SAND2017-10928C

Applying two-temperature modelling to ultrafast laser ignition of reactive nanolaminates

Michael J. Abere and David P. Adams

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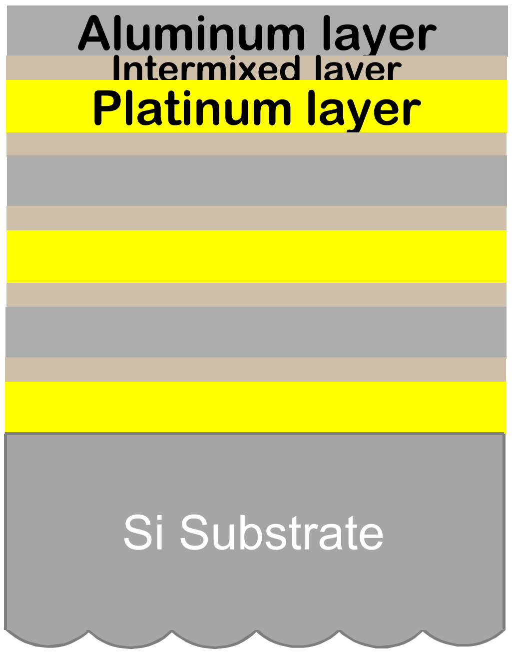
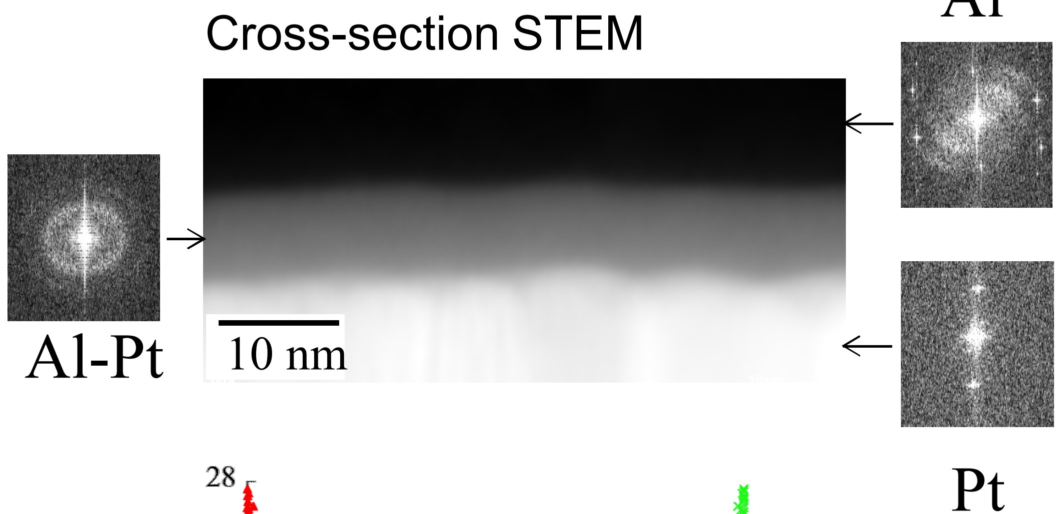
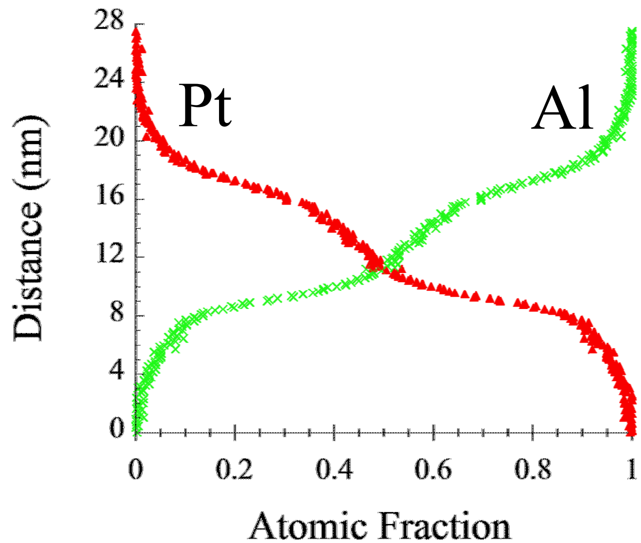
Video of Laser Ignition and Self-Propagating Reaction in Al/Pt Multilayer

760 W/cm^2
164 nm Bilayer
1.8 µs per frame, played at 4 fps

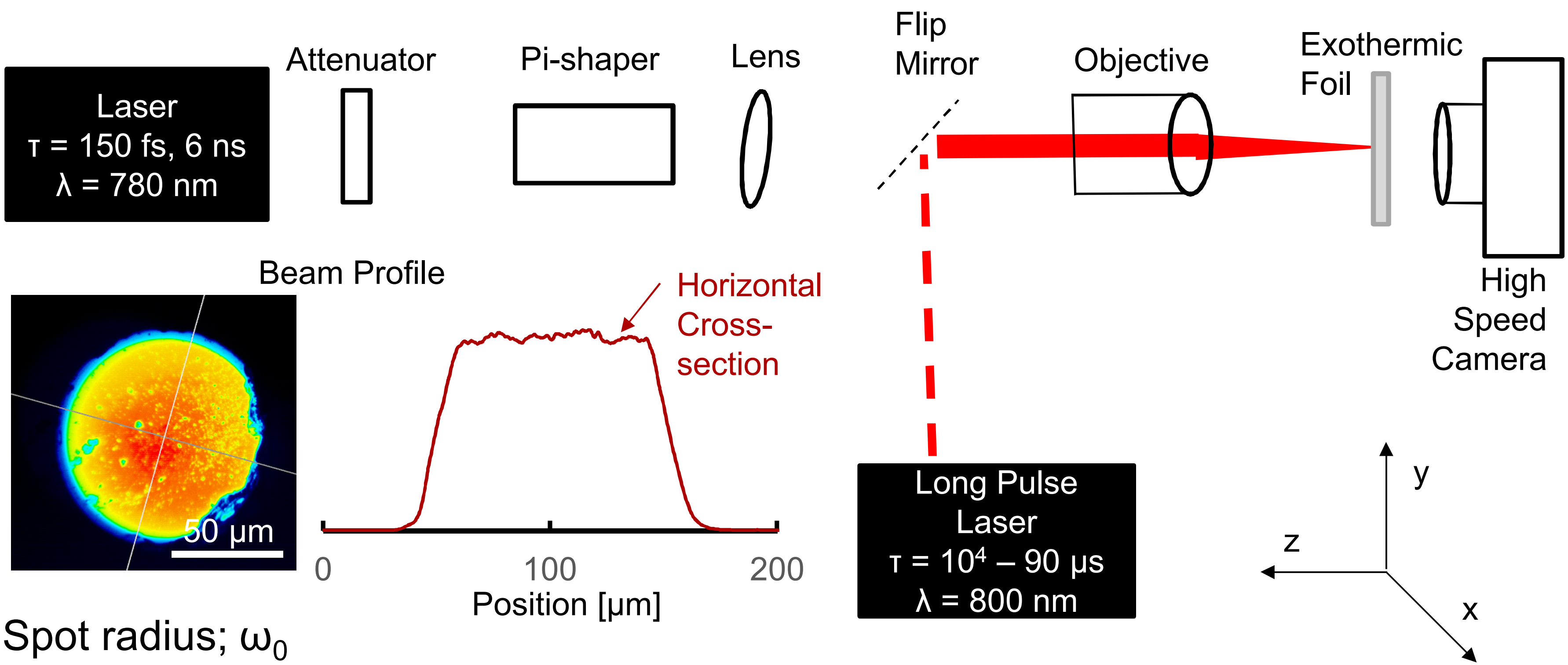
Sputter Deposition of Reactive Multilayers





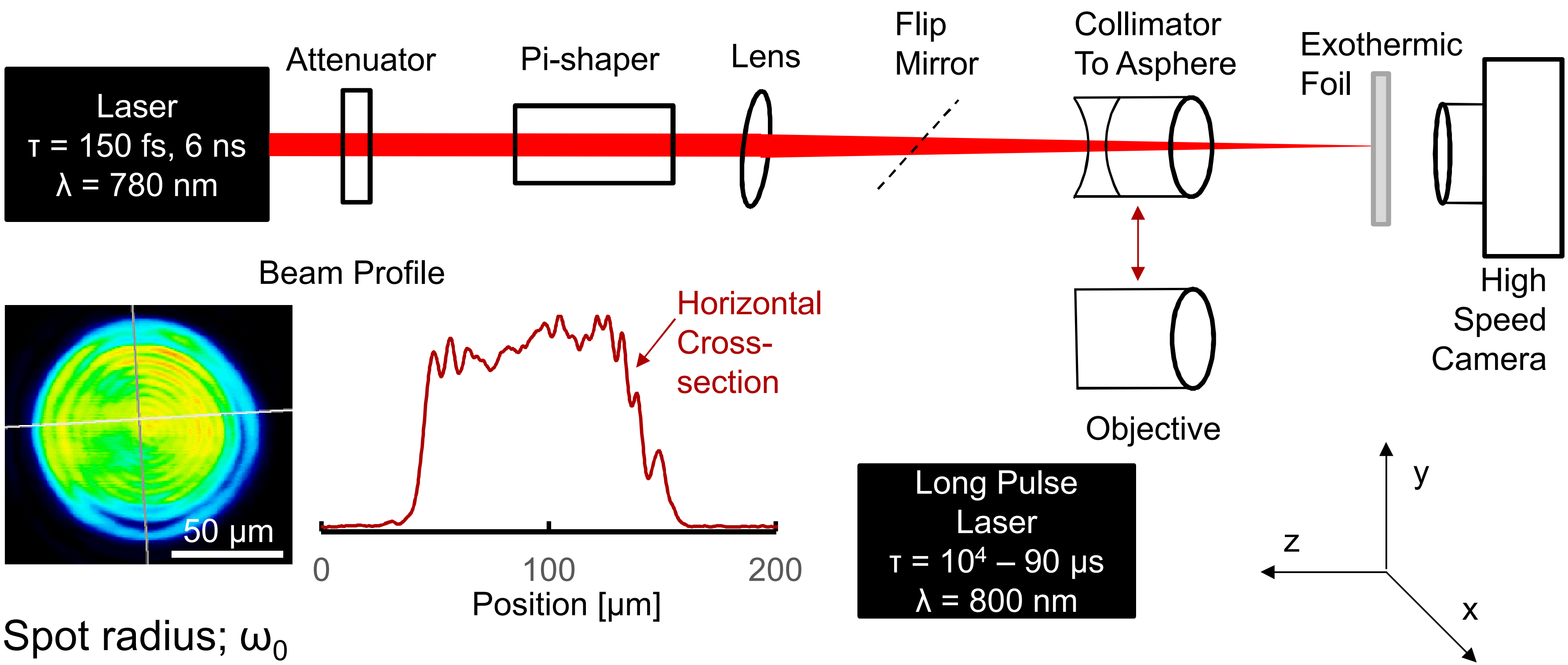


Direct Laser Ignition Method



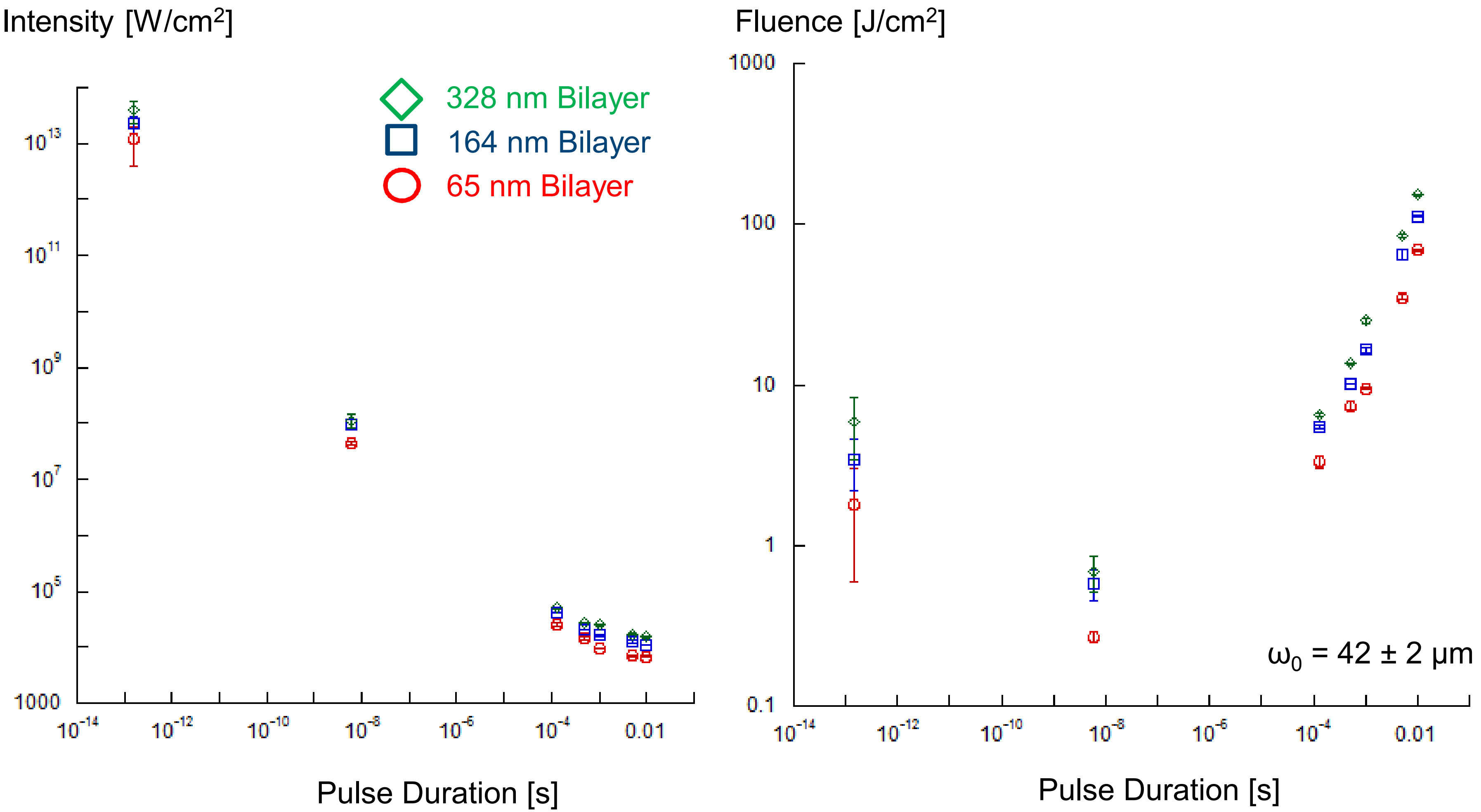
Spot radius; ω_0

Direct Laser Ignition Method

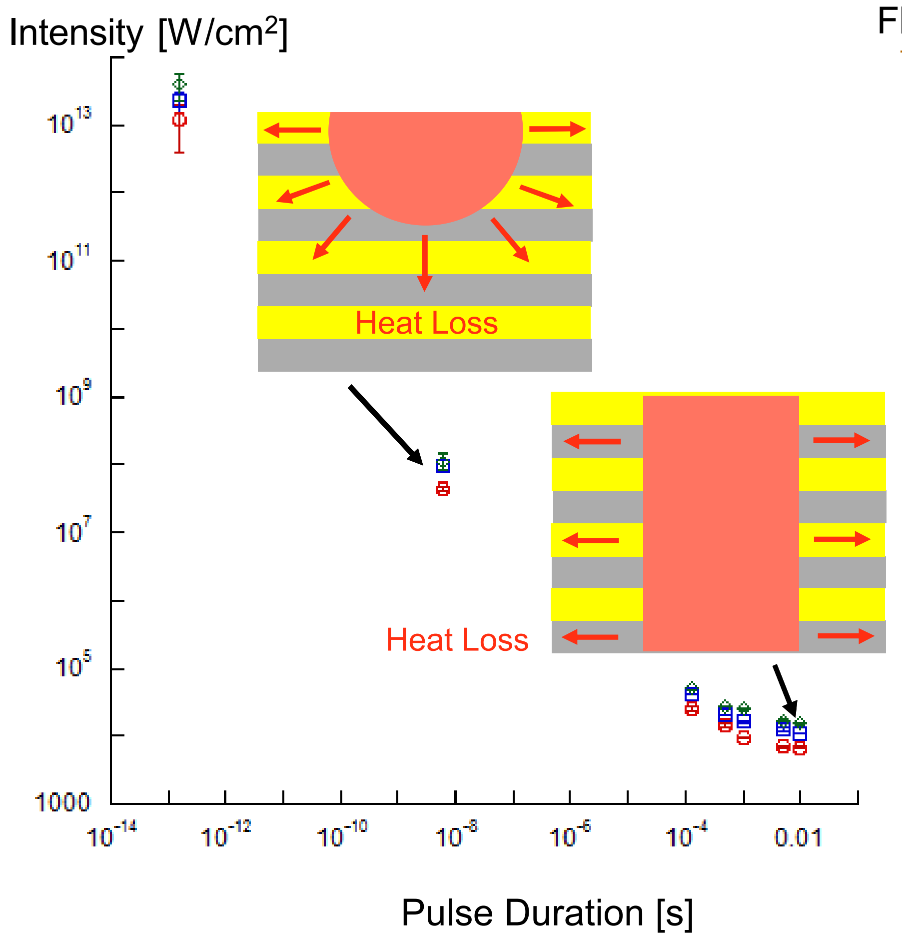


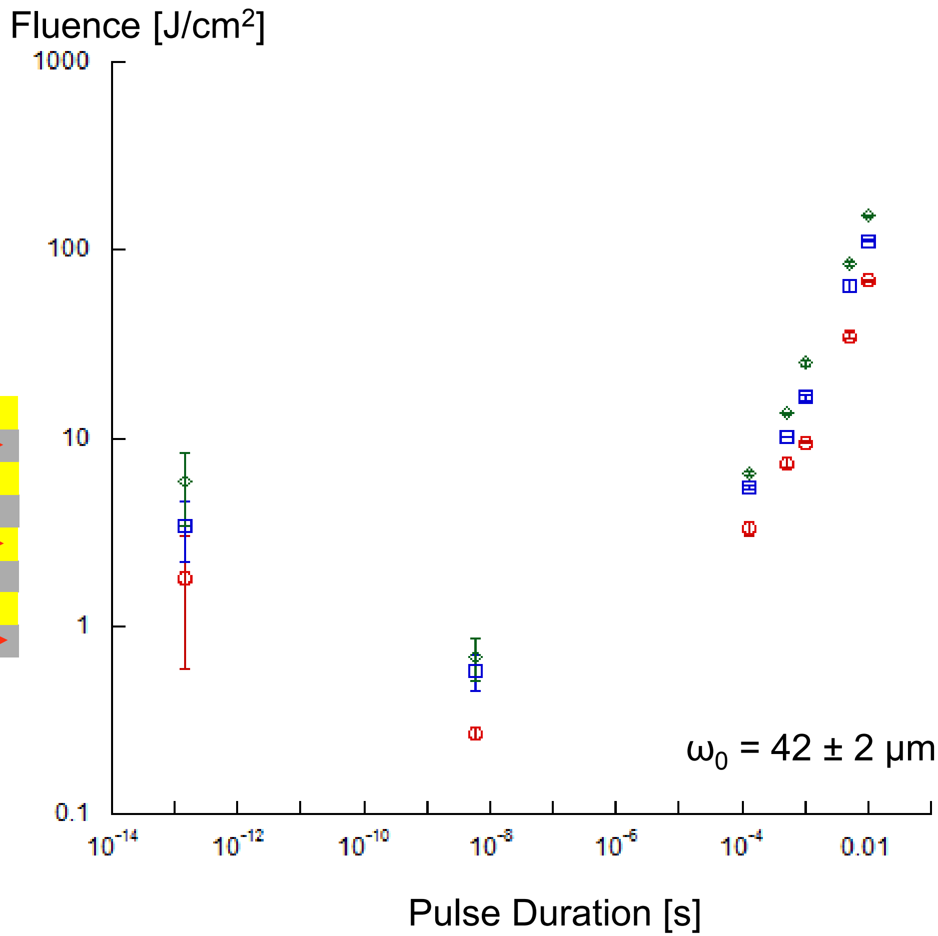
Spot radius; ω_0

Pulse Duration Dependence on Ignition Threshold in Al/Pt



Pulse Duration Dependence on Ignition Threshold in Al/Pt





◇ 328 nm Bilayer

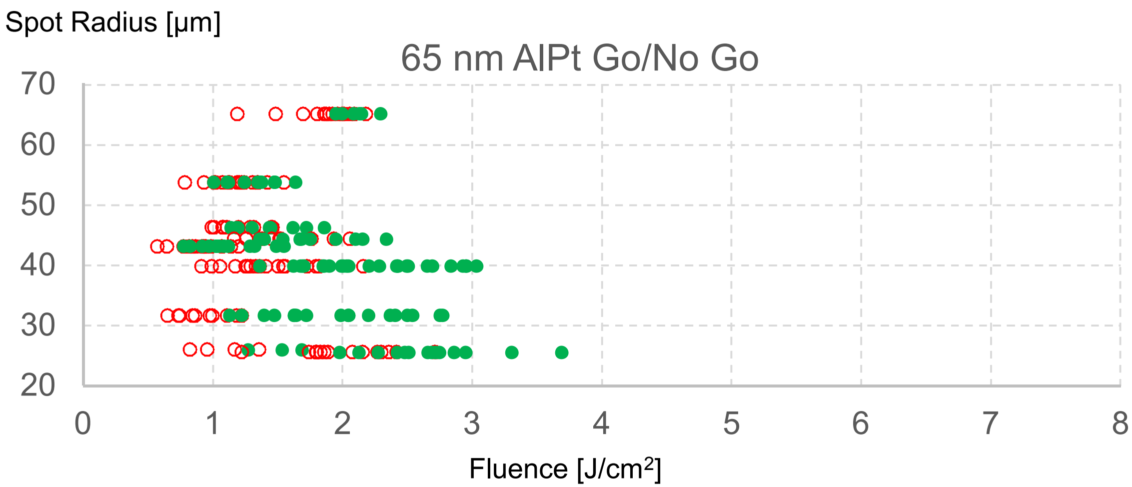
□ 164 nm Bilayer

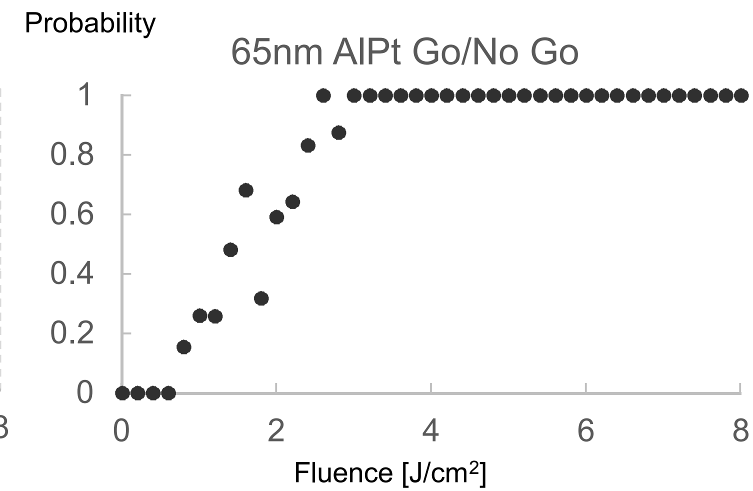
○ 65 nm Bilayer

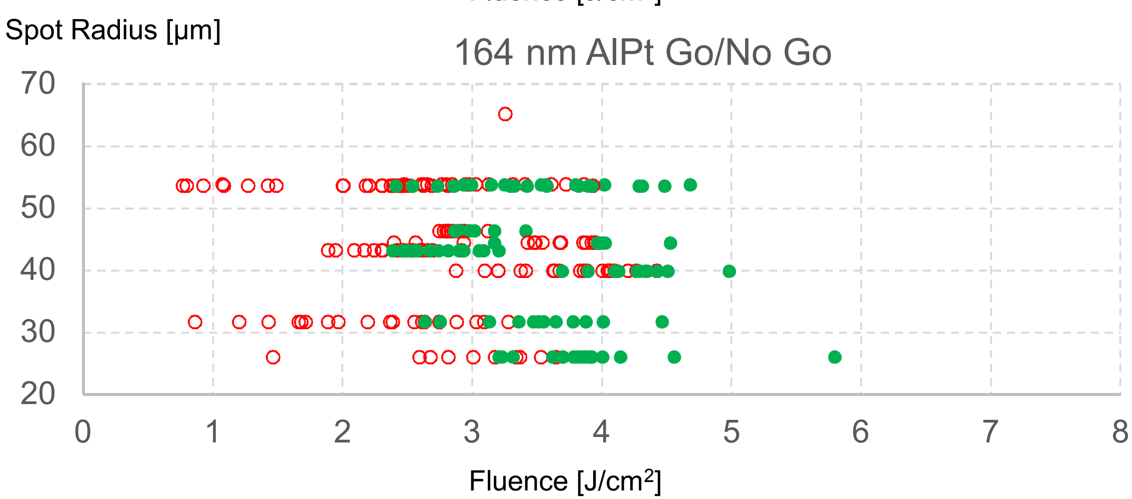
Femtosecond Laser Ignition

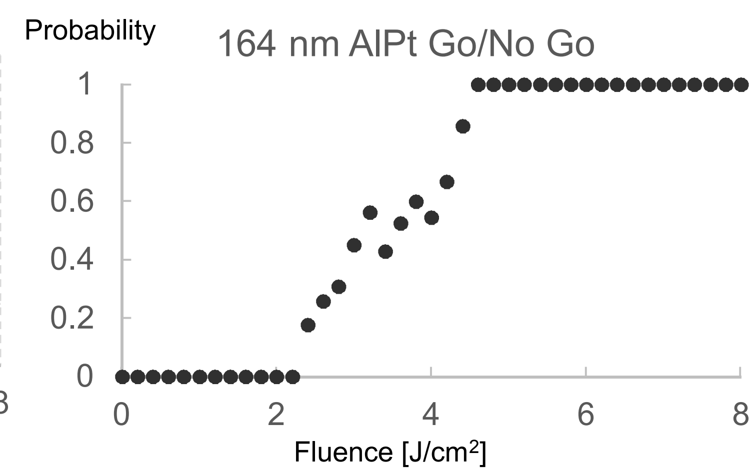
Sandia National Laboratories

● Go ○ No Go





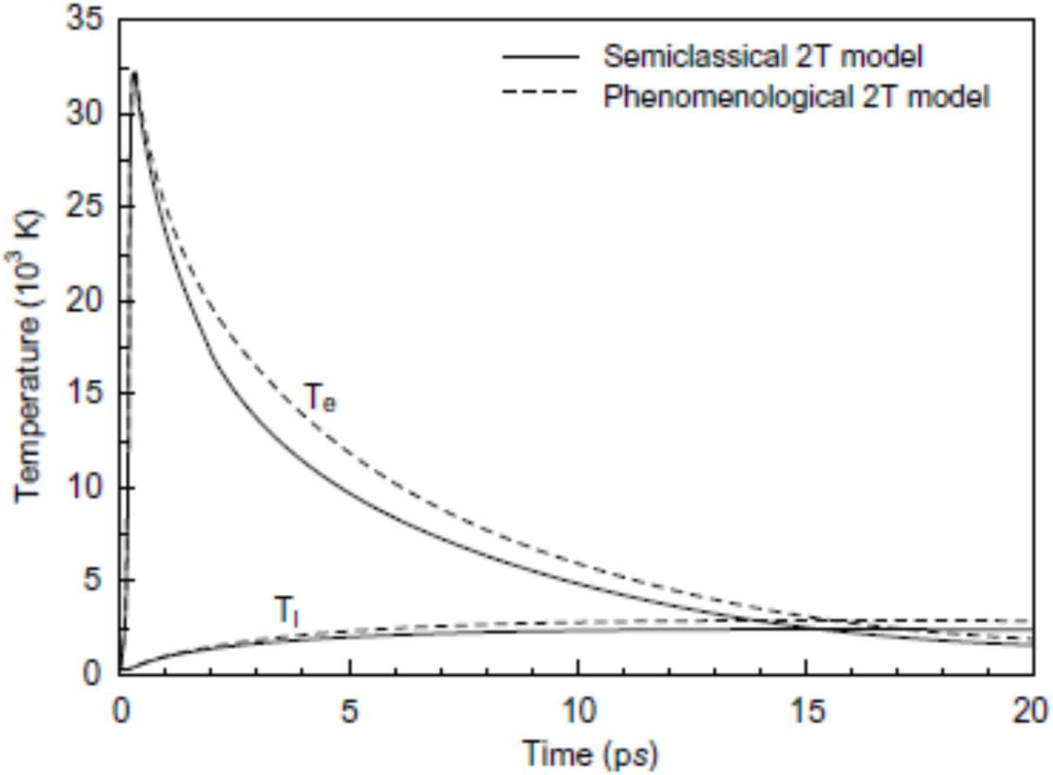




150 fs Pulses

Femtosecond laser excitation places metal into an extreme non-equilibrium condition

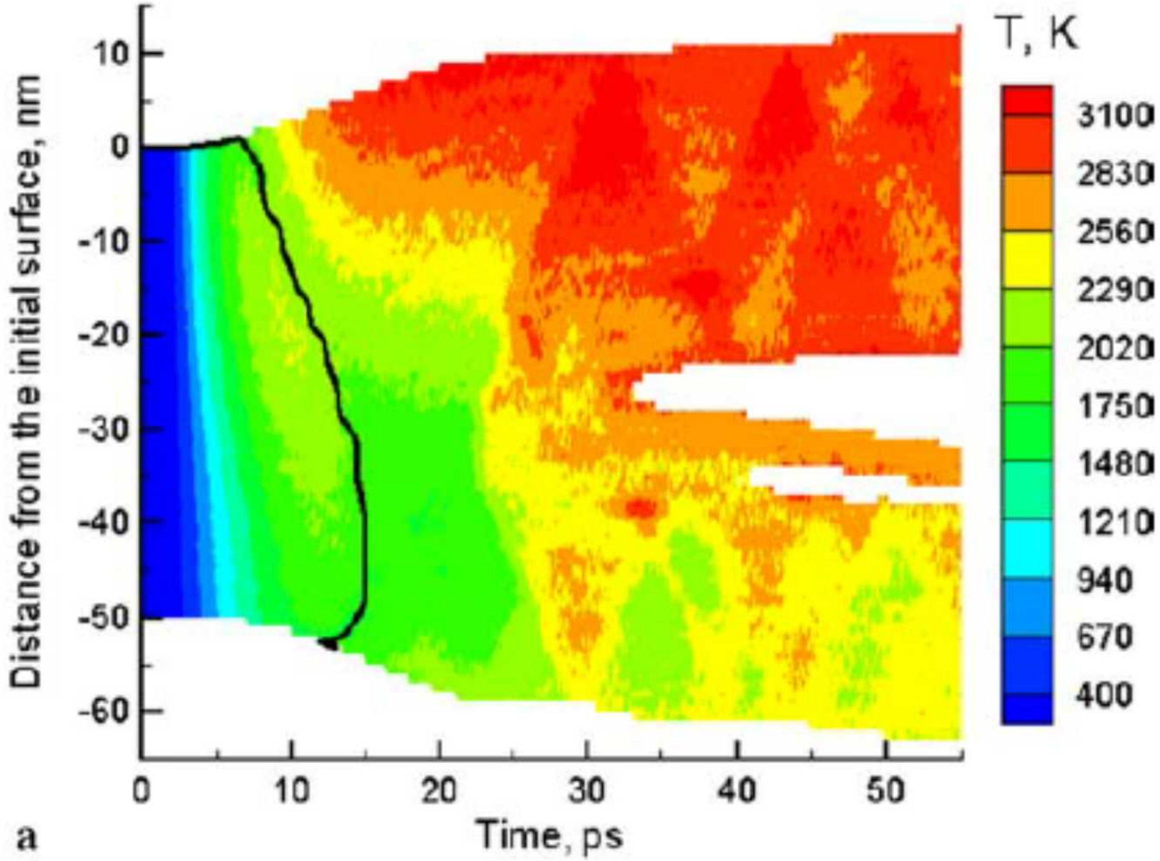
Electron and phonon systems at drastically different temperatures



J.K. Chen, D. Y. Tzou, & J.E. Beraum, Heat and Mass Transfer (2006).

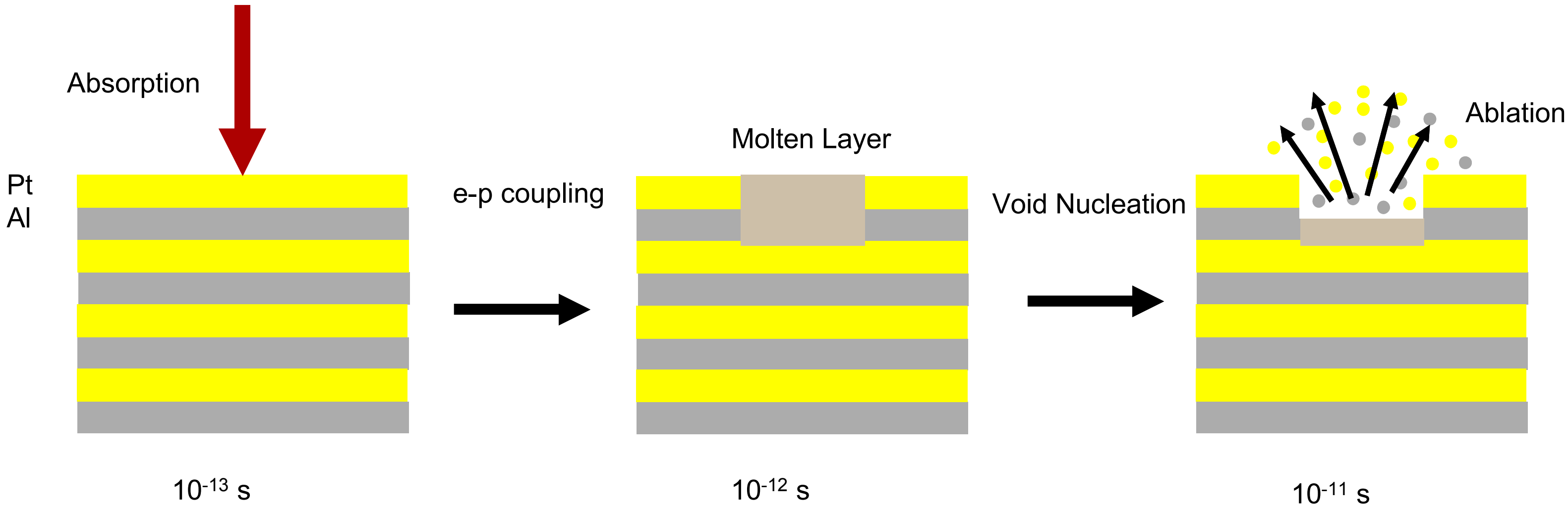
Femtosecond laser excitation places metal into an extreme non-equilibrium condition

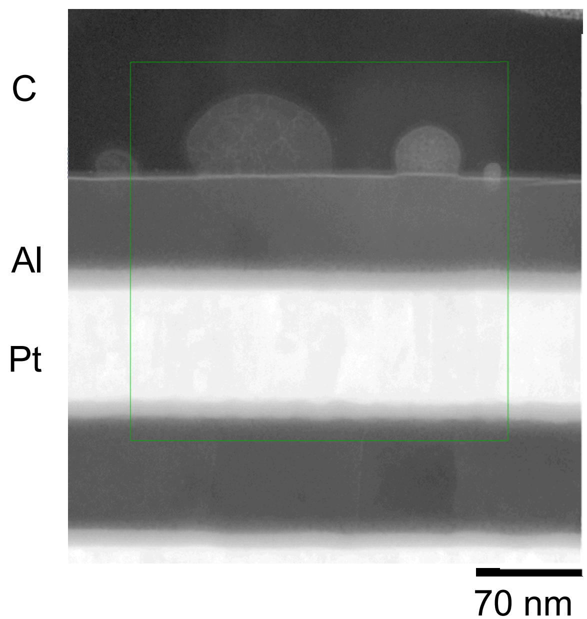
Two-Temperature Model Coupled to Molecular Dynamics



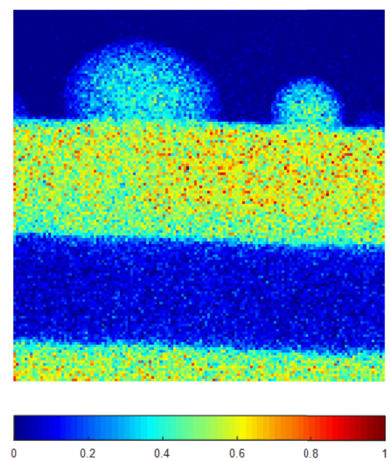
E. Levengule, D.S. Ivanov, & L.V. Zhiglei, Appl. Phys. A. (2004).

Laser Ablation Crater in cross-section TEM



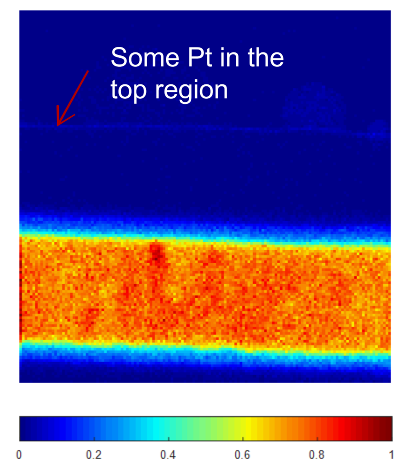


Al Component image



260 nm field of view

Pt Component image



260 nm field of view

Dark field image of Irradiation at 3.5 J/cm²

Two Temperature Model Setup

Equation 1:
Electron System Heat Transport

$$C_e \frac{\partial T_e}{\partial t} = \frac{\partial}{\partial x}\left(k_e \frac{\partial T_e}{\partial x}\right) - G(T_e - T_l) + S(x,t)$$

Equation 2:
Lattice System Heat Transport

$$C_l \frac{\partial T_l}{\partial t} = \frac{\partial}{\partial x}\left(k_l \frac{\partial T_l}{\partial x}\right) + G(T_e - T_l)$$

Equation 3:
Laser Source Term

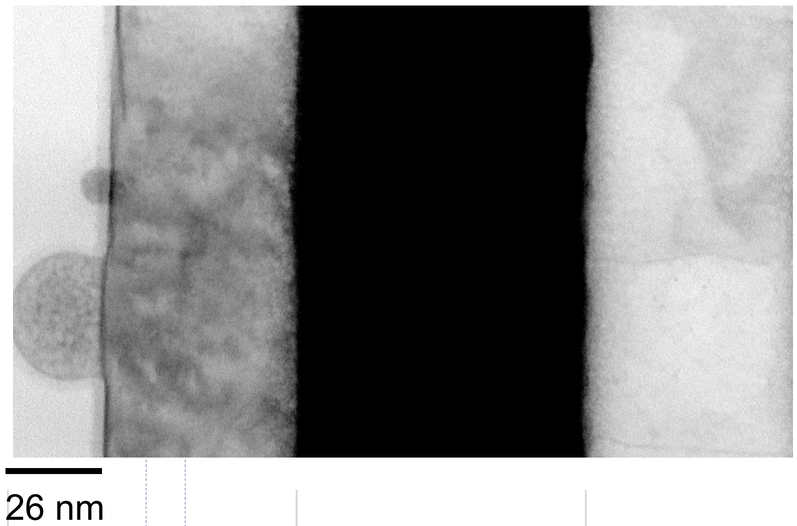
$$S(x,t) = \sqrt{\frac{4ln2}{\pi}} \cdot \frac{[1-R]\varphi}{(\delta + \delta_b)t_p} \cdot exp\left\{\frac{-x}{(\delta + \delta_b)} - 4ln2\left[\left(\frac{t - 2t_p{}^2}{t_p}\right)\right]\right\}$$

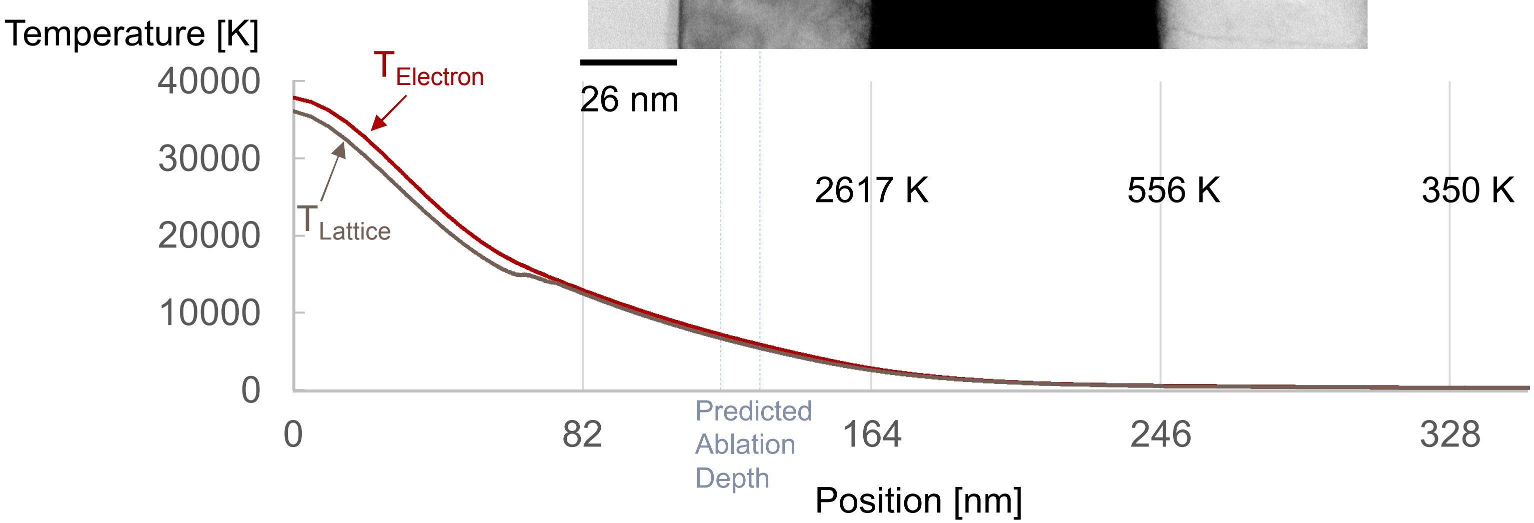
Equation 4:
Electron Thermal Conductivity
(Room Temp to Fermi Temp)

$$k_e = \alpha \frac{\left[\left(\frac{T_e}{T_F}\right)^2 + 0.16\right]^{5/4}\left[\left(\frac{T_e}{T_F}\right)^2 + 0.44\right]\left(\frac{T_e}{T_F}\right)}{\left[\left(\frac{T_e}{T_F}\right)^2 + 0.092\right]^{1/2}\left[\left(\frac{T_e}{T_F}\right)^2 + \beta\frac{T_l}{T_F}\right]}$$

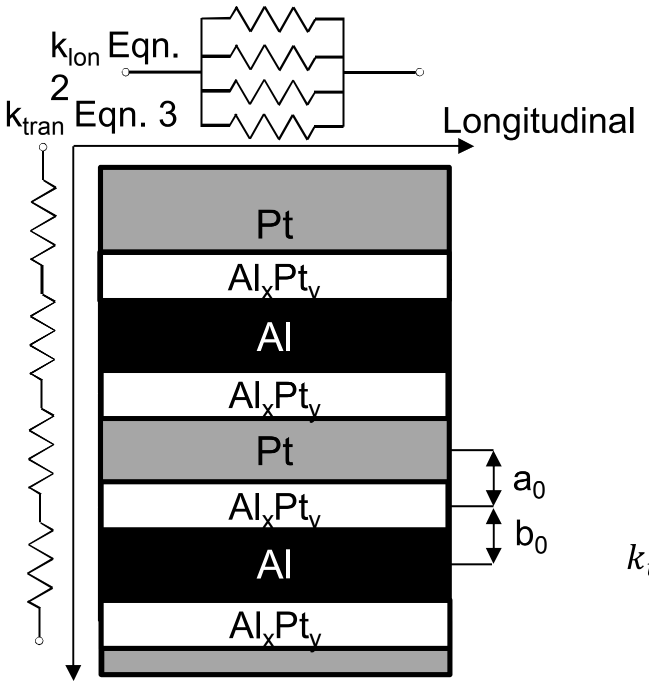
Two Temperature Model of Foil Temperature at 30 ps

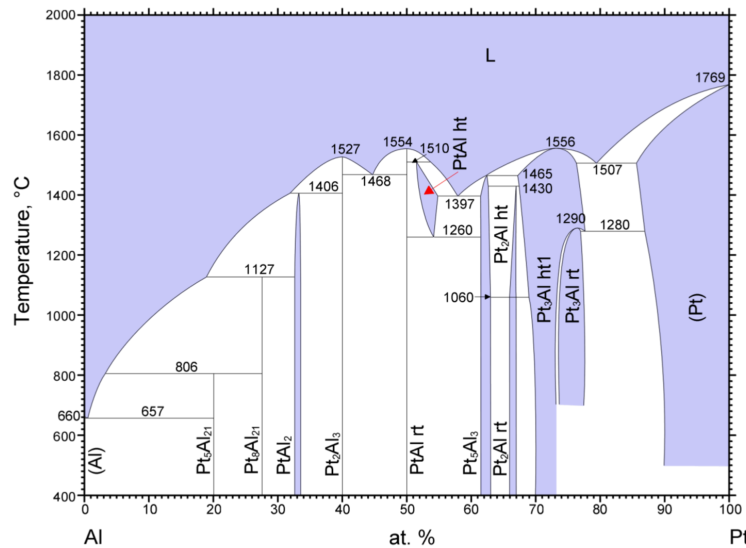
Irradiation at 3.5 J/cm^2
150 fs pulse
ω_0 = 42 μm
164 nm Bilayer
~108 nm of Ablation
Bright Field Image





Mott s-d scattering model for heat transport in amorphous Al/Pt





$$k_{trans(e)} = LT_e\left(\sigma_{s(Al)} + \sigma_{d(Pt)}\right)$$

$$k_{trans(e)} = LT_e\left(\frac{2e^2 v_{F(Al)}^2 N(\varepsilon_F)_{Al}\tau_{Al}}{3V_{M(Al)}} + \frac{e^2 K_0^5}{12\pi^4 m_e v_{F(Pt)} \Gamma N_d(\varepsilon_F)_{Al} V_{M(Pt)}}\right)$$

K_0 := Constant derived from energy levels of d-band states in Pt

Γ := linewidth in d-band

τ := electron scattering time

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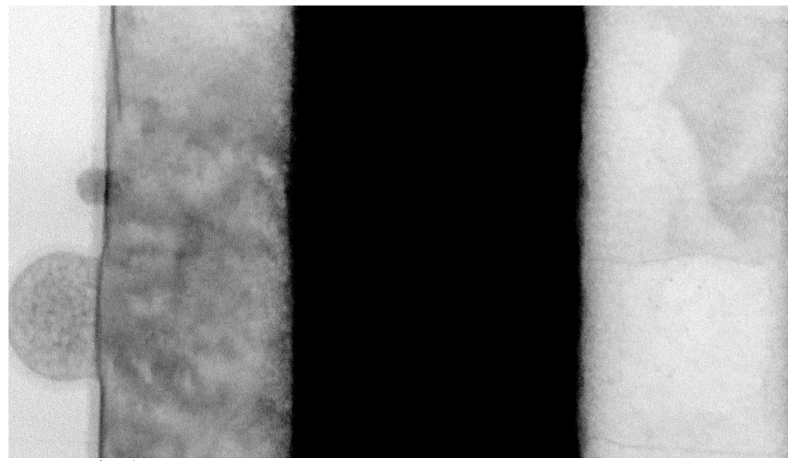
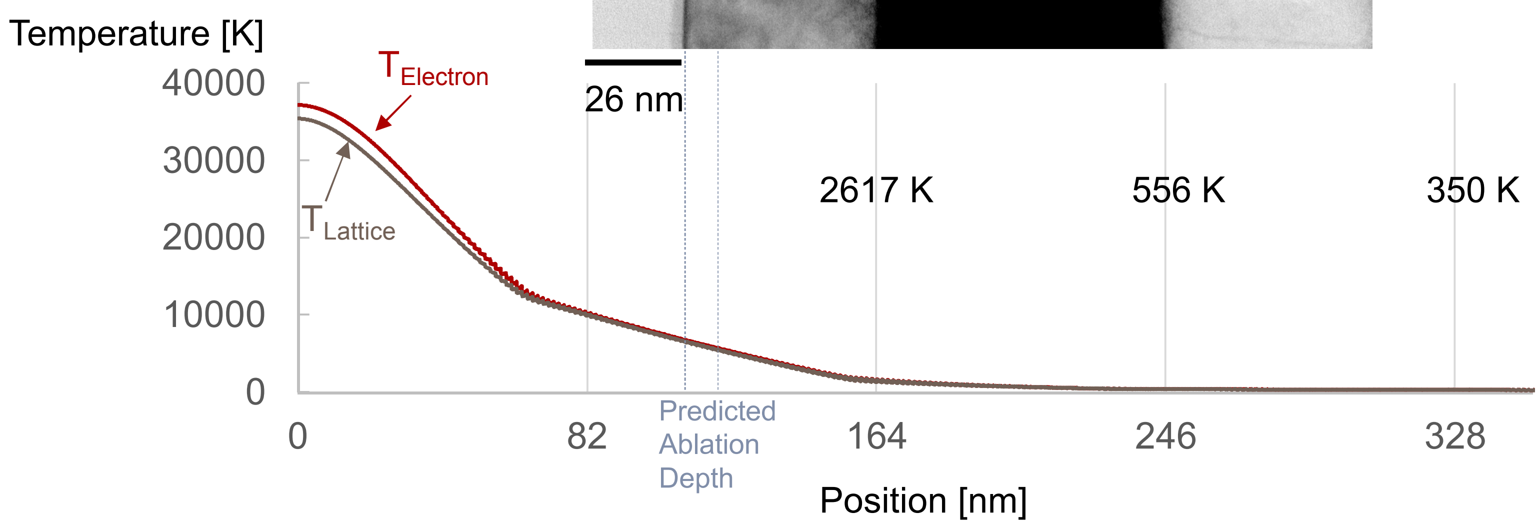
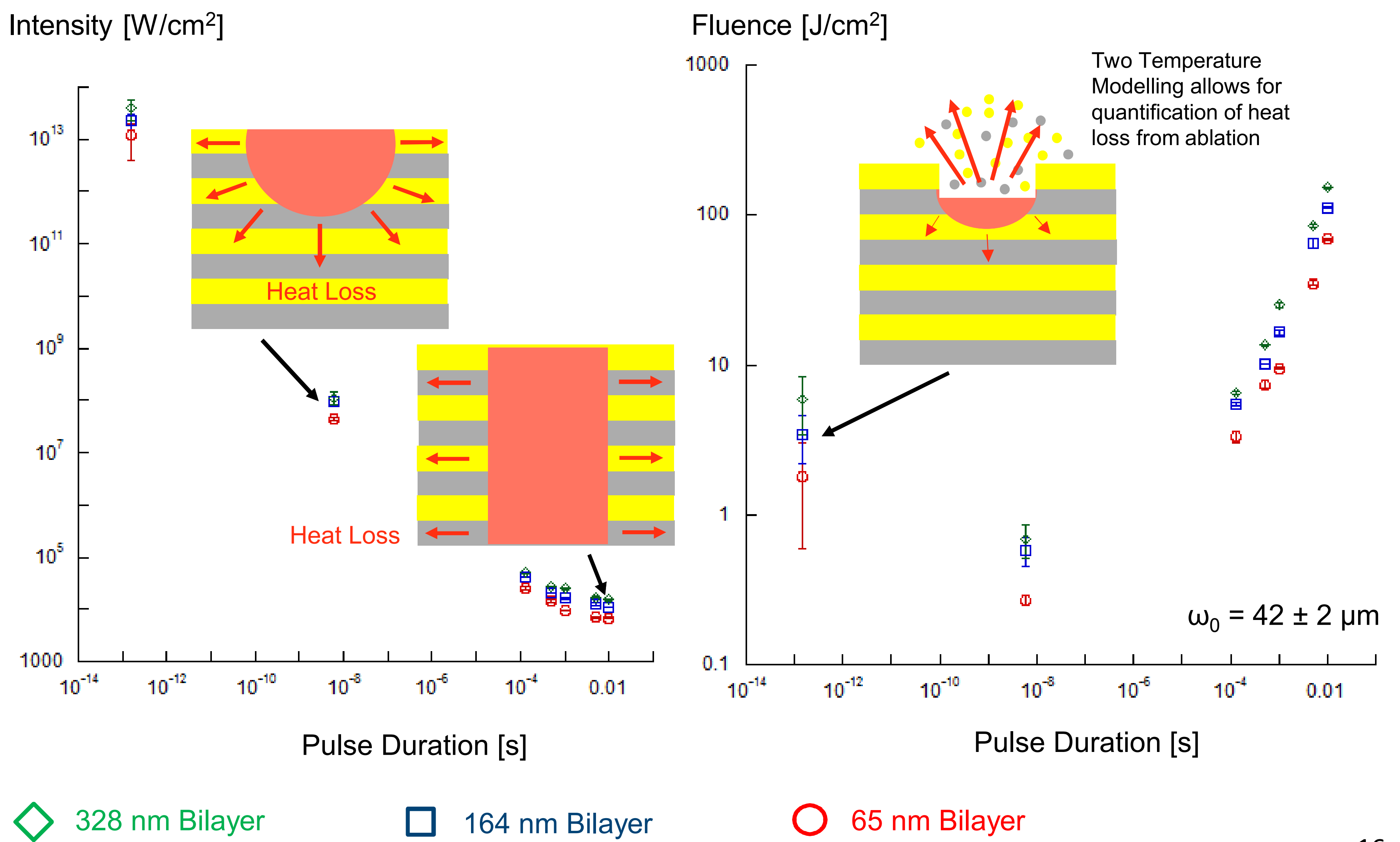




Summary


Intensity [W/cm2]
10^13
10^11
10^9
10^7
10^5
1000
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
0.01
Pulse Duration [s]
Heat Loss
Heat Loss
Fluence [J/cm2]
1000
100
10
1
0.1
Two Temperature Modelling allows for quantification of heat loss from ablation
ω0 = 42 ± 2 μm
Pulse Duration [s]
328 nm Bilayer
164 nm Bilayer
65 nm Bilayer