma

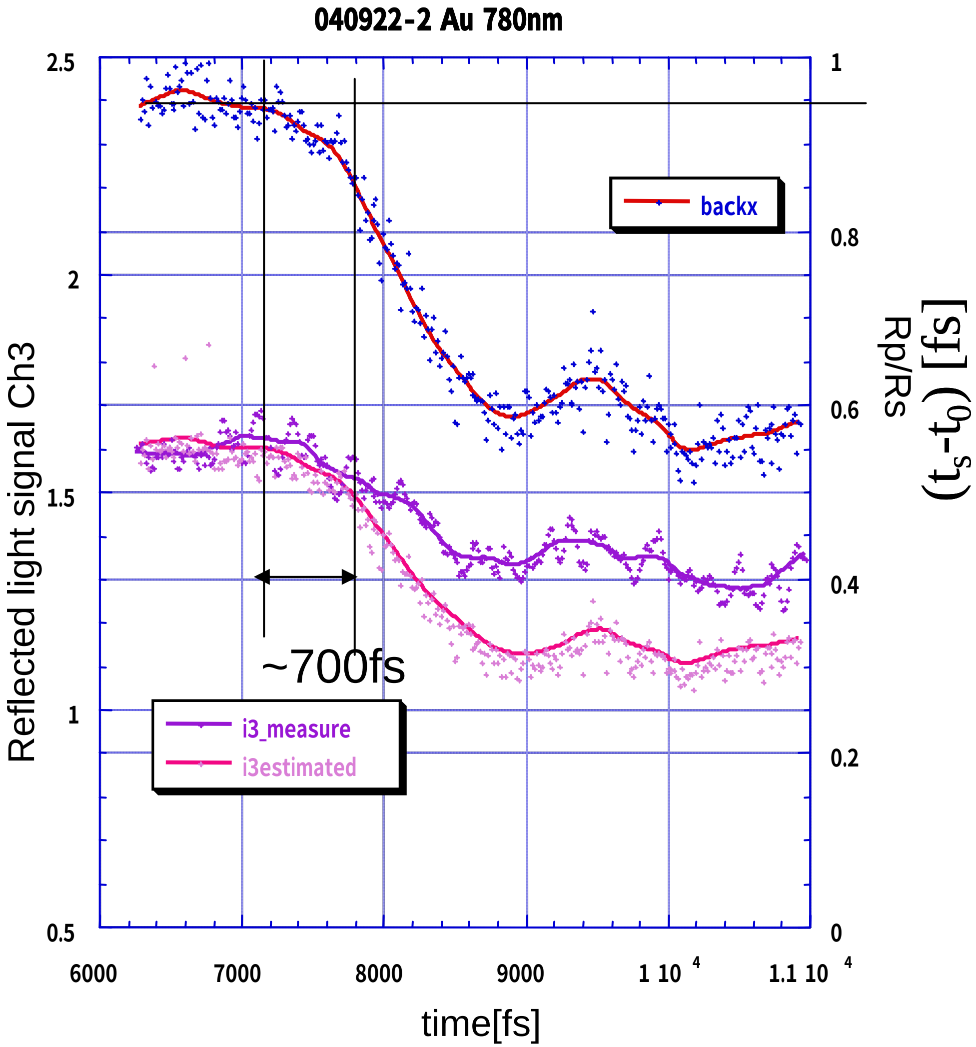
expansion=>r_p decreases, -> both of X,Y decrease
Y increase at 850nm=> change of δ should be latge

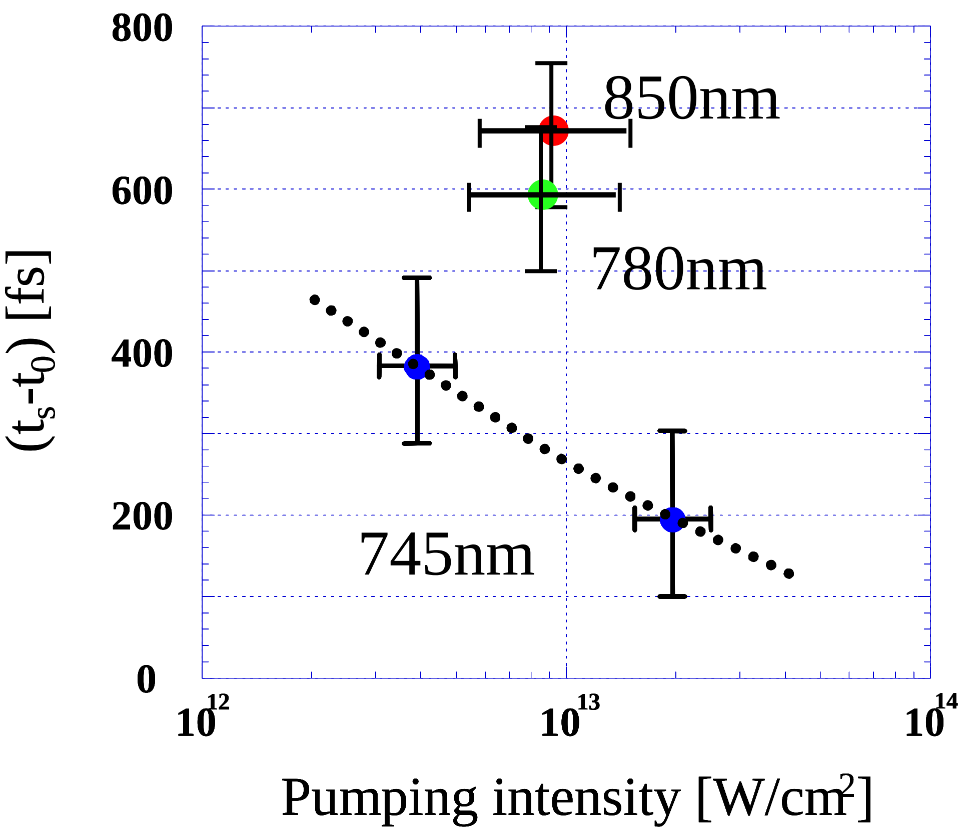




Reconstruction method shows surface expansion

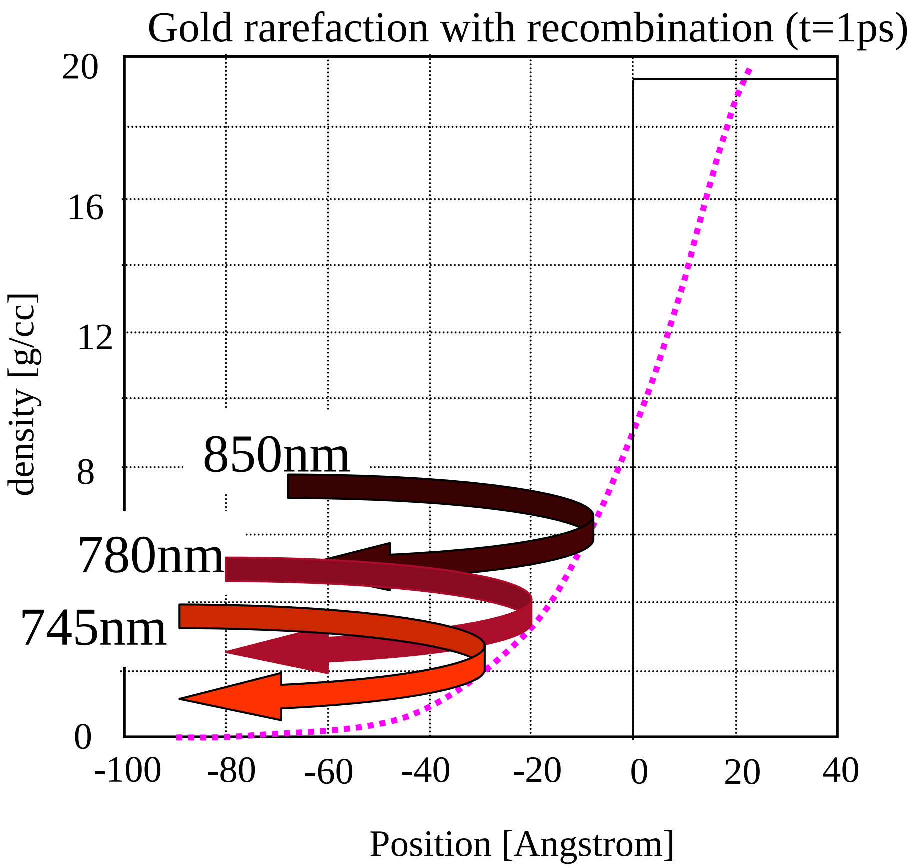
Probe laser of longer wavelength looks at deeper region?

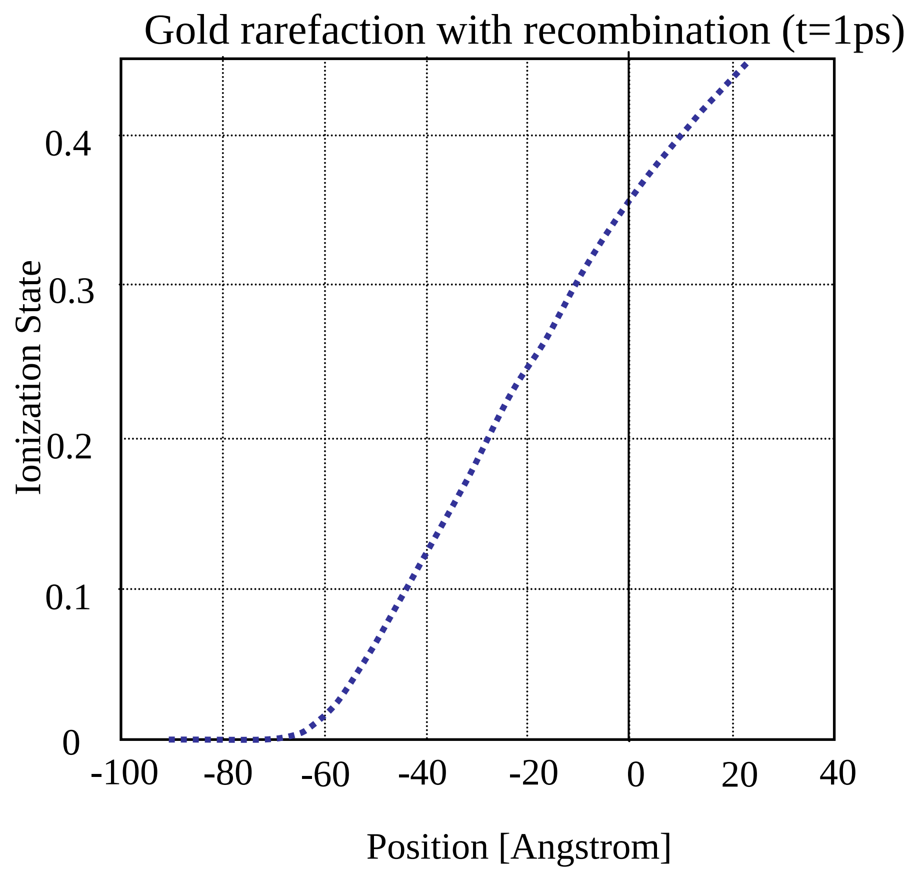




Different frequency probe observes different plasma?

Each probe frequency may see different region.



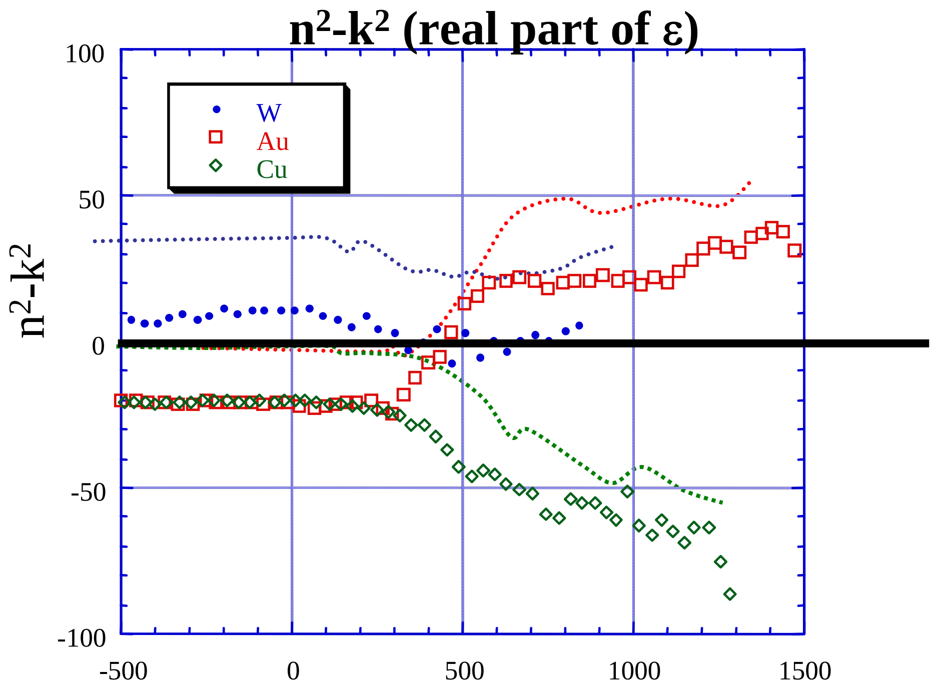


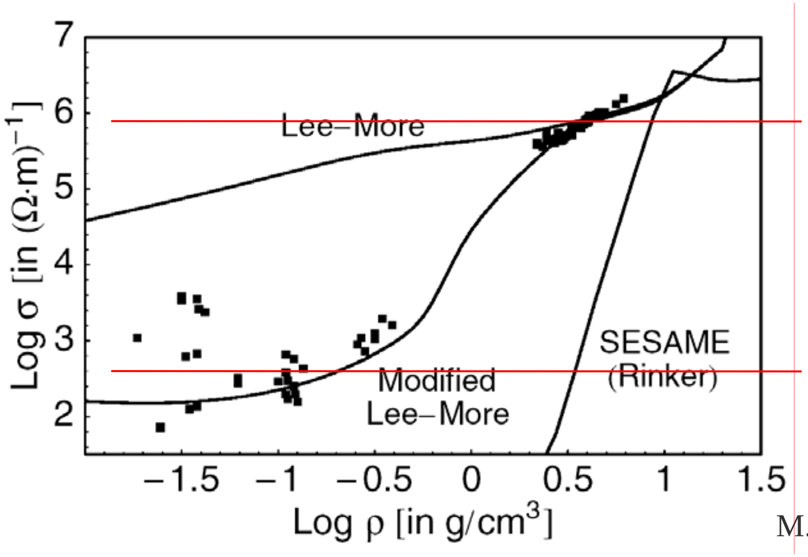
atom density for Au solid = **5.9×10^{22}cm^{-3}**

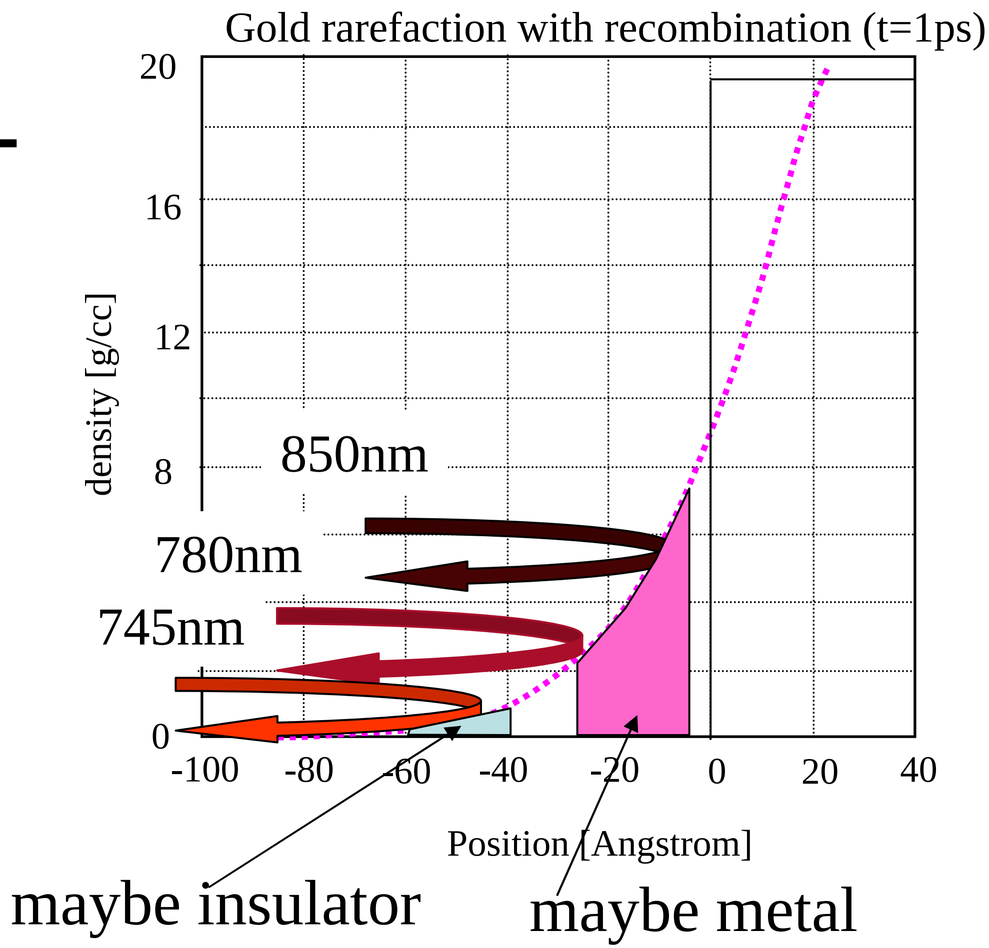
Here long wavelength penetrates more deeply,
Contrary to usual plasma behavior.

Electron localization in WDM

M-NM transition(?) may be faster process in USP plasma.





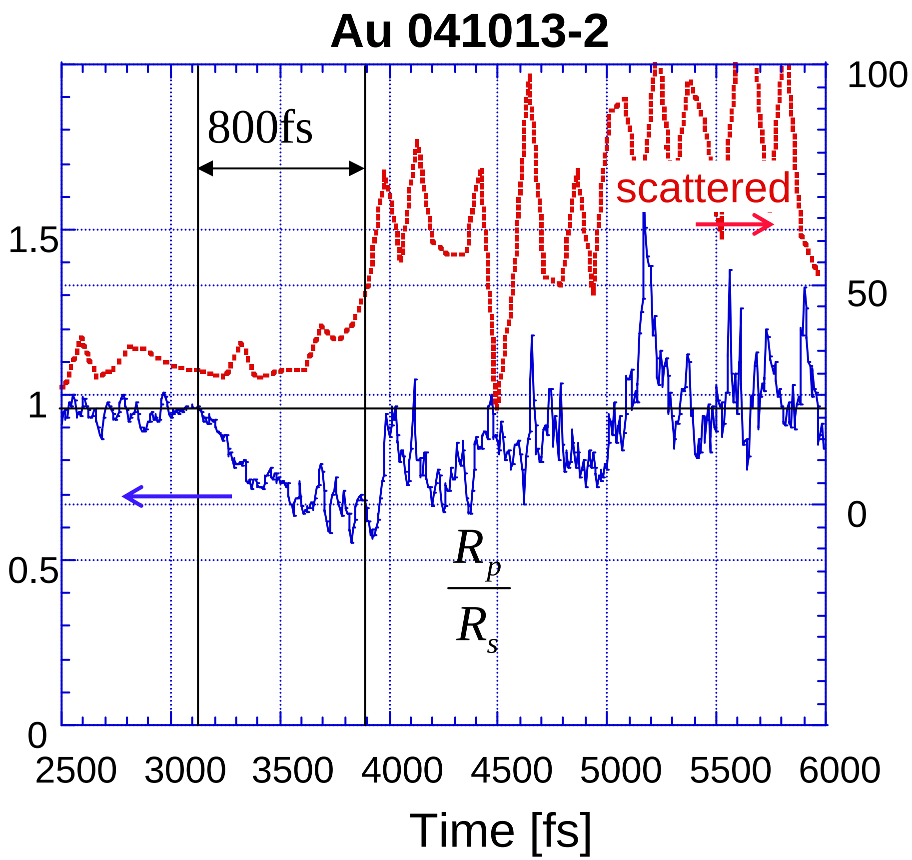


M.P. Desjarlais, **Volume 41, Issue 2-3 , Pages 267 - 270 (2001)**

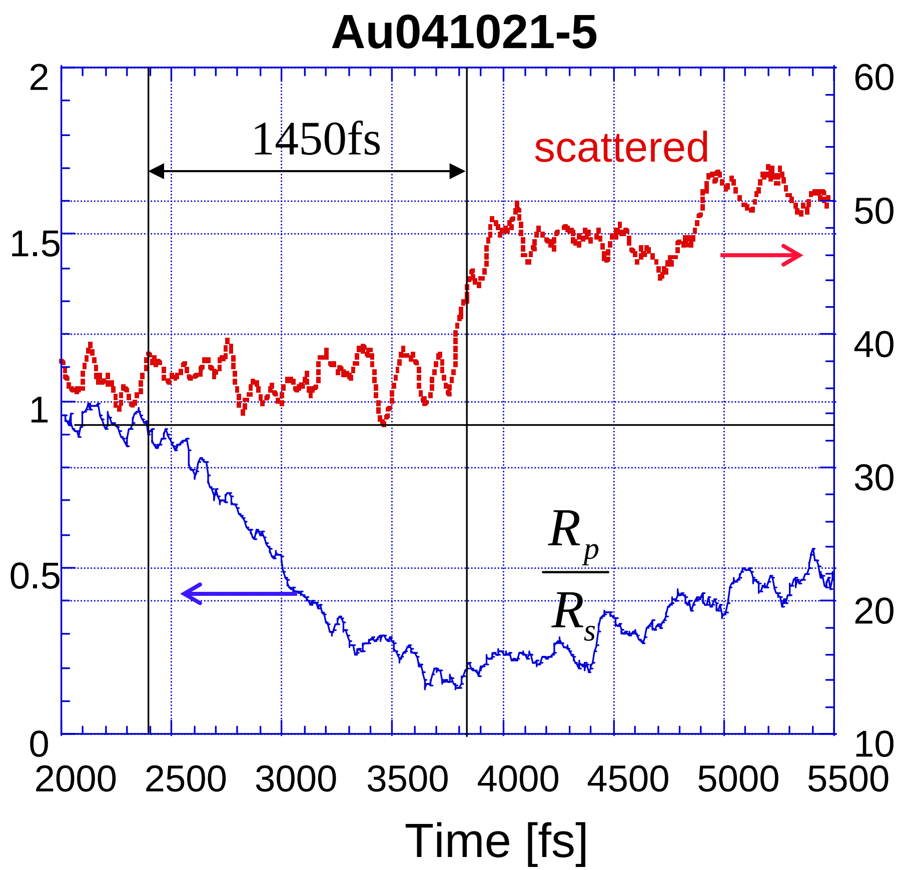
Two phase region
Droplet formation

Time resolved diffuse scattering by Au targets

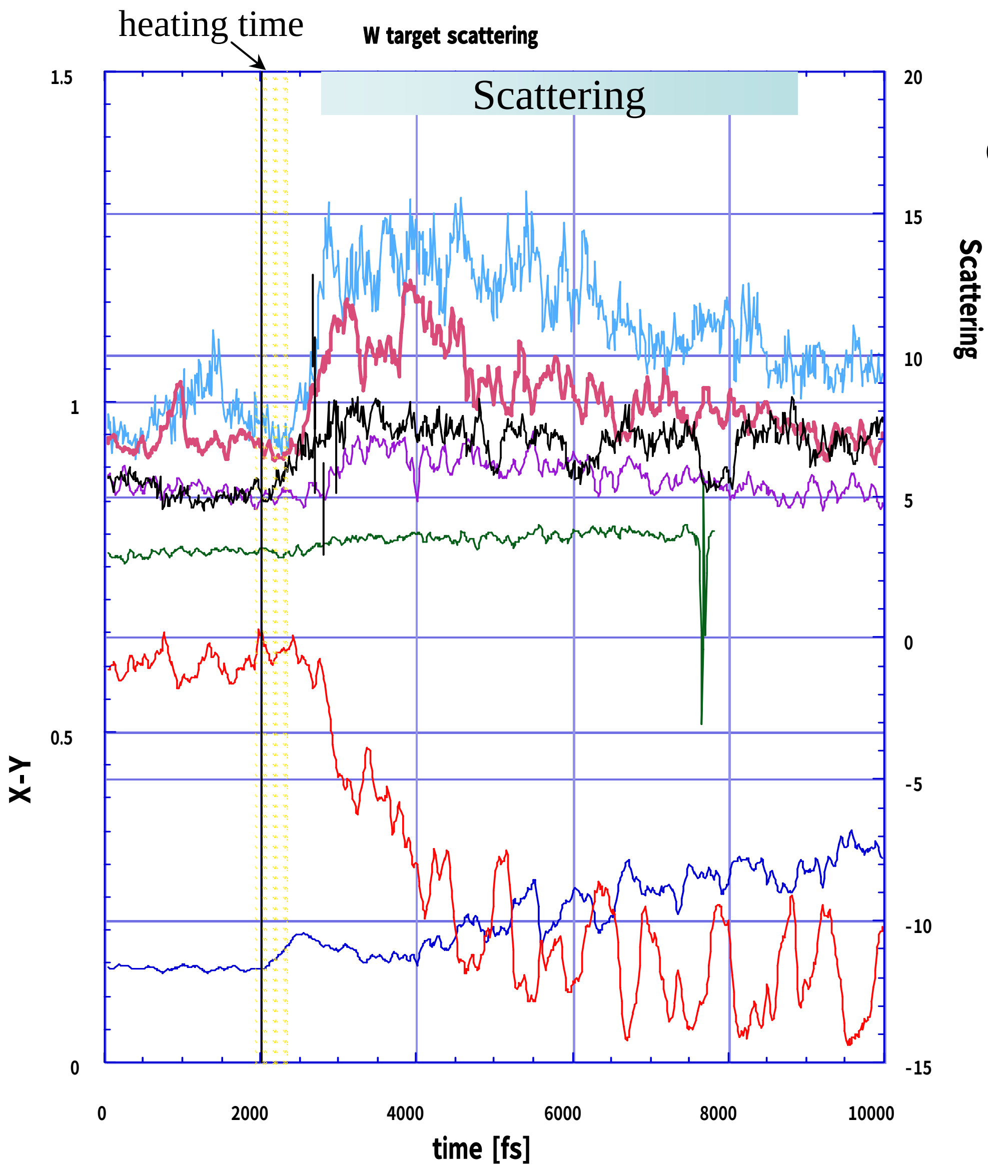
lower pump intensity



higher pump intensity



Turn-on time of W scattering is shorter than that of Au.



onset time of diffuse scattering

Au 0.8~2.6ps

W 0.75~1ps
(with 0.3ps heating duration)

$I=10^{13}\sim10^{14} W/cm^2$

Summary

1. Strong reduction of AC conductivity is observed in ellipsometric measurements.
2. Frequency dependence also denotes small contribution of free-electron.
3. We observed some evidence of Au^{+}-Au^{-} plasmas.
4. These results give us the evidence of localization of electron in WDM.
5. Diffused scattering signal due to reach the two phase boundary can be detected.
6. Droplet formation looks very fast.
7. New EOS for Tin. We propose new measured method to detect critical point for metals.