2008 Warm Dense Matter Winter School

Laser Experiments

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Schedule for Laser Exp. Lecture (2008/1/10,11,14)

- 1st; Introduction to WDM experiments with Lasers: History, fundamental physics to understand USP-laser interaction,
- 2nd; Techniques for measurement of WDM condition, creation of WDM with laser, advantage and disadvantage,
- 3rd; advanced technique, future plans,

Introduction

- Solid surface heating with lasers
- Absorption measurements
- Pump probe measurements
- Interferometer
- Nonlinear optical measurements
- Scattering measurements

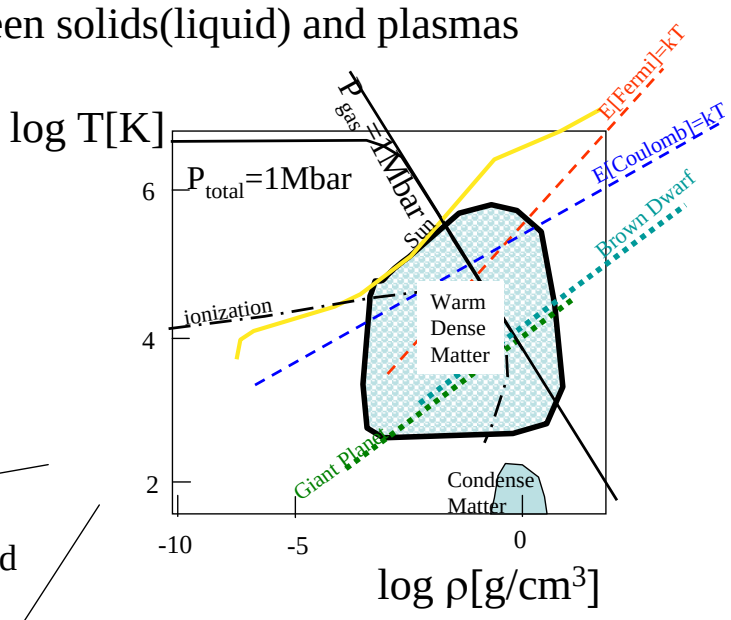
Laser produced
Warm dense matter condition

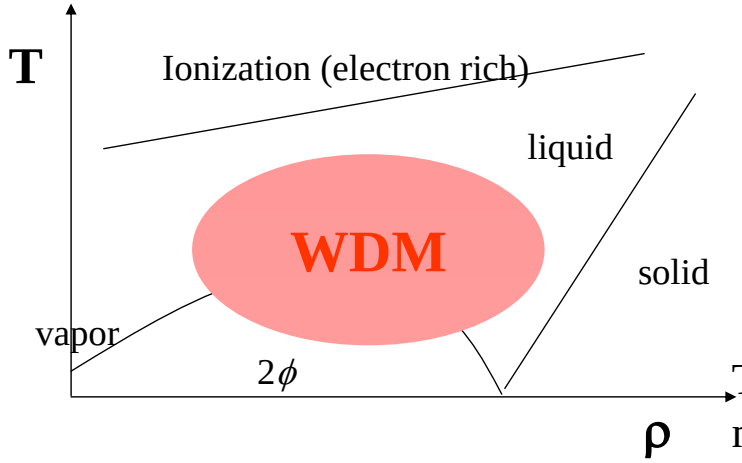
How to create? What are key points?

Warm dense matter

Material properties between solids(liquid) and plasmas

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



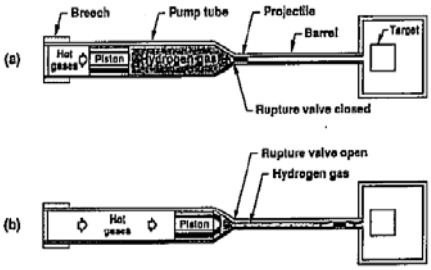


Strong inter atomic interaction + electronic excitations

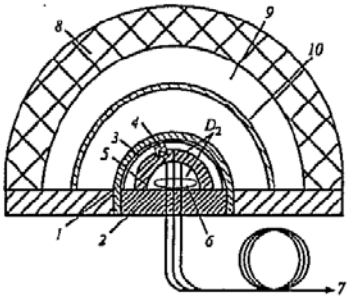
There is a lot of new physics and many uncertain phenomena.

Variety of WDM experiments

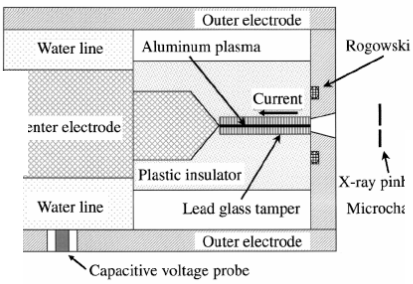
Gas gun



Converging shock

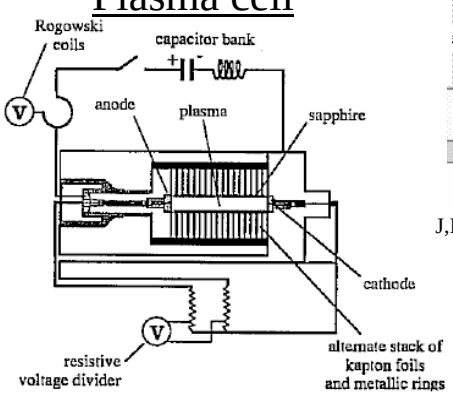


Fast discharge

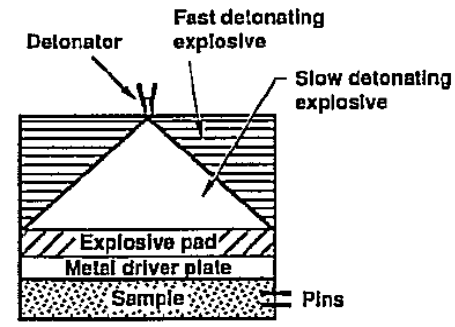


J,F. Benarge, et. Al., PRL 83-15 (1999)

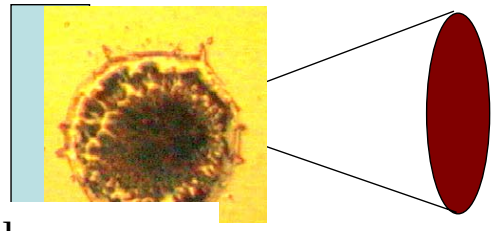
Plasma cell



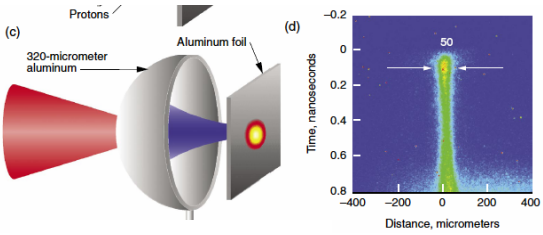
explosive shock



Variety of WDM experiments

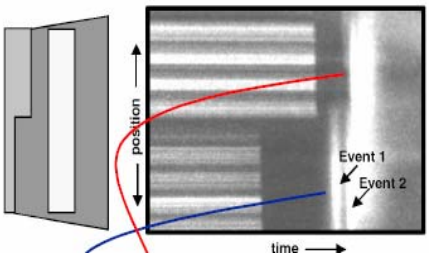


USP laser

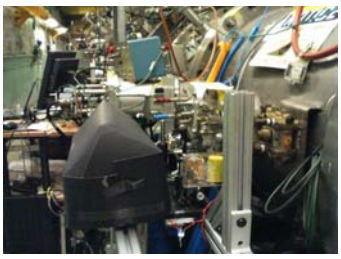


USP Ion beam

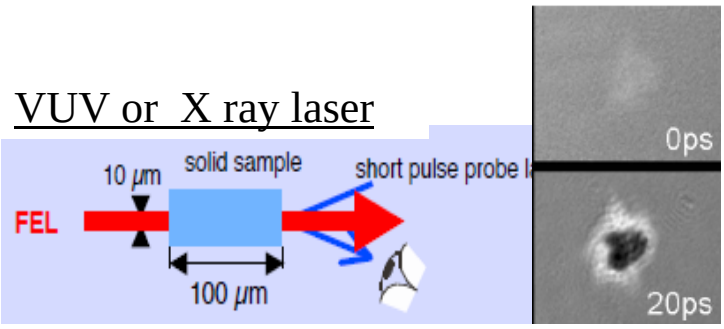
Laser shock (solid and form)



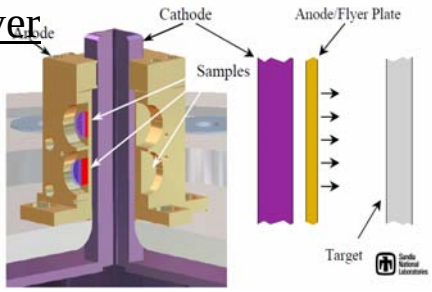
Accelerator Ion beam



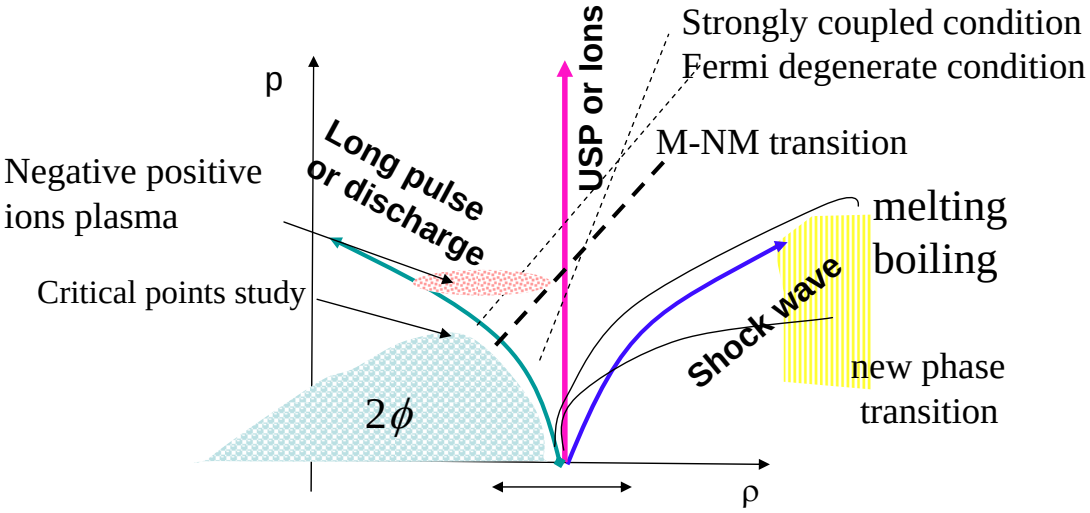
VUV or X ray laser



Flyer



Where do you want to go?
What topics are you going to discuss?
Is it possible to measure the physical parameters?

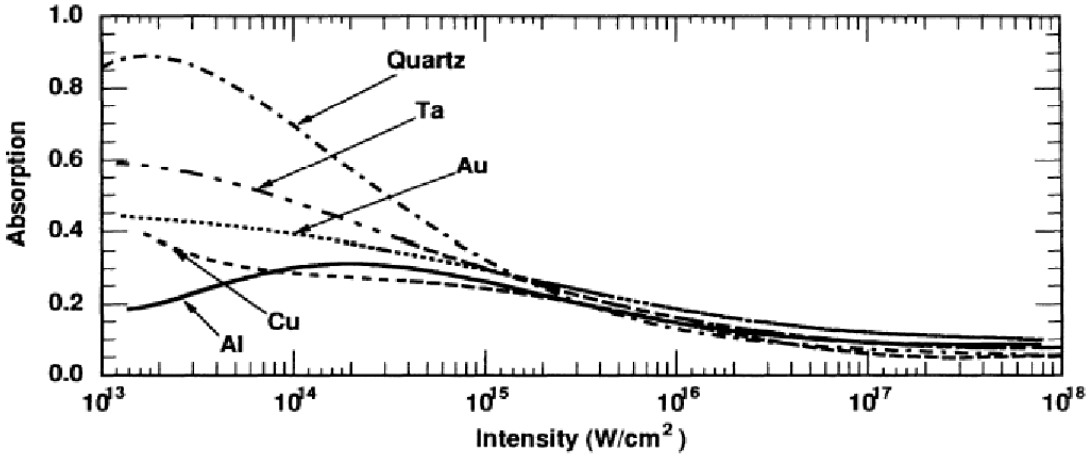


Start points:
Solid, liquid, gas, low density foam?

Laser heating

Guide line for heating intensity

USP laser absorption measurements
(D.F.Price, et al.,PRL, Vol.75-2, 252 (1995))



Warm dense matter

Laser heating

1. Easy to heat up WDM temperature

~10^{14}W/cm^2, 10μmϕ, 100fs => 10μJ
at 1kHz, only 10mW laser!

10nJ from Kerr-lens mode-locked oscillator
3mJ from CW pumped Regenerated amplifier(300kHz RegA-9000)
3μJ from fiber fs laser(200kHz IMRA-FCPA)

We will produce WDM with a "Lunch box size laser".

High repetitive experiments
⇒Large photon number
⇒Excellent S/N ratio

Laser heating

2. Interaction (how to absorb pumping laser energy)

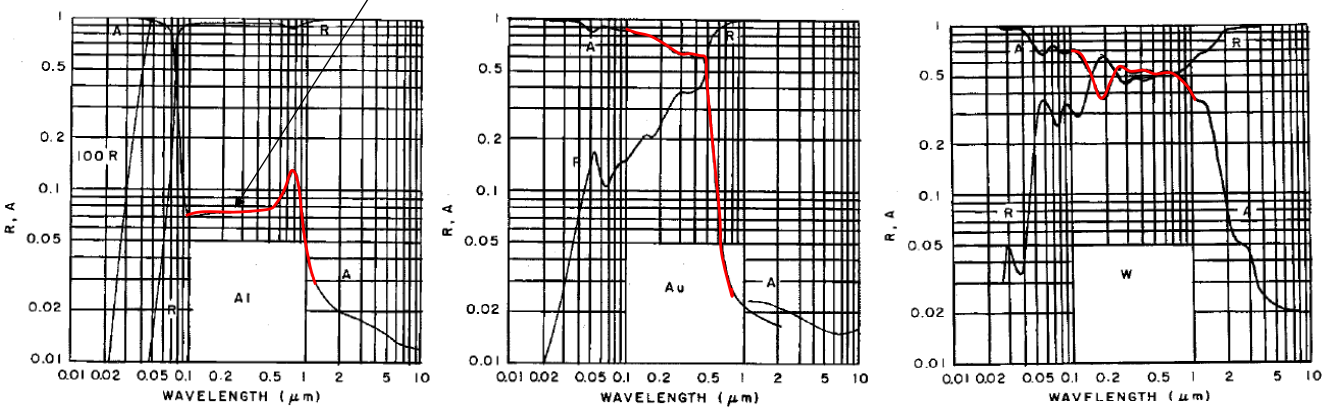
Metals Joule heating (Inverse Bremsstrahlung)

Even with Al, about 8% absorption at room temperature.

10^{13}W/cm^2/ 10nm => E_{abs}~8x10^{17}W/cm^3!

Dielectric materials

Resonance, multi-photon absorption

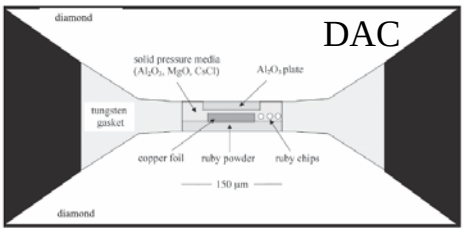


Handbook of OPTICS II, McGRAW-HILL

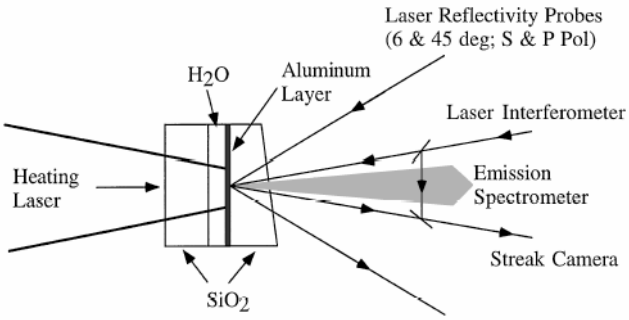
Laser heating

How to heat

1. Direct illumination (thickness > skin depth)
2. Thin foil heating (thickness < skin depth)
3. Conversion from NIR laser to shorter wavelength photon
4. Tamped by transparent material
5. Low density form?
6. Pre-pressured (diamond anvil cell)

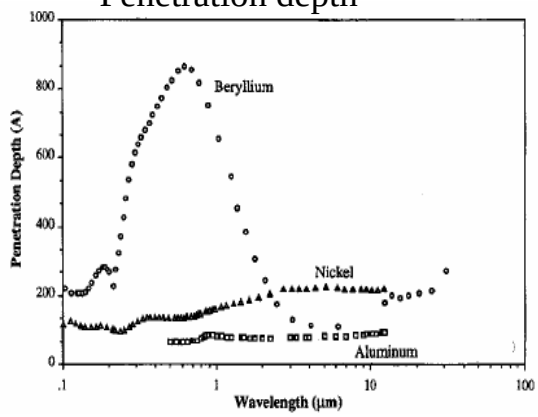


S. Japel, et al., PRL. 95, 167801 (2005)



A.N. Mostovych, PRL, 79 (1997)

Penetration depth



Hand book of Optics, McGraw-Hill

NASA Web site:http://stardust.jpl.nasa.gov/photo/aerogel.html

Laser heating

Absorbed energy measurements

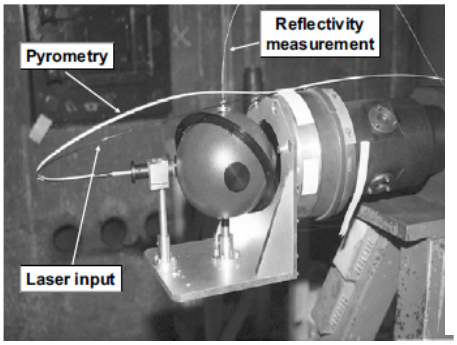
1. Incident energy measurements

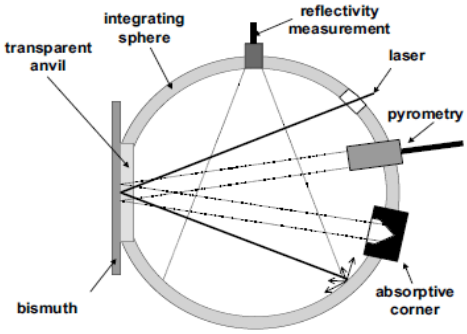
   Assumption: good absorption at WDM region (DUV, EUV, XUV lasers)

2. Measurements of specular reflected light

   Assumption: smaller re-emission and scattering

3. Integrated sphere + bolometer





D. Partouche-Sebban, J.L. P´elissier, Shock Waves (2003) 13: 69–81

Laser heating

Tamped method

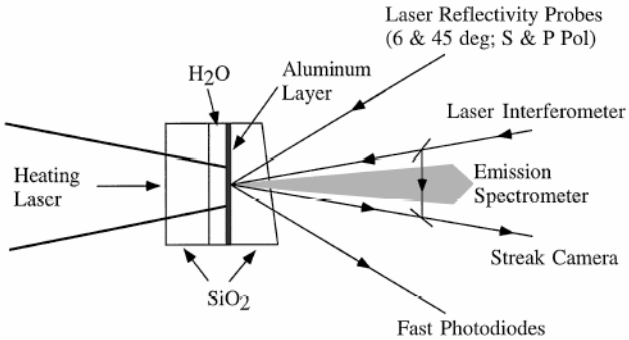
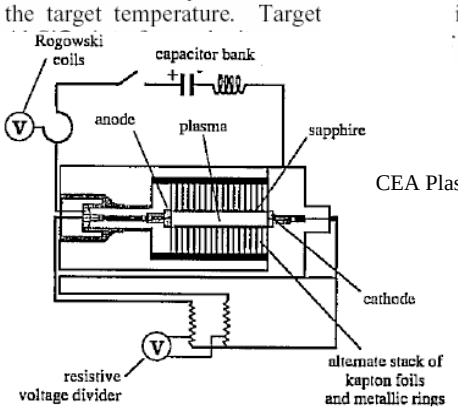
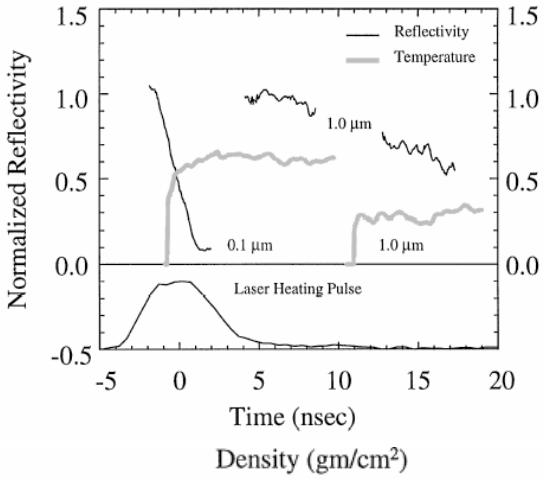
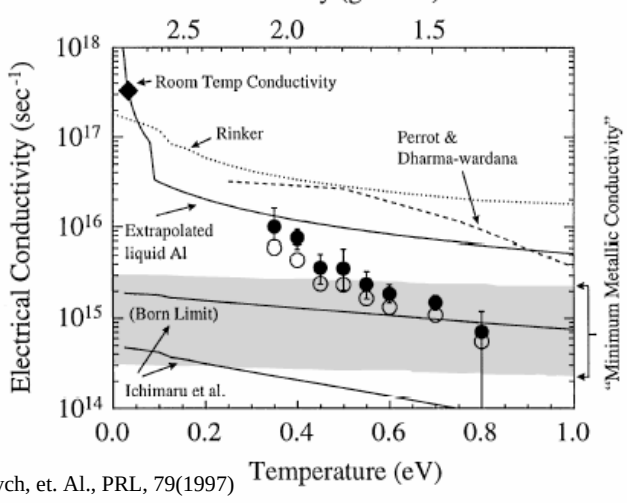


FIG. 1. Schematic of tamped targets and diagnostics. Pulsed laser probes at 6° and 45° measure aluminum layer reflectivity while an absolutely calibrated spectrometer is used to measure the target temperature. Target inferred from the interferometry.



CEA Plasma Cell





A.N. Mostovych, et. Al., PRL, 79(1997)

Sub-ps pulse power type X ray source with synchronizing usp laser

J. Cao

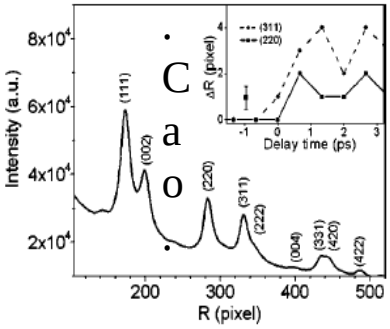


FIG. 4. A static diffraction intensity curve as a function of diffraction angle (pixel distance from the center beam) from a 400-Å Ag film recorded with the FED system. Inset: The shift of Bragg peaks of (220) and (311) as a function of delay time after femtosecond laser excitation at fluence of 6 mJ/cm^2. The time step is 600 fs.

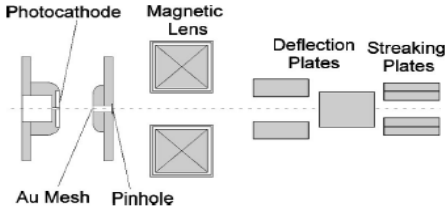


FIG. 1. Schematic of femtosecond electron gun used in FED system.

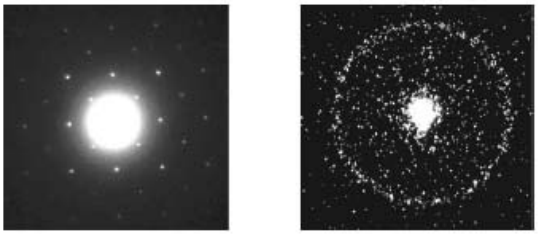
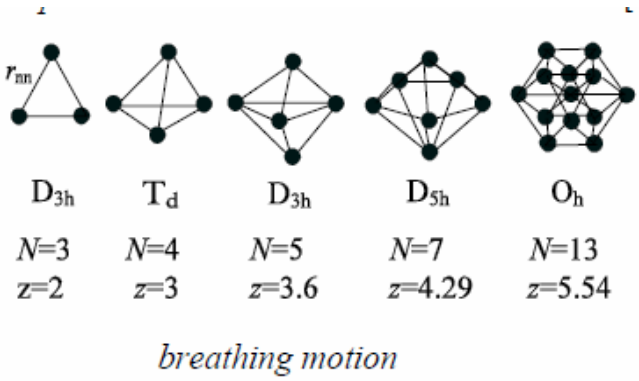


FIG. 3. Left panel: Diffraction image of $La_{0.8}Sr_{0.2}MnO_3$ in [100] direction recorded with $\sim 4\times10^7$ electrons. Right panel: Diffraction image of 400-Å Al film taken with a single electron pulse with $\sim$4000 electrons ($\sim$700 fs). The ring in the image corresponds to the (220) Bragg peak. Each bright spot in the images represents a single detected electron.

J. Cao, et. at., Appl. Phys. Lett., vol.83-5 (2003) p.1044

Photoelectron spectrum of Hg
(band gap information)
(single electron detection)



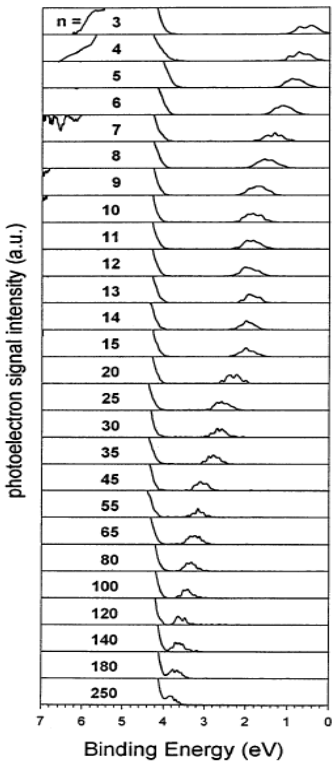
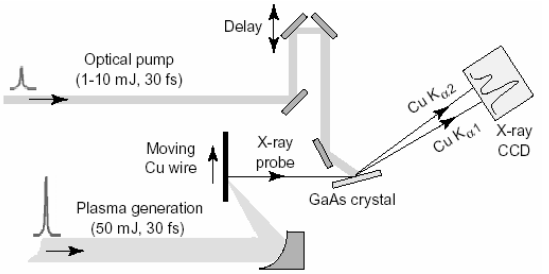


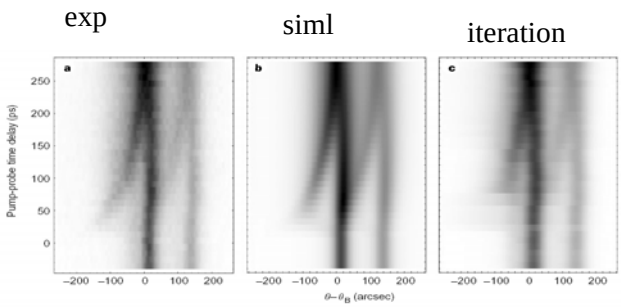
FIG. 2. Photoelectron spectra of Hg^-_n in the size range of n = 3–250 taken with 7.9 eV laser excitation. The spectra are scaled and truncated to show a constant intensity of the single peak of the detached $6p$ electron. The fine structure of the $6p$ peaks is due to statistical scatter of photoelectron counts.

Phys. Rev. Lett. 81, 3836–3839 (1998)

Combination of optical probe with X ray diffraction



C. Rose-Petruck et al., Nature (London) 398, 310 (1999)



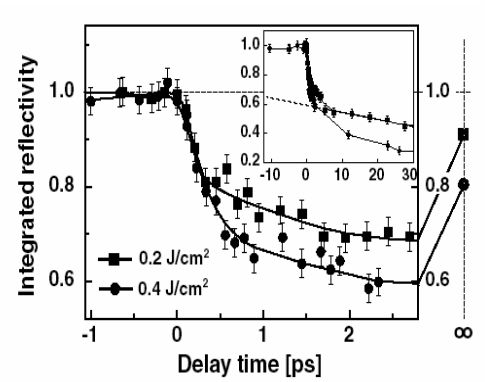
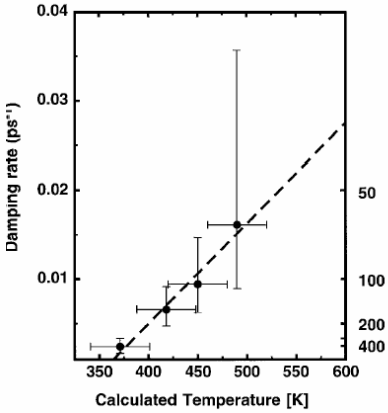
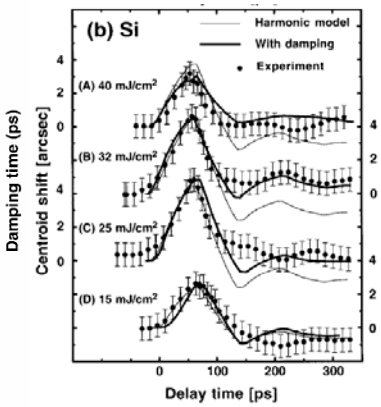


FIG. 1. X-ray diffraction efficiency (integrated reflectivity) versus delay time. Infinity symbol: measurement a few minutes after the pump pulse. Inset: integrated reflectivity for an extended time span. Dashed line: melt-front velocity of 850 m/s for rapid thermal melting.





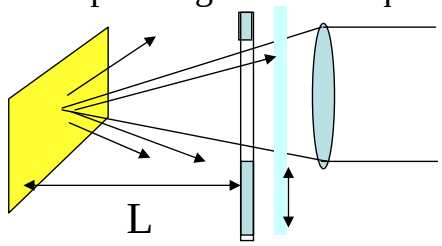
A. Cavalleri, et al., Anharmonic Lattice Dynamics in Germanium Measured with Ultrafast X-Ray Diffraction, PRL, 85-3, 586(2000)

Laser heating

Merit of smaller WDM experiments

For highly repetitive WDM experiments, smaller pump energy is preferable due to the debris problem even with moving debris shield.

=> Precision of pointing and beam quality for pump probe system should be increased.

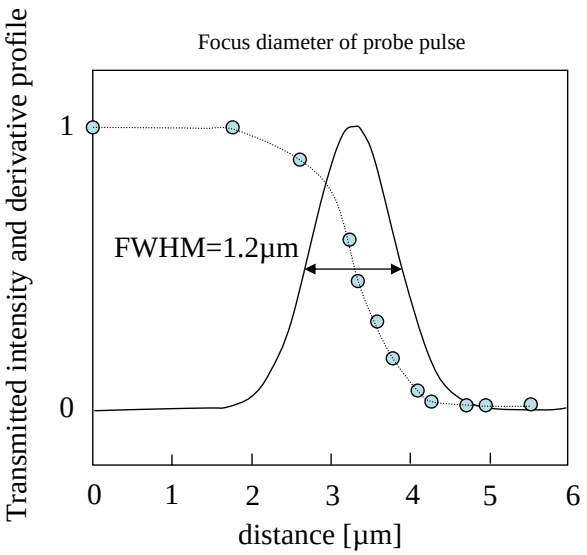


Thickness at nearest optics < skin depth/10

$$= \frac{500nm \cdot \pi r_{\text{focus}}^2}{\pi \cdot L_{\text{distance}}^2} \times Shot \quad number$$

$$\approx \frac{500 \cdot (10\mu)^2}{(20mm)^2} \times 10^4 \approx 1nm$$

(5ps/10fs*30~15000shot)



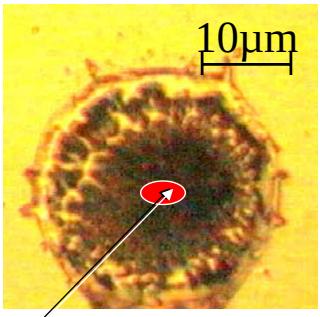
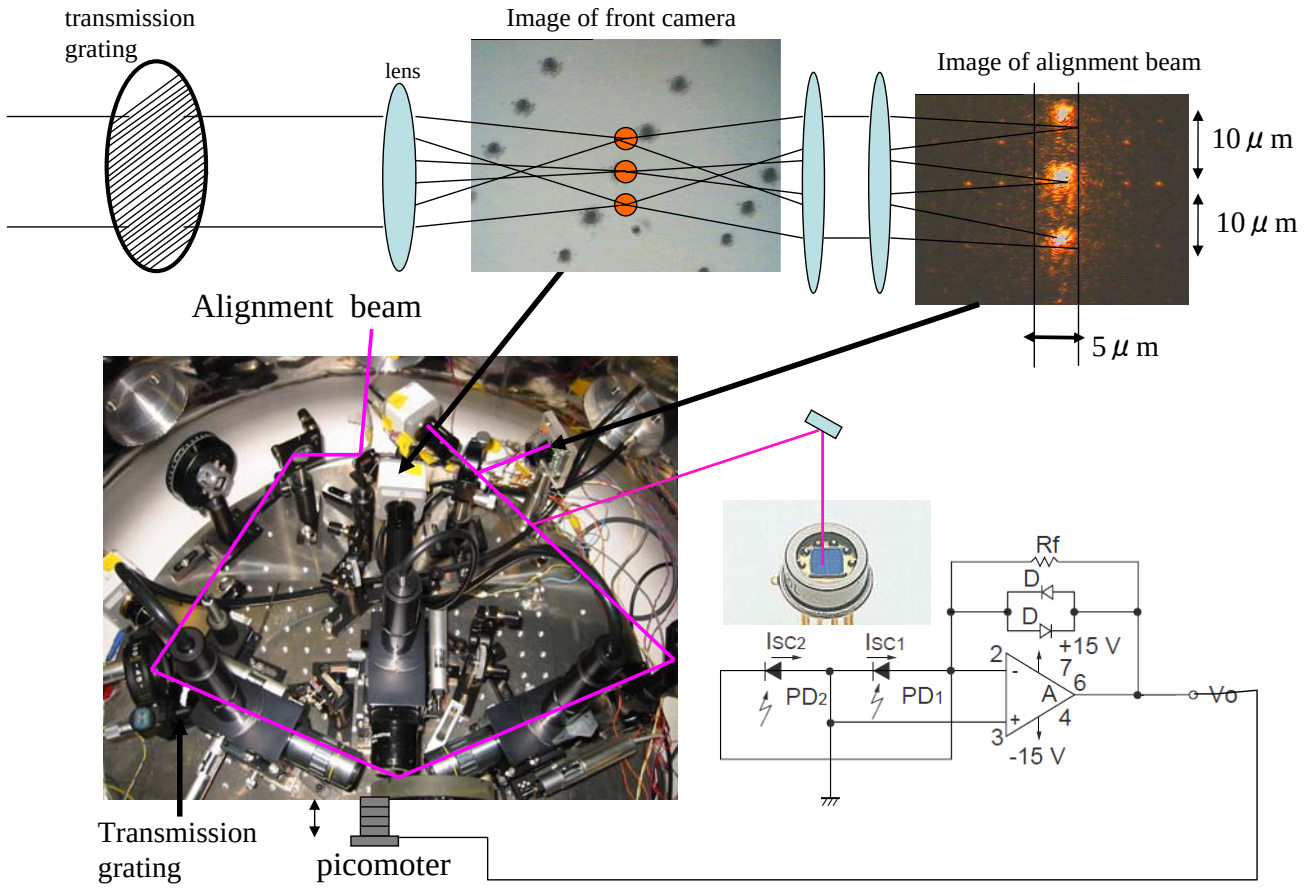


Image of Al target damage

probe beam diameter

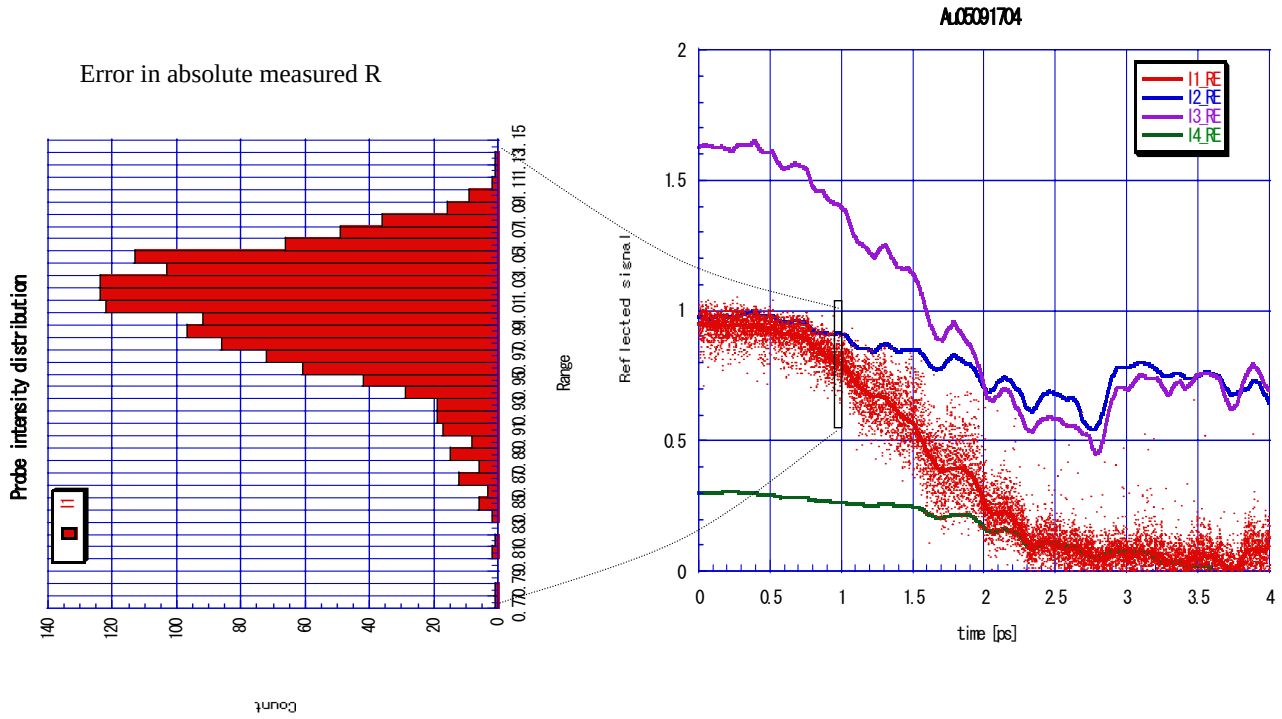
Laser heating

Highly precise auto-alignment system is needed.

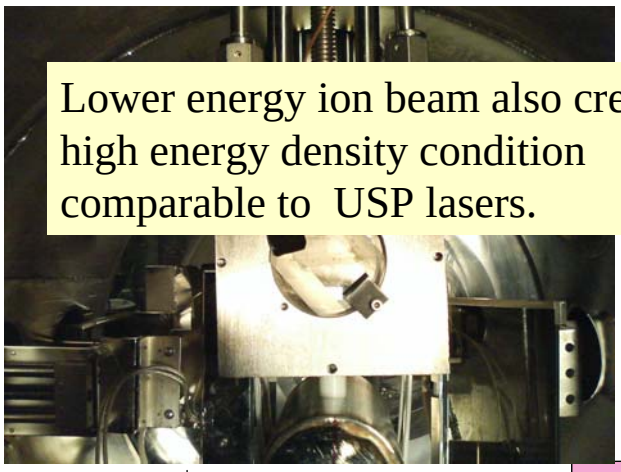


Laser heating

High precision data is obtained with high rep-rate plasma experiments

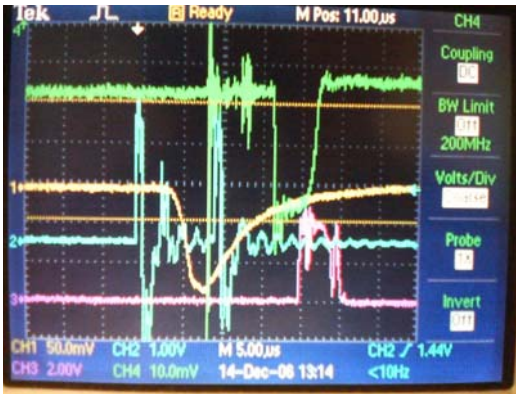


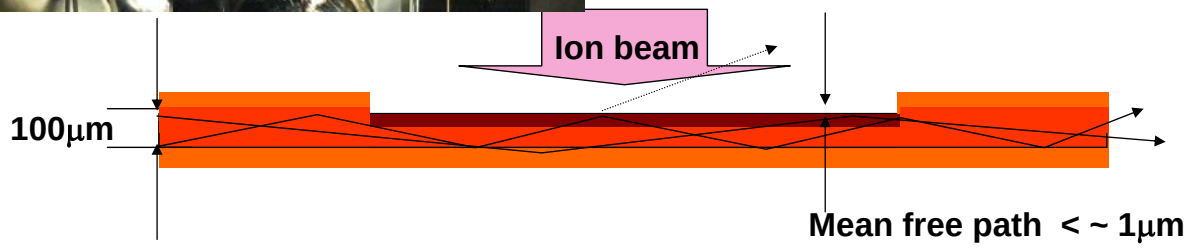
Comments



Lower energy ion beam also creates high energy density condition comparable to USP lasers.

Well defined ion beam





USP laser

10^{13}W/cm^2/ 10nm

=> E_{abs}~8x10^{17}W/cm^3 x 10^{-13}s =8x10^4J/cm^3

Ion beam 2MeV, 100mA/cm^2
5µs
=>10^4J/cc

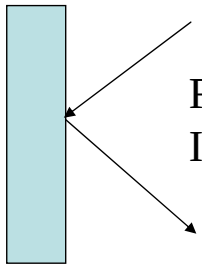
Laser diagnostics for WDM study

Laser diagnostics has a lot of potential

- Ultra-fast measurements (<100fs)
- A lot of excellent detection systems (~visible and NIR)
- Good optics and easy to install
- Easy to change different quantum beams ((higher) harmonics, beams, ..)
- Optical (AC) conductivity
- Energy states related to the outer orbital electrons
- Chemical bonding or band gap feature (at the resonant frequency)
- Other wave detection with wave coupling mechanism (acoustic wave, plasmon decay…)
- Many effects can be used such as Faraday effect
- Re-pumping will be utilized
- Coherent detection (phase measurements)
- Holographic and CT measurements
- ……..

Pump-probe experiments

What optical electromagnetic waves see

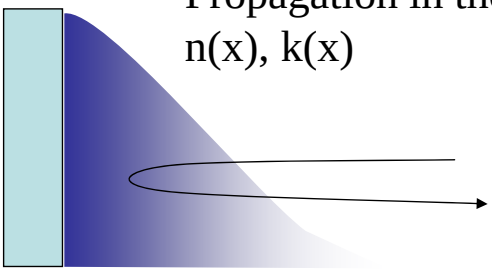


Reflection at sharp boundary
Impedance mis-matching

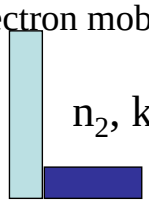
$$r = \frac{(n+ik)-1}{(n+ik)+1} = \frac{\sqrt{\varepsilon_1 + i\varepsilon_2} - 1}{\sqrt{\varepsilon_1 + i\varepsilon_2} + 1}$$

reconstruction method

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



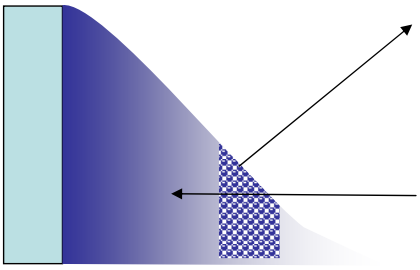
AC conductivity
electron mobility+atomic polarizability



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

Simple figures in laser interaction with solid dense matter

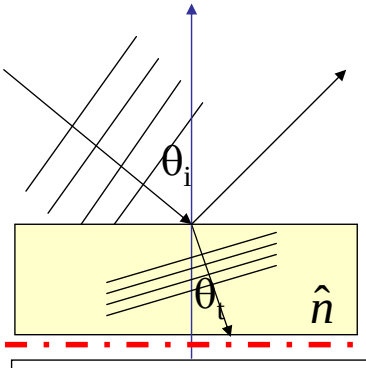
- Fresnel's Law
- Snell's Law

It is enough to consider as the first step.

Refraction of transparent materials

Snell's law $\sin\theta_t = \frac{1}{\hat{n}}\sin\theta_i$

phase front ~ iso-amplitude surface

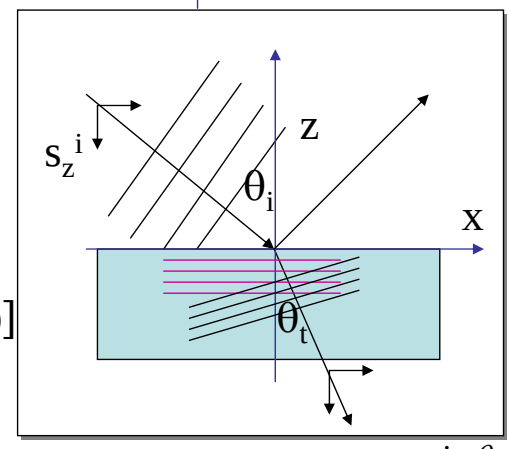


Reflection and penetration of metals

$$\varepsilon, \mathbf{k}, n, k \rightarrow \hat{\varepsilon}, \hat{\mathbf{k}}, \hat{n}, \hat{k}$$

$$\hat{k}(\mathbf{r}\cdot\mathbf{s}^t) = \frac{\omega}{c}(n+ik)(xs_x^t + zs_z^t)$$

$$= \frac{\omega}{c}\left[x\sin\theta_i + zq(n\cos\gamma - k\sin\gamma) + izq(k\cos\gamma + n\sin\gamma)\right]$$



$$s_z^t = \cos\theta_t$$

$$= \sqrt{1 - \frac{n^2-k^2}{(n^2+k^2)^2}\sin^2\theta_i + i\frac{2nk}{(n^2+k^2)^2}\sin^2\theta_i} = qe^{i\gamma}$$

$$s_x^t = \frac{\sin\theta_i}{n+ik}$$

⇨ Inhomogeneous waves

Fresnel's law

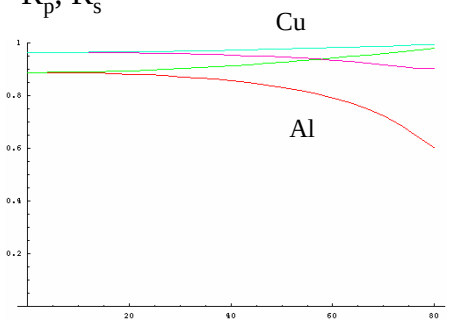
$$R_p = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)}$$

$$R_s = \frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)}$$

λ=0.8μm

Material	n	k
Al	2.4	8.62
Cu	0.22	4.4
W	3.56	2.73
Si	3.93	0.136

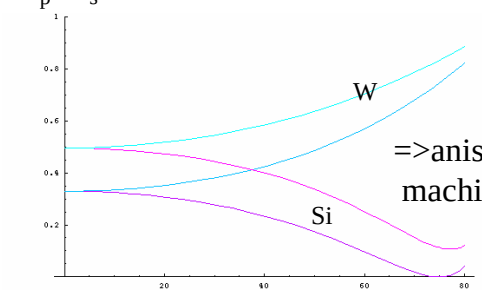
R_p, R_s



θ_i

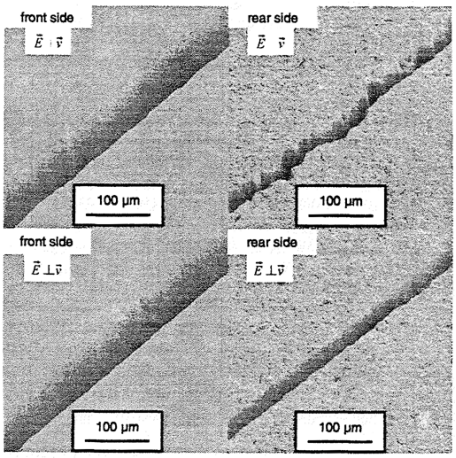
$\theta_i \xrightarrow{\text{Snell' law}} \theta_t \xrightarrow{\text{Fresnel Eq.}} R_p, R_s$

R_p, R_s



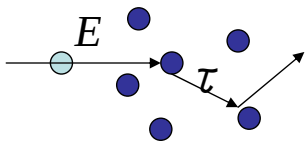
θ_i

=>anisotropic machining



H.K.Tonshof, et al., SPIE Vol.4830, p.531

Drude Model for free (free-electron-like) electrons



$$m\left(\frac{d}{dt}+\frac{1}{\tau}\right)\delta v(t)=F=-eE\exp[-j\omega t]$$

$$\delta v(t)=\delta v_0\exp[-j\omega t]$$

$$\delta v_0=-\frac{e\tau/m}{1-j\omega\tau}E$$

$$J=nq\delta v=\frac{ne^2\tau}{m(1-j\omega\tau)}E$$

Electrical conductivity

$$\sigma(\omega)=\frac{ne^2\tau}{m(1-j\omega\tau)}=\frac{ne^2\tau}{m}\frac{1+j\omega\tau}{1+(\omega\tau)^2}$$

ω -> 0

$$\sigma_{DC}=\frac{ne^2\tau}{m}$$

Damping factor g?

$$g=1/\tau=\frac{ne^2}{m\sigma_{DC}}$$

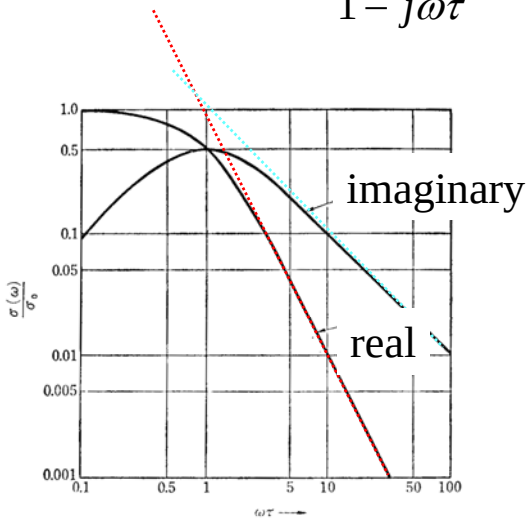


図 8・1 伝導率と ωτ との両対数関係. ω は角振動数, τ は緩和時間.

C.Kittel Introduction of Solid state Physics

Relation between AC(IR frequency) and DC conductivity

$$\sigma=\frac{Ne^2}{m(g-i\omega)}$$

$$\hat{\varepsilon}=\hat{n}^2=1+\frac{i\sigma}{\varepsilon_0\omega}=1-\frac{Ne^2}{m\varepsilon_0}\frac{1}{\omega(\omega+ig)}$$

$$=1-\frac{\omega_c^2}{(\omega^2+g^2)}+i\frac{\omega_c^2}{(\omega^2+g^2)}\frac{g}{\omega}$$

$$\hat{n}=n+ik$$

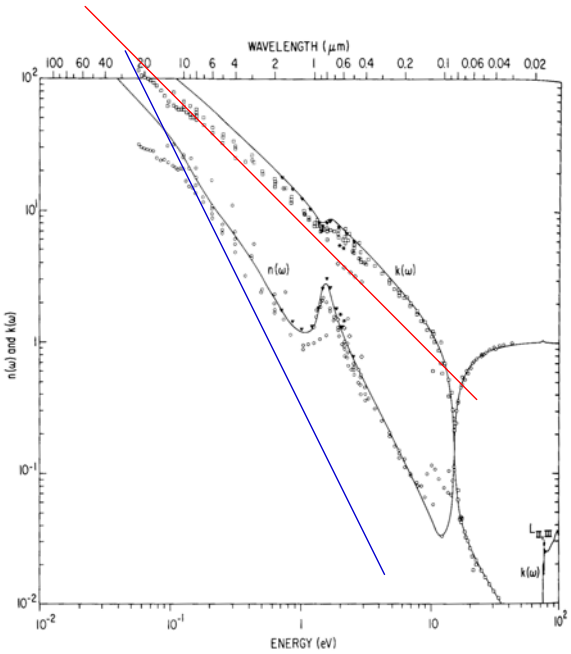
$$\mathrm{Re}\cdot\hat{\varepsilon}(\omega)\equiv n^2-k^2$$

$$\mathrm{Im}\cdot\hat{\varepsilon}(\omega)\equiv 2nk$$

$$\sigma_{DC}=\frac{Ne^2}{mg}\sim 3\times10^7[\Omega^{-1}m]$$

n_e for Al ~6x10^{22}cm^{-3}

g=5.6x10^{13}[s^{-1}], ω_{pe}=1.4x10^{16} [s^{-1}]



*From Handbook of optical constants of solids edited by E.D.Palik

n=0.39, k=13.9 ⟺ n=2.4, k=3.59

Joule heating?

Q1. Estimation of Al absorption from DC conductivity data

（Al、σ_{DC}∽3x10^7[Ω^{-1}m^{-1}]、δ∽4nm）

$$I_{abs}/I_0 = \frac{\mathrm{Re}[\sigma]E^2\delta}{I_0} = \frac{\mathrm{Re}[\sigma](\eta I_0)\delta}{I_0} = \mathrm{Re}[\sigma]\eta\,\delta = \sqrt{2\mathrm{Re}[\sigma]\eta^2/\omega\mu}$$

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

$\alpha_{measure}$~8%

$$\alpha = \sqrt{\frac{2\mathrm{Re}[\sigma]\frac{\mu}{\mathrm{Re}[\varepsilon]}}{\omega\mu}} = \sqrt{\frac{2\mathrm{Re}[\sigma]}{\omega\mathrm{Re}[\varepsilon]}} = \sqrt{\frac{2Ne^2\beta/m(\beta^2+\omega^2)}{\omega\left(1-4\pi Ne^2/m(\beta^2+\omega^2)\right)}} = \sqrt{\frac{1}{2}\frac{\omega_c^2}{(\omega^2-\omega_c^2)}\frac{\beta}{\omega}} \Rightarrow 0.11$$

$$\sigma_{DC} = \frac{Ne^2}{m\beta} \sim 3\times10^7[\Omega^{-1}m^{-1}]$$

N_e for Al n_i~6x10^{22}cm^{-3}

β=5.6x10^{13}[s^{-1}], ω_c=1.4x10^{16} [s^{-1}] for 3p

Drude components + something

λ_{pr} ~ 550nm

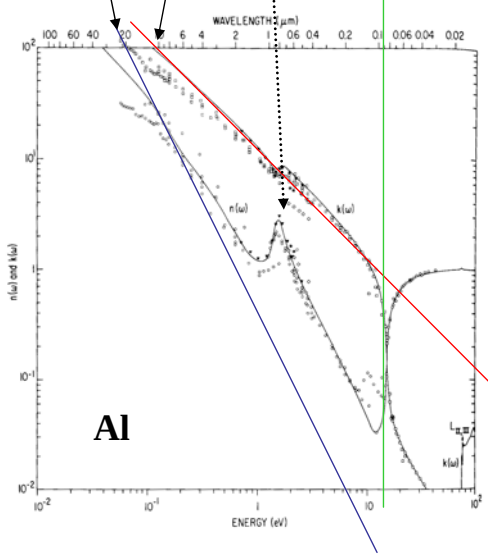
+Inter band transition

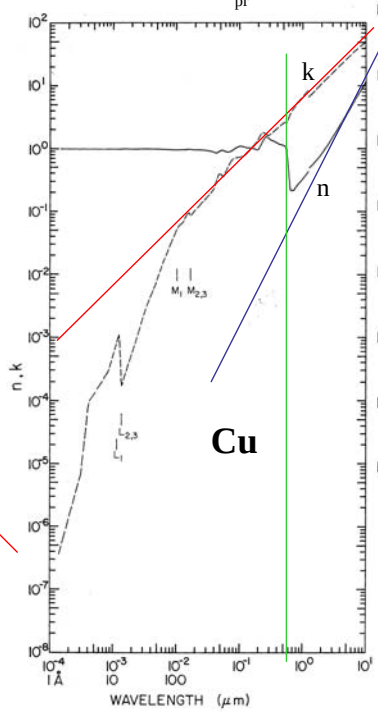
ω_{pe}=2.4x10^{16} [s^{-1}] for 3s^{2}3p
=>λ_{pr} ~ 80nm

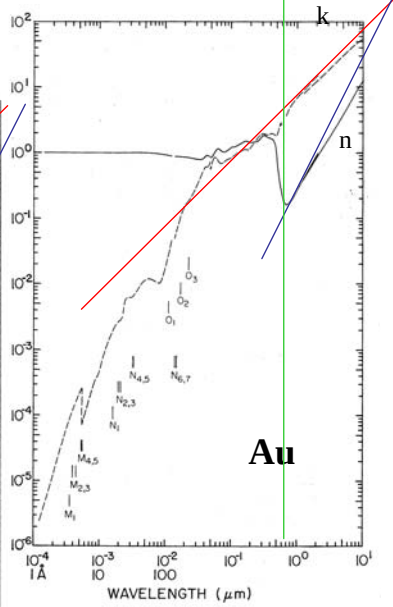
λ_{pr} ~ 600nm

$$n^2 - k^2 \Rightarrow -k^2 \sim \left(\frac{\omega_c}{\omega}\right)^2$$

$$nk \sim \omega^{-3} \Rightarrow n \sim \omega^{-2}$$







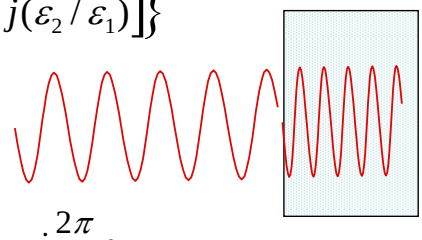
*From Handbook of optical constants of solids edited by E.D.Palik

Dielectric materials

Propagation constant $\gamma = j\omega\{(\mu\varepsilon_1)[1 - j(\varepsilon_2/\varepsilon_1)]\}^{1/2}$

$\varepsilon_2/\varepsilon_1 << 1$ or $\varepsilon_2/\varepsilon_1 >> 1$

Good transparent Strong absorption



$\varepsilon_2/\varepsilon_1 << 1$ $\quad \gamma = j\omega(\mu\varepsilon_1)^{1/2} = j\omega(\varepsilon_{r1})^{1/2}/c = j\dfrac{2\pi}{\lambda}n$

$\varepsilon_2/\varepsilon_1 >> 1$ $\quad \gamma = j\omega(-j(\varepsilon_2\mu))^{1/2} = \dfrac{\sqrt{2}}{2}\omega\sqrt{\varepsilon_2\mu} + j\dfrac{\sqrt{2}}{2}\omega\sqrt{\varepsilon_2\mu}$

Attenuation coefficient $\alpha = \omega\sqrt{\mu\varepsilon_2/2} = \dfrac{2\pi}{\lambda_0}\sqrt{\mu_r\varepsilon_{2r}/2}$ $\quad \varepsilon_{2r} >> \varepsilon_{1r} \geq 1$

$\Rightarrow$ $\alpha > \dfrac{1}{\lambda_0}$ $\Rightarrow$ $\alpha > 10^4 \mathrm{cm}^{-1}$!

~Metal skin depth
but no joule heating

Inter band transition

Optical refractive index for non absorbing materials

$$\frac{n^2-1}{n^2+2} = \frac{1}{3\varepsilon_0}\frac{Ne^2}{m(\omega_0^2-\omega^2)}$$

Optical refractive index for absorb materials

$$m\ddot{r} + qr + g\dot{r} = eE$$

$$\omega_0 = \sqrt{q/m} \qquad r = \frac{eE_0\sin[\omega t]}{m(\omega_0^2-\omega^2) - j\omega g}$$

Putting this term

then

$$\varepsilon_{1R} = 1 + (Ne^2/m\varepsilon_0)\frac{\omega_0^2-\omega^2}{(\omega_0^2-\omega^2)^2+g^2\omega^2}$$

$$\varepsilon_{2R} = (Ne^2/m\varepsilon_0)\frac{g\omega}{(\omega_0^2-\omega^2)^2+g^2\omega^2}$$

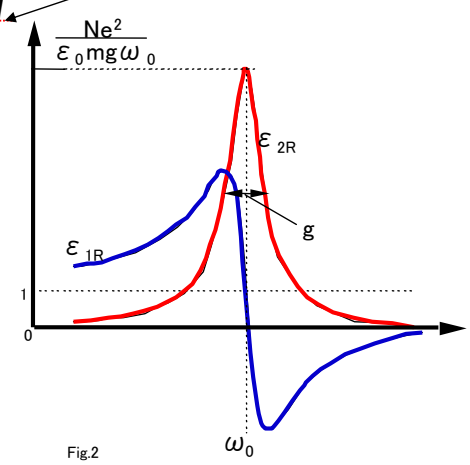


Fig.2

Lorentz-Lorenz model $\Leftrightarrow$ ω_0=0（Drude model）

Formula for optical refractive index

$\varepsilon_{1r}, \varepsilon_{1r}$ ➡

$$n = \left\{ \left[(\varepsilon_1^2 + \varepsilon_2^2)^{1/2} + \varepsilon_1 \right] / 2 \right\}^{1/2}$$

$$k = \left\{ \left[(\varepsilon_1^2 + \varepsilon_2^2)^{1/2} - \varepsilon_1 \right] / 2 \right\}^{1/2}$$

????

➡ $\varepsilon_2 / \varepsilon_1 >> 1$

$$\alpha = \omega \sqrt{\mu \varepsilon_2 / 2} = \frac{2\pi}{\lambda_0} \sqrt{\mu_r \varepsilon_{2r} / 2}$$

$$\alpha = (2\pi / \lambda_0) \left((\mu_R / 2)(Ne^2 / m\varepsilon_0) \frac{g\omega}{(\omega_0^2 - \omega^2)^2 + g^2 \omega^2} \right)^{1/2}$$

➡ $g << 1$

$$n^2(\lambda) = A + k^2(\lambda) + \sum_{i=1}^{J} \frac{B_i \lambda^2 (\lambda^2 - C_i)}{(\lambda^2 - C_i)^2 + D_i^2 \lambda^2}$$

$$k(\lambda) = \frac{1}{n(\lambda)} \sum_{i=1}^{J} \frac{B_i D_i \lambda^3}{(\lambda^2 - C_i)^2 + D_i^2 \lambda^2}$$

➡ Drude model case

$$\alpha = (2\pi / \lambda_0) \left((\mu_R / 2)(Ne^2 / m\varepsilon_0) \frac{g}{\omega(\omega^2 + g^2)} \right)^{1/2}$$

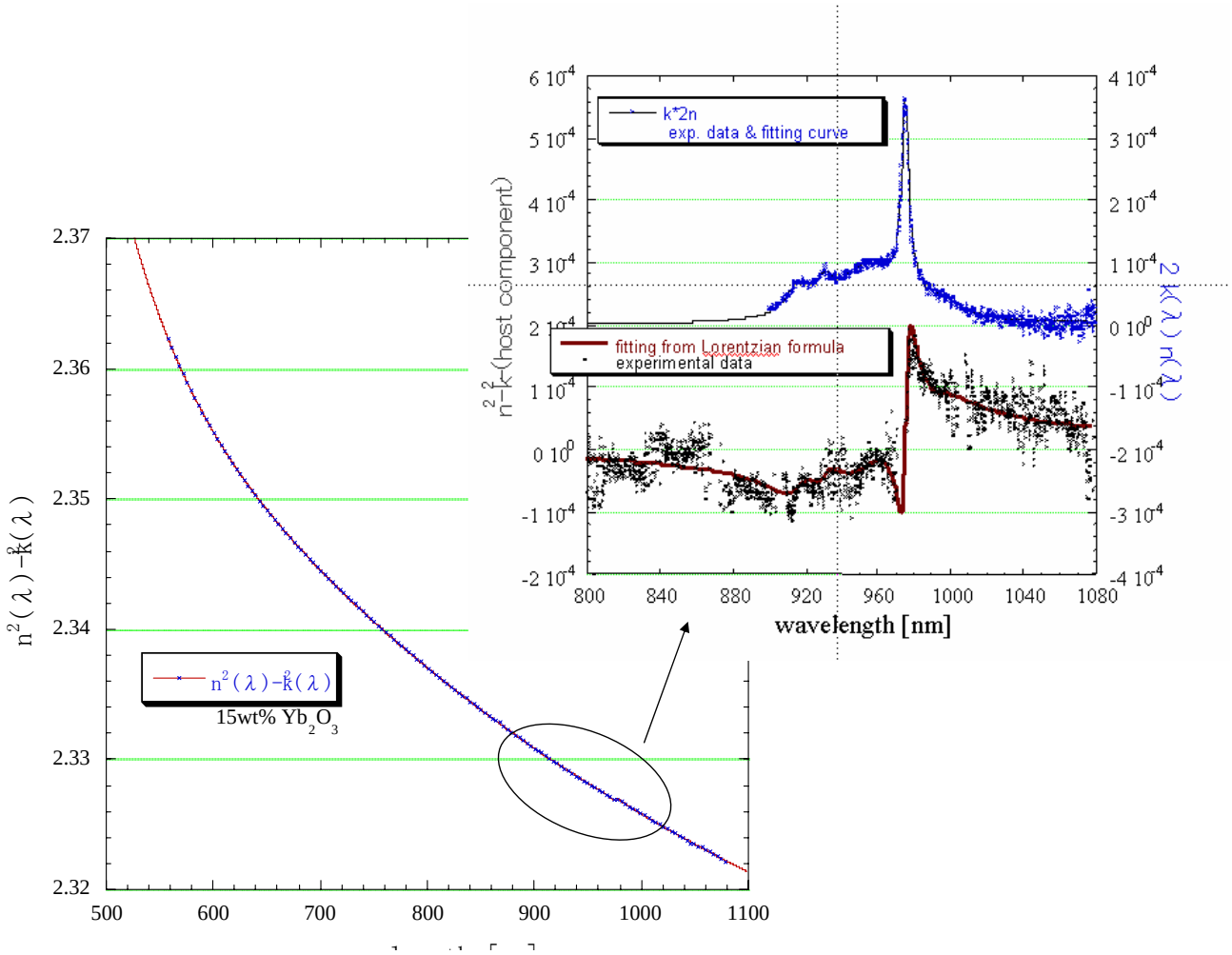
Can we use such formula for real materials?

YES!

	i th	B_i	C_i [nm]	D_i
host	1	0.8180	233.7	90.39
	2	0.1156	458.0	522.5
dopant	3	7.803×10^{-7}	915.7	17.49
	4	4.396×10^{-7}	930.3	11.93
	5	4.045×10^{-6}	955.2	43.09
	6	1.590×10^{-6}	975.2	5.127
	7	4.976×10^{-7}	995.1	22.64

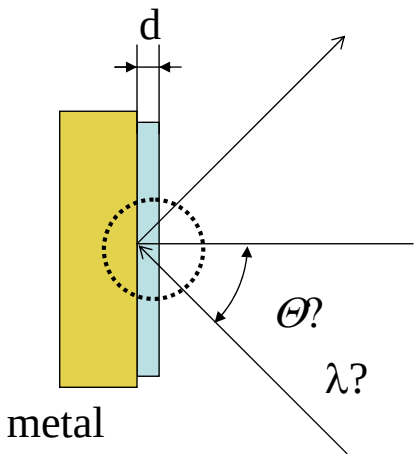
$$n^2(\lambda) = A + k^2(\lambda) + \sum_{i=1}^{J} \frac{B_i \lambda^2 (\lambda^2 - C_i)}{(\lambda^2 - C_i)^2 + D_i^2 \lambda^2}$$

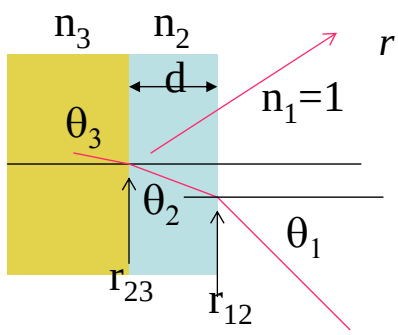
$$k(\lambda) = \frac{1}{n(\lambda)} \sum_{i=1}^{J} \frac{B_i D_i \lambda^3}{(\lambda^2 - C_i)^2 + D_i^2 \lambda^2}$$



How to estimate ?

Resolution and Sensitivity





$$r = \frac{r_{12} + r_{23}e^{2i\beta}}{1 + r_{12}r_{23}e^{2i\beta}}$$

$$r_{12//} = \frac{n_1\cos\theta_1 - n_2\cos\theta_2}{n_1\cos\theta_1 + n_2\cos\theta_2}$$

$$r_{12\perp} = \frac{n_2\cos\theta_1 - n_1\cos\theta_2}{n_2\cos\theta_1 + n_1\cos\theta_2}$$

$$\beta = \frac{2\pi}{\lambda_0} n_2 d\cos\theta_2$$

real: θ_1, n_1
complex: n_2, n_3, θ_2, θ_3

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

like Lorentz-Lorenz model like Drude model

$$\mathbf{P} = N\mathbf{p} = N\alpha\mathbf{E}'$$

$$\alpha = \frac{3}{4\pi N}\frac{\varepsilon - 1}{\varepsilon + 2} = \frac{3}{4\pi N}\frac{n^2 - 1}{n^2 + 2}$$

Cold gold can be understood with Drude model.

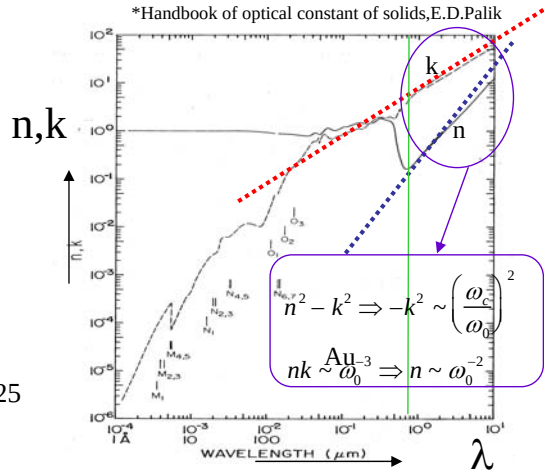
$$\frac{\omega_{pe}^2}{\omega_0^2} = 22.29, \quad \omega_0\tau = 14.25$$

for λ=745nm

similar to $\left(\frac{\omega_{pe}^2}{\omega_0^2}\right)_{cold_gold} = 29.25$

(m_{eff}=>1.33m_{e0})

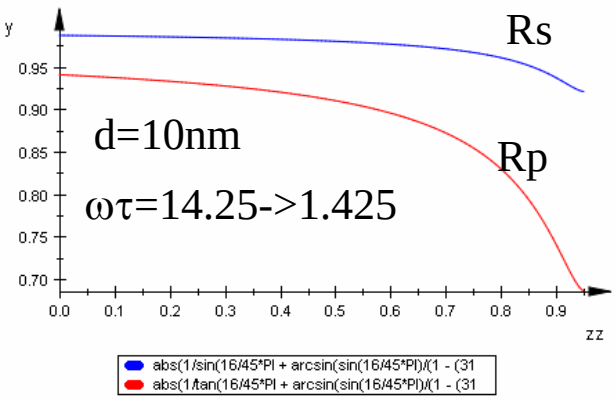
*Handbook of optical constant of solids,E.D.Palik



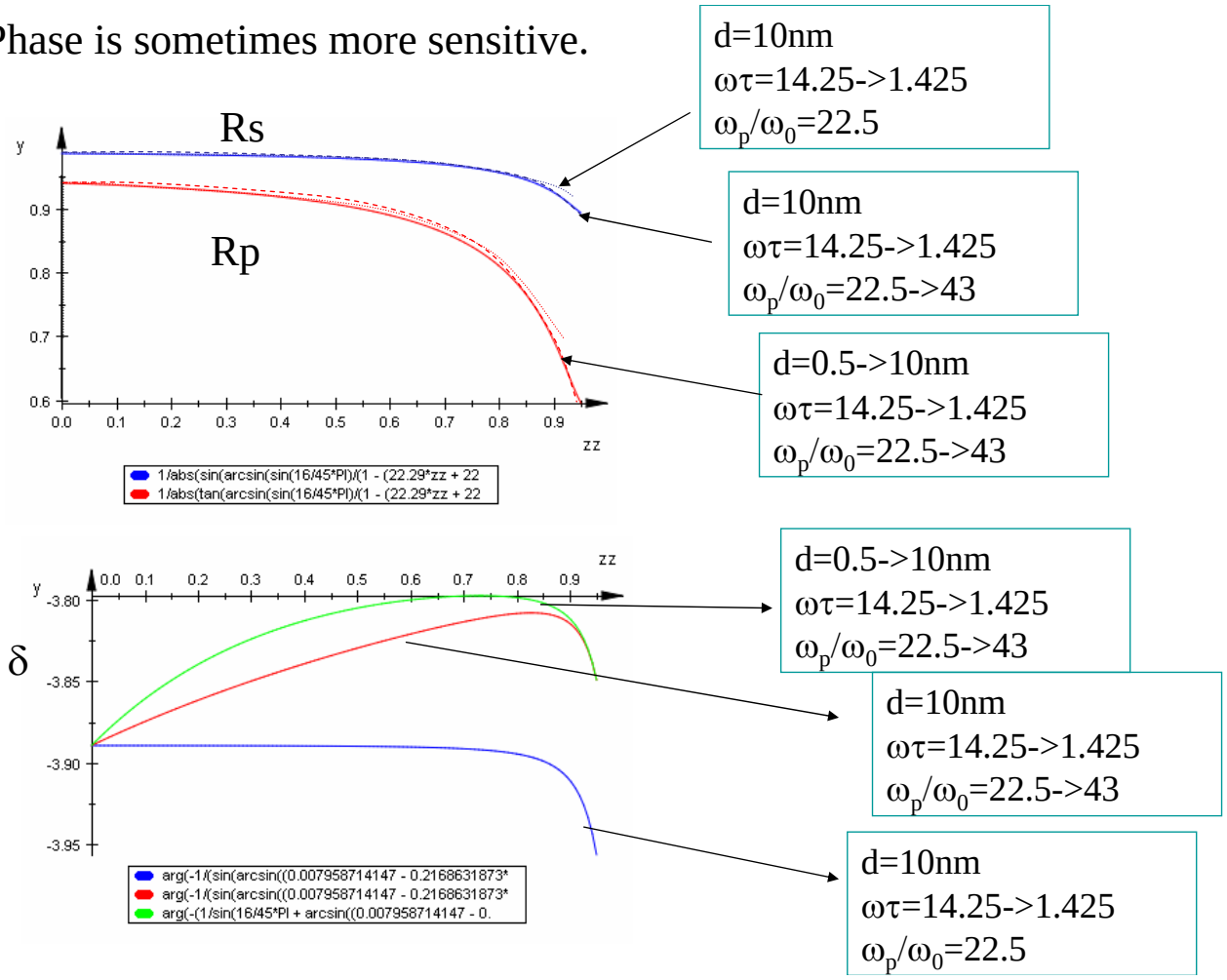
$$\hat{n} = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2 \frac{(\omega\tau)^2}{1+(\omega\tau)^2} + i\left(\frac{\omega_p}{\omega}\right)^2 \frac{(\omega\tau)}{1+(\omega\tau)^2}}$$

$\omega\tau$:14.25 => *decrease*

$(\omega_p/\omega)^2 = (n_e/n_c)^2$ => *increase*

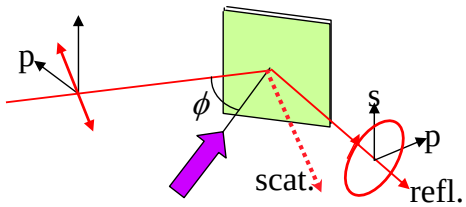


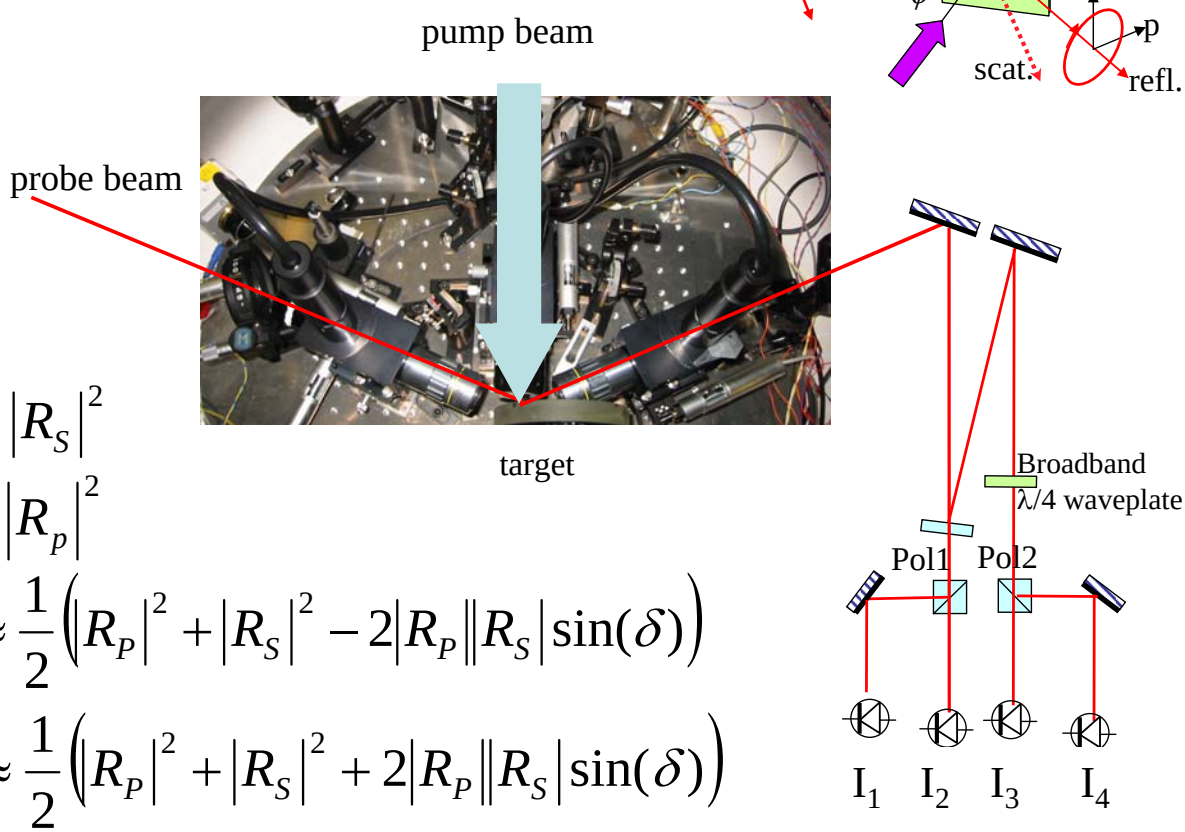
Phase is sometimes more sensitive.



How to measure the phase of optical probe?

Measurements of ellipsometric parameter





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

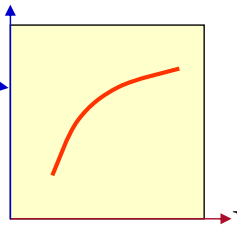
$$I_2 \approx |R_p|^2$$

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

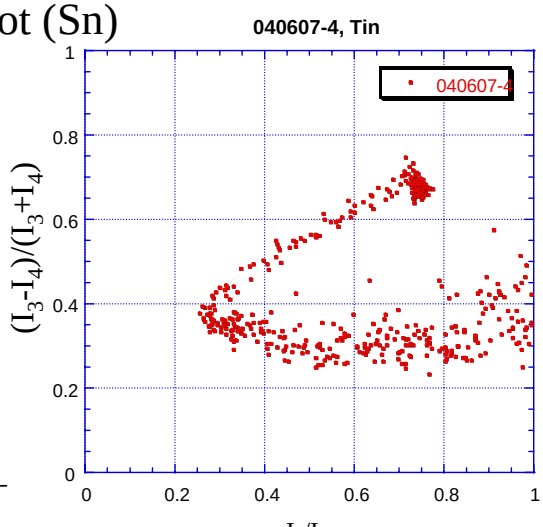
$$I_4 \approx \frac{1}{2}\left(|R_P|^2 + |R_S|^2 + 2|R_P||R_S|\sin(\delta)\right)$$

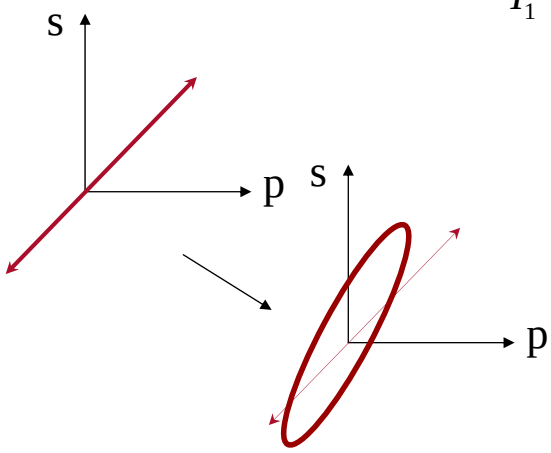
X-Y plot (Sn)

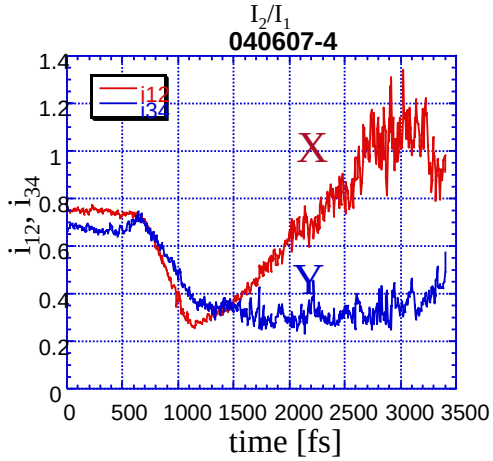
$$Y = \frac{I_3 - I_4}{I_3 + I_4} = \frac{2|R_S||R_P|\sin(\delta)}{|R_S|^2 + |R_P|^2}$$



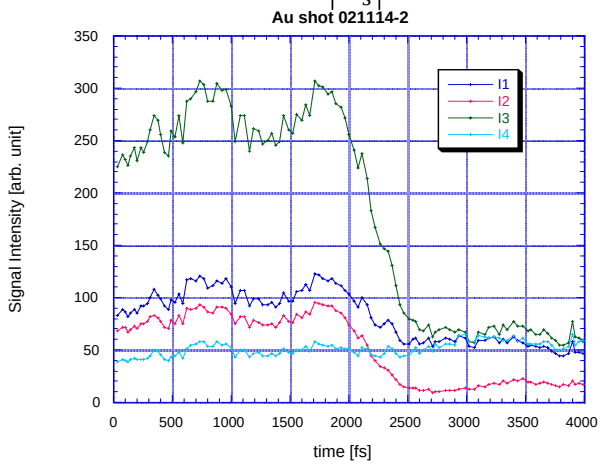
$$X = \frac{I_2}{I_1} = \frac{|R_p|^2}{|R_s|^2}$$







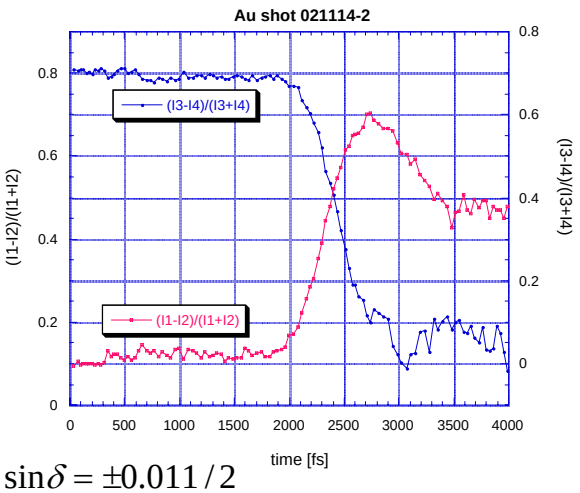
$$X = \frac{I_2}{I_1} = \frac{|R_p|^2}{|R_s|^2} \qquad Y = \frac{I_3 - I_4}{I_3 + I_4} = \frac{2|R_S||R_P|\sin(\delta)}{|R_S|^2 + |R_P|^2}$$



Raw data from four channels

Good Signal/Noise measurement

Key point:
1. Subtract
2. Normalized



Even though probe laser intensity fluctuates very much(+-8%), good S/N can be obtained in X and Y value.

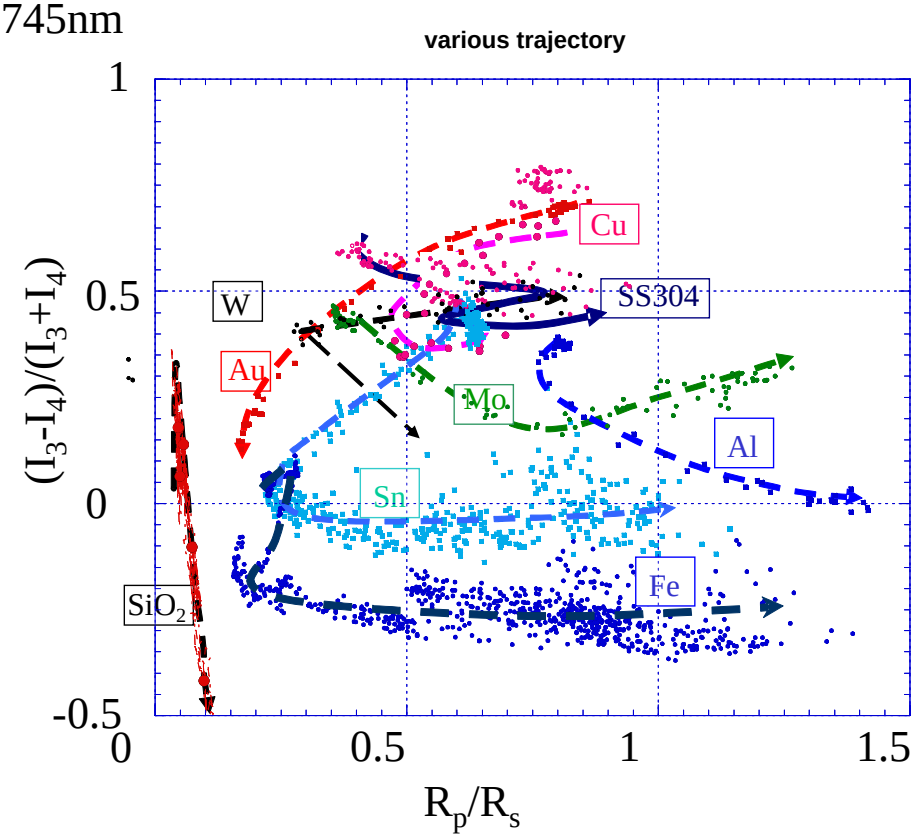
$$\Delta\left[\frac{I_3 - I_4}{I_3 + I_4}\right] \approx \sin\delta = \pm 0.011/2$$

dn = ± 0.015 for $n_0 = 0.1$
dk = ± 0.05 for $k_0 = 4.6$

$$\delta_{\min} = 5 \times 10^{-3}\, rad \;\; !$$

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

For λ=745nm

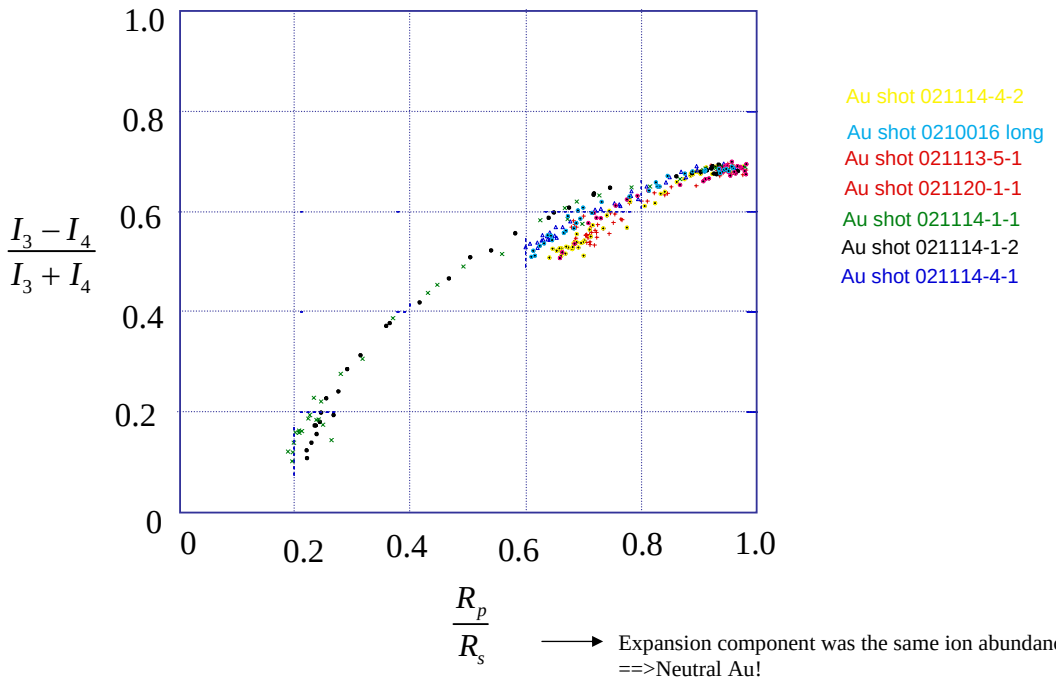


+Zn..

to be continued

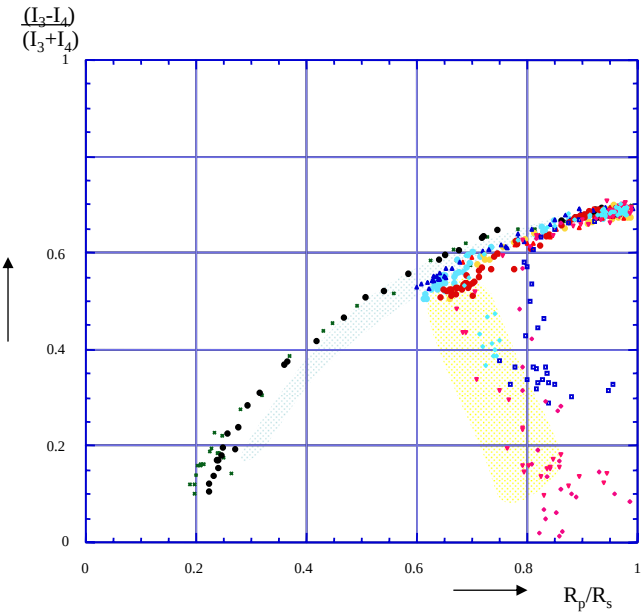
$X=R_p/R_s$, $Y=(I_3-I_4)/(I_3+I_4)$ trajectories are similar with different pump intensity.

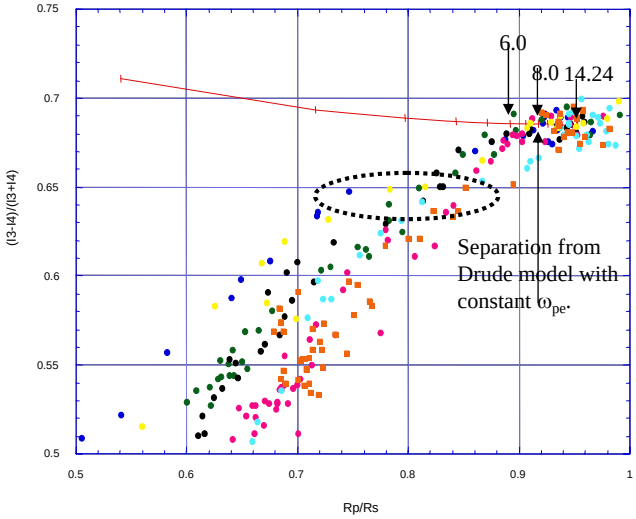
Pump intensity changed from $I=2\times10^{13}W/cm^2 \sim 4\times10^{12}W/cm^2$.

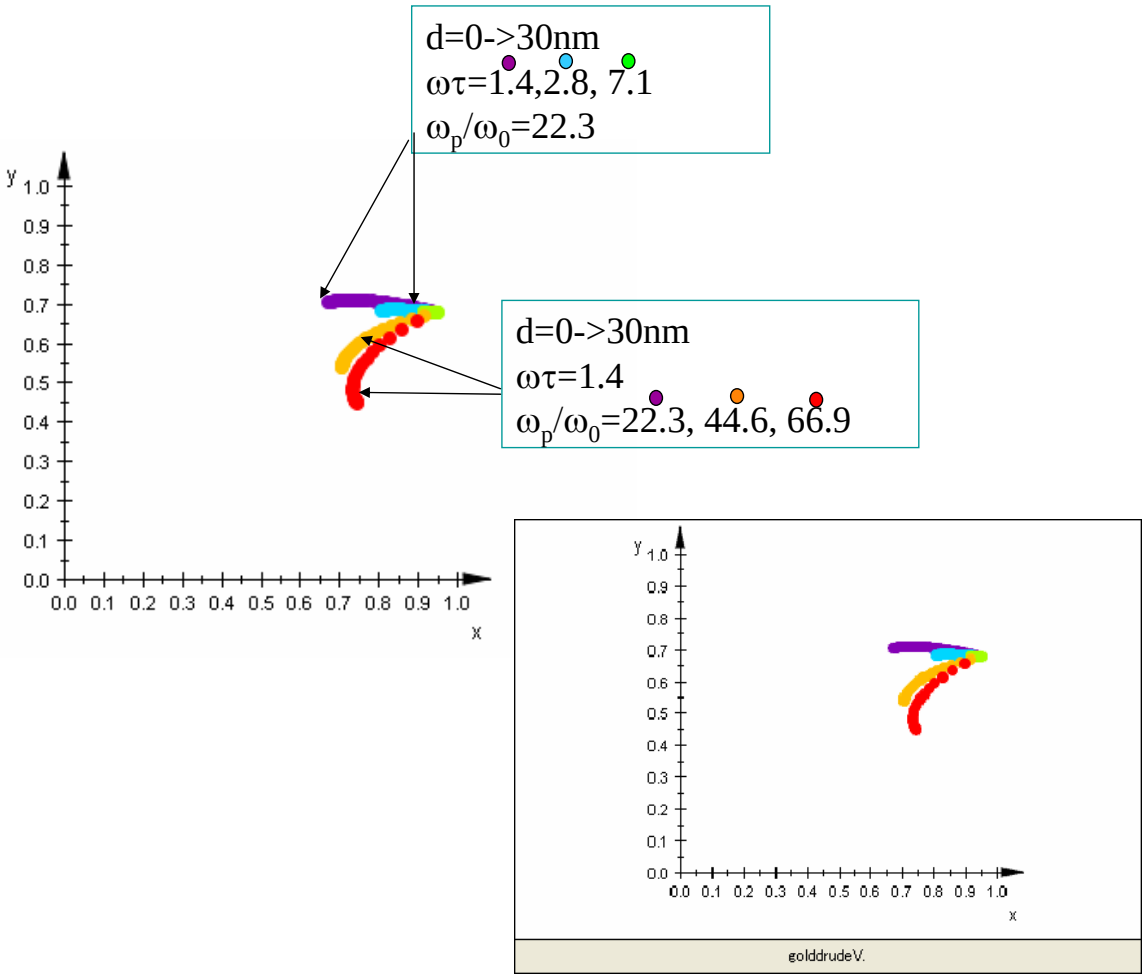


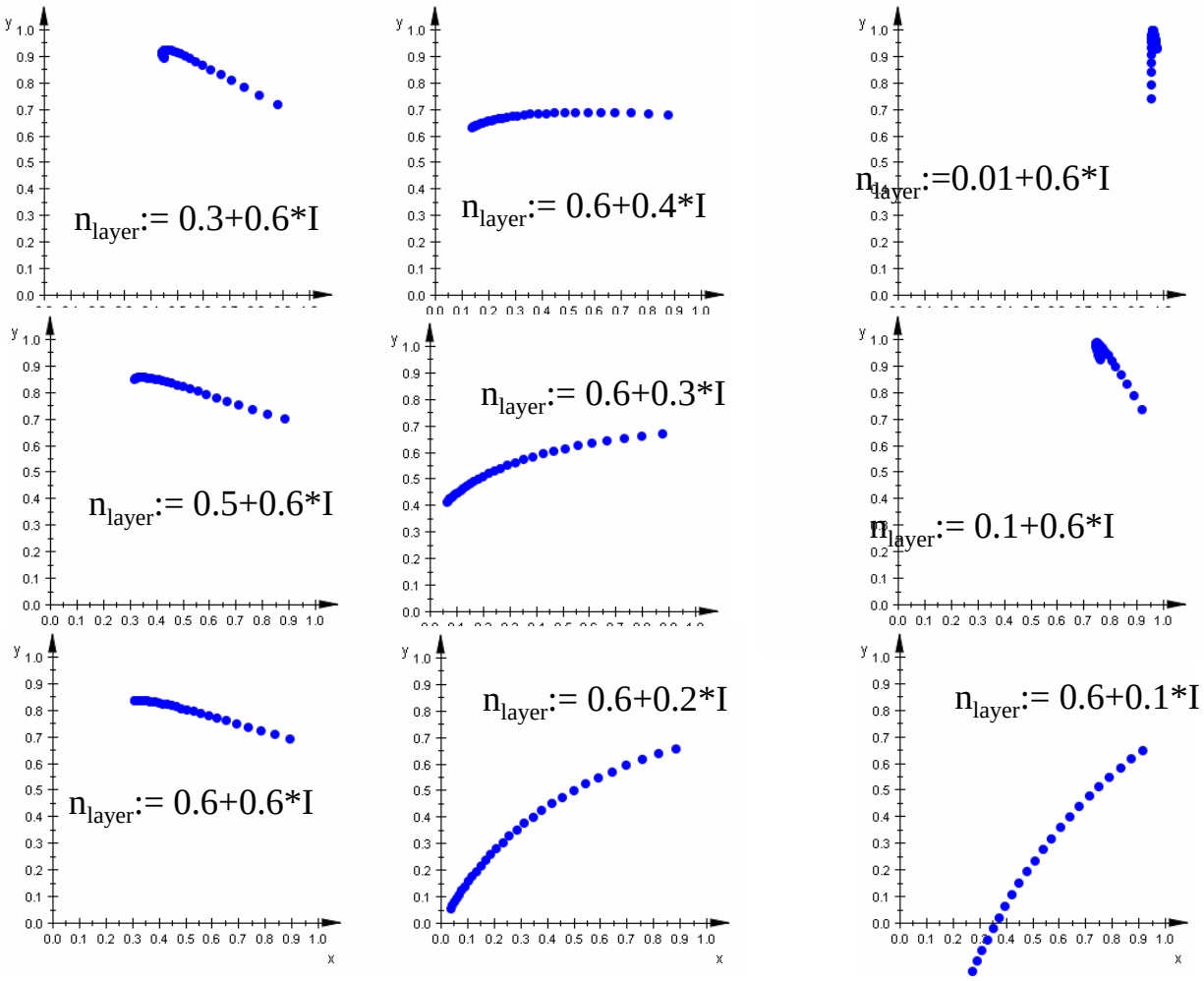
→ Expansion component was the same ion abundance.
==>Neutral Au!

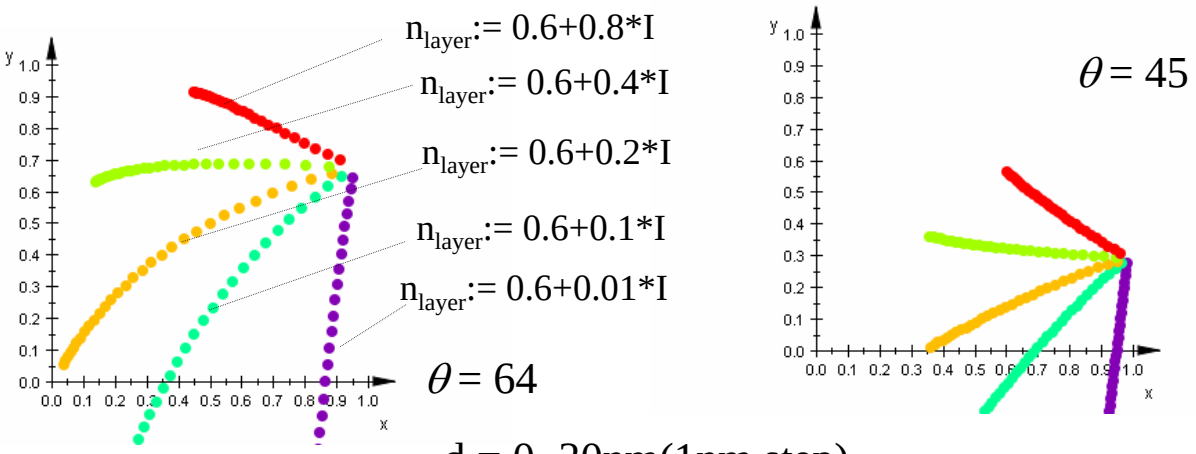
Au trajectory (experimental data)



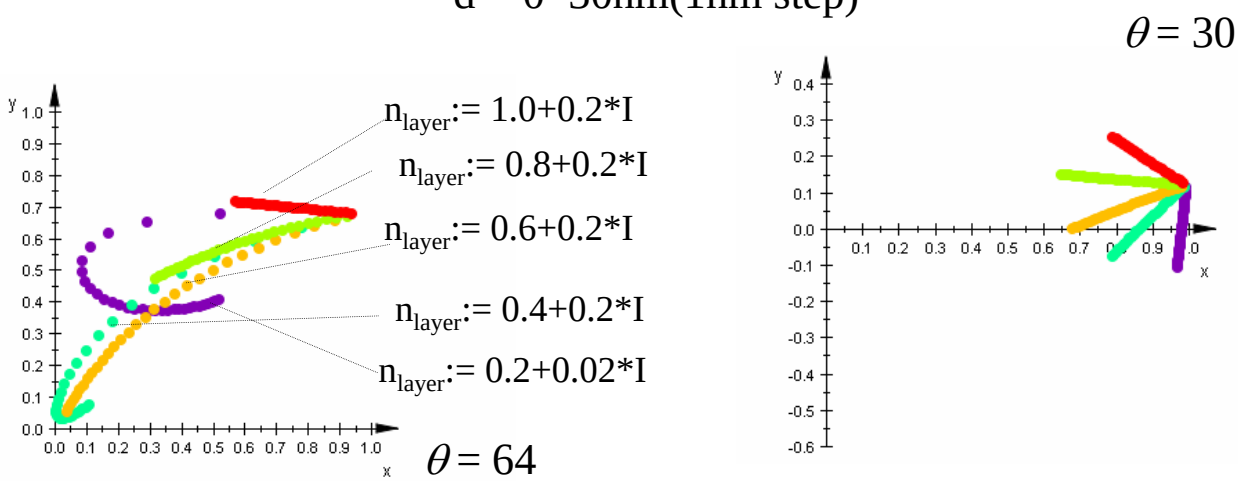


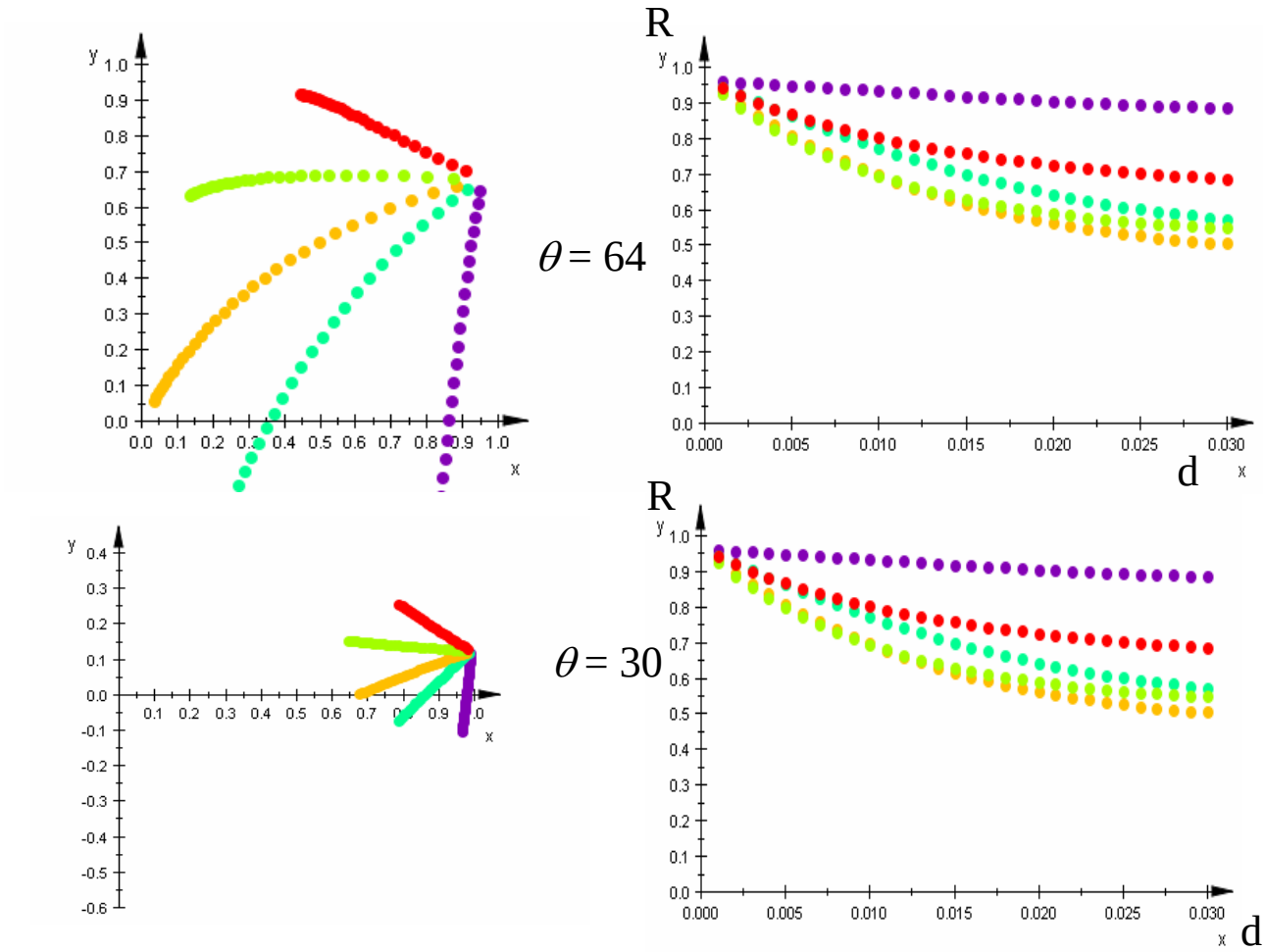






d = 0~30nm(1nm step)





Calculated Au trajectories (small dependence on initial T)

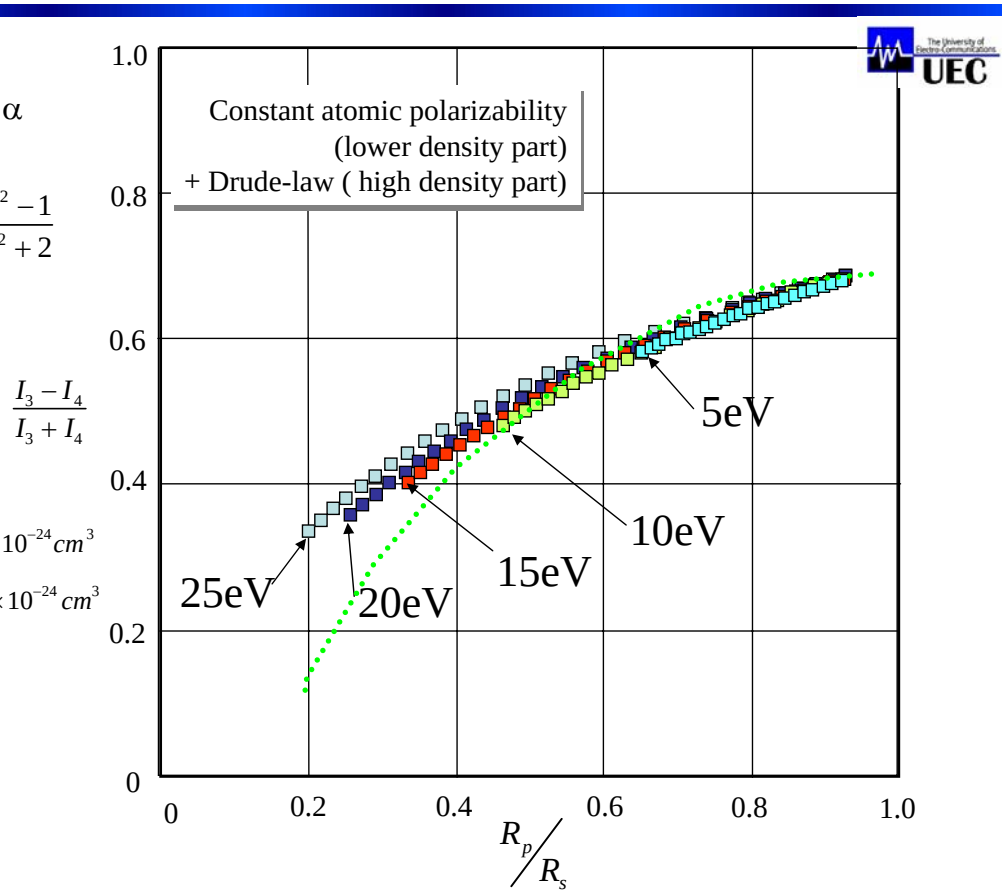
atomic polarizability α

$$\mathbf{P} = N\mathbf{p} = N\alpha\mathbf{E}'$$

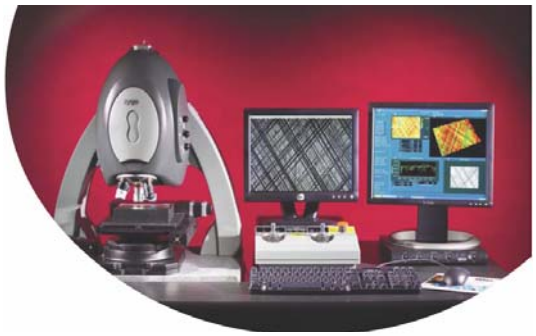
$$\alpha = \frac{3}{4\pi N}\frac{\varepsilon - 1}{\varepsilon + 2} = \frac{3}{4\pi N}\frac{n^2 - 1}{n^2 + 2}$$

$$\alpha(vapor) = (-1.75 + 0.2i) \times 10^{-24} cm^3$$

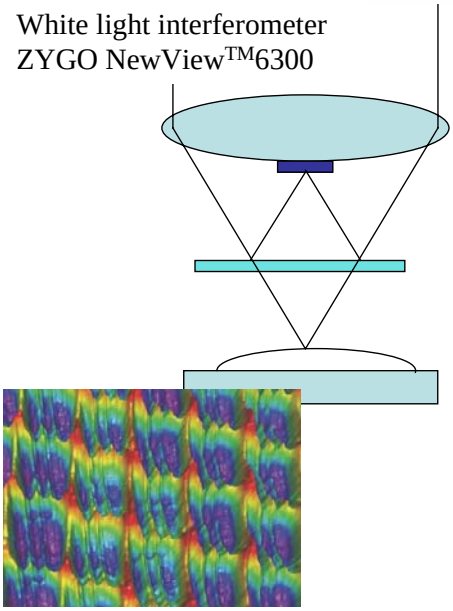
$$\alpha(metal) = (-29.4 + 0.14i) \times 10^{-24} cm^3$$



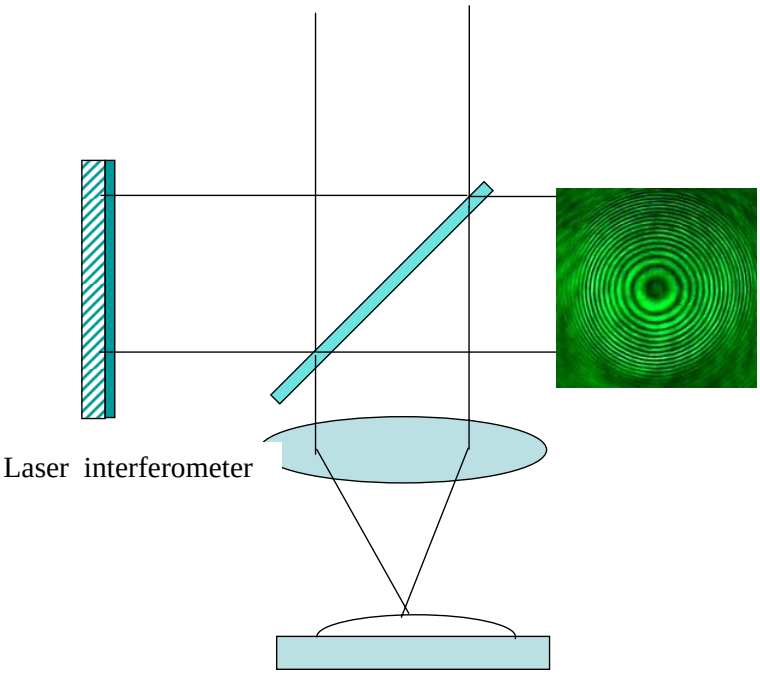
Interferometers



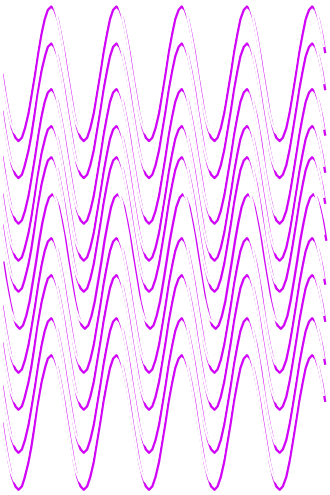
White light interferometer
ZYGO NewView^{TM}6300

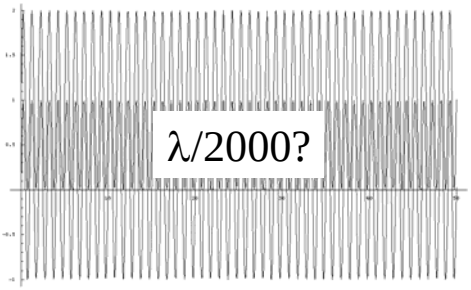


Vertical Resolution ~0.1nm



Vertical Resolution ~λ/40?





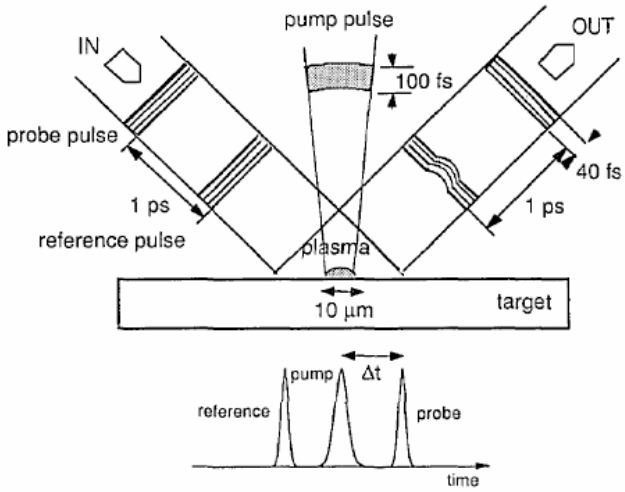
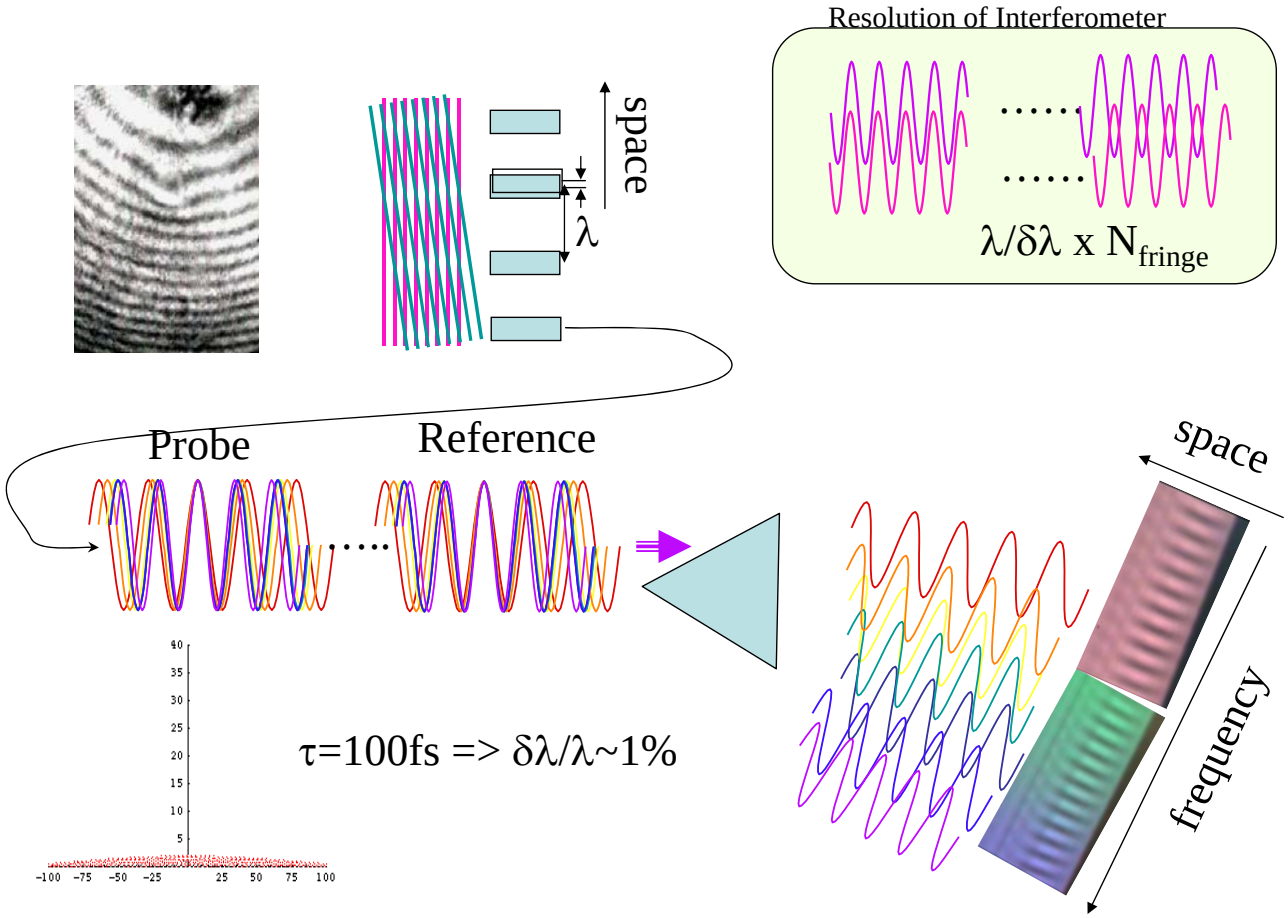


Fig. 1. Frequency-domain interferometer principle. Typical dimensions and times are indicated. The probe and reference pulses interfere after passing through a grating pulse stretcher.

λ/2000 phase resolution is described.

JP Geindre, et al., Opt. Lett., vol.19, 1997(1994)

White light/ Frequency resolved interferometer



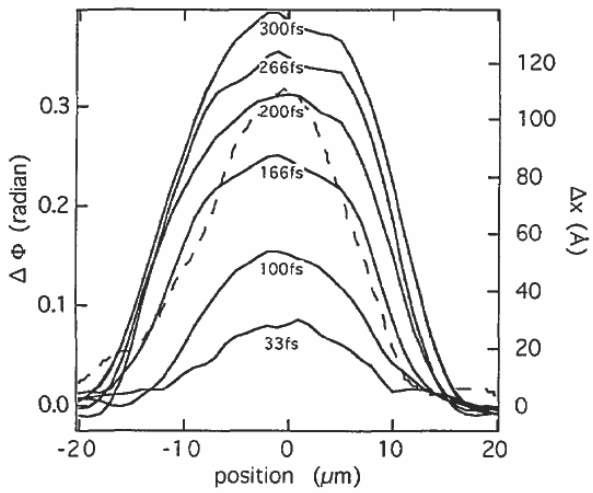


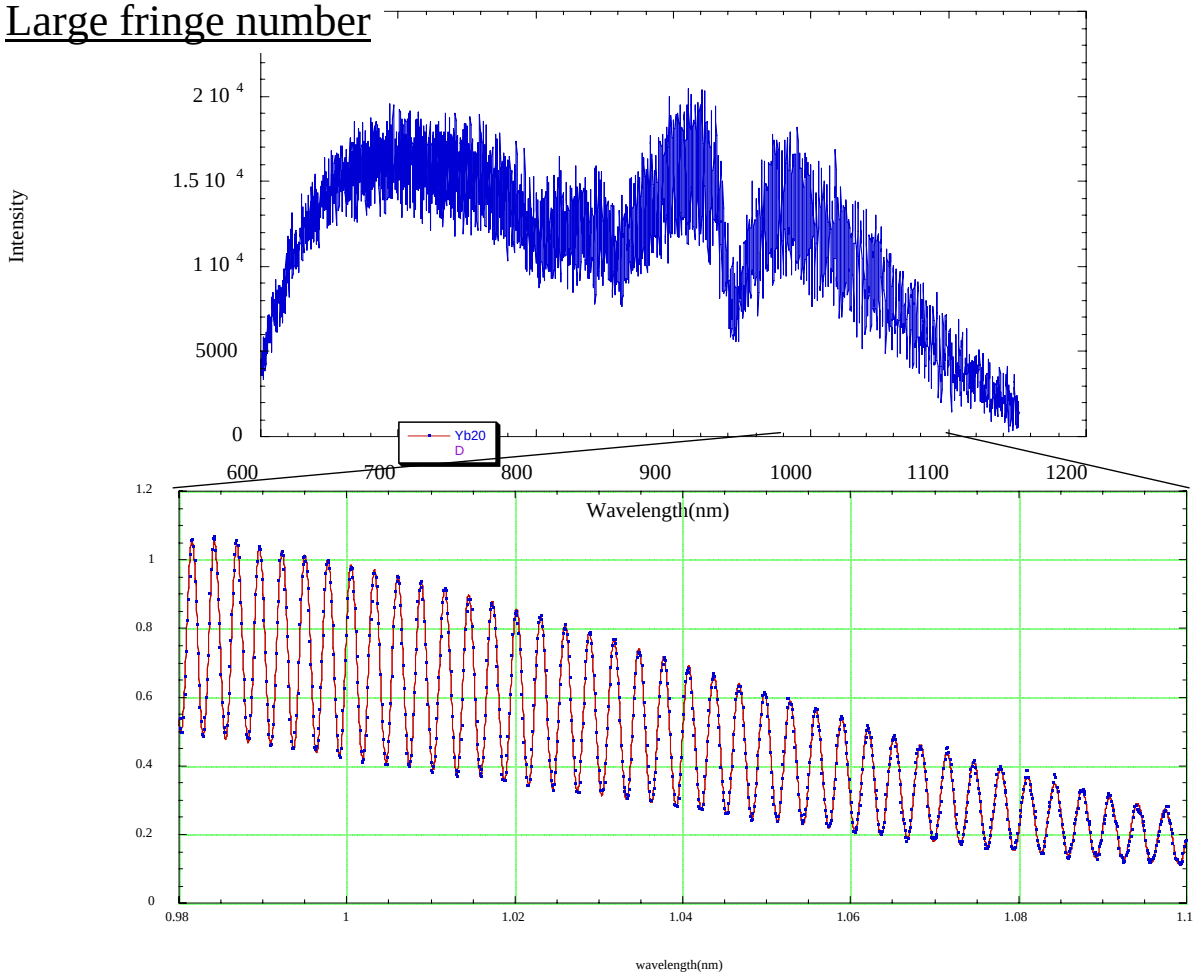
Fig. 2. Space- and time-resolved phase measurement of an aluminum plasma at 3×10^{15} W/cm^2 irradiance. Phases have been converted to positions along the normal to the target surface on the right-hand scale. The radial laser intensity shape (in linear arbitrary units) is given by the dashed curve.

JP Geindre, et al., Opt. Lett., vol.19, 1997(1994)

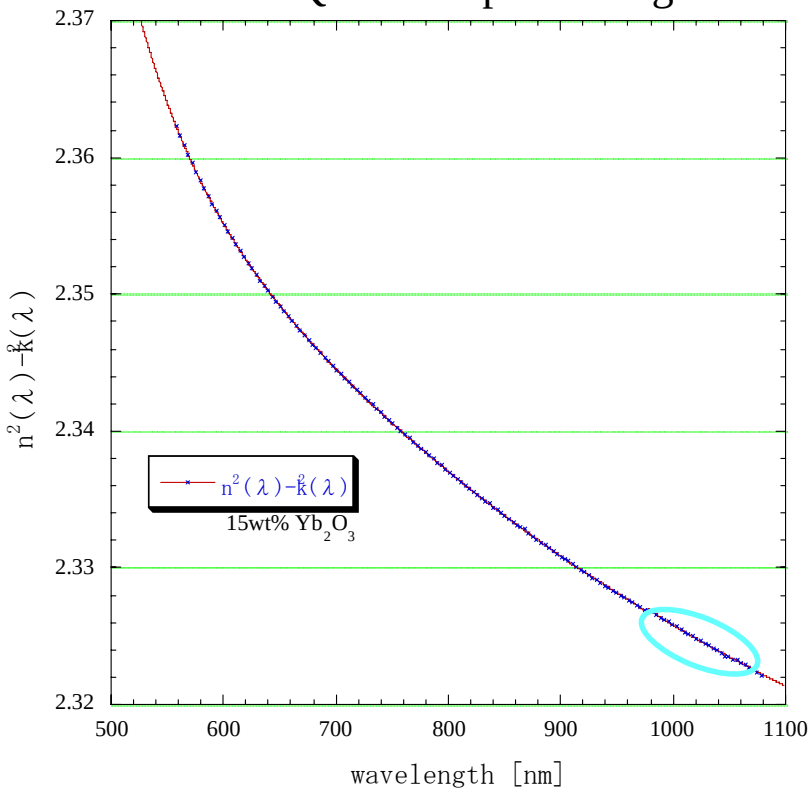
Toward

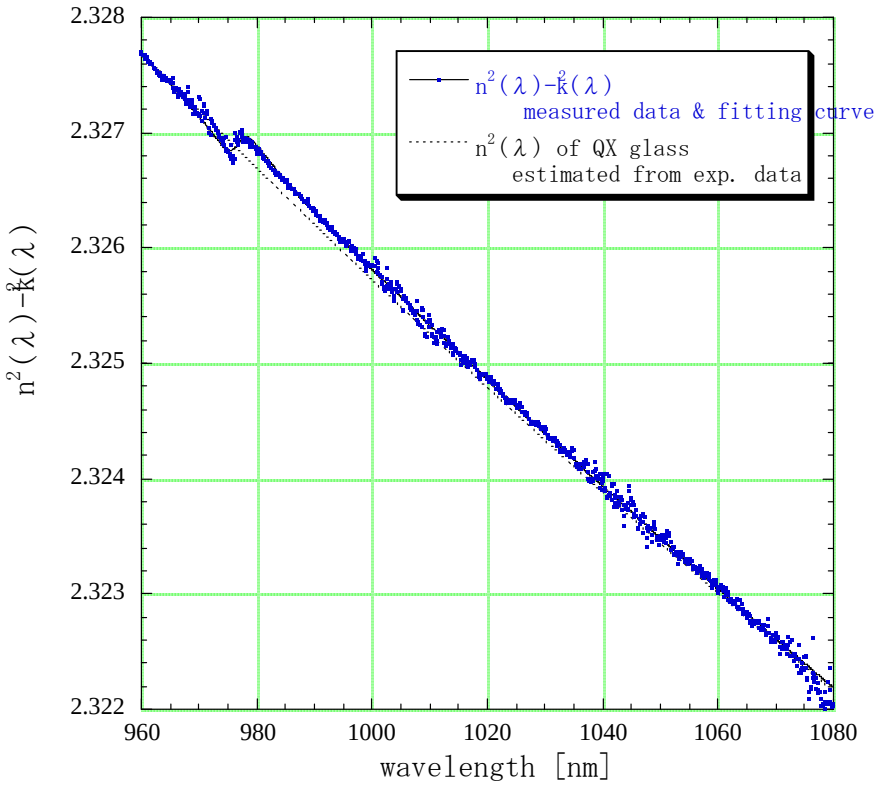
more precise measurements

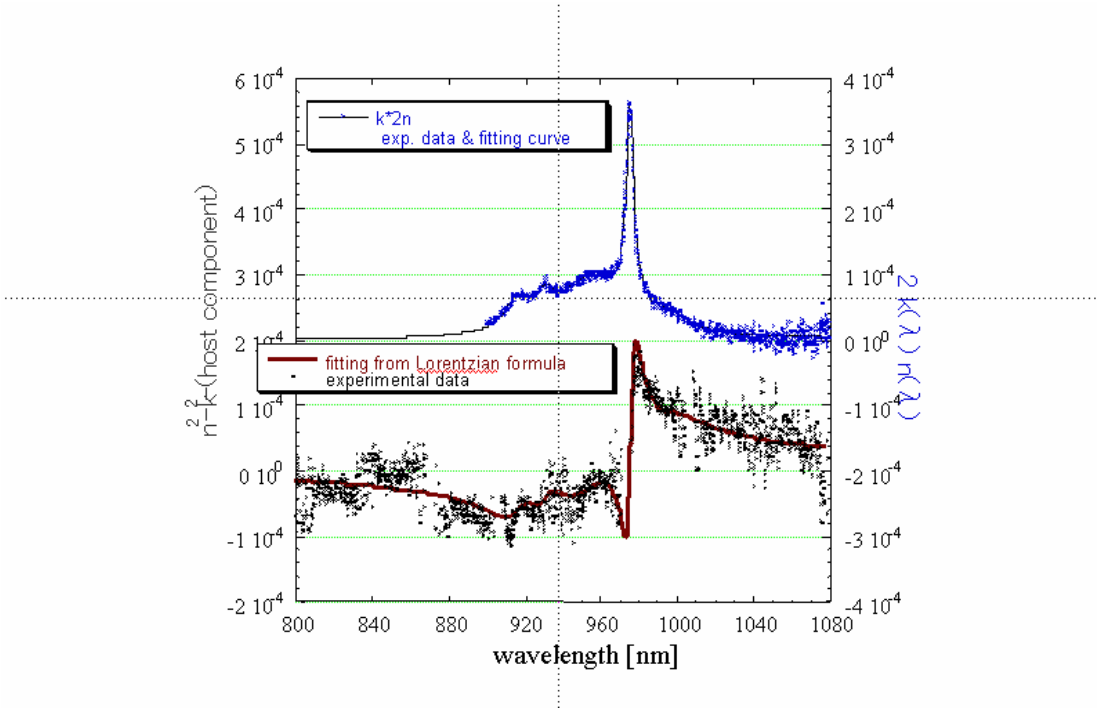
Large fringe number



QX Yb-doped laser glass







$d\phi < 10^{-5}$

Models (formula)

for optical refractive index

at high temperature

Temperature dependence of optical refractive index

Which parameters do change in temperature?

$$n^2 = \varepsilon_{1R}(\omega) = 1 + \left(Ne^2 / m\varepsilon_0\right)\frac{\omega_0^2 - \omega^2}{(\omega_0^2 - \omega^2)^2 + g^2\omega^2} = 1 + F_s\frac{\omega_p^2}{(\omega_0^2 - \omega^2)}$$

$$\omega_p^2 = \frac{Ne^2}{m\varepsilon_0}$$

Then

$$2n\frac{dn}{dT} = F_s\left[\frac{1}{(\omega_0^2 - \omega^2)}\frac{d}{dT}\omega_p^2 + \omega_p^2\frac{d}{dT}\frac{1}{(\omega_0^2 - \omega^2)}\right]$$

Then

$$2n\frac{dn}{dT} = F_s\left[-3\alpha_{\exp}\frac{\omega_p^2}{(\omega_0^2 - \omega^2)} - \frac{\omega_p^2}{(\omega_0^2 - \omega^2)^2}\frac{d}{dT}\omega_0^2\right]$$

$$2n\frac{dn}{dT} = F_s\frac{\omega_p^2}{\omega_0^2}\left[-3\alpha_{\exp}\frac{\omega_0^2}{(\omega_0^2 - \omega^2)} - \frac{\omega_0^2}{(\omega_0^2 - \omega^2)^2}\frac{d}{dT}\omega_0^2\right] = \left(n_\infty^2 - 1\right)\left(-3\alpha_{\exp}R - \frac{1}{E_{bg}}\frac{dE_{bg}}{dT}R^2\right)$$

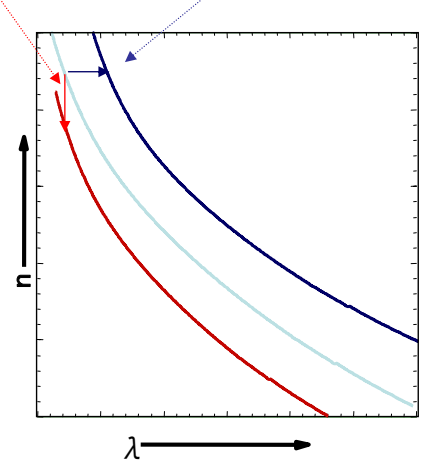
$$R = \frac{\omega_0^2}{(\omega_0^2 - \omega^2)} = \frac{\lambda^2}{(\lambda^2 - \lambda_0^2)}$$

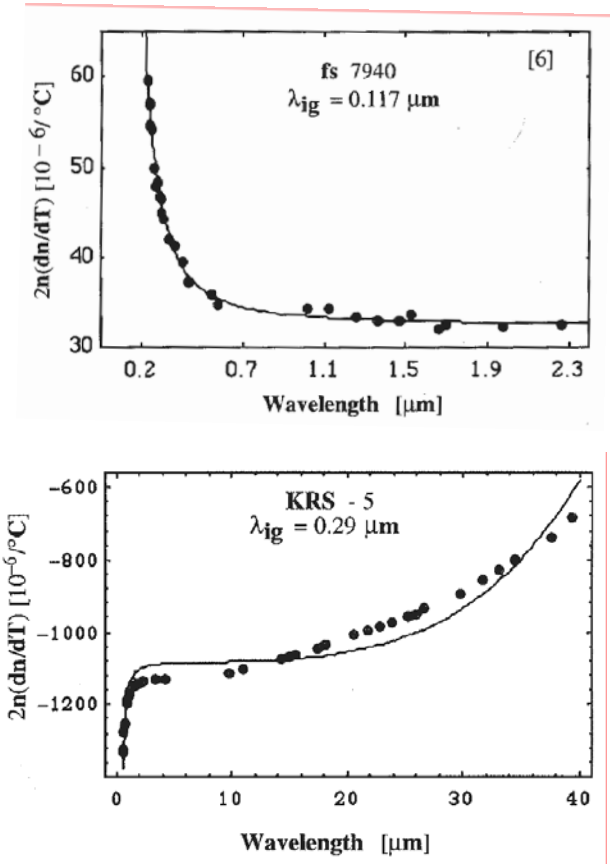
$$2n\frac{dn}{dT} = \left(n_\infty^2 - 1\right)\left(-3\alpha_{\exp}R - \frac{1}{E_{bg}}\frac{dE_{bg}}{dT}R^2\right)$$

ω->0 components

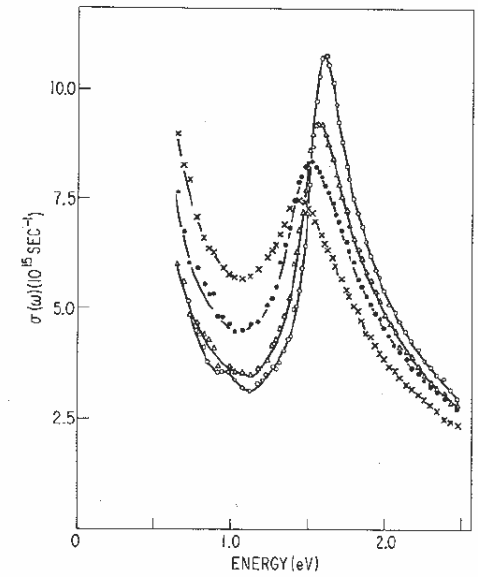
Expansion term

Terms for band gap energy change with temperature





G Gosh, Handbook of Thermo-Optic Coeff. Of Optical Materials with Applications

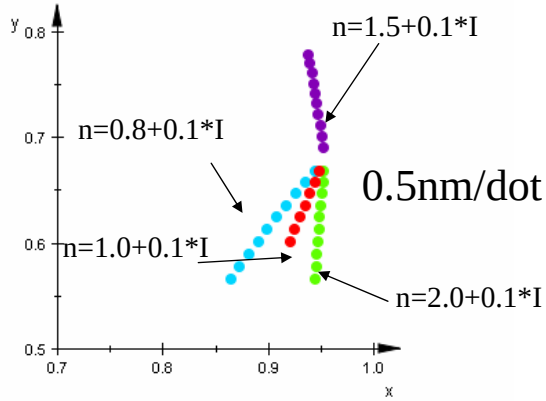


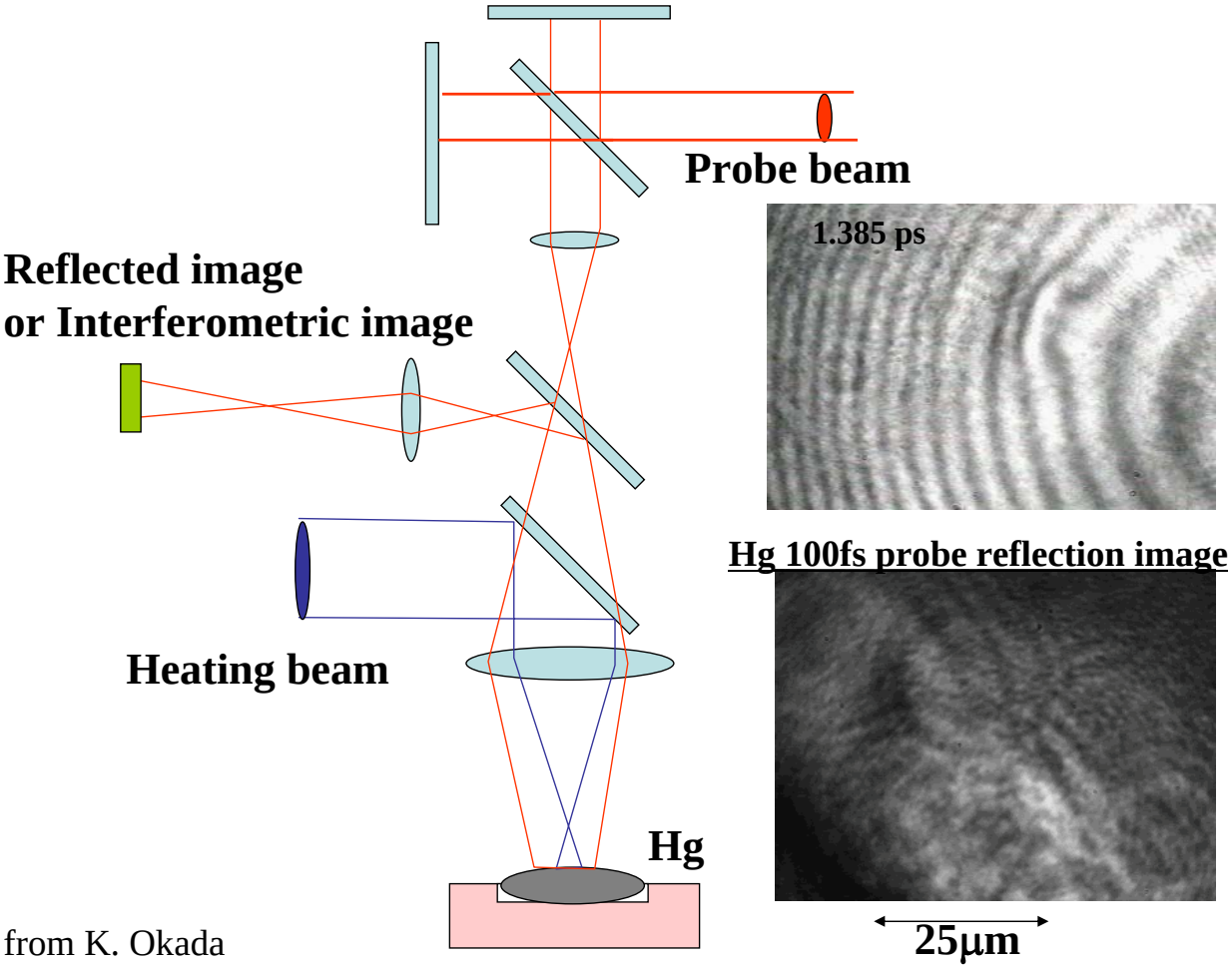
Palik, Handbook of Optical Constants of Solids

Others we should consider:

1. Impurity of material (if we carefully investigate the elements.)
2. Surface contamination layer (Oxidation layer effect)
   glow discharge cleaning, oil free vacuum system, laser cleaning just before the main shot.
3. Prepulse effect to decrease the density and to make gray region in front of the solid.
4. Spatial non-uniformity of pump laser (multimode +broadband light may relax this effect.)
5. Surface roughness of the target.
6. Reproducibility of alignment
7. Plasma background emission

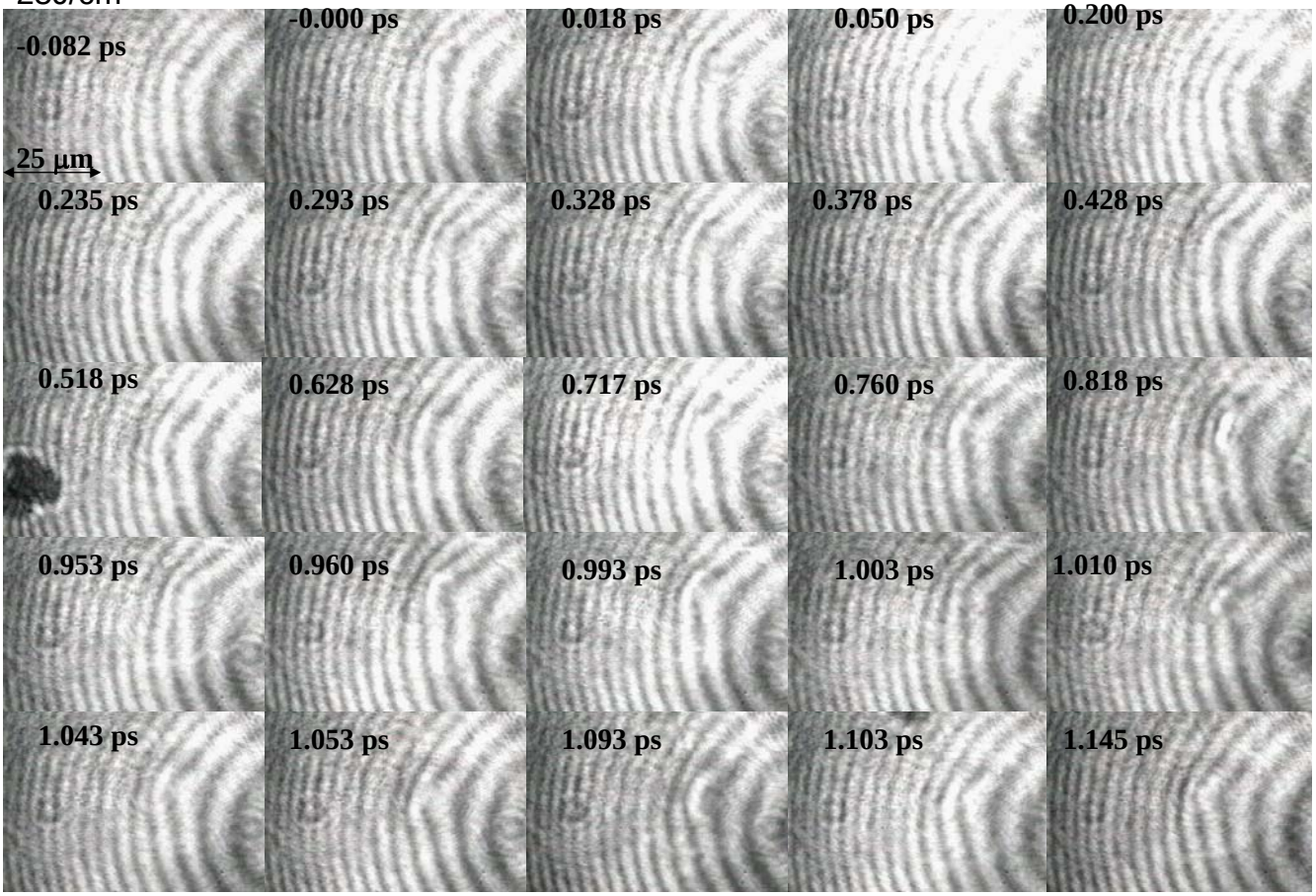
Dielectric material layer on gold

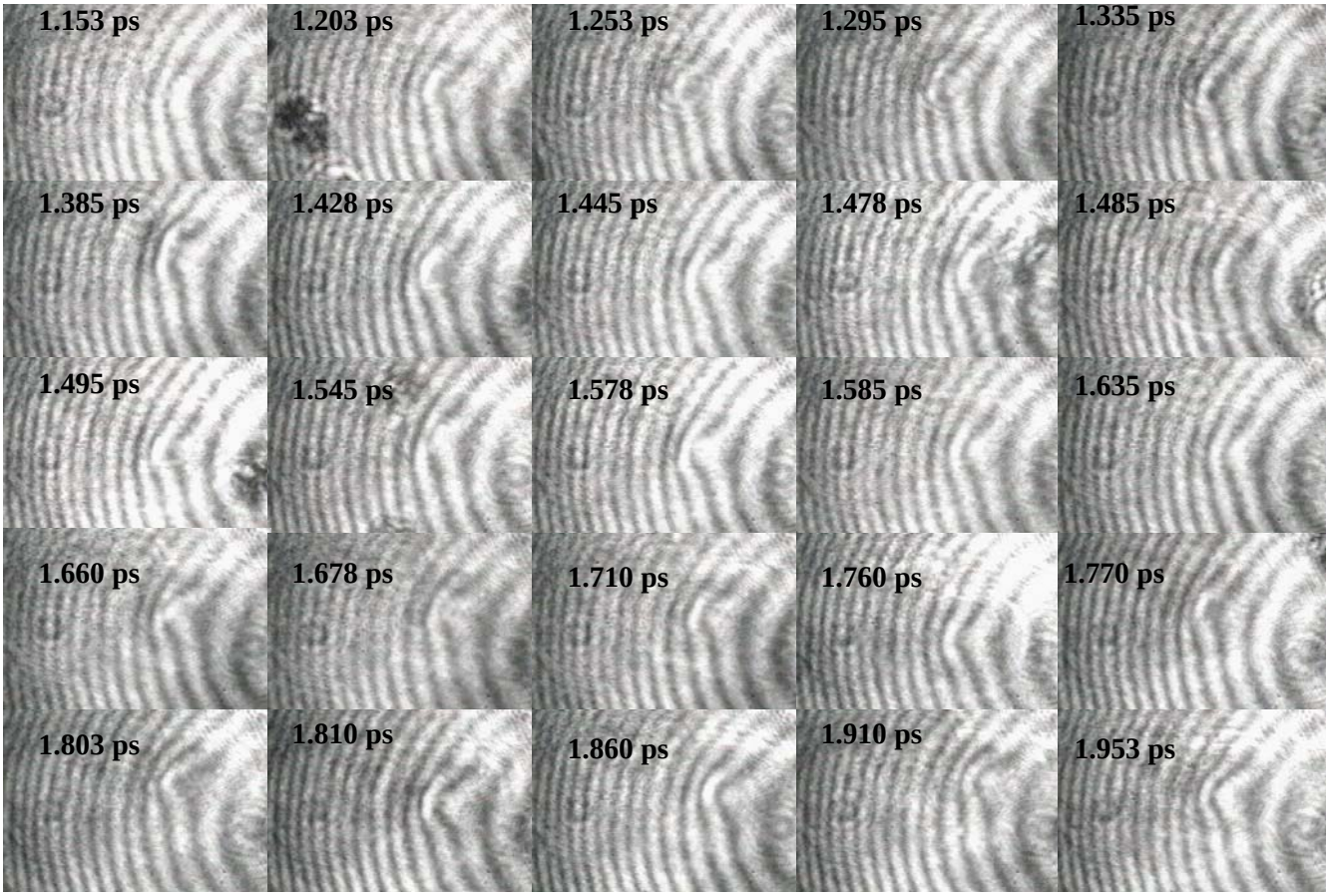


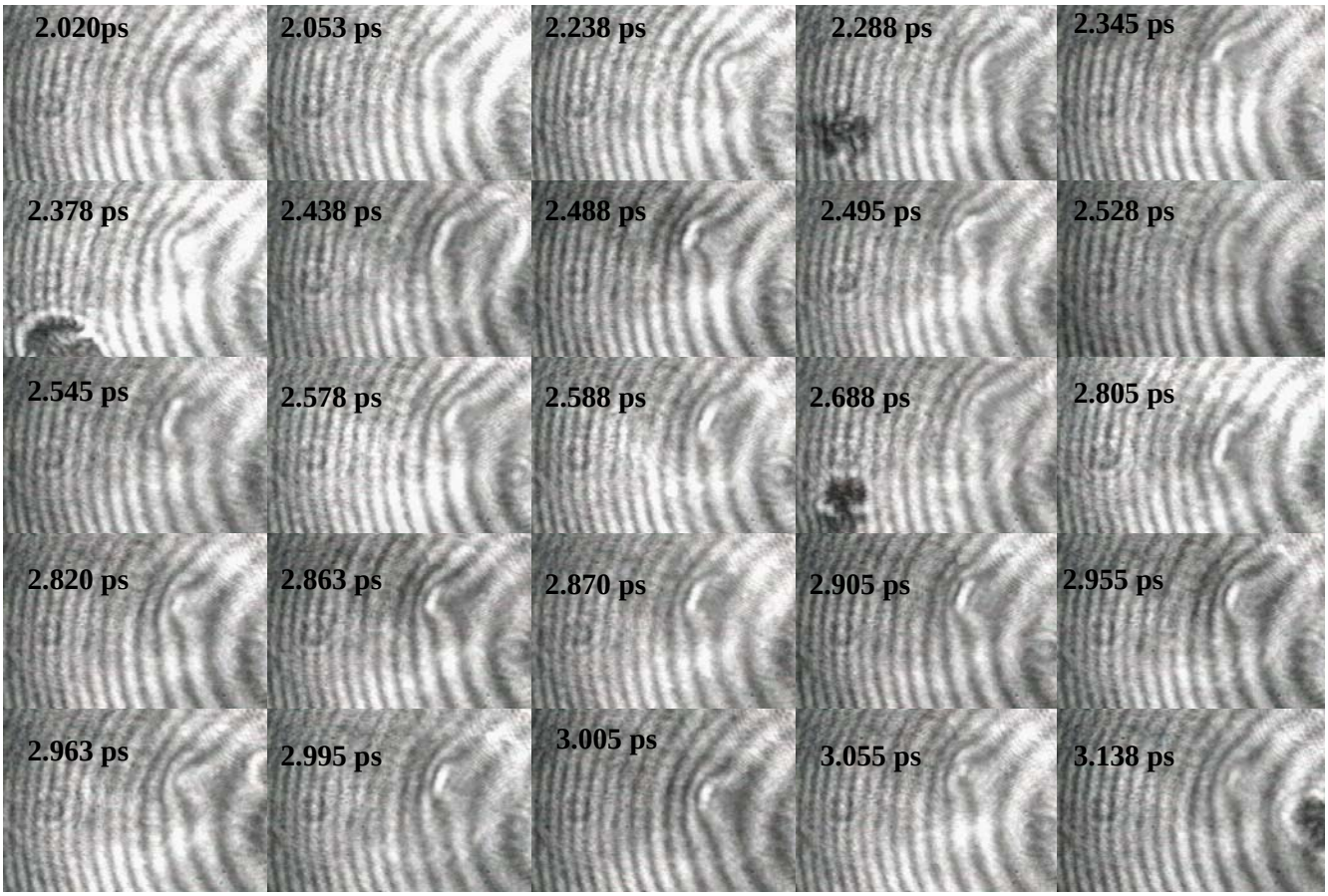


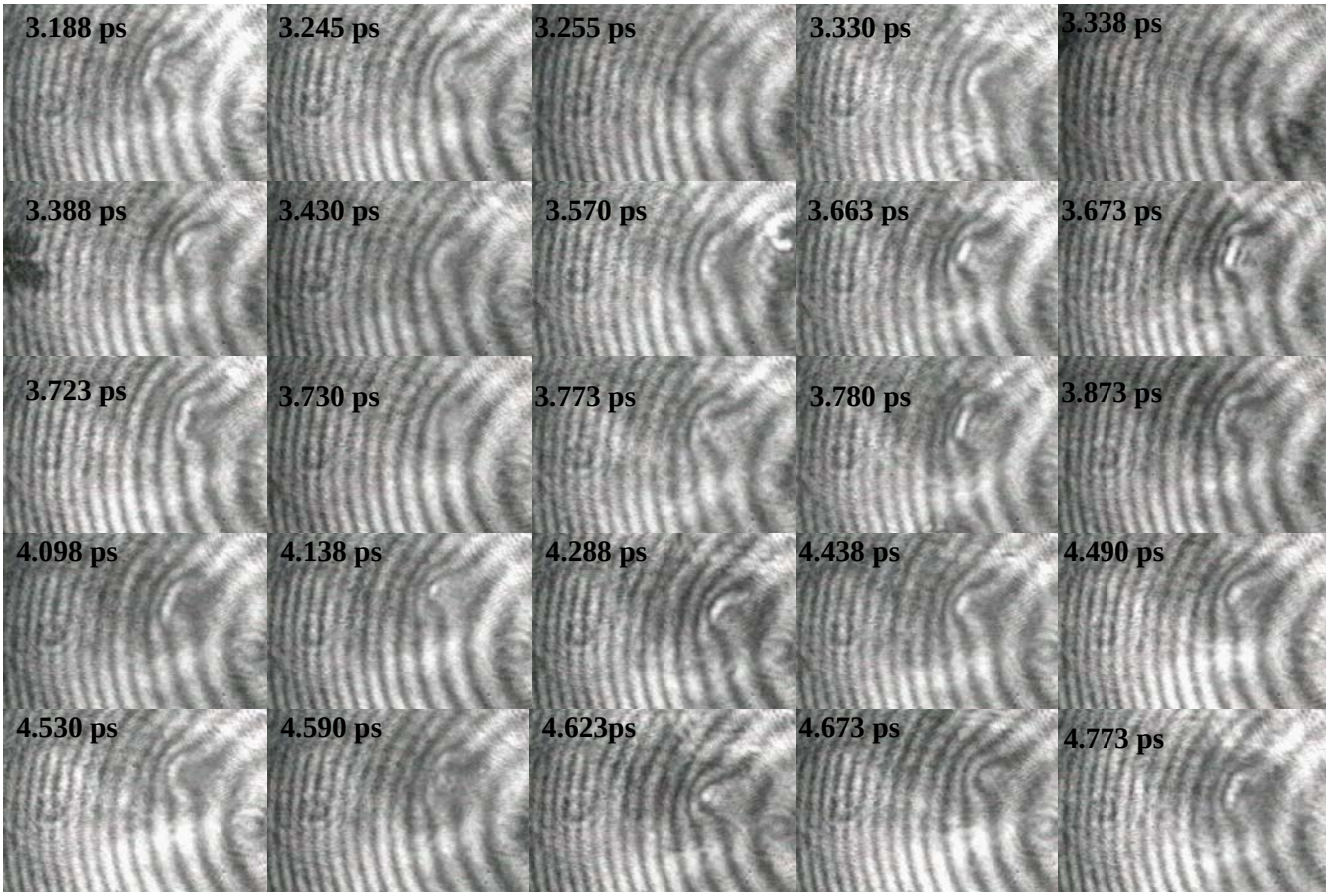
from K. Okada

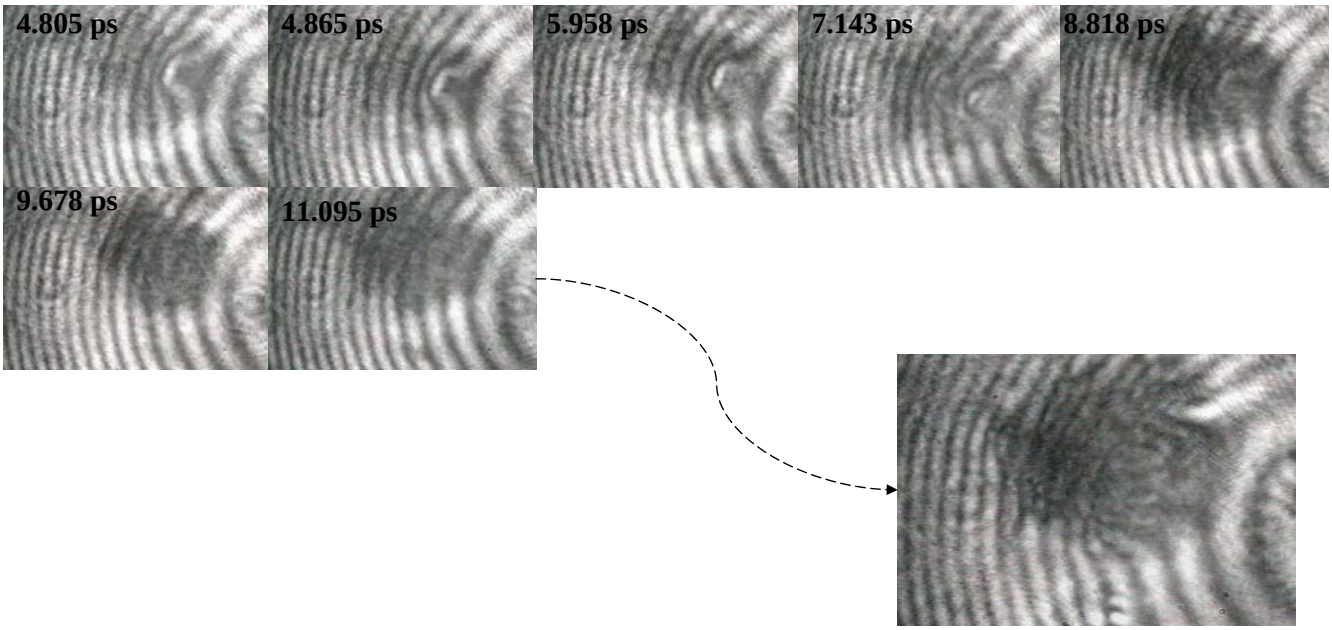
25J/cm^2




1.153 ps
1.203 ps
1.253 ps
1.295 ps
1.335 ps
1.385 ps
1.428 ps
1.445 ps
1.478 ps
1.485 ps
1.495 ps
1.545 ps
1.578 ps
1.585 ps
1.635 ps
1.660 ps
1.678 ps
1.710 ps
1.760 ps
1.770 ps
1.803 ps
1.810 ps
1.860 ps
1.910 ps
1.953 ps

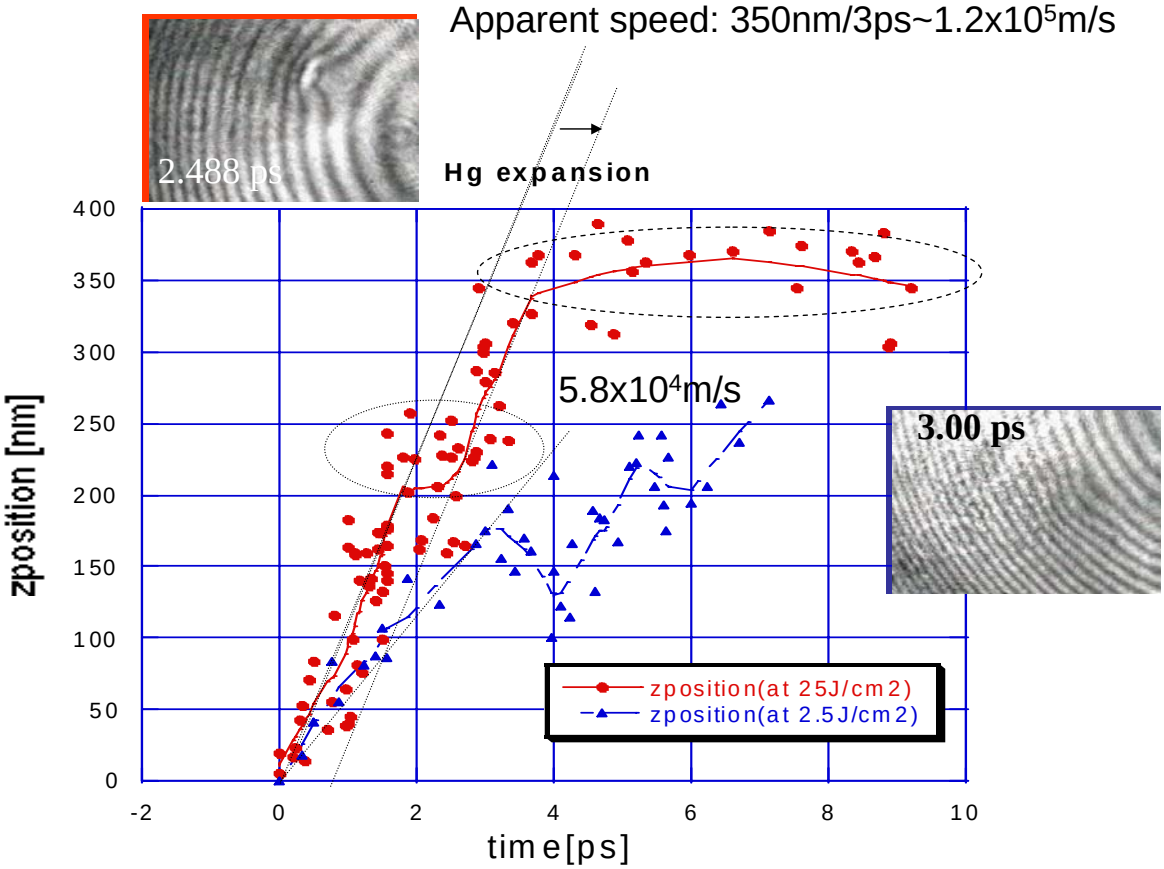

2.020ps
2.053 ps
2.238 ps
2.288 ps
2.345 ps
2.378 ps
2.438 ps
2.488 ps
2.495 ps
2.528 ps
2.545 ps
2.578 ps
2.588 ps
2.688 ps
2.805 ps
2.820 ps
2.863 ps
2.870 ps
2.905 ps
2.955 ps
2.963 ps
2.995 ps
3.005 ps
3.055 ps
3.138 ps

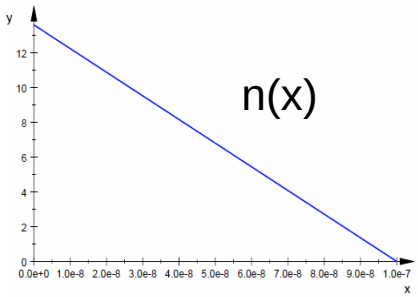

3.188 ps
3.245 ps
3.255 ps
3.330 ps
3.338 ps
3.388 ps
3.430 ps
3.570 ps
3.663 ps
3.673 ps
3.723 ps
3.730 ps
3.773 ps
3.780 ps
3.873 ps
4.098 ps
4.138 ps
4.288 ps
4.438 ps
4.490 ps
4.530 ps
4.590 ps
4.623ps
4.673 ps
4.773 ps

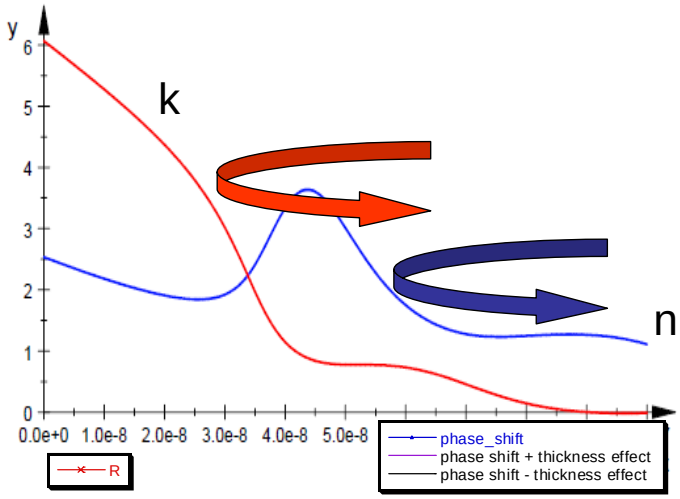

4.805 ps
4.865 ps
5.958 ps
7.143 ps
8.818 ps
9.678 ps
11.095 ps

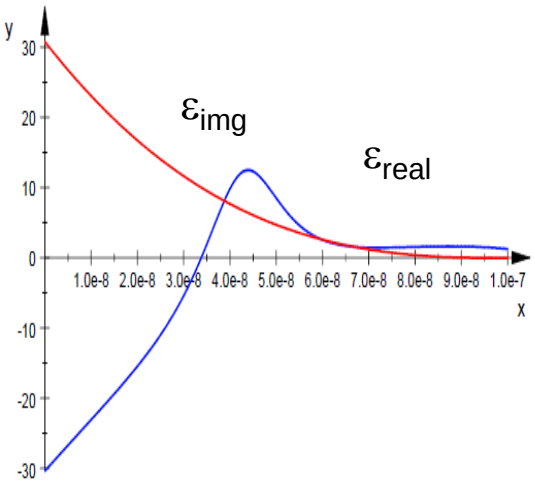
50 ps

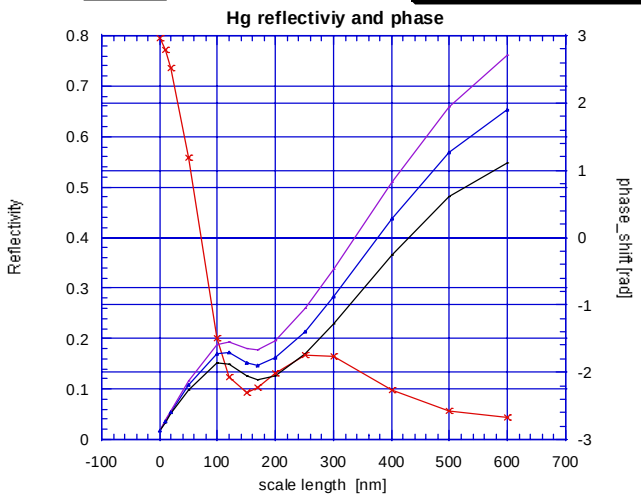
Apparent speed: 350nm/3ps~1.2x10^{5}m/s



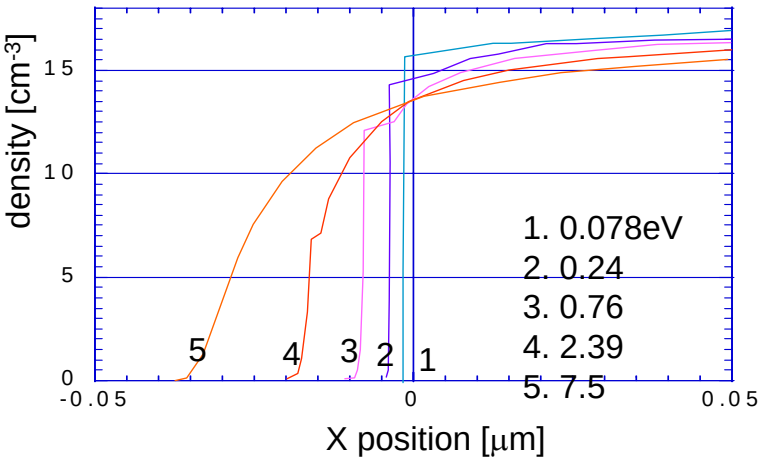


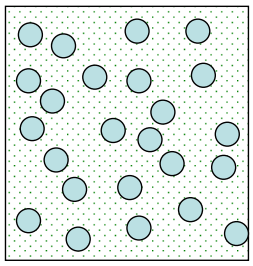


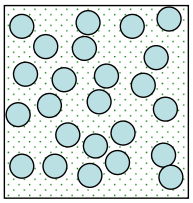




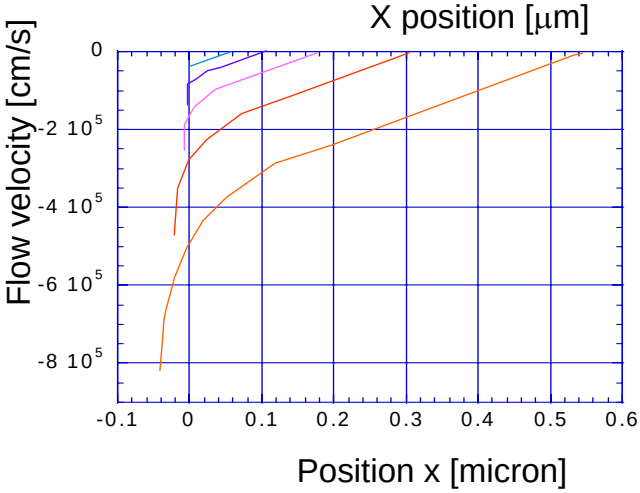
Due to EOS feature, we can expect sharp expansion front with some condition.

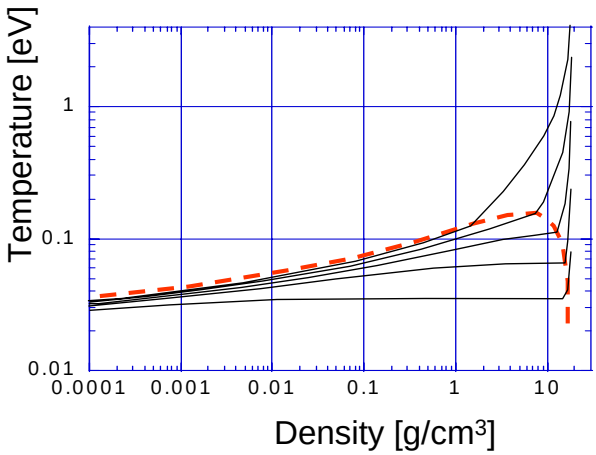






$$c^2 = \frac{\partial p}{\partial \rho}$$





Why WDM physics? (2) Critical point data of Fluid metal

	atom	Tc[K]	P_c [MPa]	Vc [m^3/Mmol]	$Z_c=P_cV_c/RT_c$	ρ_c[g/cc]
static pressure	Hg	1750	167.3	34.8	0.40	5.80
	Cs	1651	9.25	351	0.203	0.38
	Rb	1744	12.45	293	0.218	0.29
	K	1905	14.8	--	--	0.18
	Se	1903	38.0	42.7	0.103	0.103
dynamic pressure	Na	2485 or 2210	25.6 or 24.8	76.7	0.095	0.30
	Sn	8720? or 9280	210 or 370	---	--	1.5?
	Pb	5400 or 5100	85 or 250	---	--	3.2
	In	6700?	400	---	--	2.1
	Mo	14000?	57	---	--	2.9
	W	23000? or 15000	>1000	---	--	--
	Many others	??	??	??	??	??

VISAR

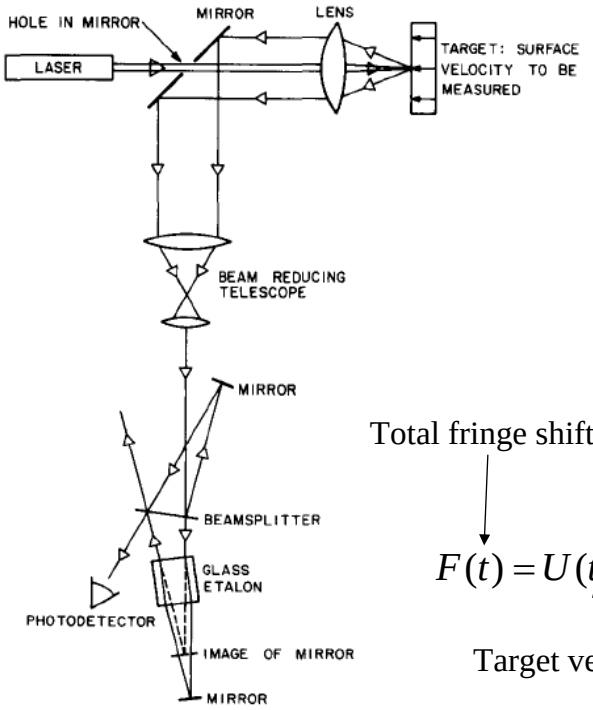
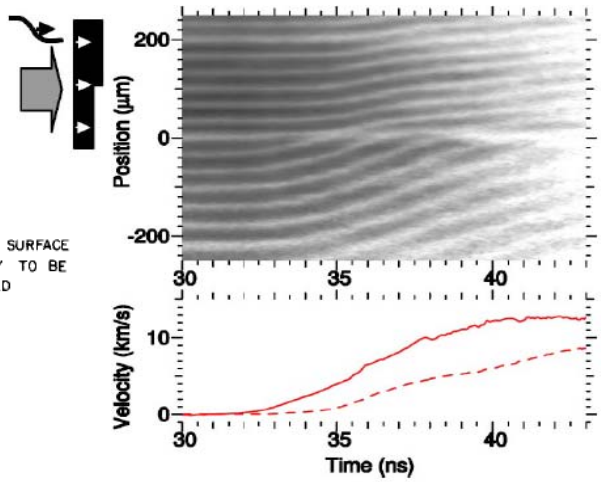


FIG. 1. Simplified VISAR showing optical paths from laser to photodetector.



motion on the rear surface of a stepped Al plate driven
ockless) stress wave. The curves show the velocities
nin (solid curve) and thick (dashed curve) steps of the

Total fringe shift

Velocity fringe constant

$$F(t) = U(t)/K = U(t)/\frac{\lambda_0 c}{4h(n-1/n)(1+\delta)}$$

Target velocity

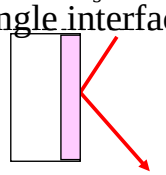
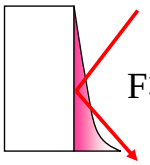
Length of etalon

Etalon index of refraction

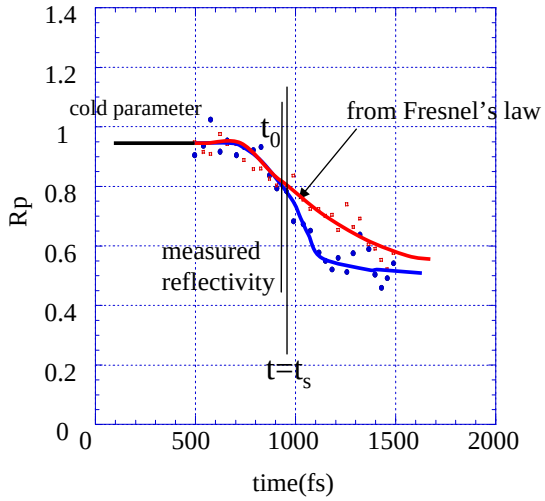
To check starting time when expansion component cannot be neglected.

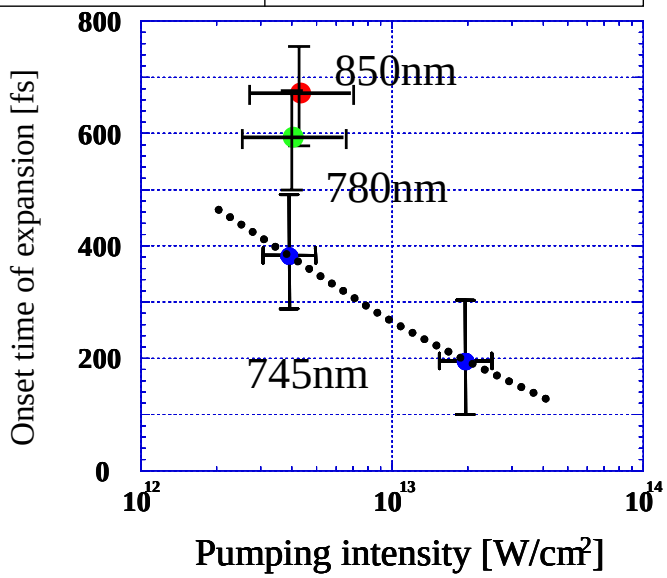
measured parameters

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

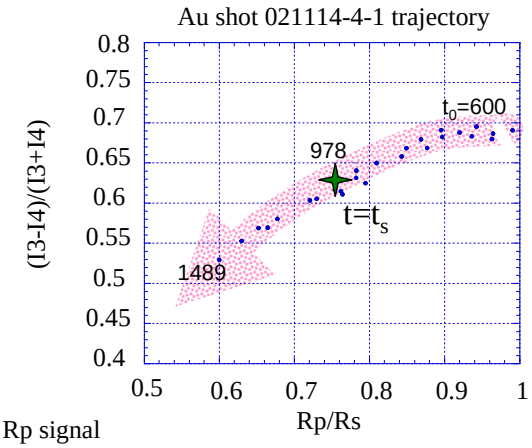
time	$t < t_s$	$t_s < t$
plasma	single interface  F=2 $\rho = \tan(\varphi)\exp(i\Delta)$	expanded plasma  F>3
Fresnel's law	available	No

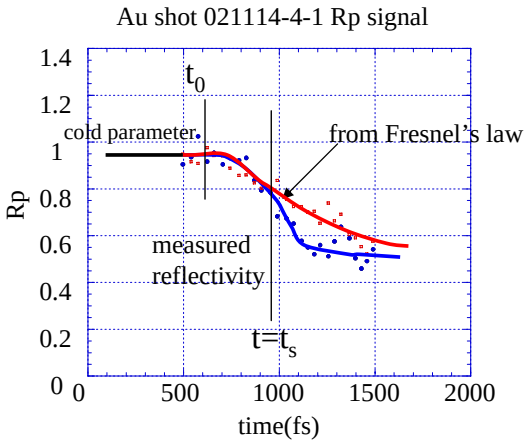
Au shot 021114-4-1 Rp signal

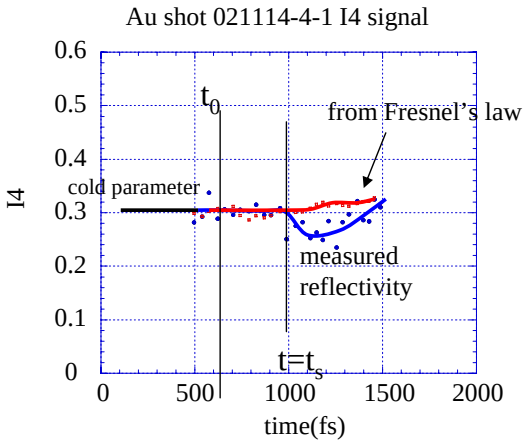




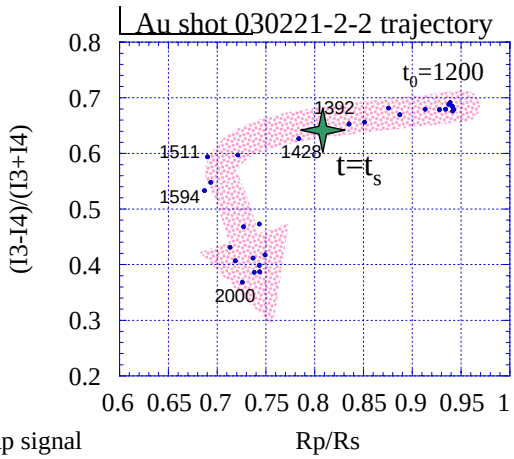
In the case of low pump intensity, reflectivity can be reproduced from only Fresnel's law at the first time.

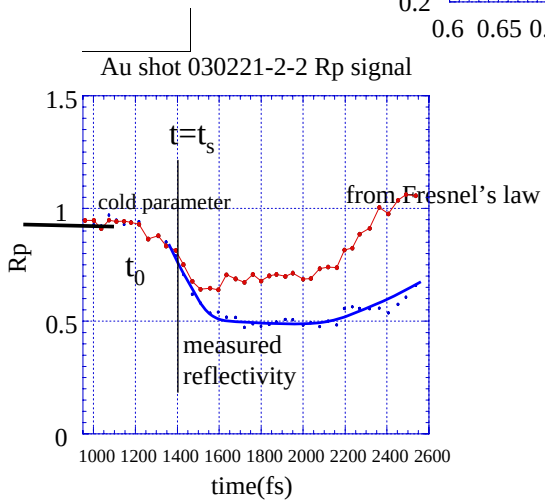


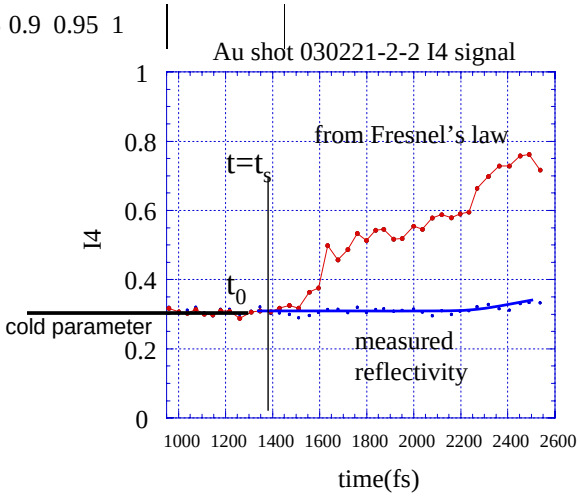


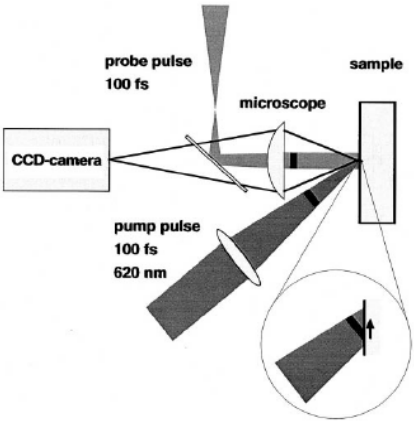


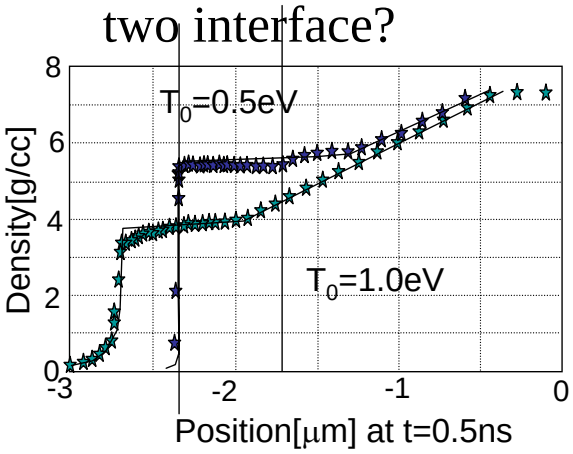
In high intensity, reflectivity separate from Fresnel's law.



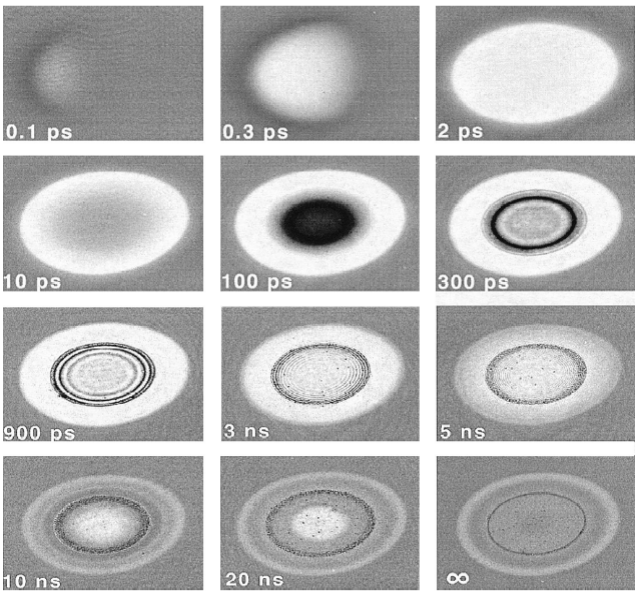




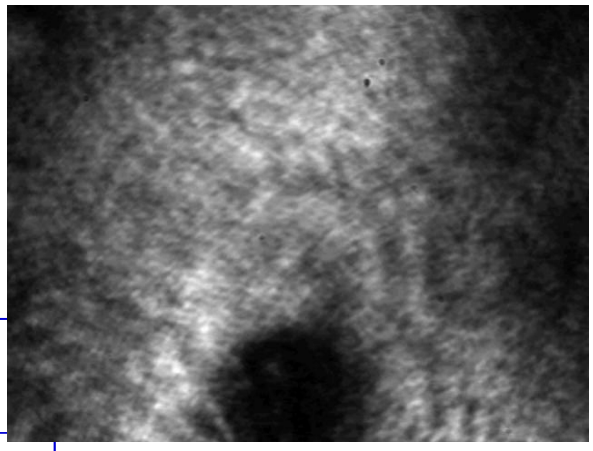


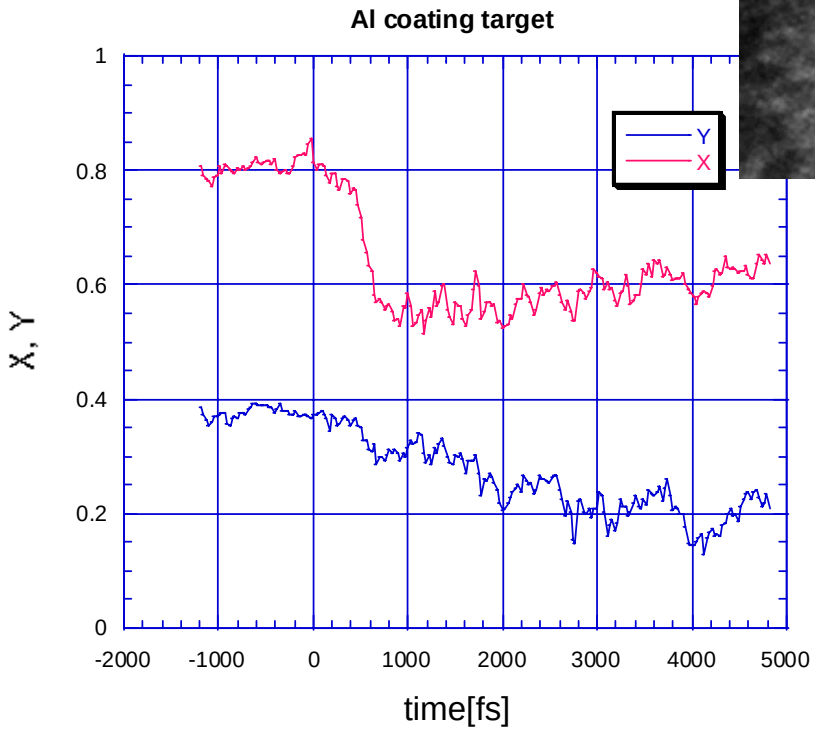


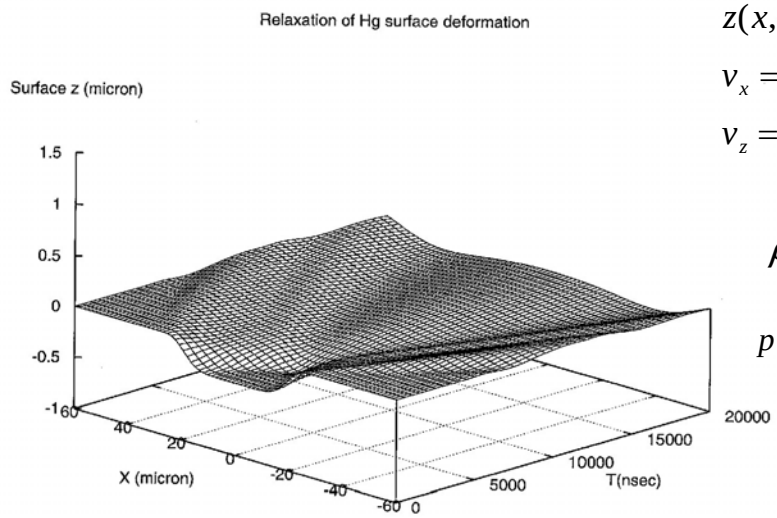
Snapshots with 100-fs time resolution. Si(111).excited with 0.47 Jrcm2. Frame size: 300 mm=220 mm.



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







$$z(x,t) = a\cos(kx)sin(\omega t)$$

$$v_x = -a\omega \cdot sin(kx) \cdot e^{kz} \cdot \cos(\omega t)$$

$$v_z = +a\omega \cdot \cos(kx) \cdot e^{kz} \cdot \cos(\omega t)$$

$$\rho \frac{\partial v}{\partial t} = -\nabla p + O(v^2)$$

$$p = \sigma k^2 a \cdot \cos(kx) \cdot e^{kz} \cdot sin(\omega t)$$

$$p_{surface} = p(x,o,t) = \frac{\sigma}{R}$$

$$\frac{1}{R} = \frac{d^2 z}{dx^2} = k^2 z$$

$$KE = \frac{\pi}{2} L\rho \frac{\omega^2 a^2}{k^2} \cos^2(\omega t)$$

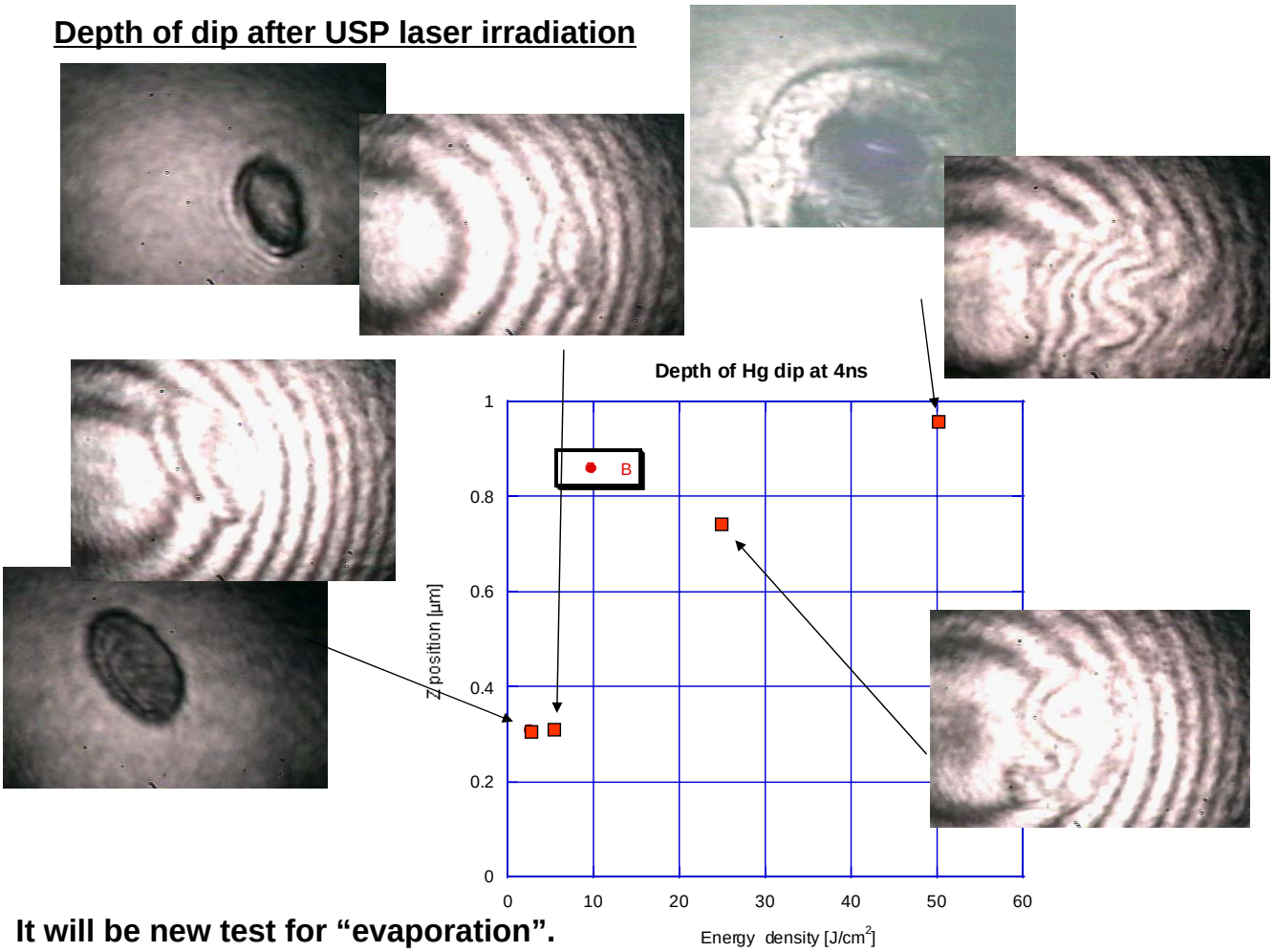
$$PE = \frac{\pi}{2} L\sigma k a^2 sin^2(\omega t)$$

$$\omega^2 = \frac{\sigma}{\rho} k^3$$

$$c_{sp} = \sqrt{\frac{2\pi\sigma}{\lambda\rho}}$$

Ex. For Hg, σ=540erg/cm^2, ρ=13g/cc
λ=10μm => c_{sp}=500cm/s = 10μm/(2μs)

Depth of dip after USP laser irradiation

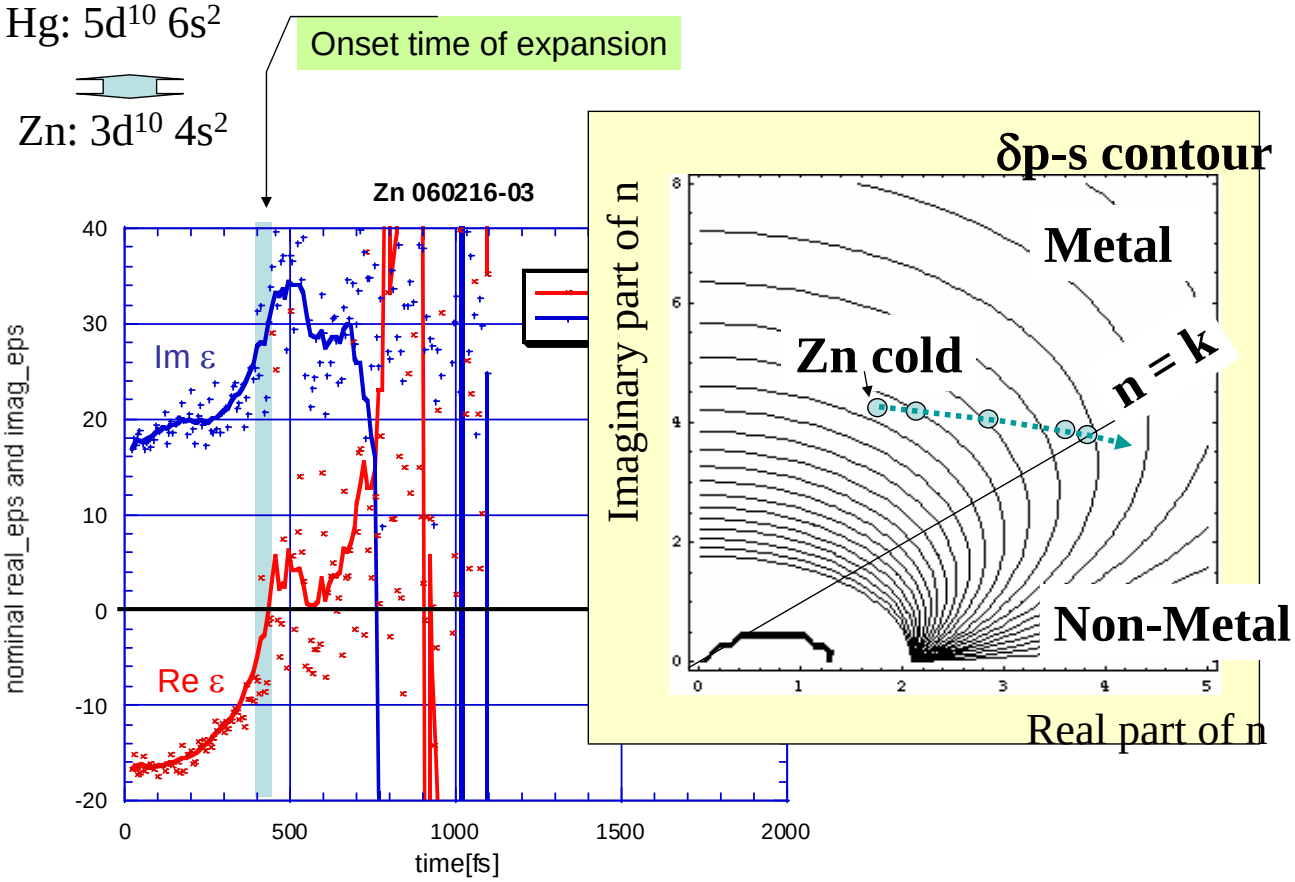


It will be new test for "evaporation".

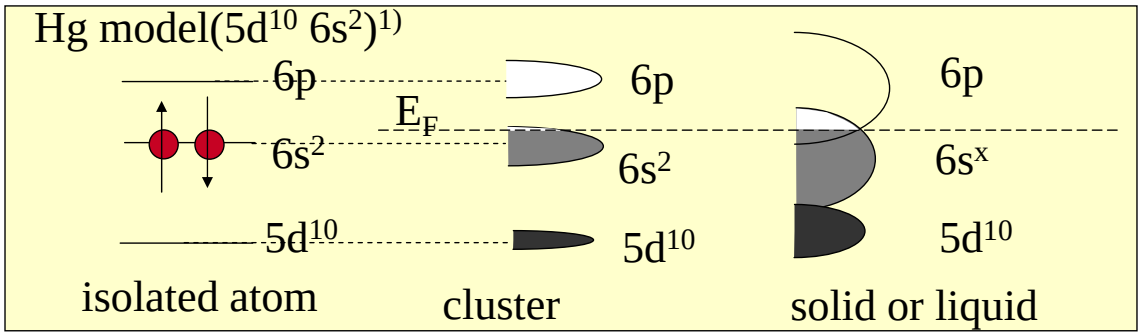
High temperature Zn goes to non-metal condition.

Hg: $5d^{10}\ 6s^2$

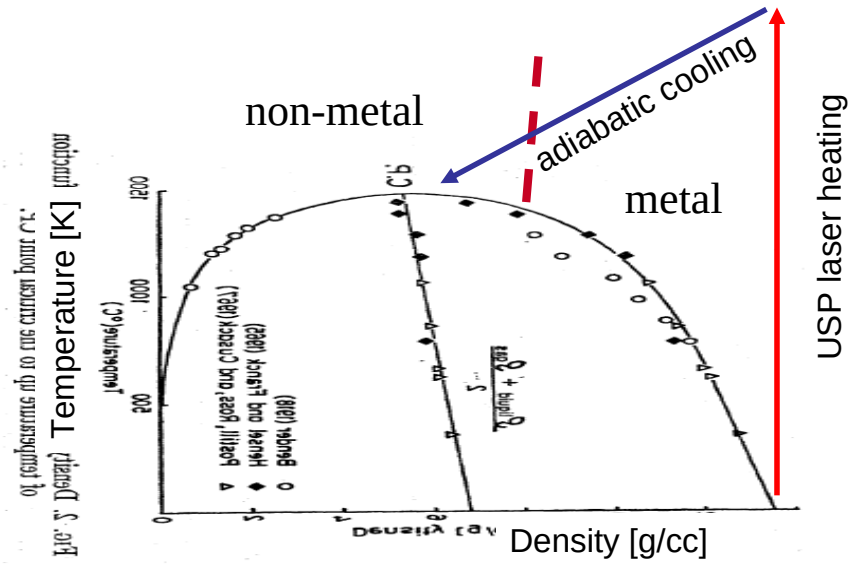
Zn: $3d^{10}\ 4s^2$



Metal-Nonmetal transition in Hg



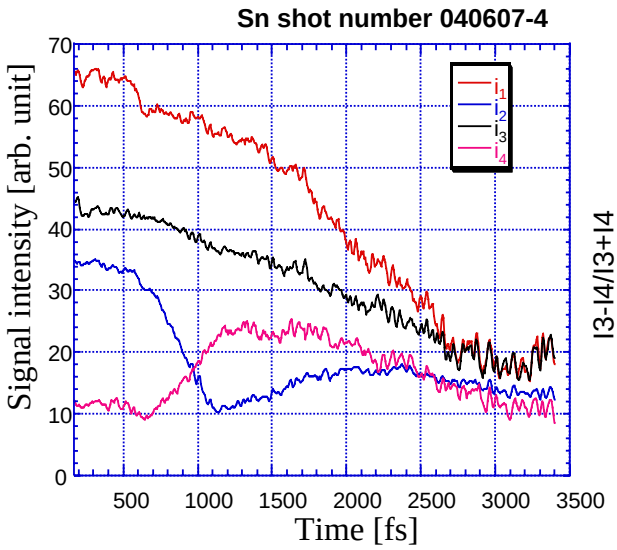
1)H. Haberland, et al., PRL, vol.69, p.3212

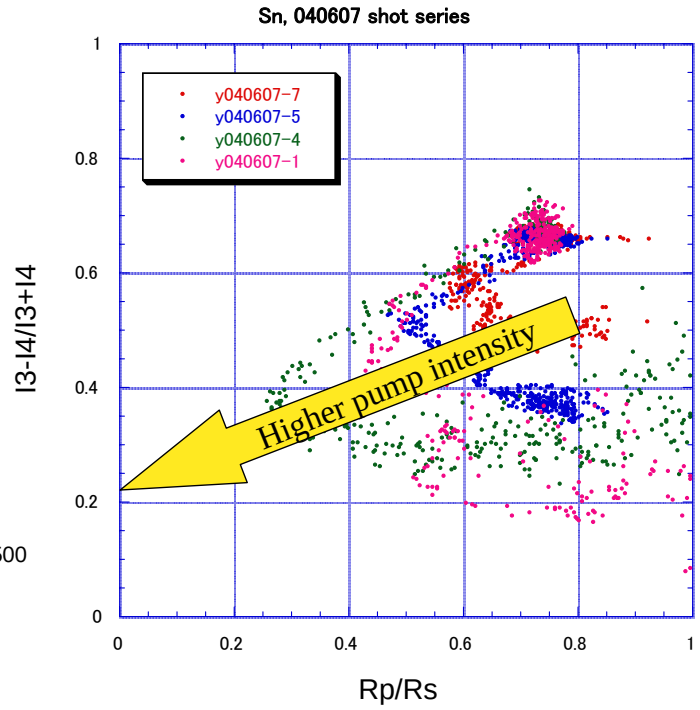


Data for Other materials

Sn, W, SS304, Mo, Fe,…

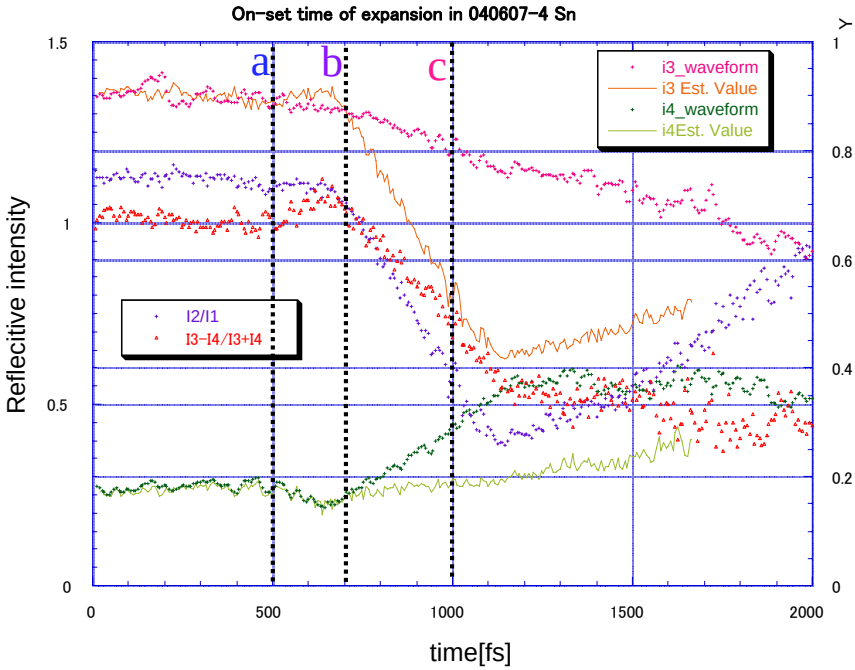
Pump intensity dependence of Sn target.

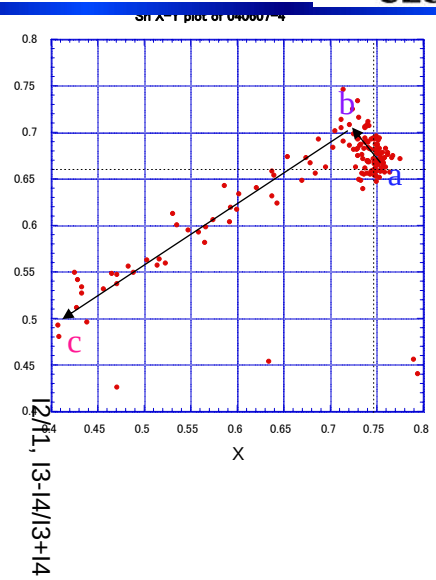




Three stages for Sn

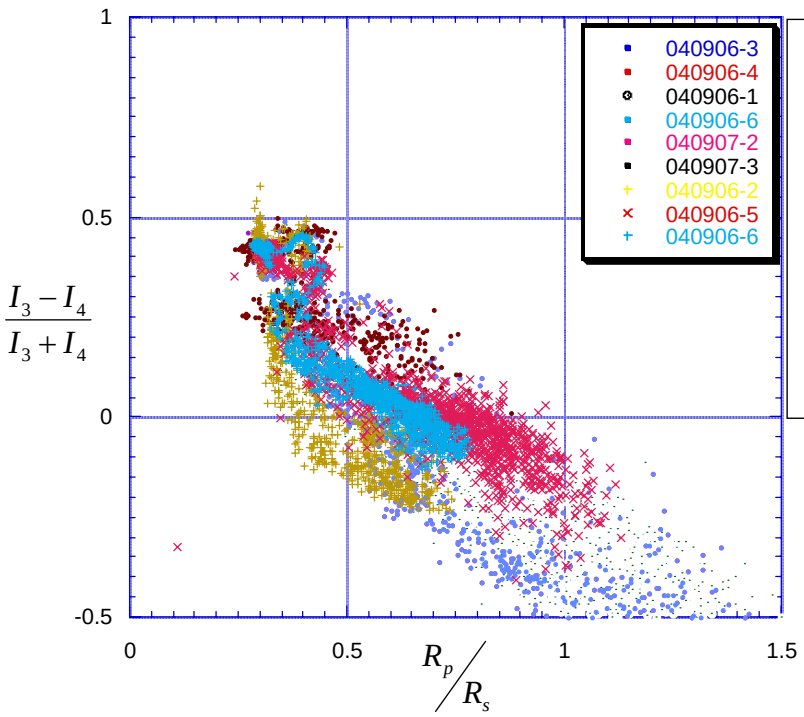
a. Warm solid density plasma
b. + expansion warm dense gas
c. + cooling dense gas & droplets

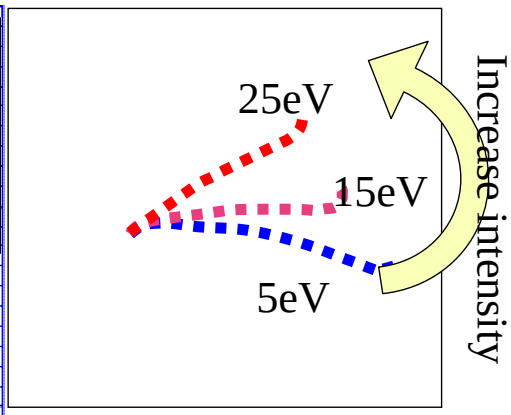




W may have large polarizability in this frequency

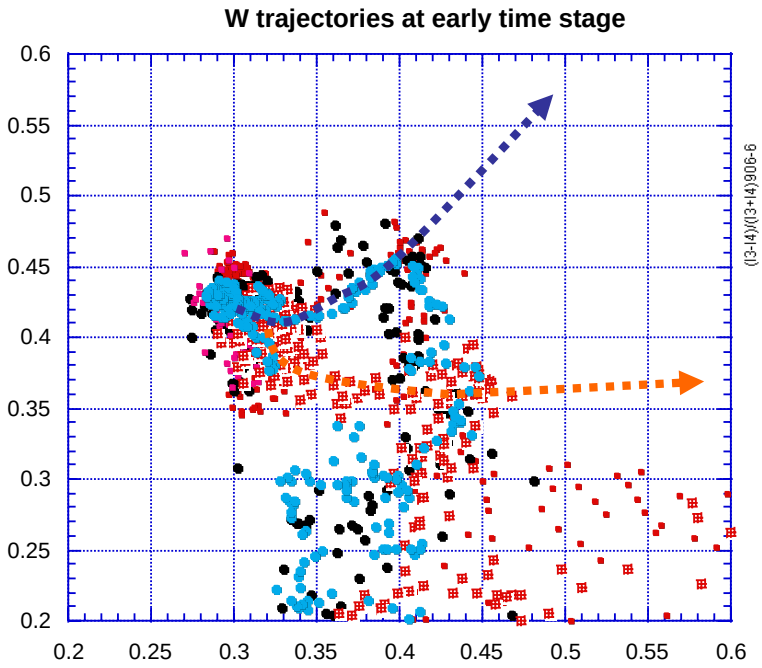
W trajectories 04906&7

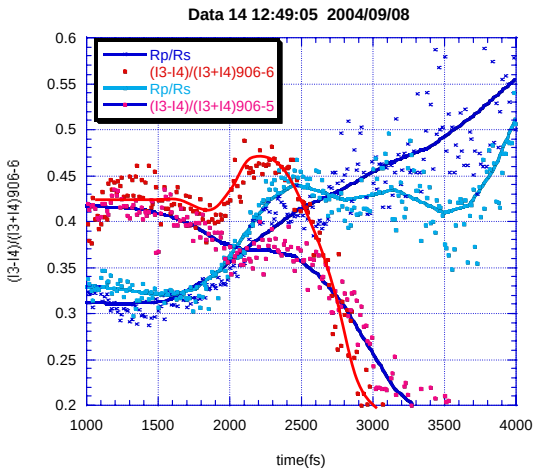




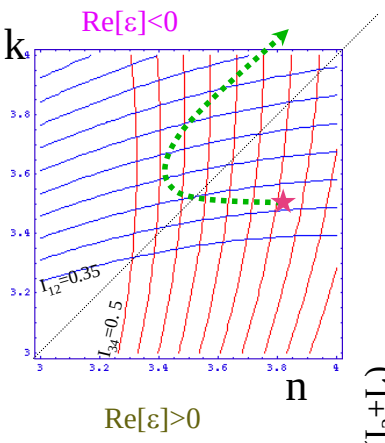
Drude/1000
+(-2600+90i)x10^{-24}cm^3 for WI
+(-1800+200i) x10^{-24}cm^3 for WII

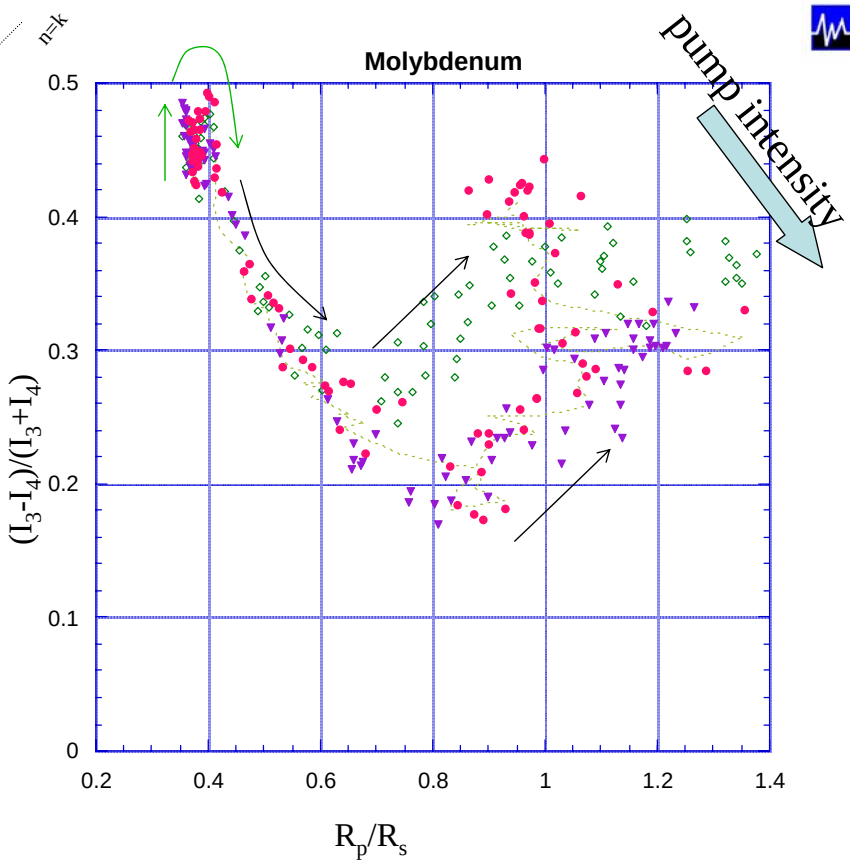
Later time behavior of W (droplet's effect?)



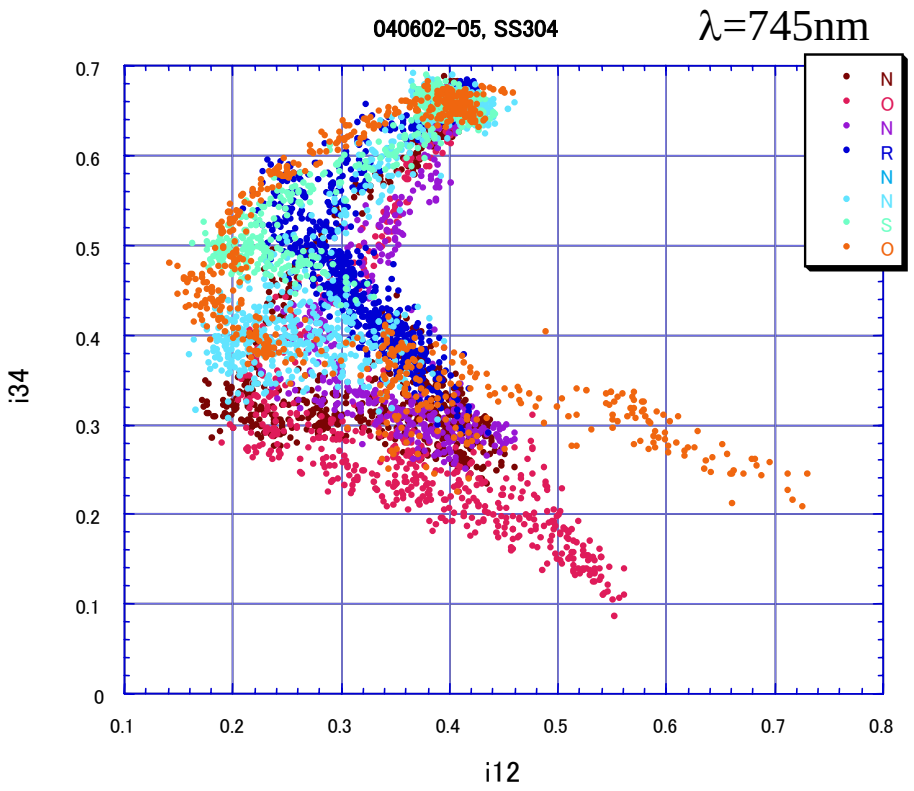


Mo

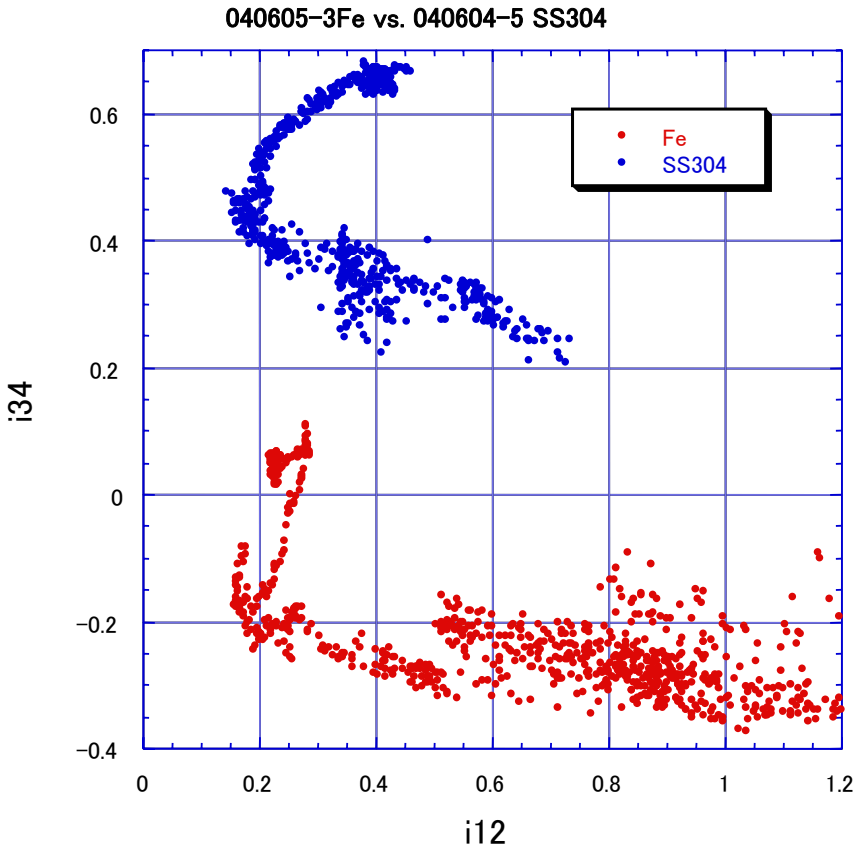




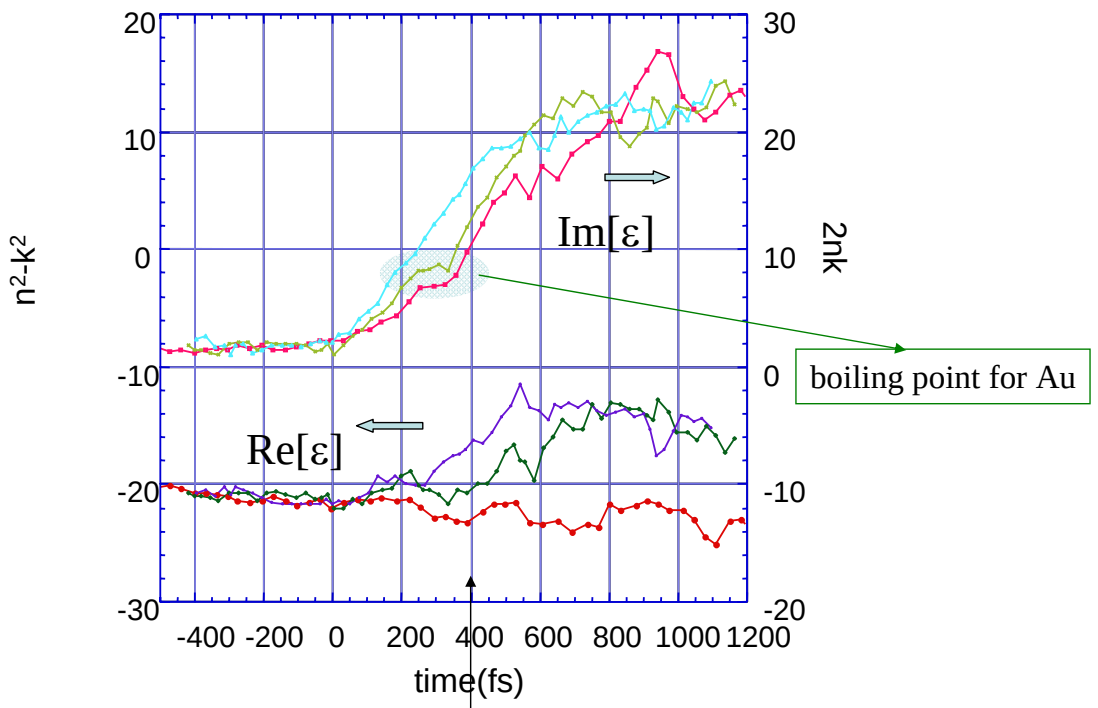
Trend of Stainless Steal 304 (pump intensity dependence)



Comparison between SS304 and Fe.



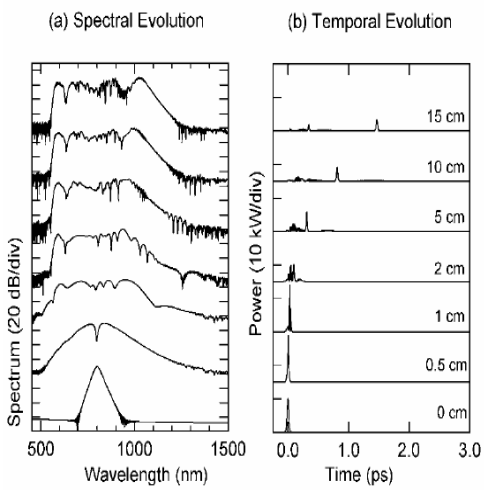
Au targets were heated to plasma temperature.



When does expansion occur?

We know it from reconstruction method.

Different frequency probe light



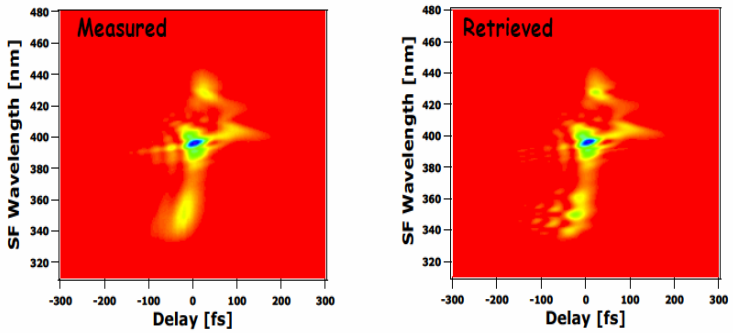


Fig. 2. The measured (left) and retrieved (right) XFROG trace of the 8 mm fiber continuum.

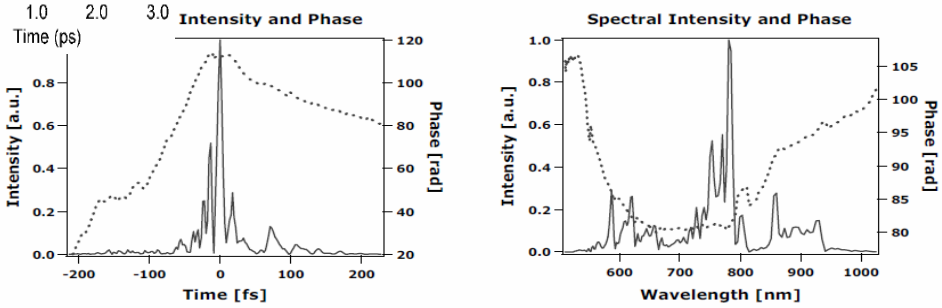
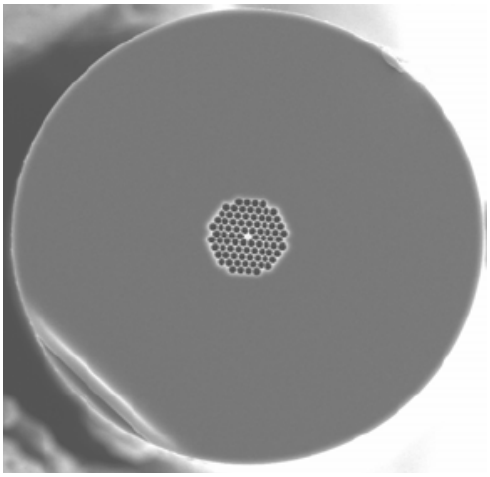


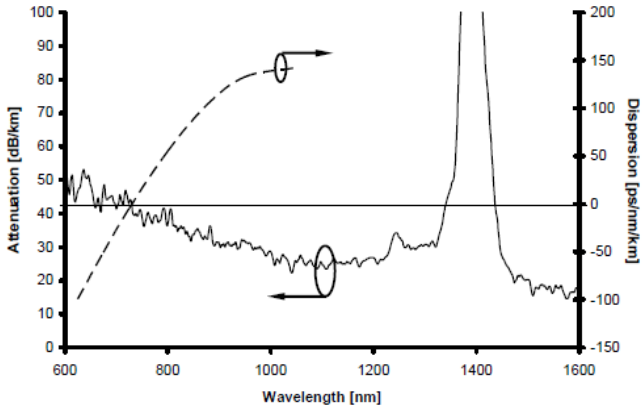
Fig. 3. The retrieved continuum intensity and phase vs. time (left), the retrieved continuum intensity and phase vs. frequency (right).

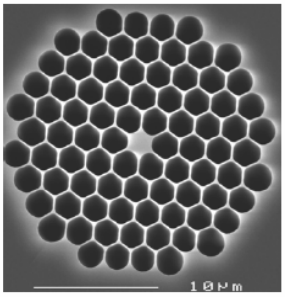
http://www.physics.gatech.edu/ **Super-continuum from a short (8-mm-long) microstructure fiber**

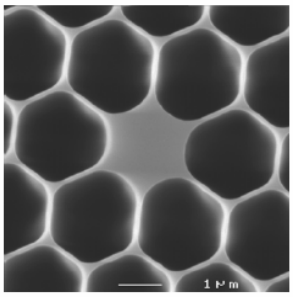
Qiang Cao, Xun Gu, Erik Zeek, Mark Kimmel, Rick Trebino, and John Dudley

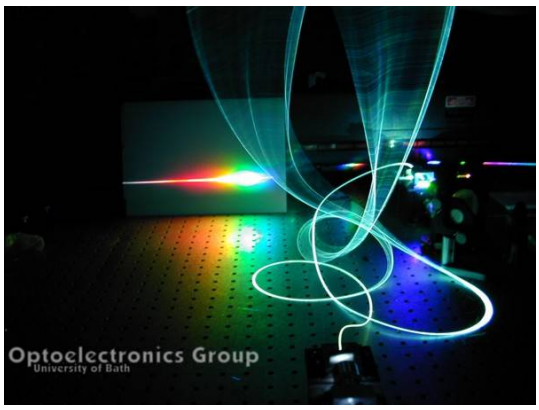
Super Continuum Generation from Photonic Crystal Fiber





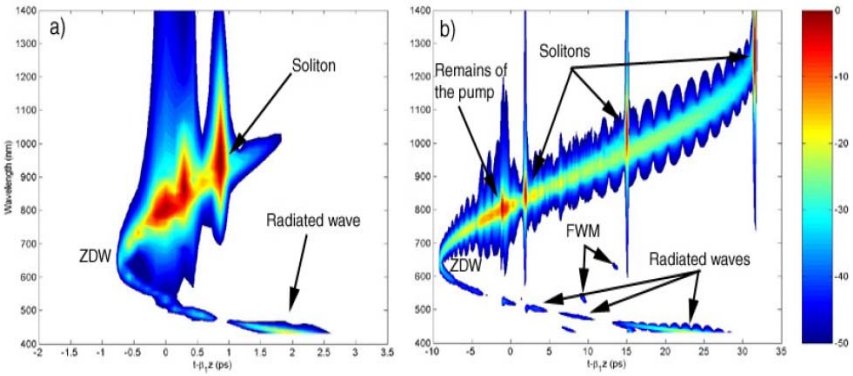






http://www.thorlabs.com/

http://www.bath.ac.uk/physics/groups/cppm/



20mW, 10cm, 1m

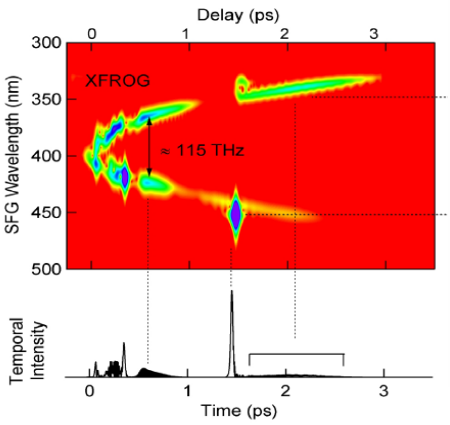
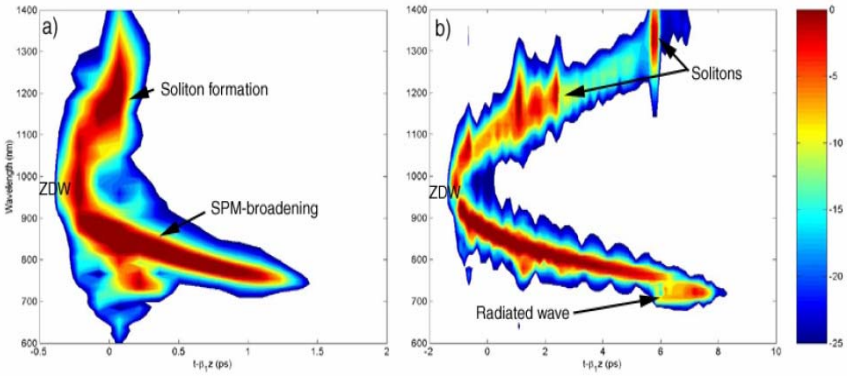


Fig. 3. (917 KB) Calculated XFROG trace with its structure correlated with the intensity and spectrum showing evolution with propagation distance. Note the nonlinear wavelength axis used in the plot of the fundamental SC spectrum.



120mW, 20cm, 1m

+What?

+Inter band transition

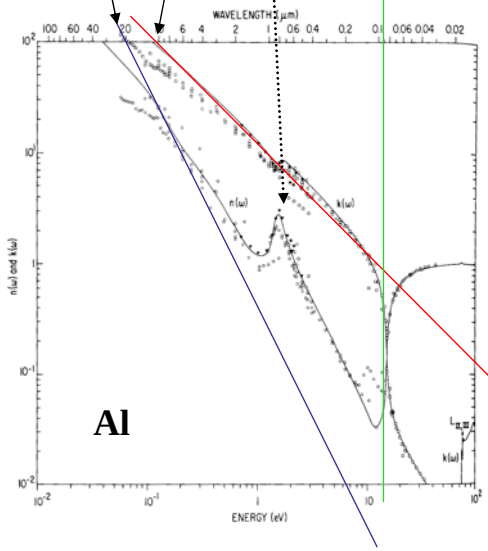
ω_{pe}=2.4x10^{16} [s^{-1}] for 3s^{2}3p
=>λ_{pr} ~ 80nm

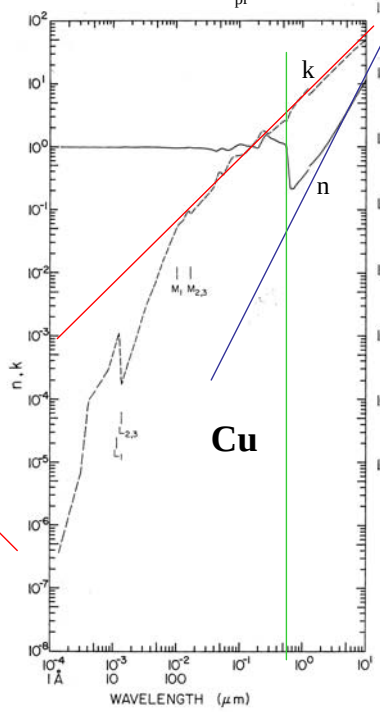
λ_{pr} ~ 600nm

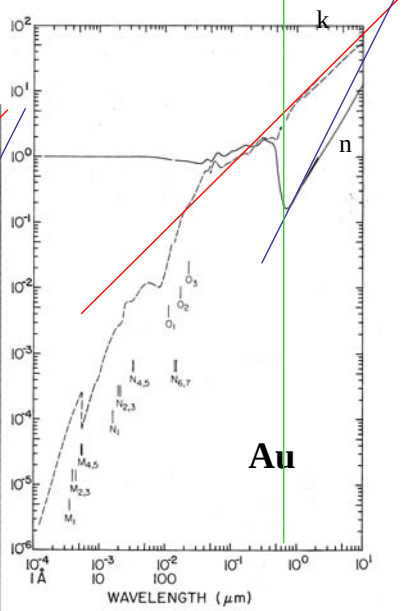
λ_{pr} ~ 550nm

$$n^2 - k^2 \Rightarrow -k^2 \sim \left(\frac{\omega_c}{\omega}\right)^2$$

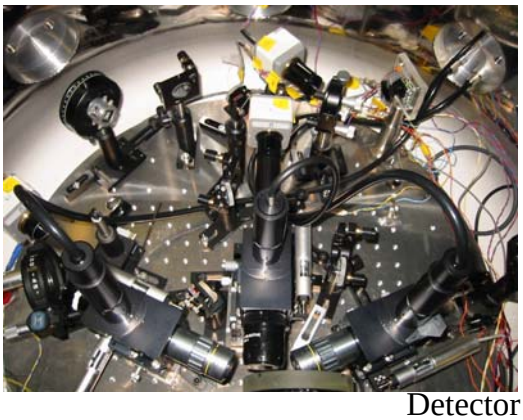
$$nk \sim \omega^{-3} \Rightarrow n \sim \omega^{-2}$$

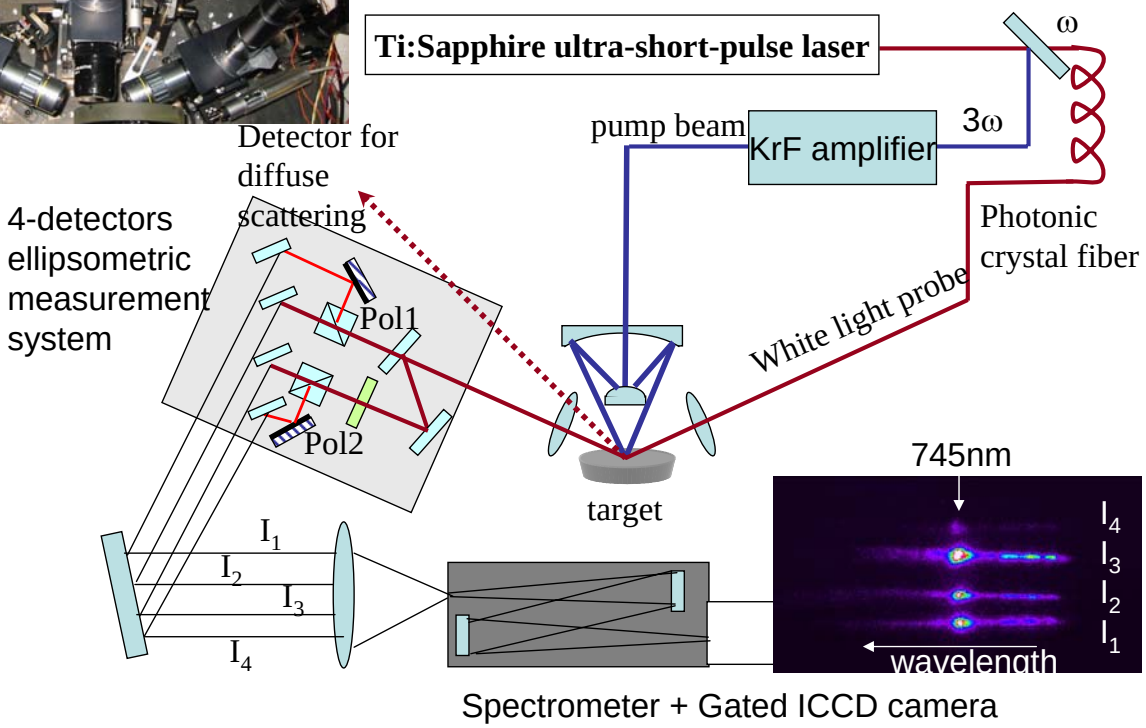




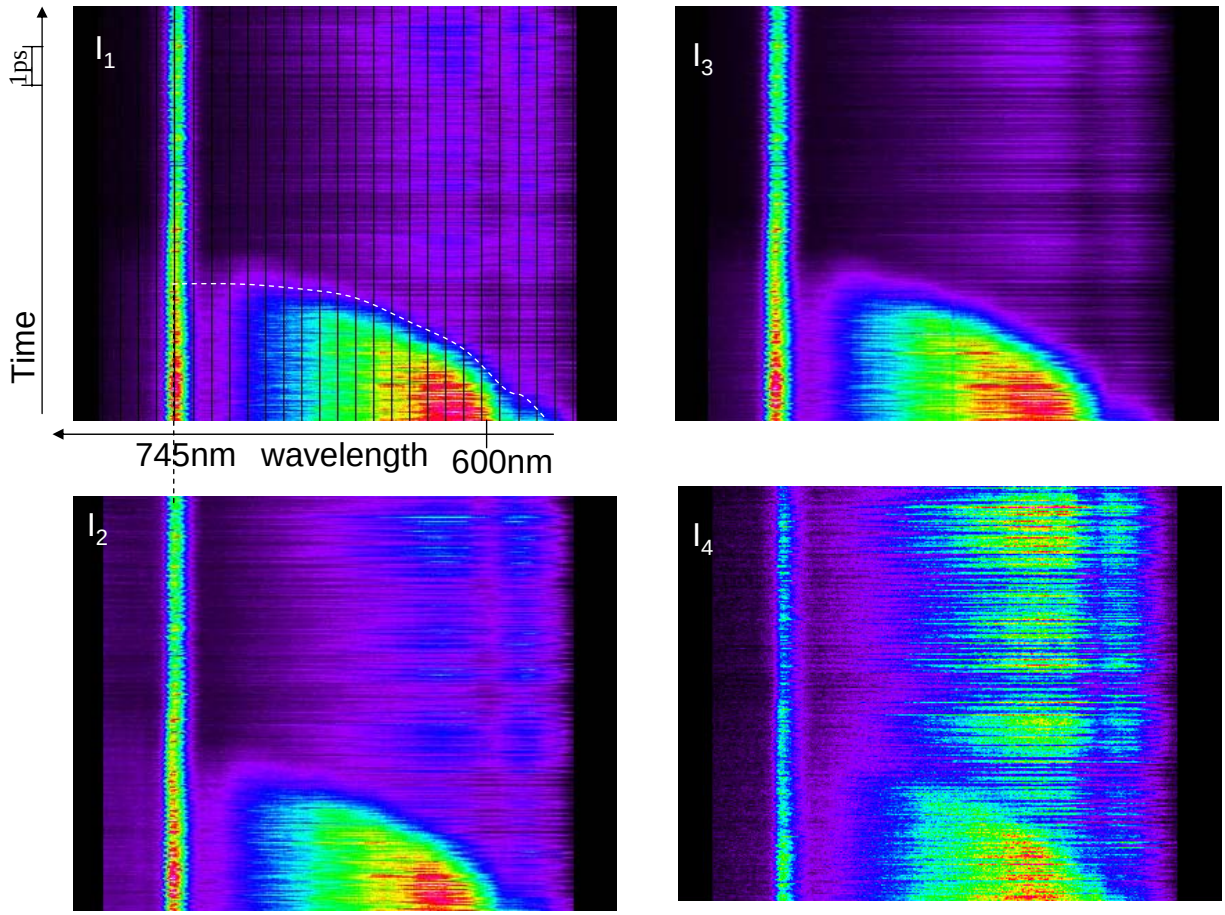


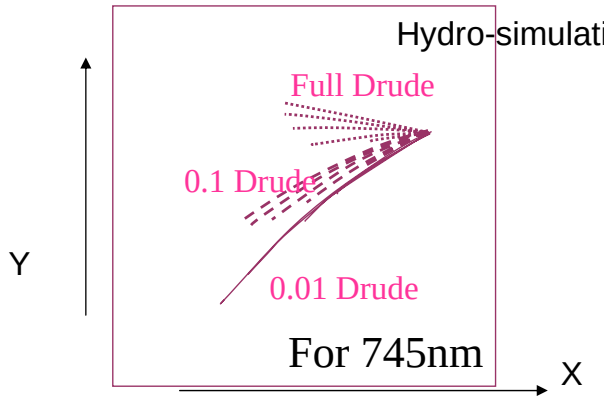
*From Handbook of optical constants of solids edited by E.D.Palik

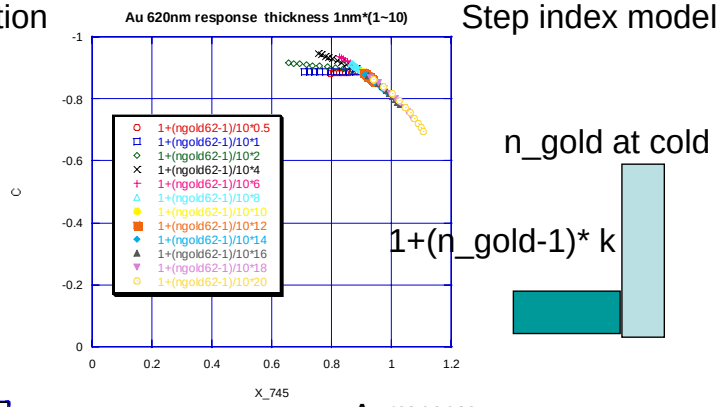


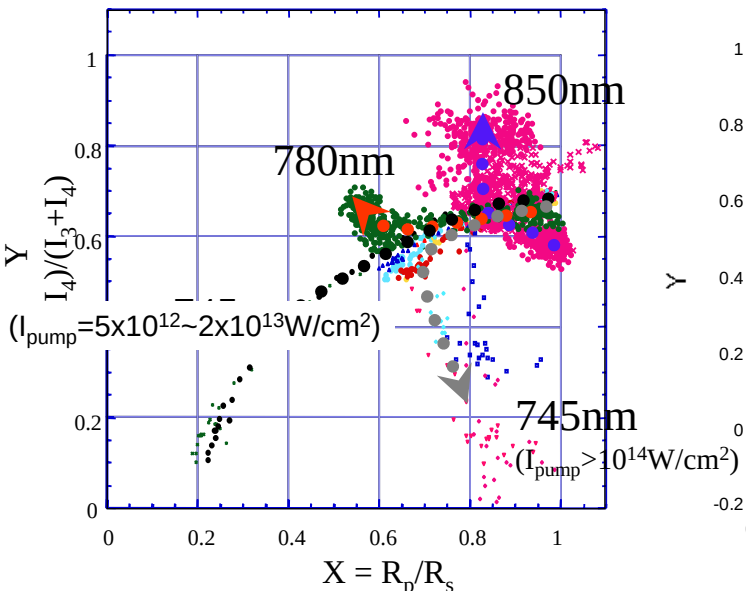


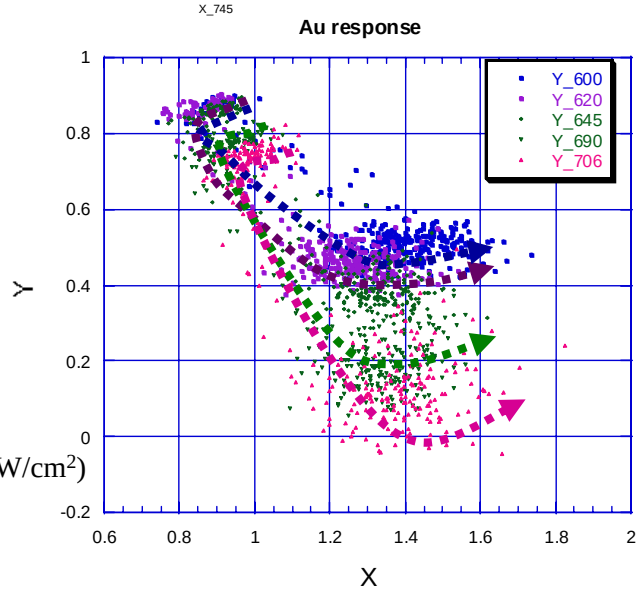
Au shot series 07061304

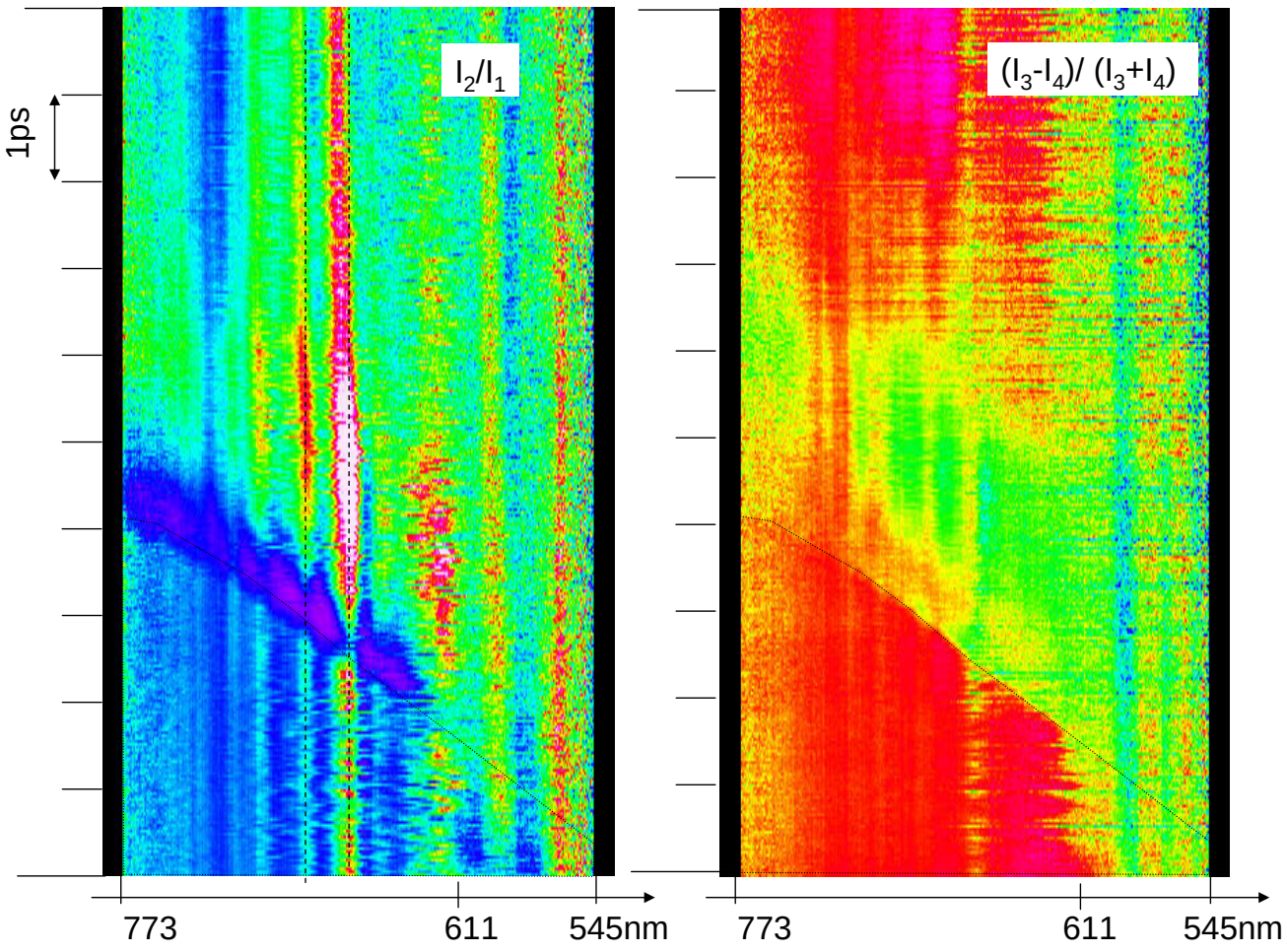


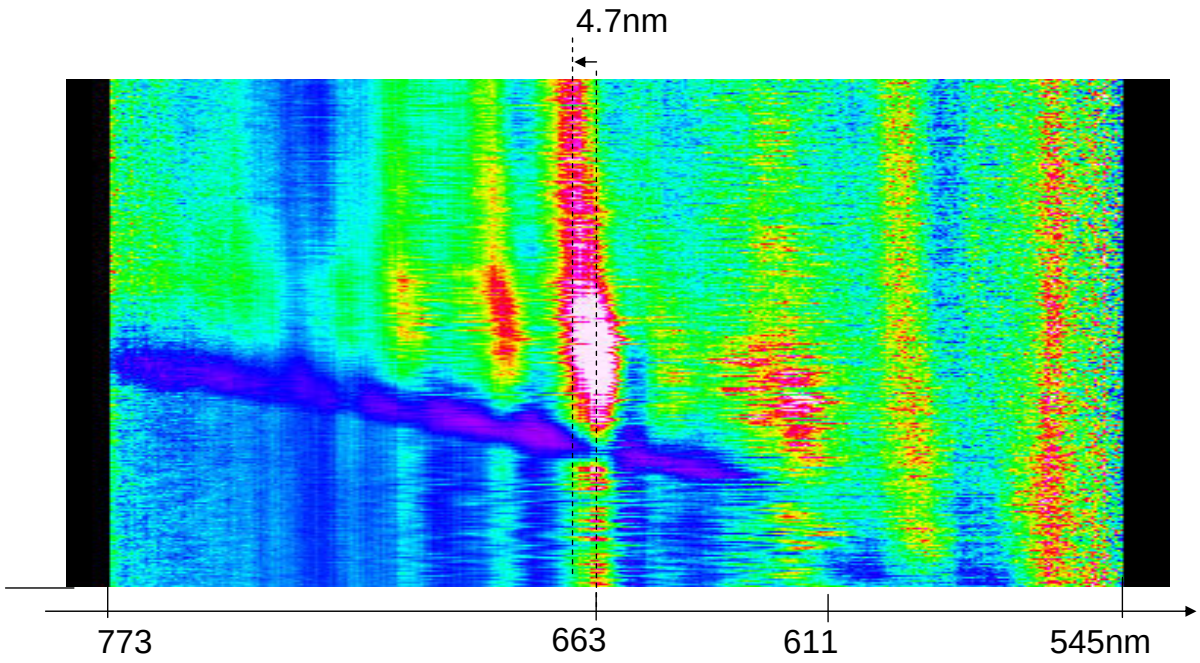




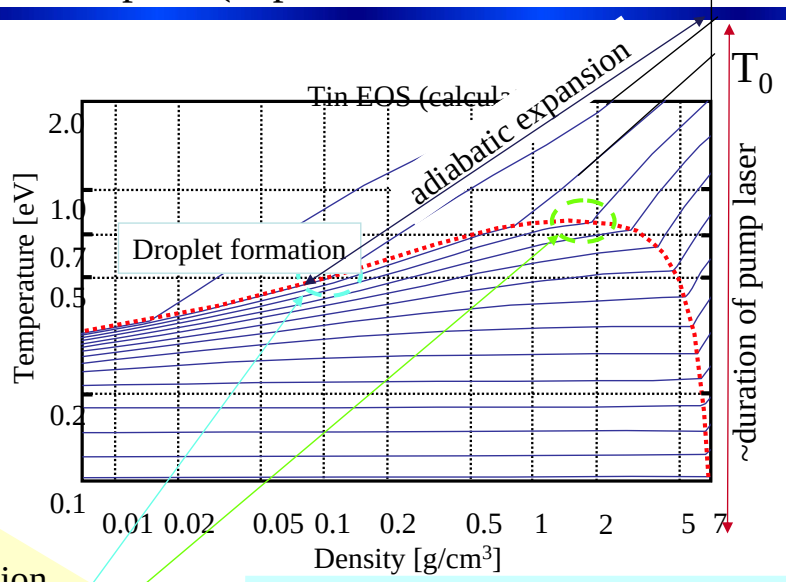


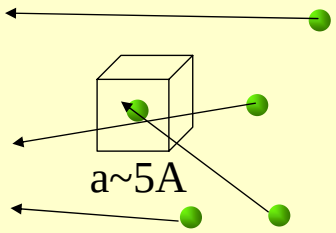



1ps
I_2/I_1
773
611
545nm
$(I_3-I_4)/(I_3+I_4)$
773
611
545nm


4.7nm
773
663
611
545nm

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





Rate of droplet formation

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

6.3×10^{10}

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

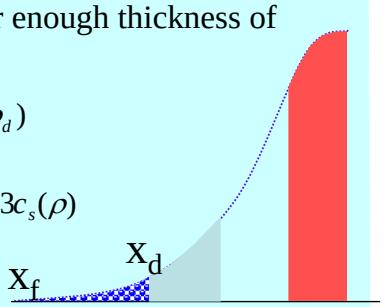
ρ=0.1g/cc, T=0.5eV
$t_{formation}$~16ps

Expansion time for enough thickness of droplet layer

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

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

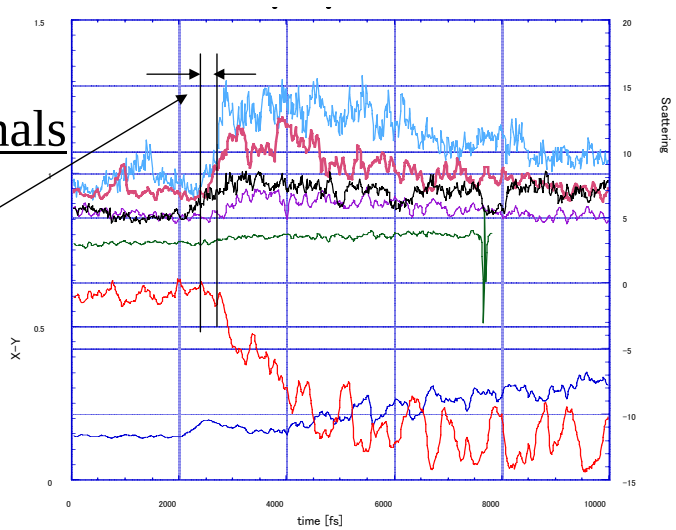
$$t_d \approx \frac{x_d - x_f}{4c_s(\rho_d)}$$

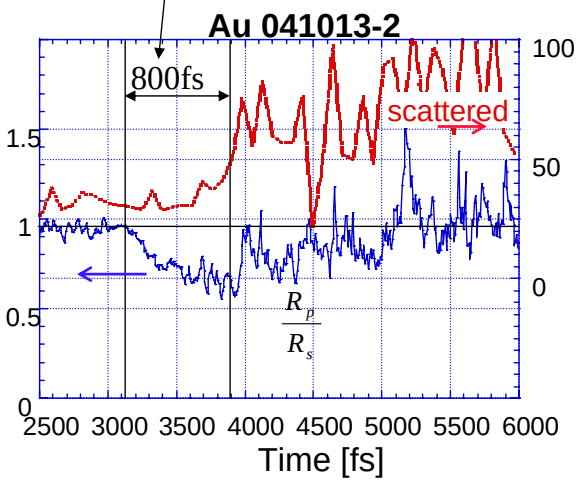


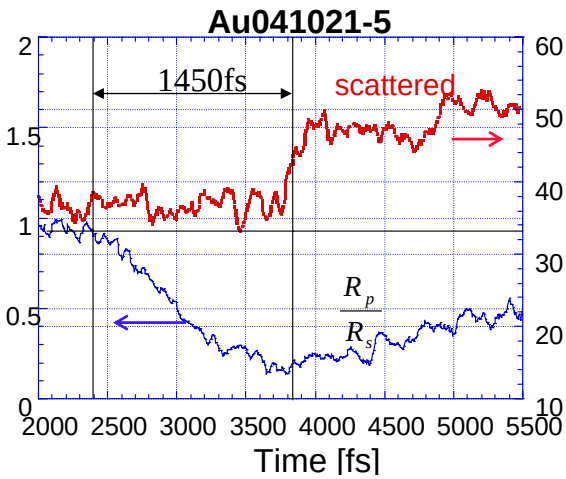
Detection of 2ϕ fluid with diffuse scattering signals

Au 0.6~2.6ps

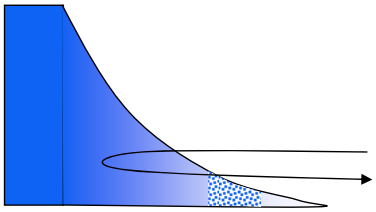
W 0.75~1ps

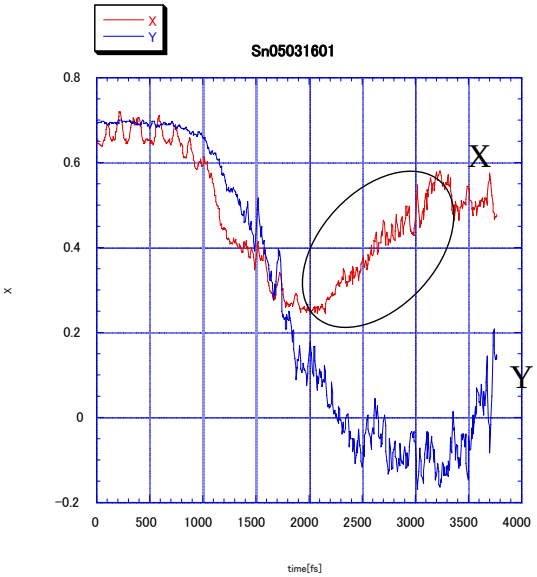


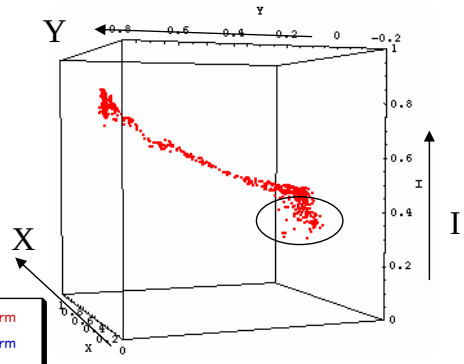


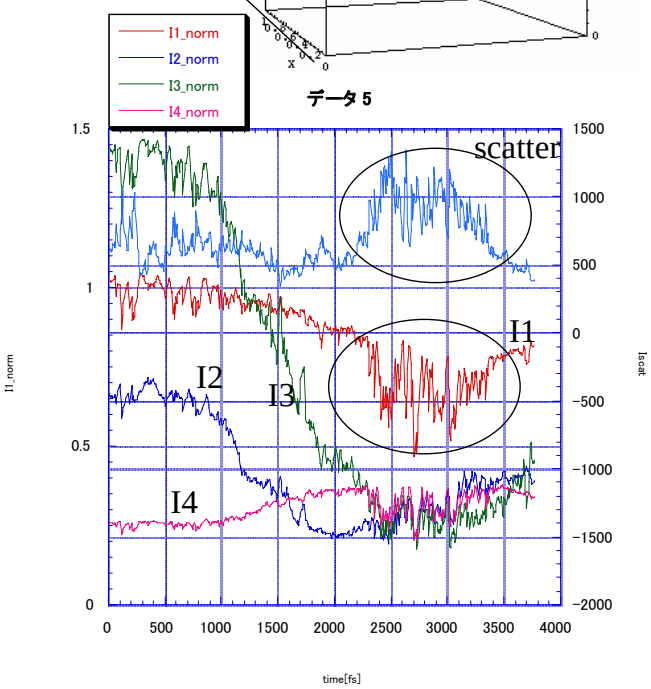


Scattering particles may have small contribution to optical constant.

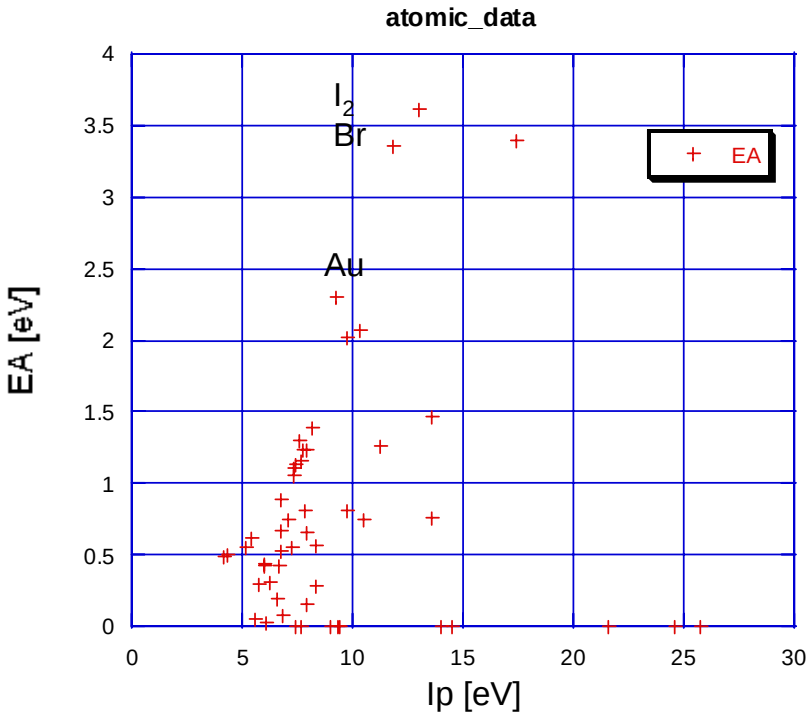




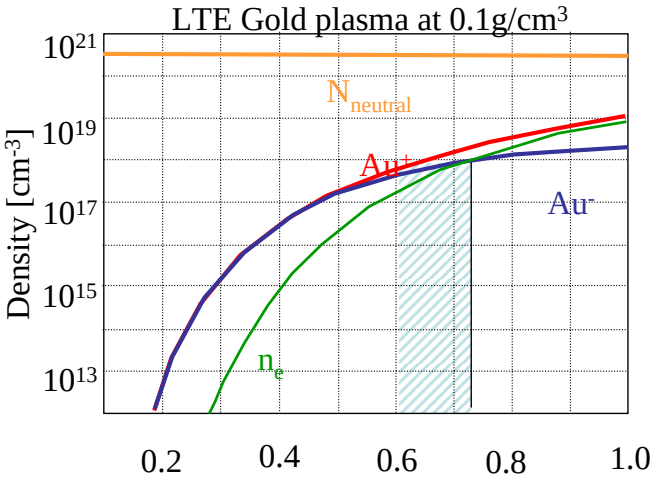


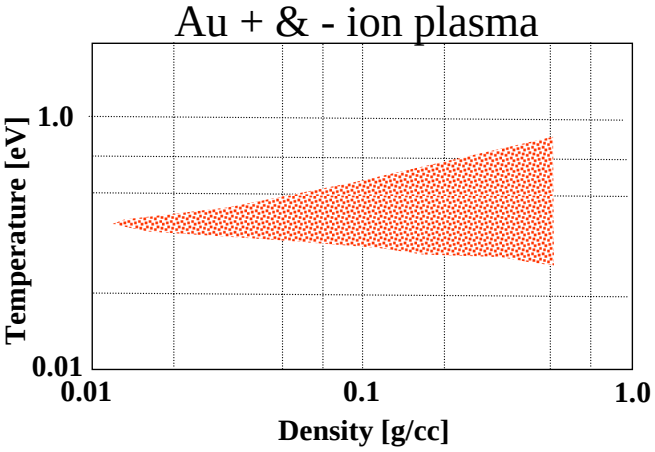


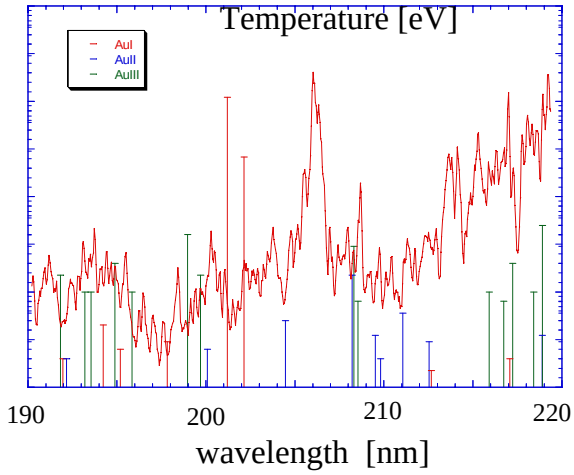
2. Electrons captured by neutrals

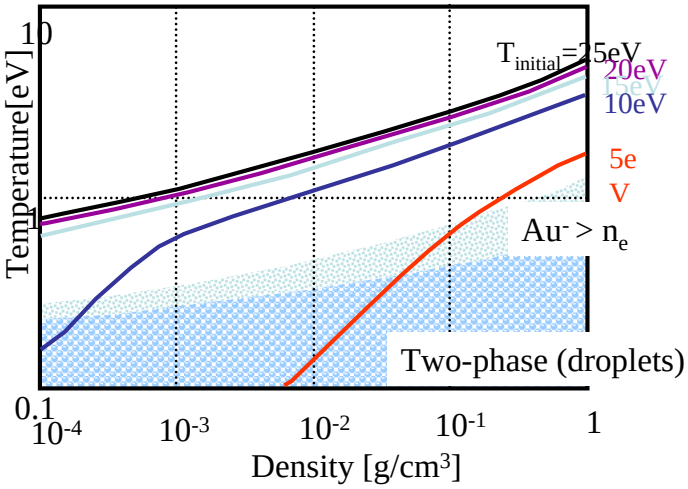


from R.M.More


LTE Gold plasma at 0.1g/cm3
Density [cm-3]
10^21
10^19
10^17
10^15
10^13
N neutral
Au+
Au-
ne
0.2
0.4
0.6
0.8
1.0
Temperature [eV]


Au + & - ion plasma
Temperature [eV]
1.0
0.01
0.01
0.1
1.0
Density [g/cc]


AuI
AuII
AuIII
190
200
210
220
wavelength [nm]


Temperature[eV]
10
1
0.1
T initial =25eV
20eV
15eV
10eV
5e
V
Au- > ne
Two-phase (droplets)
10-4
10-3
10-2
10-1
1
Density [g/cm3]