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Reactive Foil Ignition by Laser Irradiation: Experimental and Modeling Results

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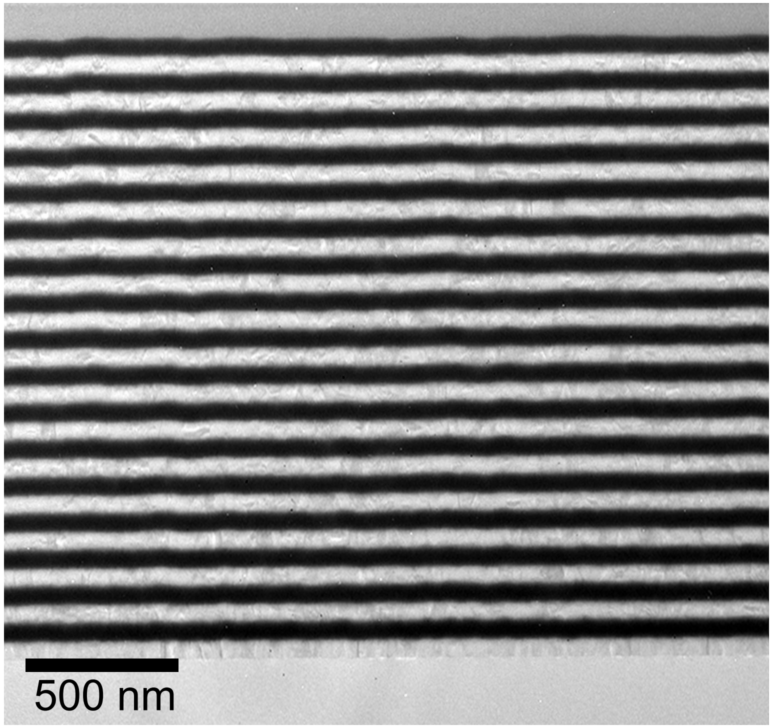
Reactive Multilayers

$Al + Pt \rightarrow AlPt$ (intermetallic phase) + 100 kJ·mol^{-1}·atm^{-1}

- Exothermic heat generation upon ignition.
- Self-propagating reaction.

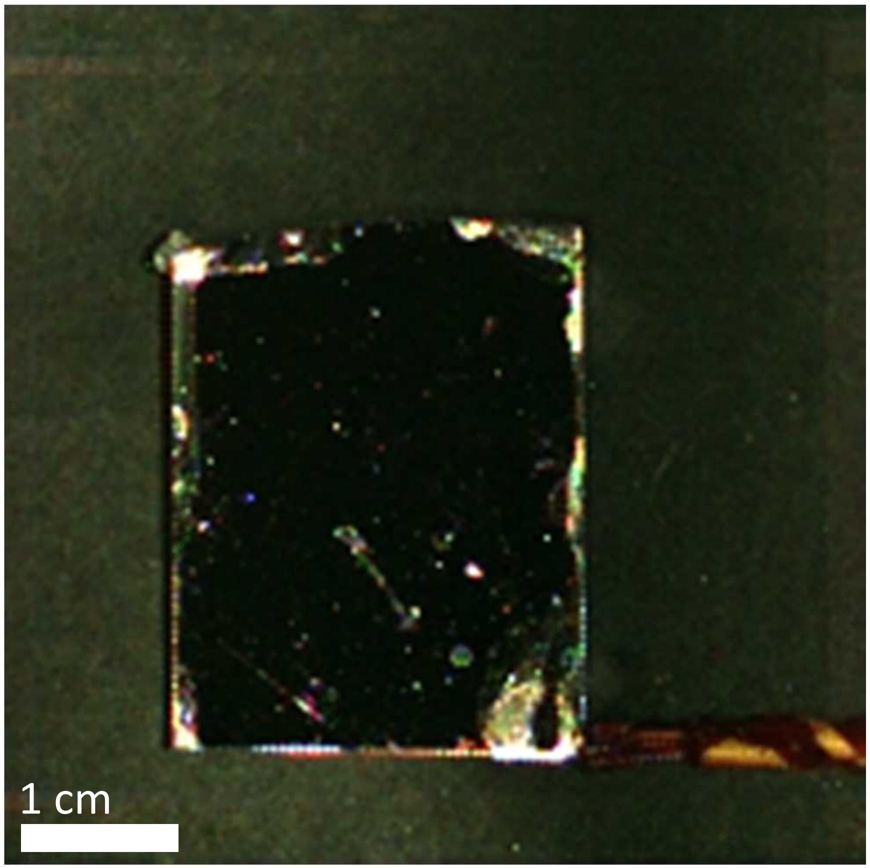
- DC Magnetron sputtered layers
- 10 - 15 Å thickness variation
- 1 to 1 Al/Pt ratio
- Adiabatic reaction temperature = 2798 °C
- <u>Melting not required for ignition</u>

Al/Pt multilayer
TEM Cross-section

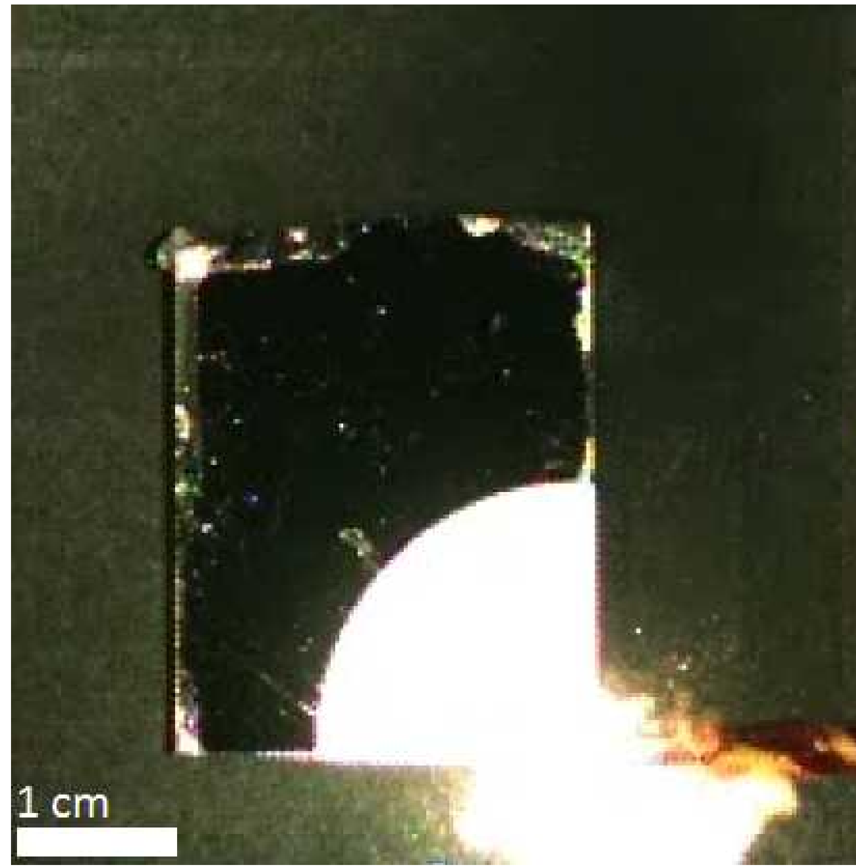


Ignition and Reaction Propagation

<u>Ignition by capacitive discharge</u>

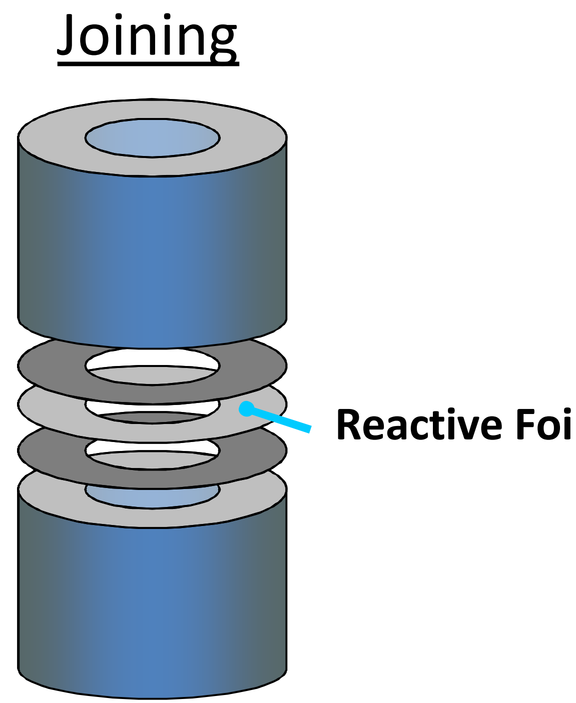


~ 600 microseconds after ignition

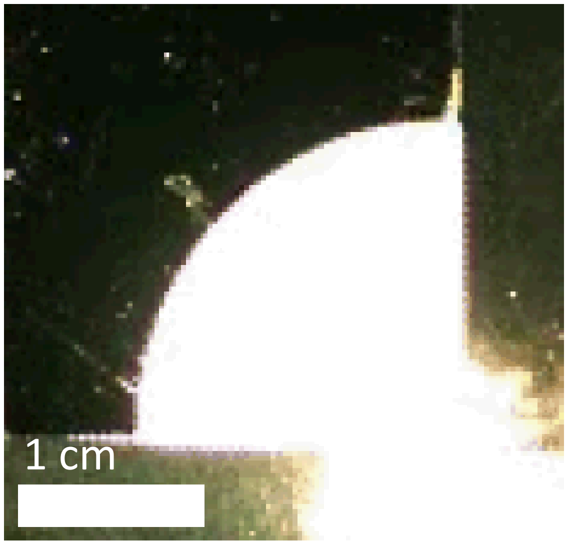


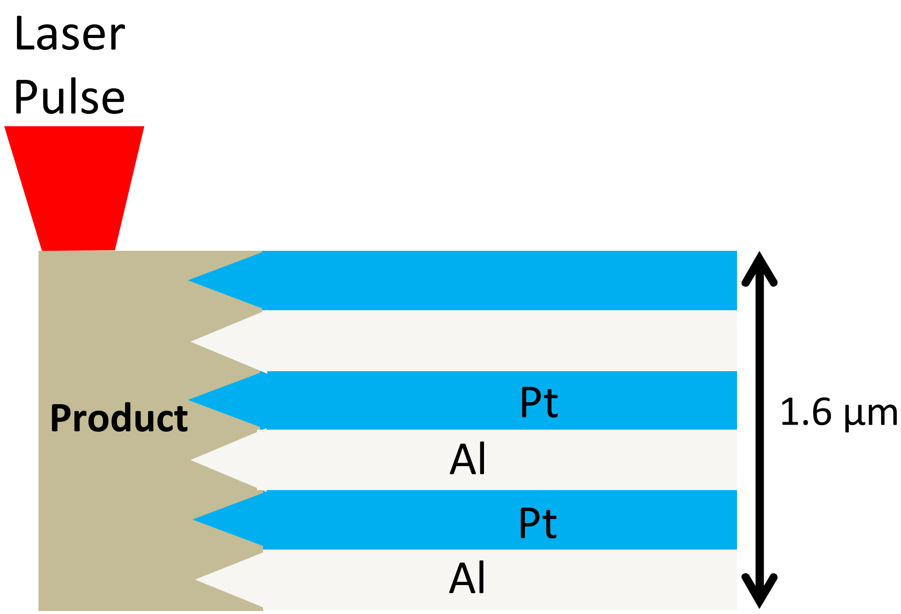
Laser Ignition

- Laser irradiation leads to more control over energy delivered to foil.
- Laser irradiation allows for remote ignition.
- Study effects of rate of heat input on ignition.
- Vary pulse length from femtosecond to millisecond to study effects of heating rate on ignition.



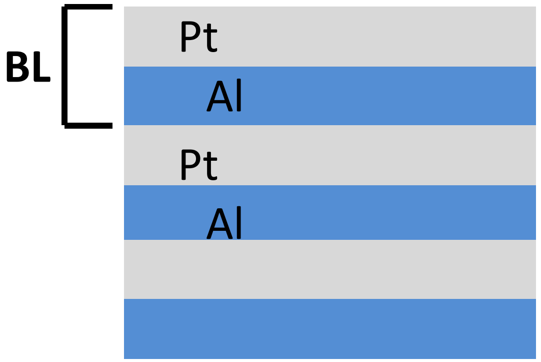
~ 600 microseconds after ignition

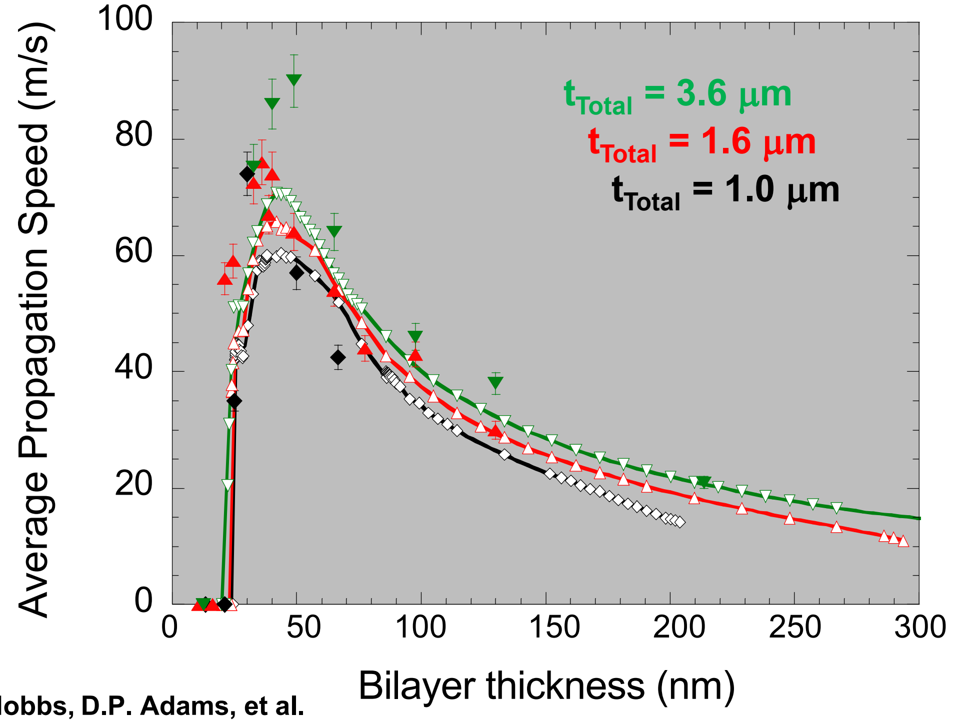




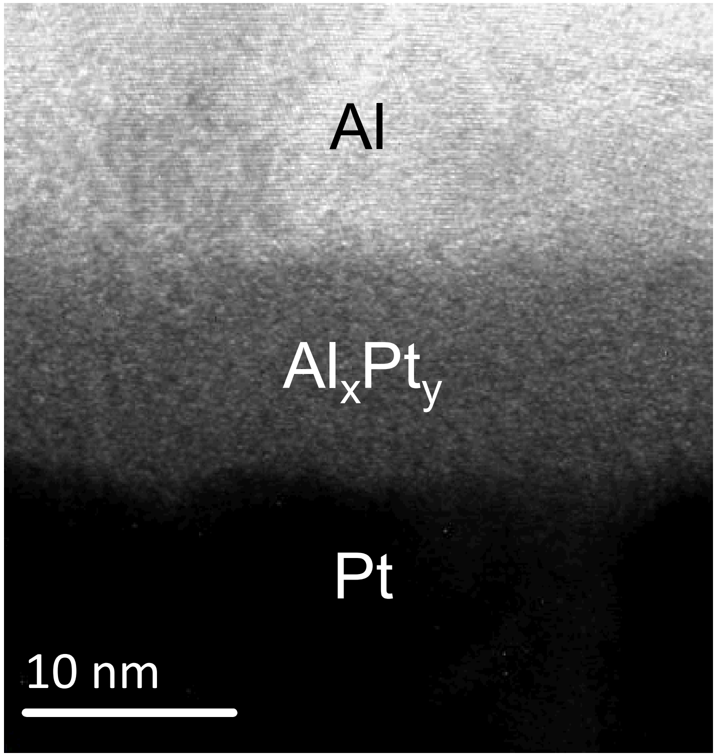
Bilayer Dependence

- Propagation speed increases with decreasing bilayer thickness.
- Shorter diffusion distances lead to shorter reaction times.
- Pre-mixing affects propagation speed of thinnest bilayers.



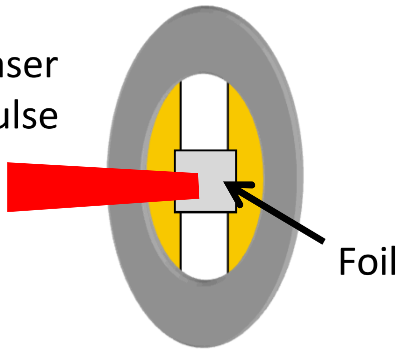


M. Hobbs, D.P. Adams, et al. 8th World Congress Comp. Mech. (2008).

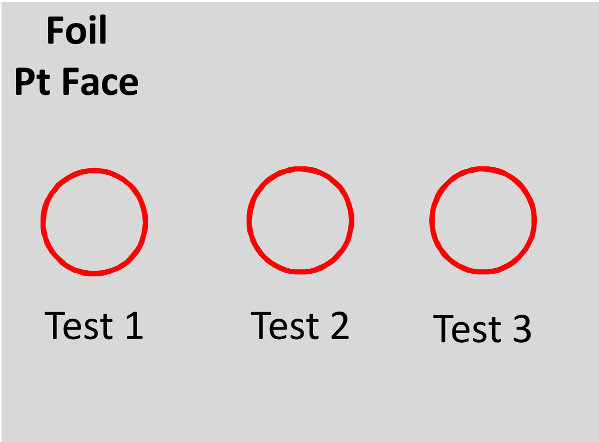


Determining Laser Ignition Threshold

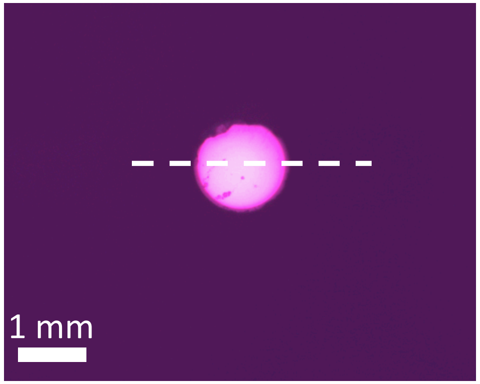
- Foil not on substrate
- Single Pulse Irradiation
- Flat-top Beam Profile
- Irradiate Pt side



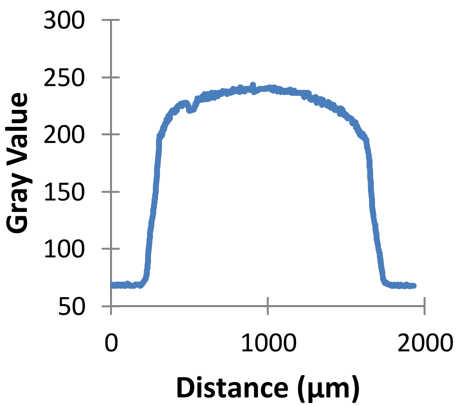
- Laser energy is increased until foil ignites.
- Non-irradiated region of sample is used for each test.

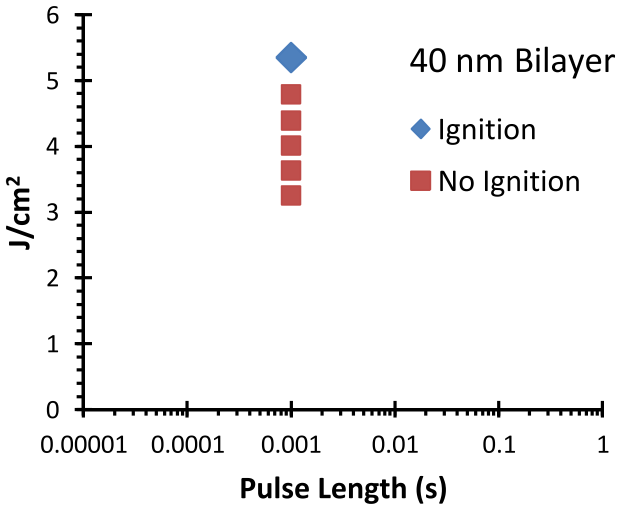


Focused Beam

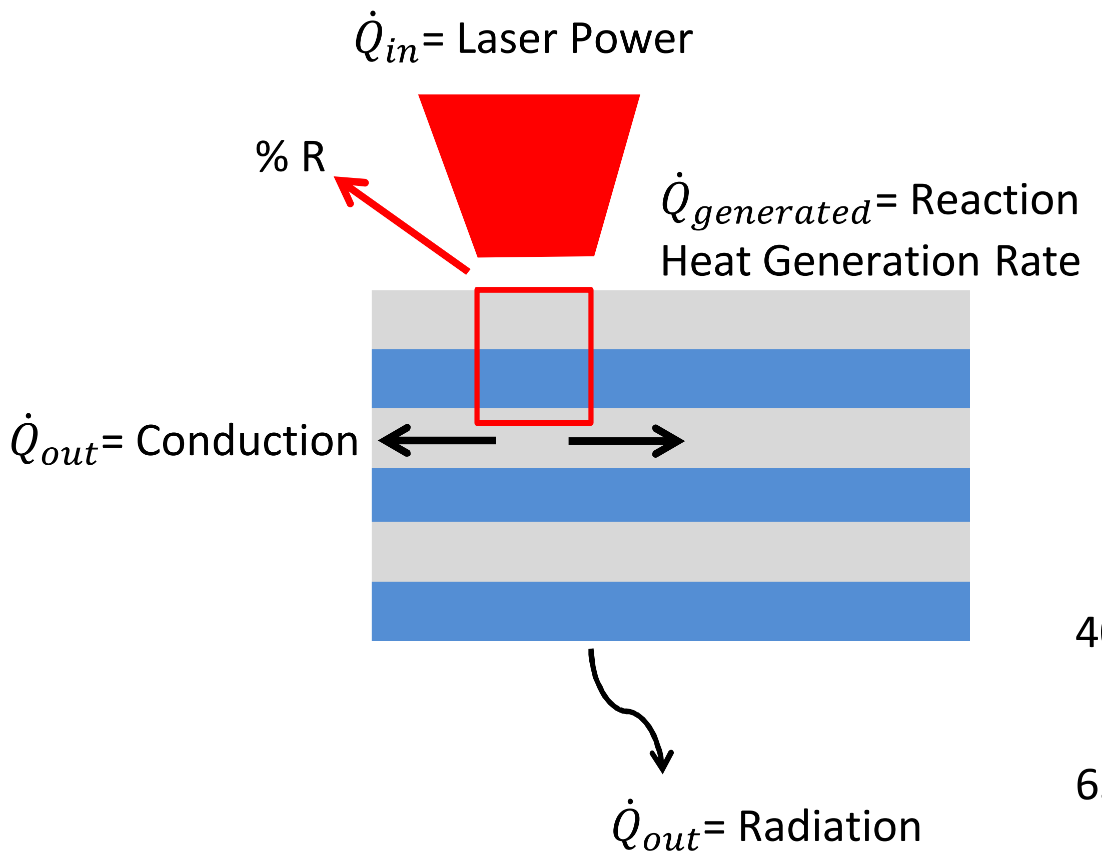


Beam Profile



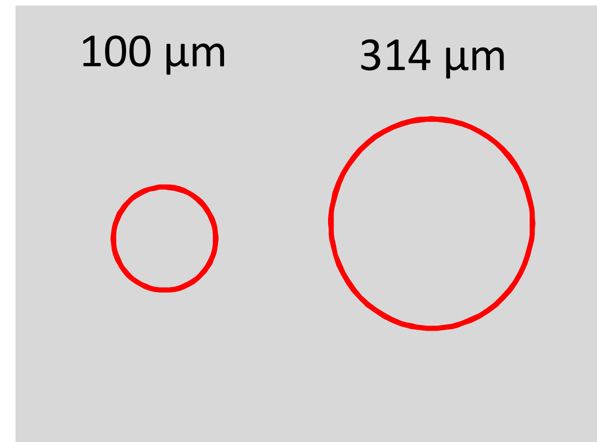


Heat Flow and Interaction Volume



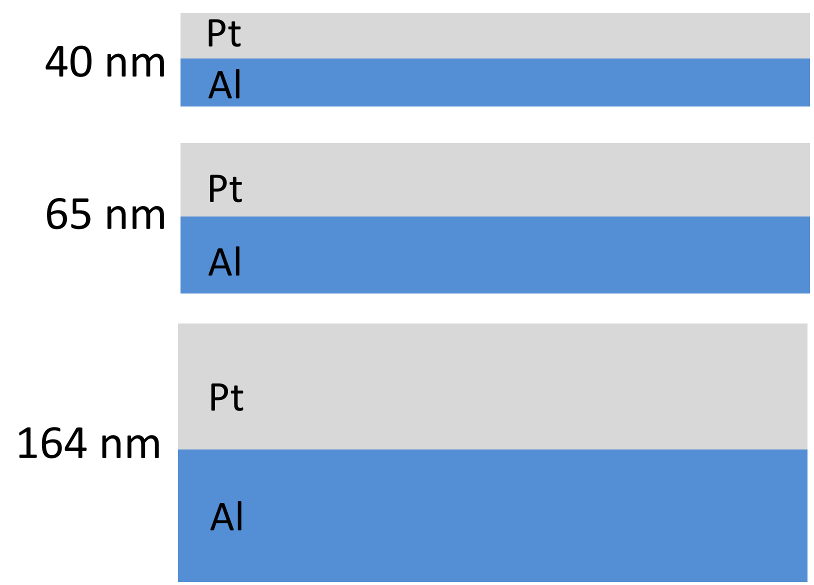
<u>Change interaction volume</u>

<u>Laser Spot Size</u>



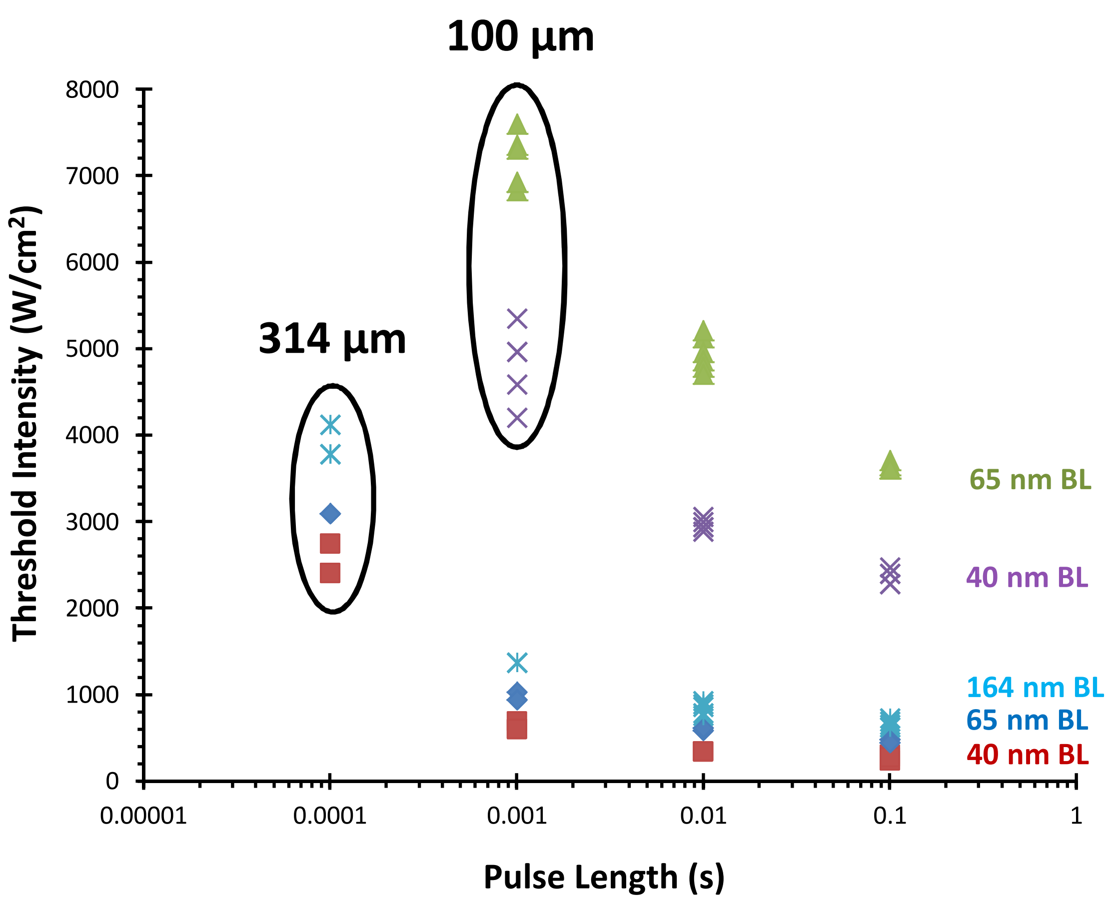
Total thickness = 1.6 μm

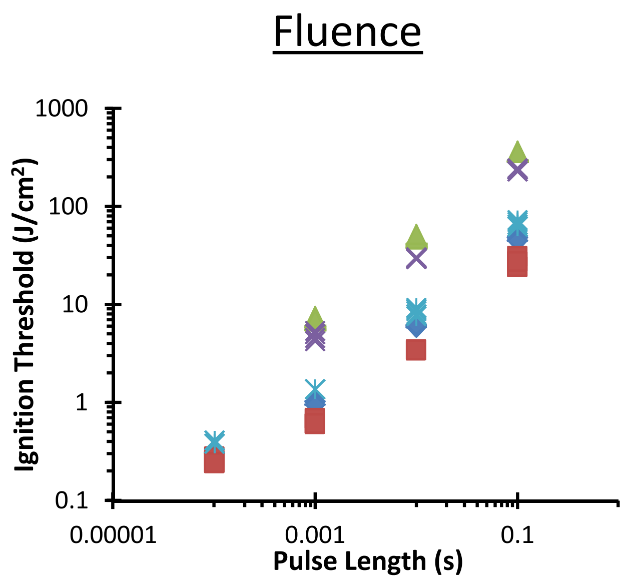
<u>Bilayer Thickness</u>

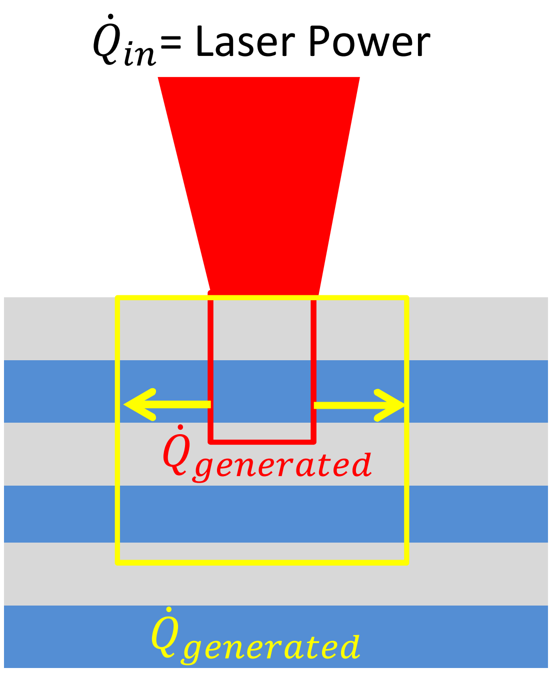


Intensity Threshold

- Intensity (W/cm^2) calculated using energy density and pulse length.
- Ignition threshold depends on intensity.
- Longer pulse lengths lower the intensity threshold.
- Longer pulse length may increase interaction volume via conduction.

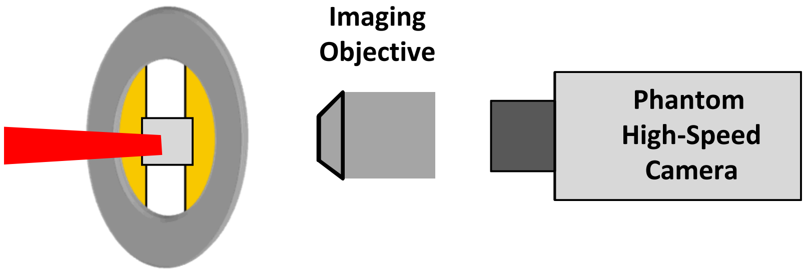






Imaging Ignition

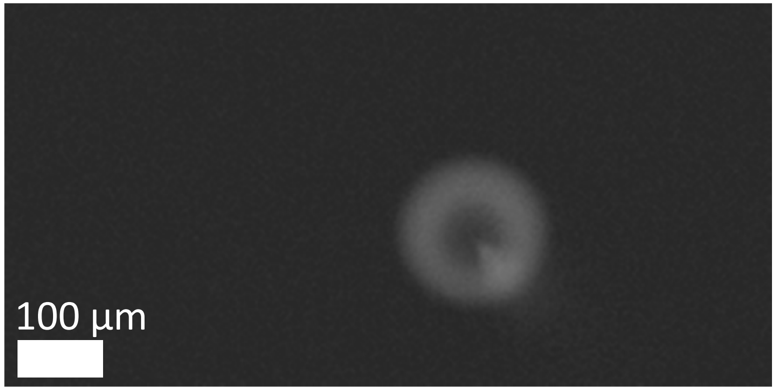
High-speed imaging of Al/Pt foil from the Al side



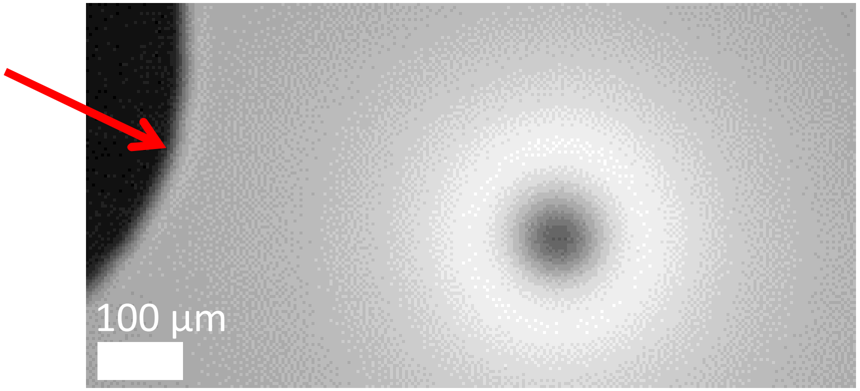
10 ms Incident Pulse
65 nm Bilayer
619 W/cm^2

t = 0 ms Laser Turns On

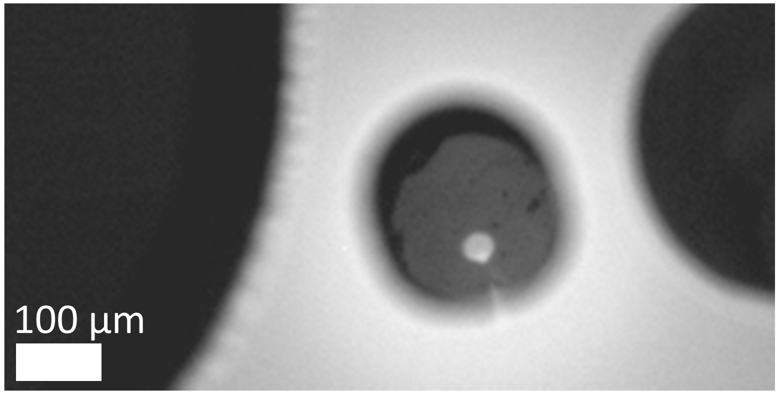
t = 2.88 ms Foil Ignites



t = 2.89 ms Entire Foil Melts

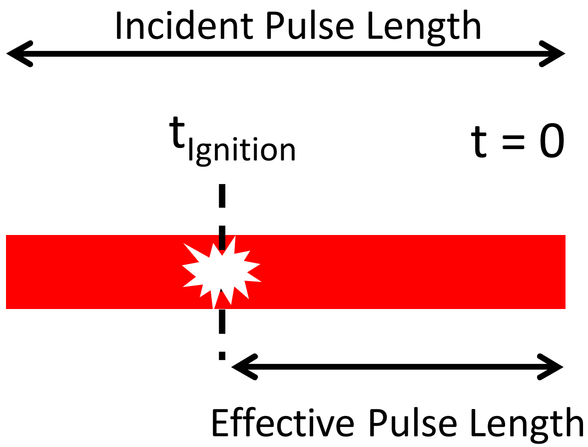


t = 2.91 ms Laser Penetrates Foil

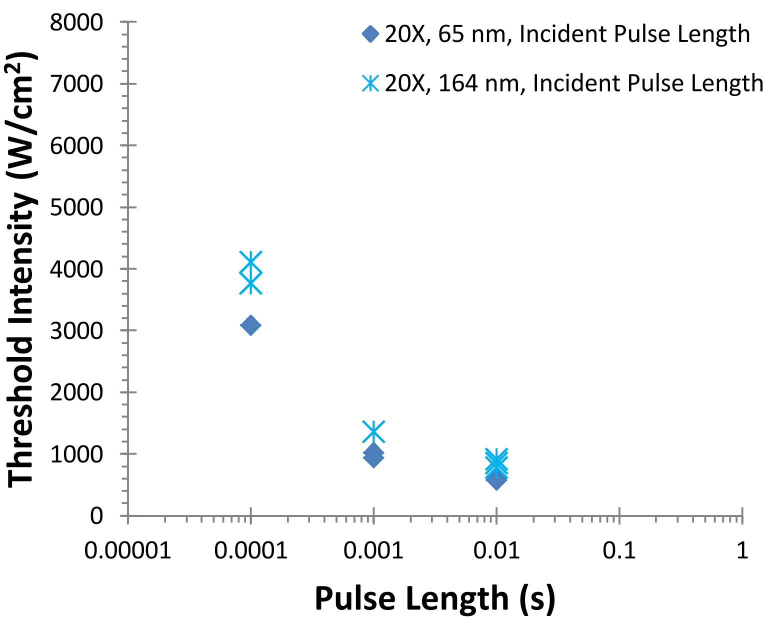


Laser-Foil Interaction Time

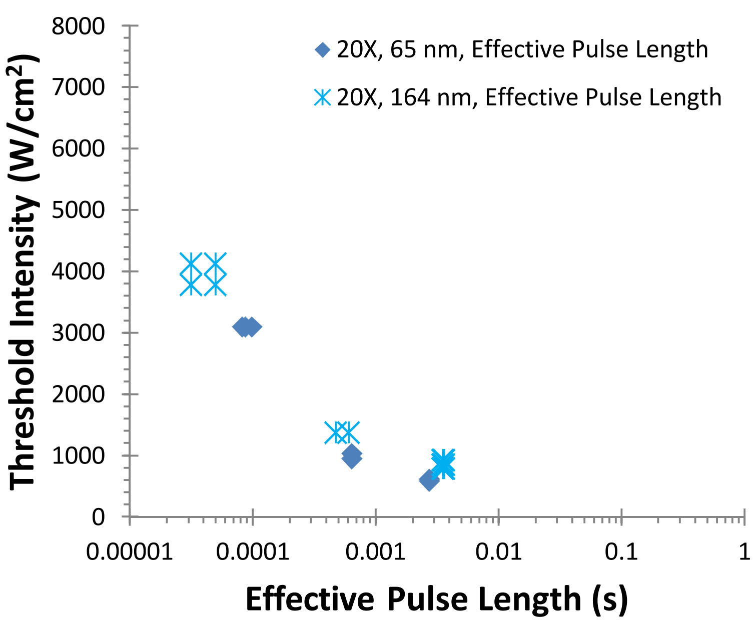
- Effective pulse length calculated by observing when ignition begins.
- Effective pulse length is usually shorter than incident pulse length.
- *Shorter pulses require energy to be delivered at a higher rate (power).*



Incident Pulse Length



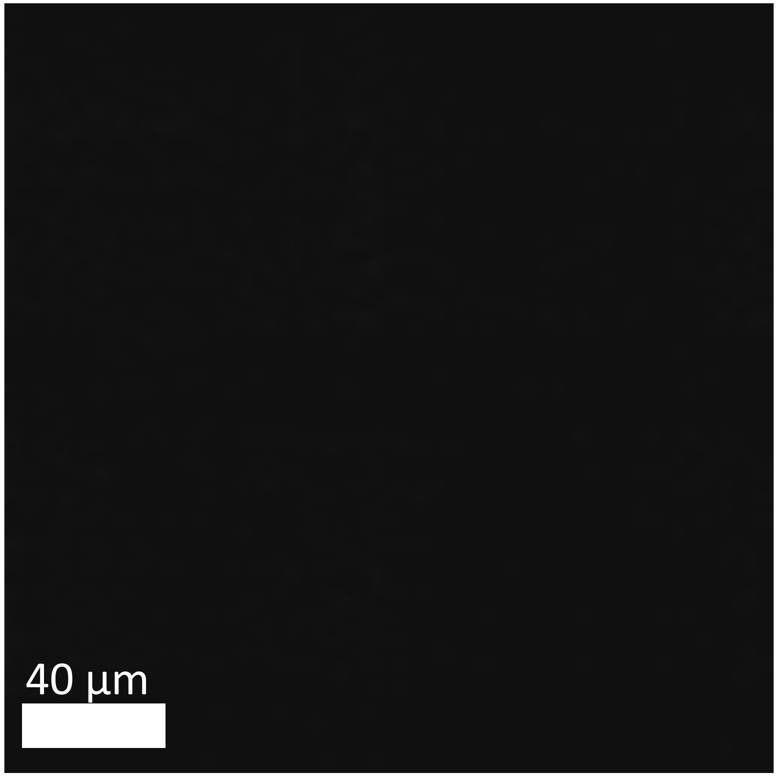
Effective Pulse Length



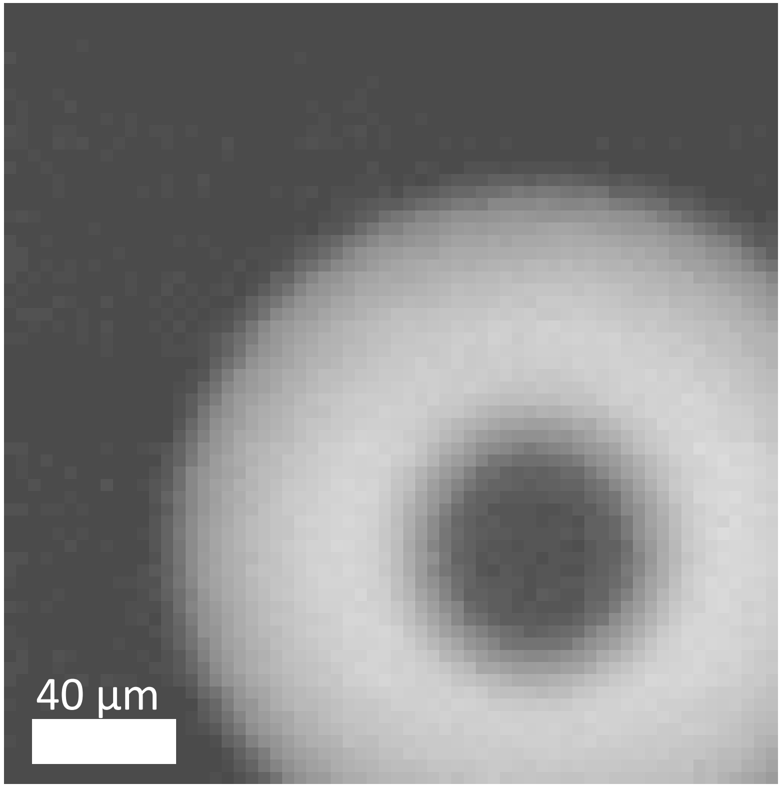
Self-Propagating Reaction after Ignition

10 ms Incident Pulse
164 nm Bilayer
894 W/cm^2

4 µs/frame

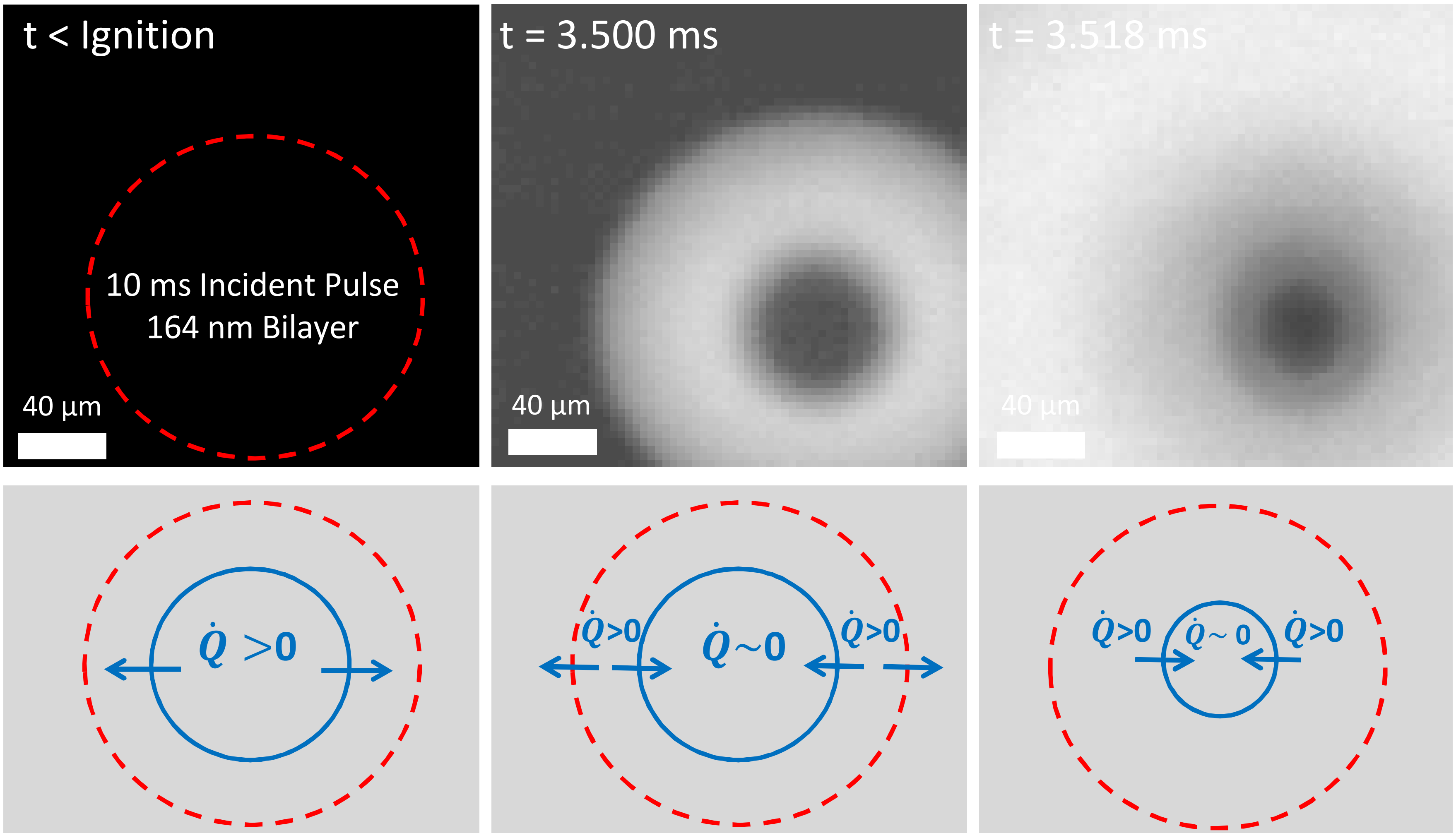


Ignition ~ 3.500 ms after laser turn on



Solid-State Reaction vs. Self-Propagating Reaction

- Dark center suggests ignition begins as a slow, non-propagating reaction.
- Bright annulus suggests these regions are hotter than surrounding regions.

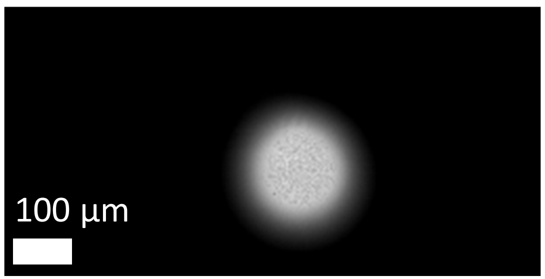


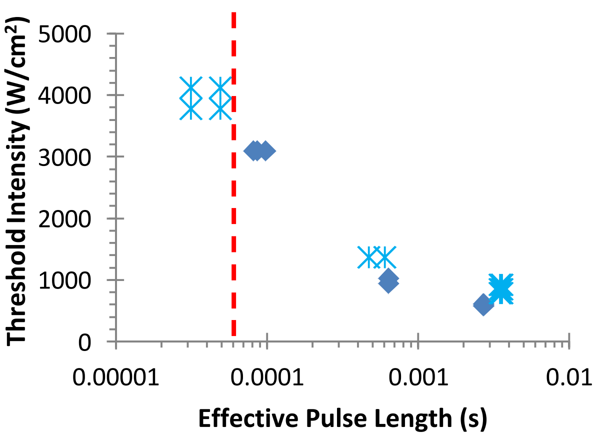
Shorter Pulses – Mechanisms Change

100 µs Pulse

- Ignition occurs – no annulus observed.
- Central, irradiated area ignites.
- Mechanisms are *intensity* dependent

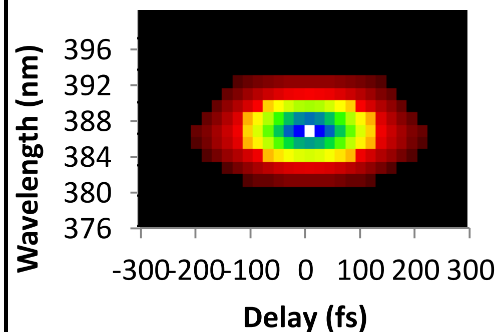
100 µs Incident Pulse
164 nm Bilayer
3.8 kW/cm^2
t = 49 µs

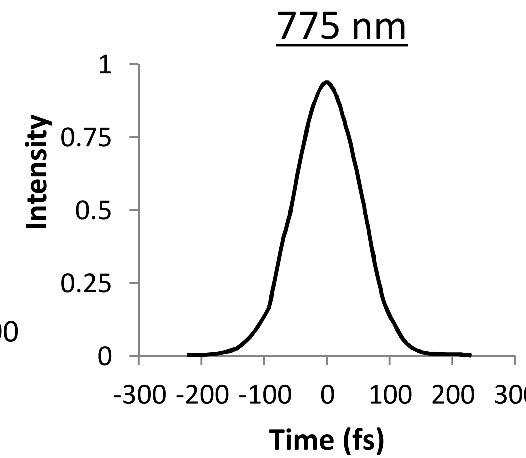




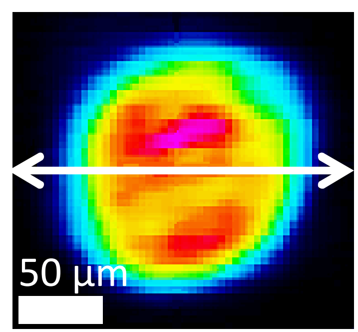
150 fs Pulse

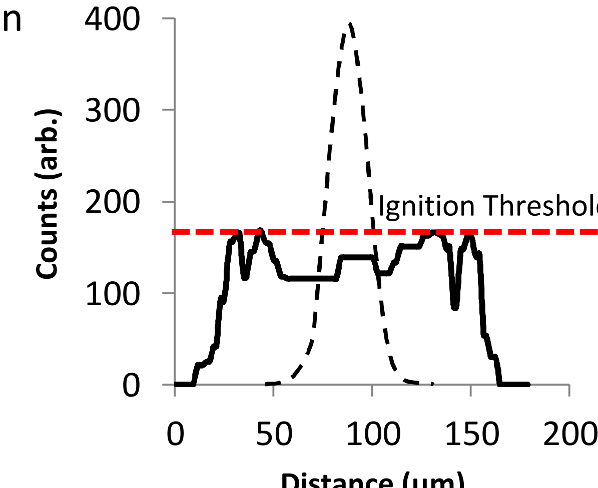
- Measured *temporal* distribution is Gaussian.
- "Flat-top" *spatial* distribution.





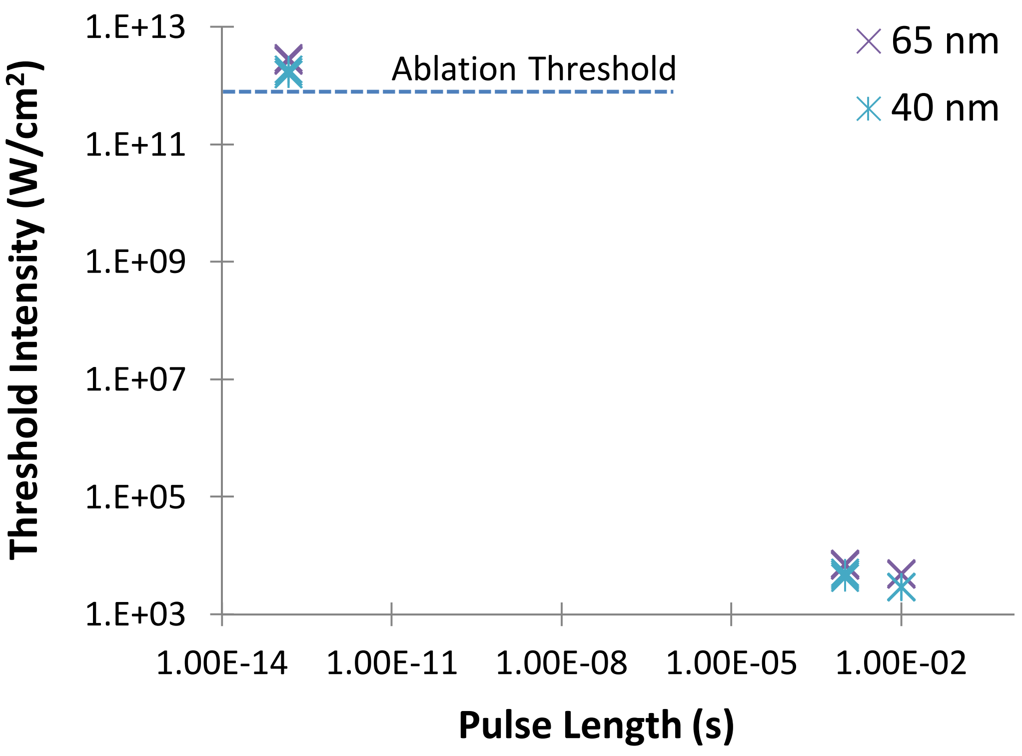
~ 30% Intensity Variation

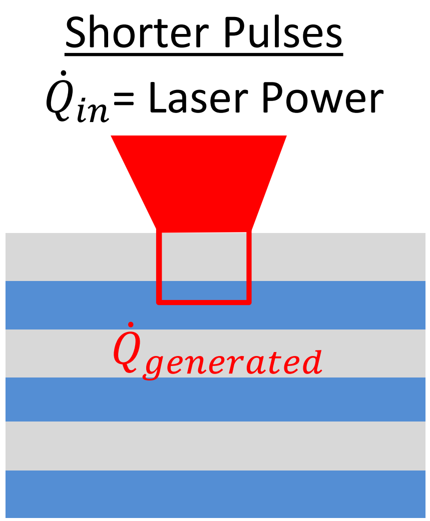


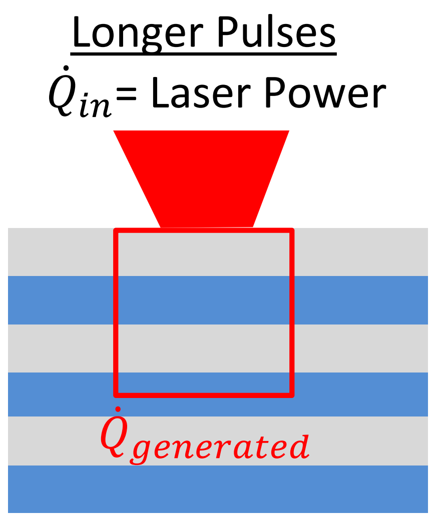


Ignition Threshold

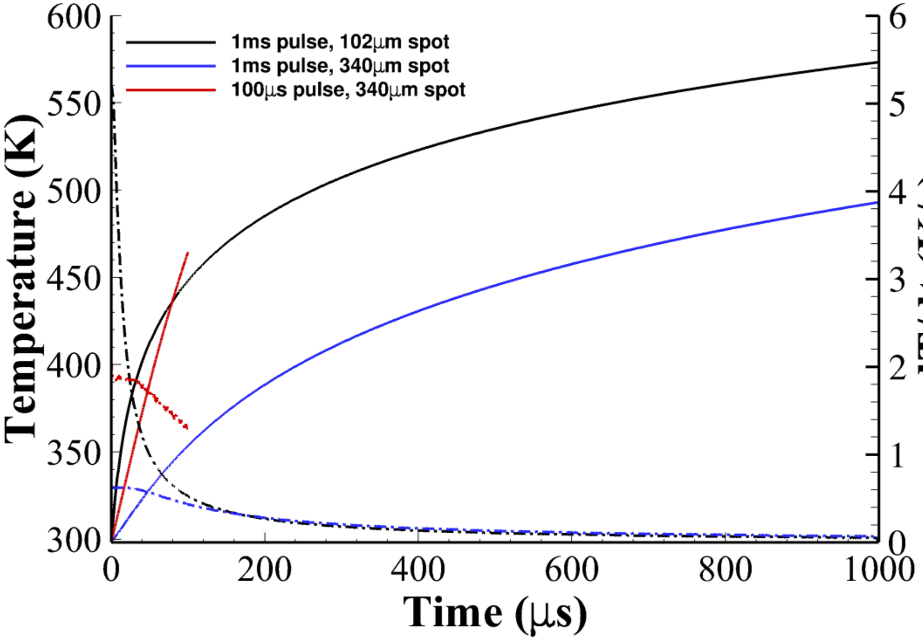
- "Flat-top" beam is used for all pulse lengths – defines the interaction area
- 150 fs: mechanism changes from solid-state ignition to laser-induced melting and ablation.

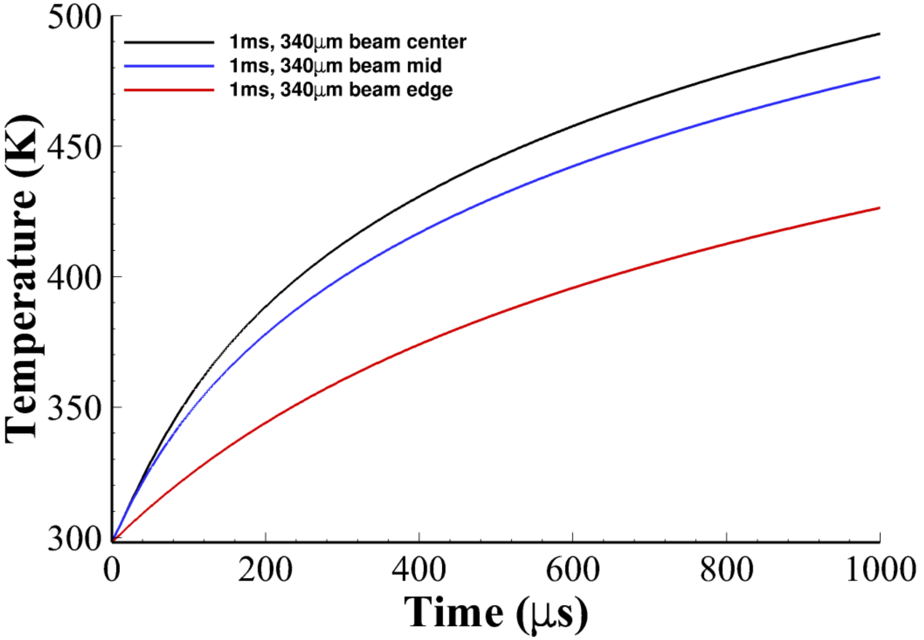




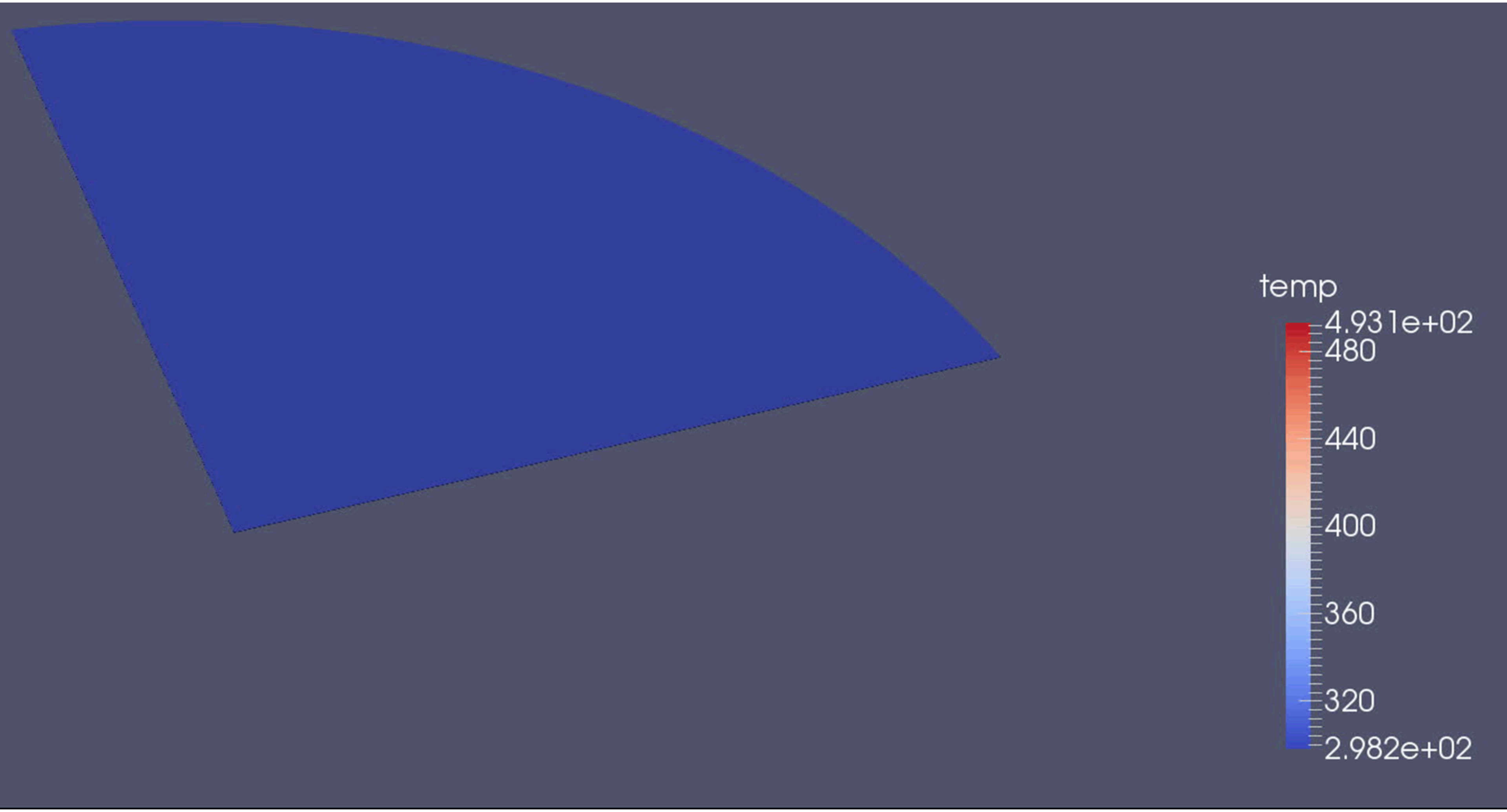


Simulation show temperature profiles as function of time





Temperature Evolution Caused by Laser Pulse

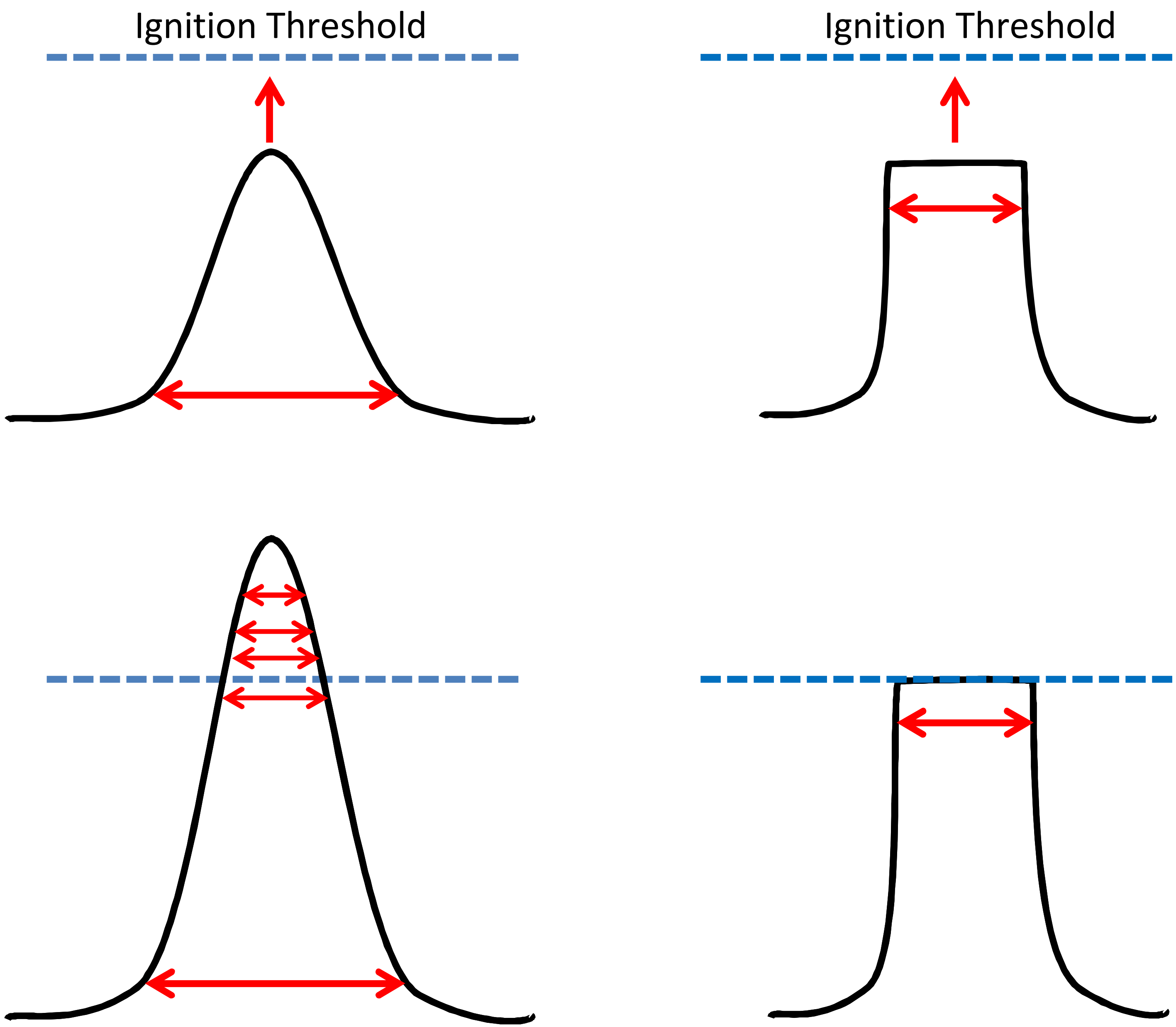


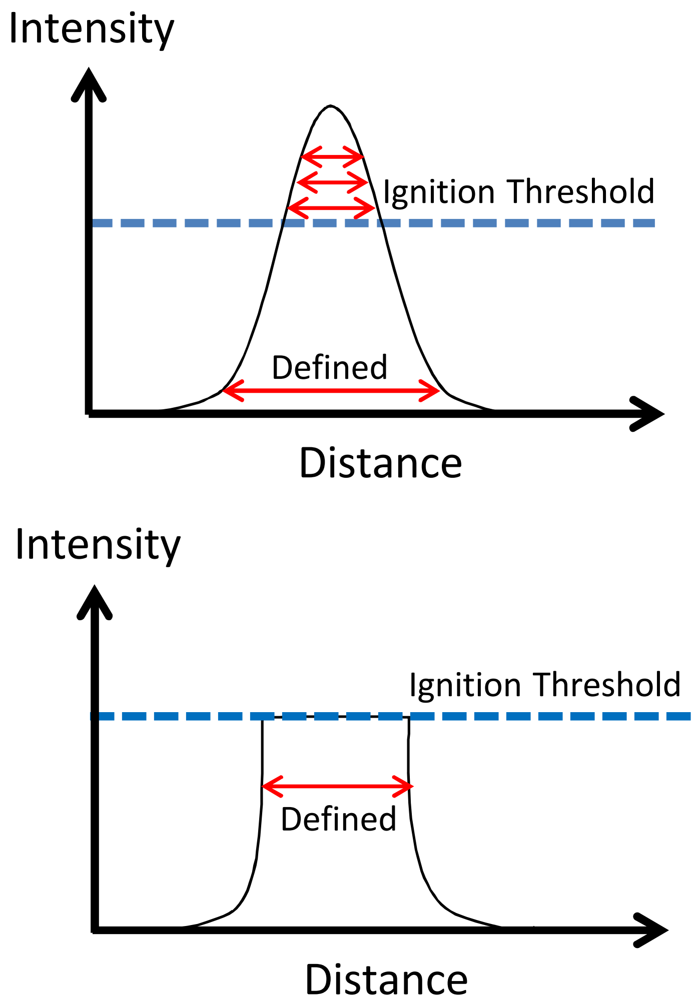
Conclusions

- Reactive foils are ignited using single laser pulses.
- Laser pulse lengths ranging from femtoseconds to milliseconds can ignite foils.
- Laser ignition threshold depends on pulse duration, laser spot size, and foil bilayer thickness.
- Increasing laser spot size and decreasing bilayer thickness increases the volume-specific interfacial surface area, leading to decreased ignition threshold.
- Dependence of threshold on laser pulse duration likely due to competition between rate of heat input delivered by laser pulse and conductive heat losses.
- High-speed photography shows ignition usually occurs during laser irradiation.
- Separate reaction zones are present during laser irradiation and ignition.
- Ignition mechanism depends on the laser pulse length.

Extra Slides

Fixed Interaction Volume



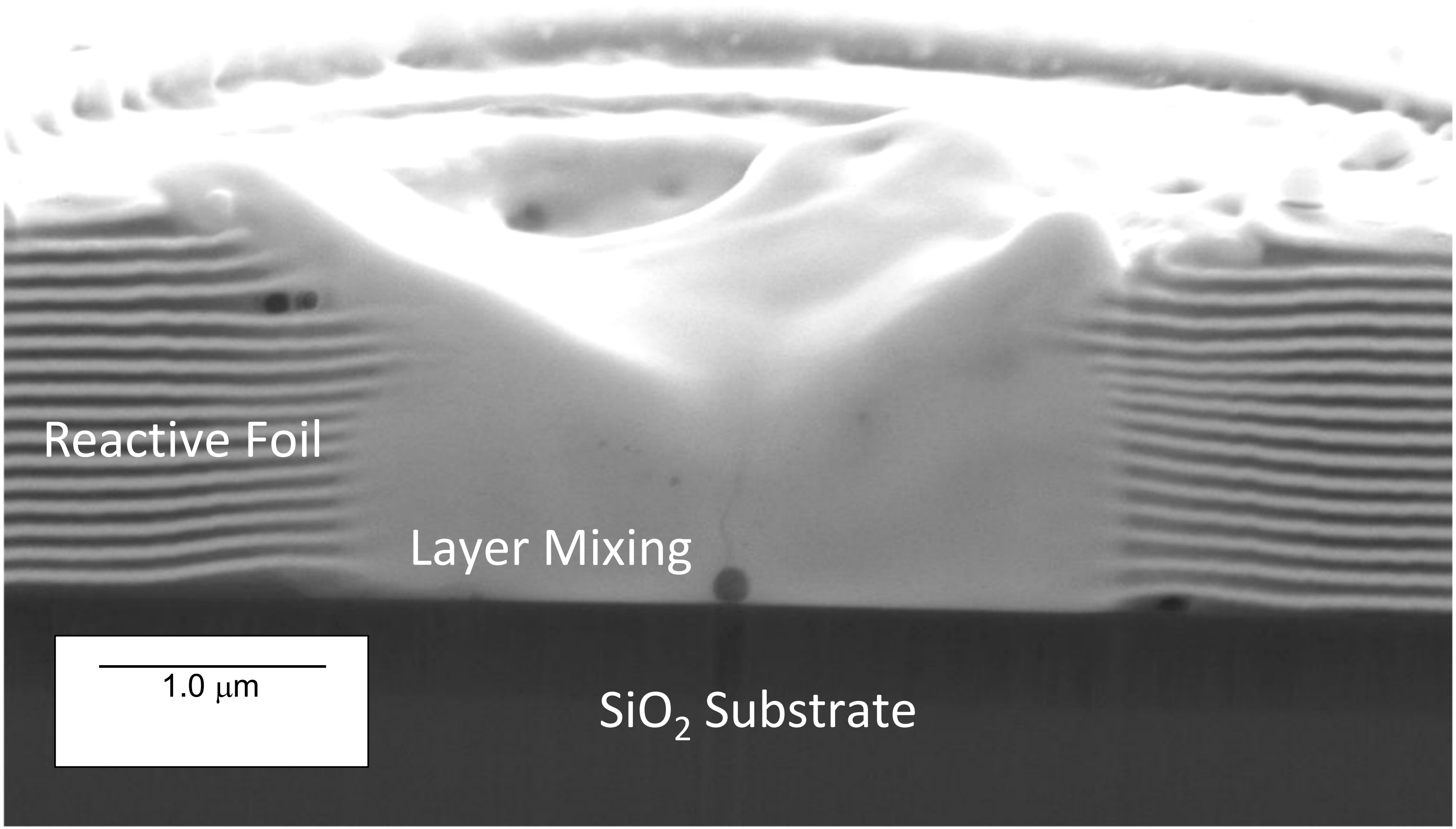

Intensity
Ignition Threshold
Defined
Distance
Intensity
Ignition Threshold
Defined
Distance

Laser Irradiation

<u>Al/Pt Irradiated at 80% ignition threshold</u>

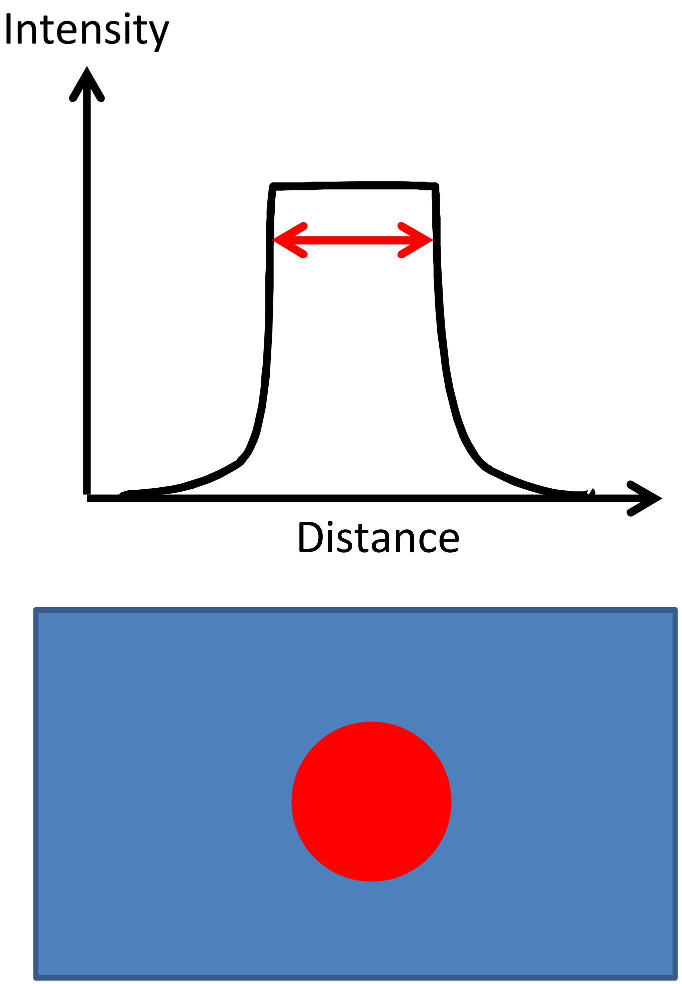
100 fs pulse

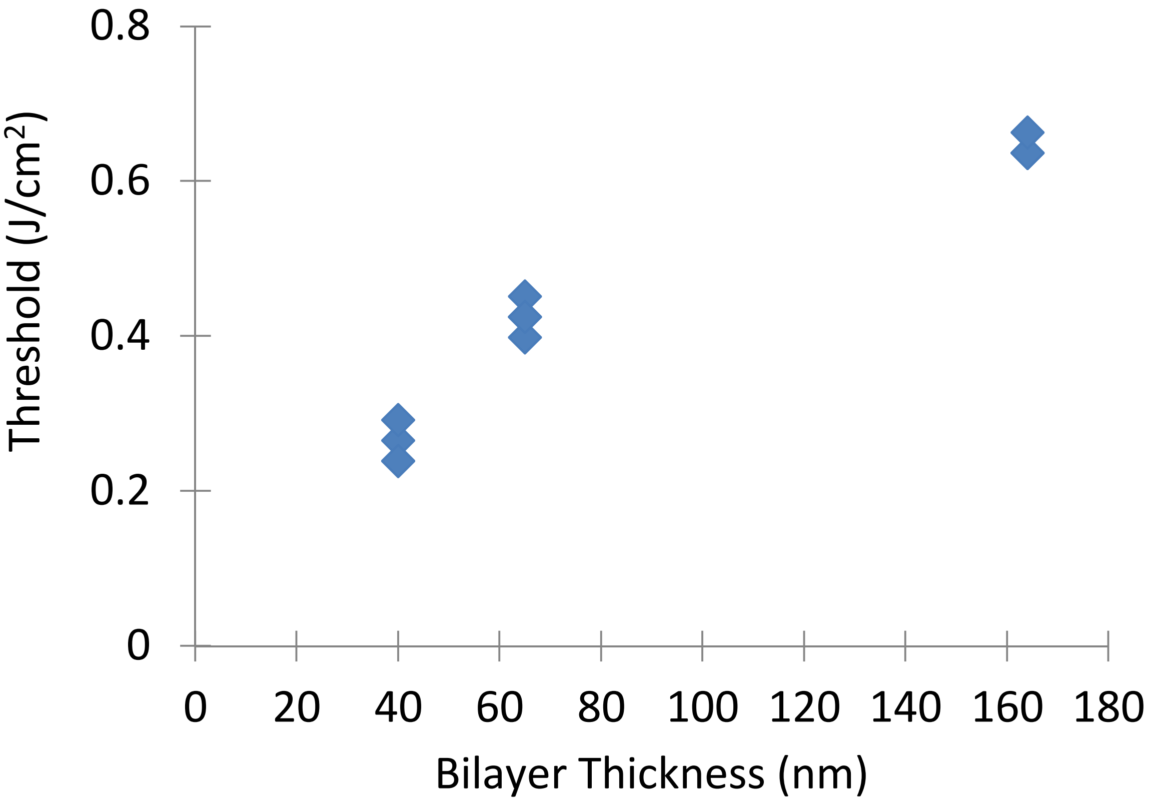
SEM Cross-section



Picard, Yoosuf N. Ph.D. thesis University of Michigan, 2006.

150 fs Ignition Threshold





Effective Pulse Length Depends on Intensity

1 ms Incident Pulse
65 nm Bilayer

% Above Threshold	Effective Pulse Length (ms)
0	0.892
49	0.440
100	0.300

Diffusion Zone Size Depends on Pulse Length

65 nm Bilayer

Incident Pulse Length (ms)	Diffusion Zone Diameter (μm)
0.1, 9 mW 0.1, 9 mW	18 18
1, 9 mW 1, 4.5 mW 1, 5.5 mW 1, 5.5 mW	42 44 28 22
10, 36 mW 10, 36 mW 10, 36 mW	73 36 44

164 nm Bilayer

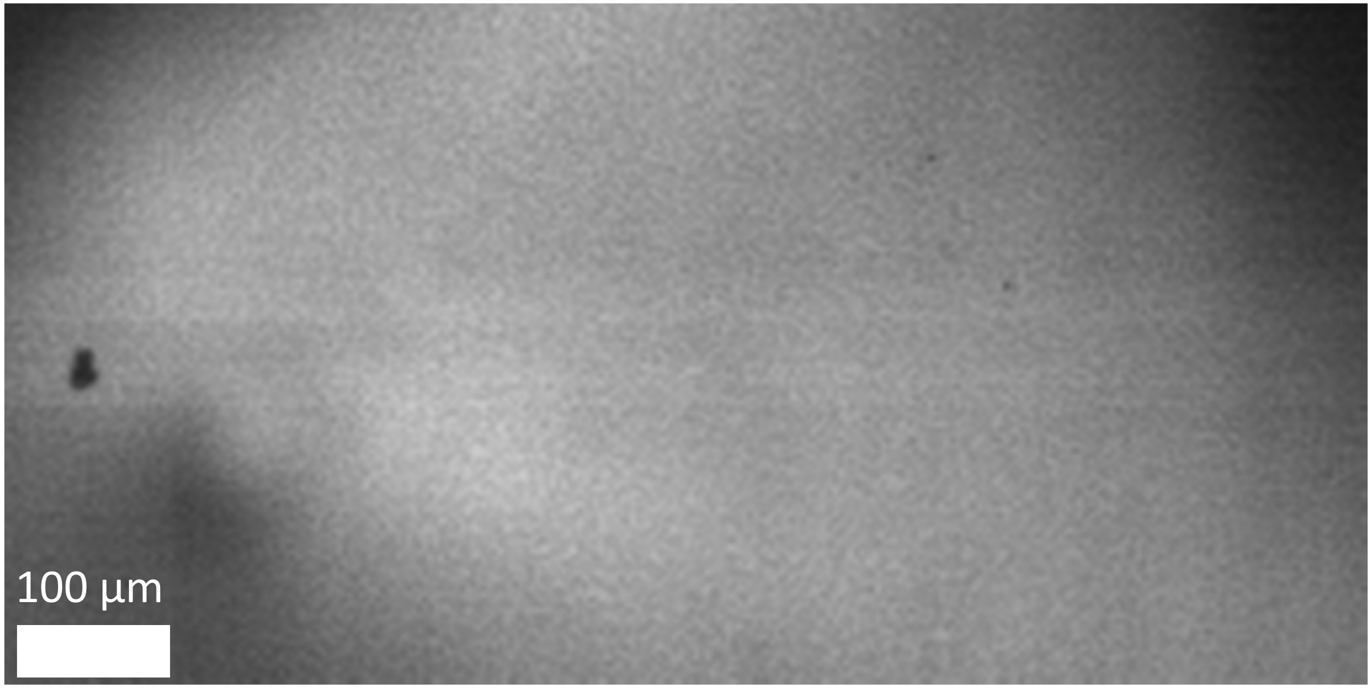
Incident Pulse Length (ms)	Diffusion Zone Diameter (μm)
0.1, 12 mW 0.1, 12 mW	0 0
1, 8 mW 1, 8 mW	18 22
10, 52 mW 10, 52 mW	49 52

Sub-threshold Irradiation

95% Ignition Threshold

2.94 ms Incident Pulse
65 nm Bilayer

10 µs/frame

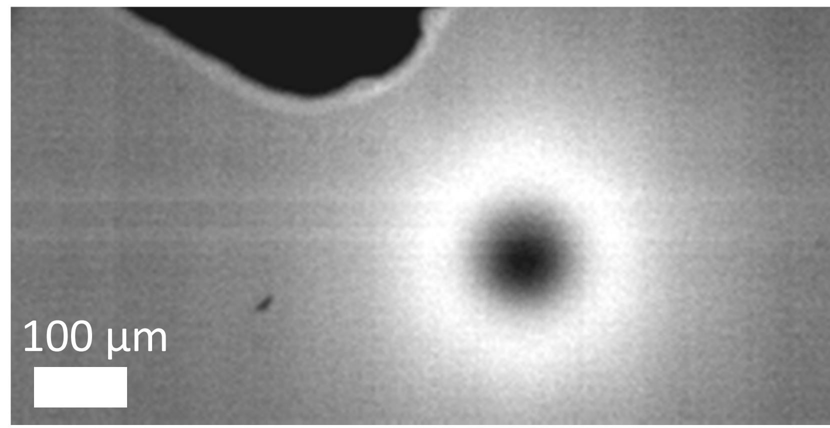


Ignition and Melting

<u>10 ms Incident Pulse</u>
65 nm Bilayer
36 mW

~ 2.60 ms after laser turns on

~ 2.61 ms after laser turns on



Reflectance Measurements

10 ms Incident Pulse
65 nm Bilayer