SAND2017-10175C

Two-temperature Modelling in Femtosecond Laser Ignition of Reactive Nanolaminates

Michael J. Abere

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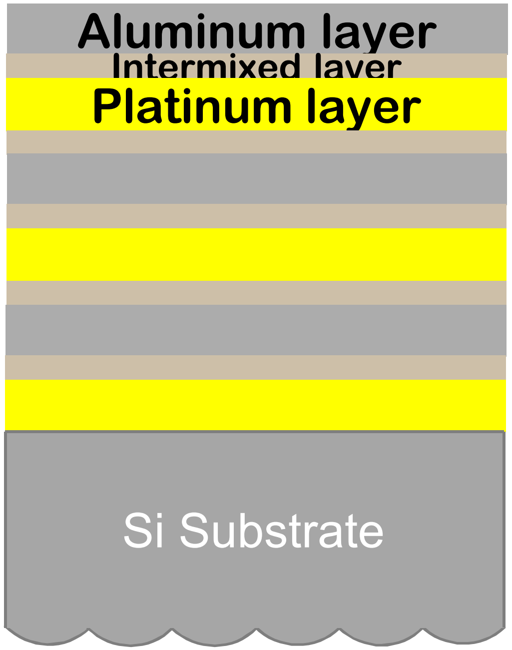
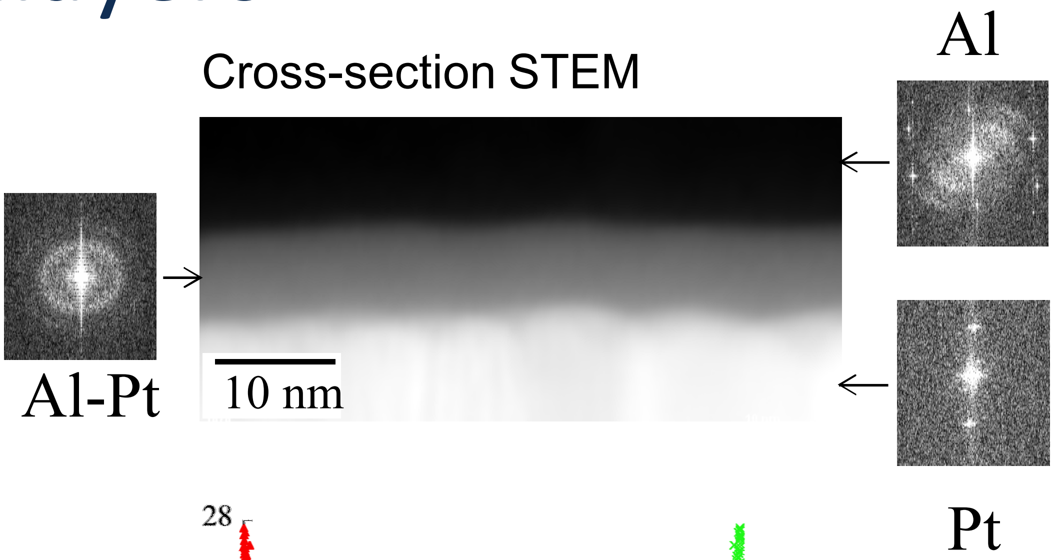
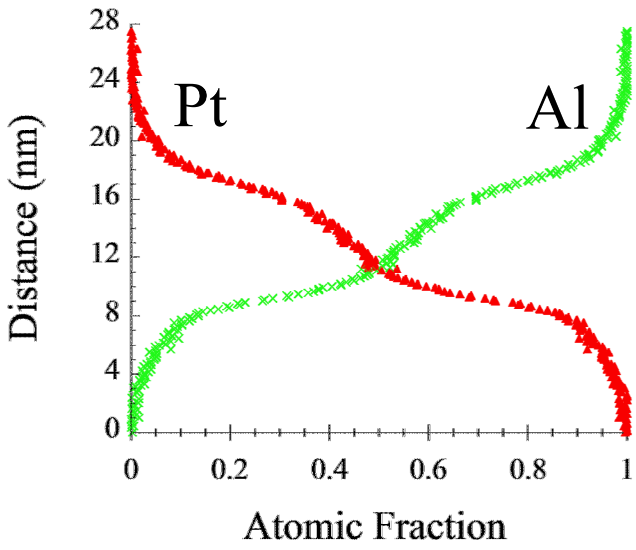
Sputter Deposition of Reactive Multilayers



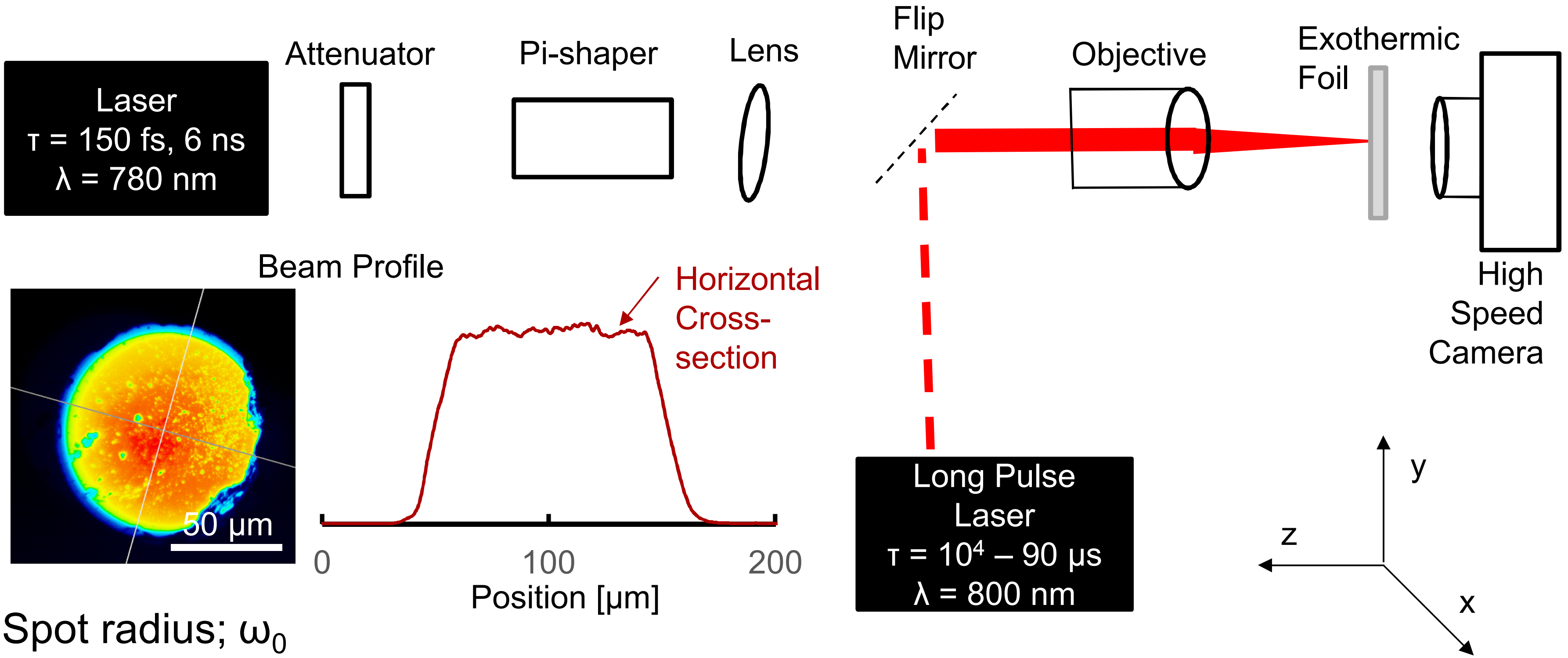




Video of Laser Ignition and Self-Propagating Reaction in Al/Pt Multilayer

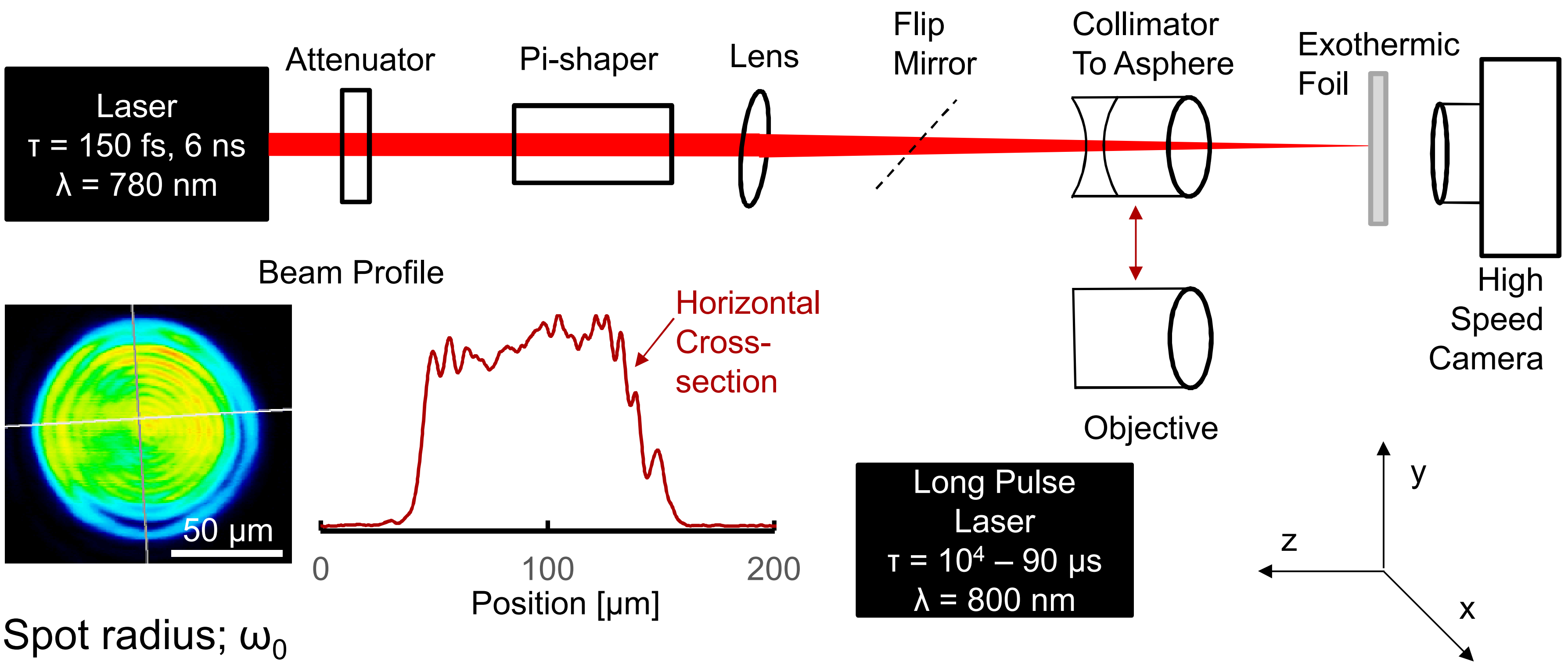
760 W/cm^2
164 nm Bilayer
1.8 µs per frame, played at 4 fps

Direct Laser Ignition Method



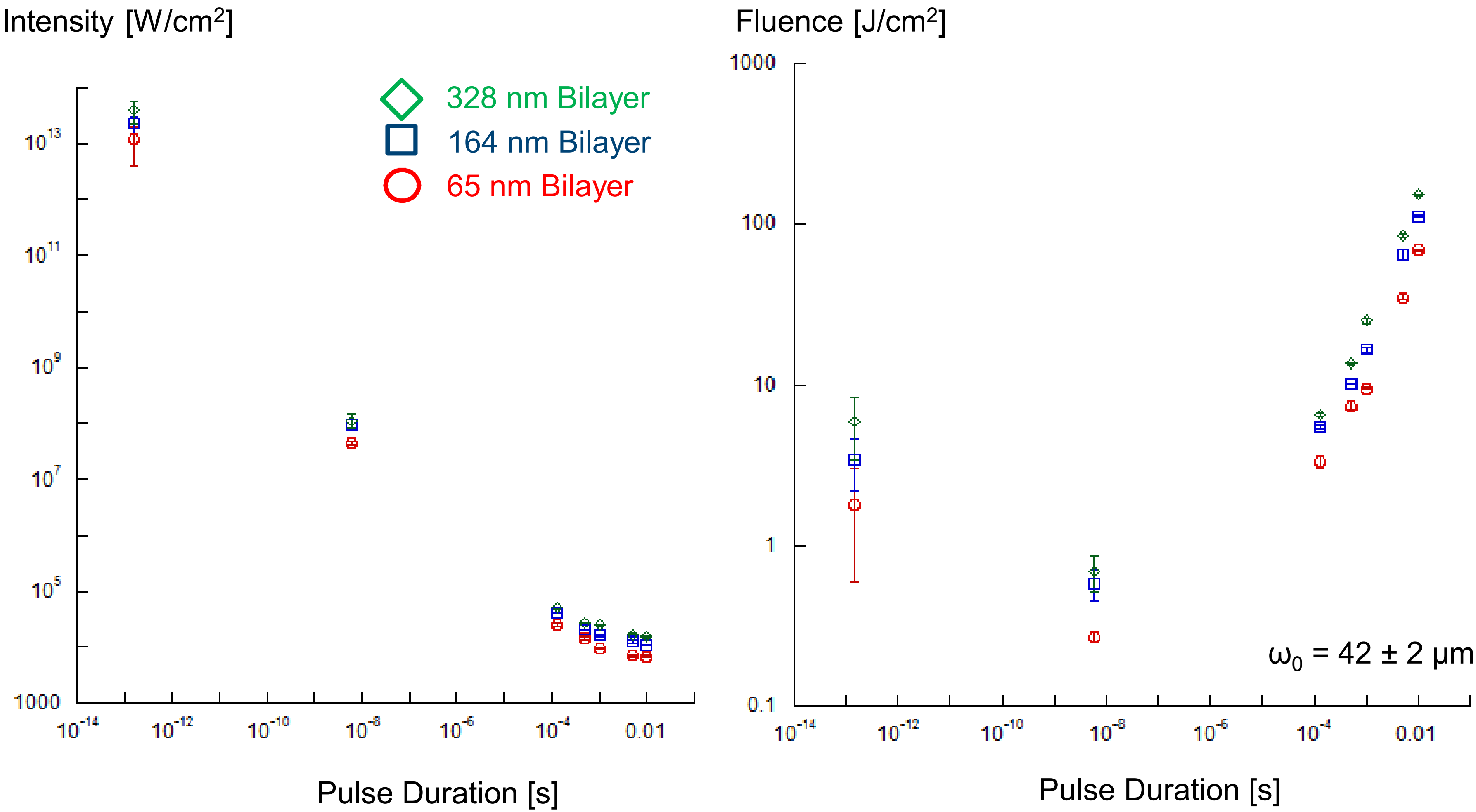
Spot radius; ω_0

Direct Laser Ignition Method

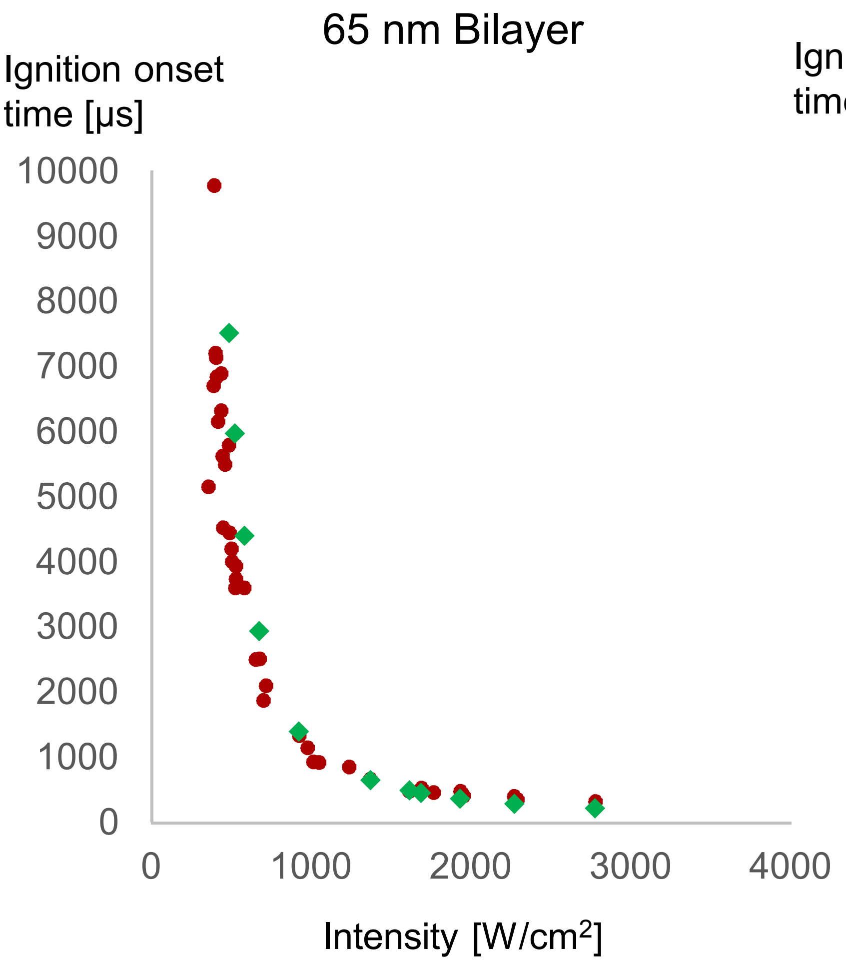


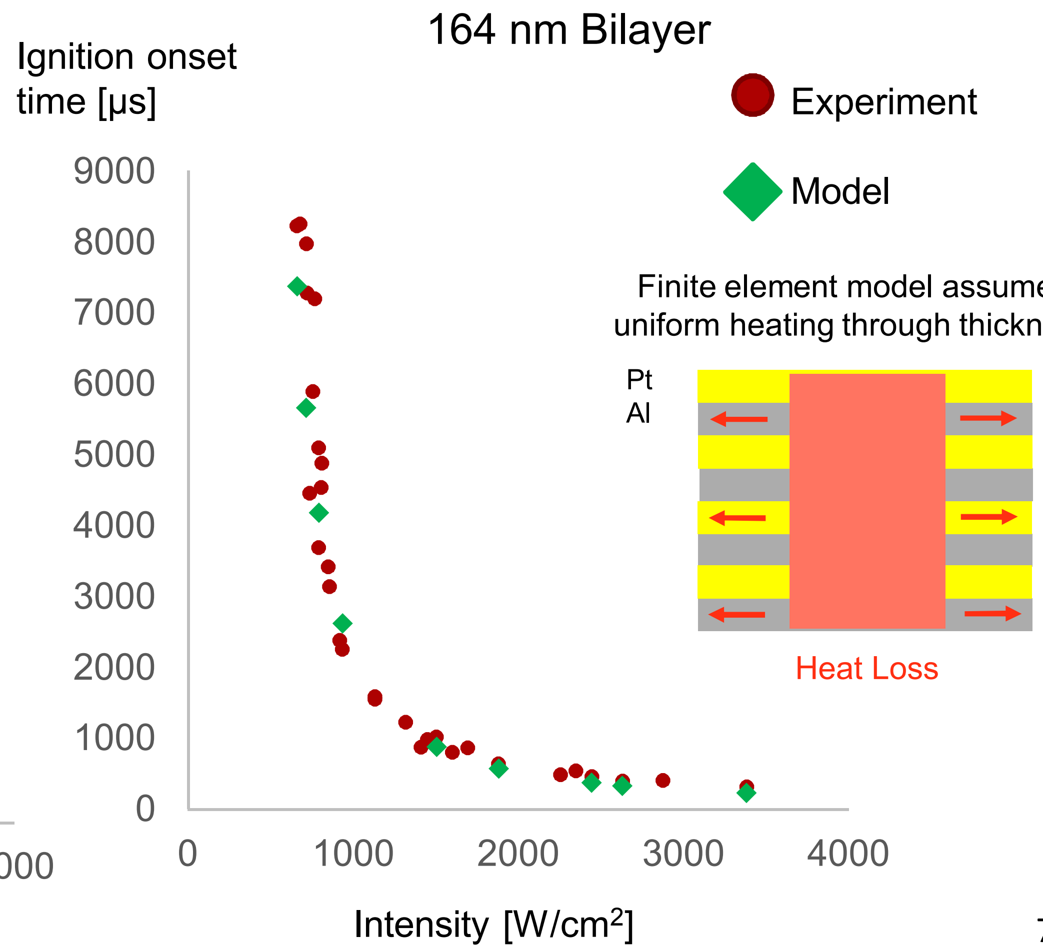
Spot radius; ω_0

Pulse Duration Dependence on Ignition Threshold in Al/Pt

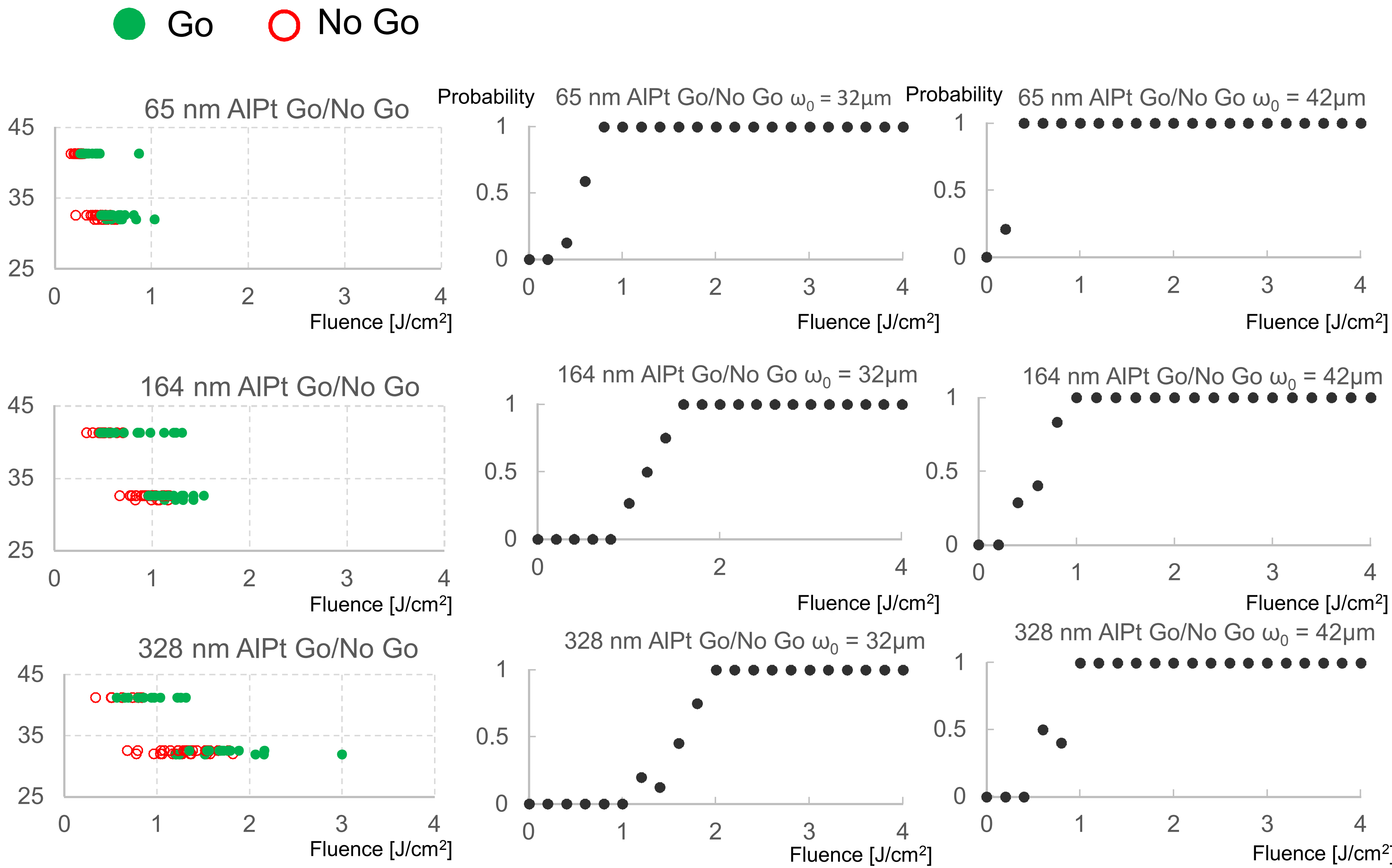


Ignition Delay for milli- and microsecond laser pulses predicted from finite element simulation

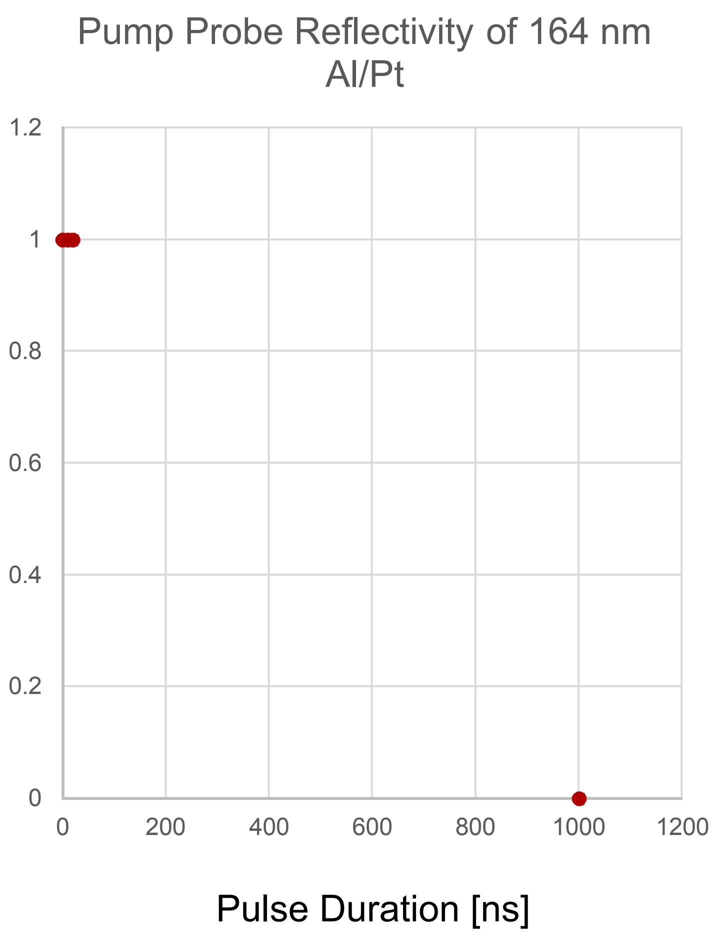


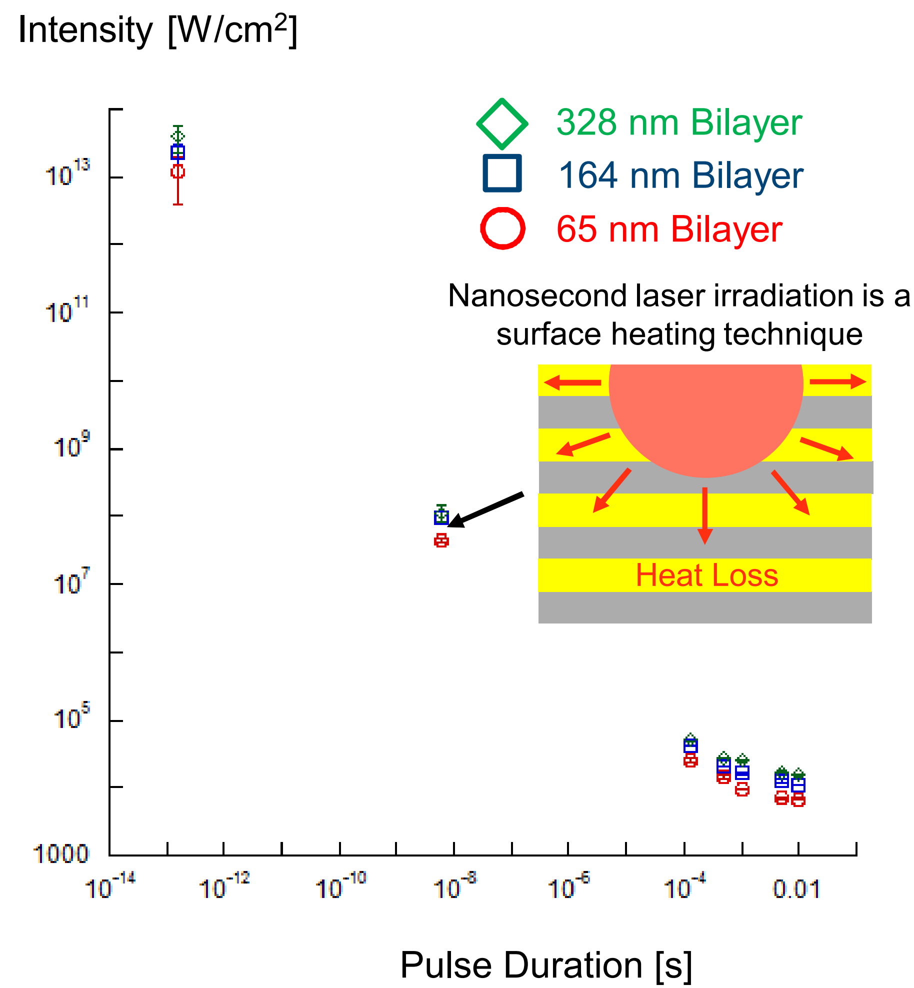


Nanosecond Laser Ignition

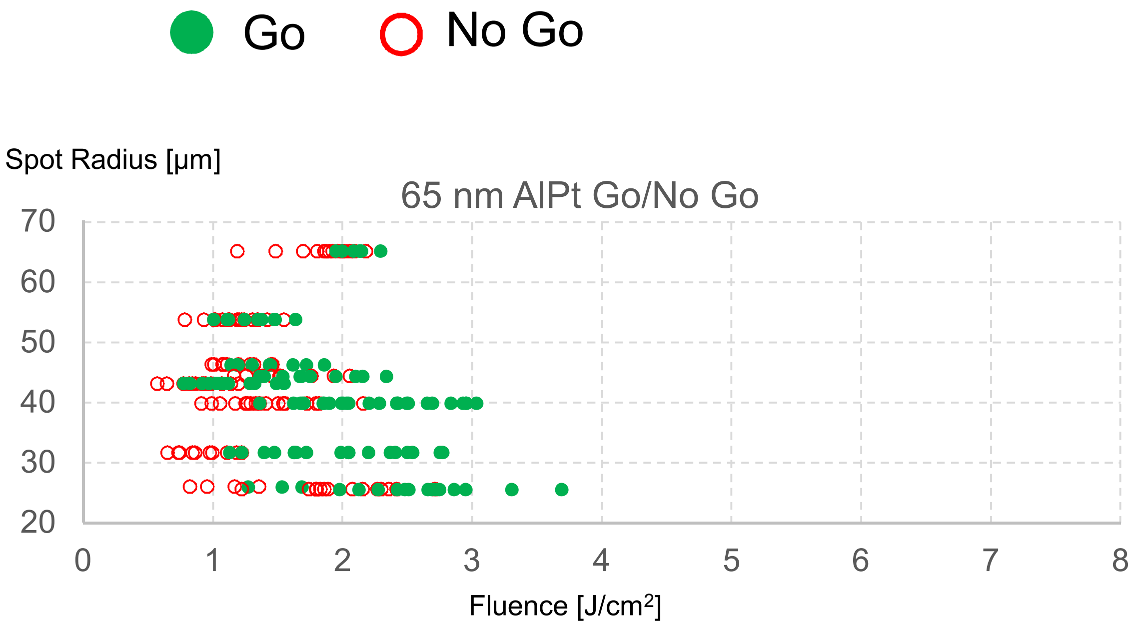


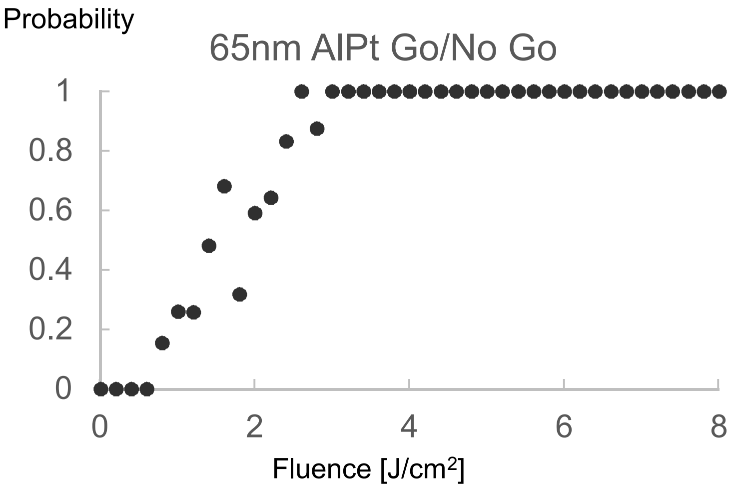
Nanosecond Laser Ignition Time

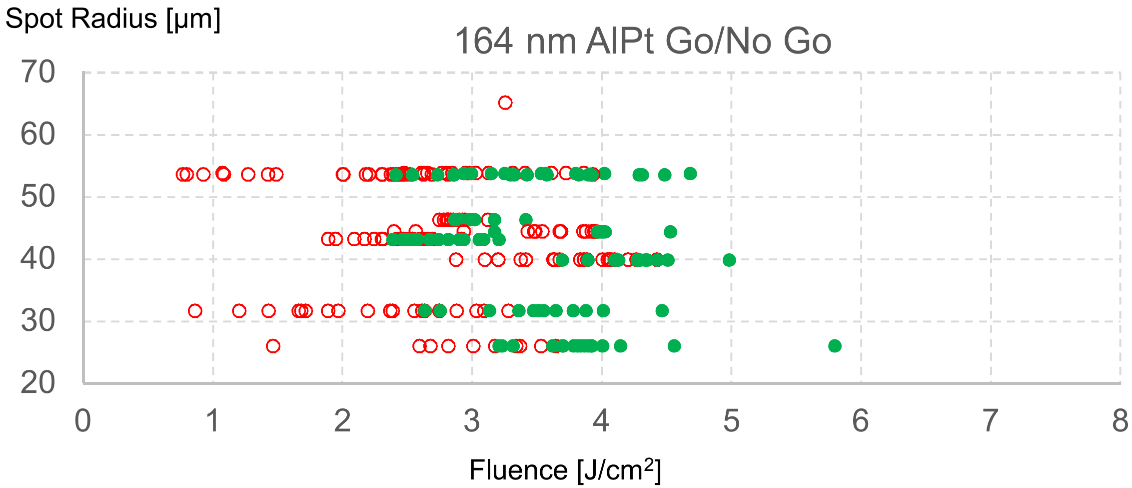


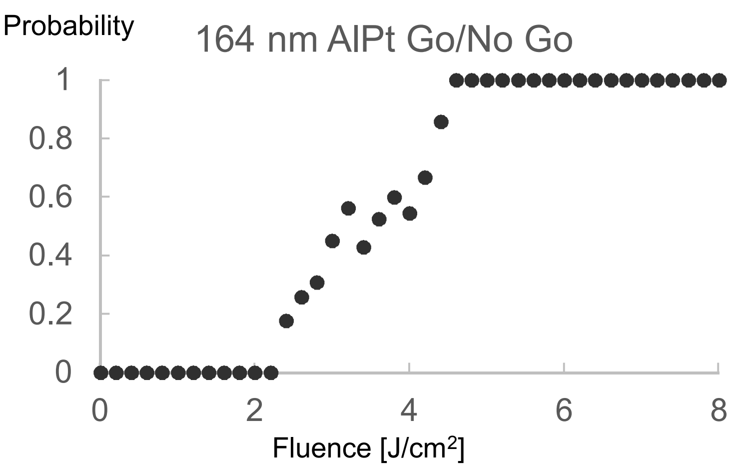


Femtosecond Laser Ignition





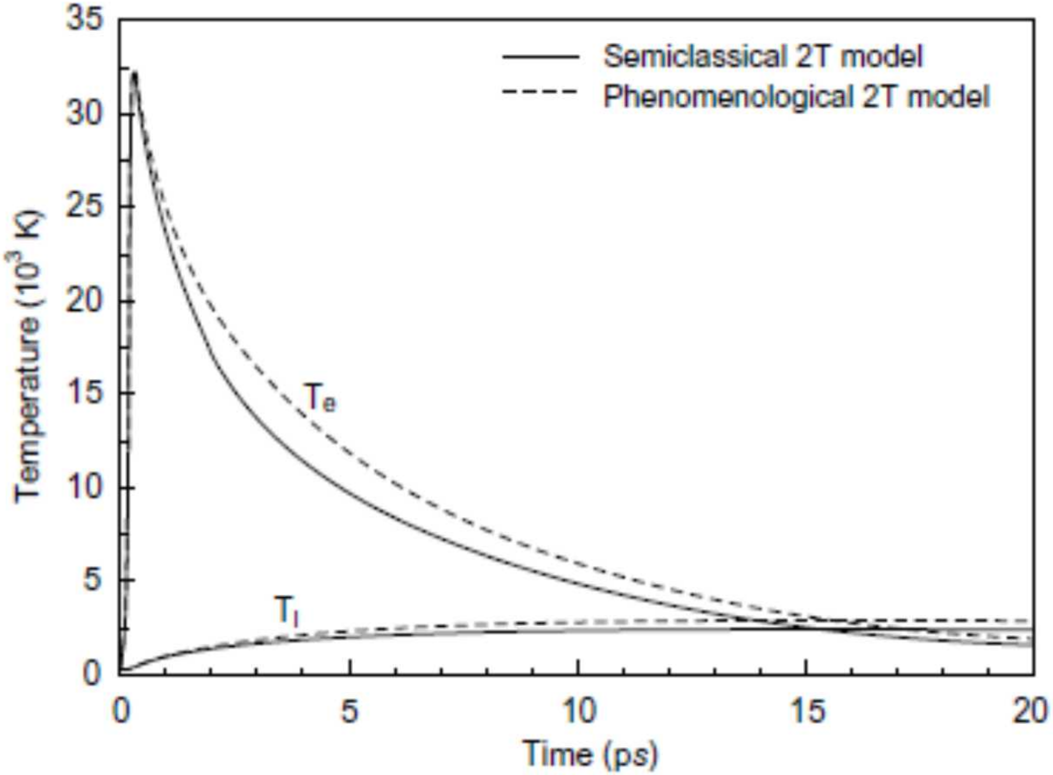




150 fs Pulses

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

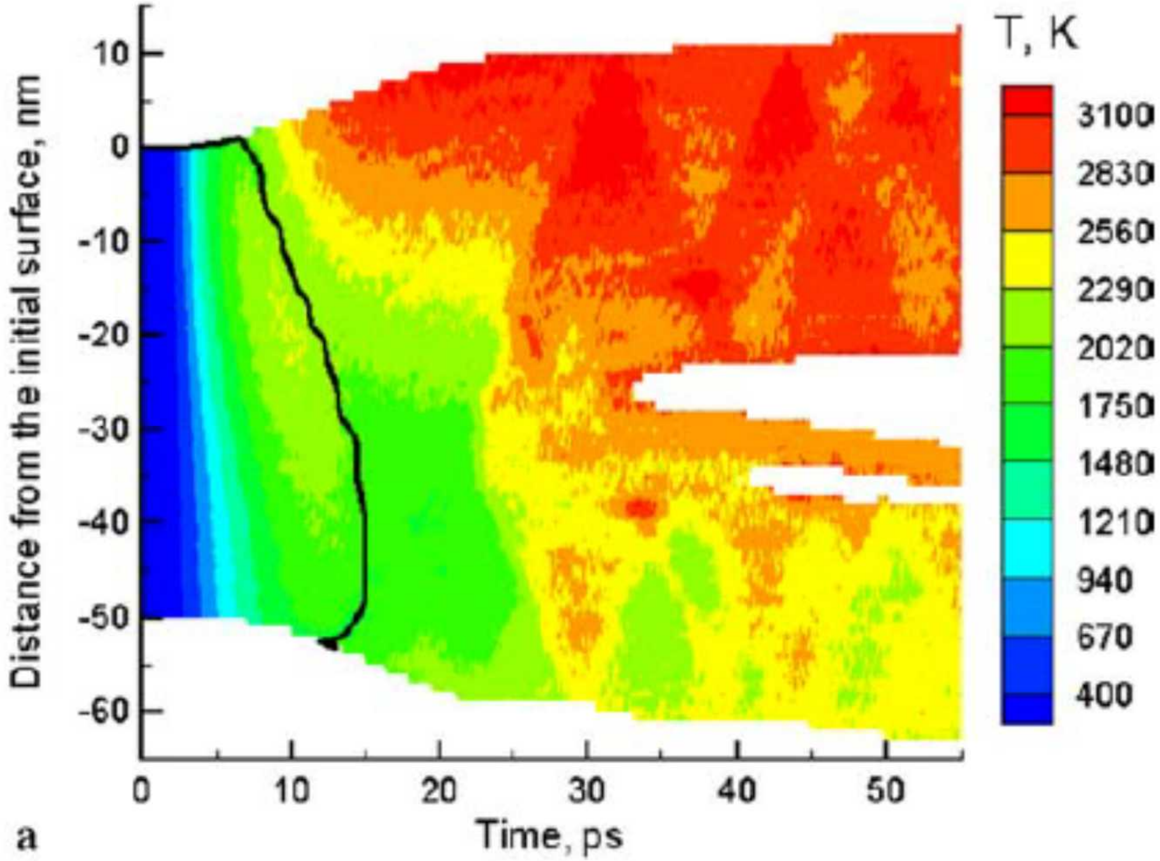
Electron and phonon systems at drastically different temperatures



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

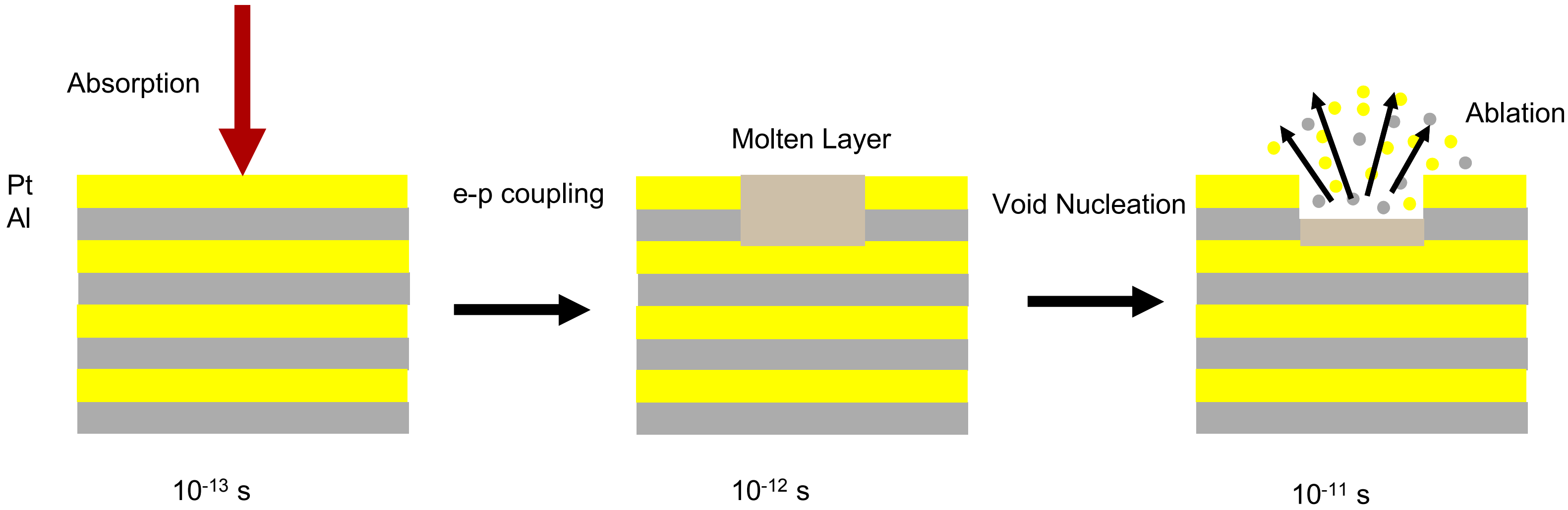
Femtosecond laser excitation places metal into an extreme non-equilibrium condition

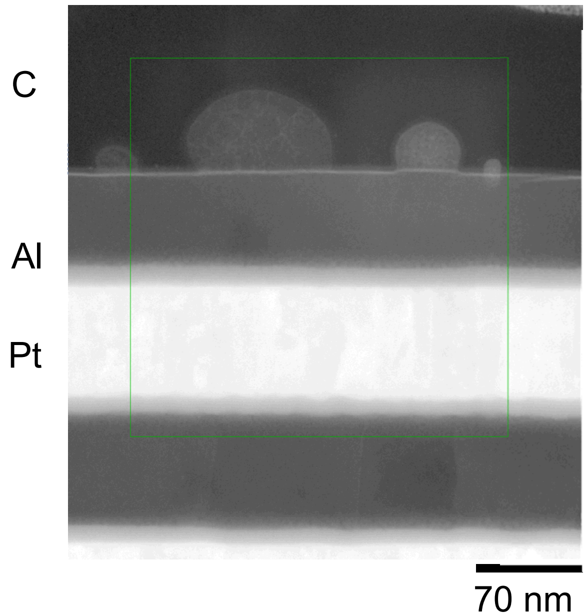
Two-Temperature Model Coupled to Molecular Dynamics



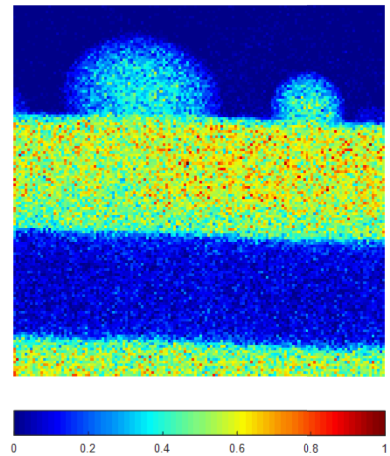
E. Levengule, D.S. Ivanov, & L.V. Zhiglei, Appl. Phys. A. (2004).

Laser Ablation Crater in cross-section TEM



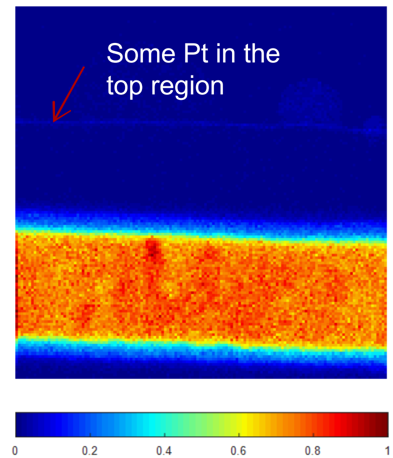


Al Component image



260 nm field of view

Pt Component image



260 nm field of view

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

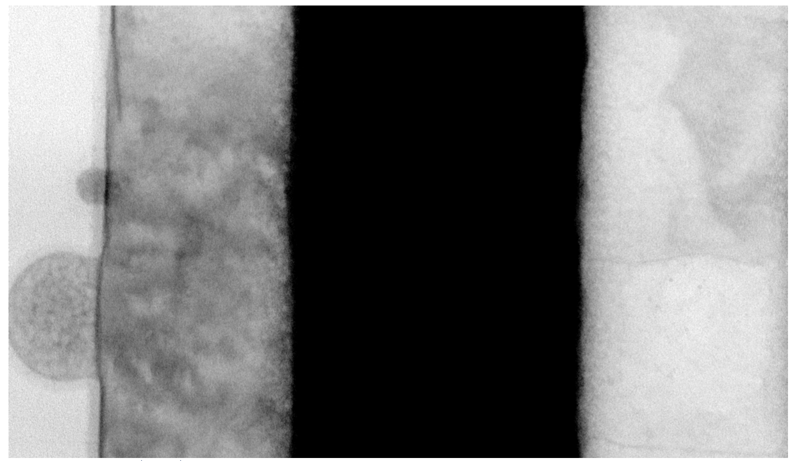
$$S(x,t) = \sqrt{\frac{4ln2}{\pi}} \cdot \frac{[1-R]\varphi}{(\delta + \delta_b)t_p} \cdot exp\left\{\frac{-x}{(\delta + \delta_b)} - 4ln2\left[\left(\frac{t - 2t_p}{t_p}^2\right)\right]\right\}$$

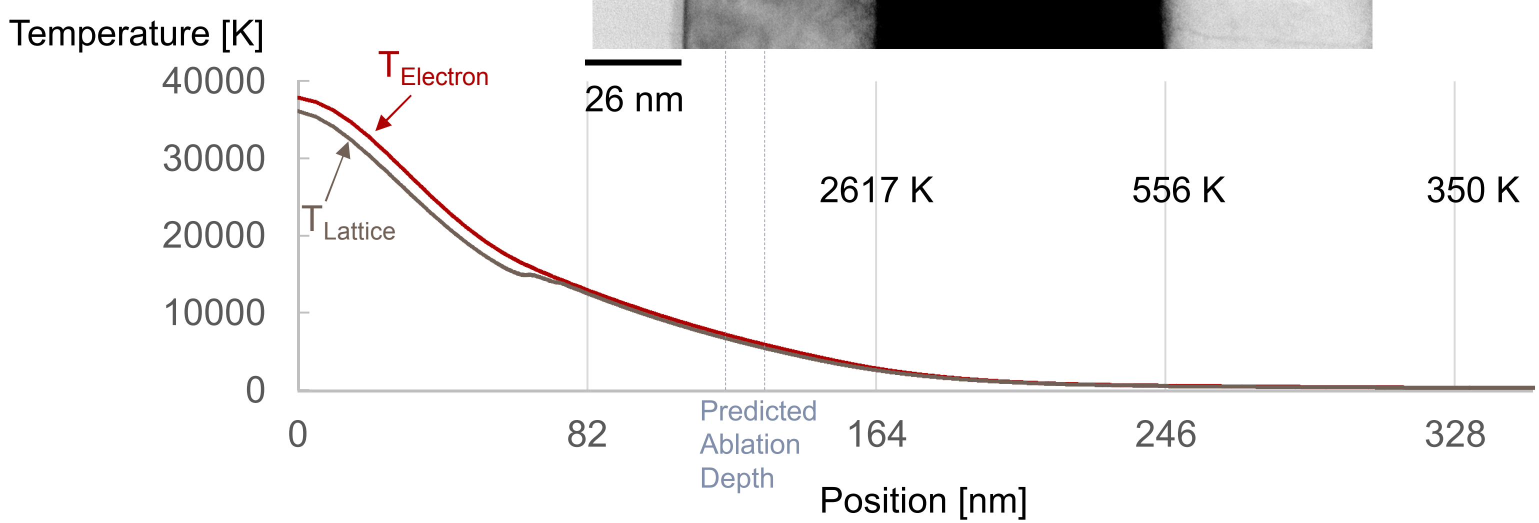
Equation 4:
Electron Thermal Conductivity
(Room Temp to Fermi Temp)

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

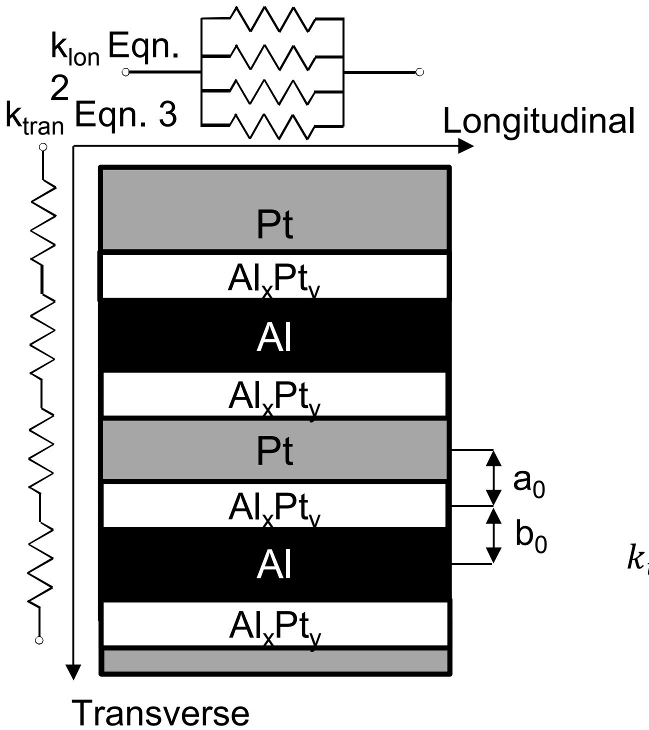
Two Temperature Model of Foil Temperature at 30 ps

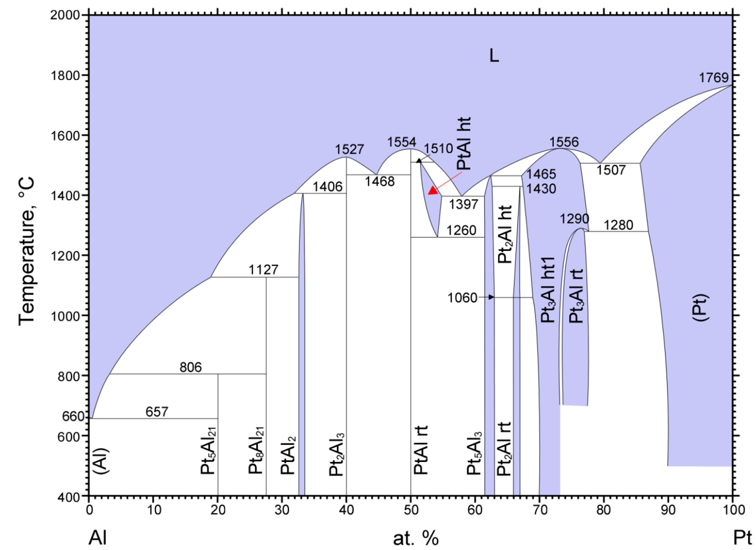
Irradiation at 3.5 J/cm^2
150 fs pulse
ω_0 = 42 µm
164 nm Bilayer
~110 nm of Ablation
Bright Field Image





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





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

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

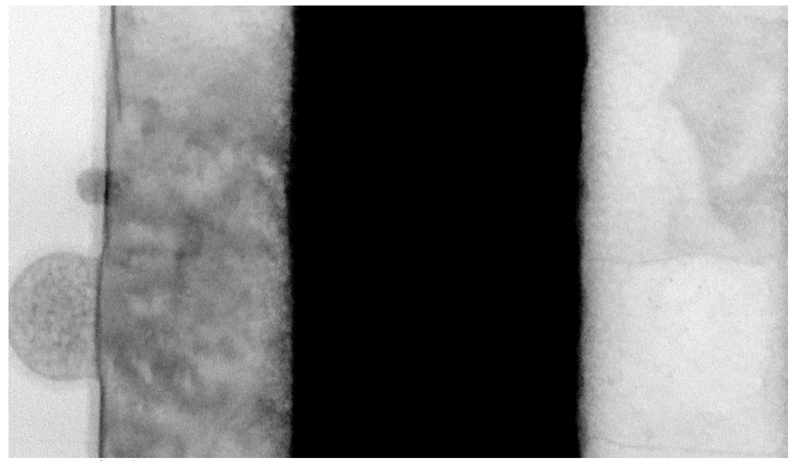
K_0 := Constant derived from energy levels of d-band states in Pt

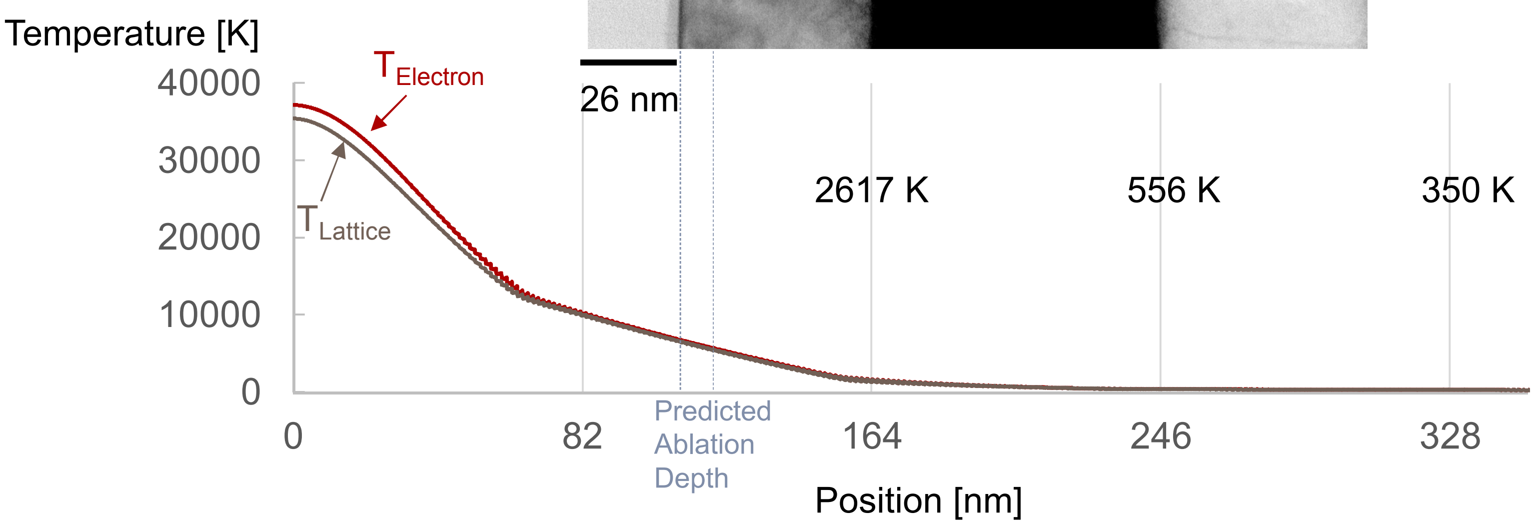
Γ := linewidth in d-band

τ := electron scattering time

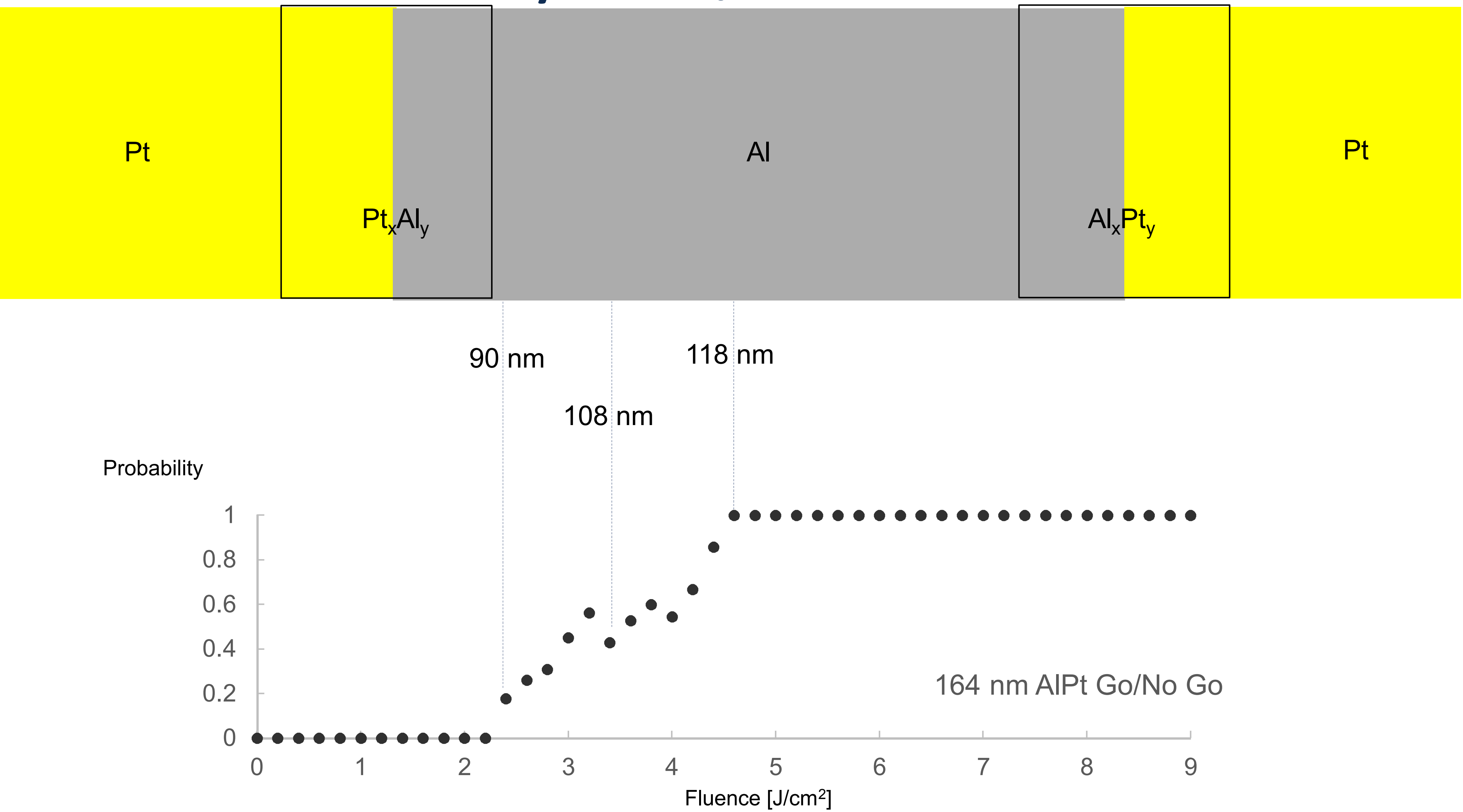
Two Temperature Model of Foil Temperature at 30 ps

Irradiation at 3.4 J/cm^2
150 fs pulse
ω_0 = 42 μm
164 nm Bilayer
~110 nm of Ablation
Bright Field Image

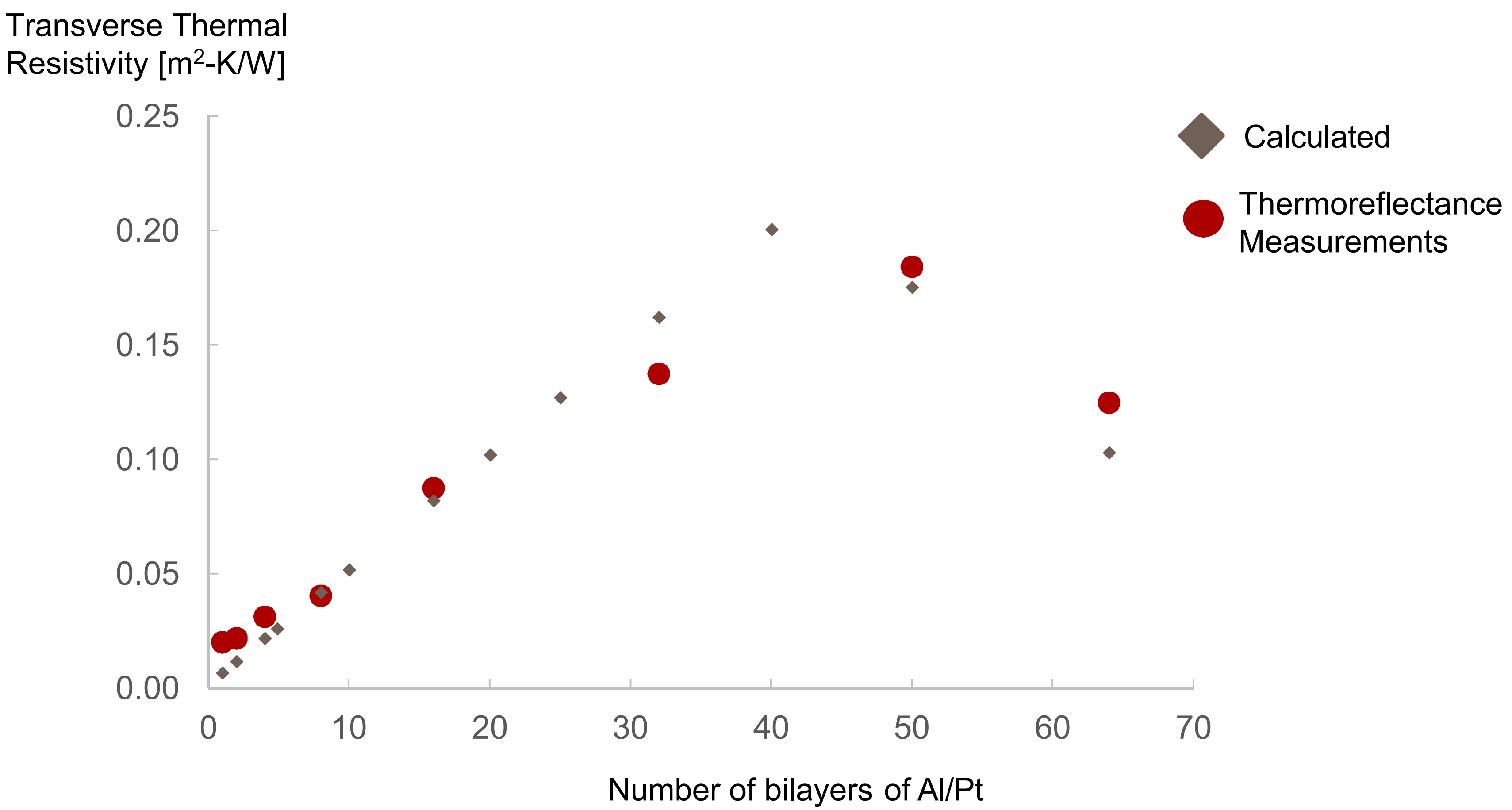




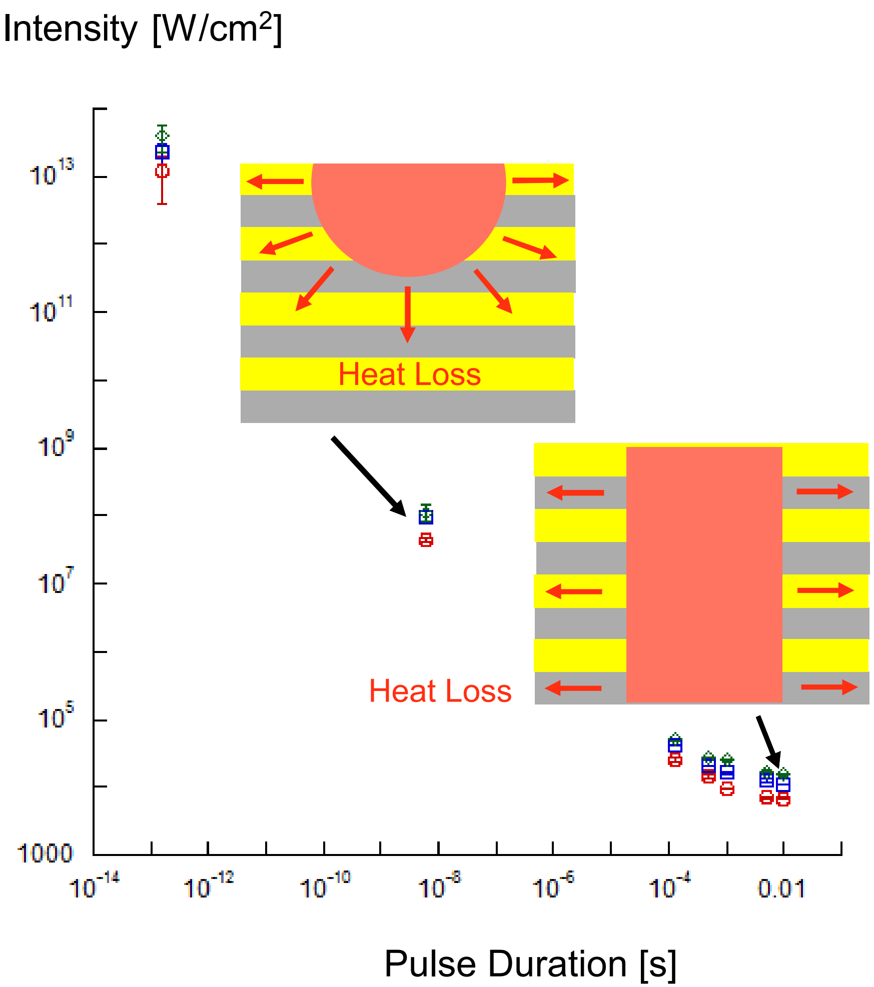
Ablation depth vs Ignition Threshold for 164 nm bilayer Al/Pt

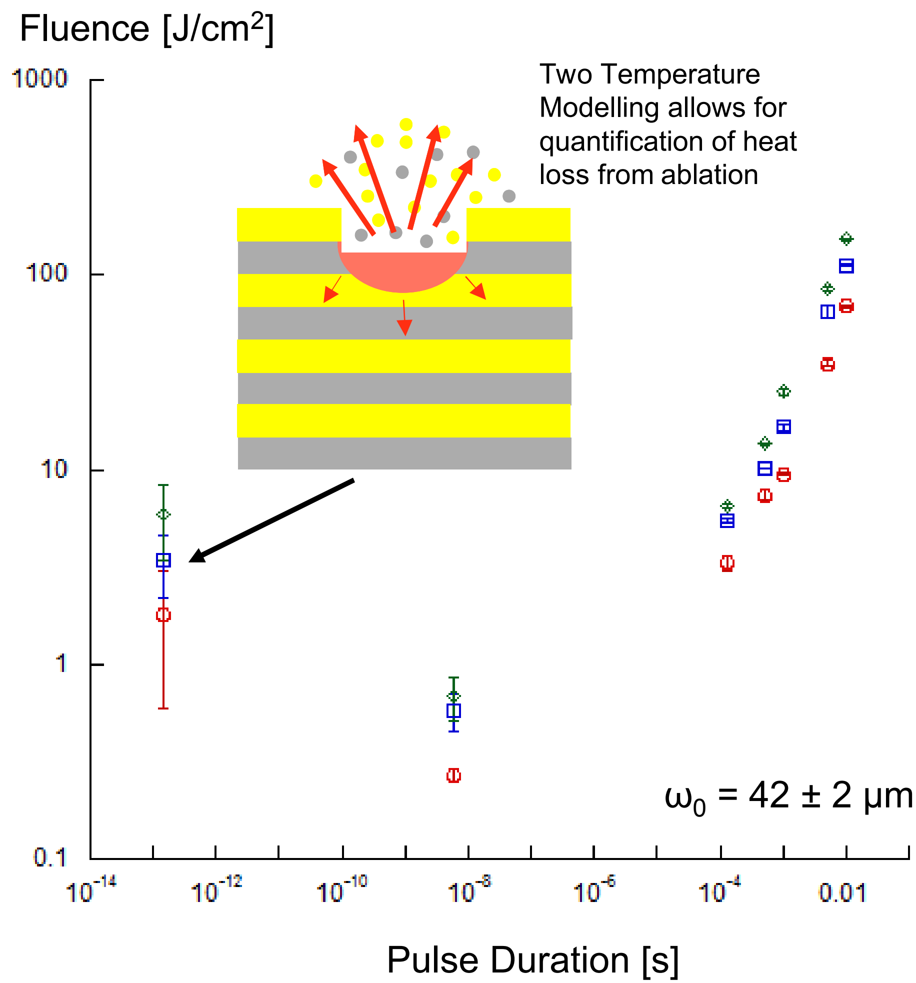


Mott s-d model improves our understanding of thermal properties for continuum simulations



Summary





◇ 328 nm Bilayer □ 164 nm Bilayer ○ 65 nm Bilayer