WDM experiments with Lasers

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RIKEN XFEL, JASRI; T. Ishikawa, H. Ohashi, H. Kimura, K. Tono,
T. Togashi, M. Nagasono, A. Higashiya, M. Yabashi

References
1. H. Kitamura, Theoretical potential energy surfaces for excited mercury trimers, Chem. Phys. 325, pp.207-219 (2006)
2. H. Yoneda, et al. Optics Express, Vol. 17 Issue 26, pp.23443-23448 (2009)
3. H. Yoneda et al., Observation of saturable absorption of Sn metal film with intense EUV laser pulse, SPIE 7501, p. 33 (2009)
4. Y, Inubushi, et. al., Measurement of saturable absorption by intense VUV free electron laser using fluorescent material, Rev. Sci. Instrum. **81**, 036101 (2010);

Outline

1. EUV laser interaction experiments

Ion excitation Energy

$$F[\rho,T] = E_{cold}[\rho] + F_{elec}[\rho,T] + F_{ion}[\rho,T] + E_{excitation}$$

EOS internal energy Cold curve Electron-Thermal Ion-Thermal

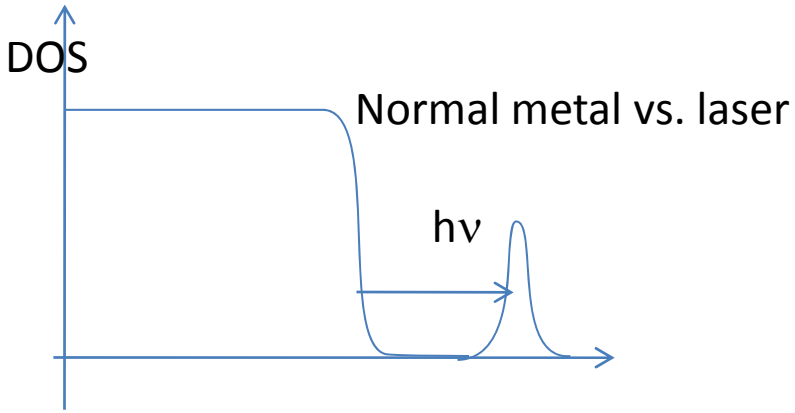
Purpose?

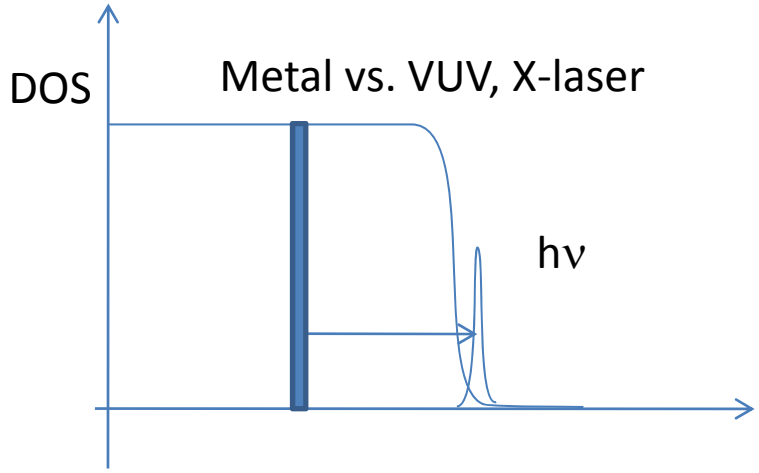
The change of energy for inner shell will be used for active devices of high energy photons.

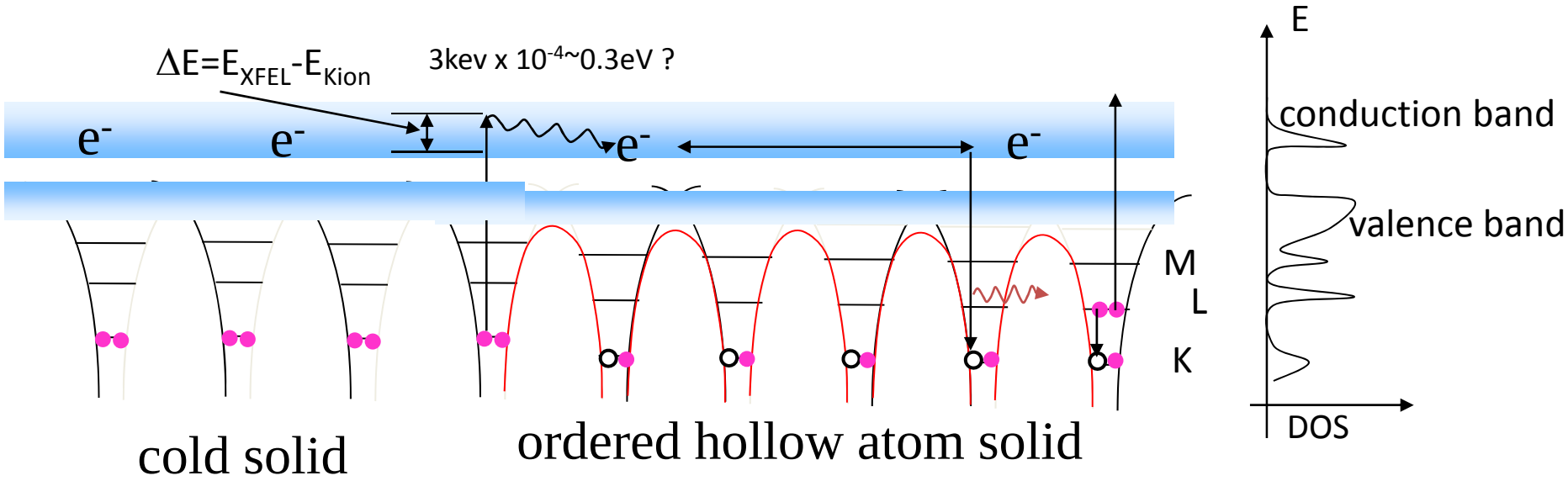
How different?

Hollow atom but condensed condition

If $\tau < \tau_{disassemble}$, ordered solid with inner shell excited ions.





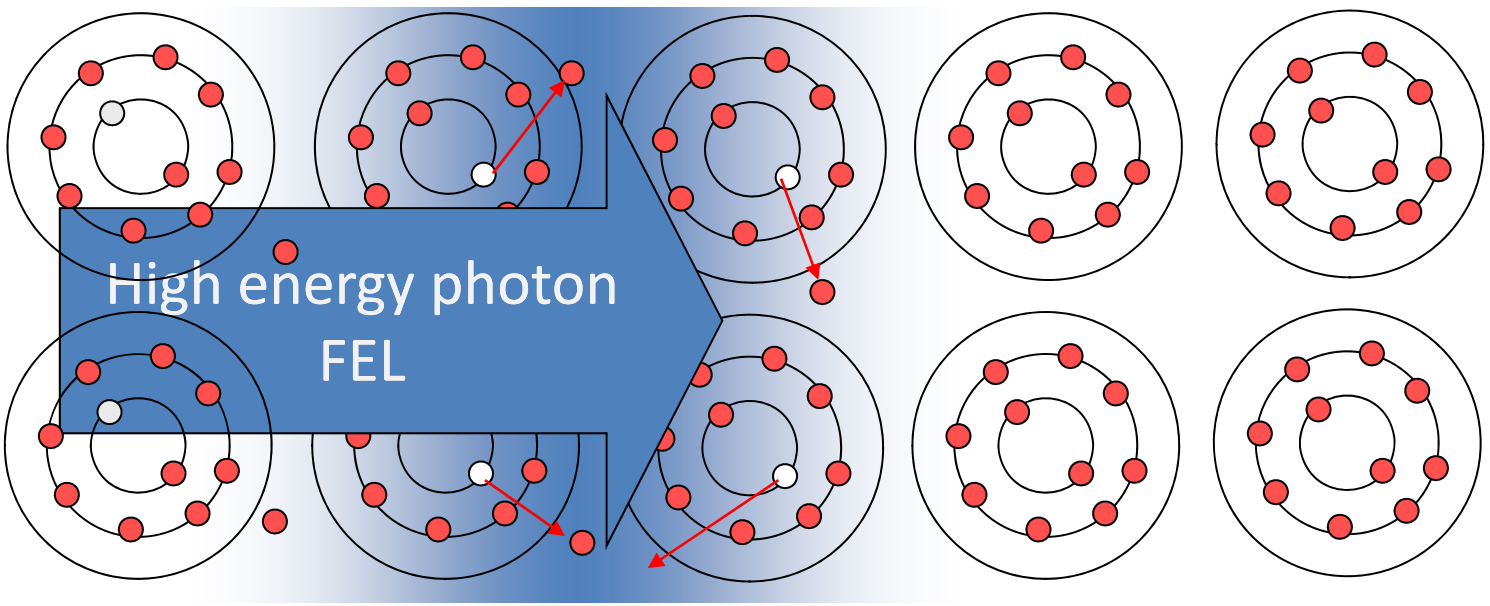


Motivation

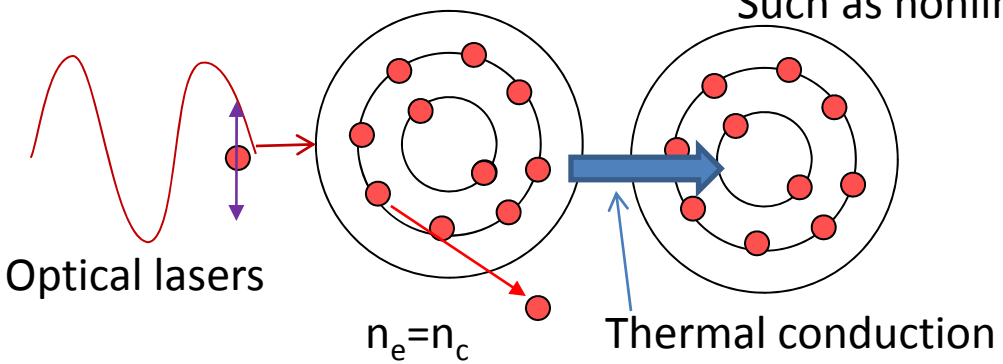
$$h\nu \geq \hbar\omega_{pe}$$

Al, ρ=2.7g/cc => ne=1.79x10^{23}cm^{-3} => λ<78nm

Even metals, we use as a transmitting materials.

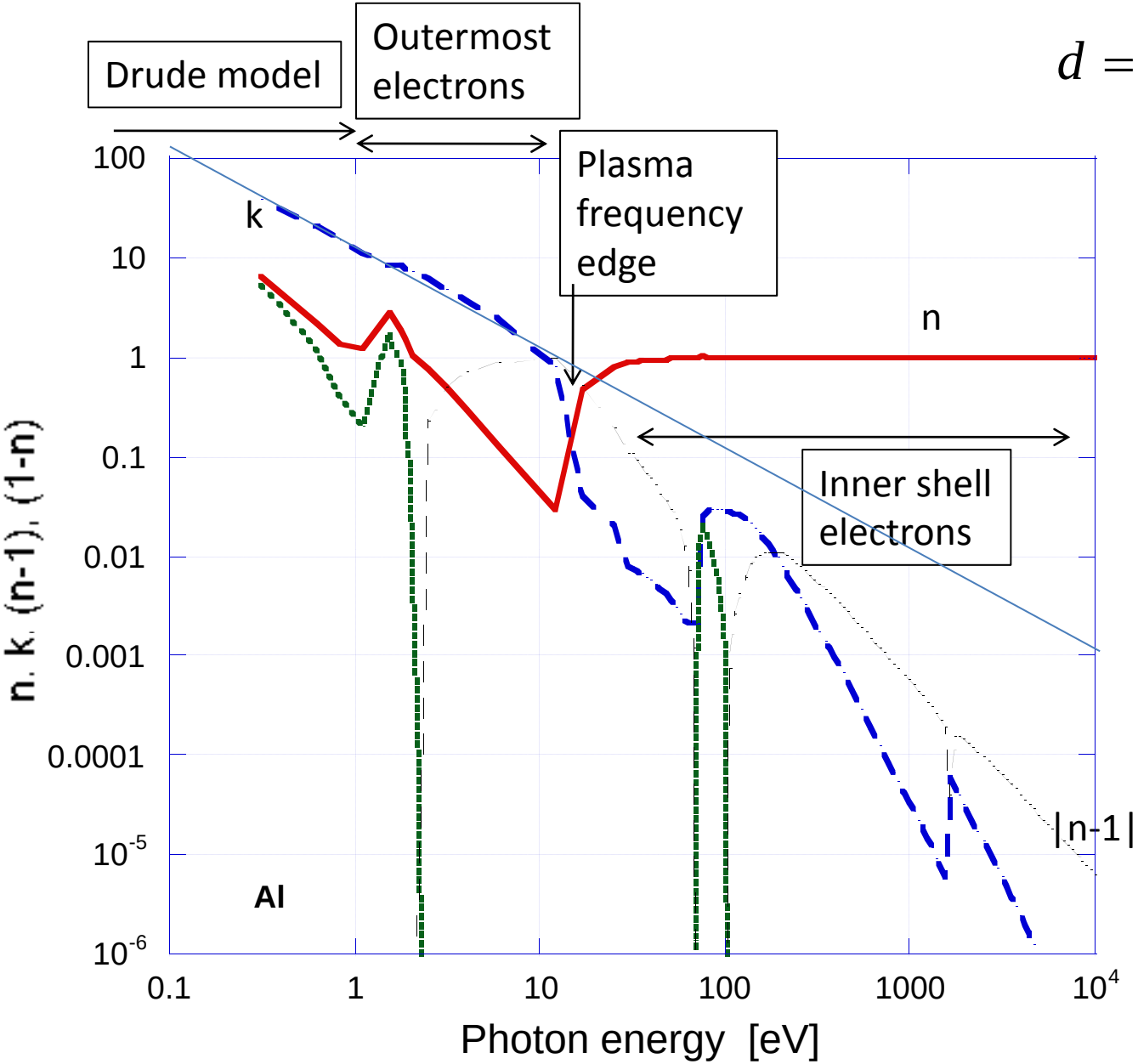


We can use metals as a general medium for functional optics.
Such as nonlinear devices



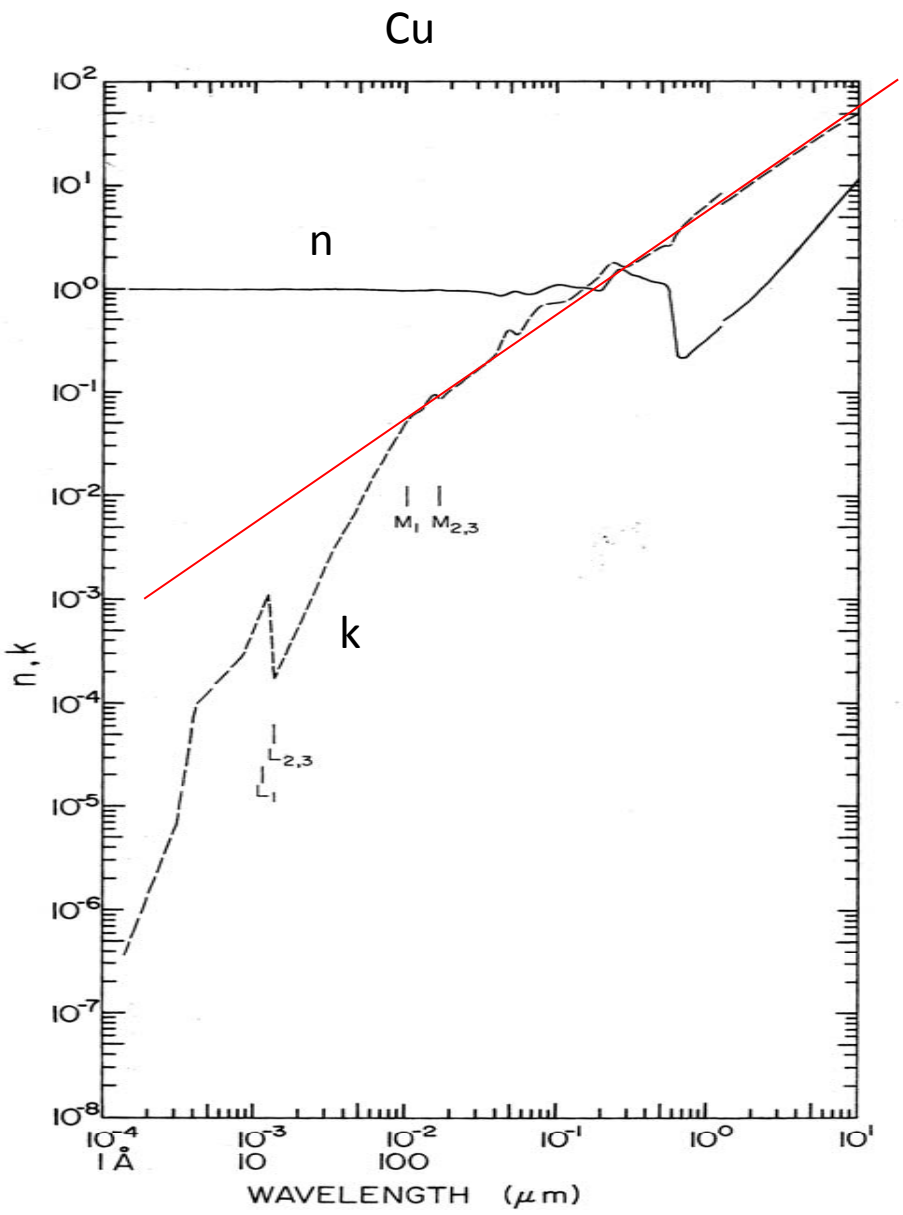
Optical Refractive index in IR, Visible UV, VUV, and X-ray wavelength

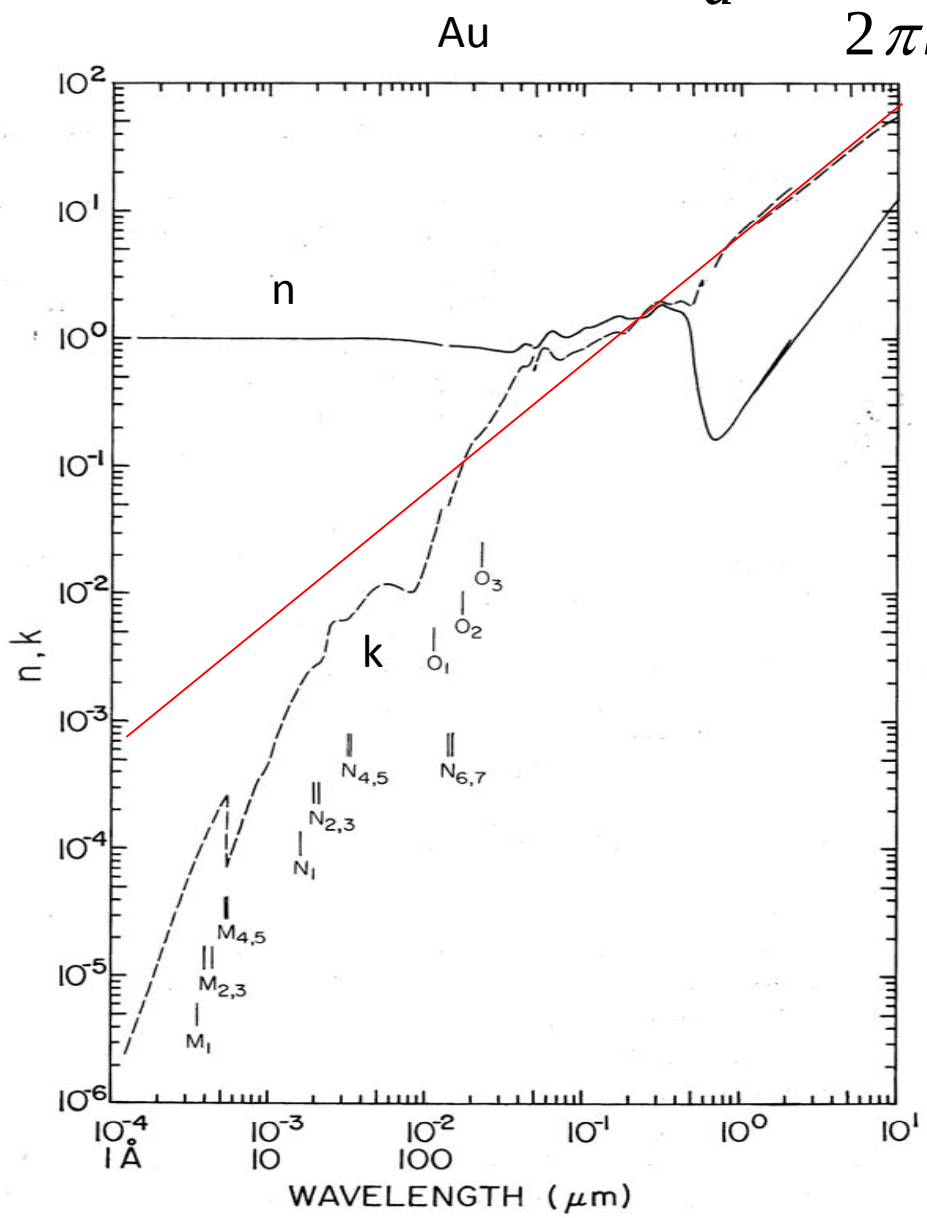
$$d = \frac{\lambda}{2\pi k}$$



Shortest absorption length(largest absorbance) is located in EUV & VUV region.

$$d = \frac{\lambda}{2\pi k}$$





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

Questions

Is it possible to achieve “silent” dense ionization condition in condensed matter?

High energy photon(keV~20eV)/atoms

*thermal energy case

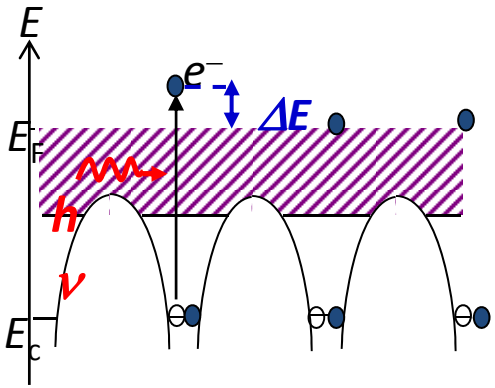
=> melting, evaporation, ionization

*10^{-4} energy accuracy of XFEL => 1000K residual energy

*resonance EUV light excitation =>more less residual energy

Unrestricted Hartree-Fock calculations

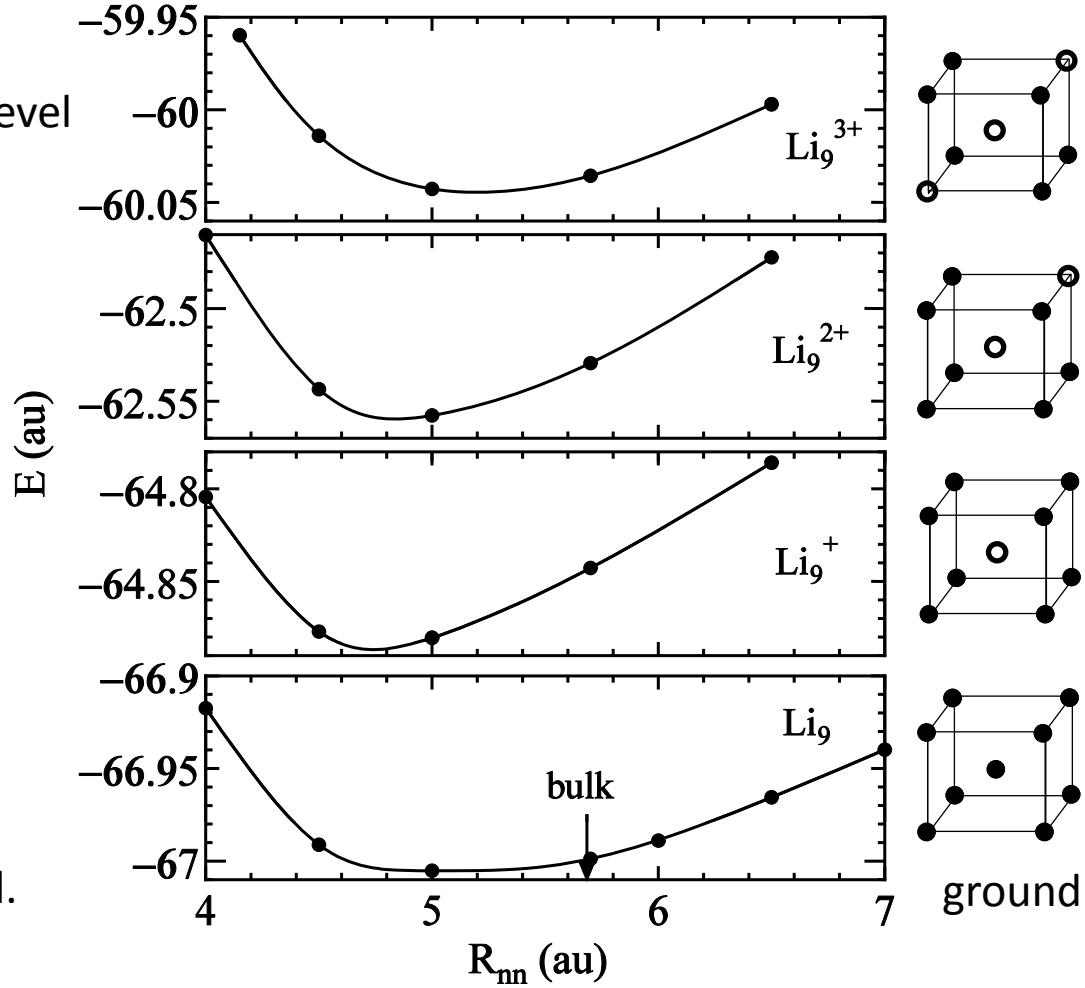
H. Kitamura, "Cluster-model study on the K-shell excited states of crystalline lithium under intense laser irradiation", Eur. Phys. J. D **52**, pp.147-150 (2009)



conduction band

core level

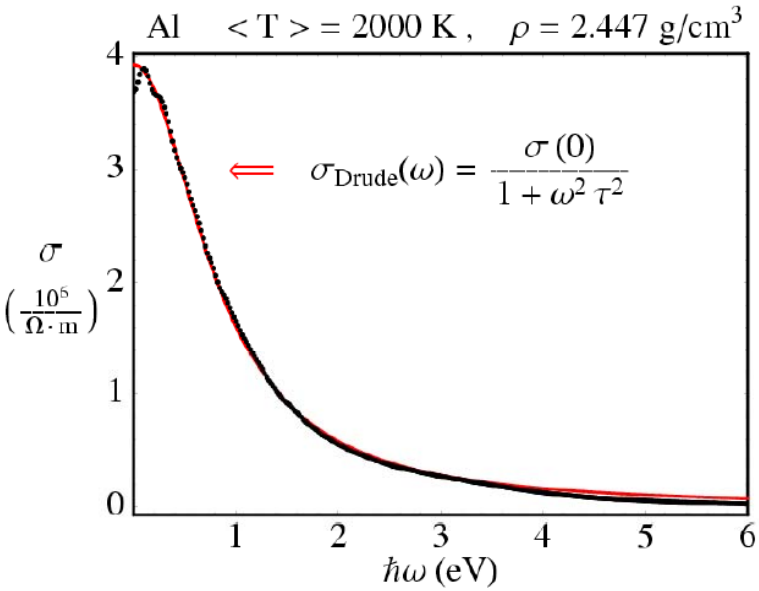
Potential energy curves for Li_9^{z+} ions



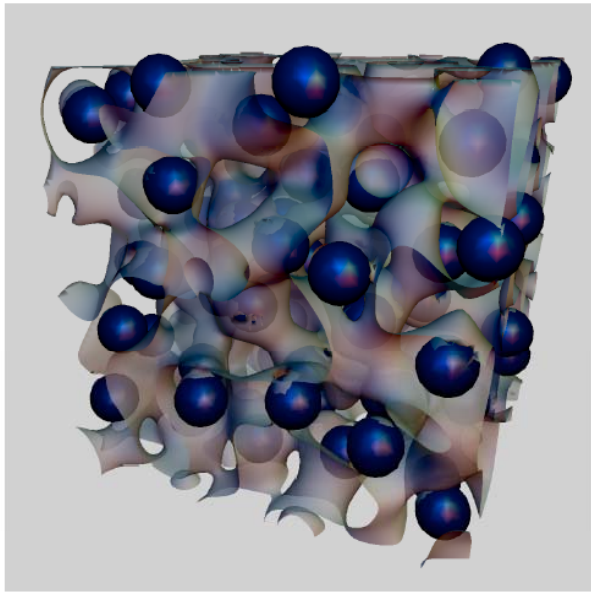
ground state

Clusters are bound at least for $z \leq 3$!

A key point is ionized electrons are trapped in the conduction band.



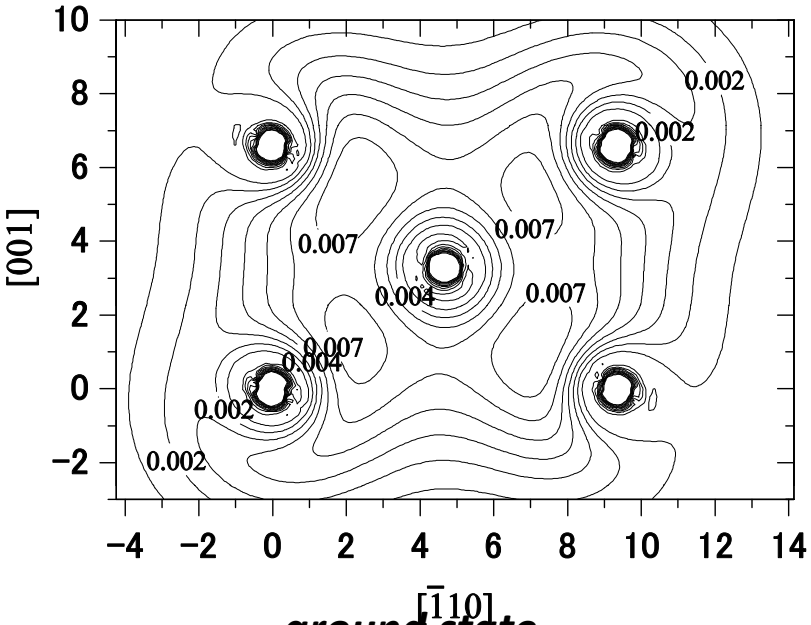
The agreement with the Drude model indicates 'nearly free' electrons



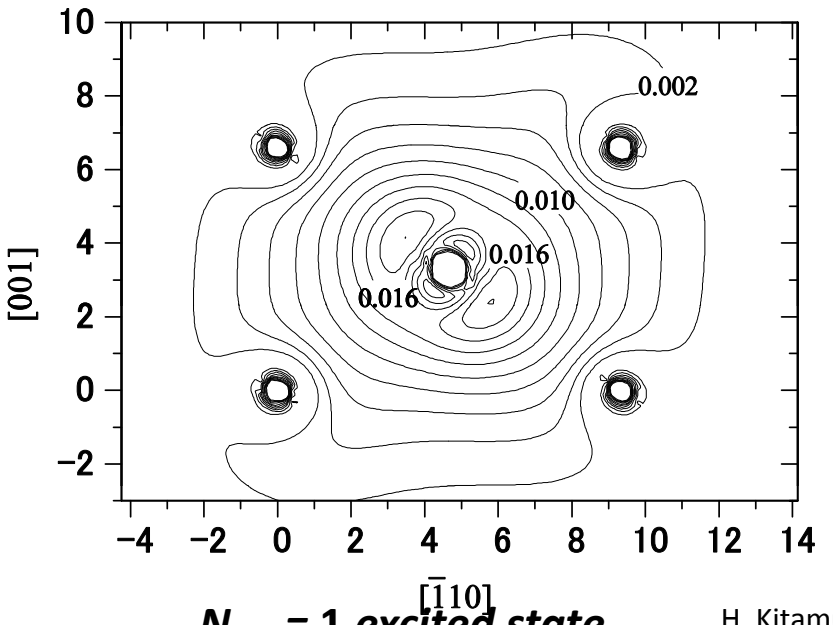
Ion cores displayed with iso-surfaces of the mean valence charge density

QMD simulation view of wdm Al interia.

Michael Desjarlais, 2008 WDM school



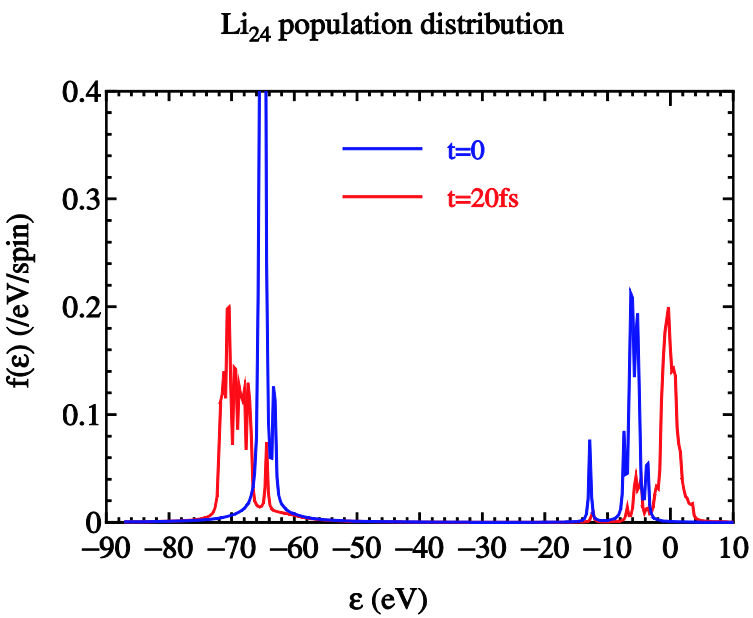
ground state

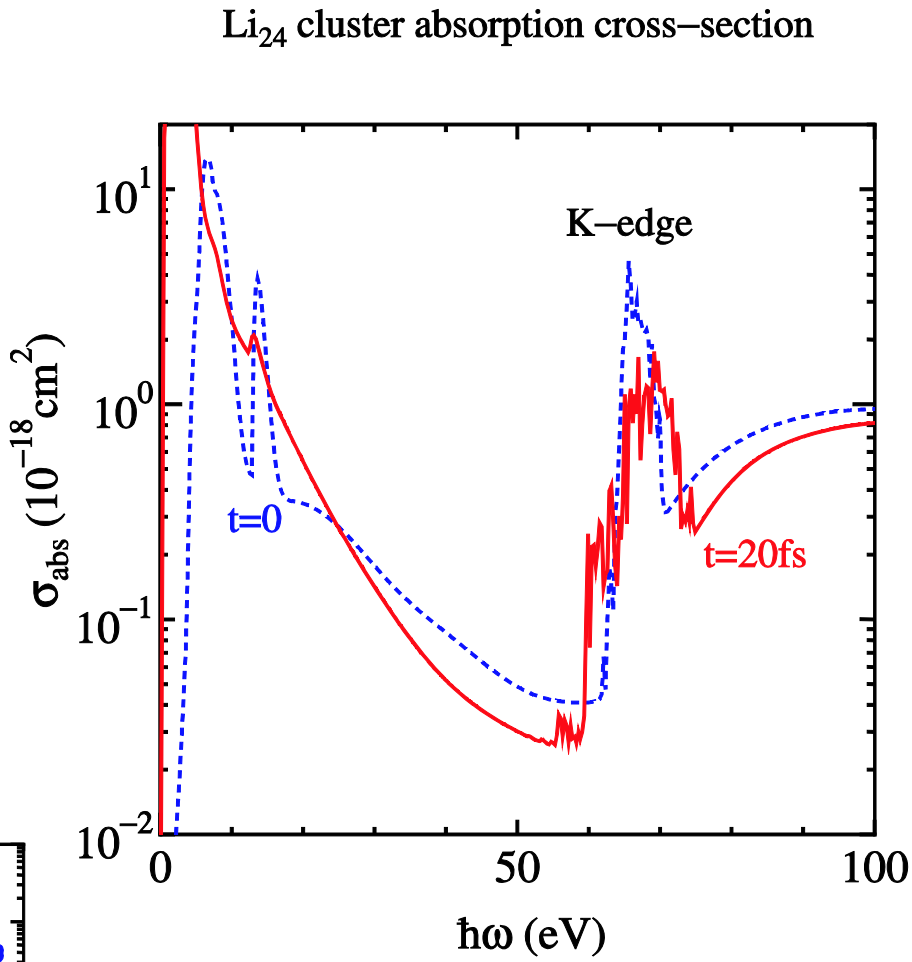


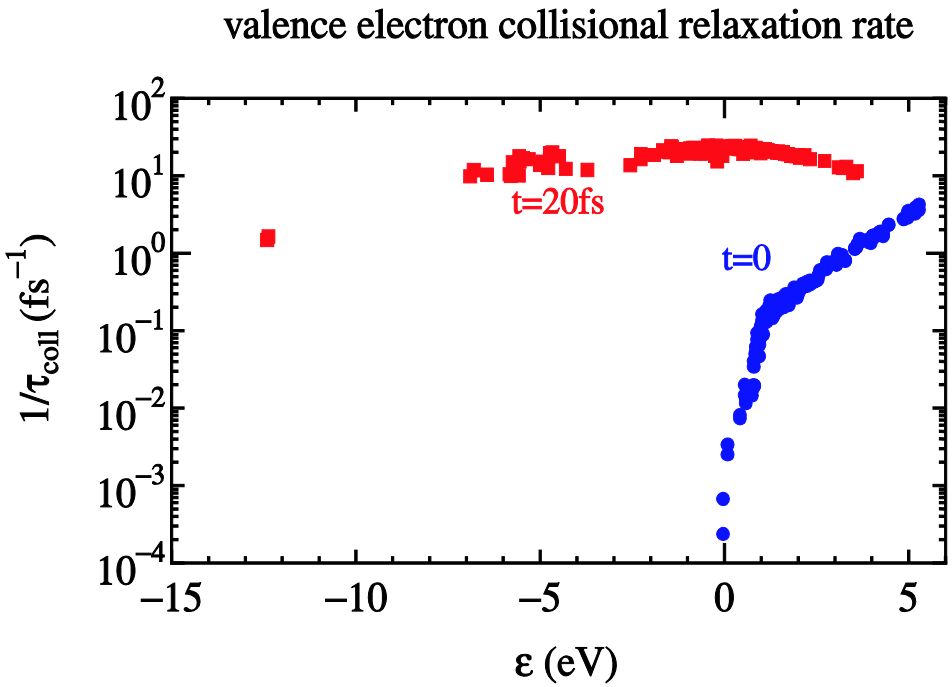
N_{exc} = 1 excited state

H. Kitamura, 2008

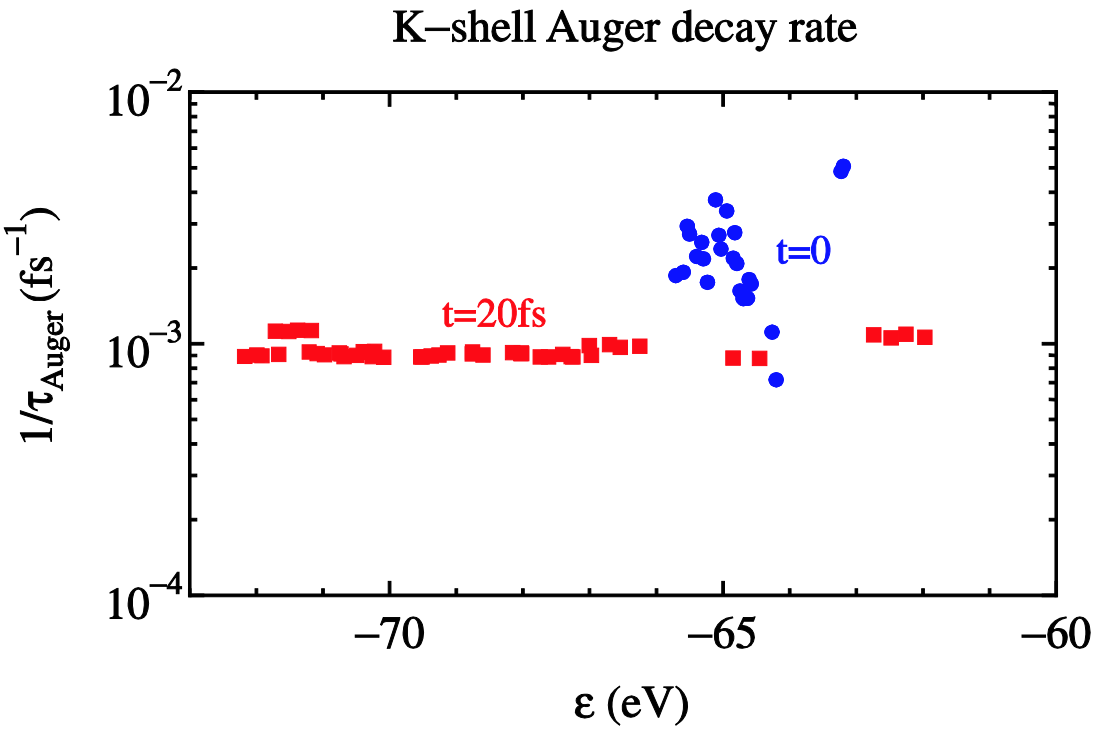
Physical modeling of Li 24 Cluster







KVV Auger decay rate



$$\frac{1}{\tau_{\text{Auger}}^{\text{in}}} \approx 10^{-3} - 10^{-2}\ \text{fs}^{-1}$$

cf. 2.6 10^{-2} fs^{-1} by Green's function theory
[Almbladh & Morales, Phys. Rev. B **39**, 3489 (1989)]

Interaction Experiments of EUV Laser

Sn, Au, Al, Ge, Ti, SiO_2, Sc…

Estimation of the requirement

ρ=7.3 g/cc, hv=24.3eV

n_i=7.3/118.6*6.02x10^{23}cm^{-3}=3.7x10^{22}cm^{-3}

E_{sat}=n_i*hv*1.602x10^{-19} =1.44x10^5J/cm^3

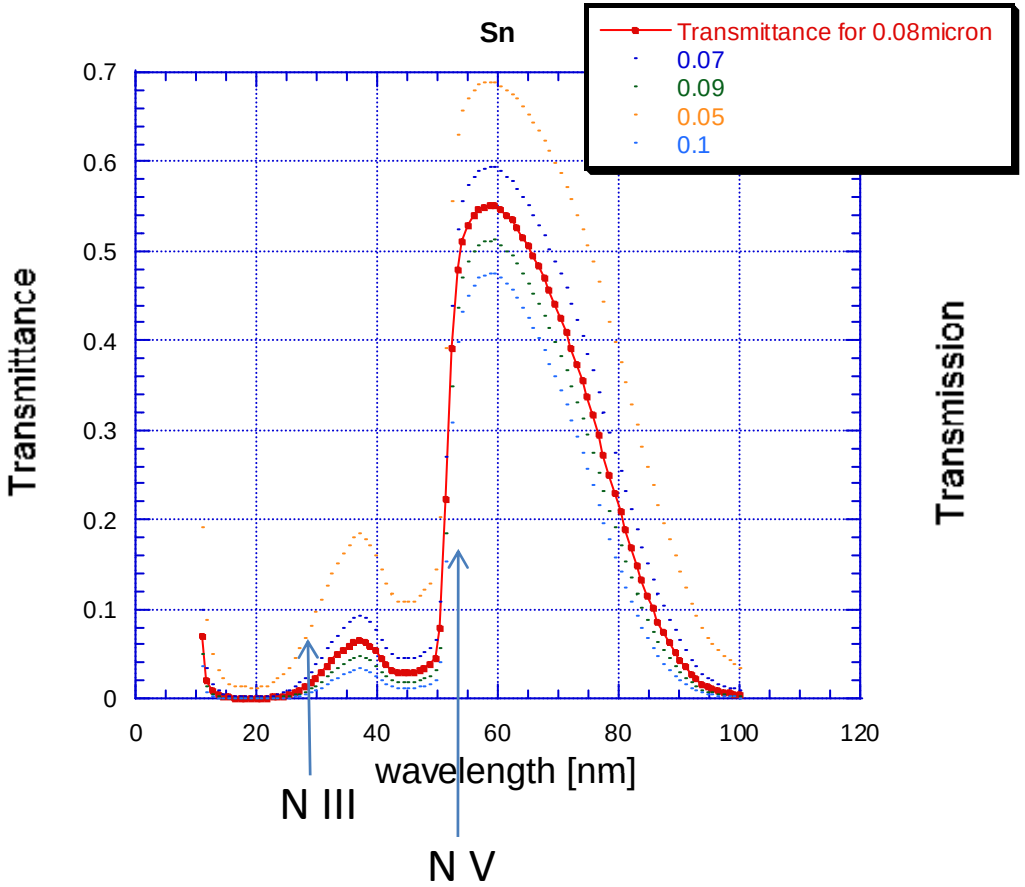
Thickness = 0.08micron

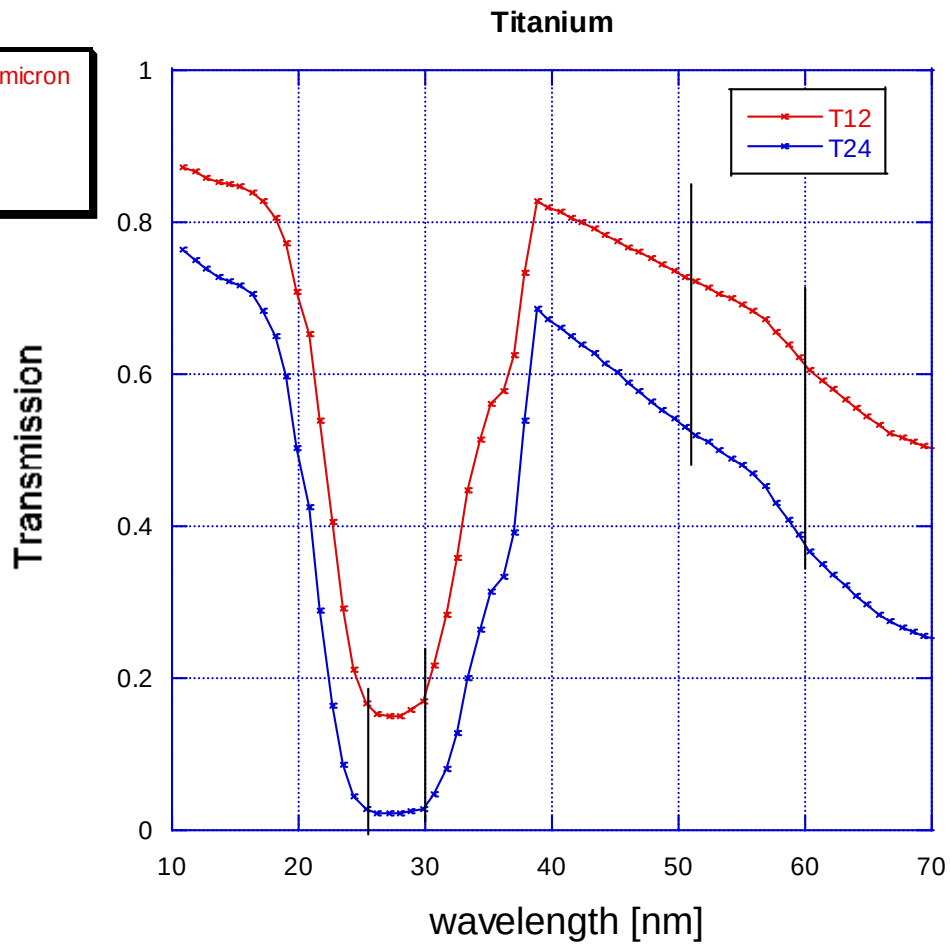
E_{flu} = 0.08x10^{-4}*E_{sat}=1.15J/cm^2

If we assume t=100fs

P_{flu} = 1.2x10^{13}W/cm^2

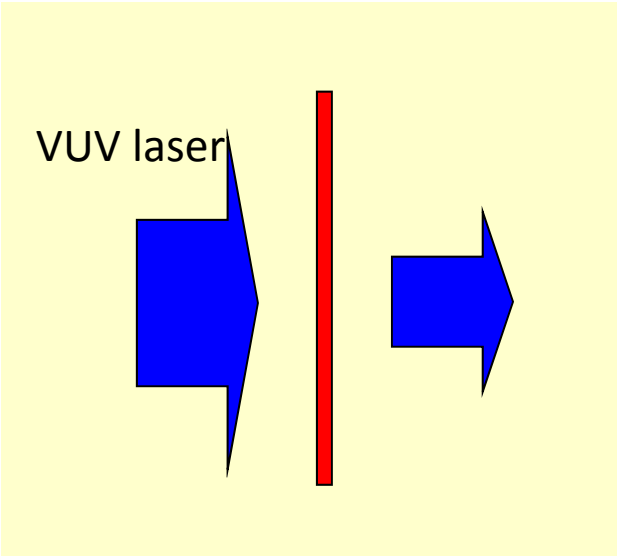
(ref: 1μJ 10μmϕ focus spot, 1.27J/cm^2)

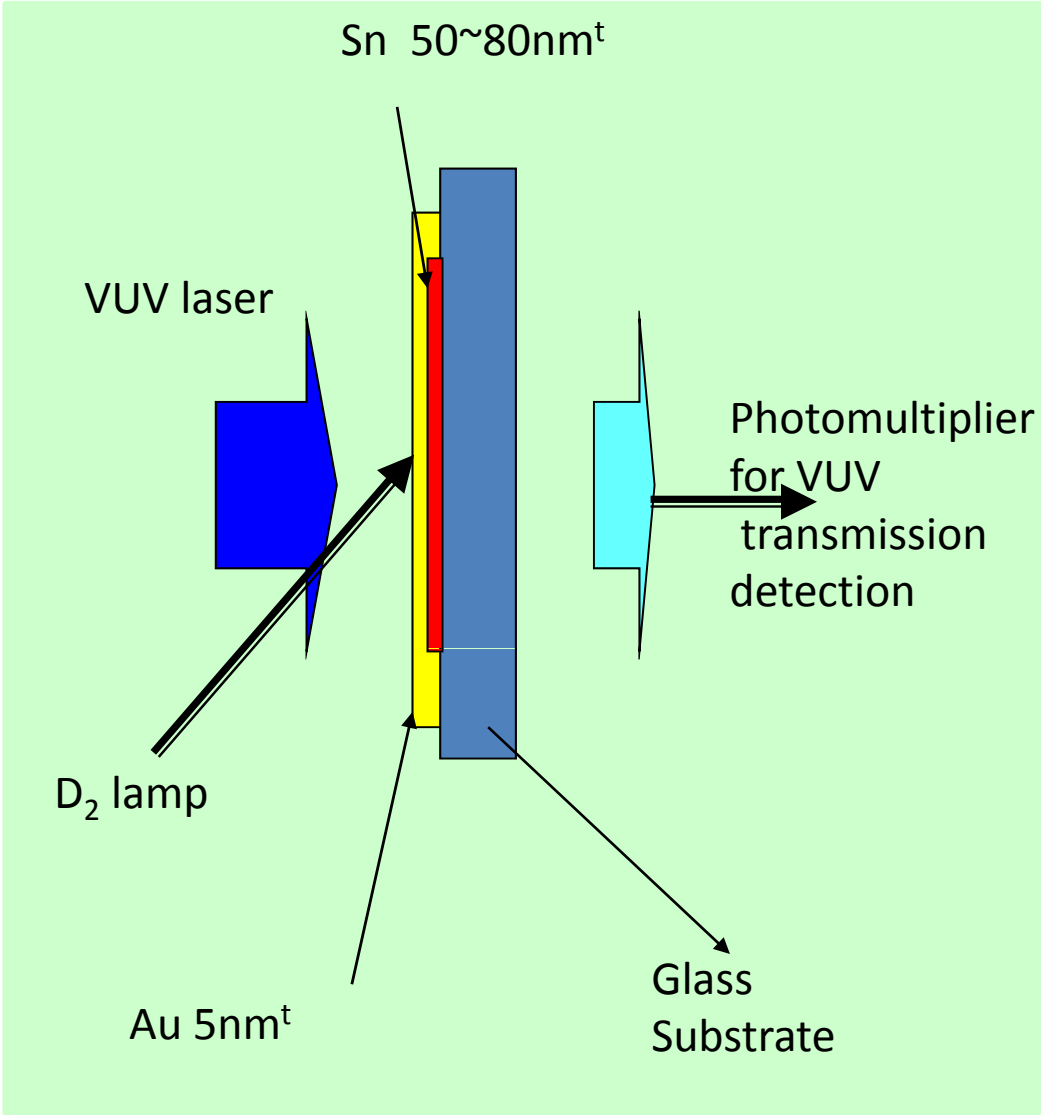




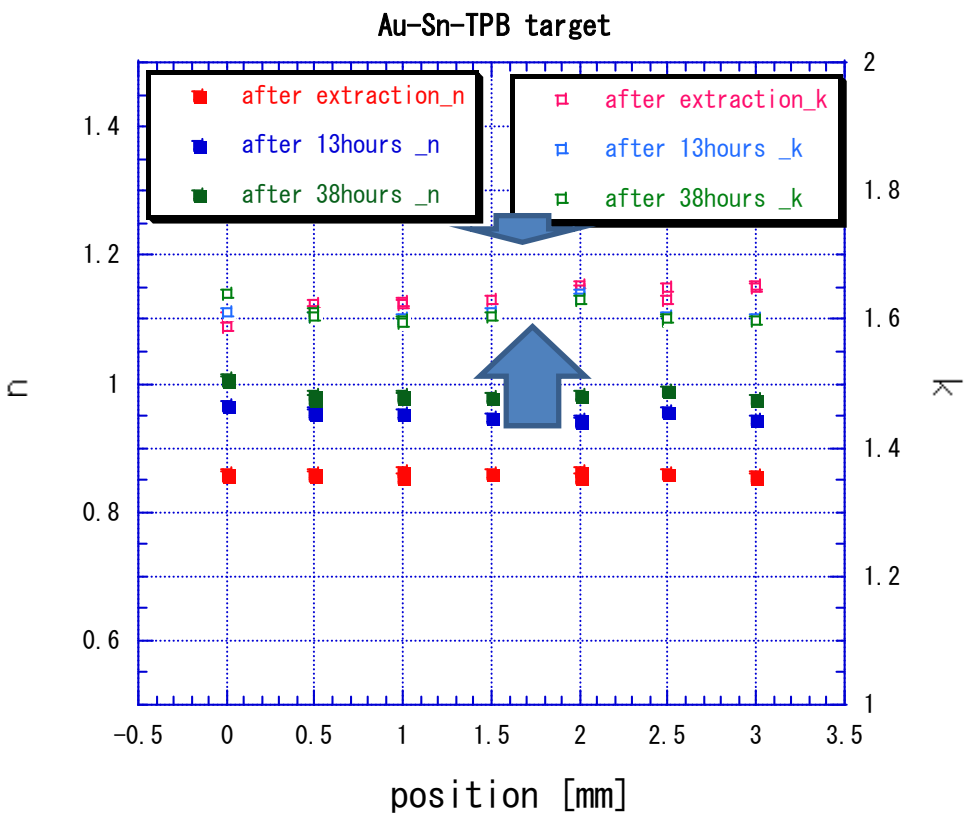
Multi layered target

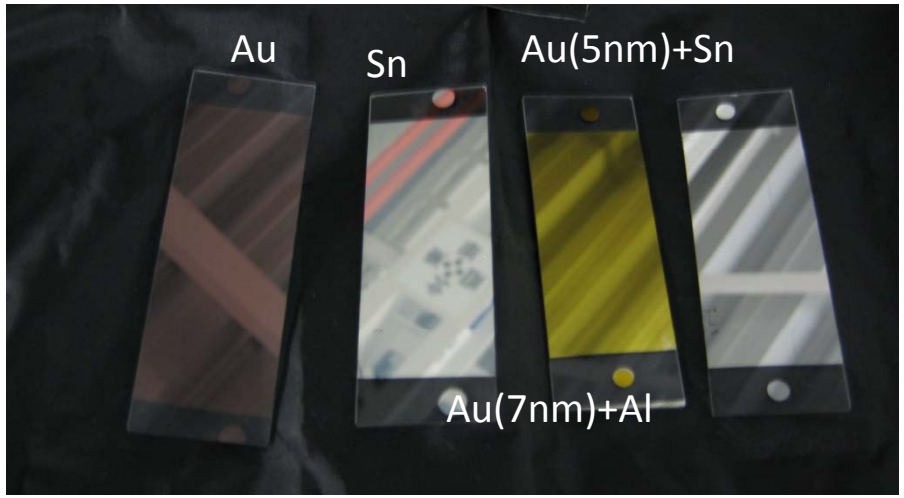
(including protection layer, target layer and fluorescence layer)

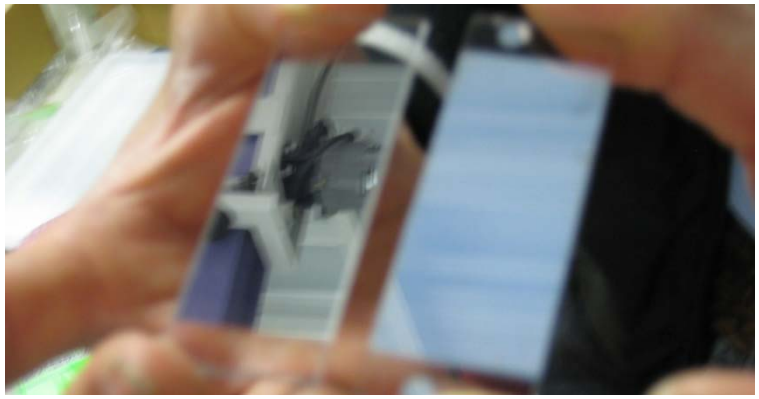




Contamination layer effect on the metal target

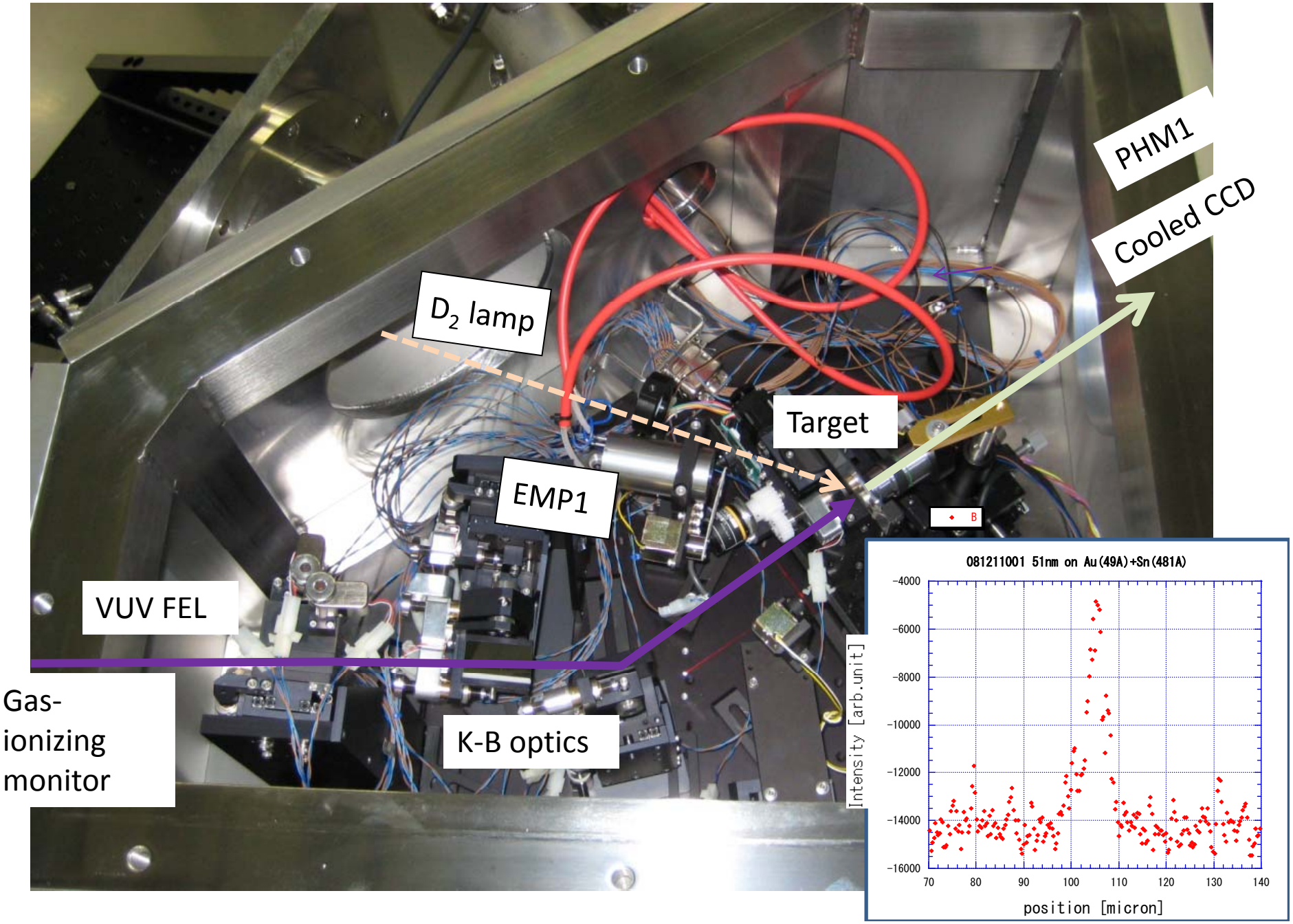




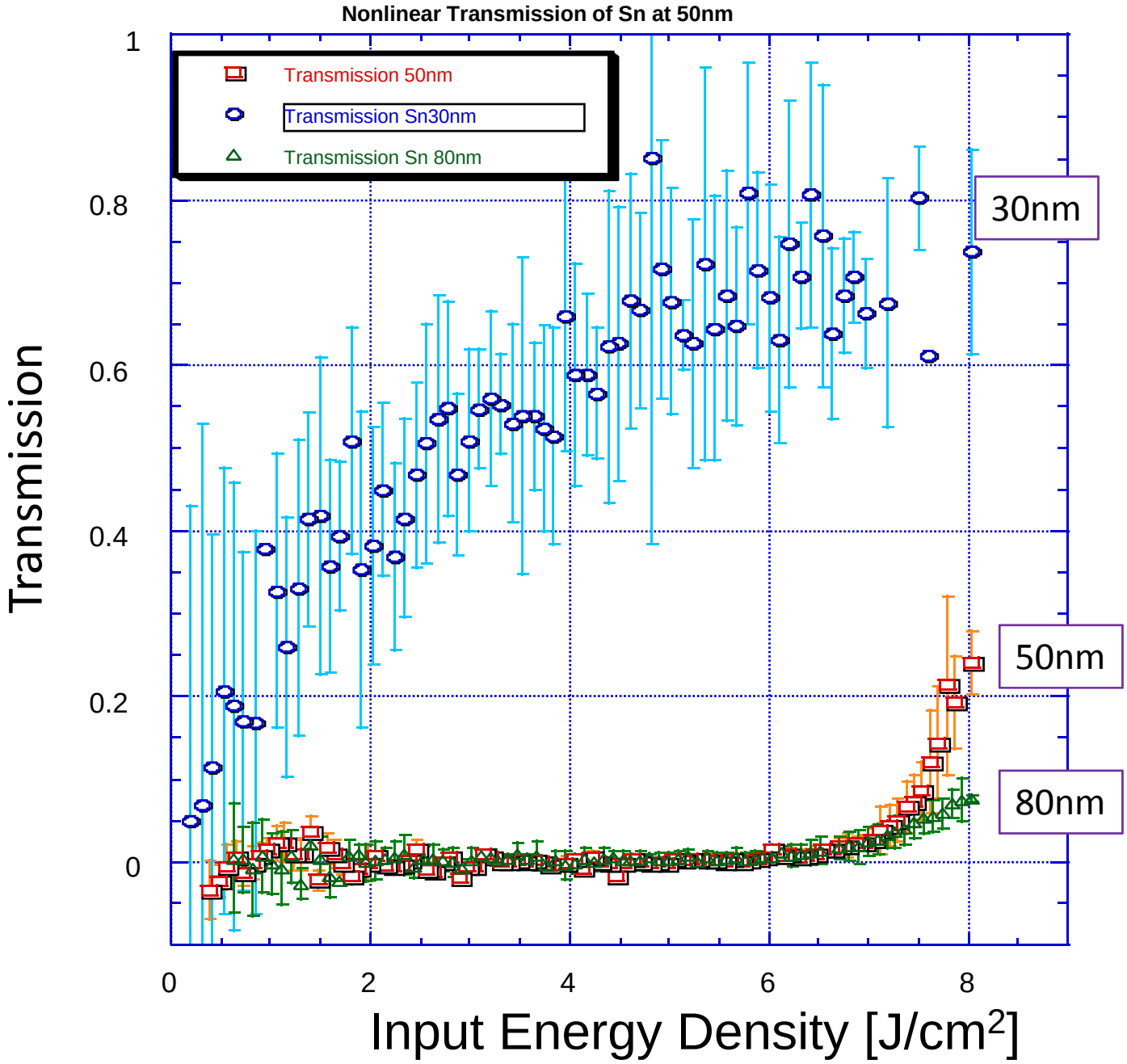


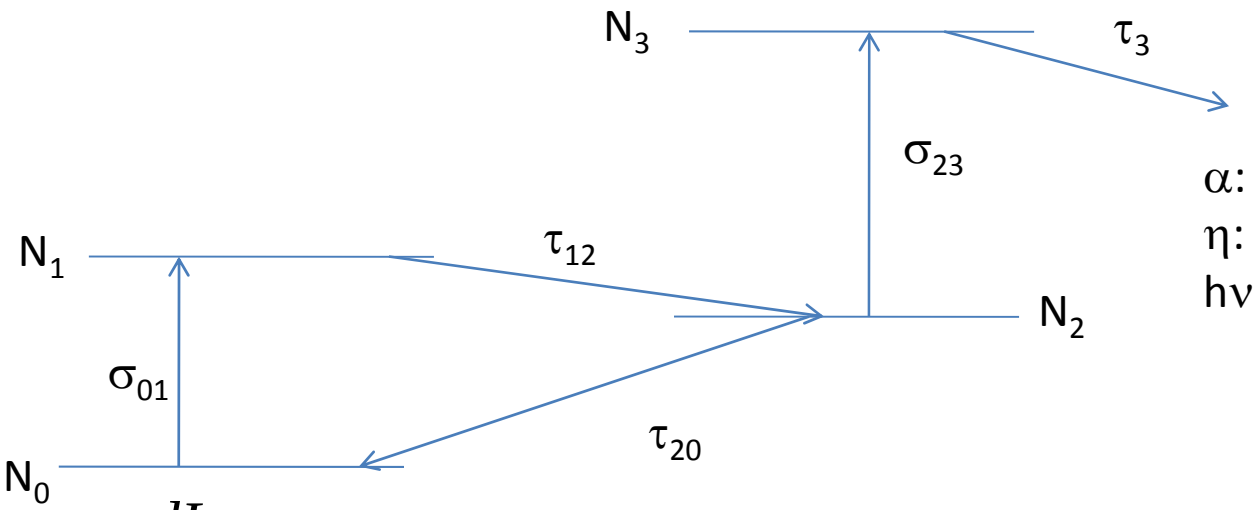
Au+Sn Sn
(stored in Atmosphere)

Experimental set up



Saturable absorption of Sn in VUV wavelength





α: absorption coefficient
η: quantum efficiency
hν: photon energy

$\sigma[cm^2]N\ [cm^{-3}] = \alpha[cm^{-1}]$

$$\frac{dI}{dx} = -\sigma_{01}(N_0 - N_1)I - \sigma_{23}(N_2 - N_3)I$$

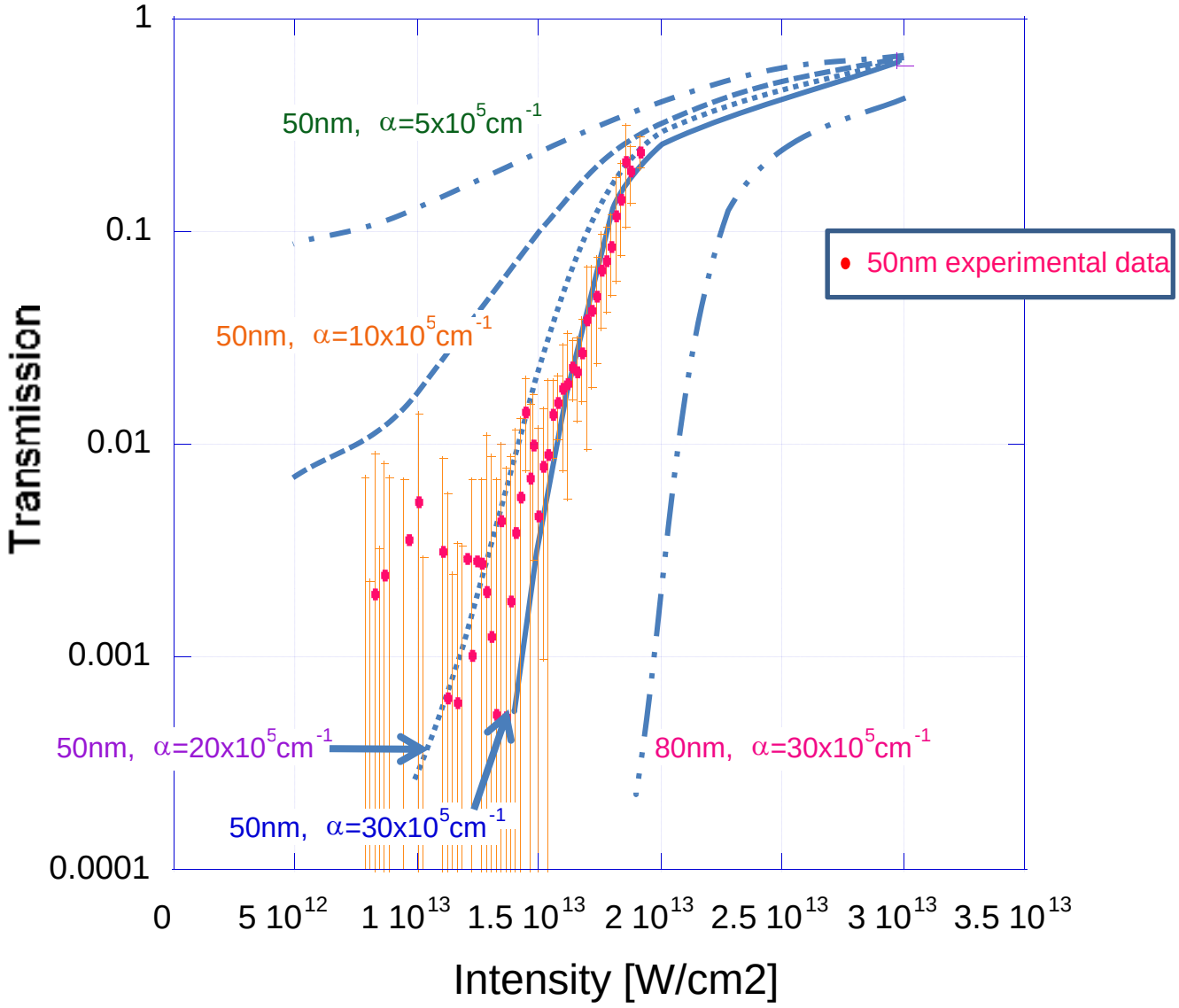
$$\frac{dN_0}{dt} = -\frac{\eta_{01}}{h\nu}\alpha_{01}I + \frac{N_2}{\tau_{20}} = -\frac{\eta_{01}}{h\nu}\sigma_{01}(N_0 - N_1)I + \frac{N_2}{\tau_{20}}$$

$$\frac{dN_1}{dt} = \frac{\eta_{01}}{h\nu}\alpha_{01}I - \frac{N_1}{\tau_{12}} = \frac{\eta_{01}}{h\nu}\sigma_{01}(N_0 - N_1)I - \frac{N_1}{\tau_{12}}$$

$$\frac{dN_2}{dt} = \frac{N_1}{\tau_{12}} - \frac{\eta_{23}}{h\nu}\alpha_{23}I - \frac{N_2}{\tau_{20}} = \frac{N_1}{\tau_{12}} - \frac{\eta_{23}}{h\nu}\sigma_{23}(N_2 - N_3)I - \frac{N_2}{\tau_{20}}$$

$$\frac{dN_3}{dt} = \frac{\eta_{23}}{h\nu}\alpha_{23}I - \frac{N_3}{\tau_3} = \frac{\eta_{23}}{h\nu}\sigma_{23}(N_2 - N_3)I - \frac{N_3}{\tau_3}$$

Simulation can explain the experimental results.



Saturation intensity dN/dt =0

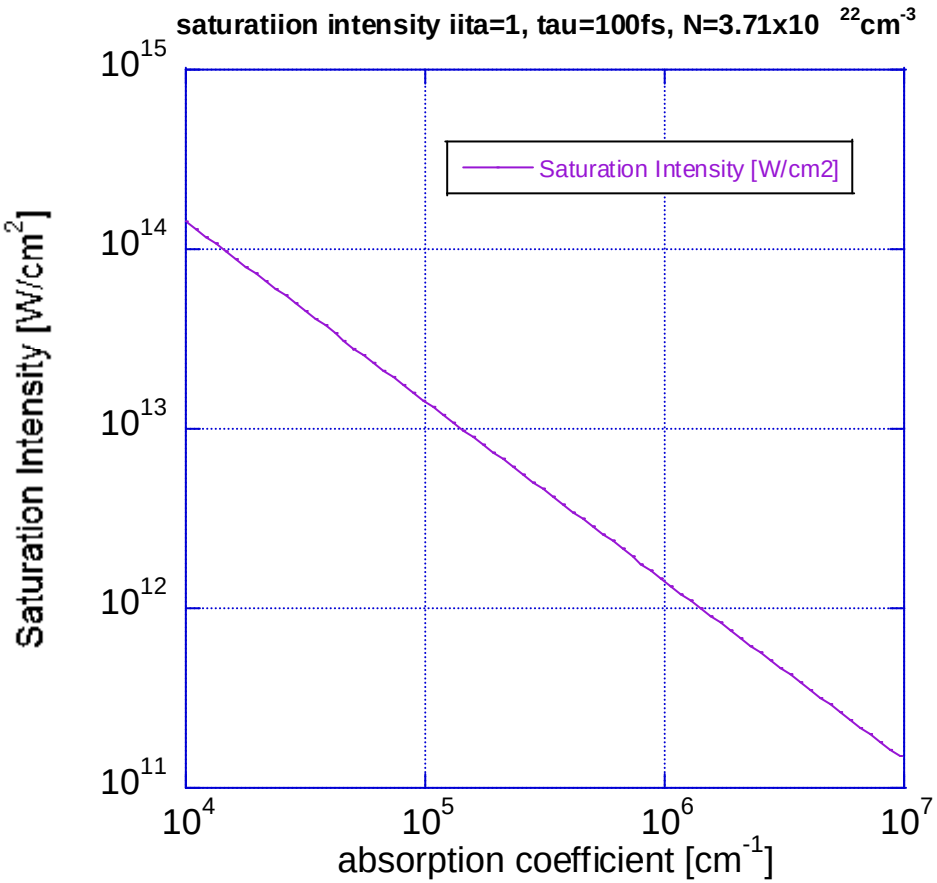
$$\frac{dN_0}{dt} = -\frac{\eta_{01}}{h\nu}\alpha_{01}I + \frac{N_2}{\tau_{20}} = -\frac{\eta_{01}}{h\nu}\sigma_{01}(N_0 - N_1)I + \frac{N_2}{\tau_{20}}$$

$$\frac{dN_1}{dt} = \frac{\eta_{01}}{h\nu}\alpha_{01}I - \frac{N_1}{\tau_{12}} = \frac{\eta_{01}}{h\nu}\sigma_{01}(N_0 - N_1)I - \frac{N_1}{\tau_{12}}$$

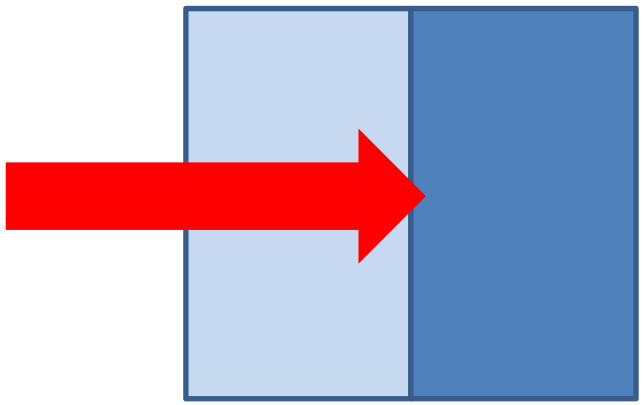
$$\frac{dN_2}{dt} = \frac{N_1}{\tau_{12}} - \frac{\eta_{23}}{h\nu}\alpha_{23}I - \frac{N_2}{\tau_{20}} = \frac{N_1}{\tau_{12}} - \frac{\eta_{23}}{h\nu}\sigma_{23}(N_2 - N_3)I - \frac{N_2}{\tau_{20}}$$

$$\frac{dN_3}{dt} = \frac{\eta_{23}}{h\nu}\alpha_{23}I - \frac{N_3}{\tau_3} = \frac{\eta_{23}}{h\nu}\sigma_{23}(N_2 - N_3)I - \frac{N_3}{\tau_3}$$

$$I_{sat} = \frac{h\nu}{2\tau_{12}\eta_{01}\sigma_{01}}$$

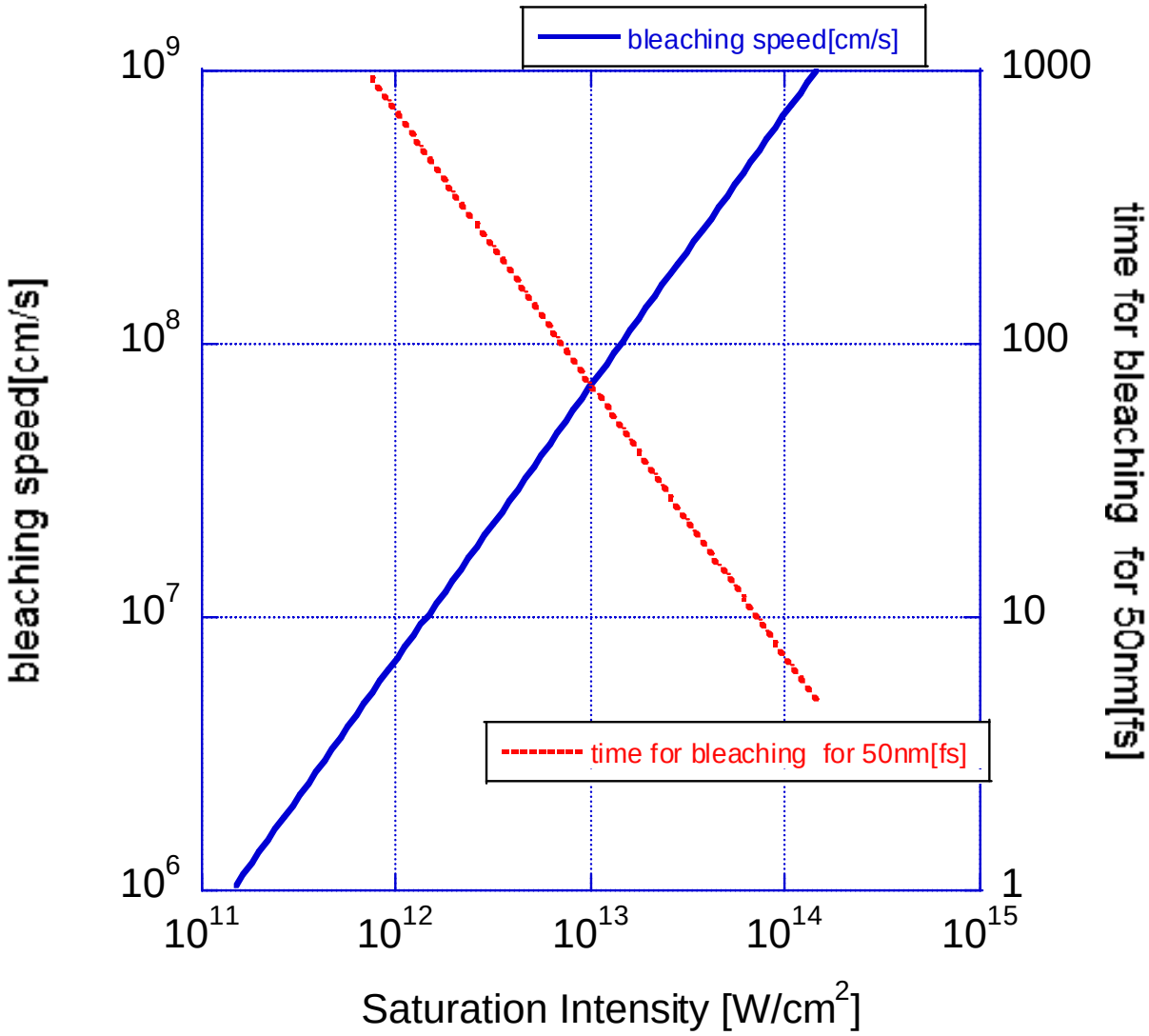


Speed of penetration

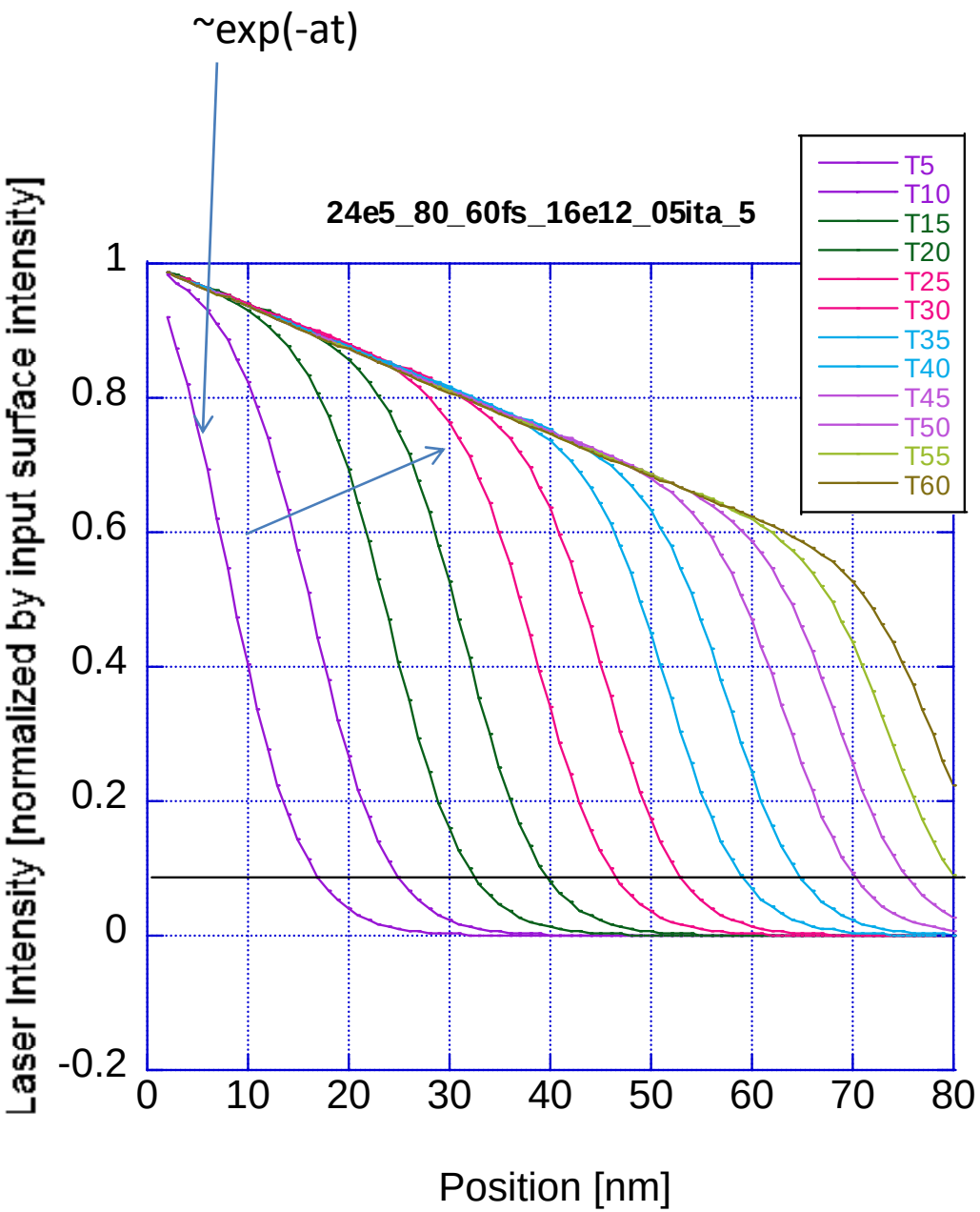


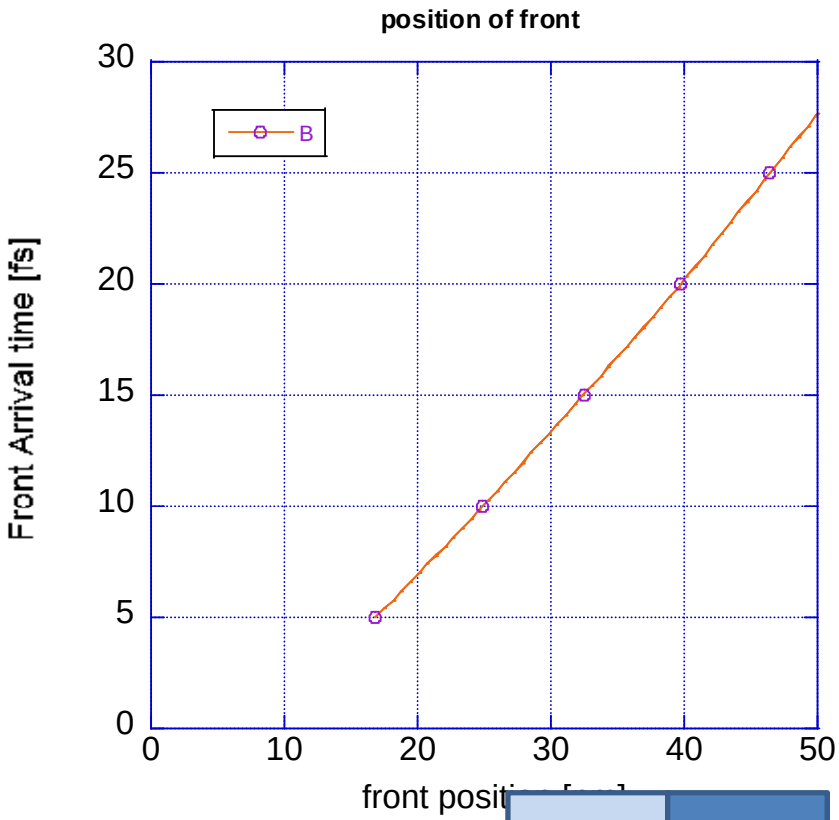
$$Nv = \frac{\eta I}{h\nu}$$

$$v = \frac{\eta I}{h\nu}\frac{1}{N}$$

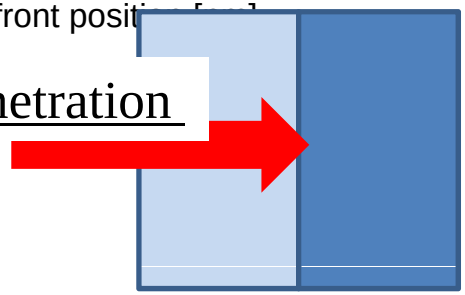


Intensity profile inside Sn film





Speed of penetration



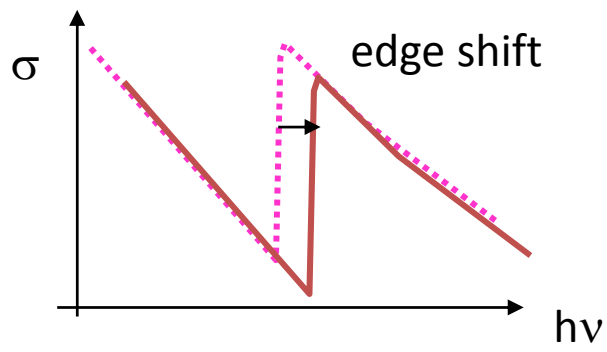
$$N\nu = \frac{\eta I}{h\nu}$$

$$\nu = \frac{\eta I}{h\nu}\frac{1}{N}$$

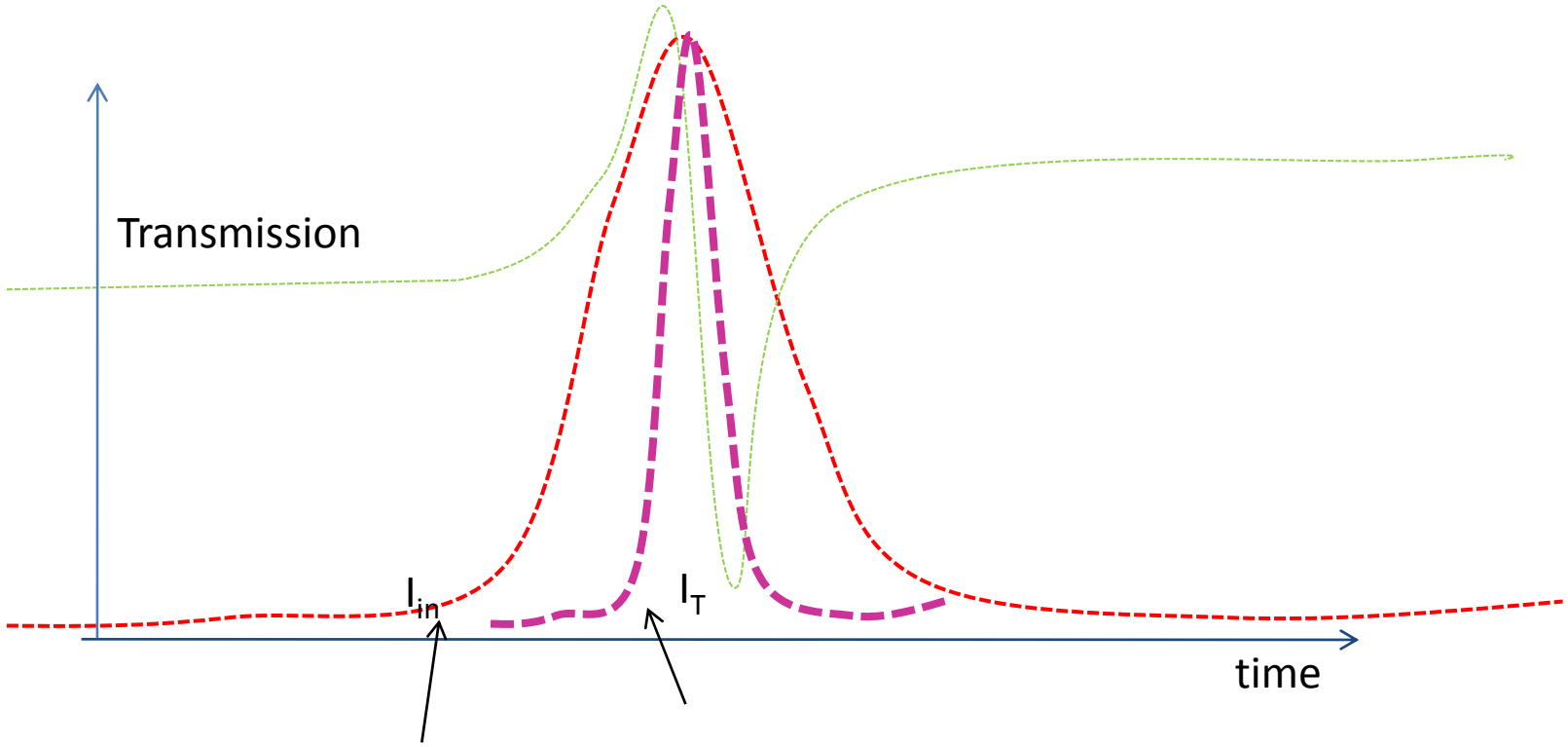
The rate of increase of transmission by

$(L/v)^{-1} = N\sigma(I_{laser}/h\nu/N) = \sigma I_{laser}/h\nu.$

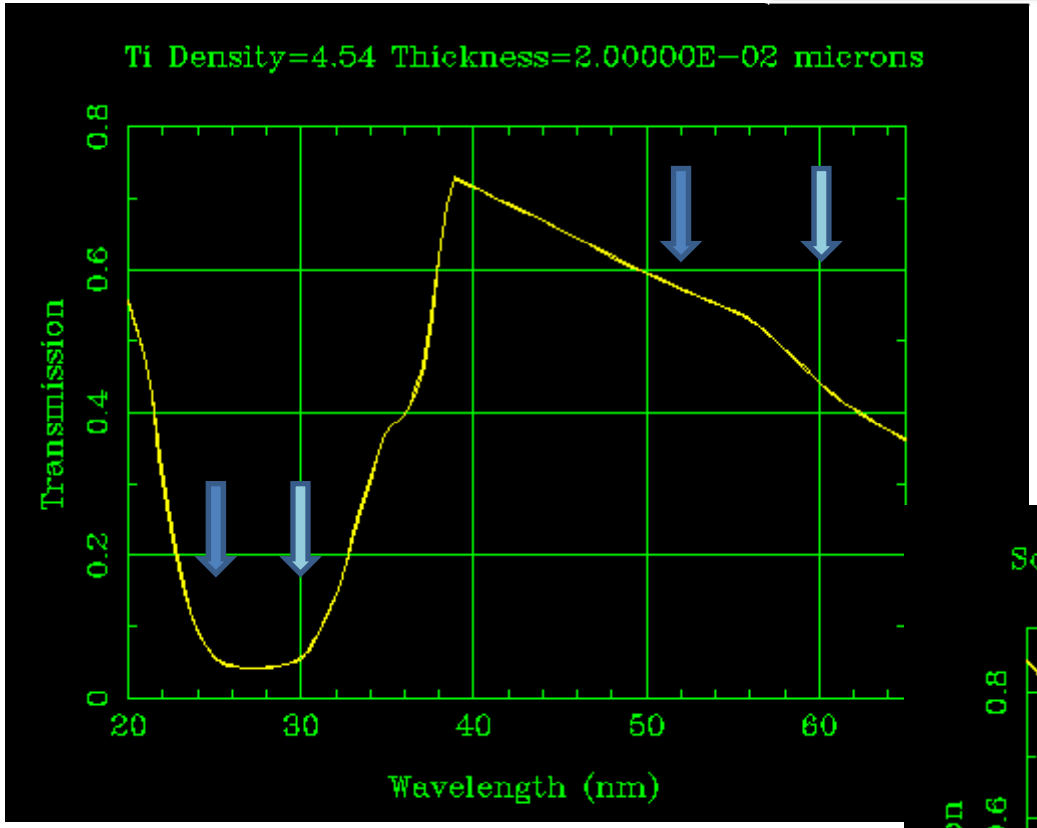
$t_{switching} = 3fs$!

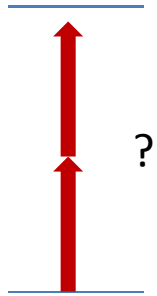


We can expect pulse shortening in VUV laser region.

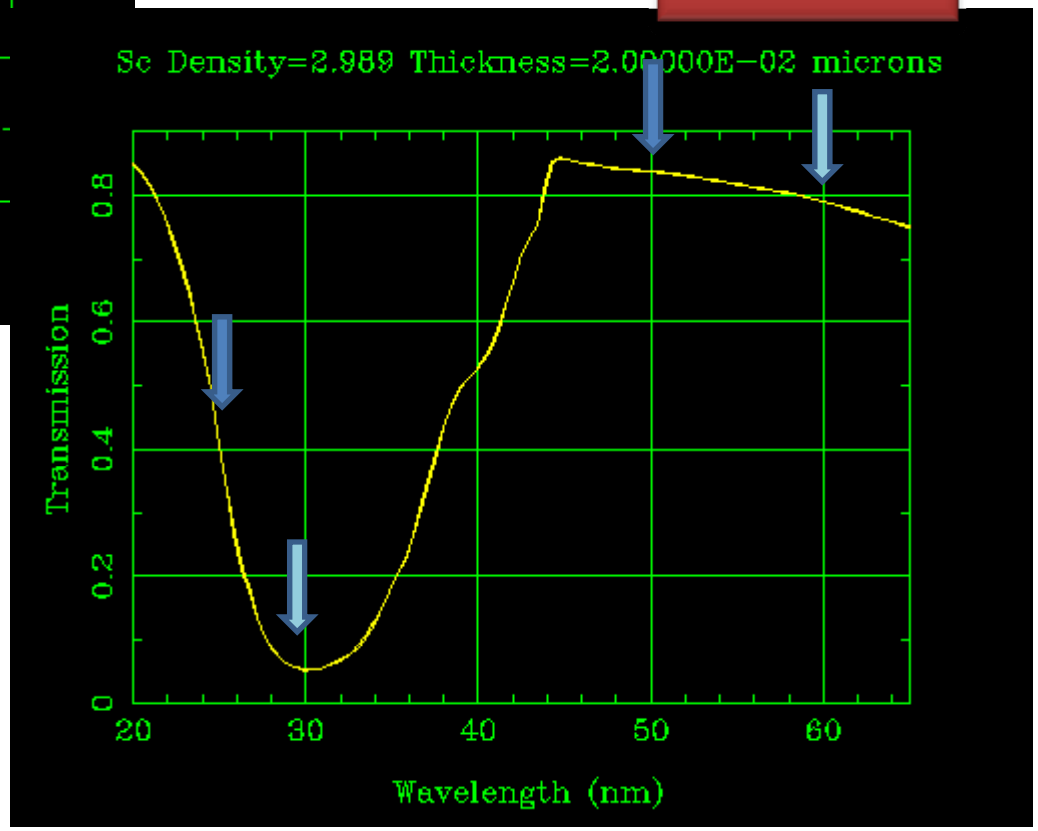


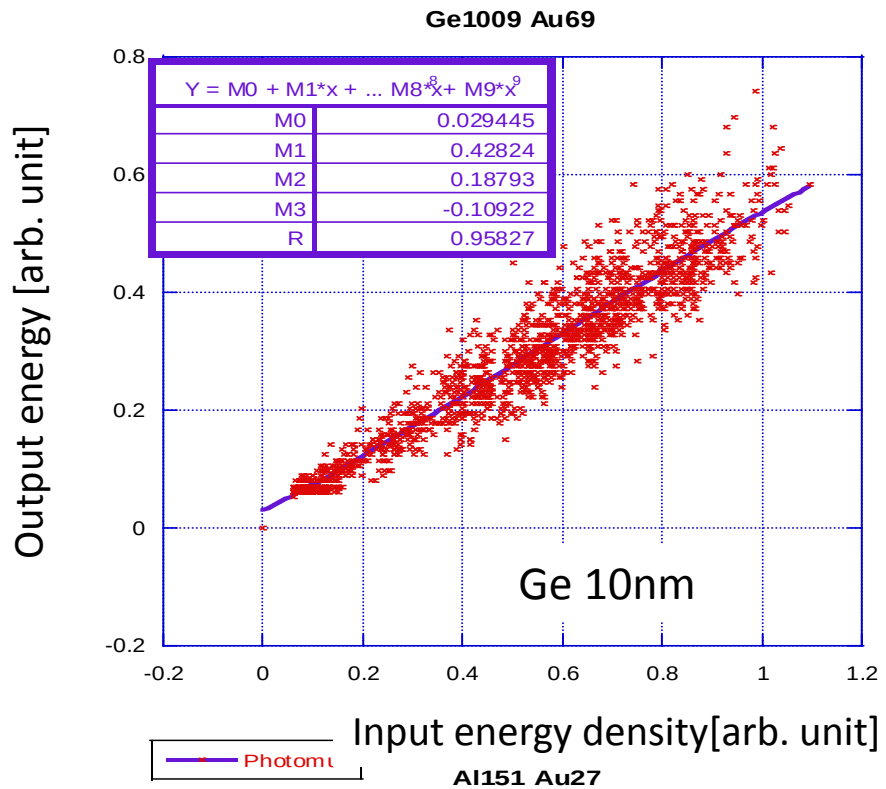
Ti 20nm

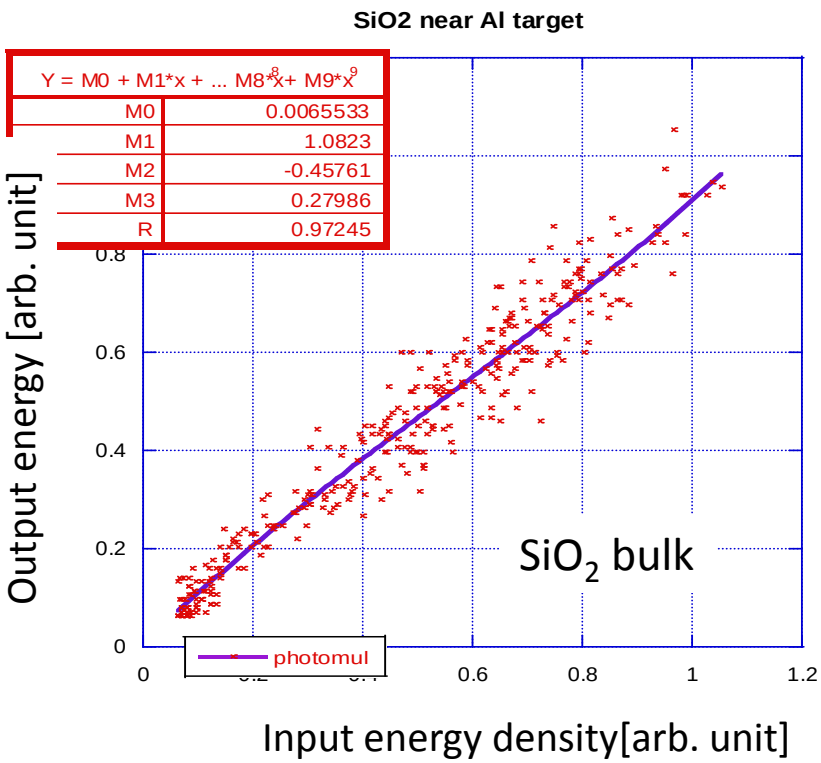


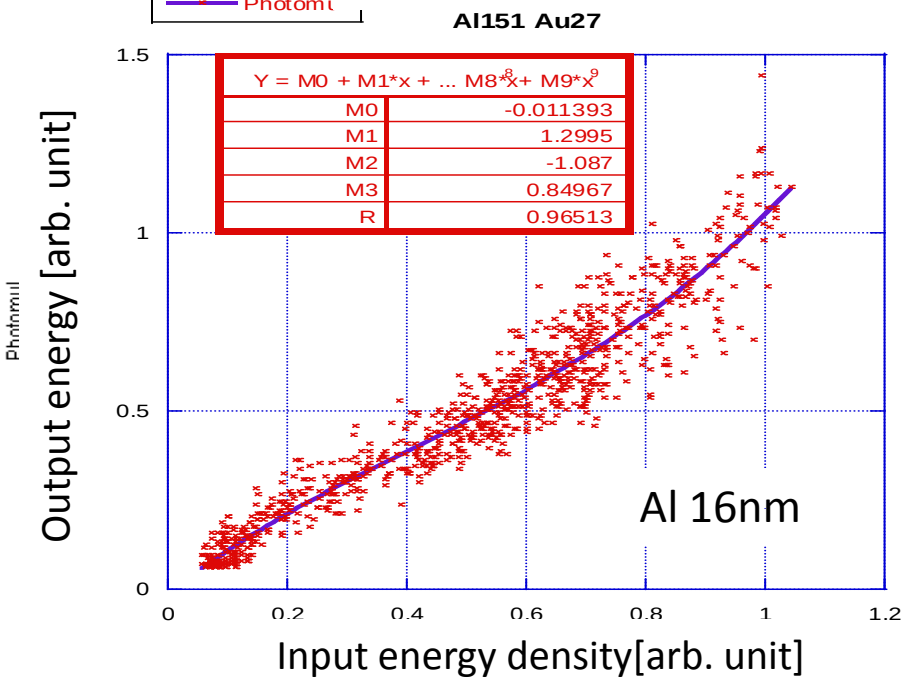


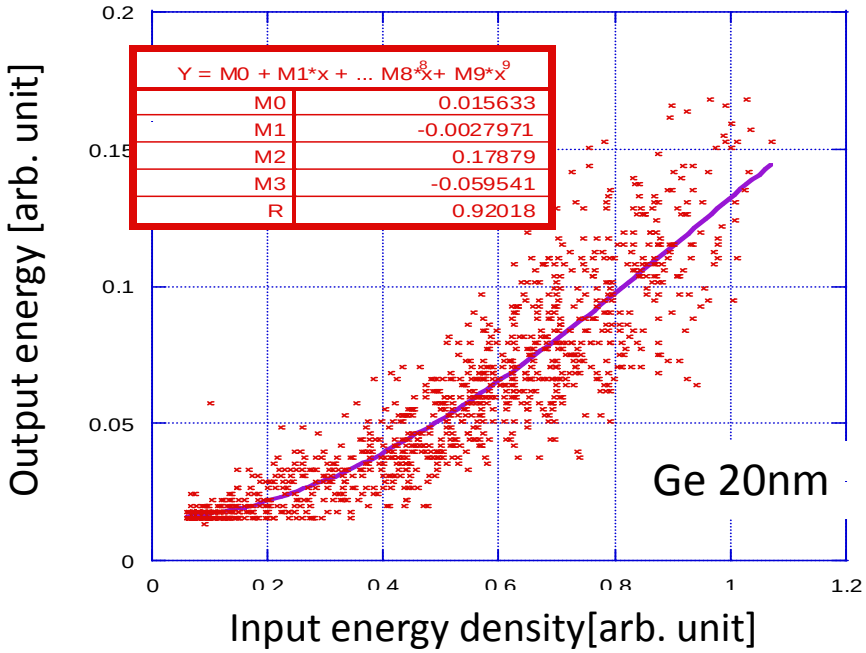
Sc 20nm




Ge1009 Au69
Y = M0 + M1*x + ... M8*x^8+ M9*x^9
M0 0.029445
M1 0.42824
M2 0.18793
M3 -0.10922
R 0.95827
Ge 10nm
Output energy [arb. unit]
Input energy density[arb. unit]
Photomu


SiO2 near Al target
Y = M0 + M1*x + ... M8*x^8+ M9*x^9
M0 0.0065533
M1 1.0823
M2 -0.45761
M3 0.27986
R 0.97245
SiO2 bulk
photomul
Output energy [arb. unit]
Input energy density[arb. unit]

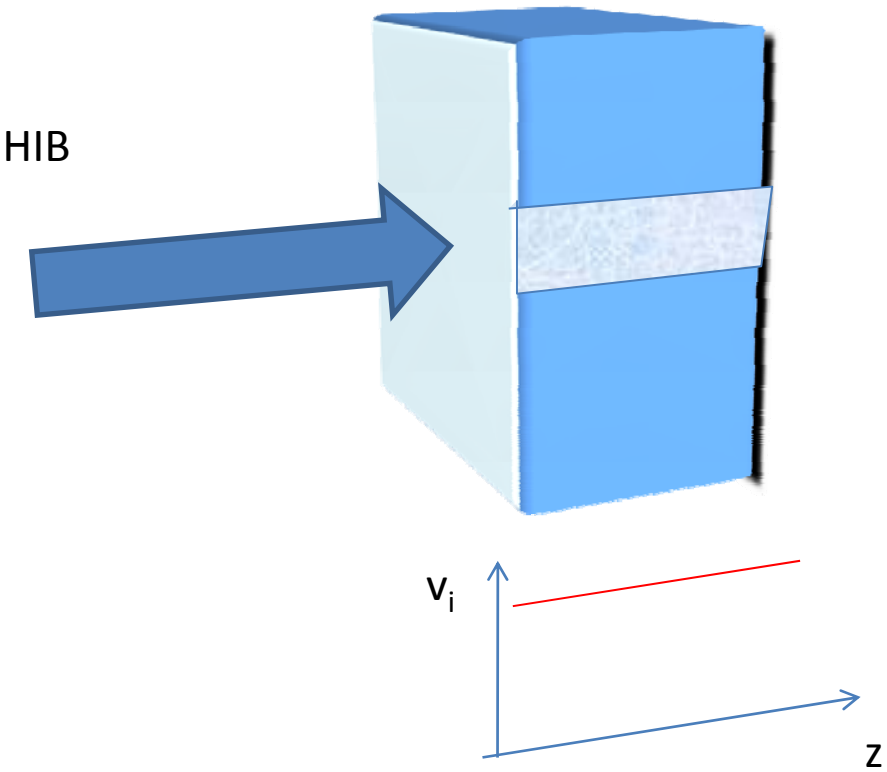

Al151 Au27
Y = M0 + M1*x + ... M8*x^8+ M9*x^9
M0 -0.011393
M1 1.2995
M2 -1.087
M3 0.84967
R 0.96513
Al 16nm
Output energy [arb. unit]
Input energy density[arb. unit]

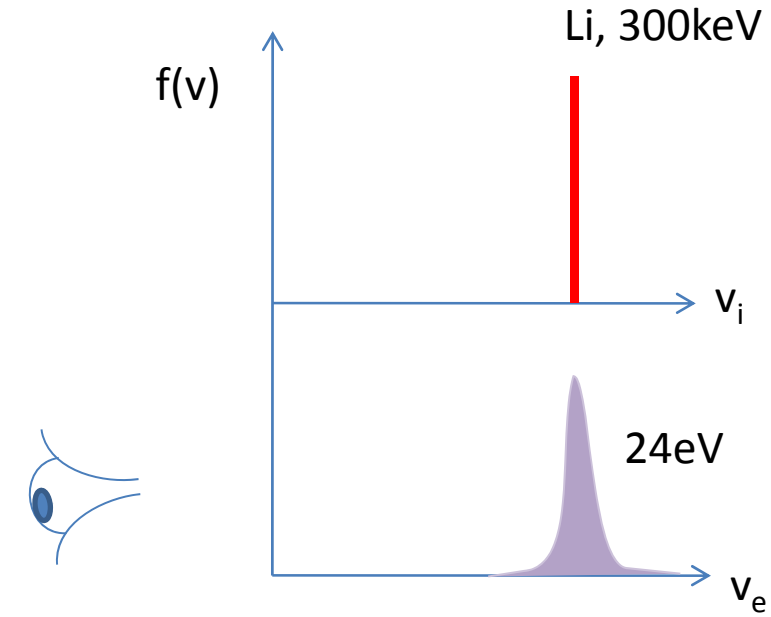

Y = M0 + M1*x + ... M8*x^8+ M9*x^9
M0 0.015633
M1 -0.0027971
M2 0.17879
M3 -0.059541
R 0.92018
Ge 20nm
Output energy [arb. unit]
Input energy density[arb. unit]

Summary

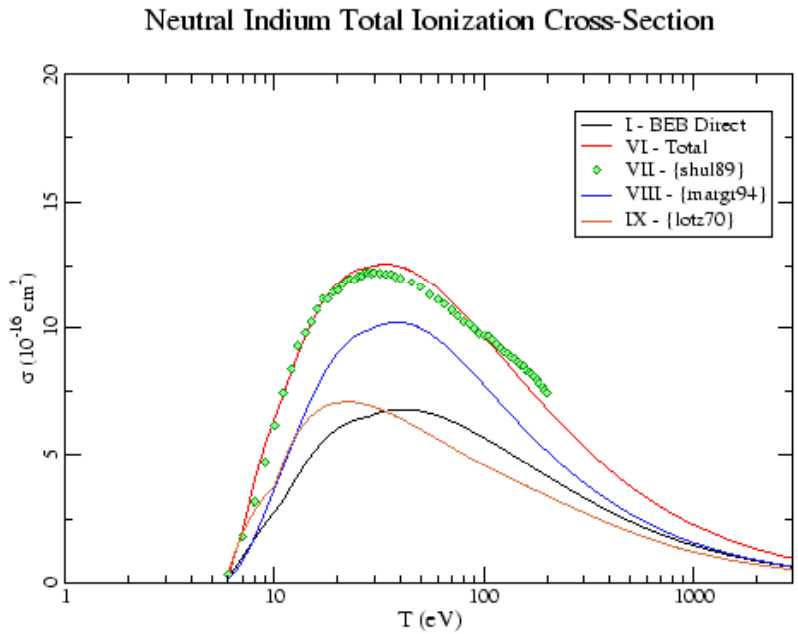
- EUV interaction experiments with various materials
- We have evidence about nonlinear optical phenomena.
- We will use these effect for real optical devices in high energy photon applications.

Suggestion to HIB experiments





$\sigma_{c,ex}$~10^{15}~10^{16}cm^2



Life time for this condition?

0.1mmϕ, 10^{13}electron event