WDM Science Using Lasers

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Outline

- Hydrodynamics feature in 2ϕ fluid
- Metal – Non-metal transition in WDM

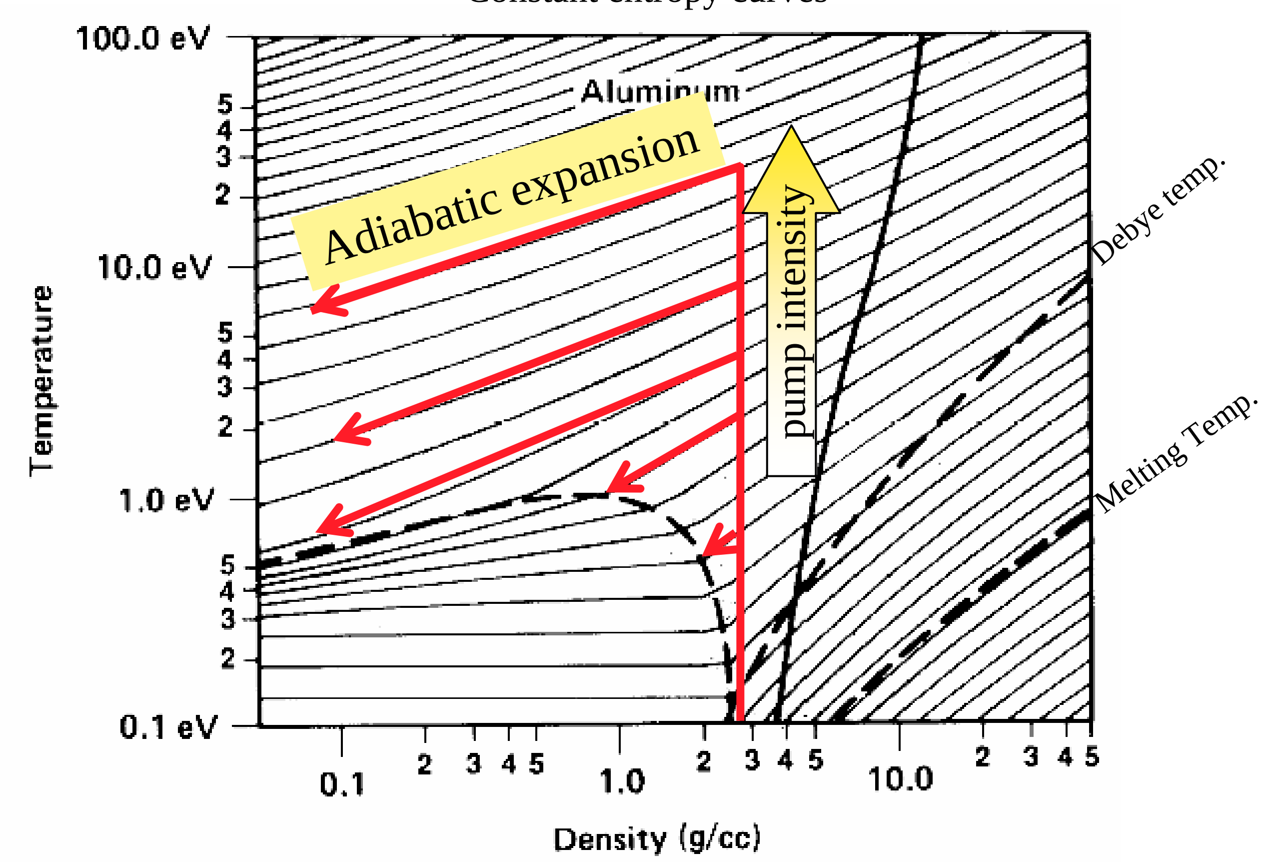
What for

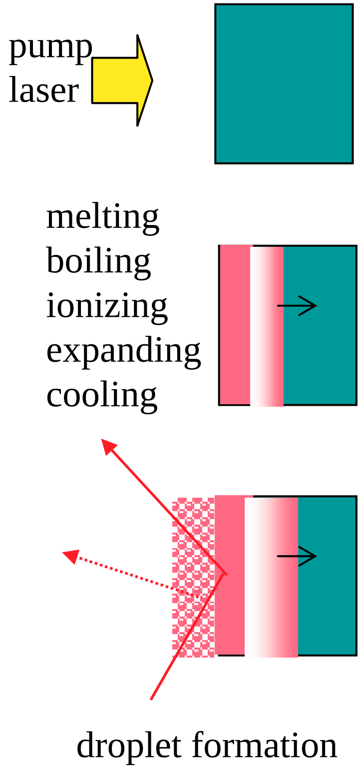
- Searching critical point for high-temperature melting-point metal
- EOS
- Check liquid metal model in WDM plasmas

How to create WDM

even the two phase fluid region

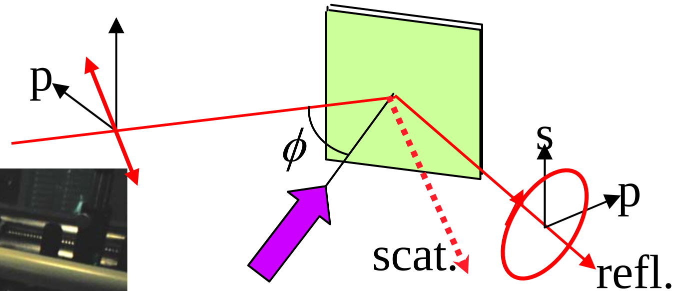
Constant entropy curves

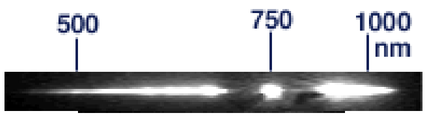


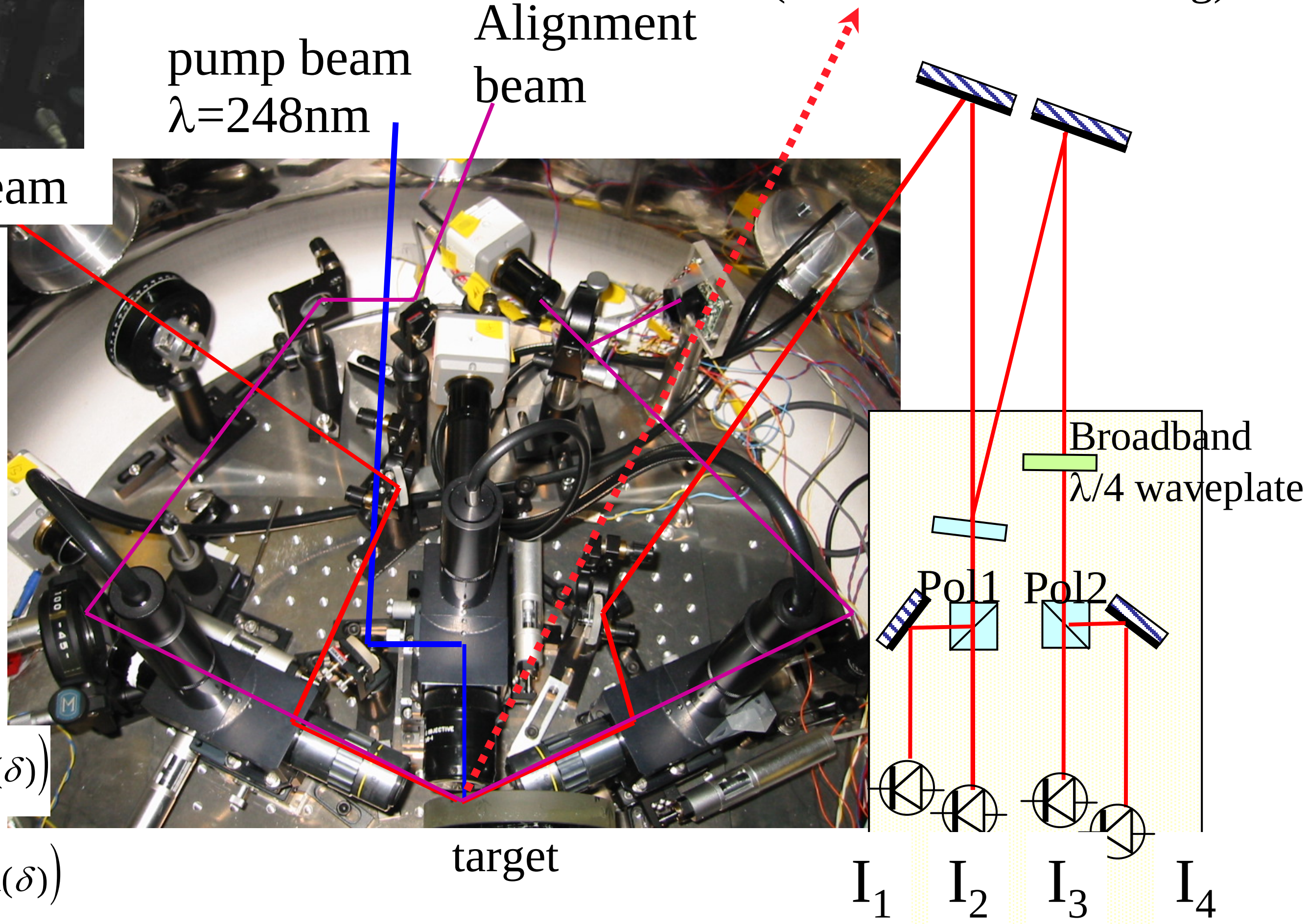


We need
heating faster than expansion, and measurements with high resolution.

Measurements of ellipsometric parameter and diffuse scattering







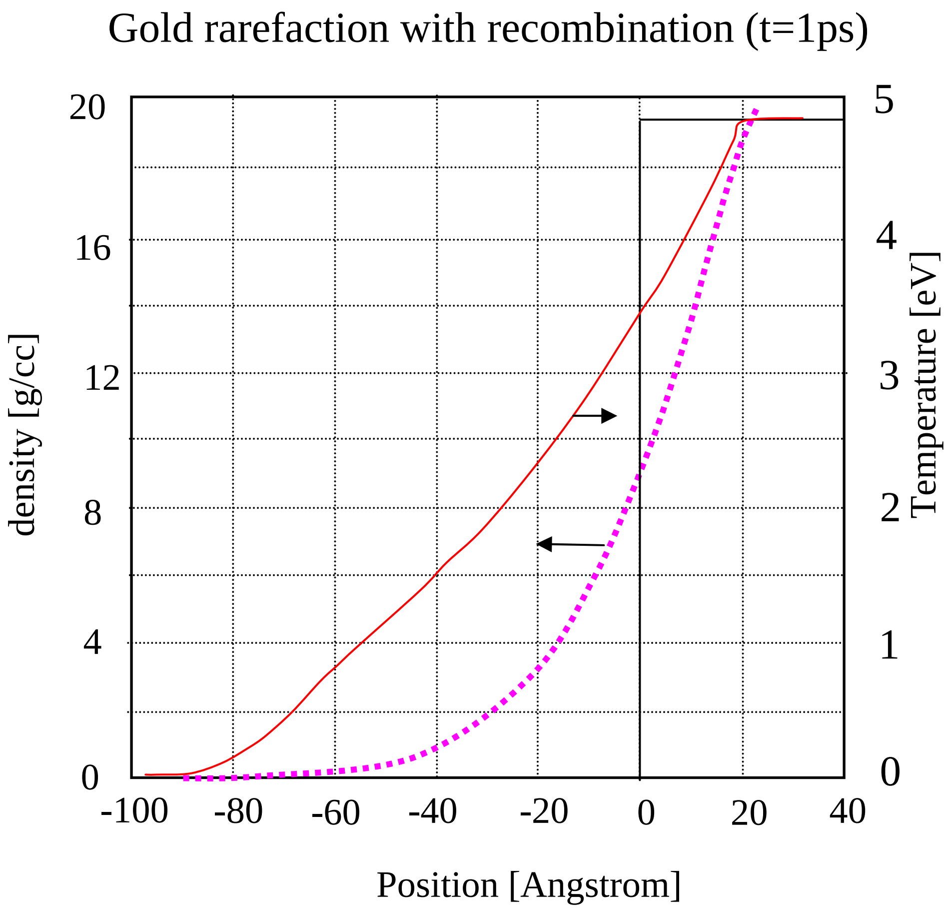
$$I_1 \approx |R_S|^2$$

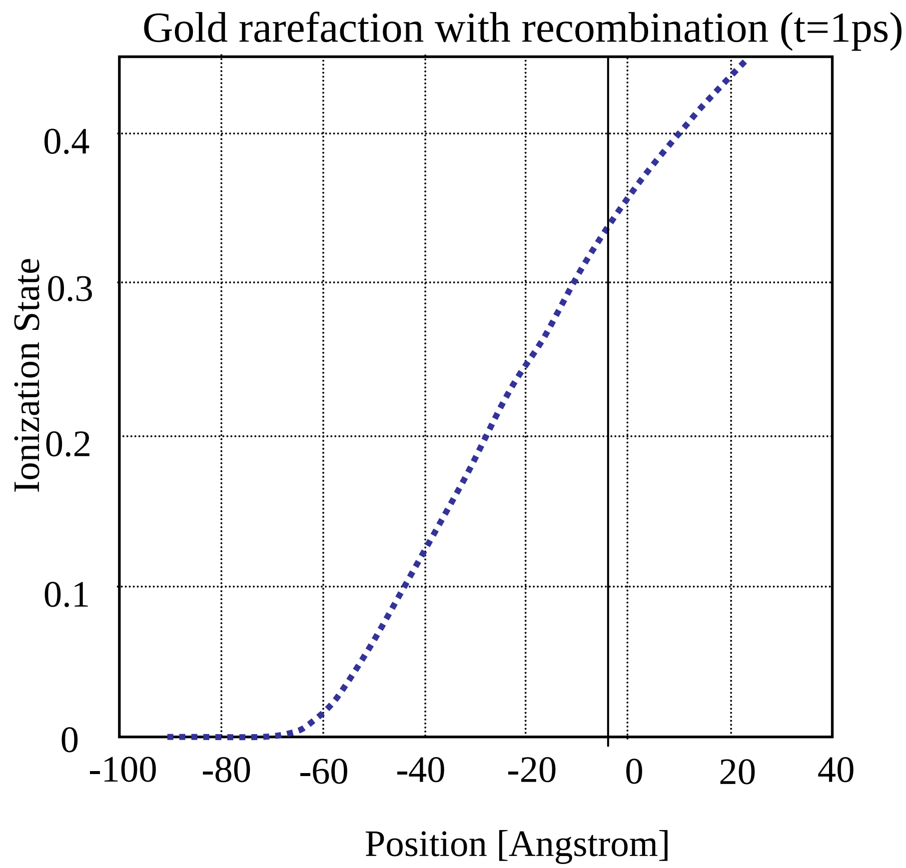
$$I_2 \approx |R_p|^2$$

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

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

There are large variety of parameters.



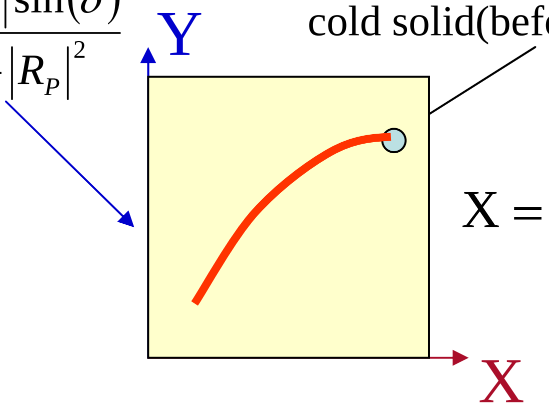


We need highly spatial and temporal resolution.

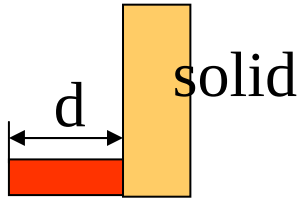
× normal interferometer

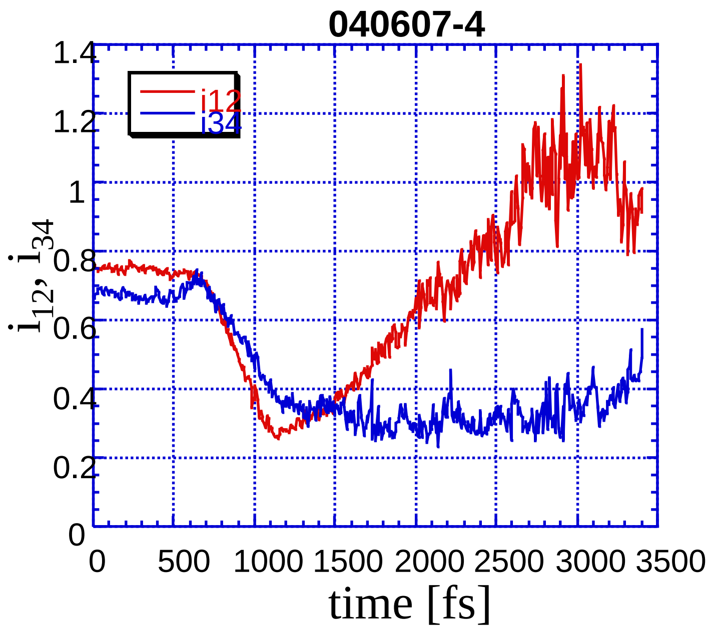
Change of polarization state of probe beam with target heating

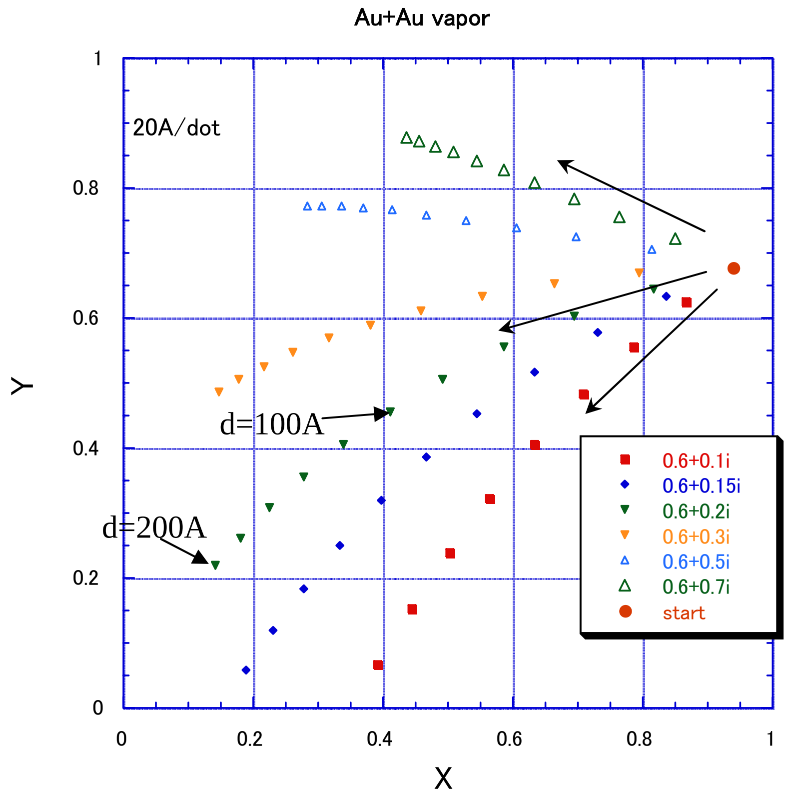
$$Y = \frac{I_3 - I_4}{I_3 + I_4} = \frac{2|R_S||R_P|\sin(\delta)}{|R_S|^2 + |R_P|^2}$$



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



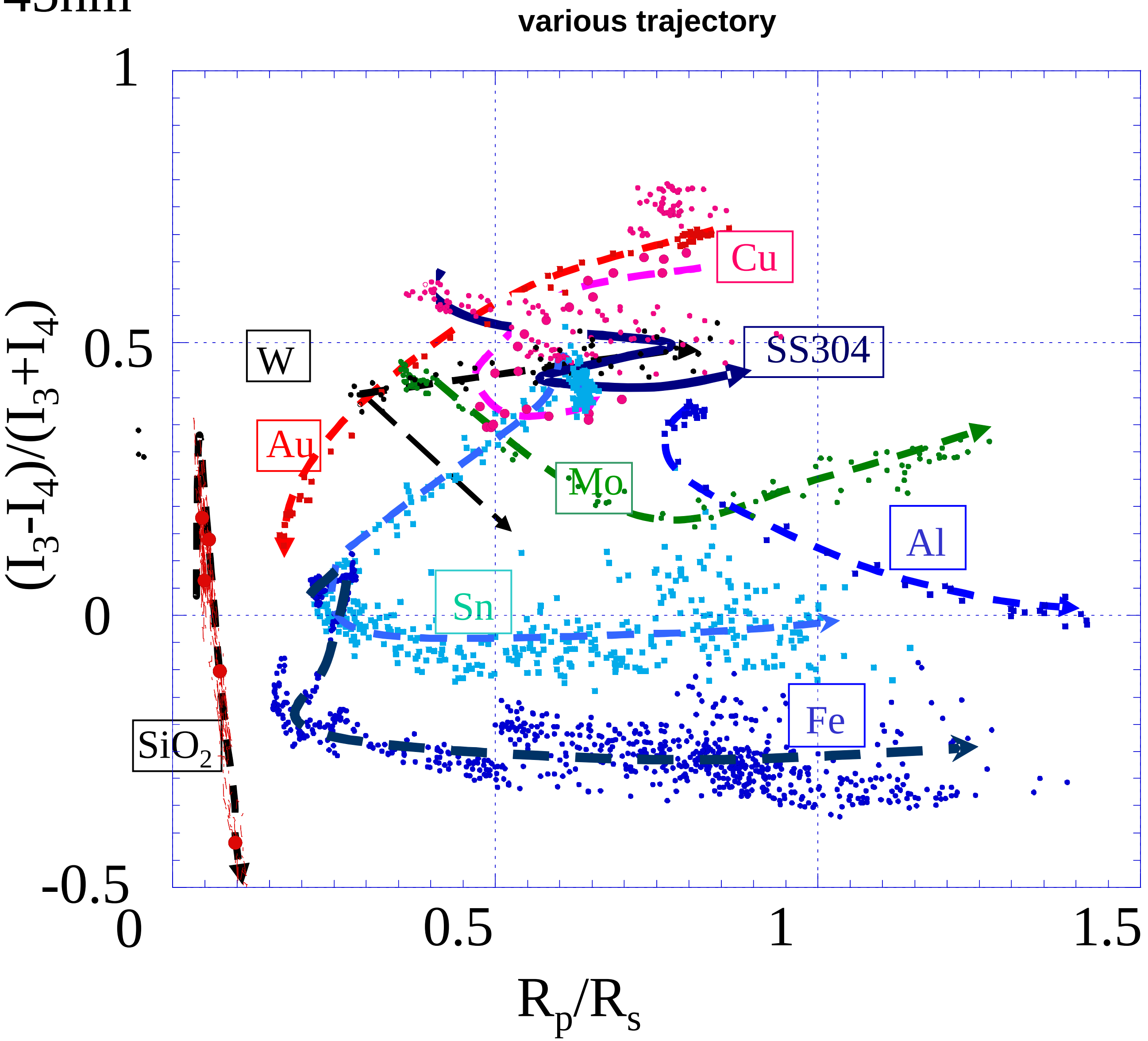




<u>Very sensitive to optical constant and thickness of plasma</u>

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

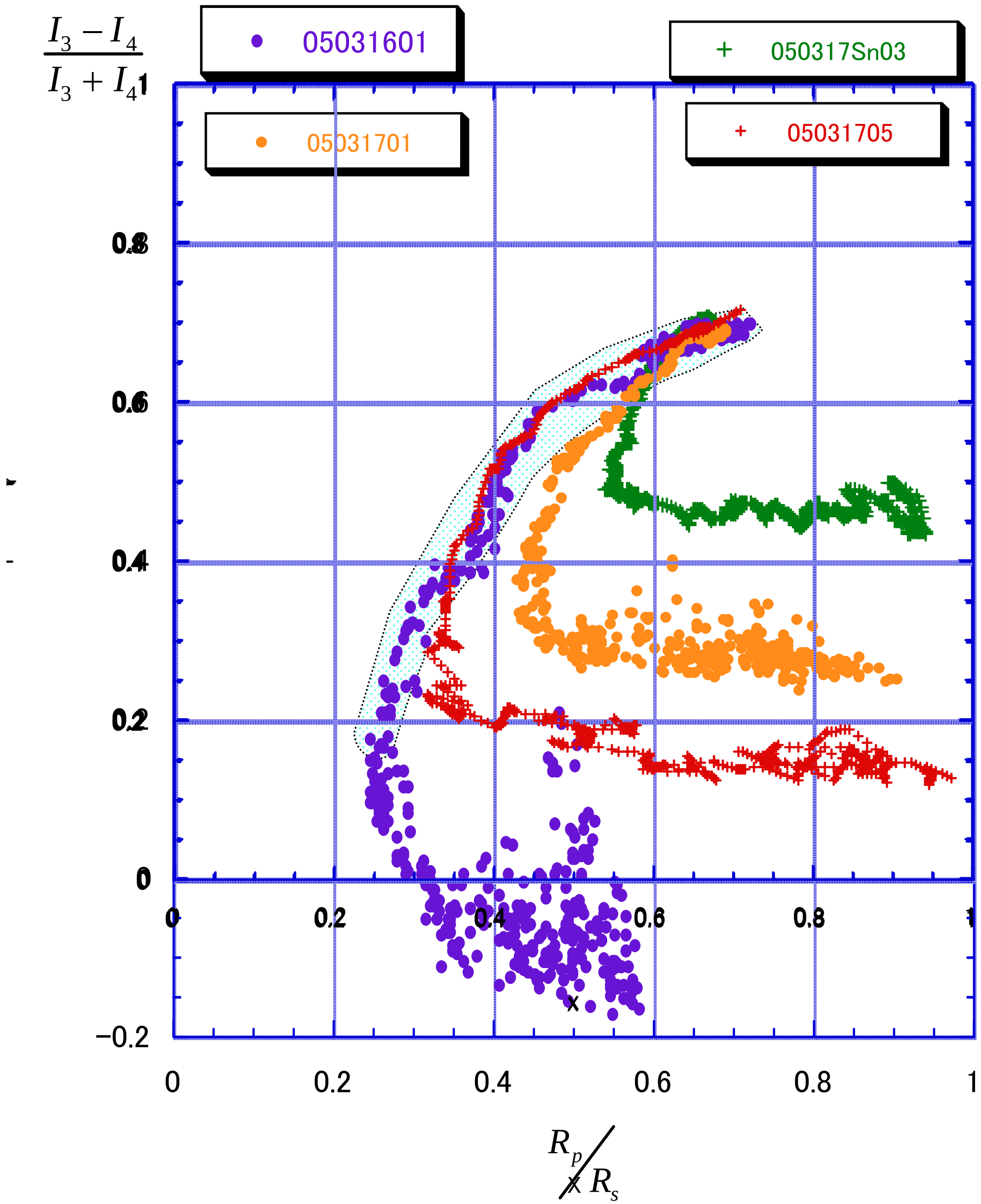
For λ=745nm

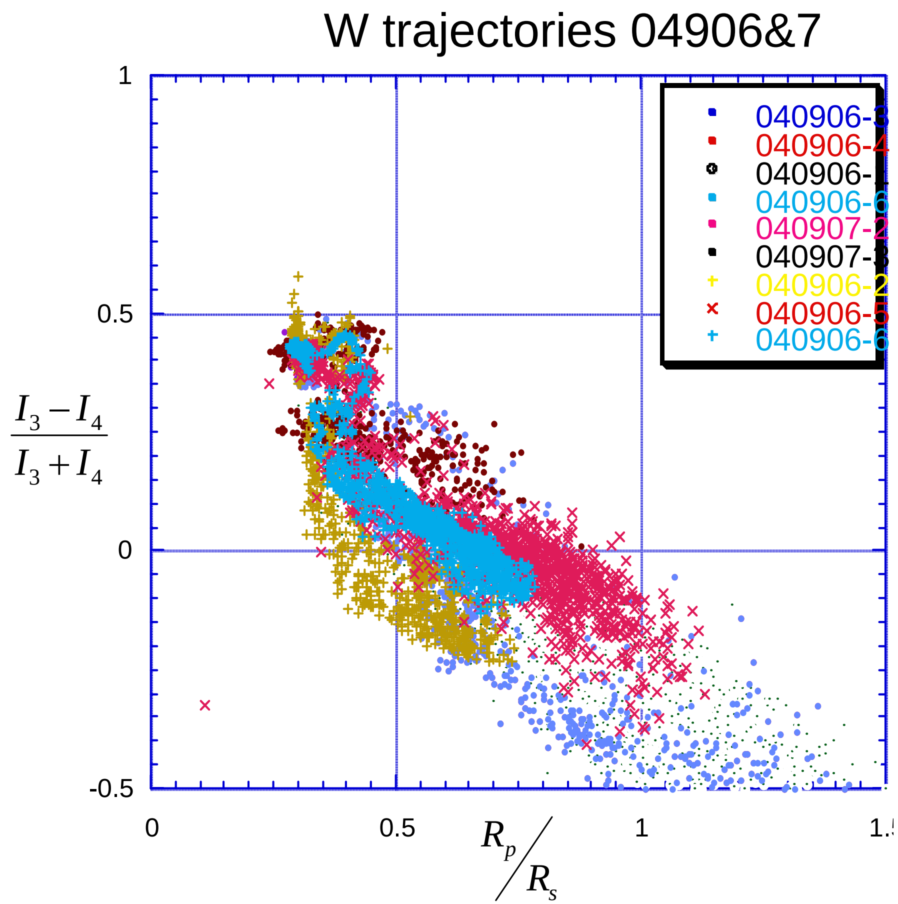


+Sn, Zn..

to be continued

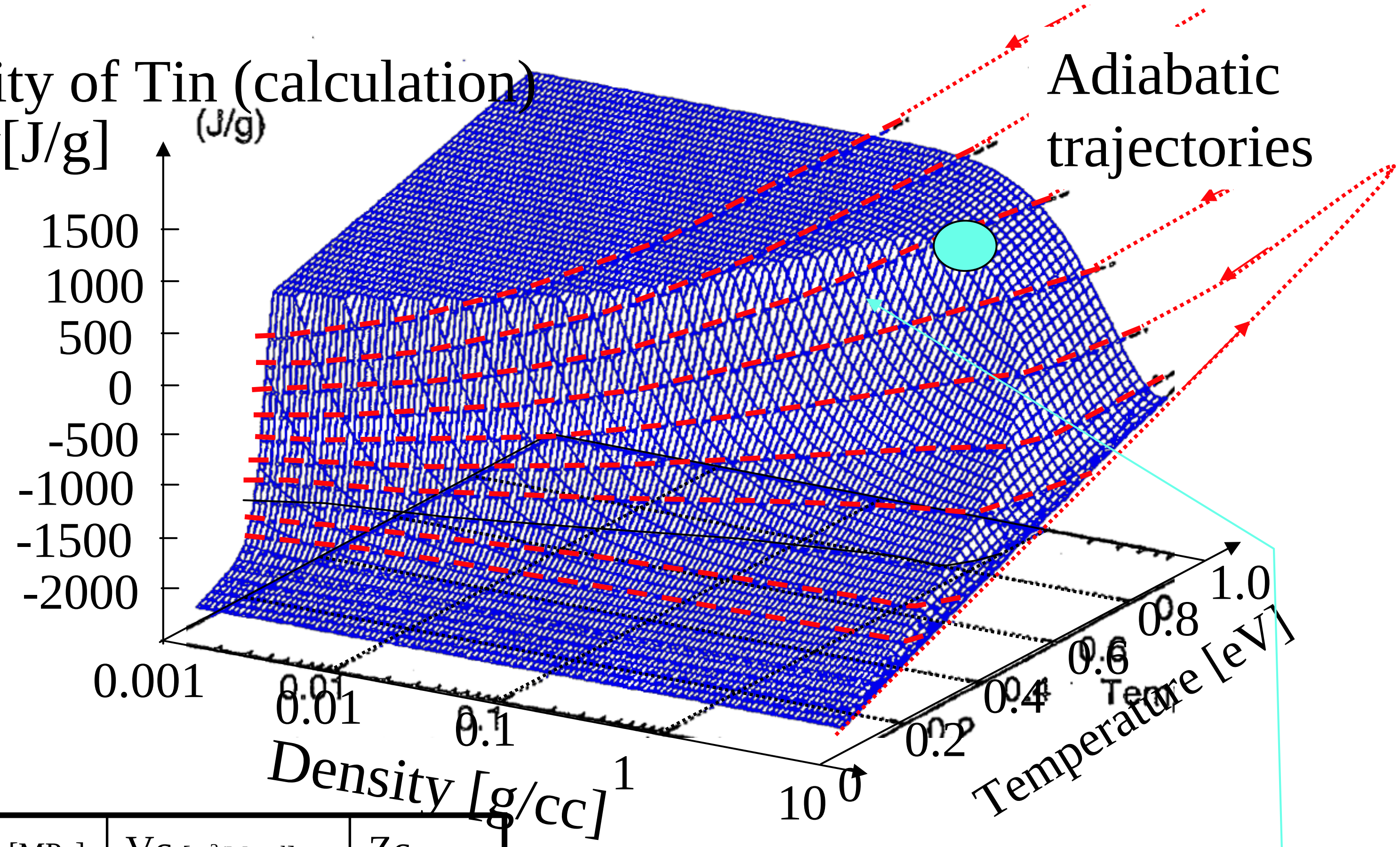
+Intensity dependence data (different T_0)





Droplet formation and detection of its signal in 2ϕ fluid region

Energy density of Tin (calculation)



Comparison with other data*

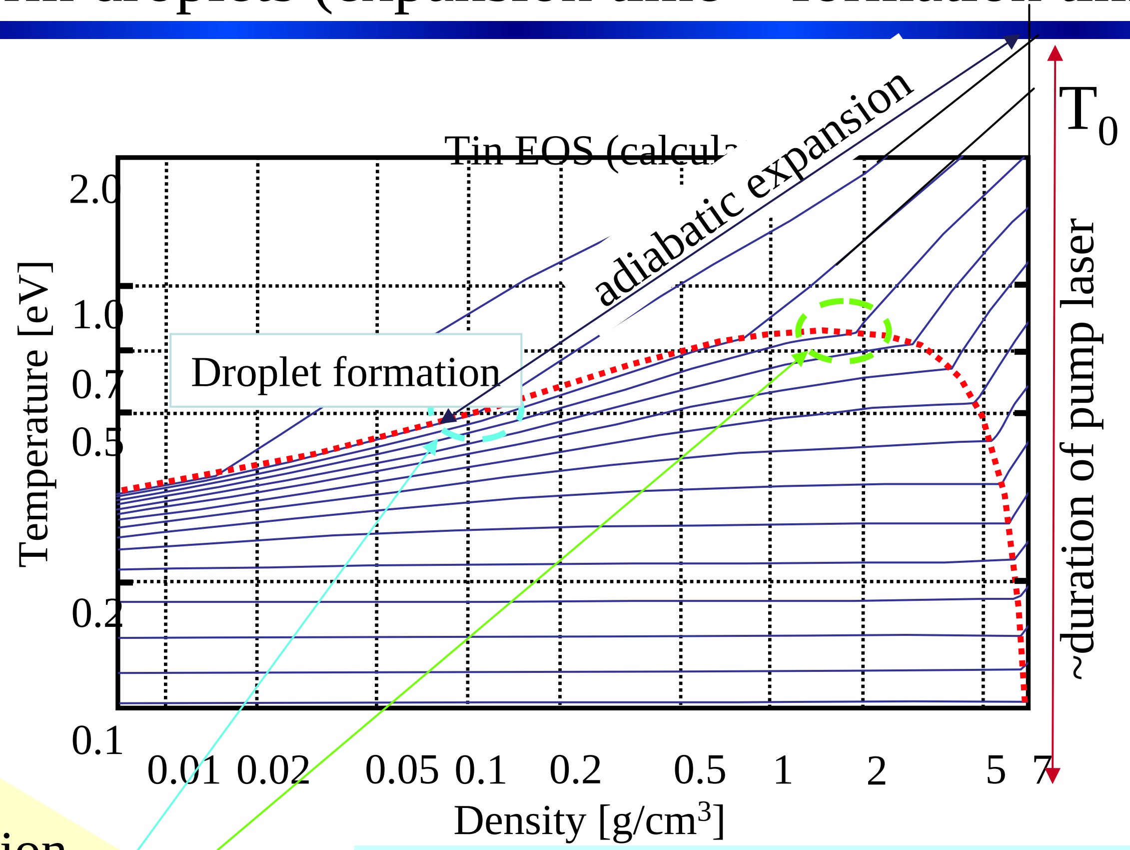
atom	Tc[K]	Pc [MPa]	Vc [m³/Mmol]	Zc
Na	2485	25.6	76.7	0.095
Se	1903	38.0	42.7	0.103
Hg	1750	167.3	34.8	0.40
Cs	2057	14.5	---	---
Sn	8720	210	---	--
Pb	5400	85	---	--
W	23000?	>1000	---	--

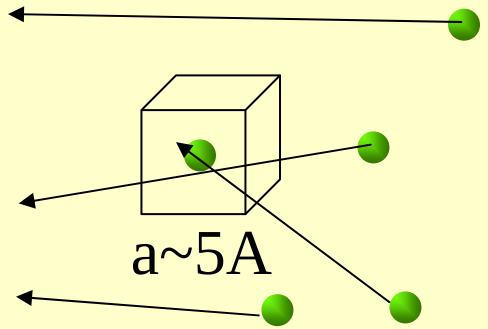
Critical point:
T~0.8eV(=9280K), ρ~1.5g/cc,
Pc~370MPa

V_c=79m³/Mmol, $Z_c=P_cV_c/RT_c$=0.38

*D. A. Young, Phase Diagrams of the Elements
** F Hensel, et al., Rev. Mod. Phys., 40, p.697 (1968)

Time required to form droplets (expansion time + formation time)





Rate of droplet formation

$$\frac{1}{R_{droplet}} = v_{atom} \cdot n_{atom} \cdot a^2 = 1.6 \times 10^{12} [s^{-1}]$$

$$6.3 \times 10^{10}$$

ρ=1.5g/cc, T=0.8eV
$t_{formation}$~600fs

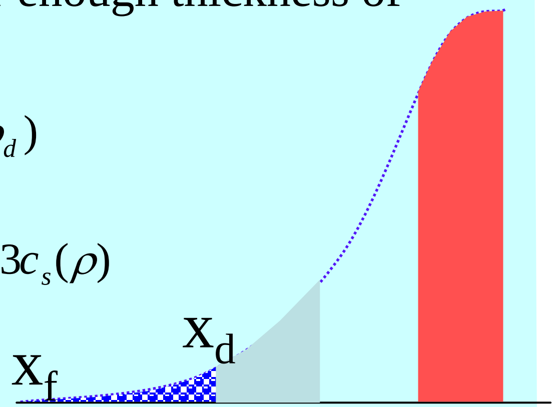
ρ=0.1g/cc, T=0.5eV
$t_{formation}$~16ps

Expansion time for enough thickness of droplet layer

$$\frac{x_d - x_f}{t_d} = R(\rho_d) + c_s(\rho_d)$$

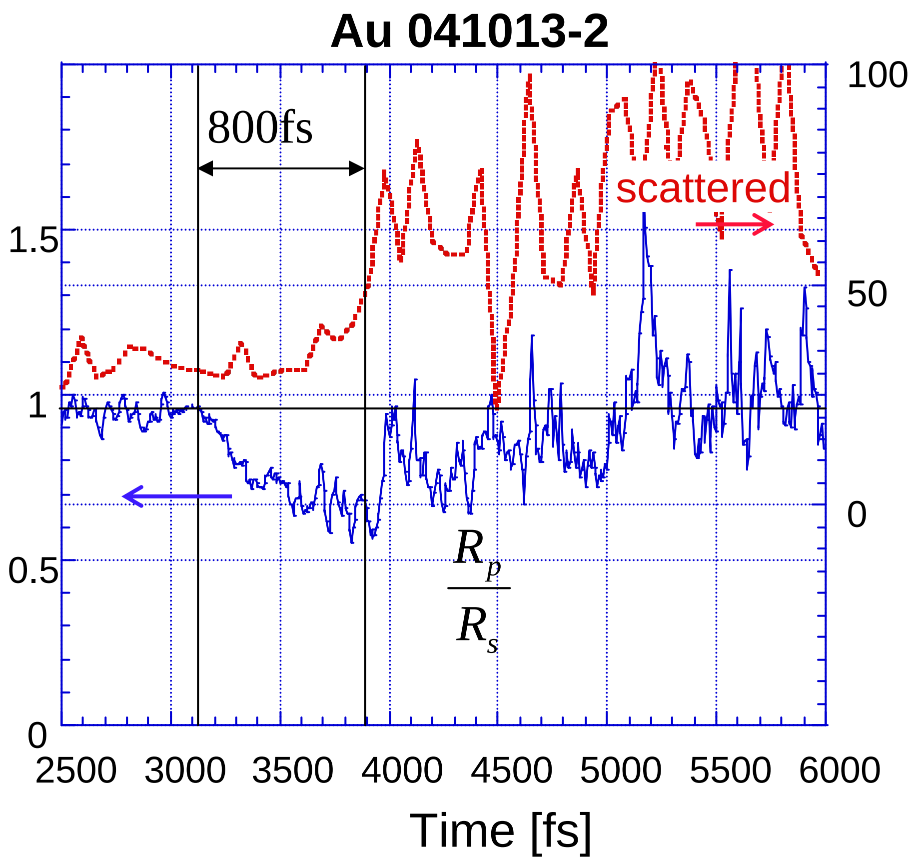
$$R(\rho) = \int_0^{\rho} d\rho' \frac{c_s(\rho')}{\rho'} \cong 3c_s(\rho)$$

$$t_d \approx \frac{x_d - x_f}{4c_s(\rho_d)}$$

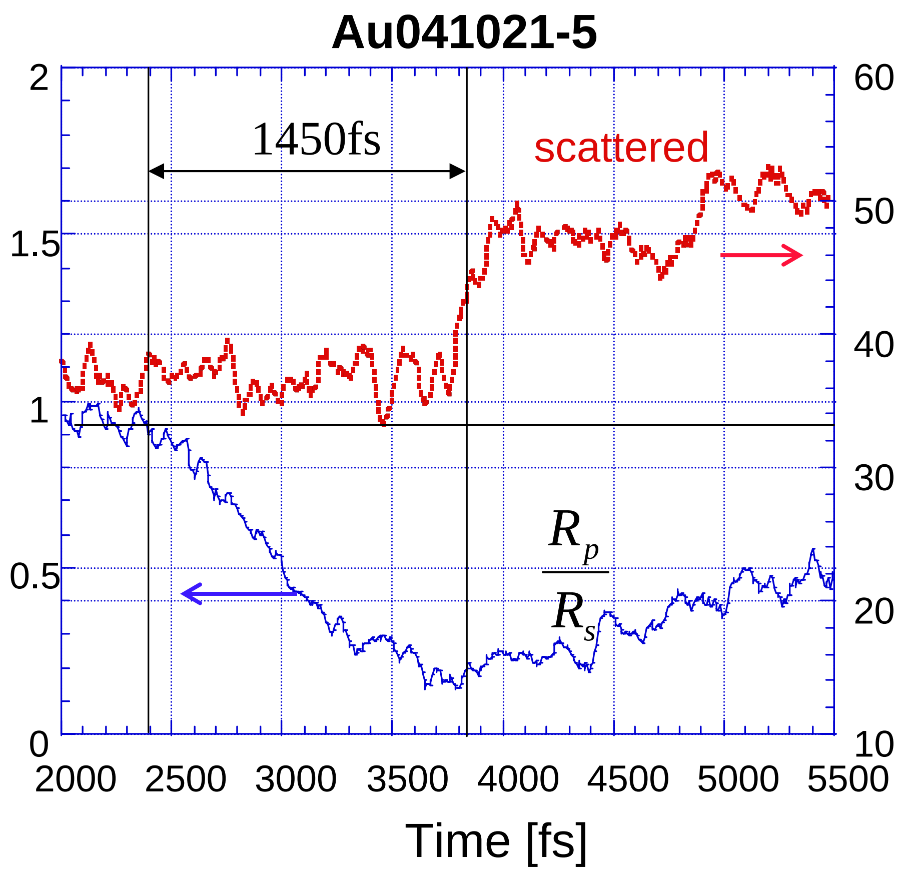


Time resolved diffuse scattering by Au targets

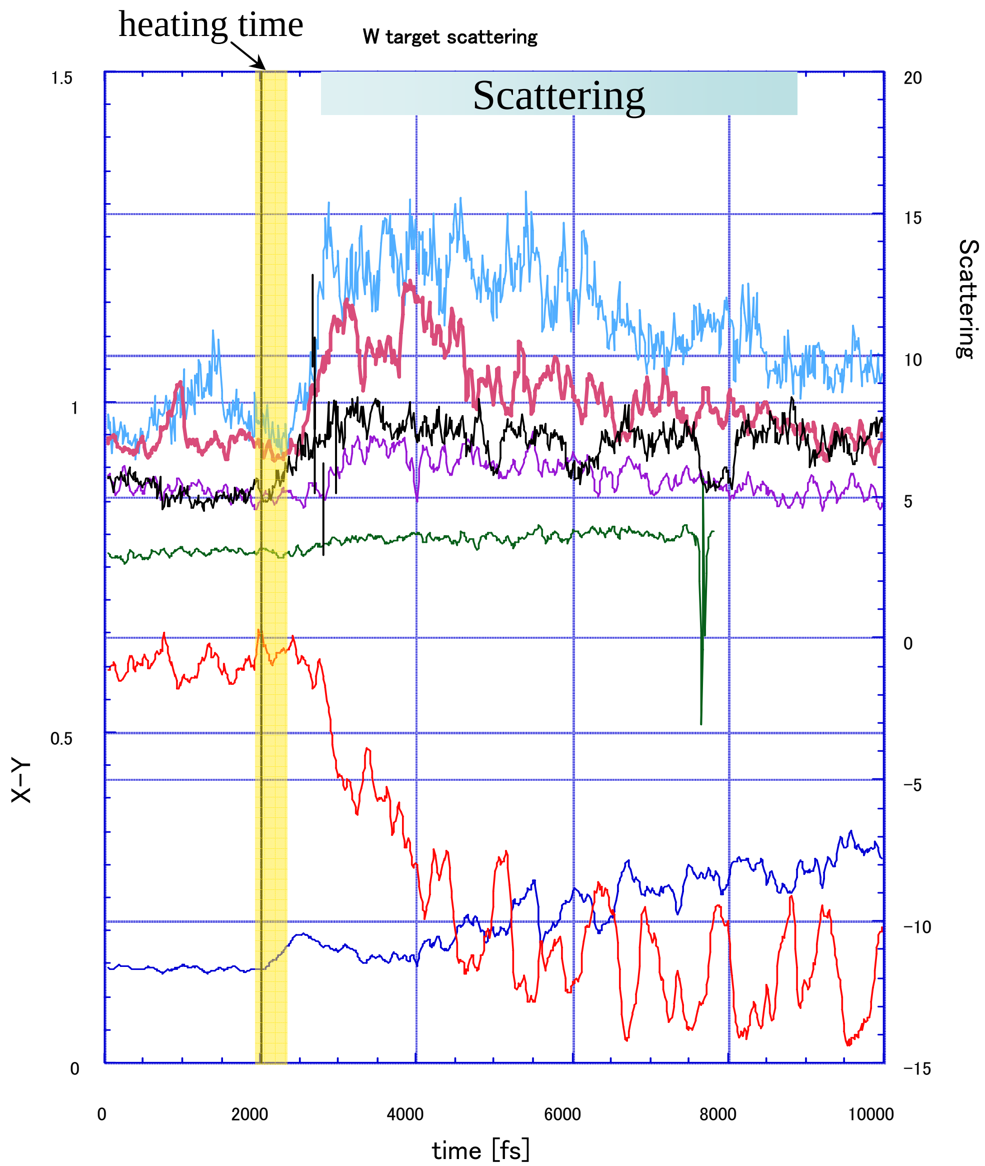
lower pump intensity



higher pump intensity



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



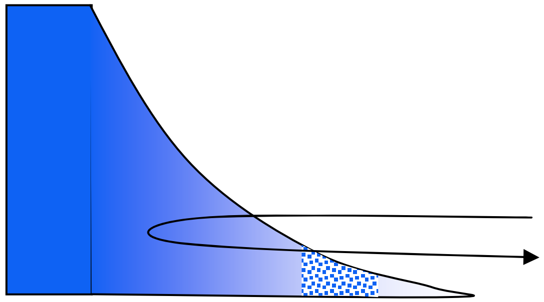
onset time of diffuse scattering

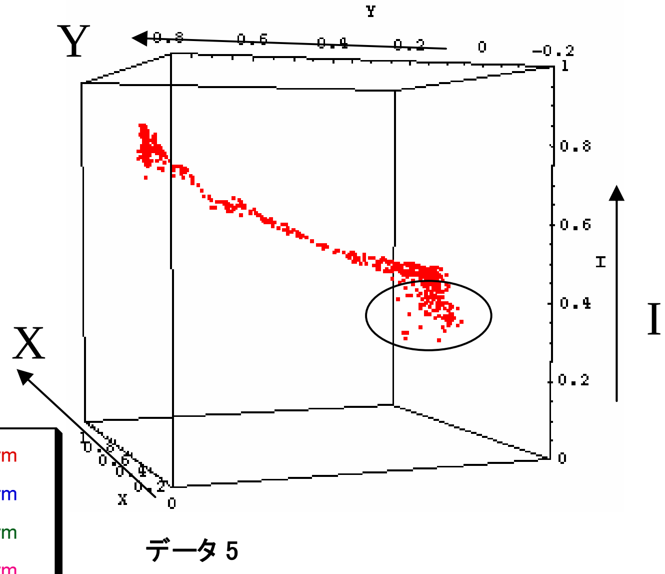
Au 0.6~2.6ps

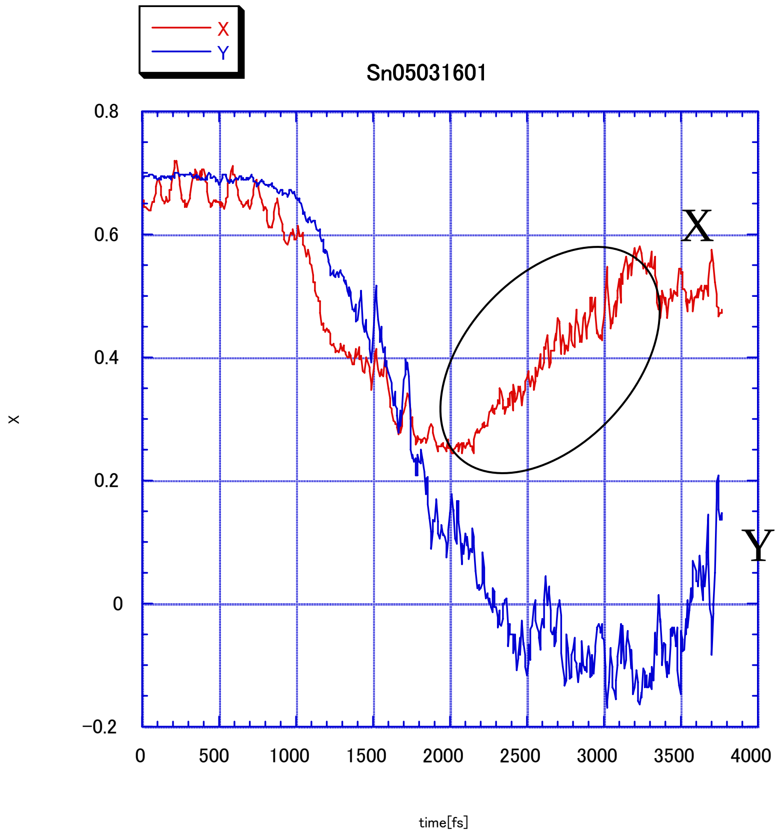
W 0.75~1ps
(with 0.3ps heating duration)

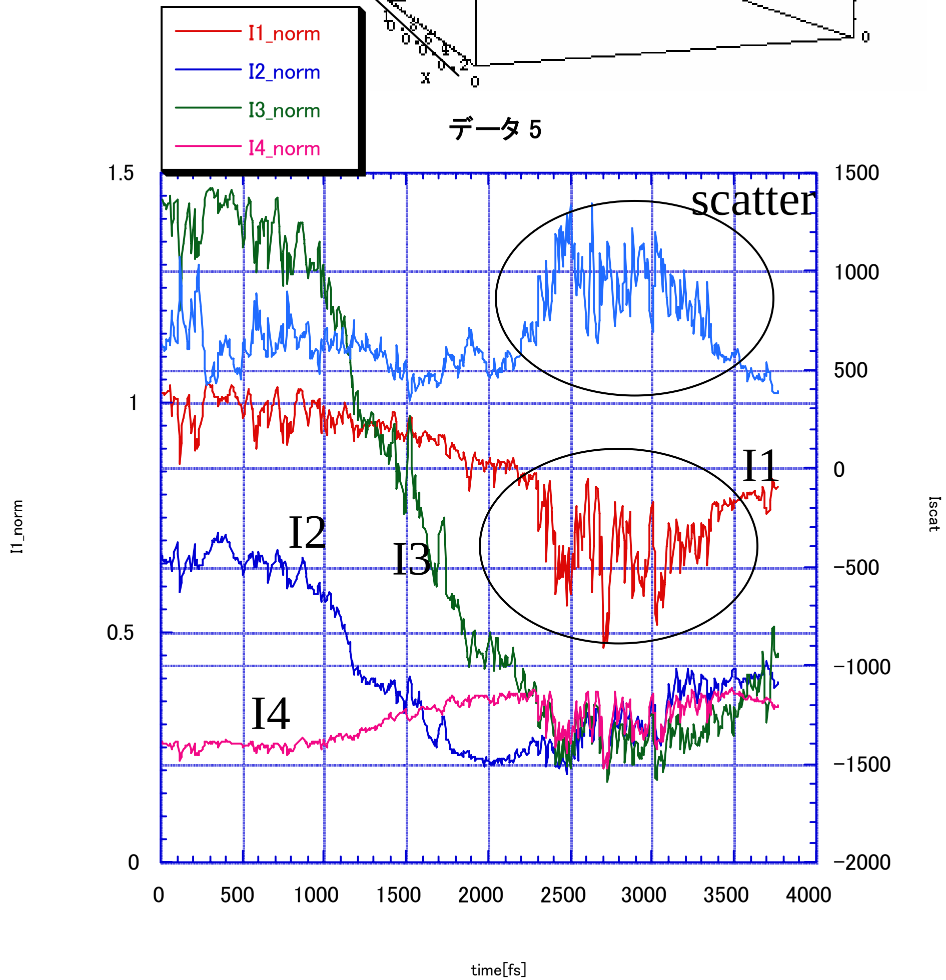
$I=10^{13}\sim10^{14} W/cm^2$

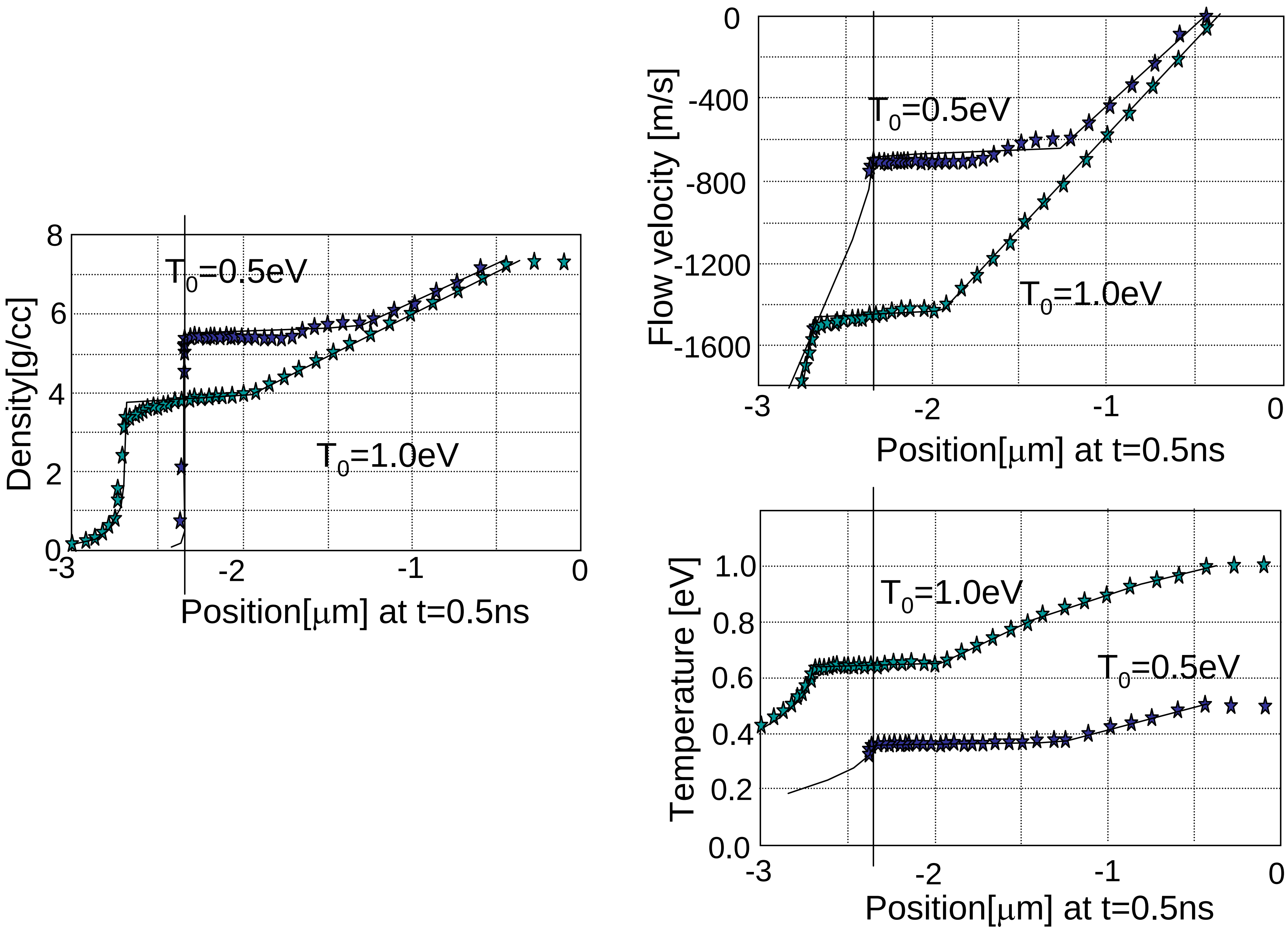
Scattering particles may have small contribution to optical constant.









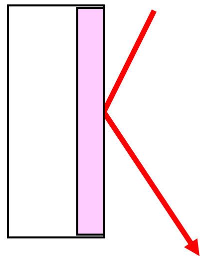
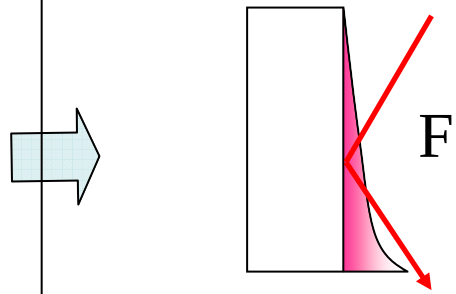


Density[g/cc]
8
6
4
2
0
-3
-2
-1
0
Position[μm] at t=0.5ns
T0=0.5eV
T0=1.0eV
Flow velocity [m/s]
0
-400
-800
-1200
-1600
-3
-2
-1
0
Position[μm] at t=0.5ns
T0=0.5eV
T0=1.0eV
Temperature [eV]
1.0
0.8
0.6
0.4
0.2
0.0
-3
-2
-1
0
Position[μm] at t=0.5ns
T0=1.0eV
T0=0.5eV

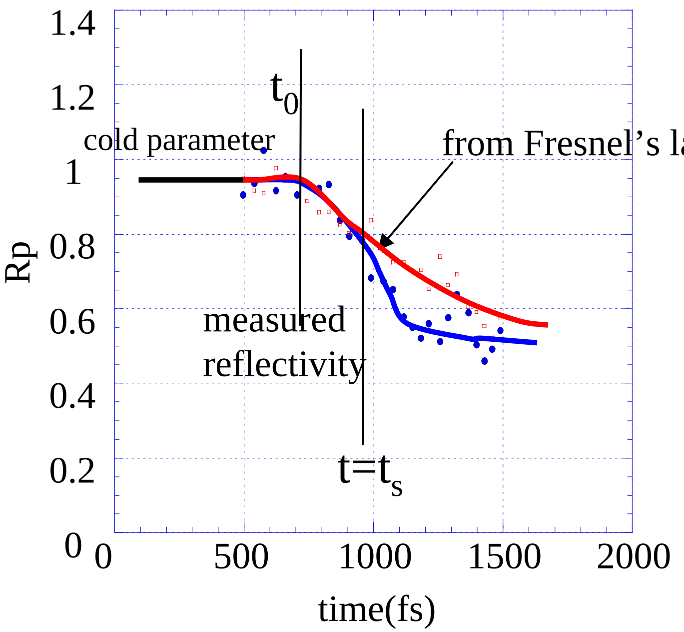
To check starting time when expansion component cannot be neglected.

measured parameters

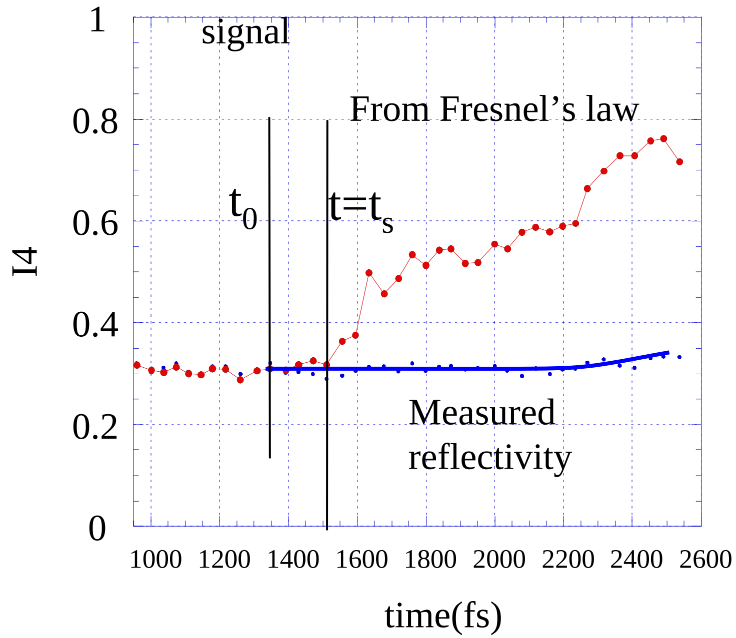
Stokes' parameters
$s_1(t)$, $s_2(t)$, $s_3(t)$,
(s_0)
F=3

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



Au shot 030221-2-2 I4 signal



Metal-Nonmetal transition

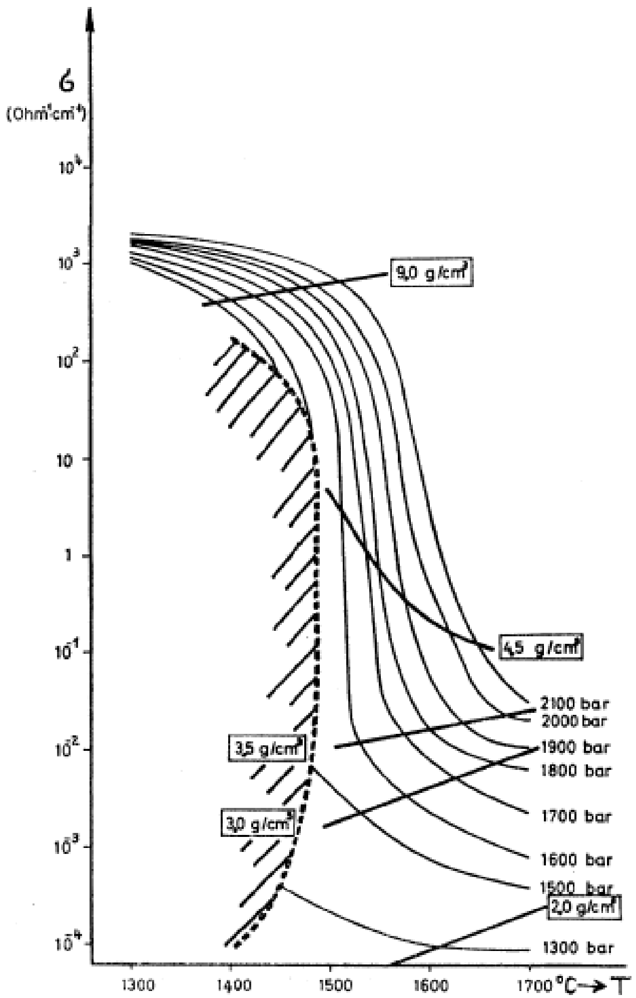


FIG. 10. Temperature dependence of the specific conductivity of mercury at constant pressures and constant densities.

F Hensel, et al., Rev. Mod. Phys., 40, p.697 (1968)

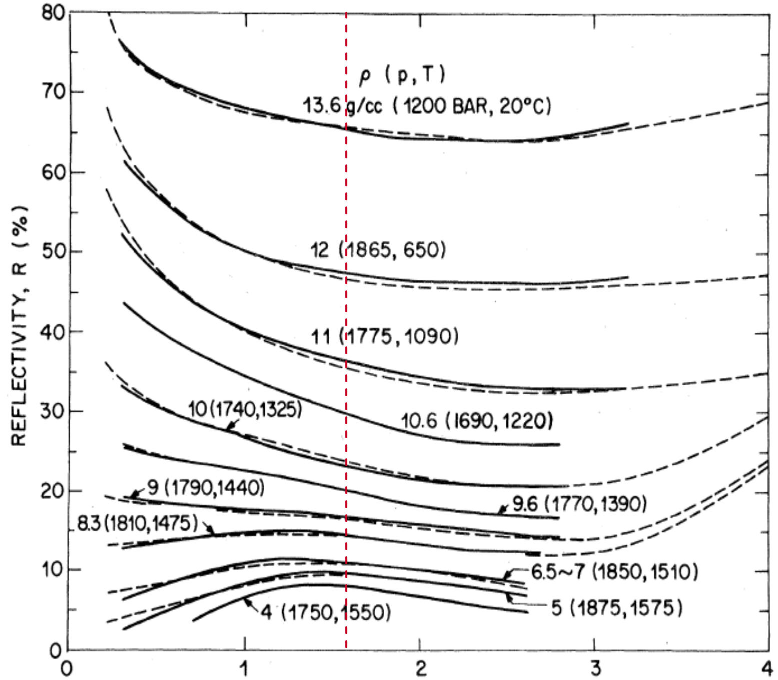


FIG. 1. Reflectivity as a function of frequency at different densities. Solid lines; experimental values. Dashed lines; calculated values by using Eqs. (1)–(3). The numbers labeled on each line are the density in g/cm^{-3}, the pressure in bar, and the temperature in °C.

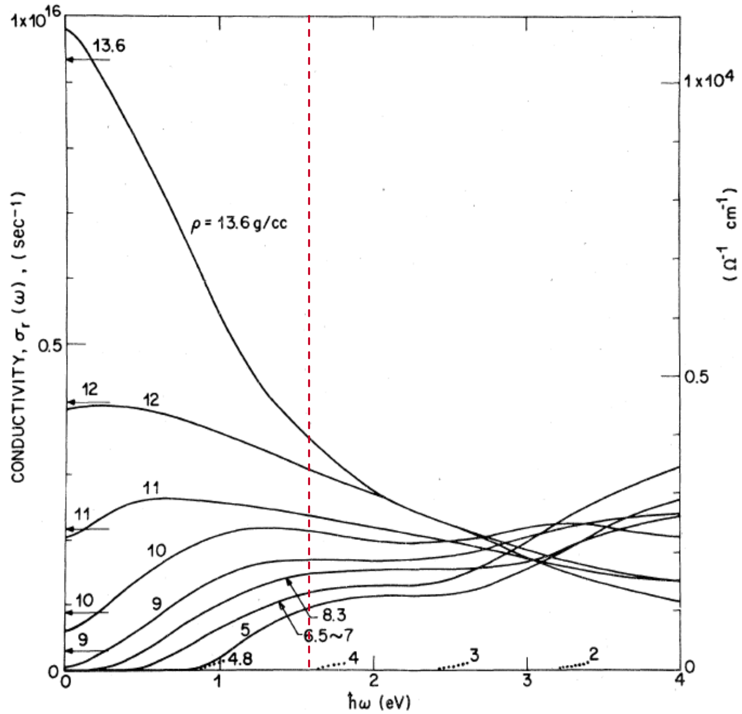
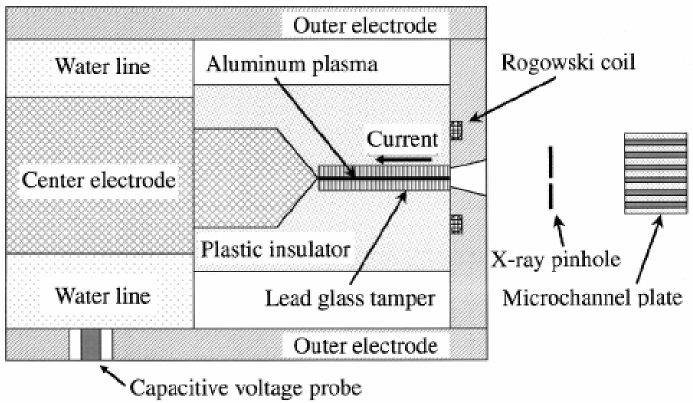
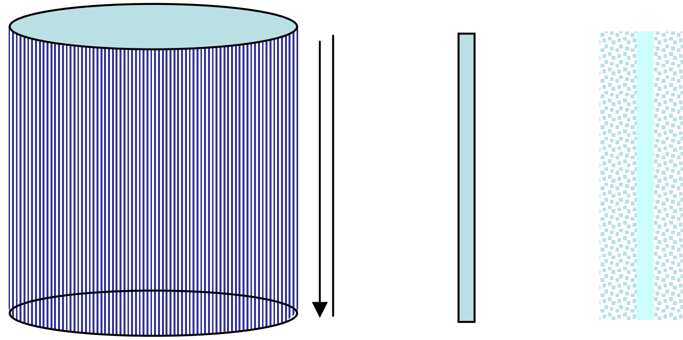
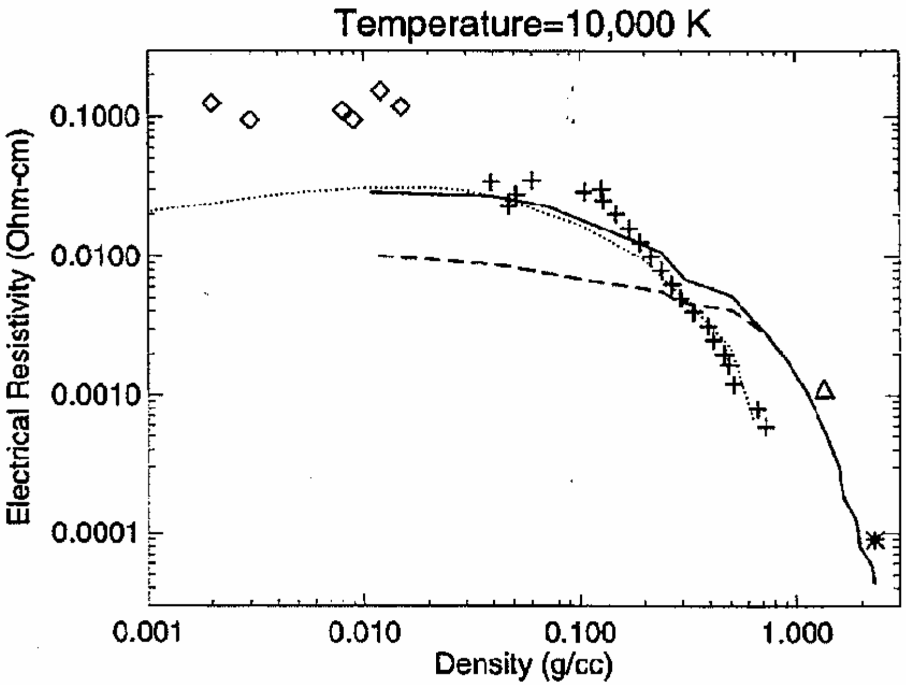


FIG. 2. Calculated conductivity by using observed reflectivity data ($\rho \geq 5$ g/cm^{-3}) and absorption data ($\rho \leq 4.8$ g/cm^{-3}) by Uchtman and Hensel, Ref. 6. We have used $\sigma_r = (c\epsilon_r^{1/2}/2\pi)K$ and $\epsilon_r^{1/2} = 3$.

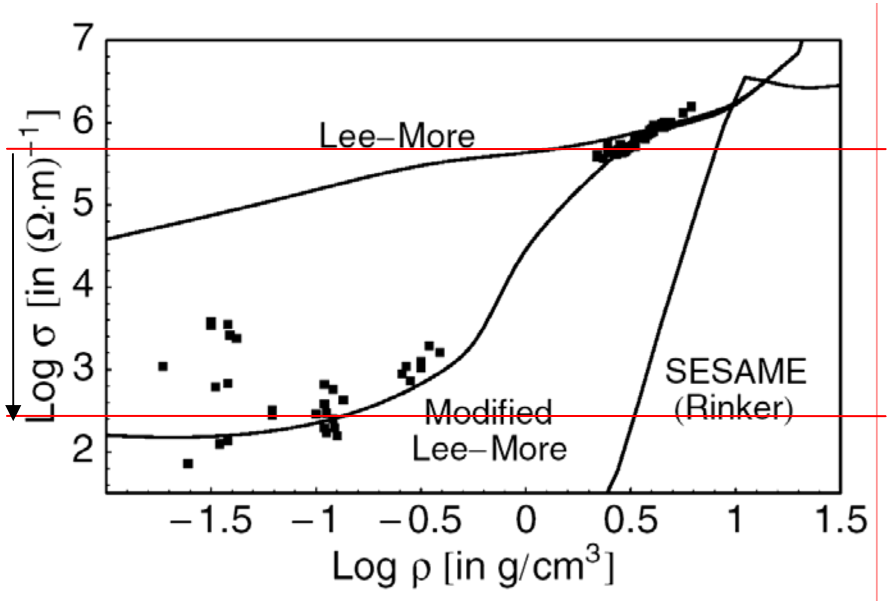


SNL Z machine





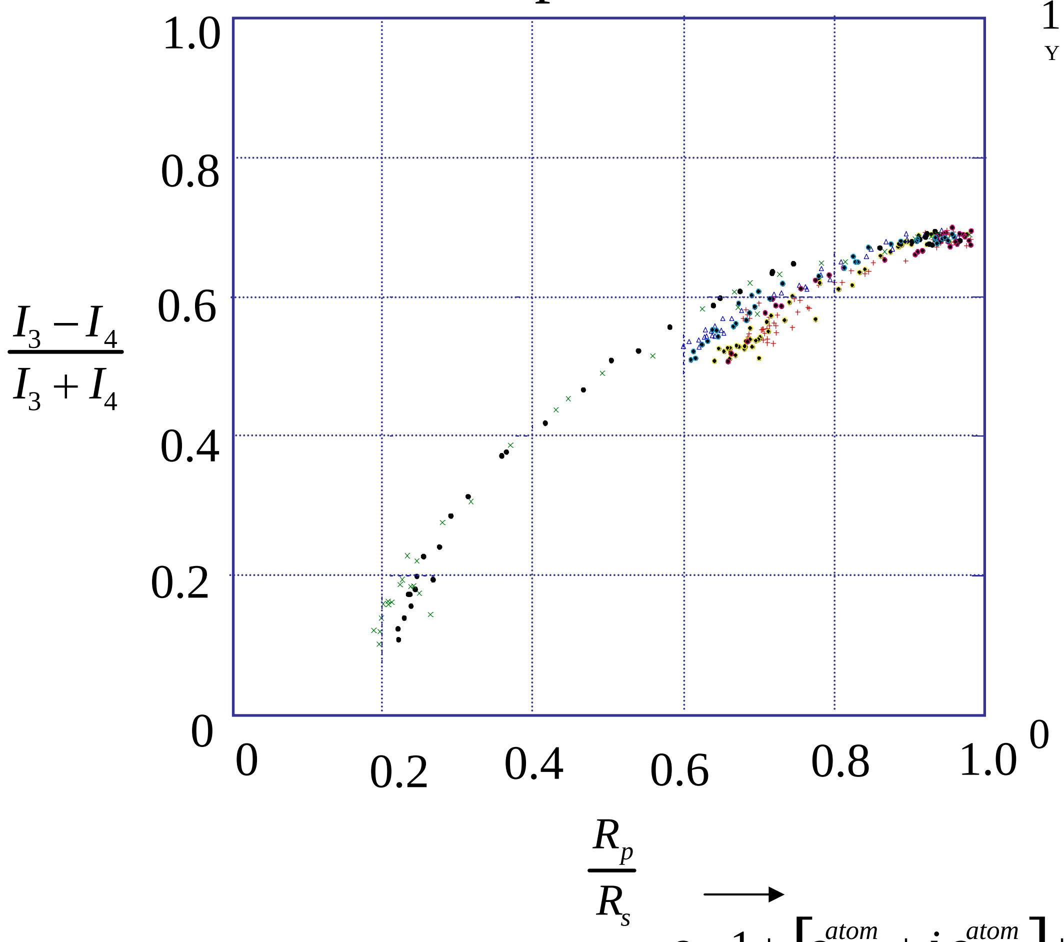
J. F. Benage, Jr., Phys. of Plasmas.(2000)



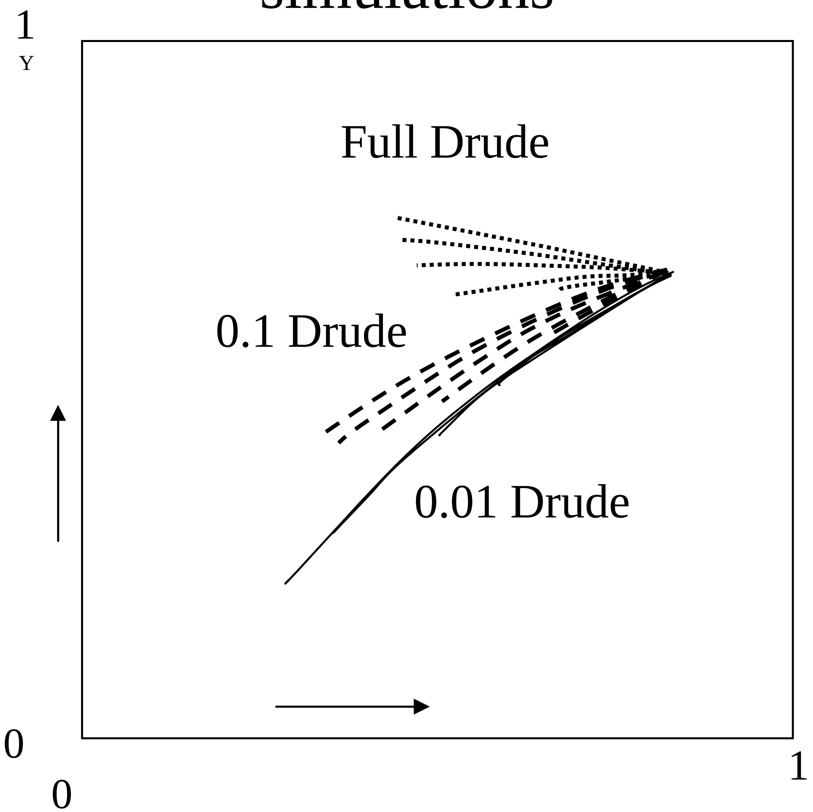
M.P. Desjarlais, **Volume 41, Issue 2-3 , Pages 267 - 270 (2001)**

· AC conductivity in Au

experiments



simulations

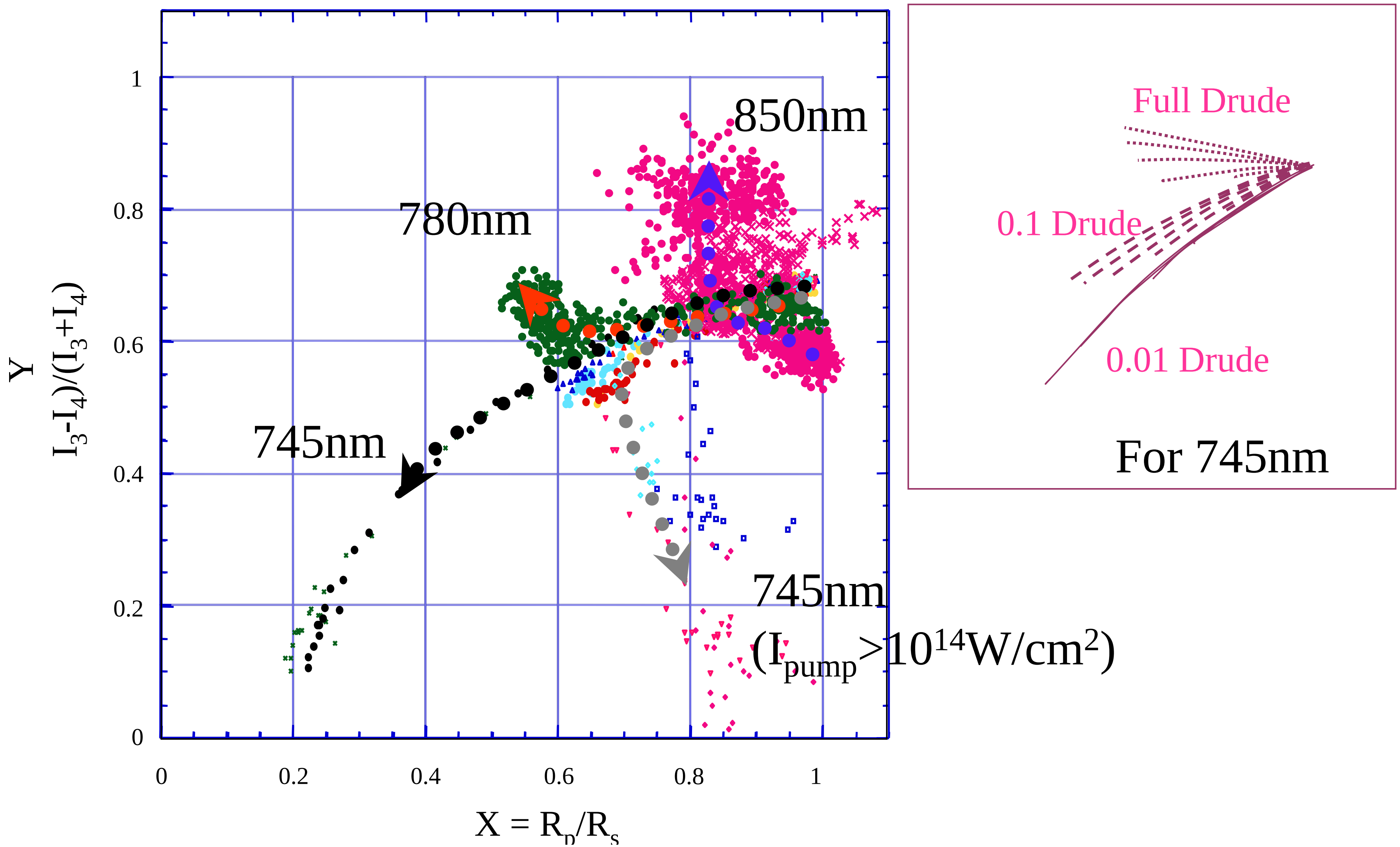


$$\varepsilon = 1 + \left[\varepsilon_r^{atom} + i\,\varepsilon_i^{atom}\right] + \left[-\frac{\omega_p^2}{\omega^2}\frac{(\omega\tau)^2}{1+(\omega\tau)^2} + i\frac{\omega_p^2}{\omega^2}\frac{\omega\tau}{1+(\omega\tau)^2}\right]^{free-electron}$$

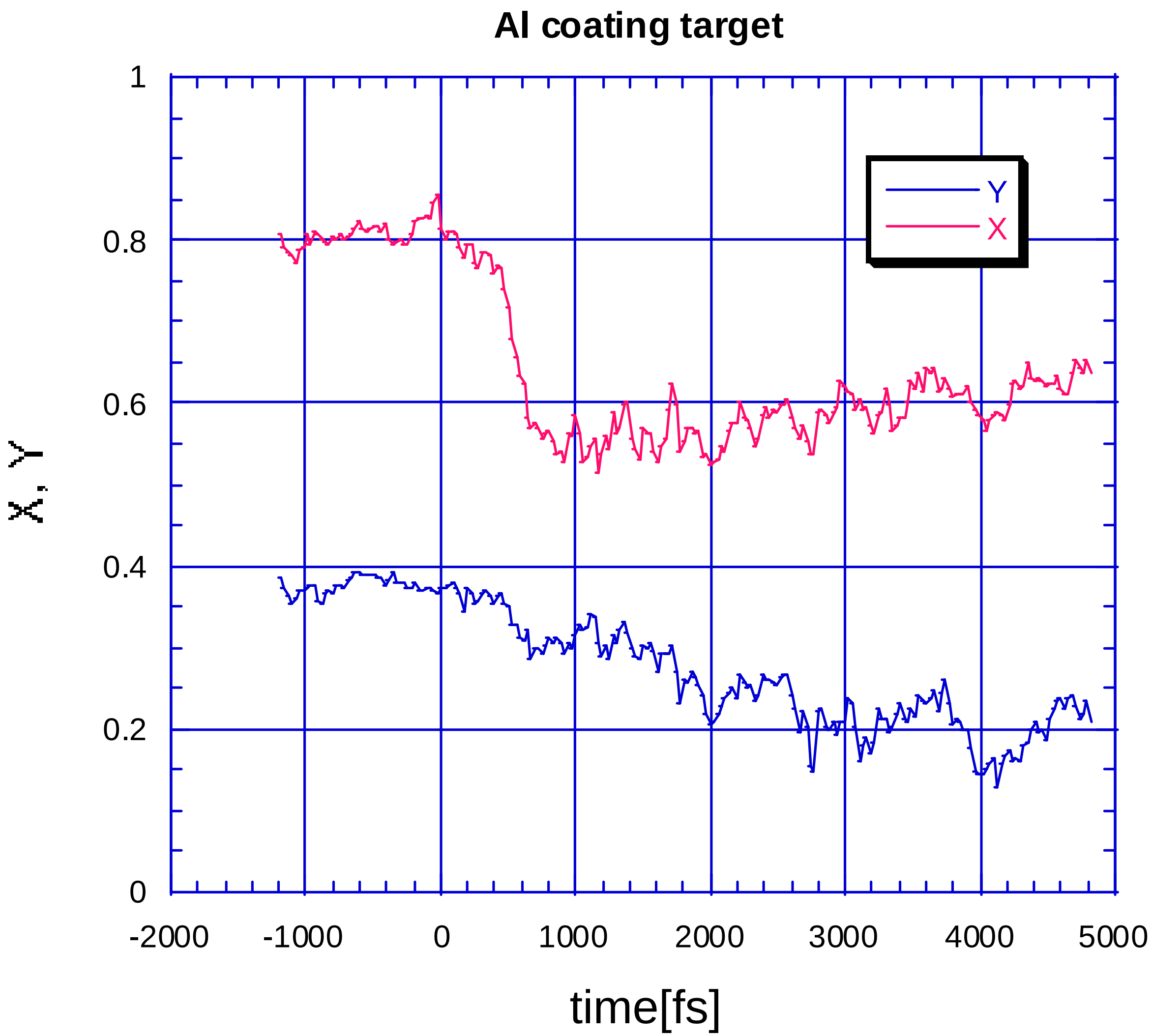
Lorentz-Lorenz model Drude model

Multi frequency probe of warm dense Au plasma

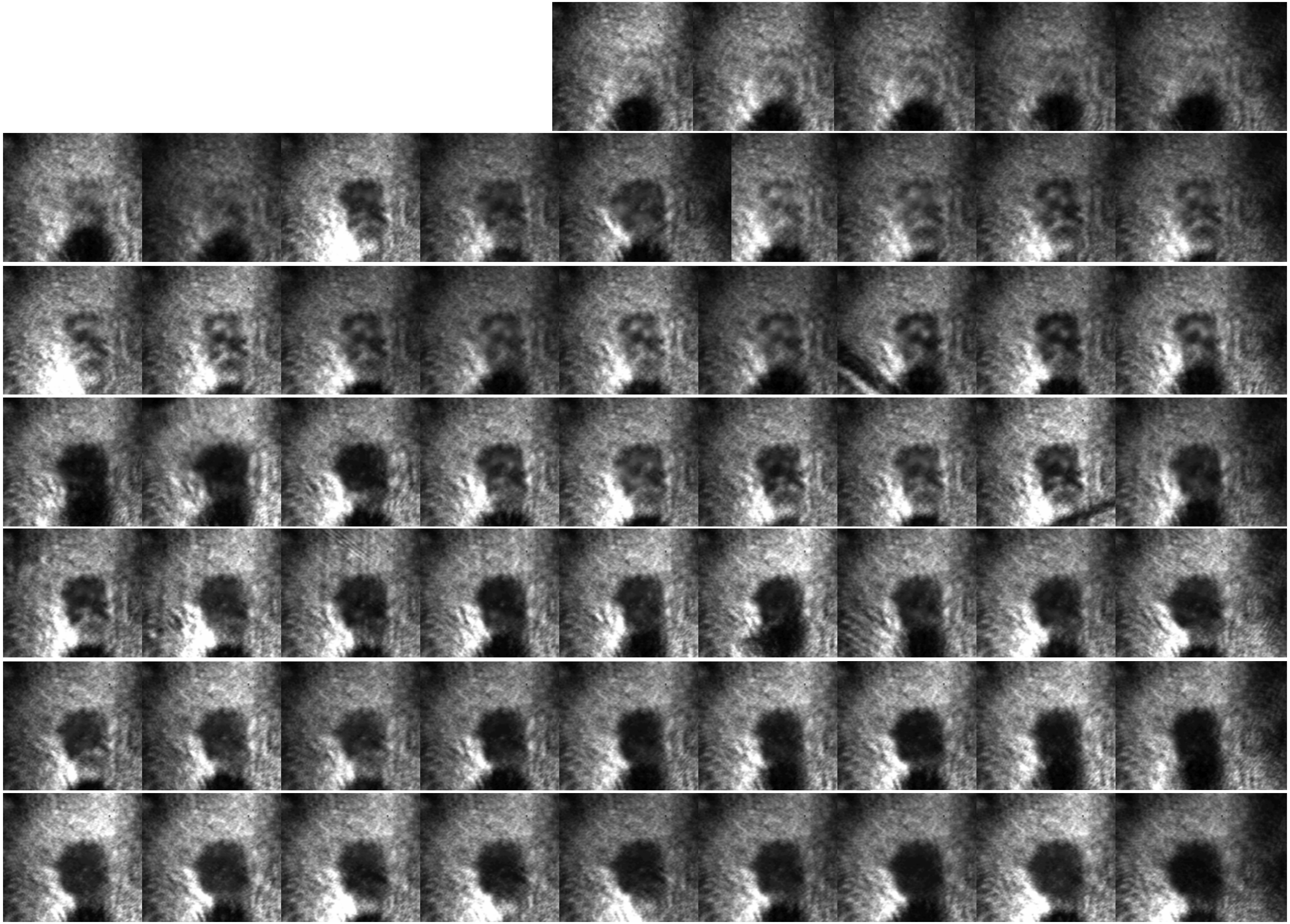
expansion=>r_p decreases, -> both of X,Y decrease
Y increase at 850nm=> change of δ should be latge

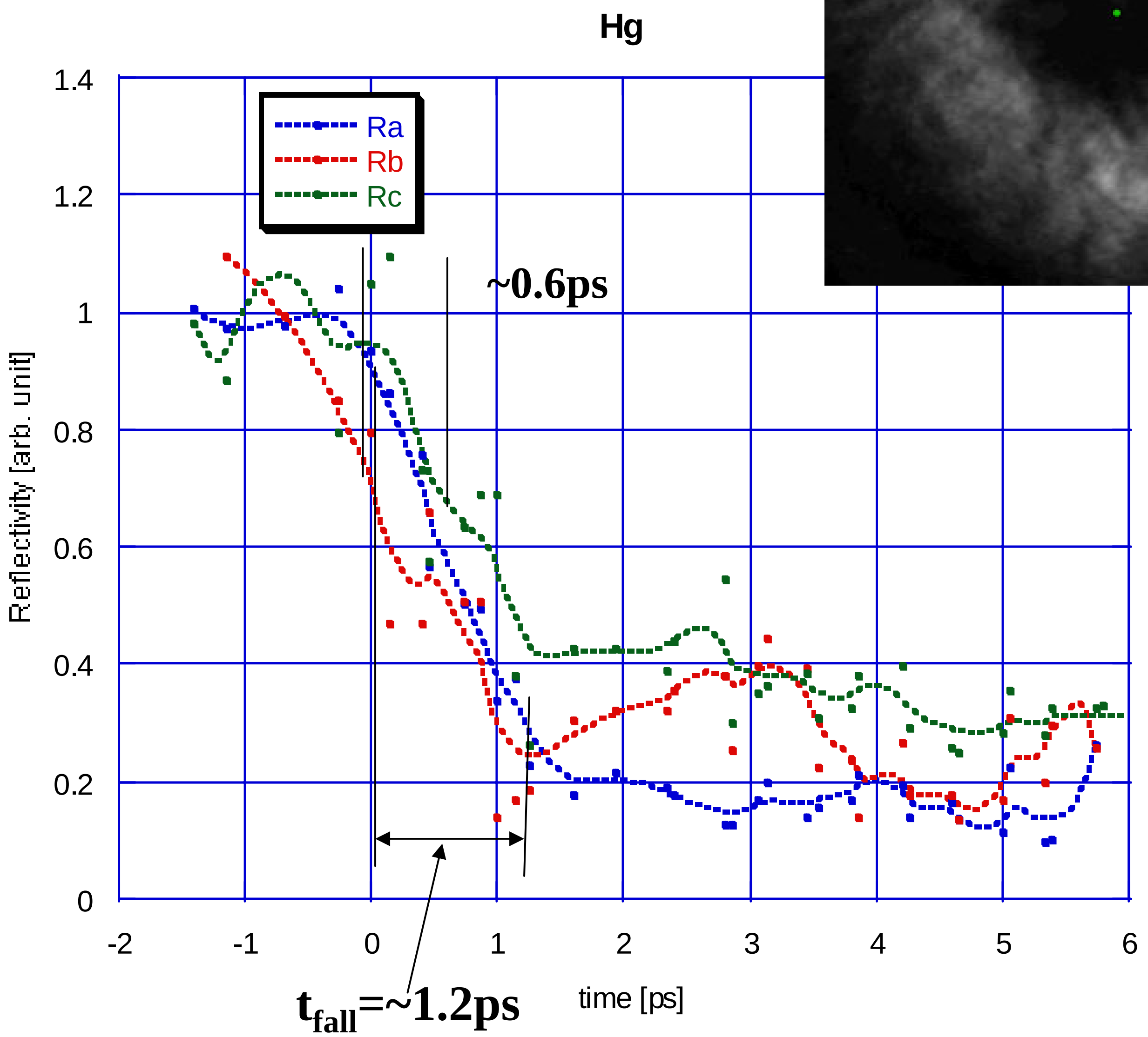


2D pump-probe image observations

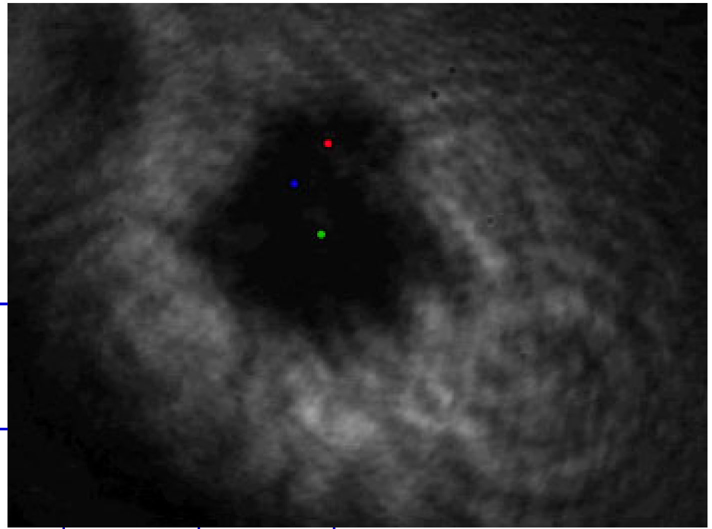


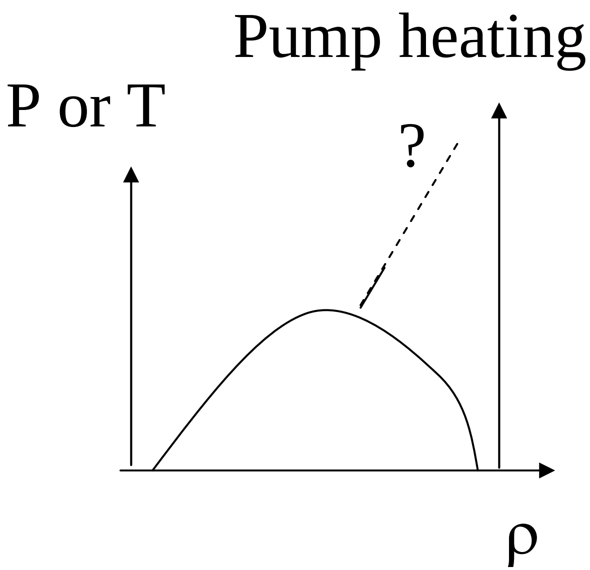
Al coating target
1
0.8
0.6
0.4
0.2
0
X, Y
Y
X
-2000
-1000
0
1000
2000
3000
4000
5000
time[fs]



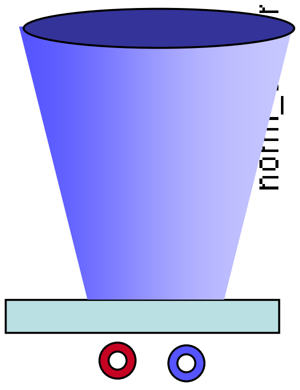


Hg
Ra
Rb
Rc
~0.6ps
Reflectivity [arb. unit]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2
-1
0
1
2
3
4
5
6
time [ps]
t_{fall}=~1.2ps

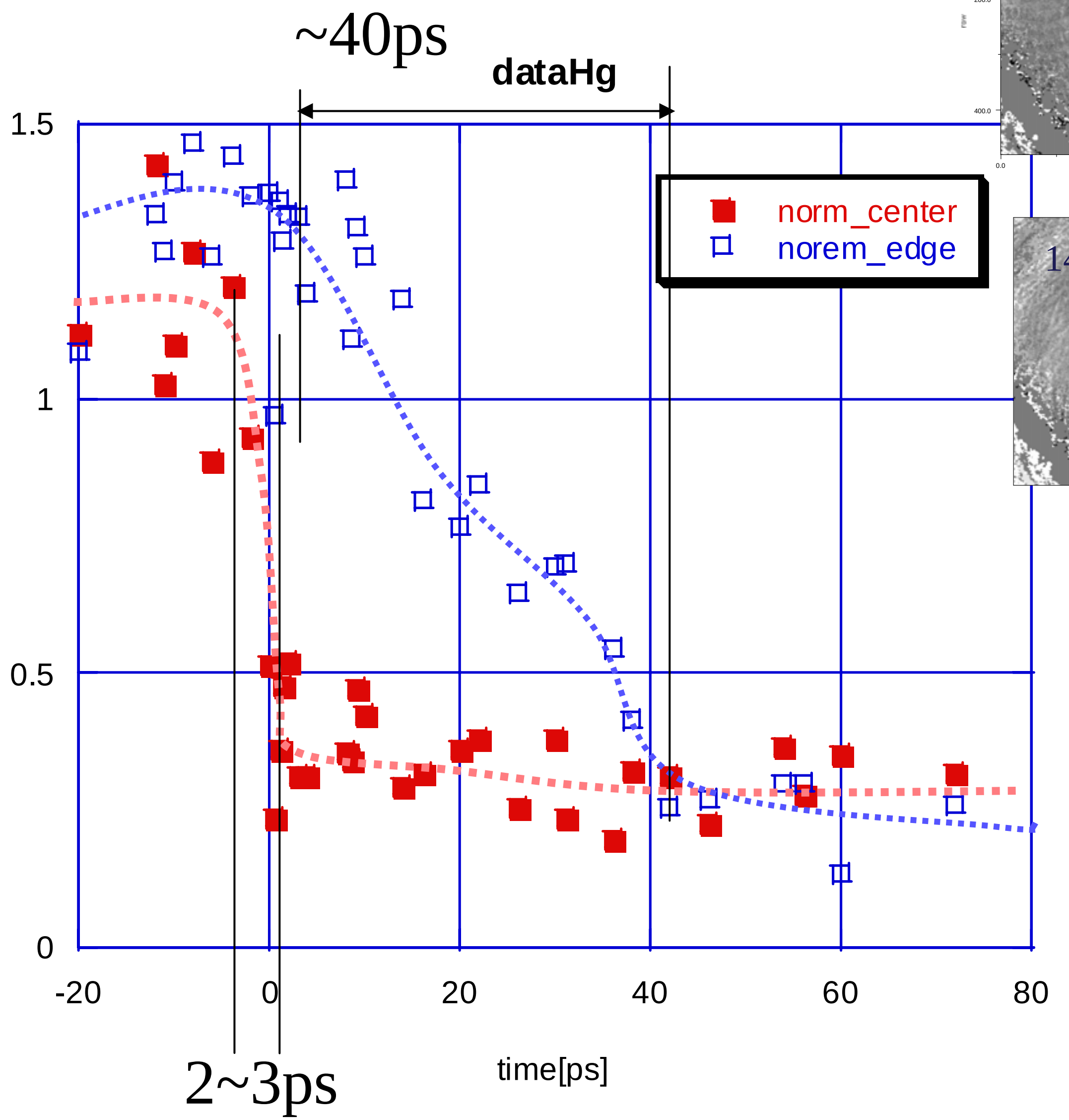


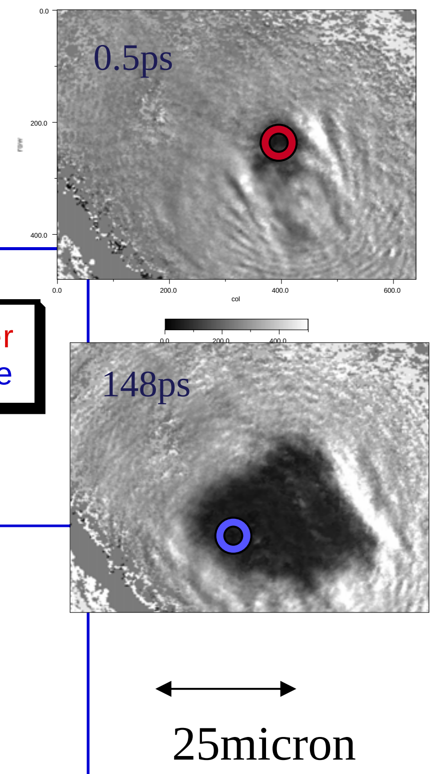


Pump heating
P or T
?
ρ



?


~40ps
dataHg
1.5
1
0.5
0
-20
0
20
40
60
80
time[ps]
norm_center
norem_edge
2~3ps


0.5ps
148ps
25micron

We observed bright fringe in Hg illumination spot.

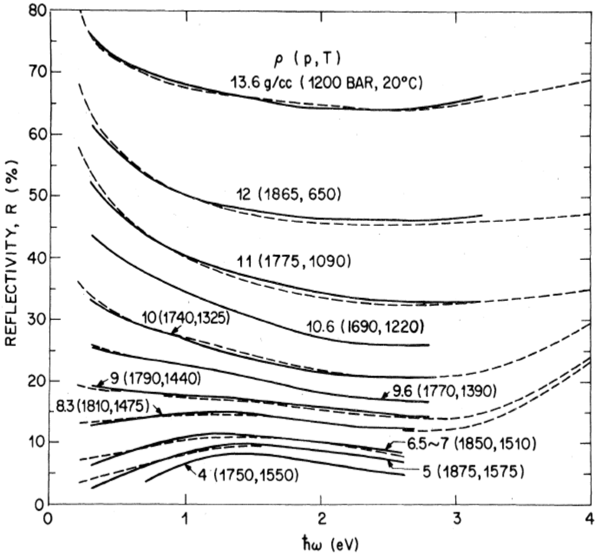
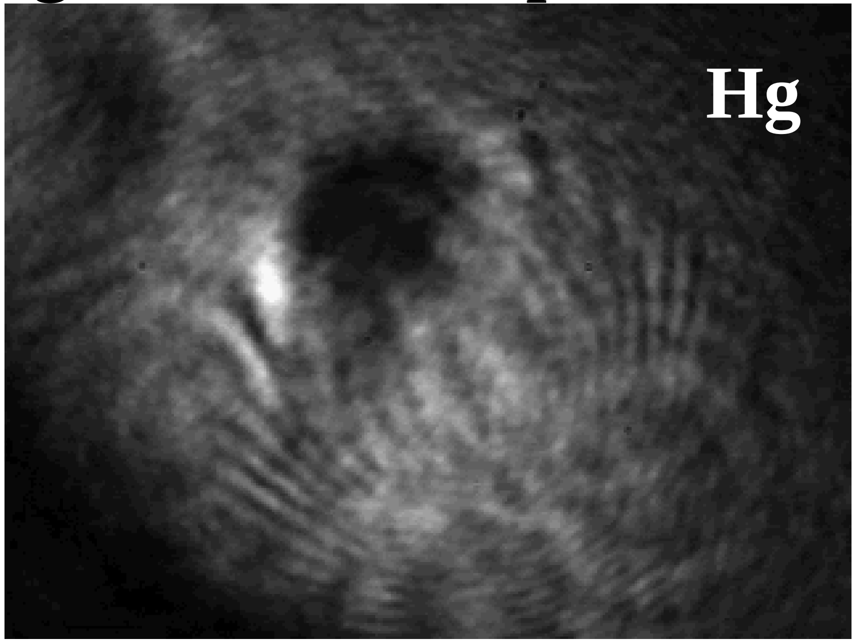
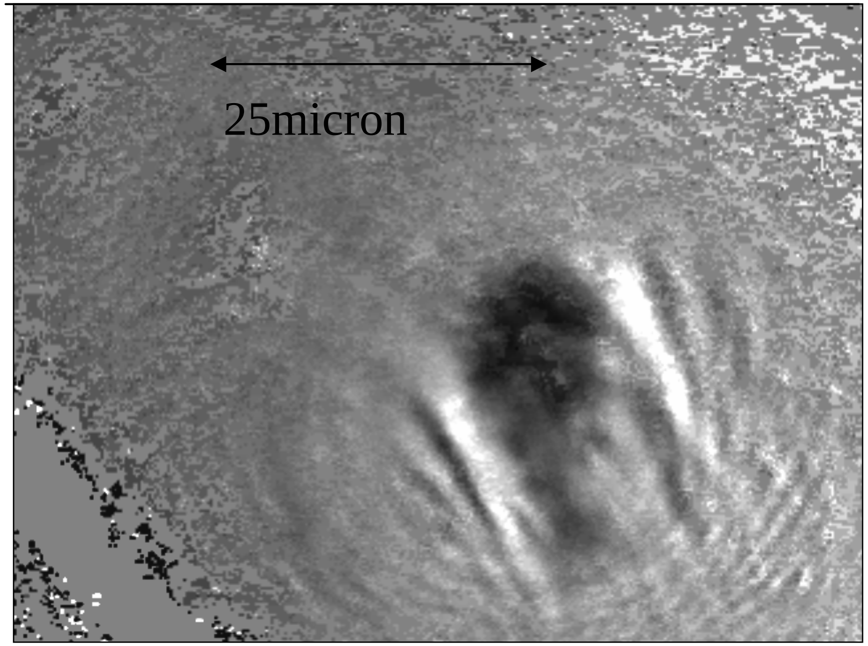


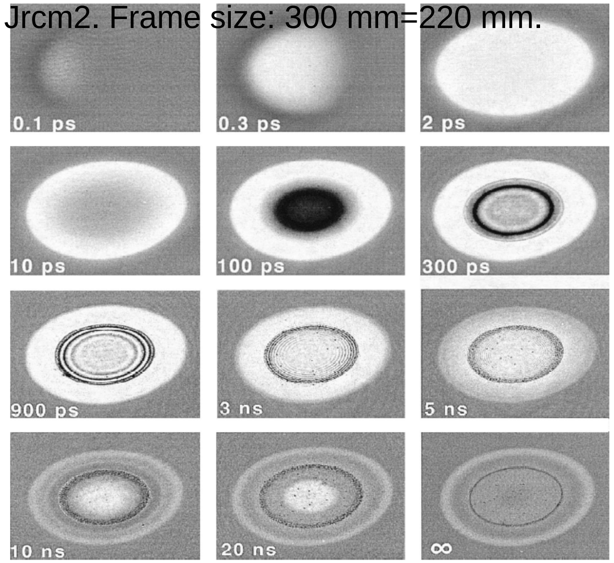
FIG. 1. Reflectivity as a function of frequency at different densities. Solid lines; experimental values. Dashed lines; calculated values by using Eqs. (1)-(3). The numbers labeled on each line are the density in g/cm^{-3}, the pressure in bar, and the temperature in °C.

F Hensel, et al., Rev. Mod. Phys., 40, p.697 (1968)





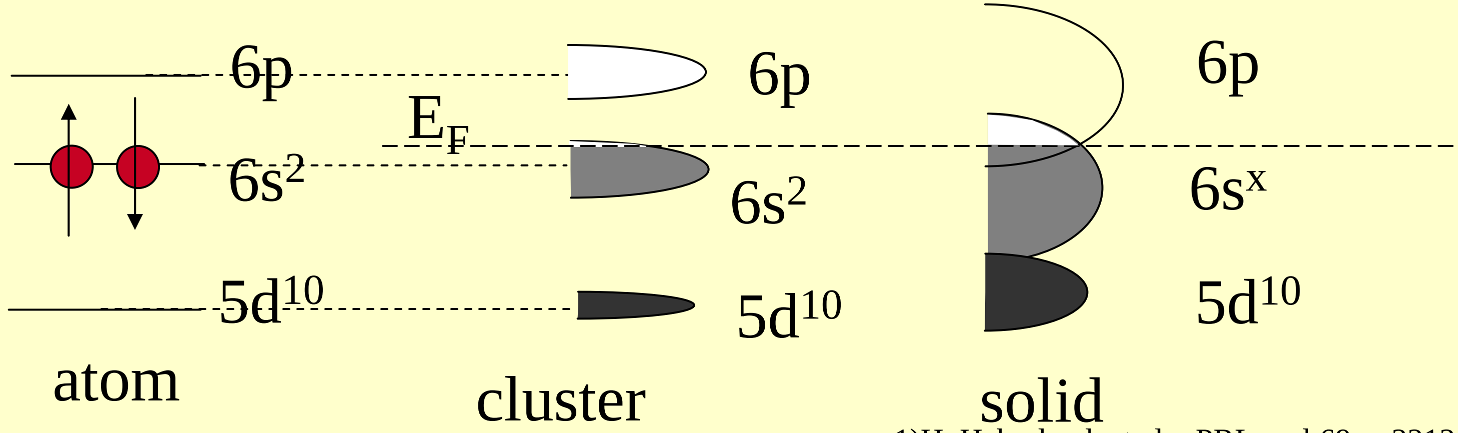
Snapshots with 100-fs time resolution. Si111.excited with 0.47 Jrcm2. Frame size: 300 mm=220 mm.



D. von der Linde, Applied Surface Science 154–155(2000), p.1–10

Metal-Nonmetal transition

Hg model($5d^{10}\ 6s^2$)[1)]

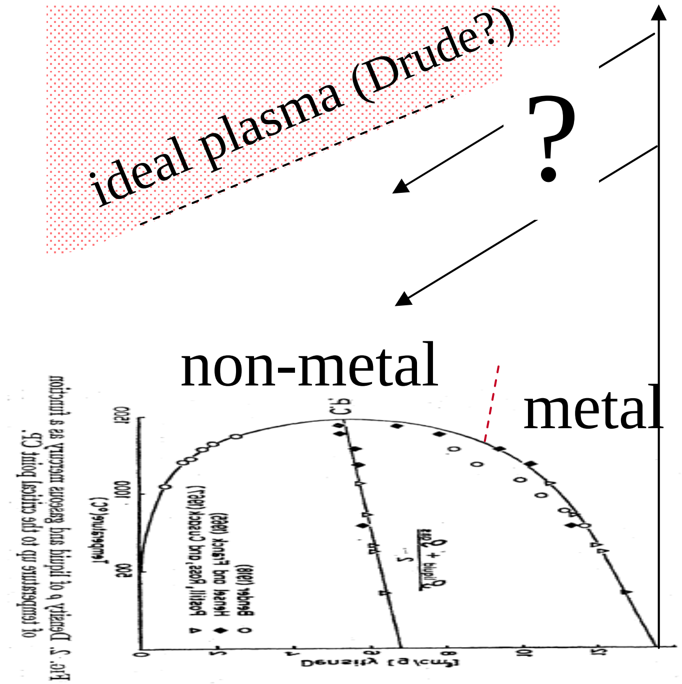


1)H. Haberland, et al., PRL, vol.69, p.3212

Hg model?

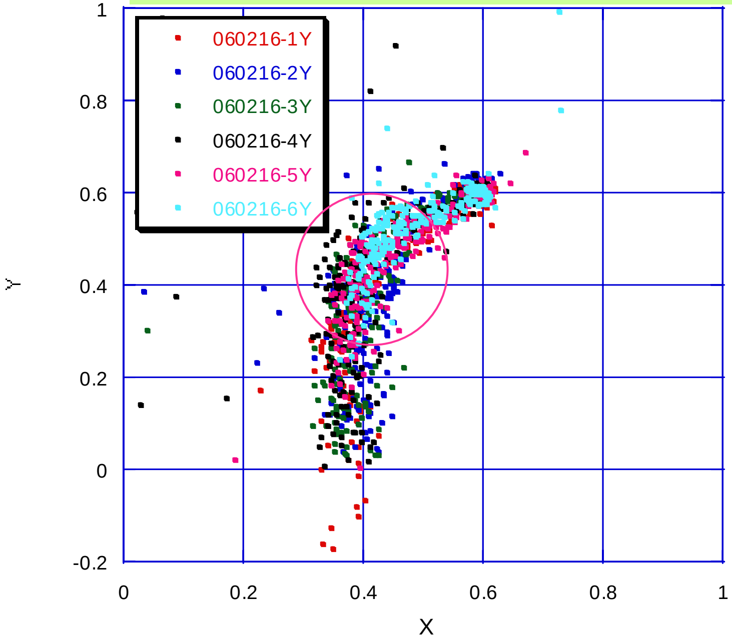
???

Cd: $4d^{10}\ 5s^2$	Au: $5d^{10}\ 6s$
Zn: $3d^{10}\ 4s^2$	W: $5d^4\ 6s^2$
	Sn: $4d^{10}\ 5s^2 5p^2$
	Mo: $4d^5\ 5s$
	Cu: $3d^{10}\ 4s$

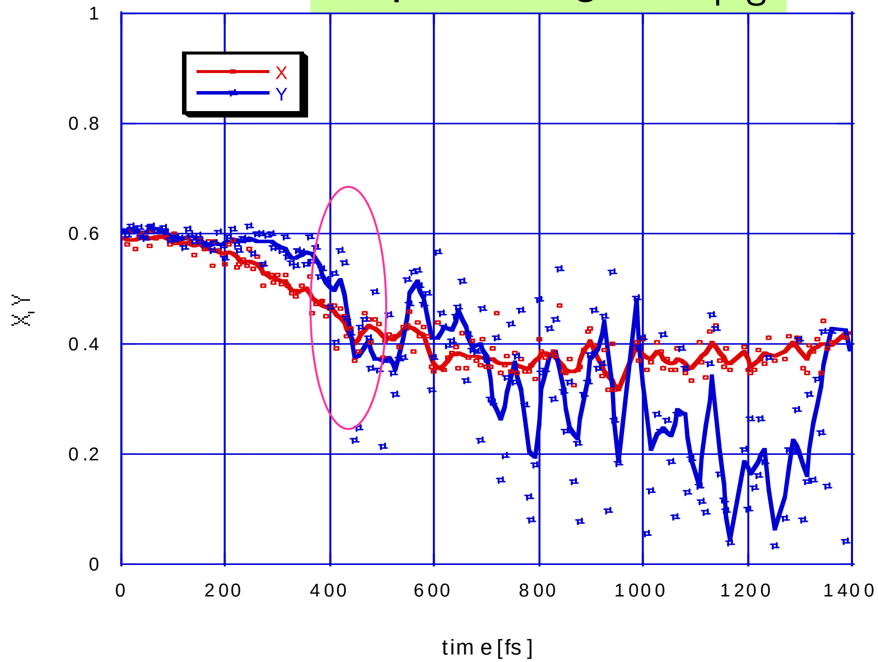


Zn

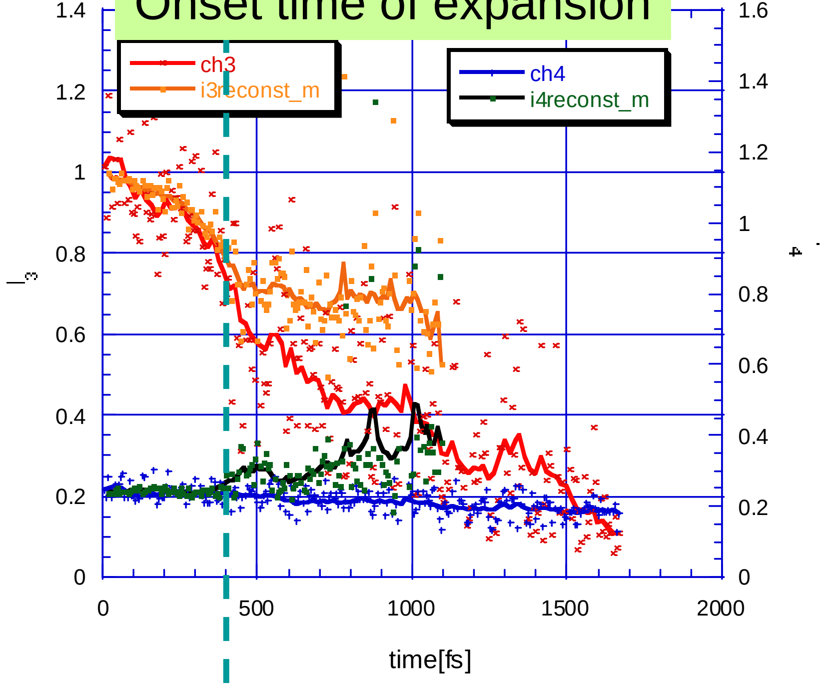
unique trajectory in X-Y plot

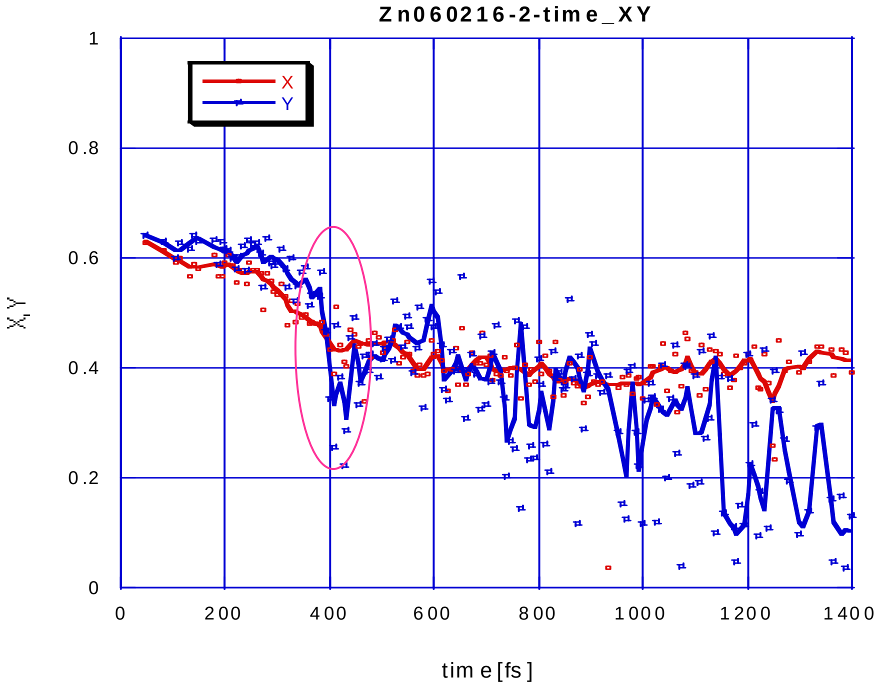


Rapid change in δ_{P-S}

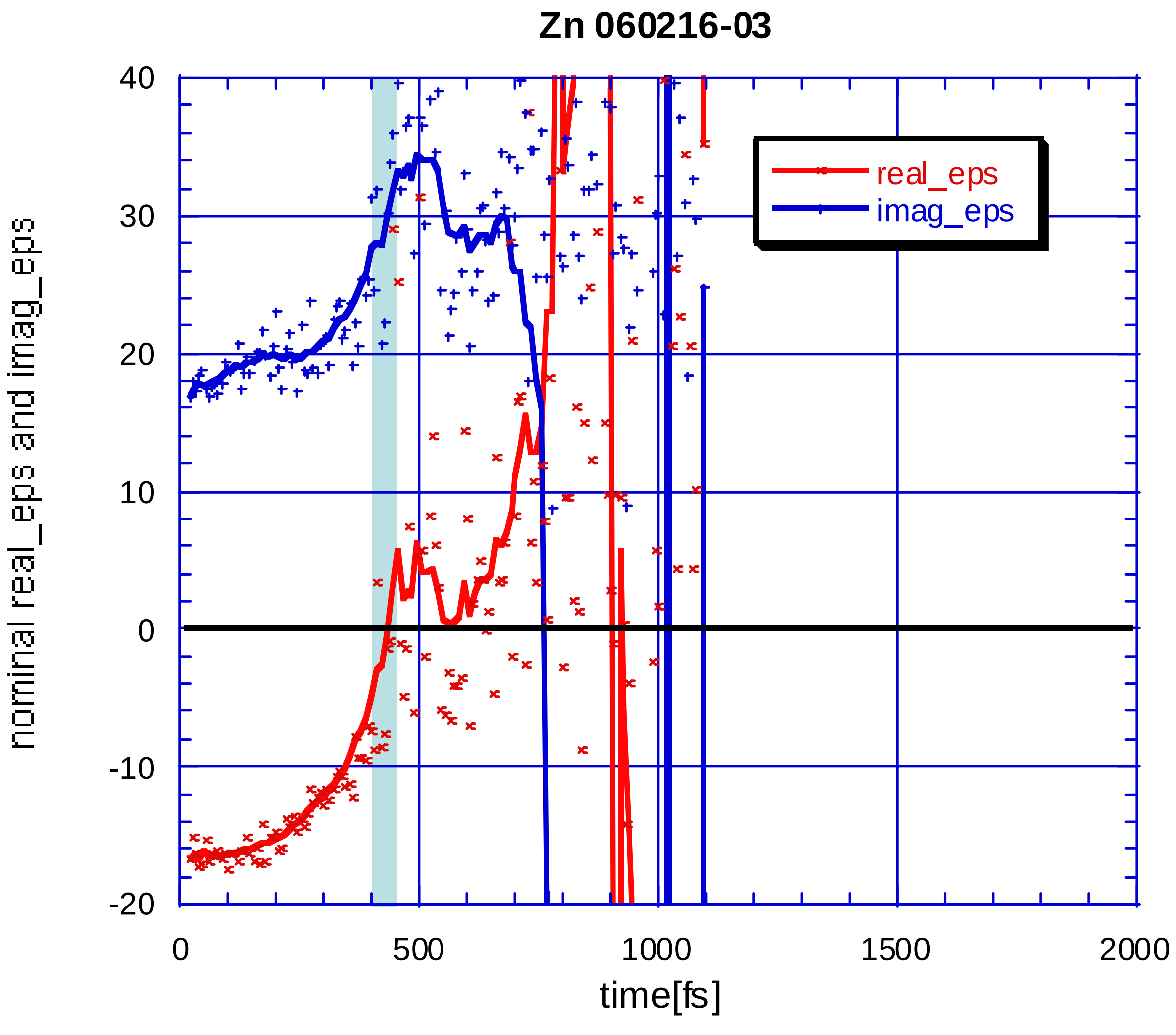


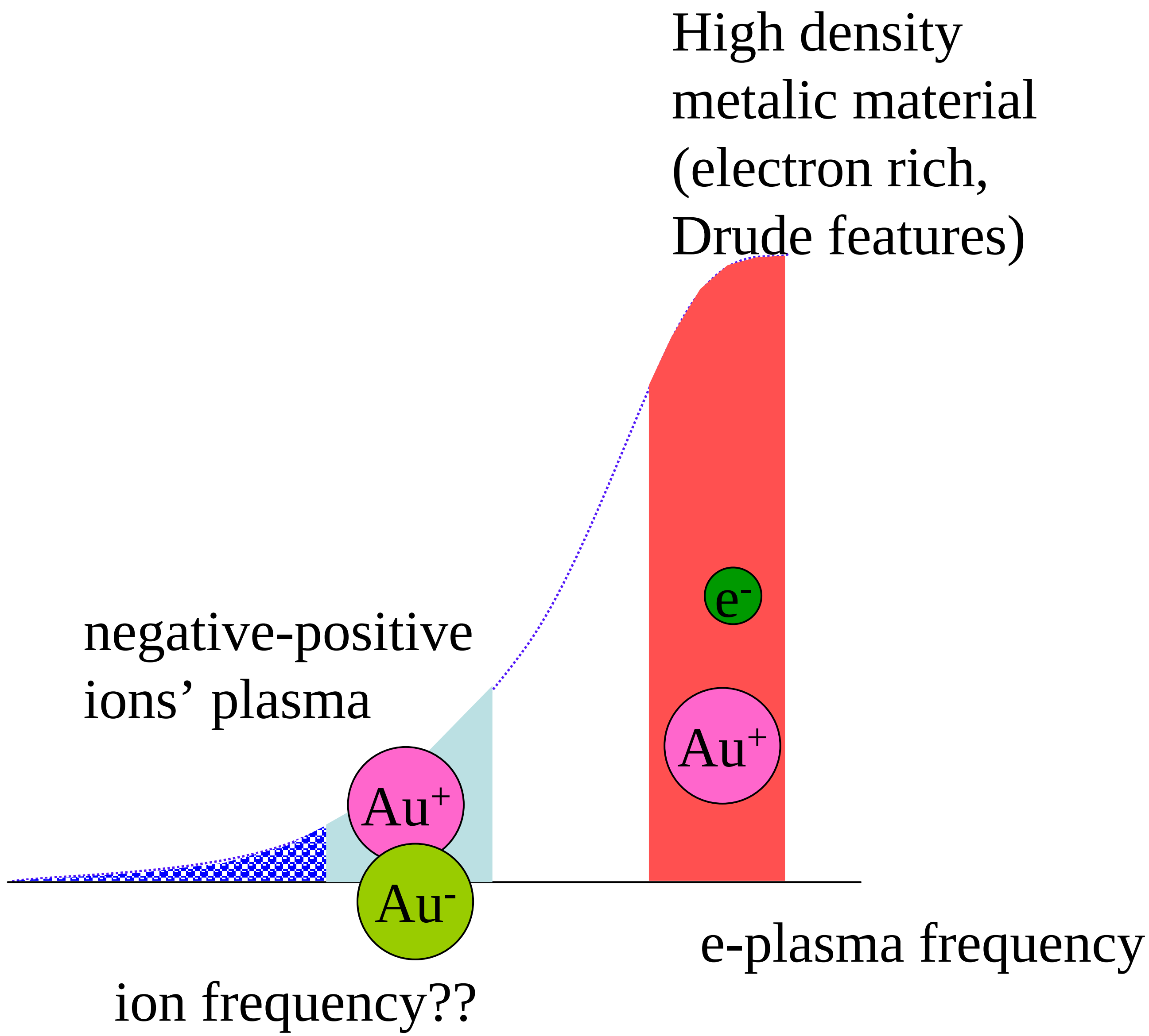
Onset time of expansion



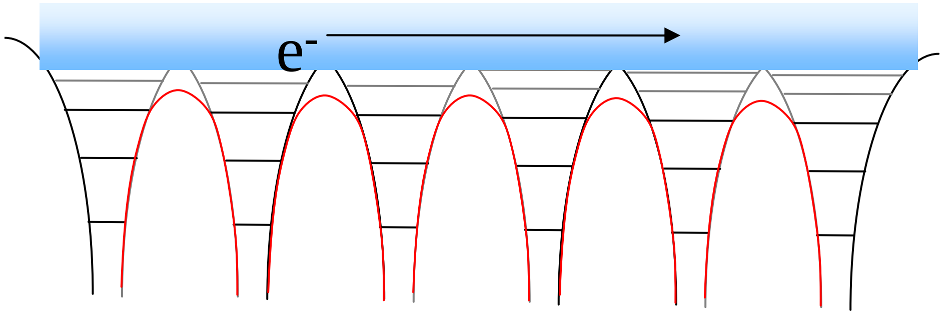


High temperature Zn goes to non-metal condition.

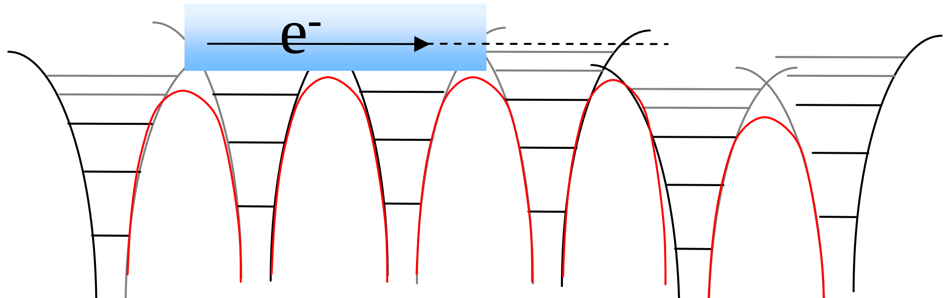




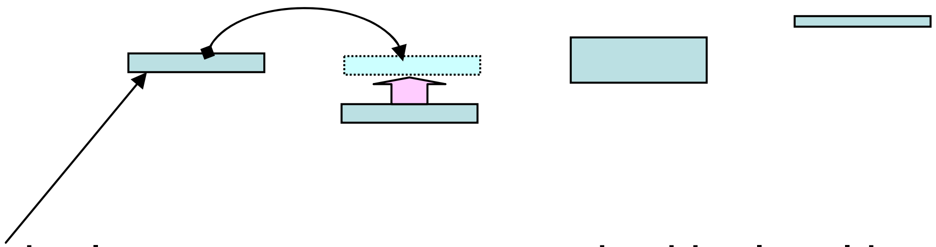
High density
metalic material
(electron rich,
Drude features)
negative-positive
ions' plasma
e^-
Au^+
Au^+
Au^-
e-plasma frequency
ion frequency??



band in ordered solid



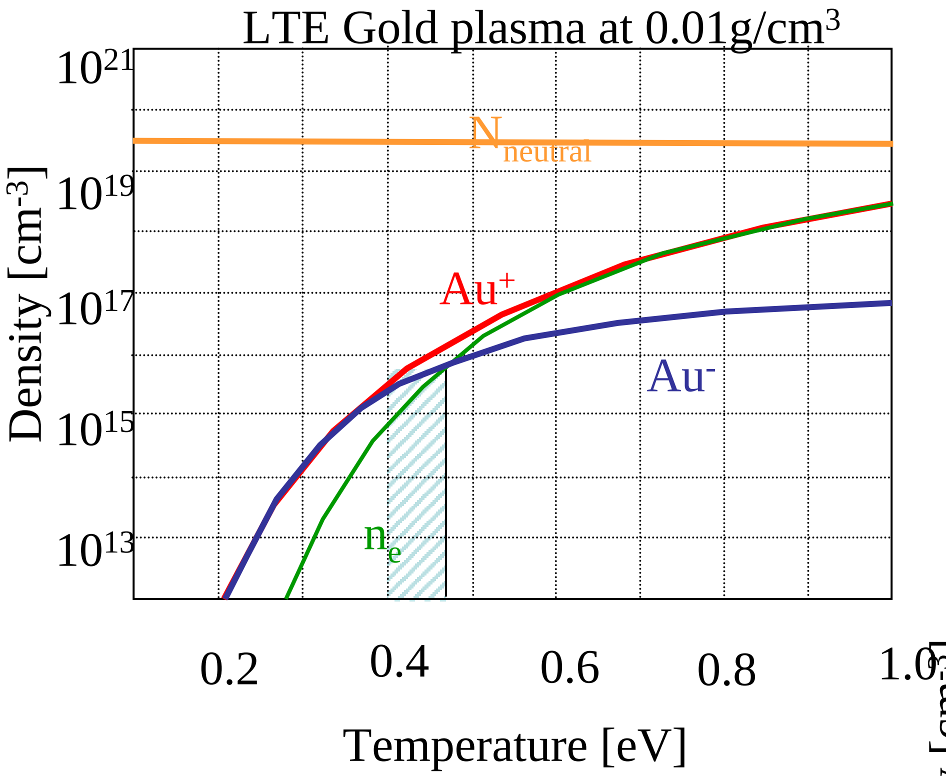
Disordering due to expansion

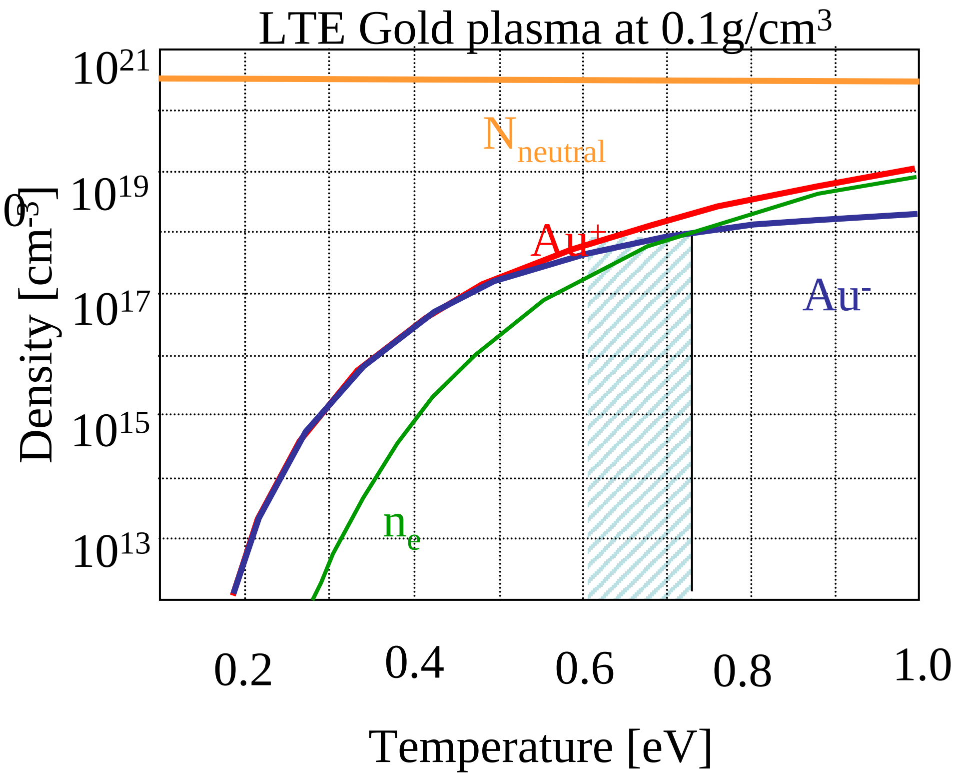


Each electron states are perturbed by local ion environment
(pressure broadening)

+ fluctuating microfields from mobile electrons make level broadening
(homogeneous width)

Equilibrium condition for gold plasma





Summary

- Hydrodynamic features in 2ϕ fluid region will help to detect the critical point.

  (diffuse scattering to detect droplets)

- Hg M-NM transition occurs within ~1ps. That indicates M-NM is located at high density in WDM region. (i.e., above critical density)
- Phenomenon of increased reflectivity is observed in Hg WDM material.
- Observe Metal-nonmetal transition in Zn