

# The Dynamics of Reactive Foil Ignition after Pulsed Laser Irradiation

*R.D. Murphy<sup>1</sup>, R.V. Reeves<sup>1</sup>, J.P. McDonald<sup>2</sup>, and D.P. Adams<sup>1</sup>*

*<sup>1</sup>Sandia National Laboratories, Albuquerque, NM USA*

*<sup>2</sup>Dow Corning Corporation, Midland, MI USA*



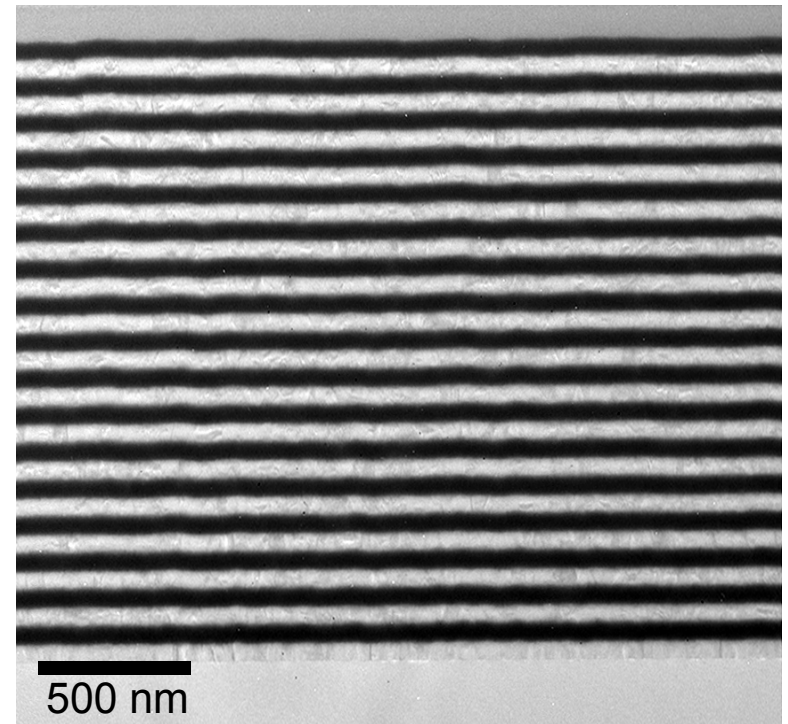
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# Reactive Multilayers

- 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
- Reaction onset temperature = 136 °C
- Melting not required for ignition

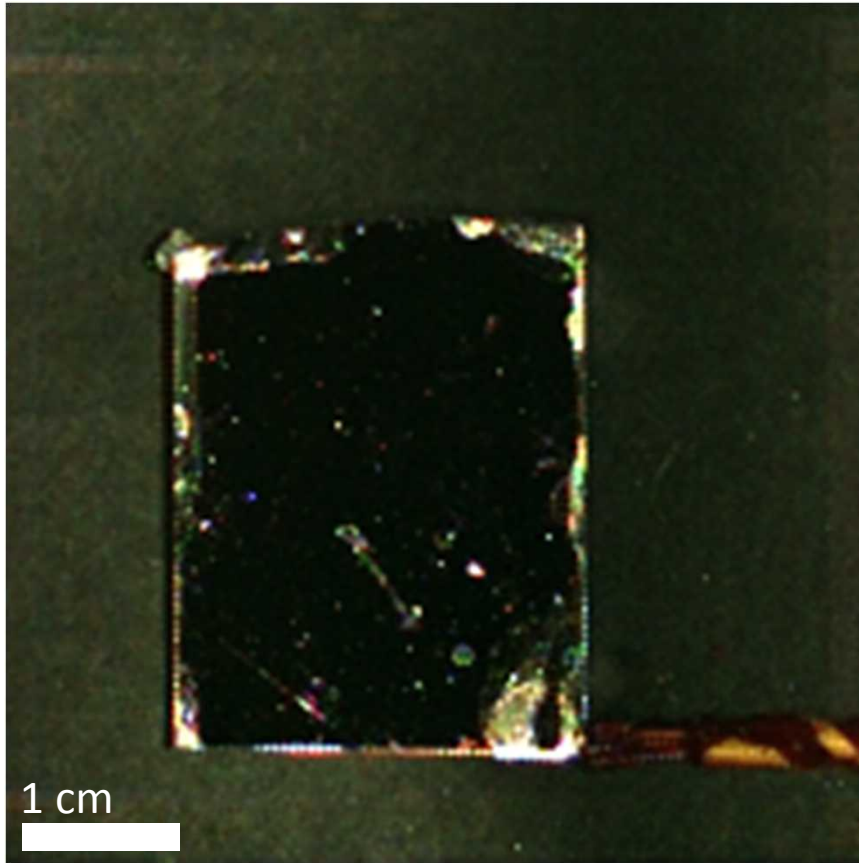


Al/Pt multilayer  
TEM Cross-section

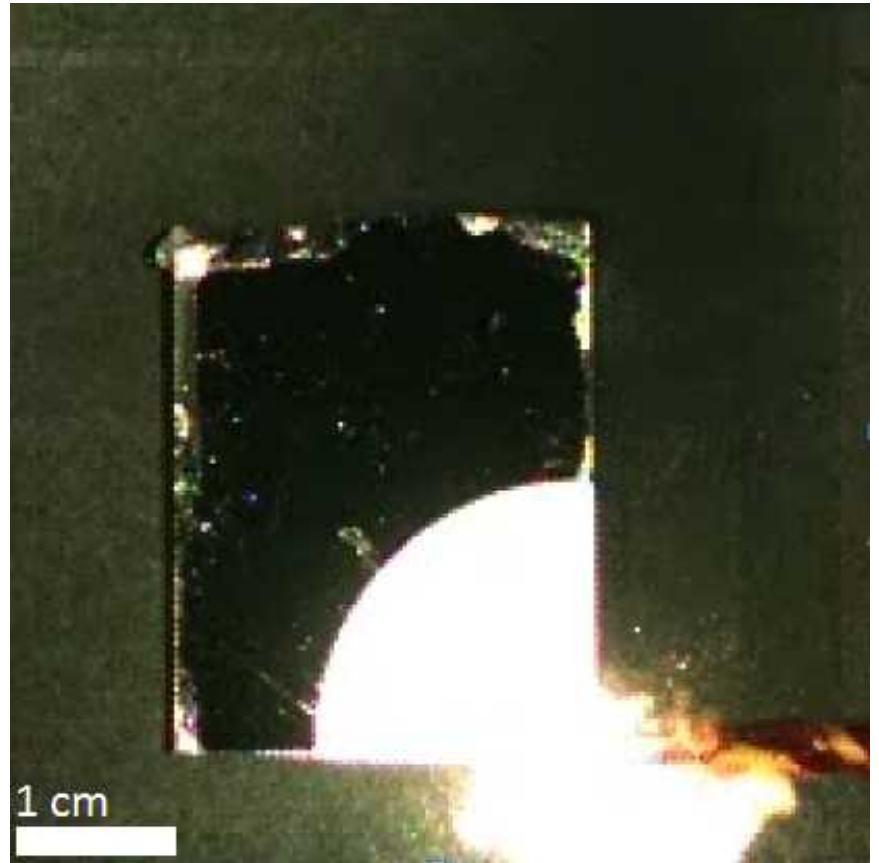


# Ignition and Reaction Propagation

Ignition by capacitive discharge

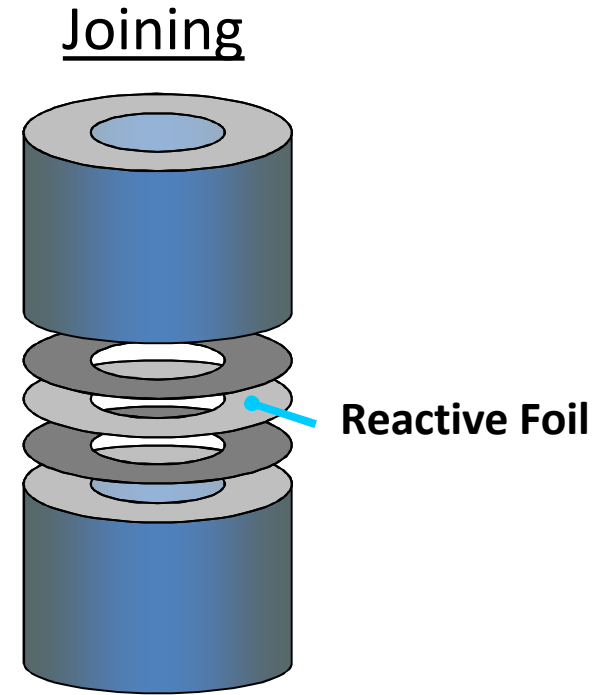


~ 600 microseconds after ignition

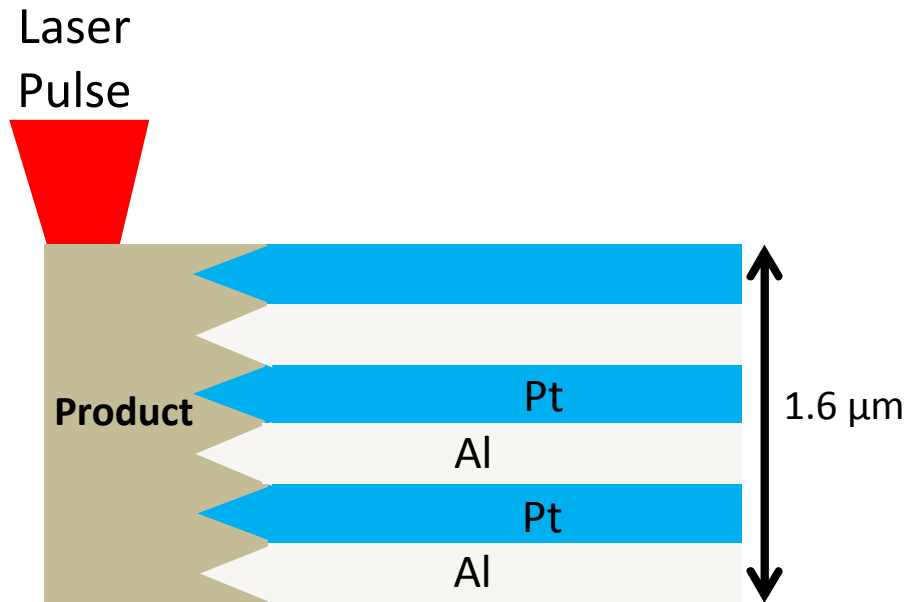
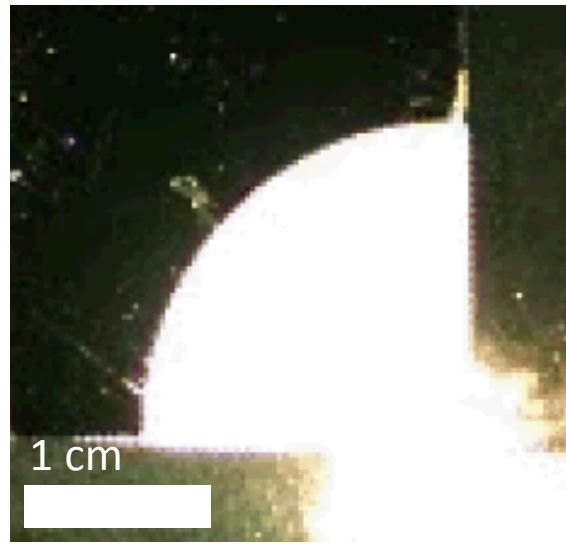


# Laser Ignition

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

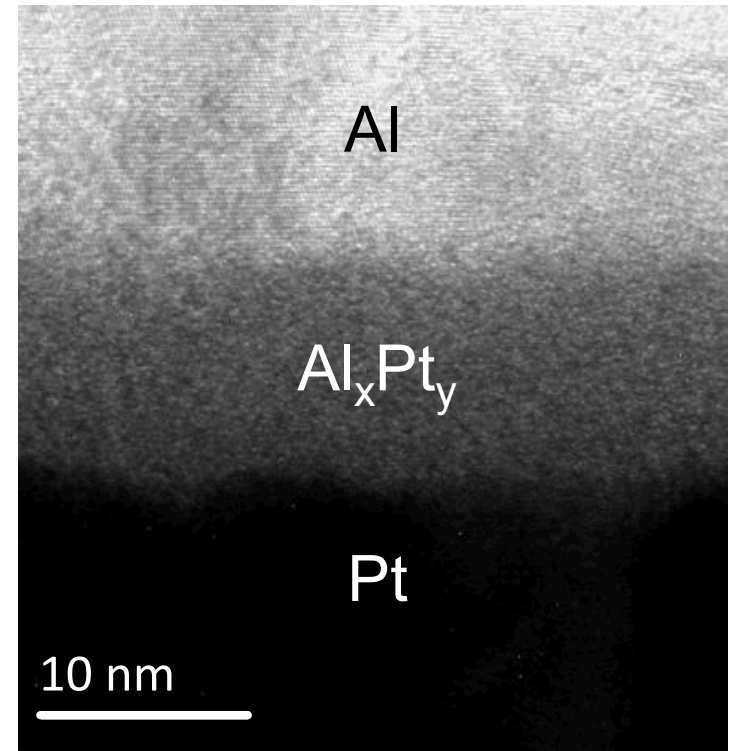
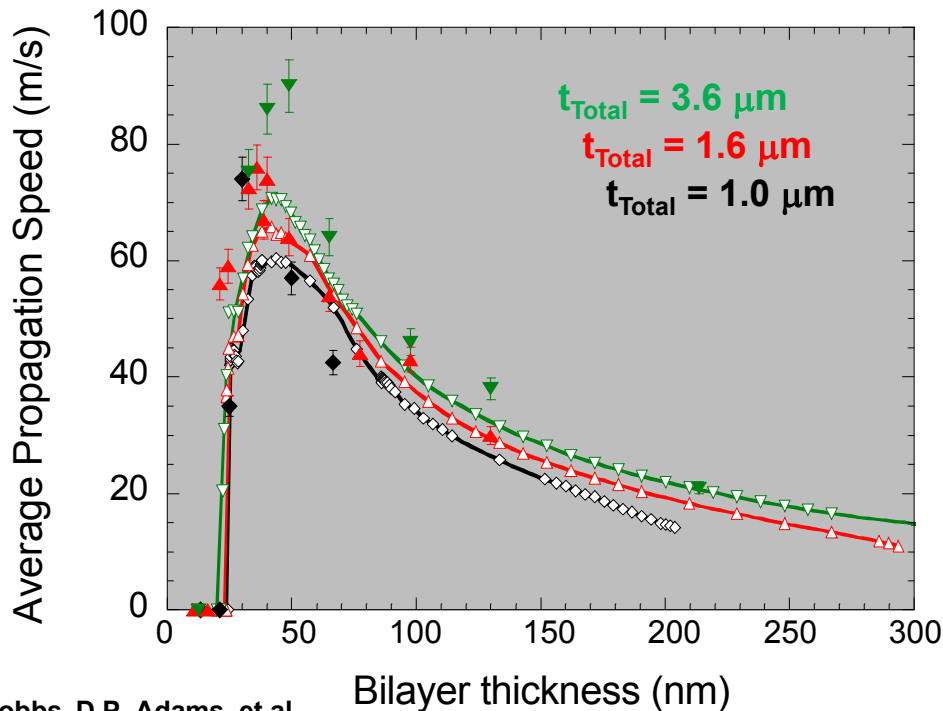
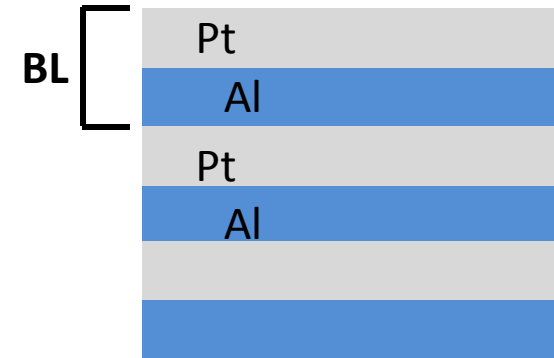


~ 600 microseconds after ignition



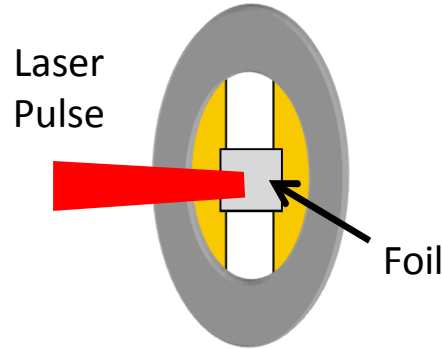
# Bilayer Dependence

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

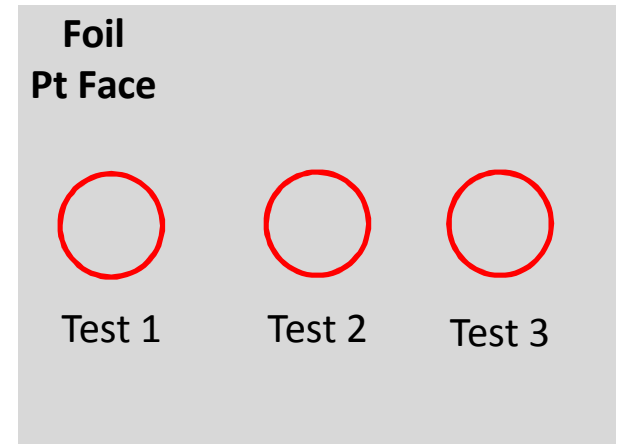


# Determining Laser Ignition Threshold

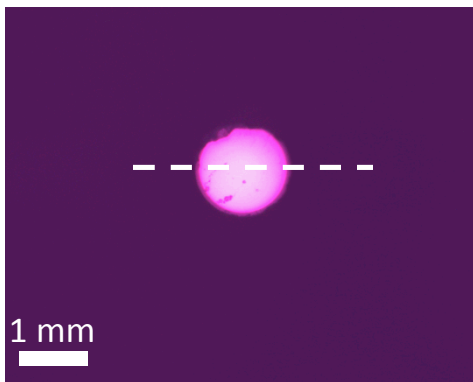
- Foil not on substrate
- Single Pulse Irradiation
- Flat-top Beam Profile
- Irradiate Pt side



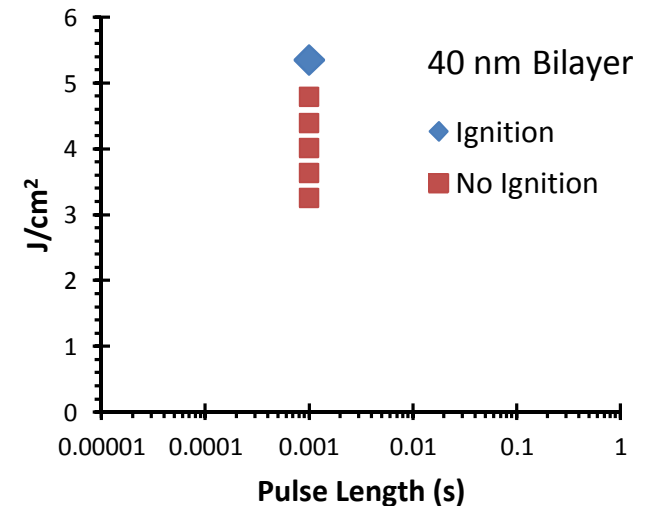
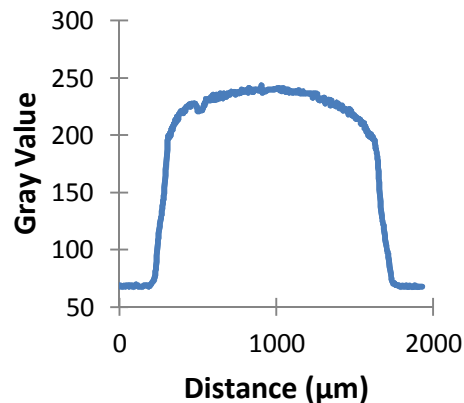
- Laser energy is increased until foil ignites.
- Non-irradiated region of sample is used for each test.



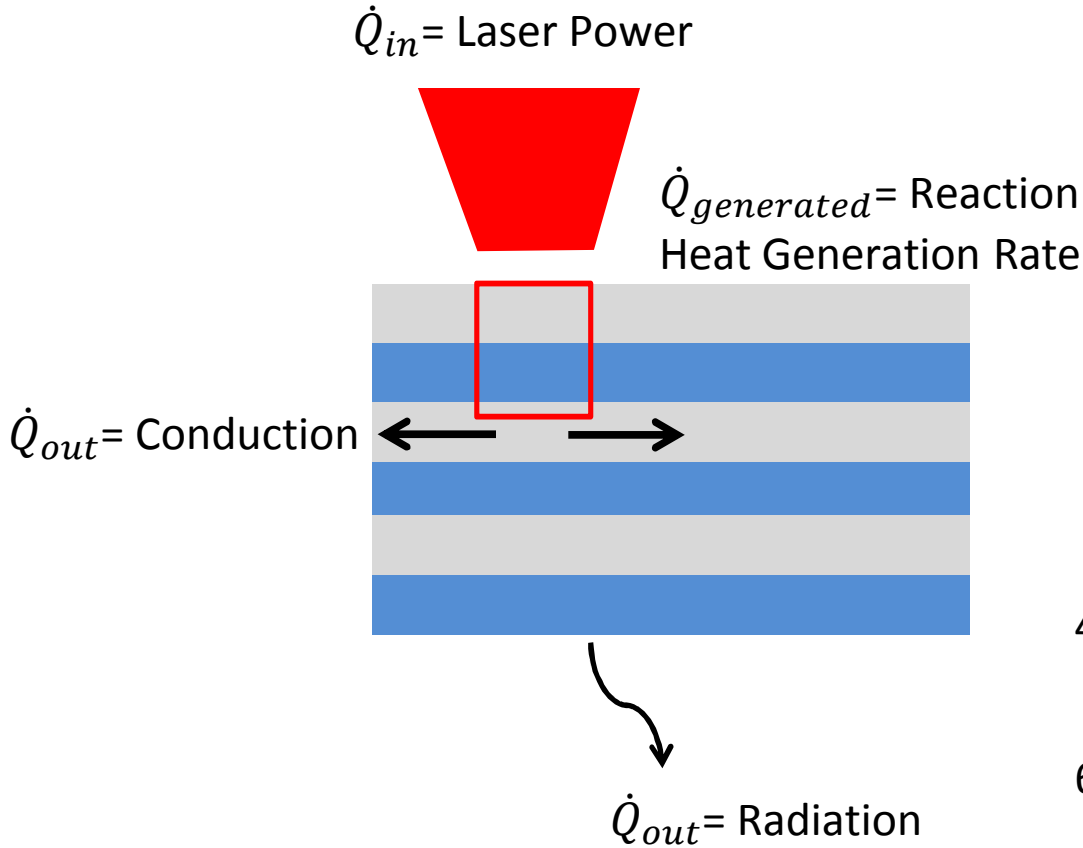
Focused Beam



Beam Profile



# Heat Flow and Interaction Volume

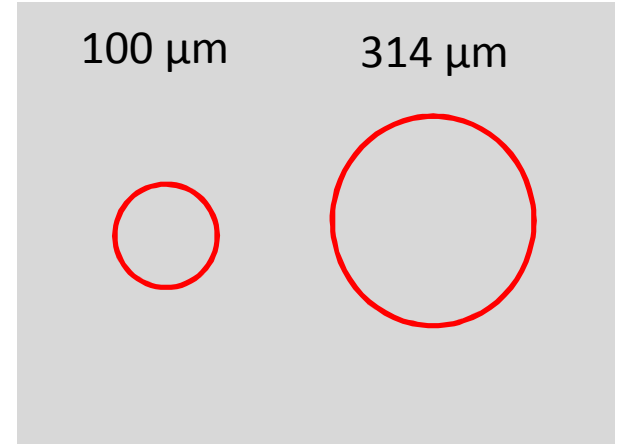


Change interaction volume

Laser Spot Size

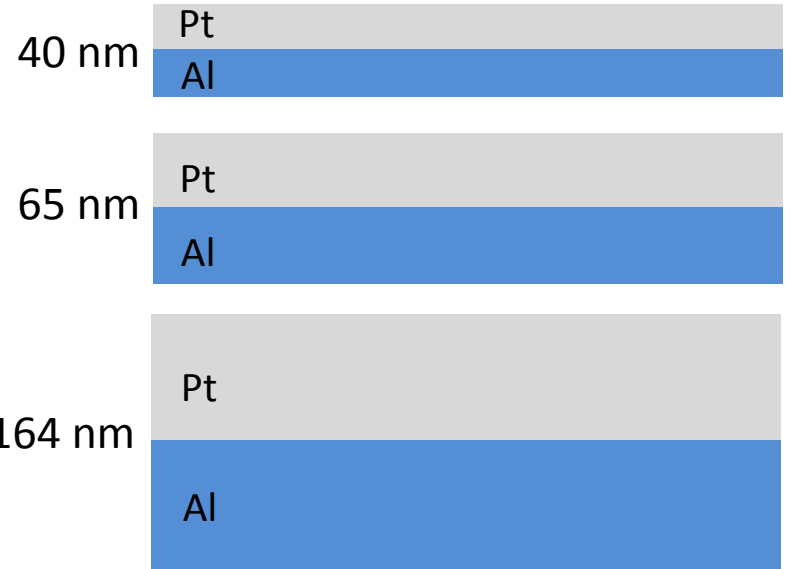
100  $\mu\text{m}$

314  $\mu\text{m}$



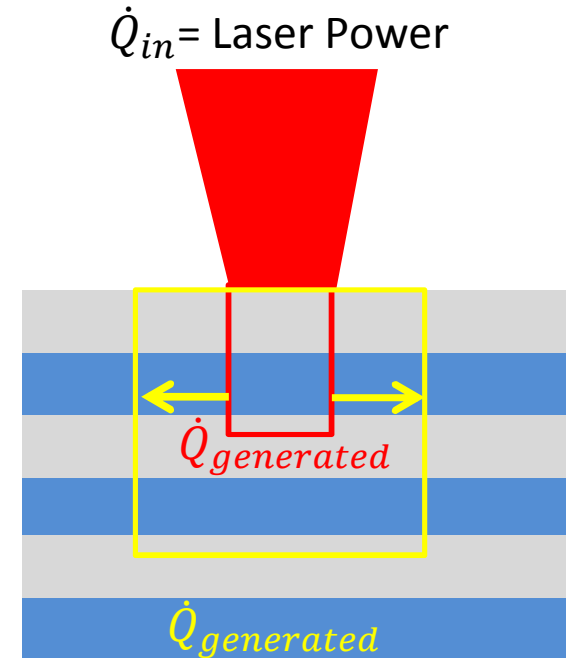
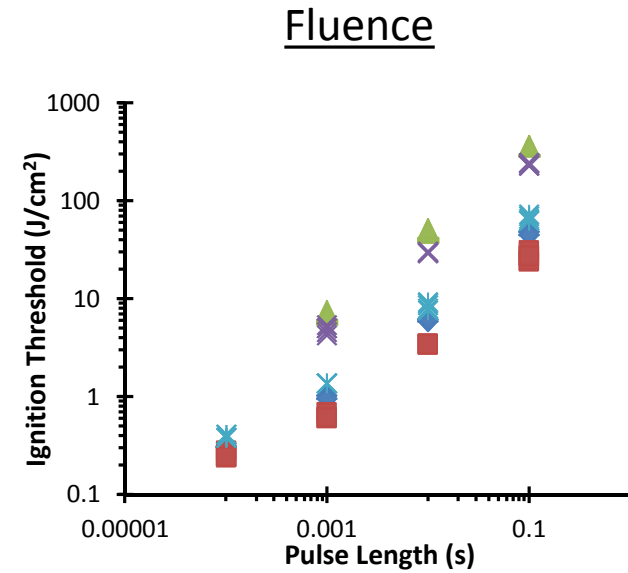
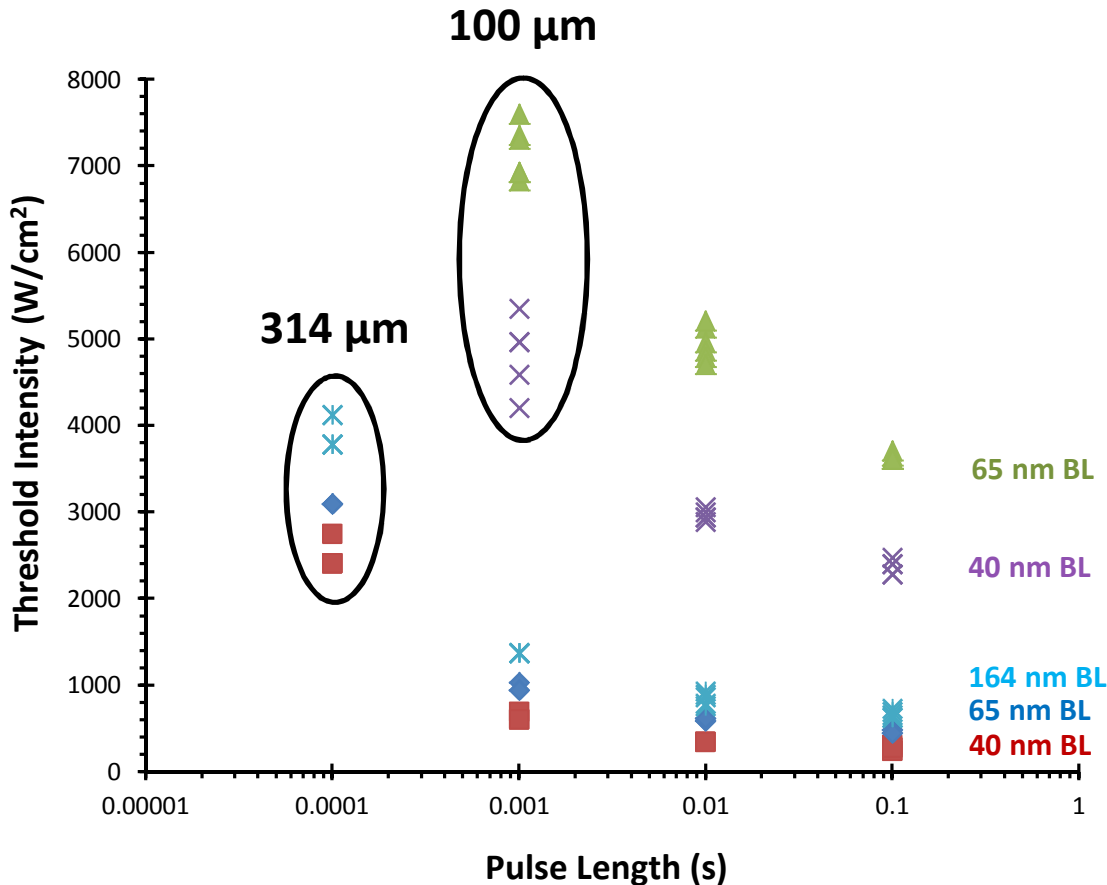
Total thickness = 1.6  $\mu\text{m}$

Bilayer Thickness



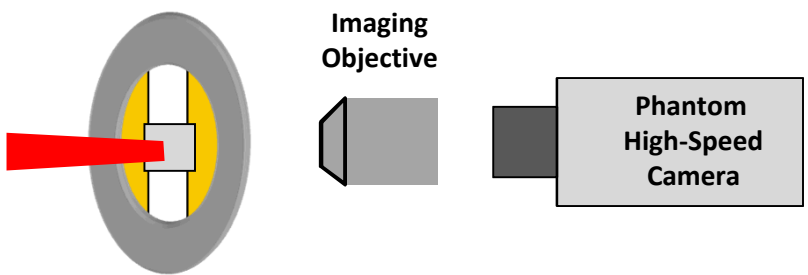
# Intensity Threshold

- Intensity ( $\text{W}/\text{cm}^2$ ) 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

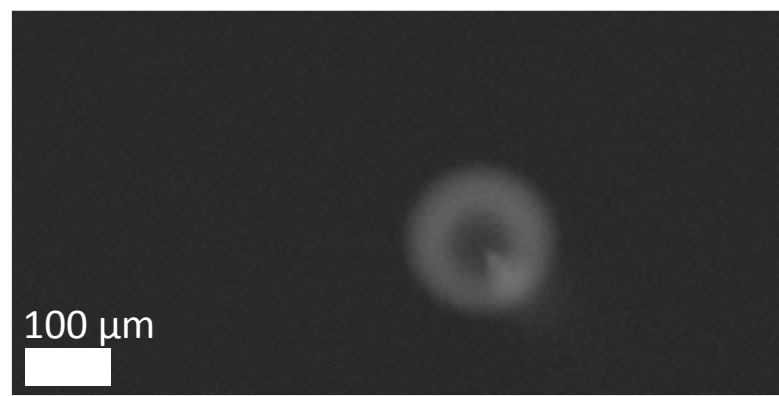


10 ms Incident Pulse  
65 nm Bilayer  
619 W/cm<sup>2</sup>

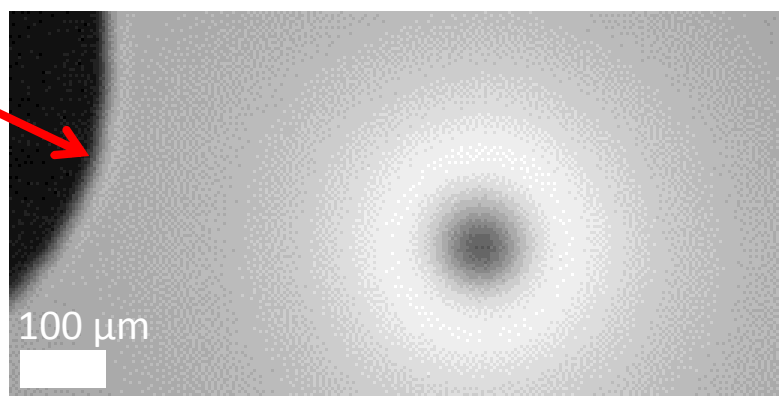
**t = 0 ms** Laser Turns On



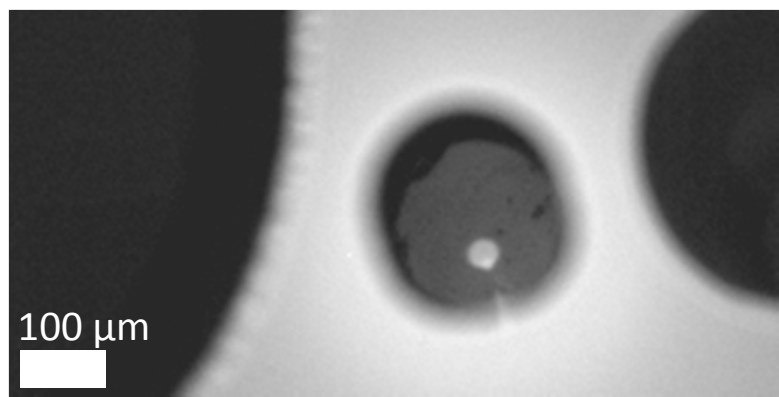
**t = 2.88 ms** Foil Ignites



**t = 2.89 ms** Entire Foil Melts

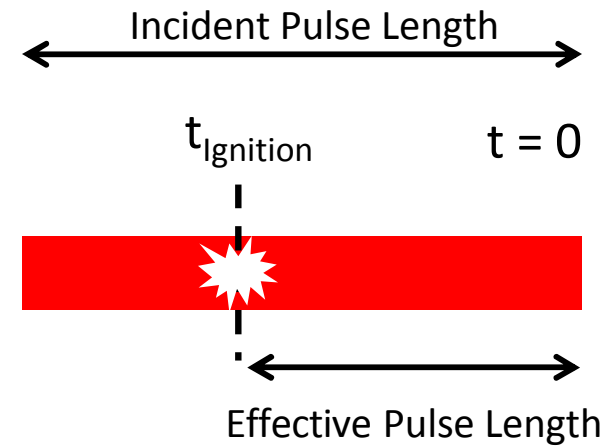


**t = 2.91 ms** Laser Penetrates Foil

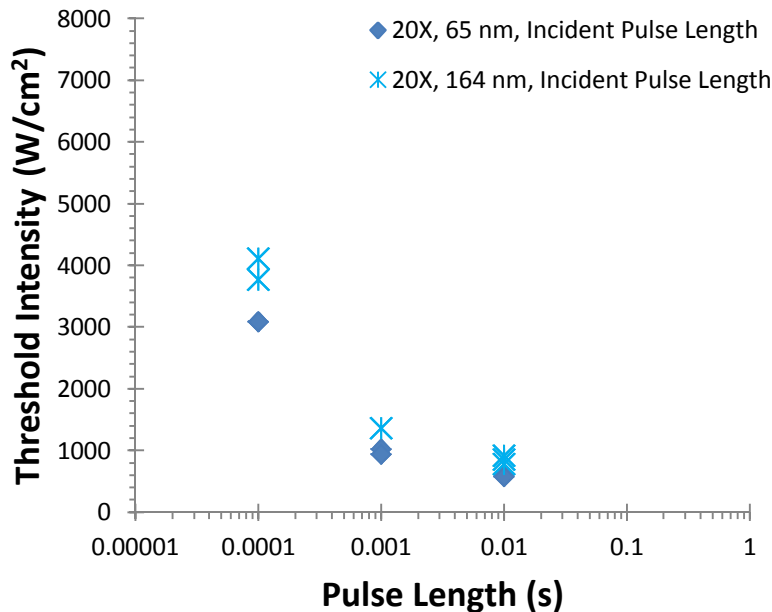


# Laser-Foil Interaction Time

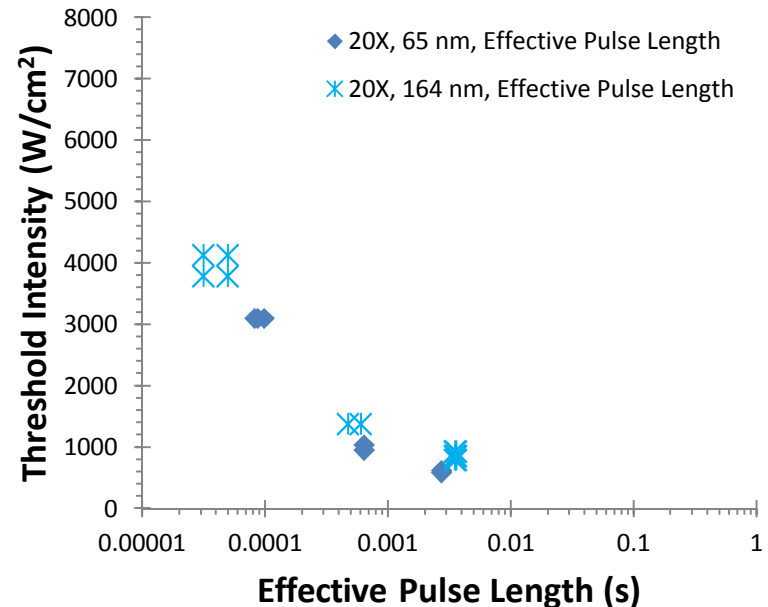
- Effective pulse length calculated by observing when ignition begins.
- Effective pulse length is usually shorter than incident pulse length.
- *Shorter pulses require energy to be delivered at a higher rate (power).*



Incident Pulse Length

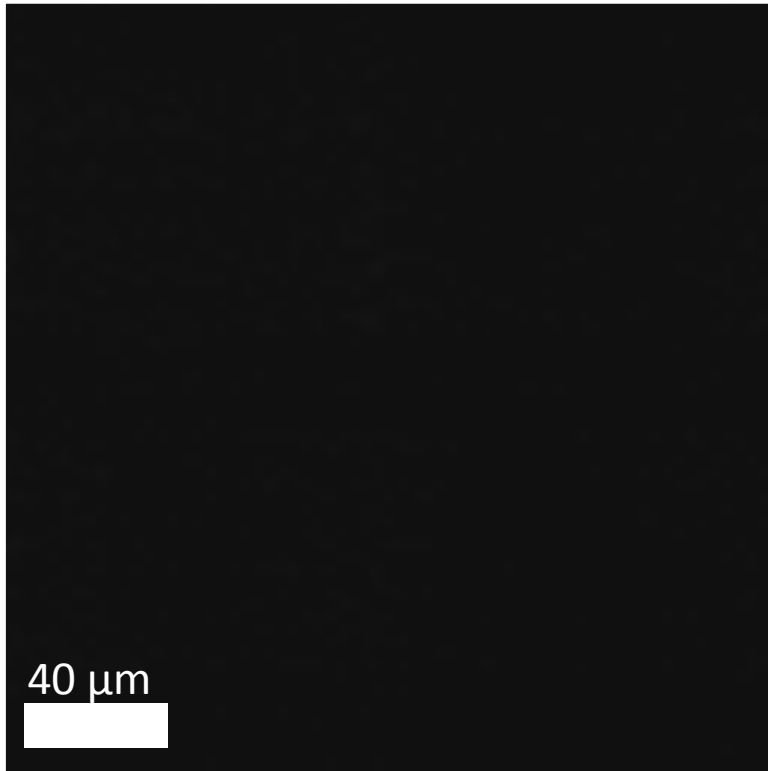


Effective Pulse Length

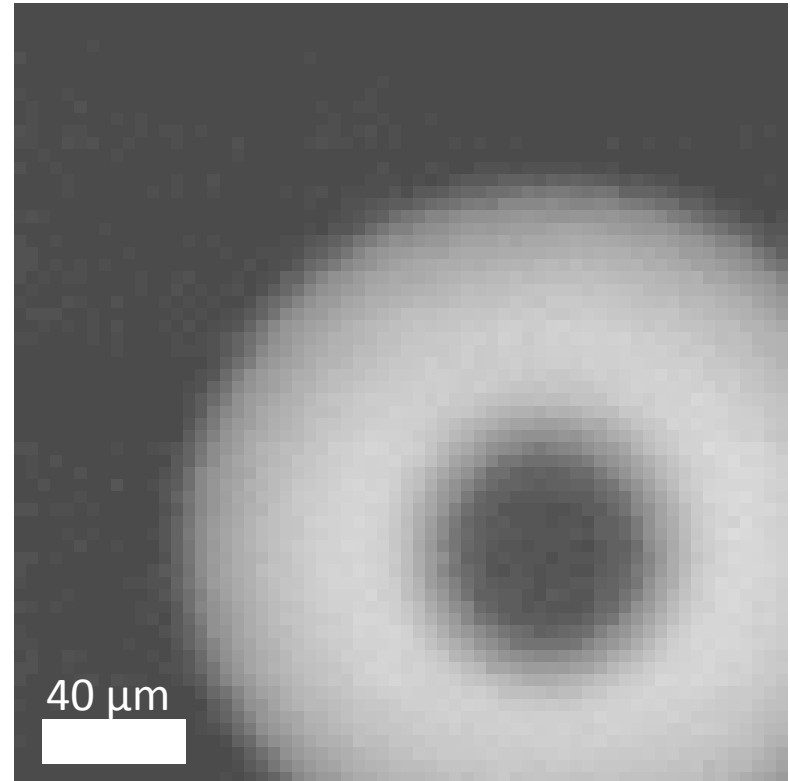


# Self-Propagating Reaction after Ignition

10 ms Incident Pulse  
164 nm Bilayer  
894 W/cm<sup>2</sup> 4 μs/frame

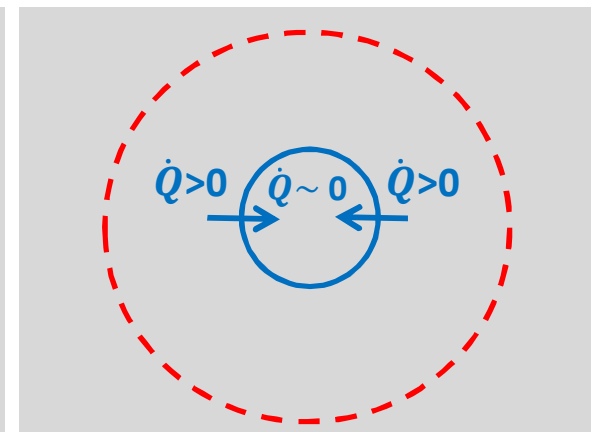
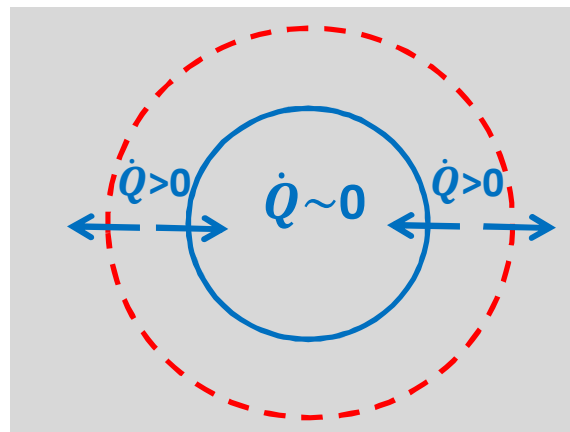
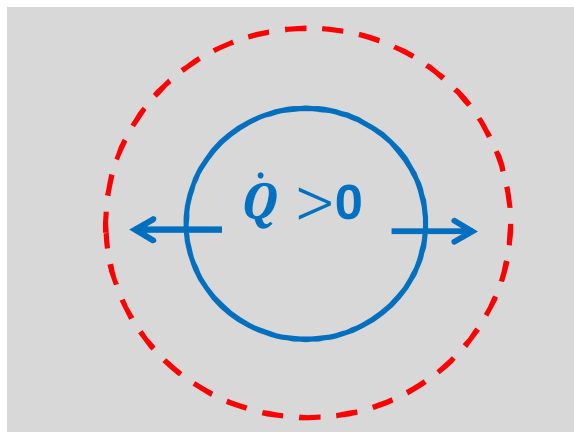
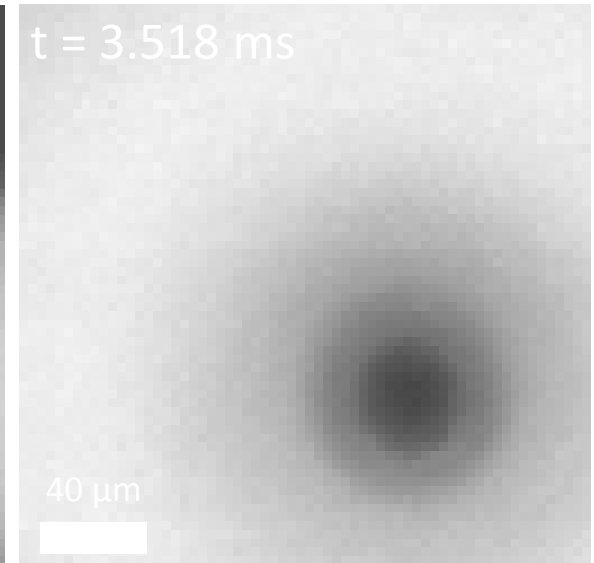
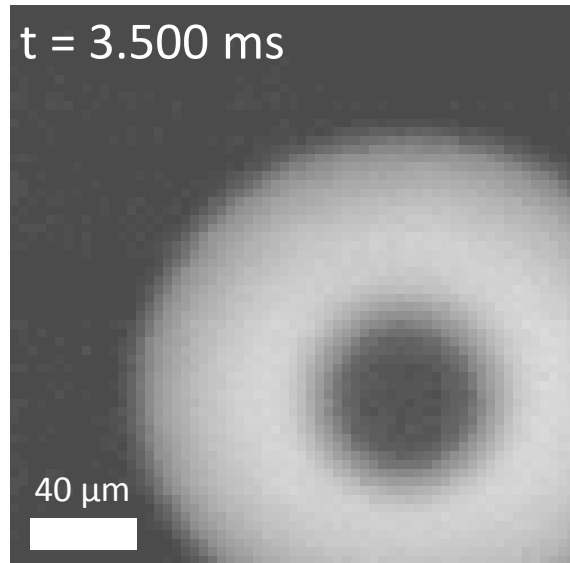
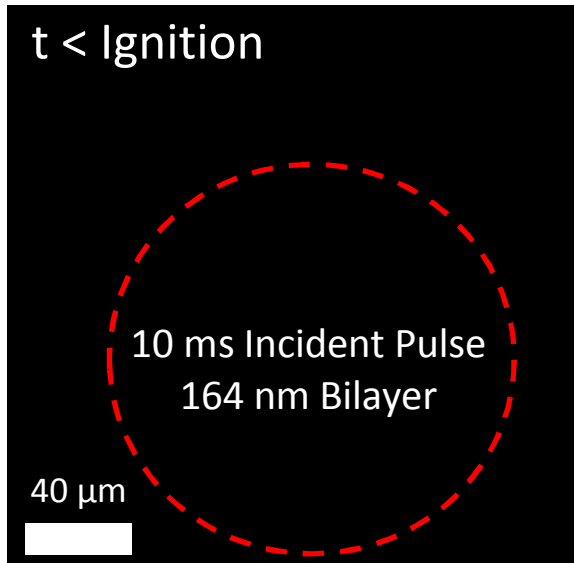


Ignition ~ 3.500 ms after laser turn on



# 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.



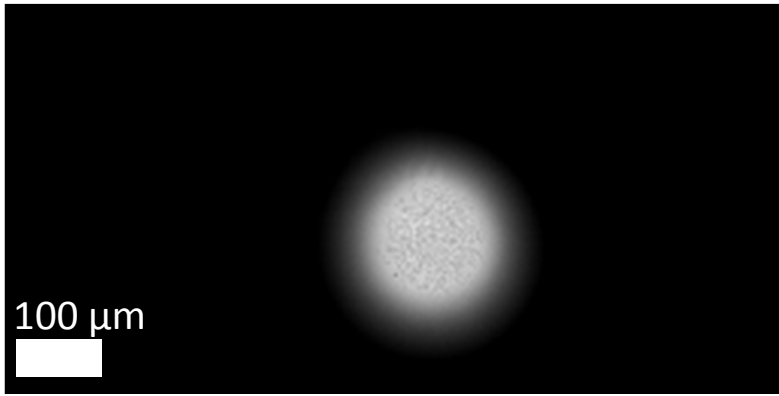
# Shorter Pulses – Mechanisms Change

## 100 $\mu\text{s}$ Pulse

- Ignition occurs – no annulus observed.
- Solid-state reaction is minimized.
- Mechanisms are *intensity* dependent

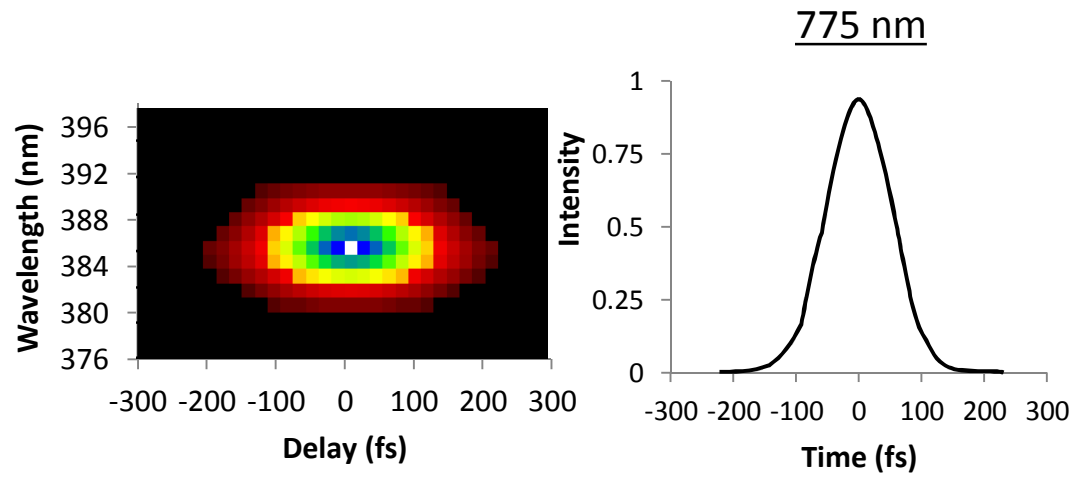
100  $\mu\text{s}$  Incident Pulse  
164 nm Bilayer  
3.8 kW/cm<sup>2</sup>

**t = 49  $\mu\text{s}$**

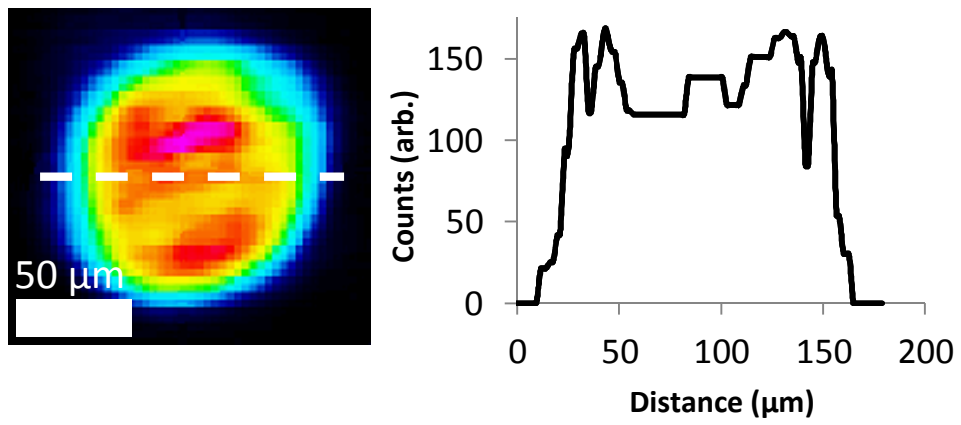


## 150 fs Pulse

- Measured pulse *temporal* distribution is Gaussian.
- “Flat-top” *spatial* distribution.

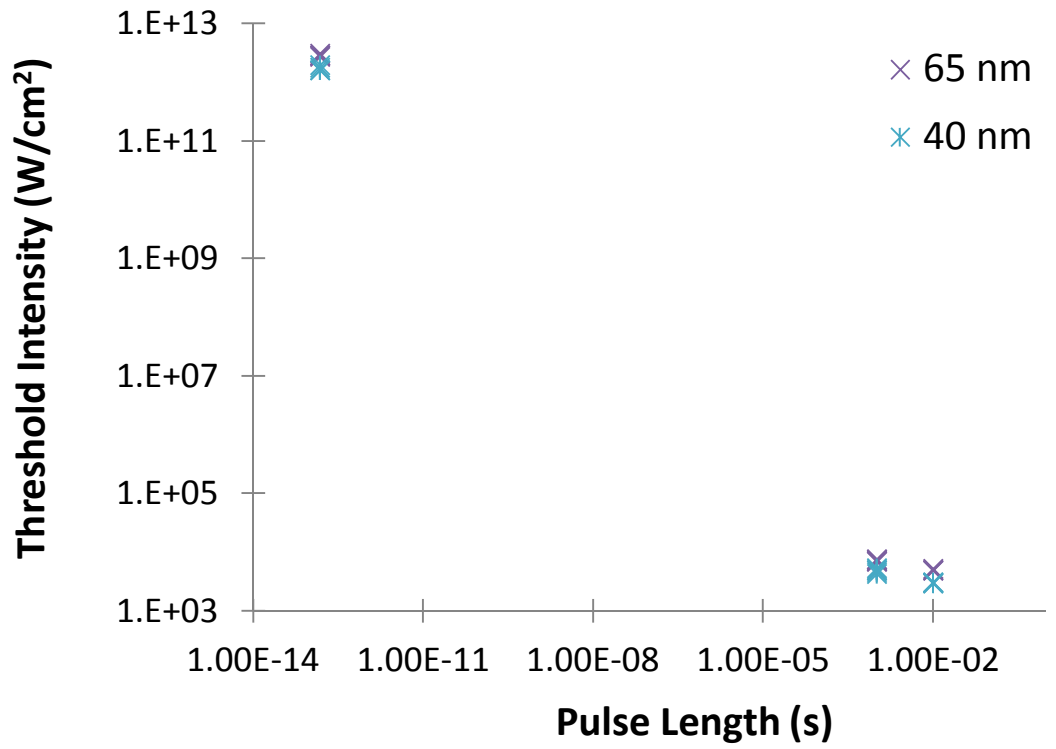
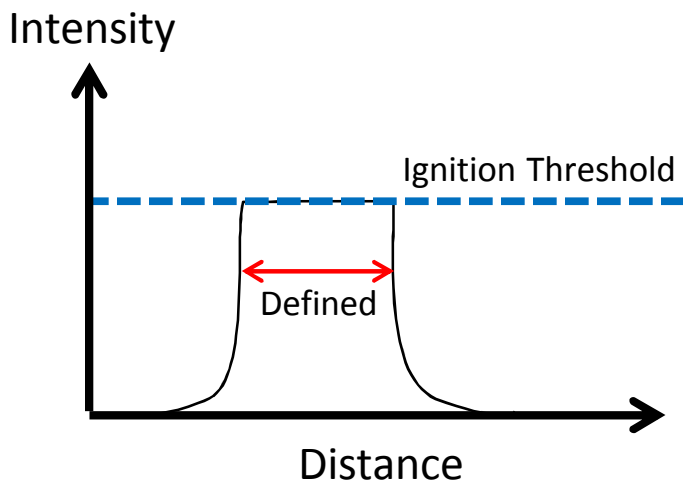
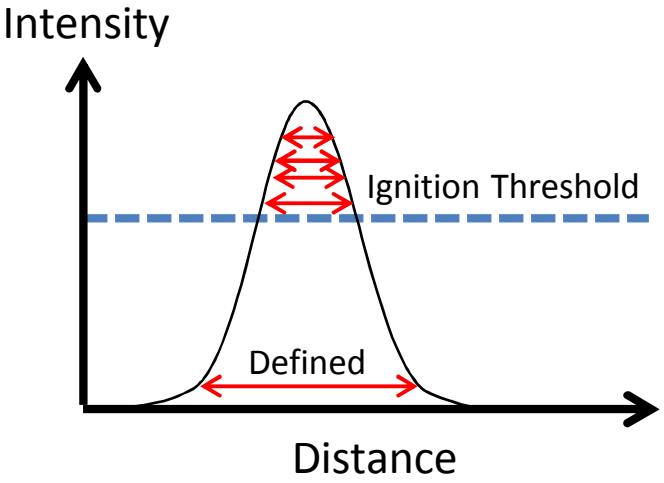


~ 30% Intensity Variation



# Ignition Threshold

- Flat-top beam is used for all pulse lengths.
- For 150 fs pulses, mechanism changes from solid-state ignition to laser-induced melting.

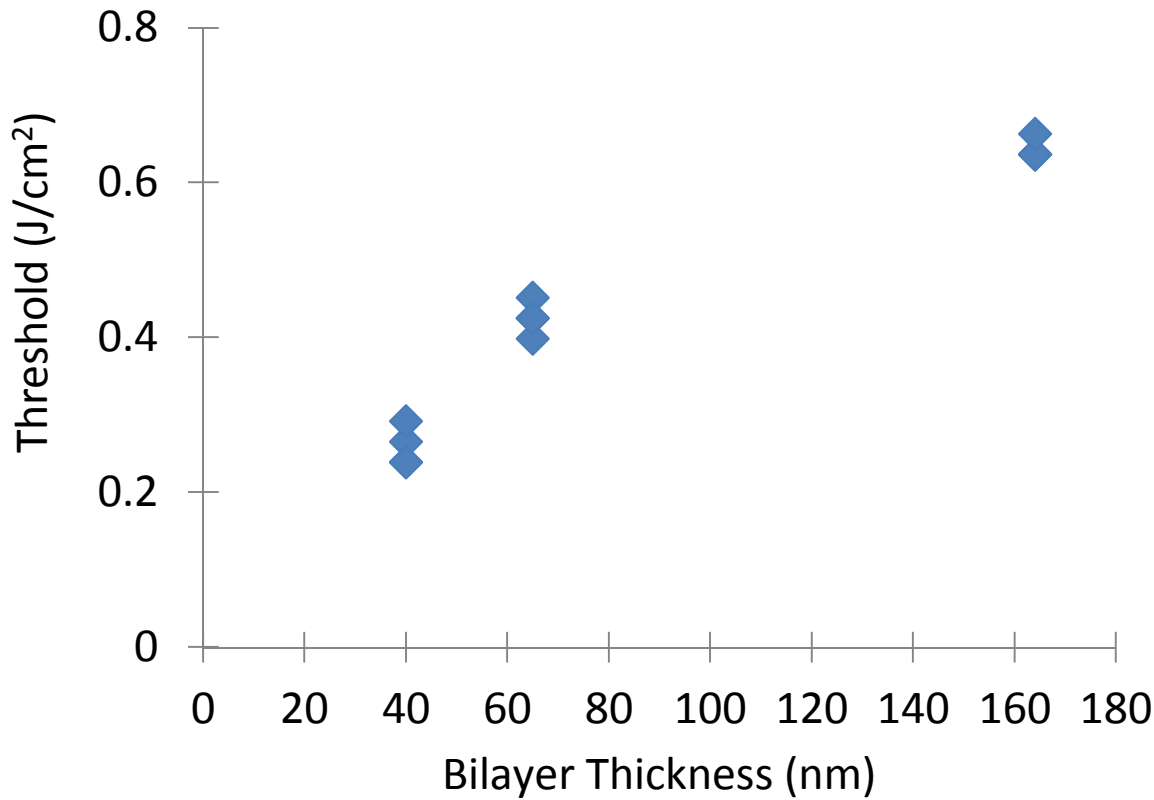
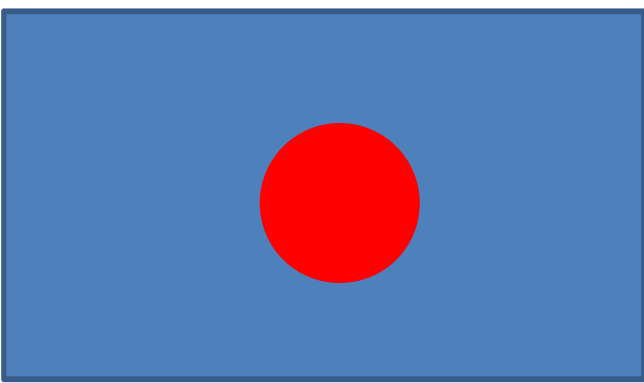
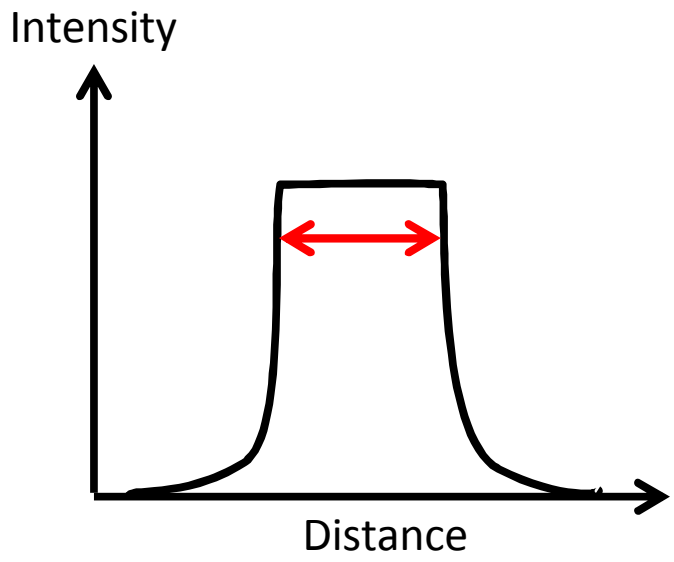


# Conclusions

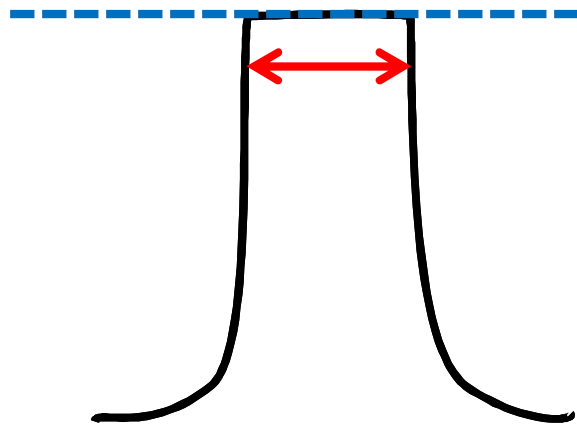
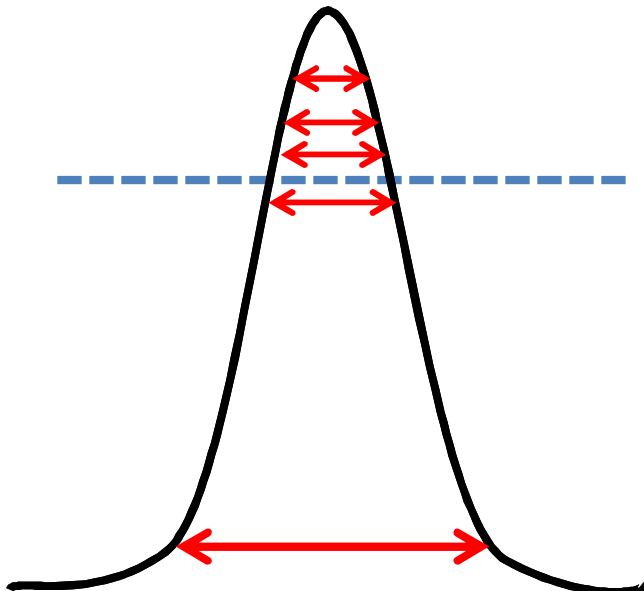
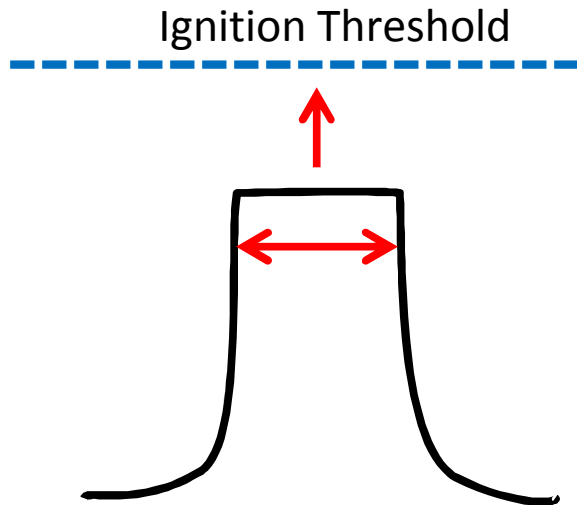
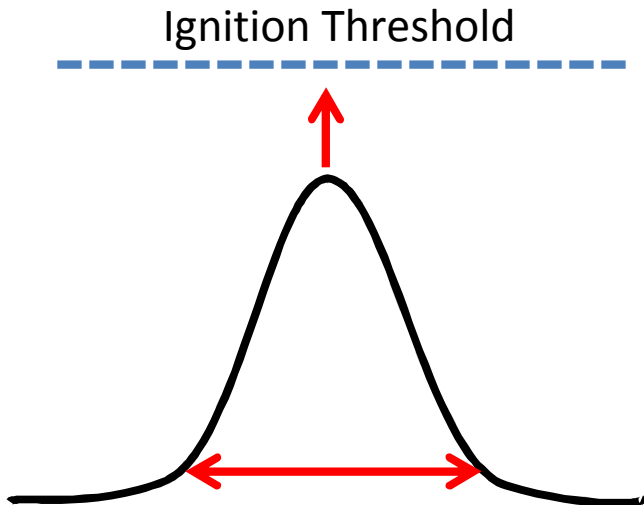
- Reactive foils are ignited using single laser pulses.
- Laser pulse lengths ranging from femtoseconds to milliseconds can ignite foils.
- Laser ignition threshold depends on pulse duration, laser spot size, and foil bilayer thickness.
- Increasing laser spot size and decreasing bilayer thickness increases 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**

# 150 fs Ignition Threshold



# Fixed Interaction Volume



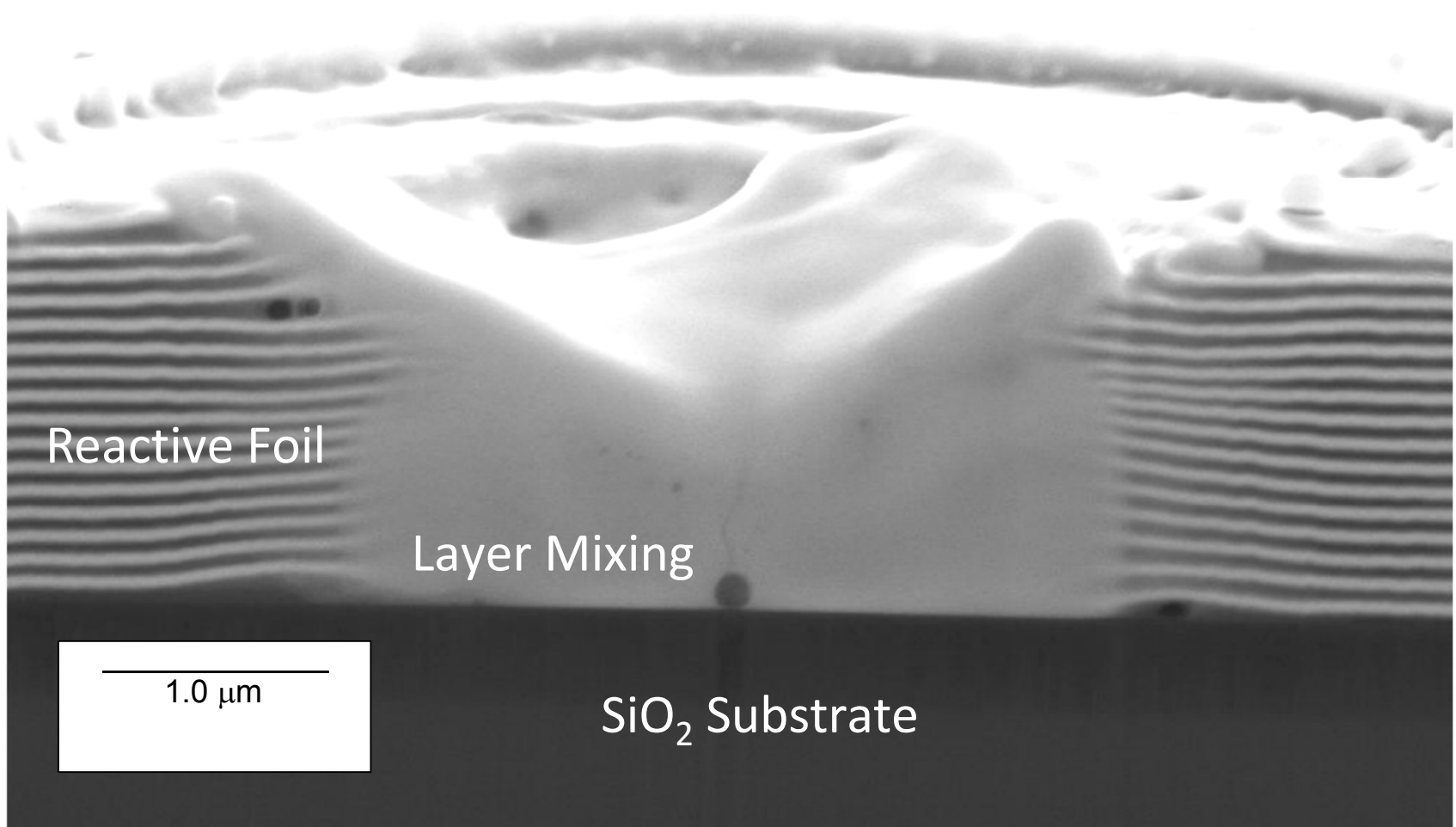
# Laser Irradiation

Al/Pt Irradiated at 80% ignition threshold

100 fs pulse



SEM Cross-section



Reactive Foil

Layer Mixing

SiO<sub>2</sub> Substrate

1.0 μm

# Effective Pulse Length Depends on Intensity

1 ms Incident Pulse  
65 nm Bilayer

<b>% Above Threshold</b>	<b>Effective Pulse Length (ms)</b>
0	0.892
49	0.440
100	0.300

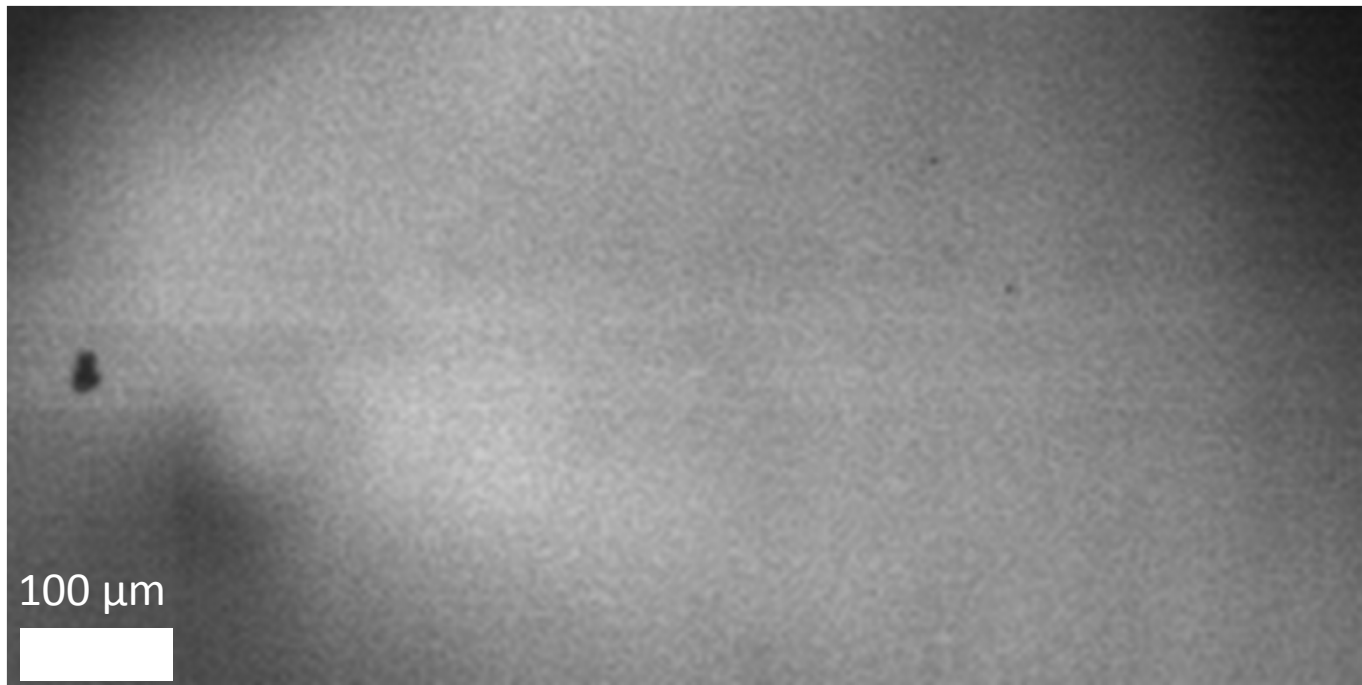
# Sub-threshold Irradiation

## 95% Ignition Threshold

2.94 ms Incident Pulse

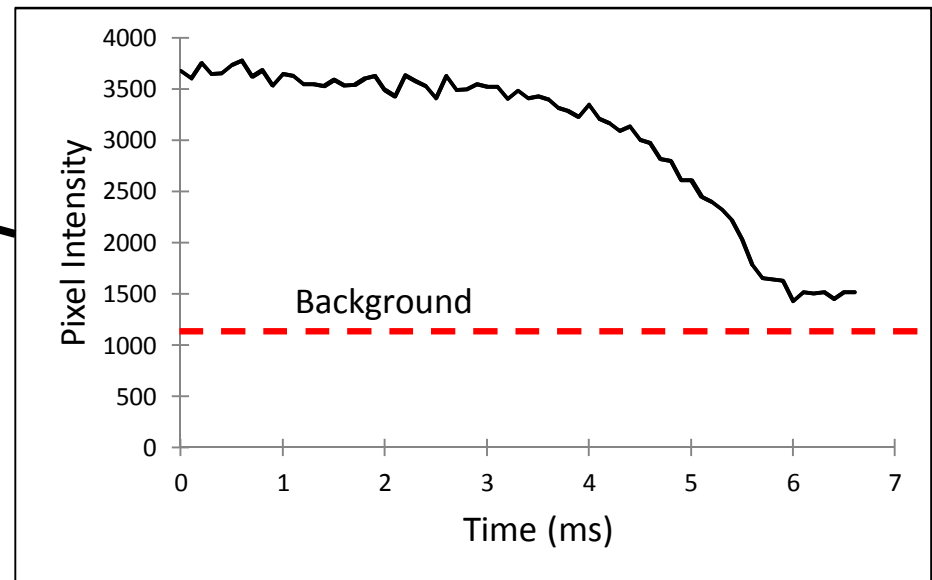
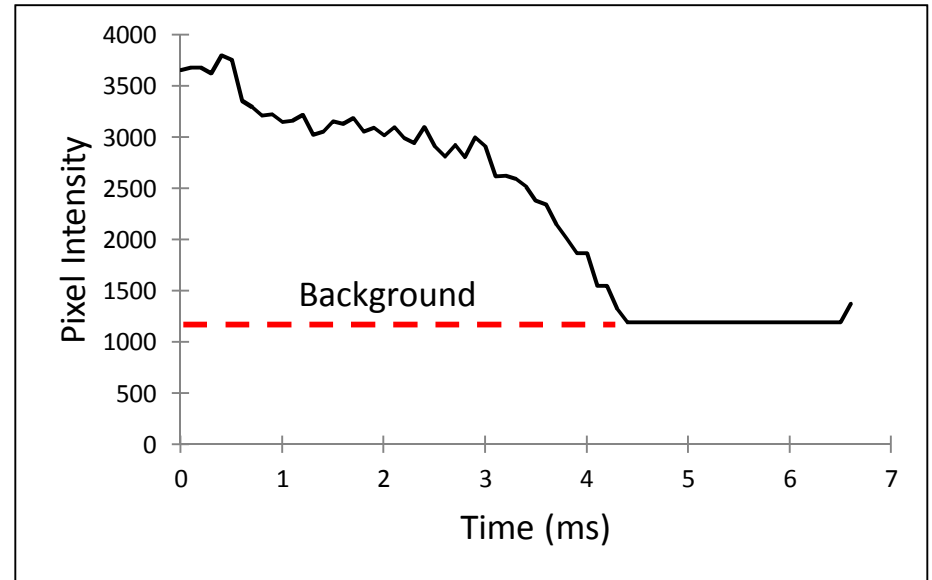
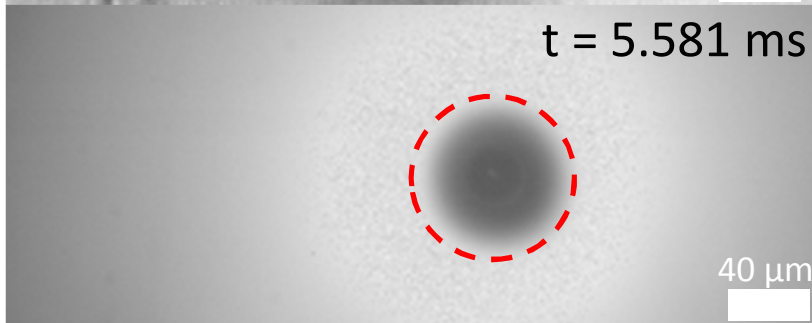
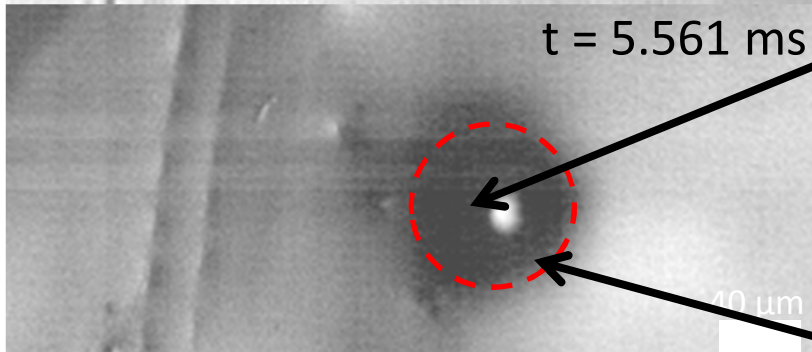
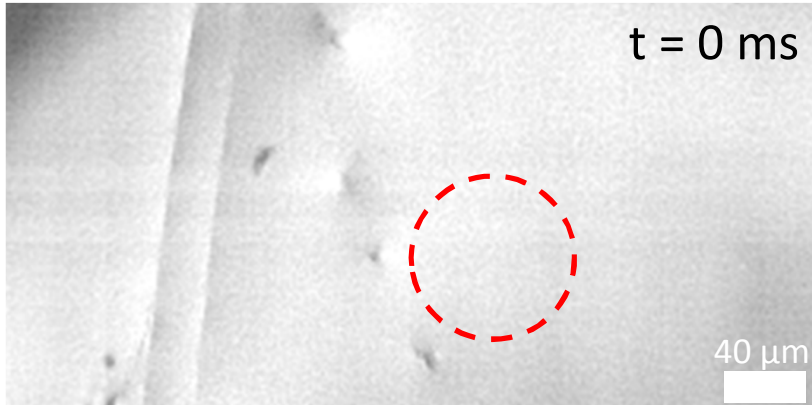
65 nm Bilayer

10  $\mu$ s/frame



# Reflectance Measurements

10 ms Incident Pulse  
65 nm Bilayer



# Diffusion Zone Size Depends on Pulse Length

## 65 nm Bilayer

Incident Pulse Length (ms)	Diffusion Zone Diameter ( $\mu\text{m}$ )
0.1, 9 mW	18
0.1, 9 mW	18
1, 9 mW	42
1, 4.5 mW	44
1, 5.5 mW	28
1, 5.5 mW	22
10, 36 mW	73
10, 36 mW	36
10, 36 mW	44

## 164 nm Bilayer

Incident Pulse Length (ms)	Diffusion Zone Diameter ( $\mu\text{m}$ )
0.1, 12 mW	0
0.1, 12 mW	0
1, 8 mW	18
1, 8 mW	22
10, 52 mW	49
10, 52 mW	52

# Ignition and Melting

10 ms Incident Pulse  
65 nm Bilayer  
36 mW

~ 2.60 ms after laser turns on



~ 2.61 ms after laser turns on

