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Detonation in Deposited Explosives Near the Critical Thickness

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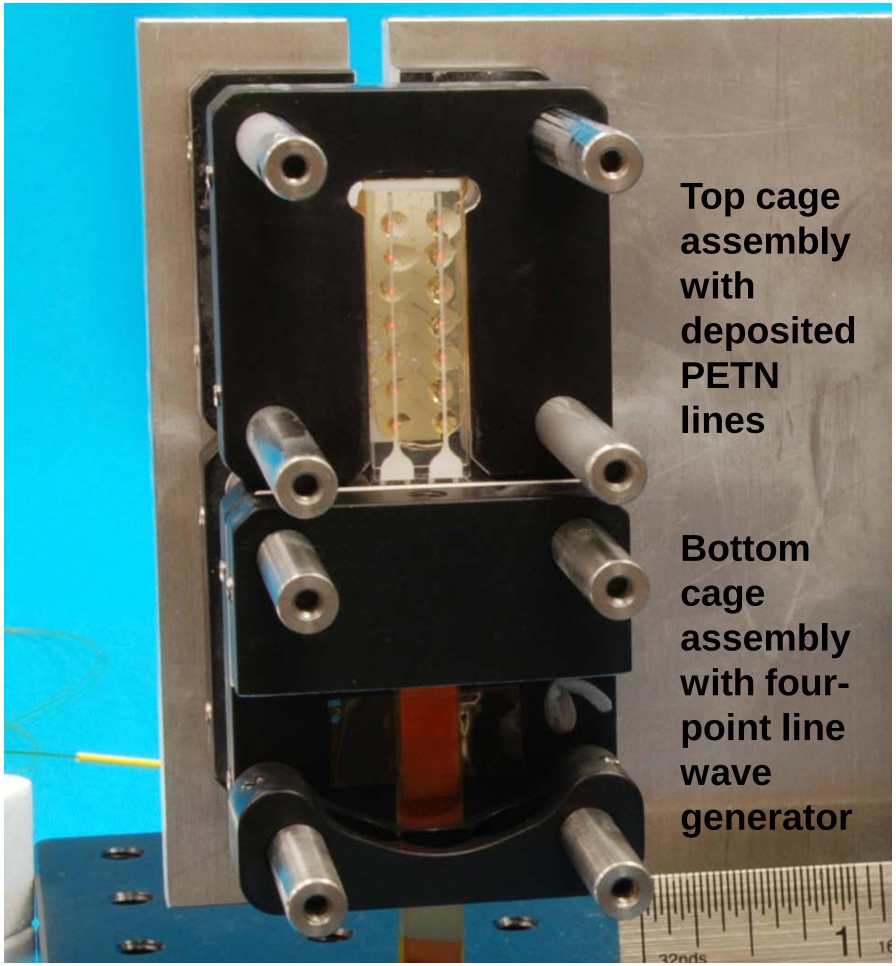
Approach

- Thin PETN samples made by physical vapor deposition
- Detonation velocity measured for different geometries by streak camera and optical fiber probe technique
- Critical thickness determined using traditional critical diameter form



Photograph of experiment used to measure detonation velocity.

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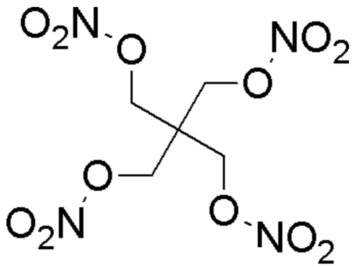
Introduction

- **Data for small-scale explosive behavior of high-density PETN do not exist**
  - **Difficult to prepare small-scale samples**
  - **Low-density PETN data exist (ca. 50% TMD)**
  - **High-density PETN data exist only for PBX with 20% binder**
    - **Critical diameter of 0.222 mm (polycarbonate confinement)**



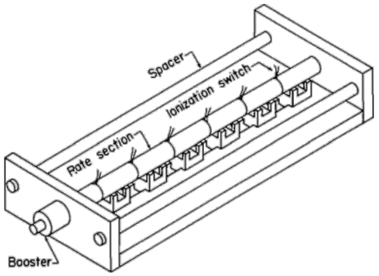
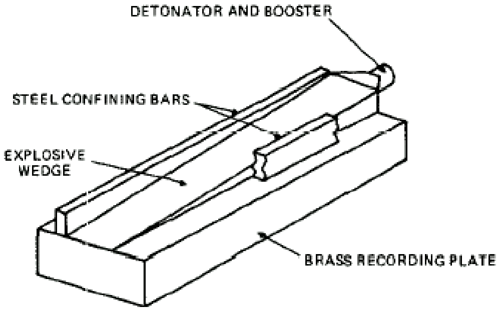


Fig. 1. Schematic of a typical rate-stick assembly.

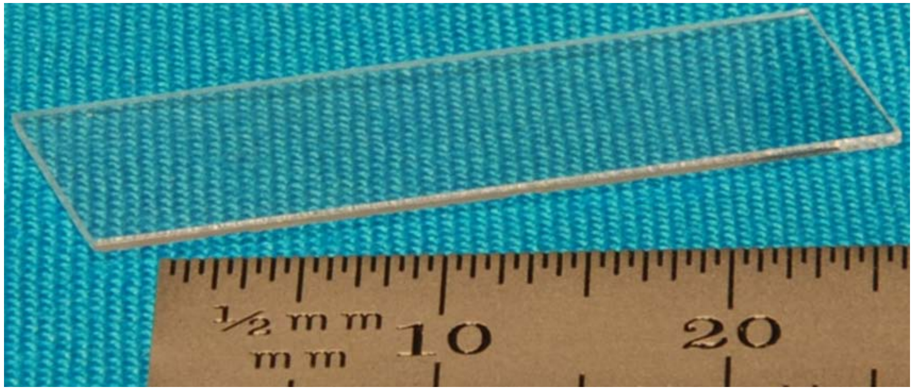


PETN ***Rate stick experiment.*** ***Detonation failure experiment.***

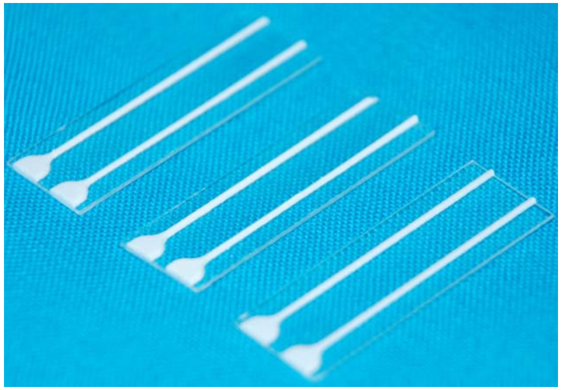
Campbell, A.W. and Engelke, R., "The Diameter Effect in High-Density Heterogeneous Explosives," *6th Symposium (International) on Detonation, Coronado, CA, August 24–27, 1976.*
Gibbs, T.R. and Popolato, A., "LASL Explosive Property Data," pp. 289–290, University of California Press, Berkeley, Los Angeles, London, 1980.

Physical Vapor Deposition Can Be Used to Make Small-Scale PETN Samples

- **Physical vapor deposition is used to sublime/evaporate PETN from a hot source onto a cool substrate**
- **Substrates are 0.5   10.0   30.0 mm fused silica**
- **Shadow masks are used to pattern lines of different widths**
  - **0.40, 0.60, 0.80, 1.00, 1.50, and 2.00 mm**
- **Deposition times control thicknesses (0.13–0.53 μm)**



Photograph of bare substrate prior to deposition.



Photograph of deposited PETN films.

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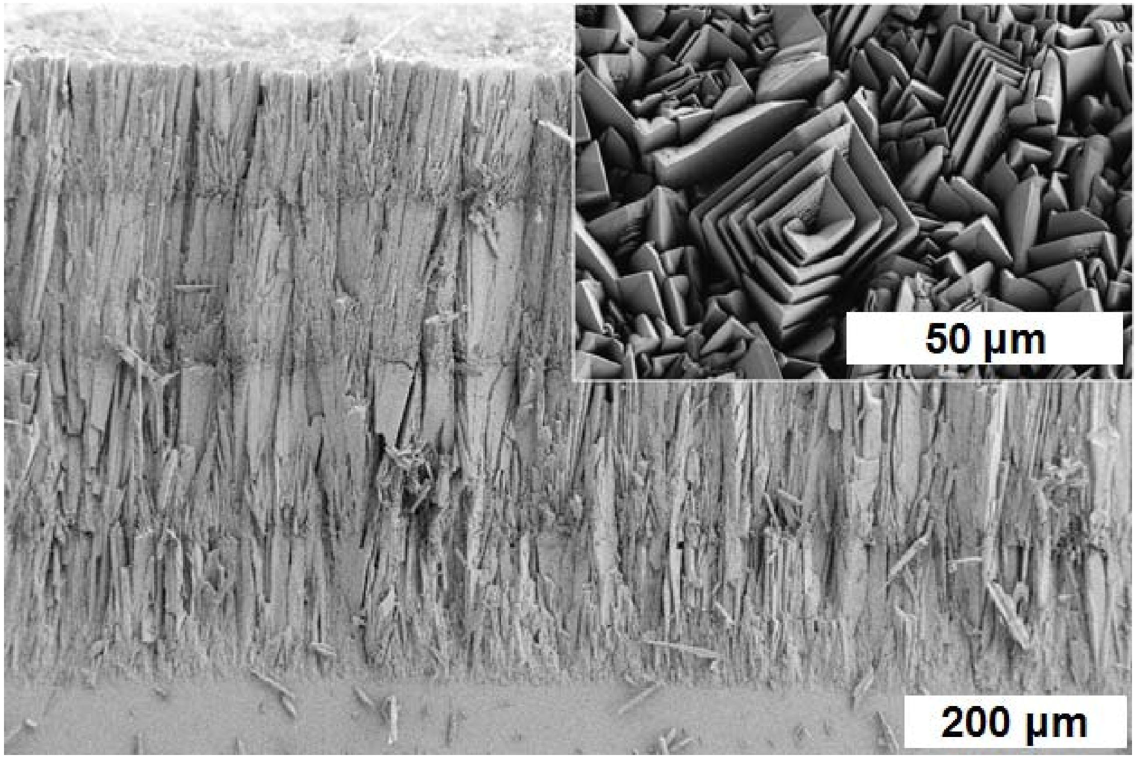
PETN Films Have High Density and Fine Grain Structure

- $1.41-1.50\ g\ cm^{-3}$ (79−84% theoretical maximum density (TMD) of $1.778\ g\ cm^{-3}$)
- Density gradient through thickness – densest at substrate
- Columnar grains of PETN elongated in the direction of film growth

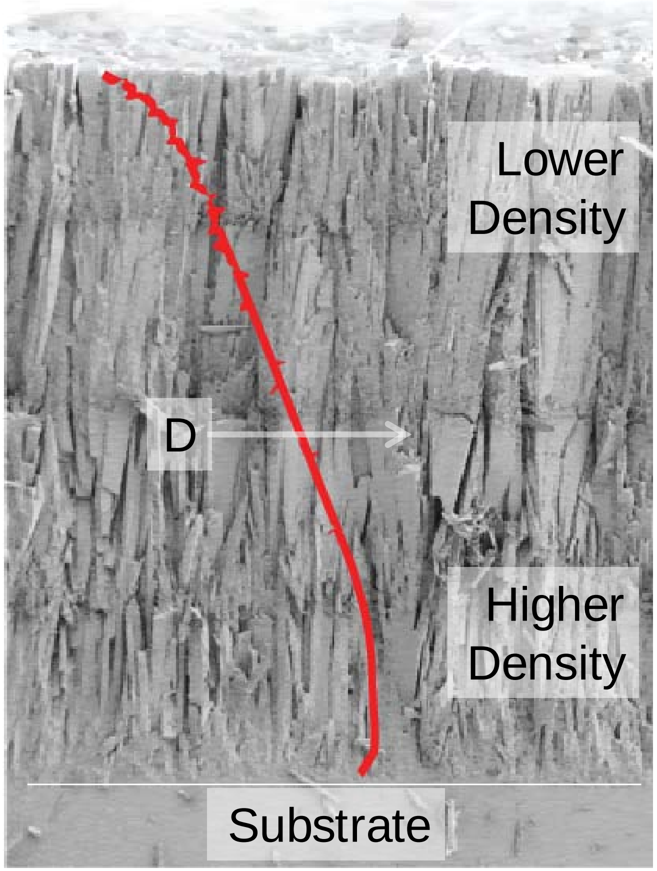


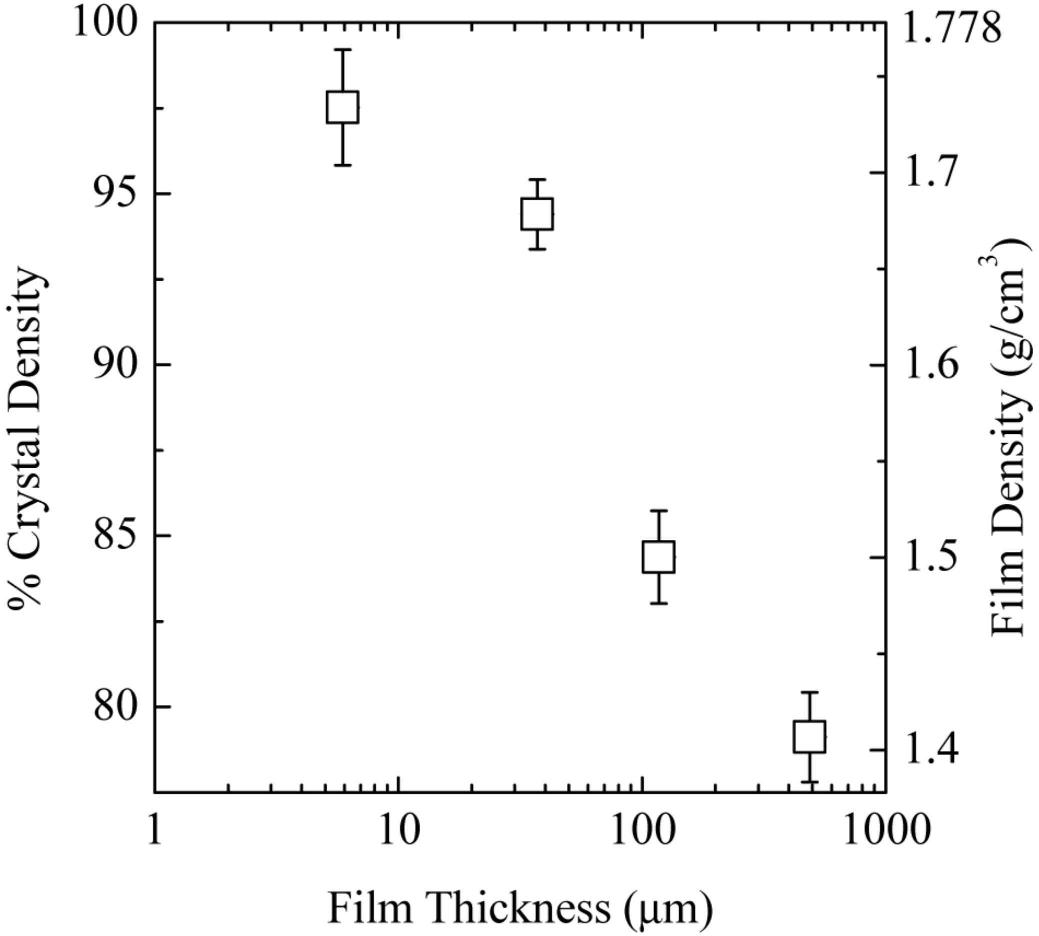
Scanning electron micrograph of fractured PETN film on fused silica. Inset shows top surface of deposited film.

Knepper, R., Tappan, A.S., and Wixom, R.R., "Controlling the Microstructure of Vapor-Deposited Pentaerythritol Tetranitrate (PETN) Films," *14th International Detonation Symposium, Coeur d'Alene, ID, April 11–16, 2010.*

Density Decreases with Increasing Film Thickness

- Density of deposited PETN at substrate interface is very high
- Self-shadowing as film grows results in voids





Density of deposited PETN film versus film thickness.

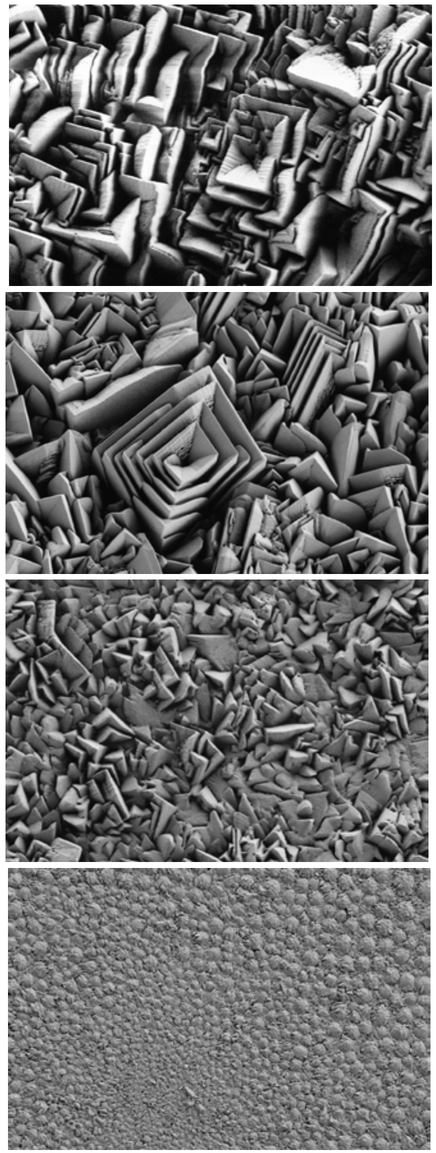
PETN Surface Roughness Evolution

488 µm

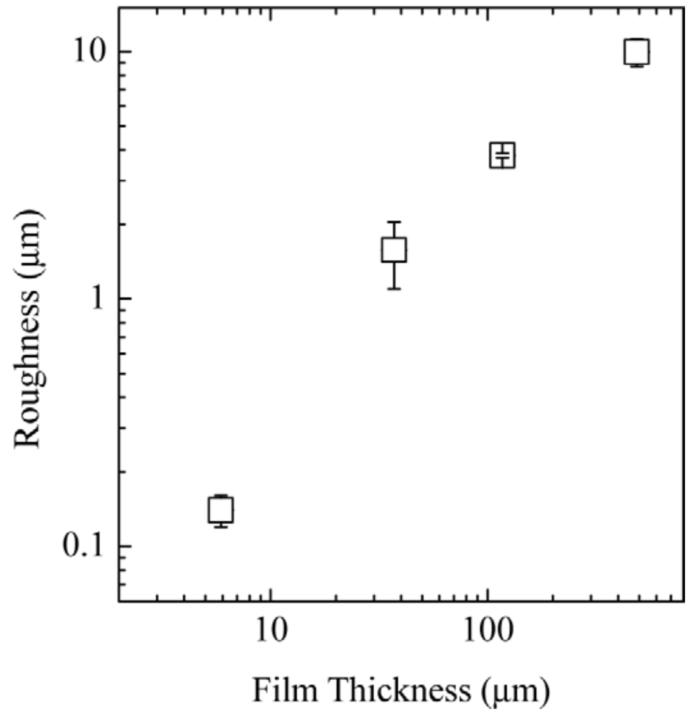
117 µm

37 µm

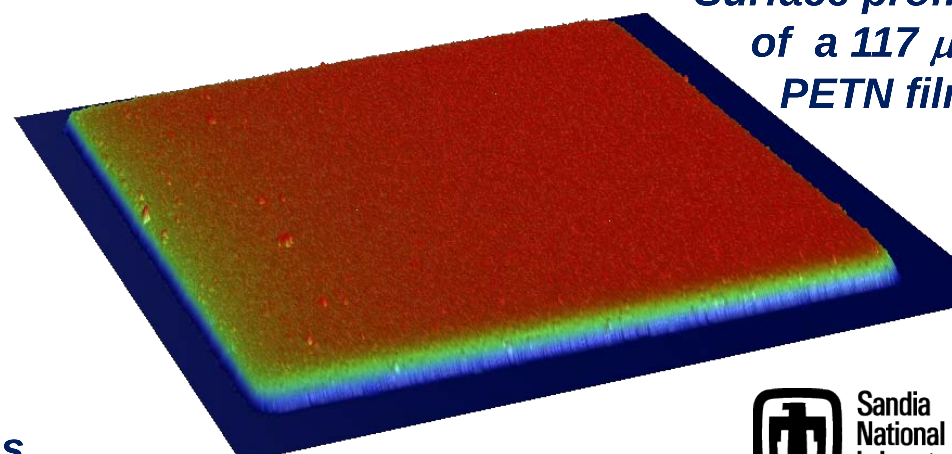
6 µm



SEMs of different film thicknesses.



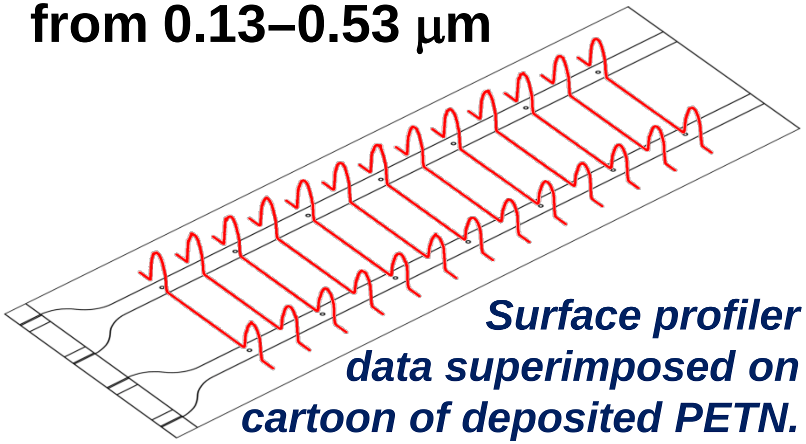
Surface roughness increases according to a power law with increasing film thickness.



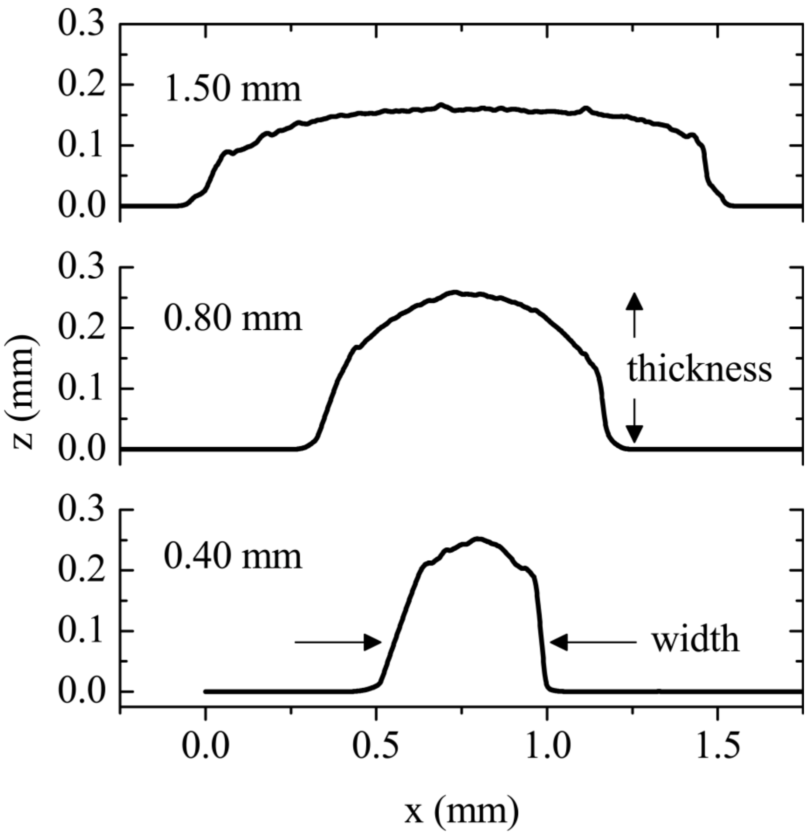
Surface profile of a 117 µm PETN film.

Surface Profiler Measurements

- **Stylus surface profiler used for measurement**
- **Center 100 μm of scan defined as film thickness**
- **Each line thickness reported as average of 13 scans across film**
- **Film thicknesses varied from 0.13–0.53 μm**



Surface profiler data superimposed on cartoon of deposited PETN.



Surface profiler single line scans of 0.40, 0.80, and 1.50 mm wide vapor-deposited PETN films.

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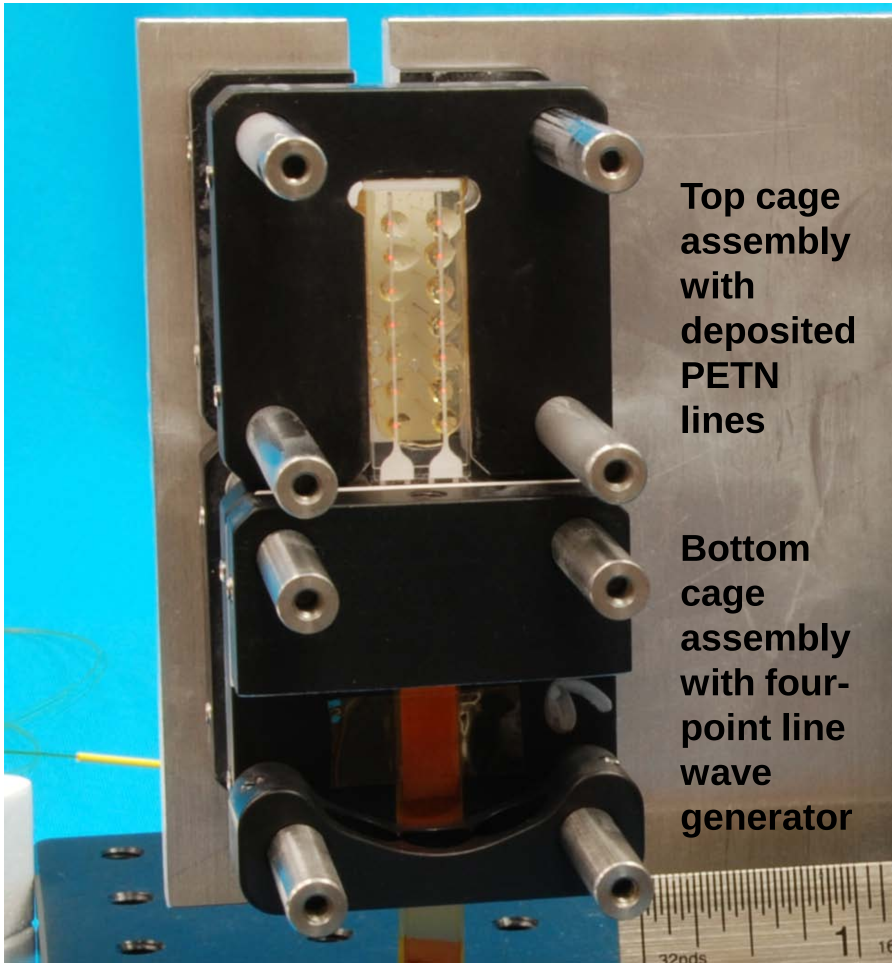
Detonation Velocity Measurement Experiment

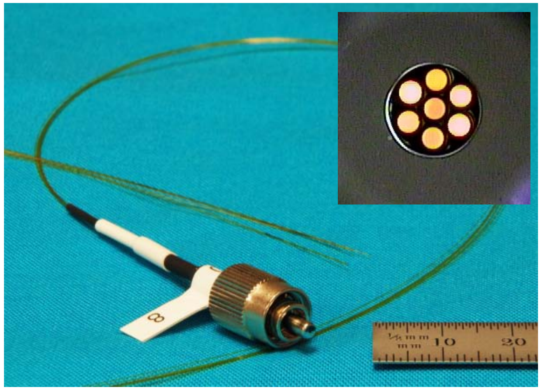
- Detonation in deposited PETN lines is achieved by a four-point line wave generator
- Up to two experiments are conducted at once
- Cage assembly accommodates different PETN line thicknesses
- PETN confined within fused silica and epoxy



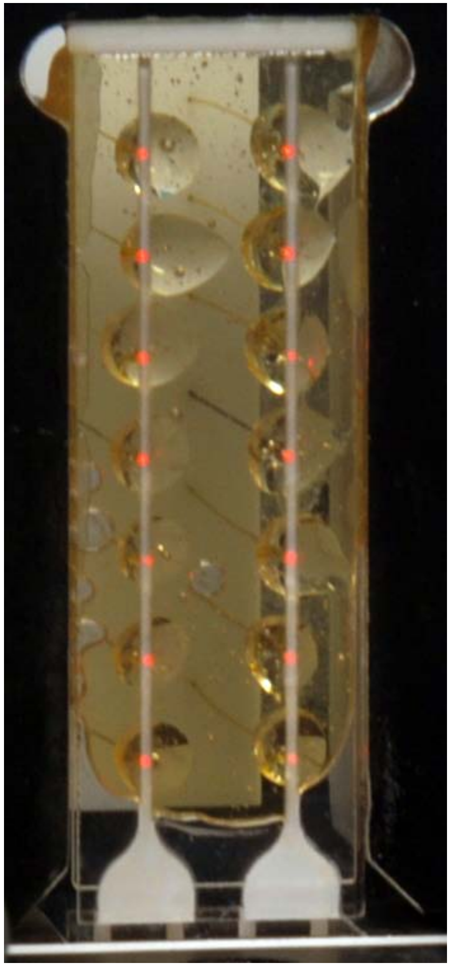
Photograph of experiment used to measure detonation velocity.

Optical Fiber Probe Is Used to Measure Detonation Velocity

- **Optical fiber probe consists of seven 100 μm core silica fibers terminated in a six-around-one connector**
- **Optical fibers inserted through laser-machined holes in fused silica lid and bonded with epoxy**
- **Polished or pre-cleaved at lid**
- **Data acquisition with Si photodetector**



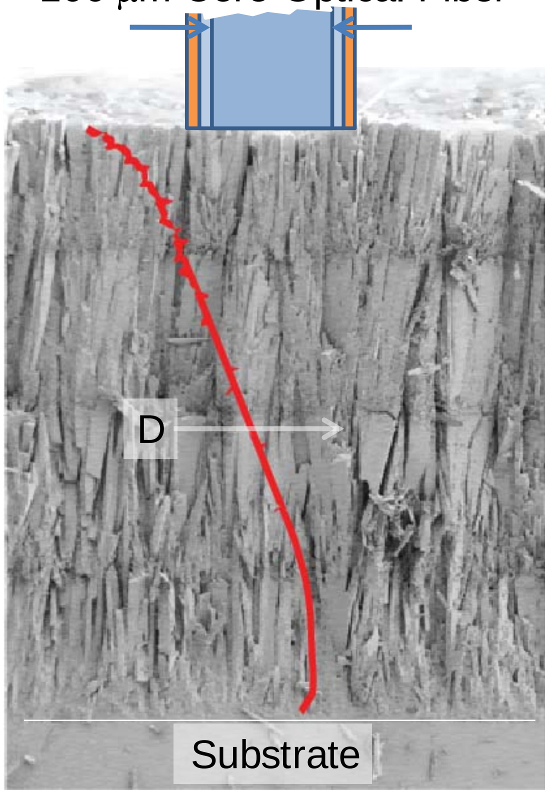
Photograph of optical fiber probe with inset showing six-around-one connector.

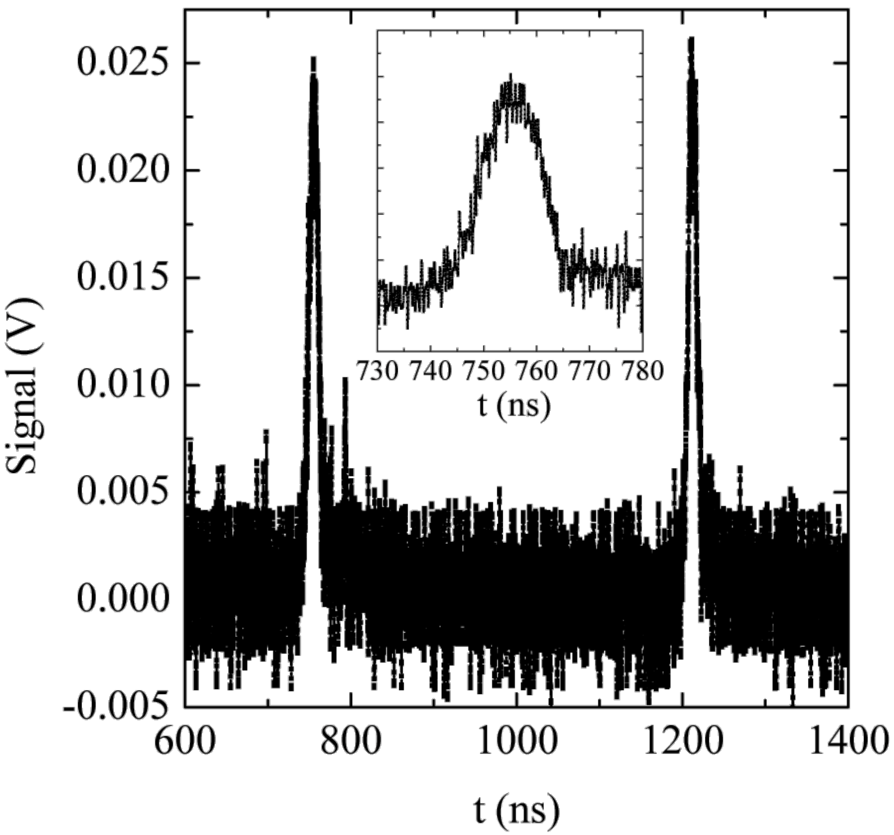


Photograph of optical fiber probe lid on deposited PETN. Optical fibers illuminated to show position.

Optical Fiber Probe Signal Has Fast Rise and Fall Times

- **Full-width-half-maximum = 13 and 11 ns for graph at right**
- **0.1 mm core / 7.5 mm/μs = 13 ns**

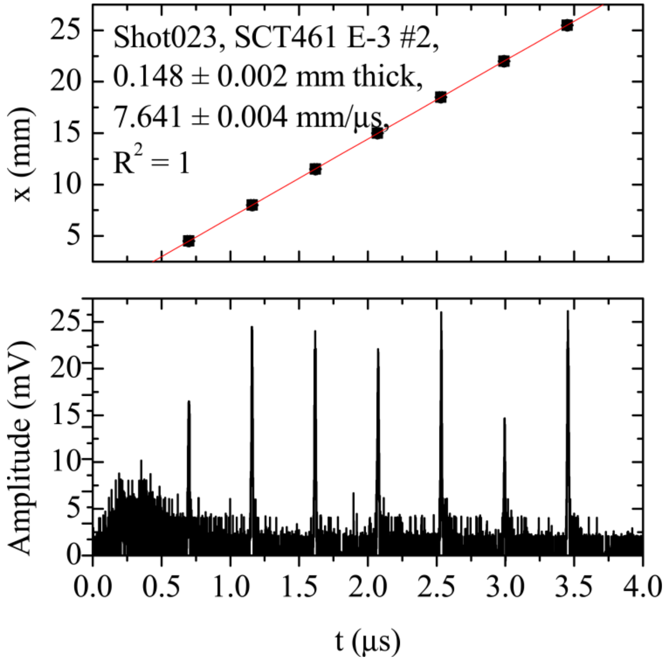


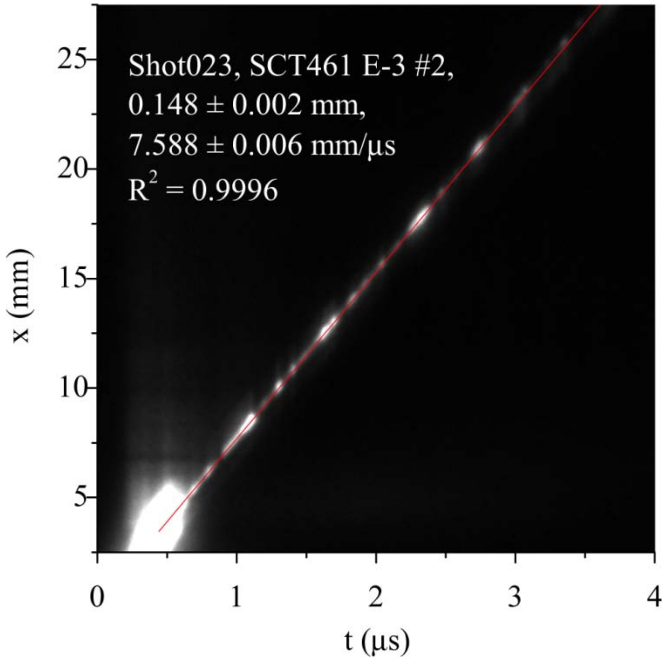


Optical signal from two of seven fibers used to measure detonation light. An expanded view of the left pulse is shown in the inset.

Optical Fiber Probe Velocity Correlates Well with Streak Camera

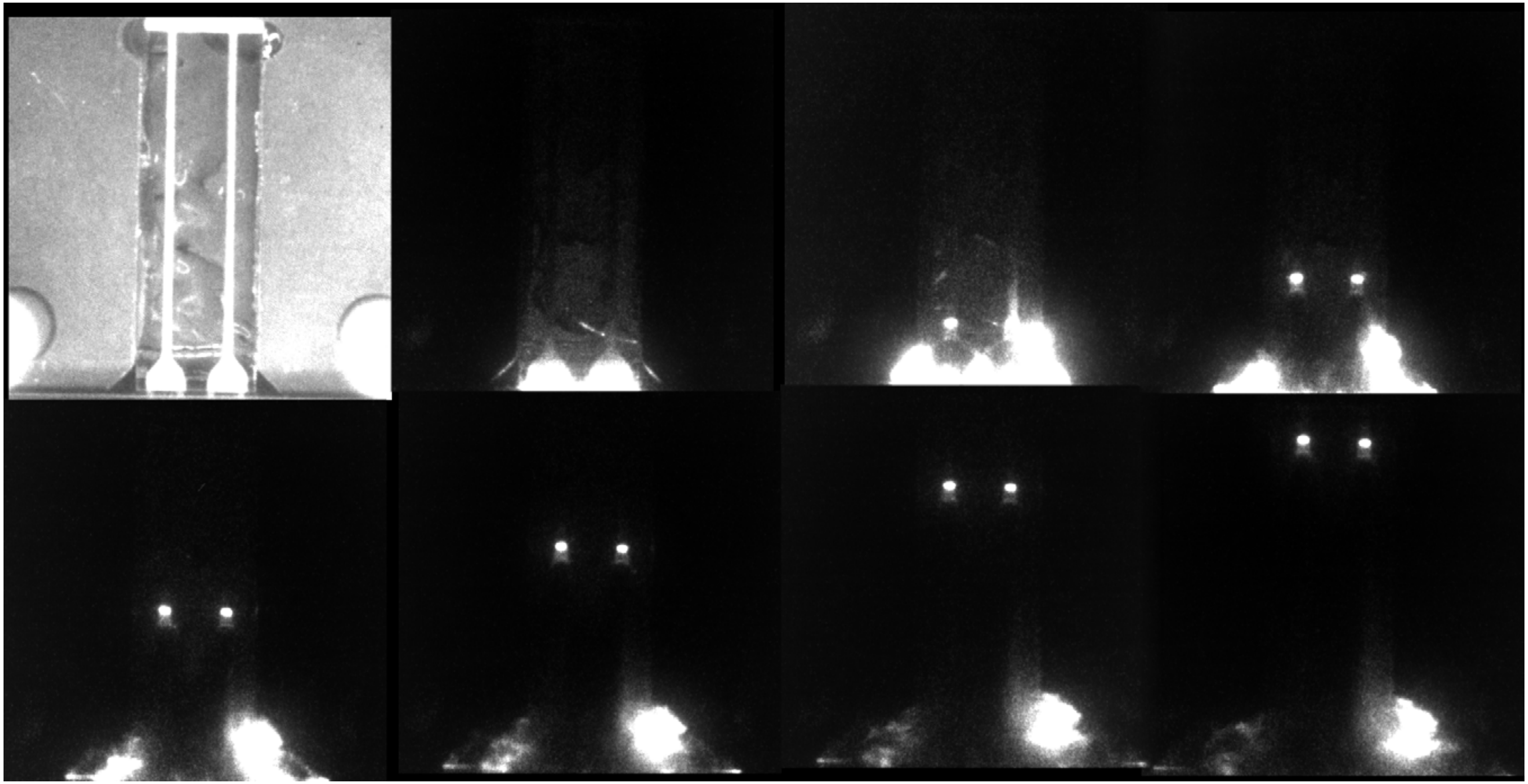
- Optical fiber probe and streak camera velocities agree to within 1% on multiple experiments
- Analysis of optical fiber probe data is less subjective
- When both are available, optical fiber data are used





Optical fiber data and streak camera data from the same experiment.

Framing Camera Used for Qualitative Detonation Information



Framing camera images of detonation in deposited PETN lines.
1.67 million frames per second (1/600 ns), 20 ns exposure time.

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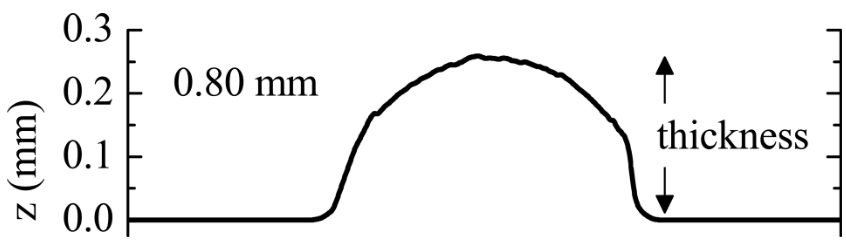
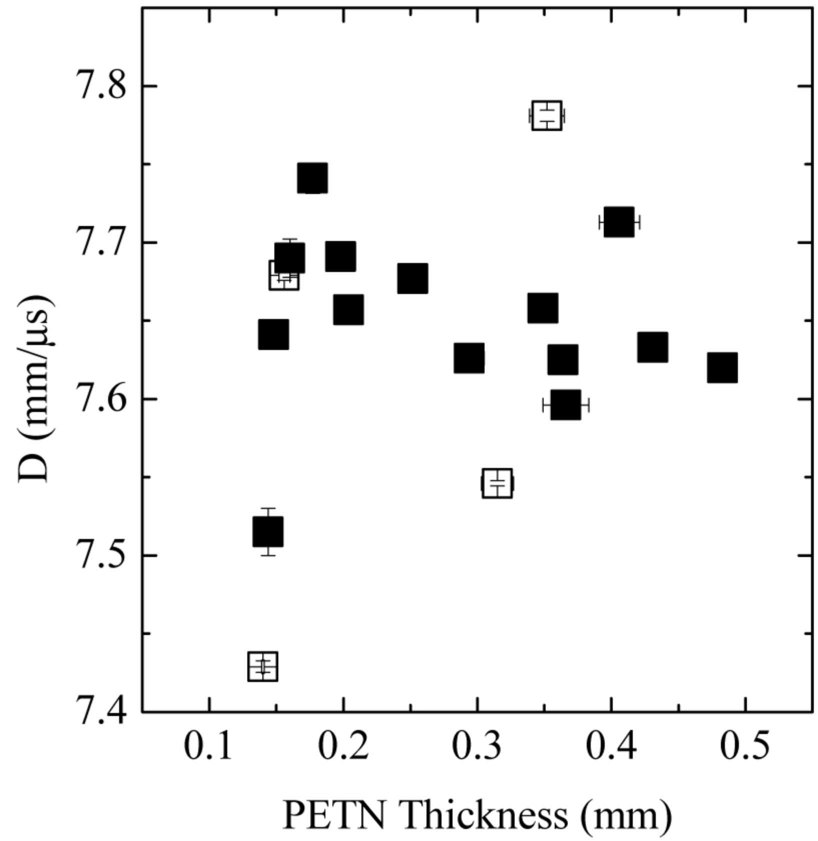
Detonation Velocity Versus Thickness: 0.80 mm wide PETN

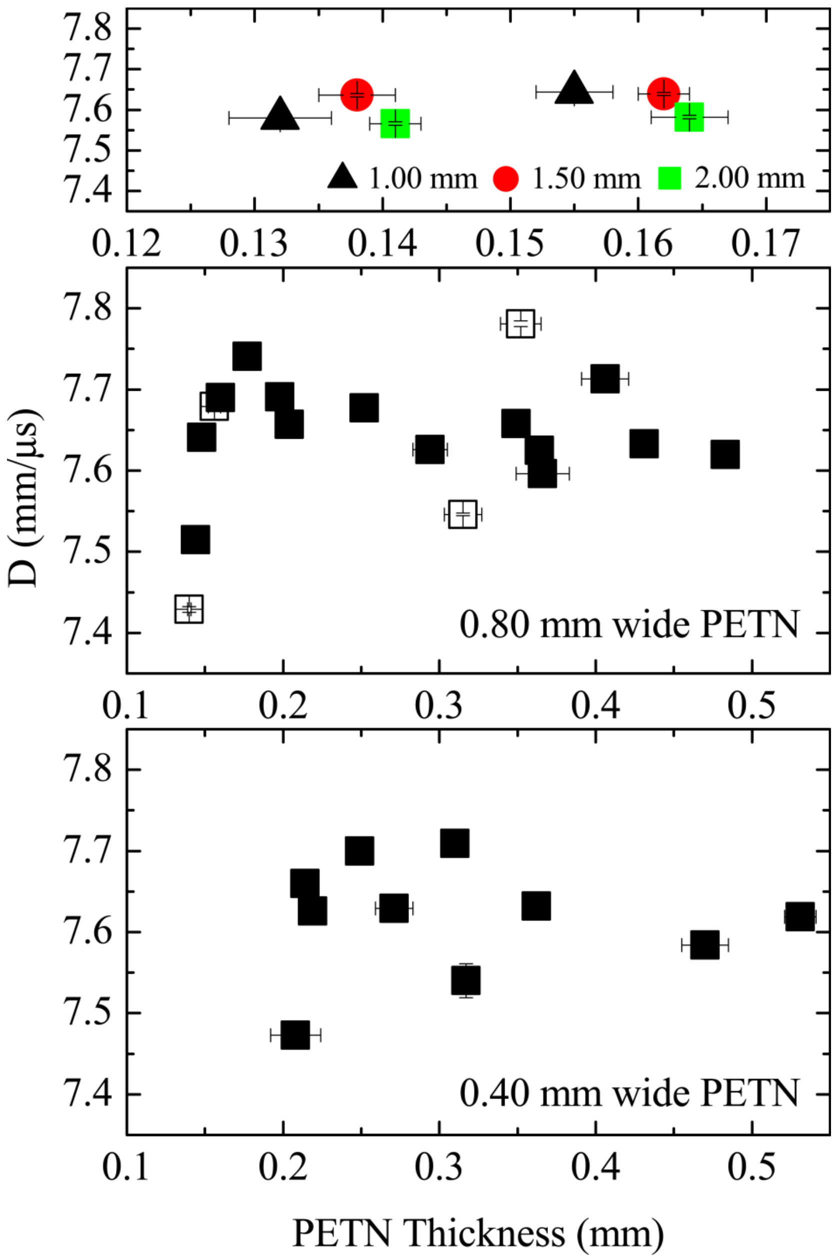
- **Scatter in velocity due to competing effects:**
- **“Density-velocity deficit”**
  - **Detonation velocity decreases with decreasing density**
  - **Seen as film thickness increases**
  - **Maximum velocity exceeds that expected from density calculation**
- **“Thickness-velocity deficit”**
  - **Detonation velocity decreases with decreasing film thickness**





Summary of detonation velocities for 0.80 mm wide PETN films of different thicknesses. Open symbols represent streak camera data.

Detonation Velocity Vs. Thickness Summary



- **Film width affects thickness-velocity deficit**
- **Thickness-velocity deficit not yet seen in wide films**
  - **Thicknesses of 0.130−0.165 mm**
  - **Detonation failure at < 0.12 mm**
- **"Infinite width" > 0.80 mm**

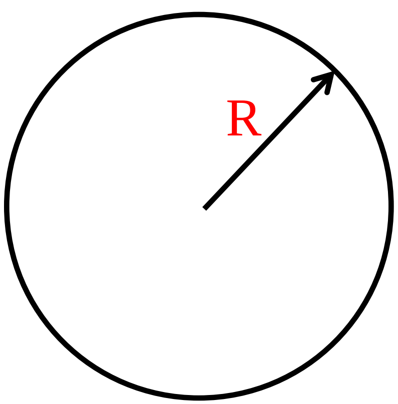
Summary of detonation velocities for different widths. Open symbols represent streak camera data.

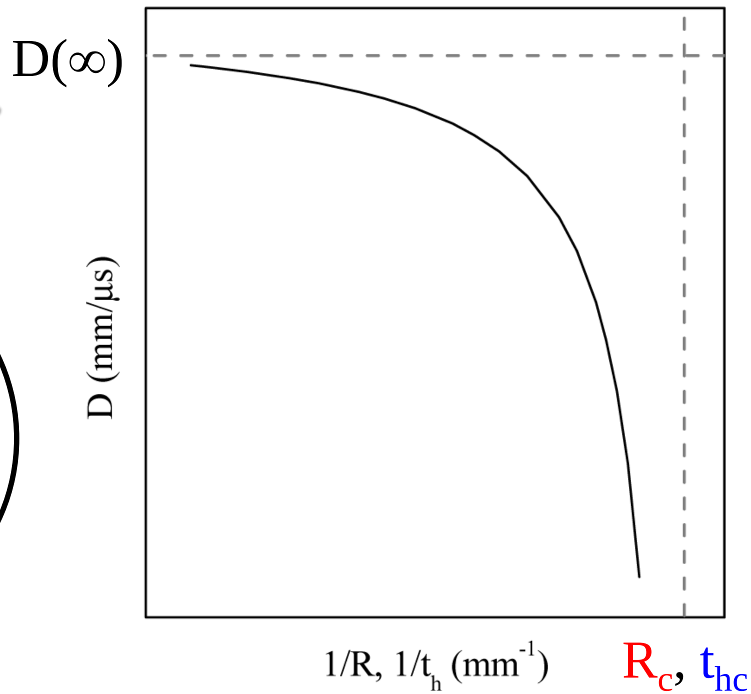
Data Analysis Is Conducted Using the Standard Critical Diameter Form

$$D(R) = D(\infty)\left[1 - \frac{1}{R}\left(\frac{A}{1 - R_c\frac{1}{R}}\right)\right]$$

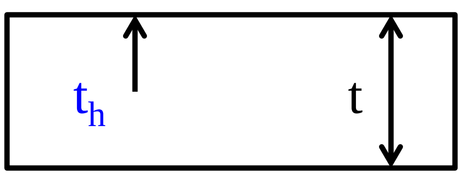
$$D(R) = D(\infty)\left[1 - \frac{1}{t_h}\left(\frac{A}{1 - t_{hc}\frac{1}{t_h}}\right)\right]$$

Critical diameter configuration.





Critical thickness configuration.

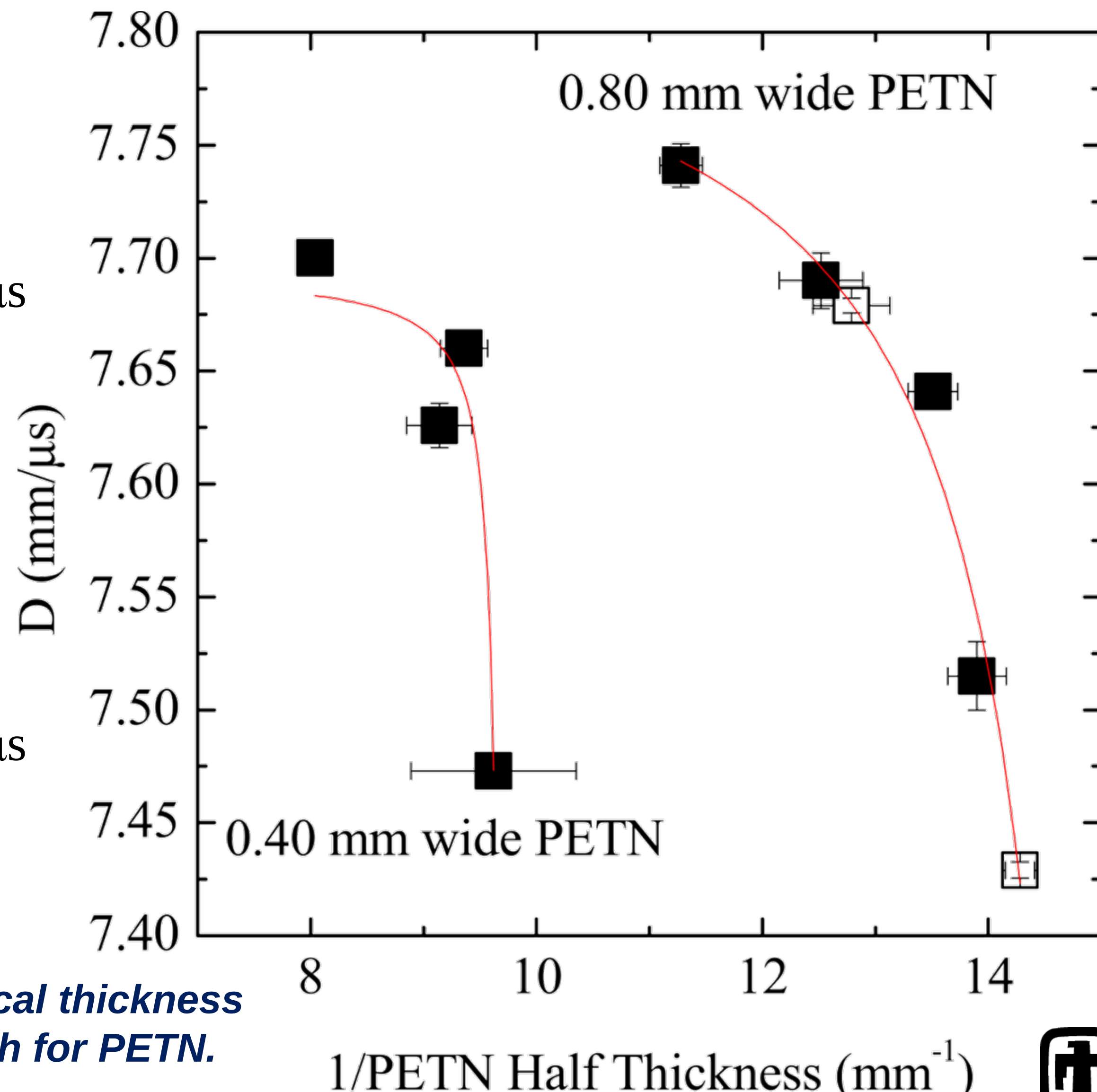


Campbell, A.W. and Engelke, R., "The Diameter Effect in High-Density Heterogeneous Explosives," *6th Symposium (International) on Detonation, Coronado, CA, August 24–27, 1976.*

Critical Thickness Measured for PETN

0.80 mm wide PETN
D(∞) = 7.82   0.05 mm/µs
t_c = 0.131   0.003 mm

0.40 mm wide PETN
D(∞) = 7.70   0.05 mm/µs
t_c = 0.206   0.001 mm



Critical thickness graph for PETN.

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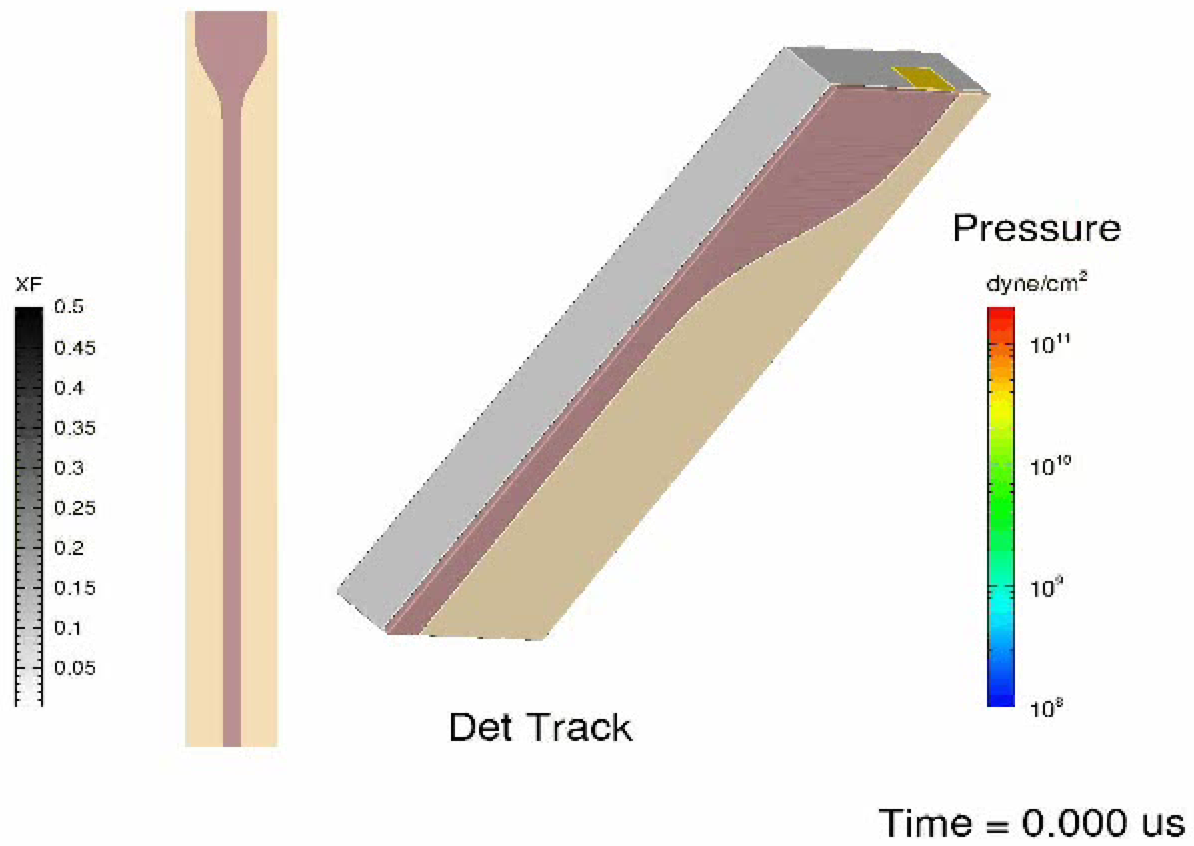
CTH Simulation of Deposited PETN Movie

- **Density gradient captured, HVRB fit to Pop-Plot data**



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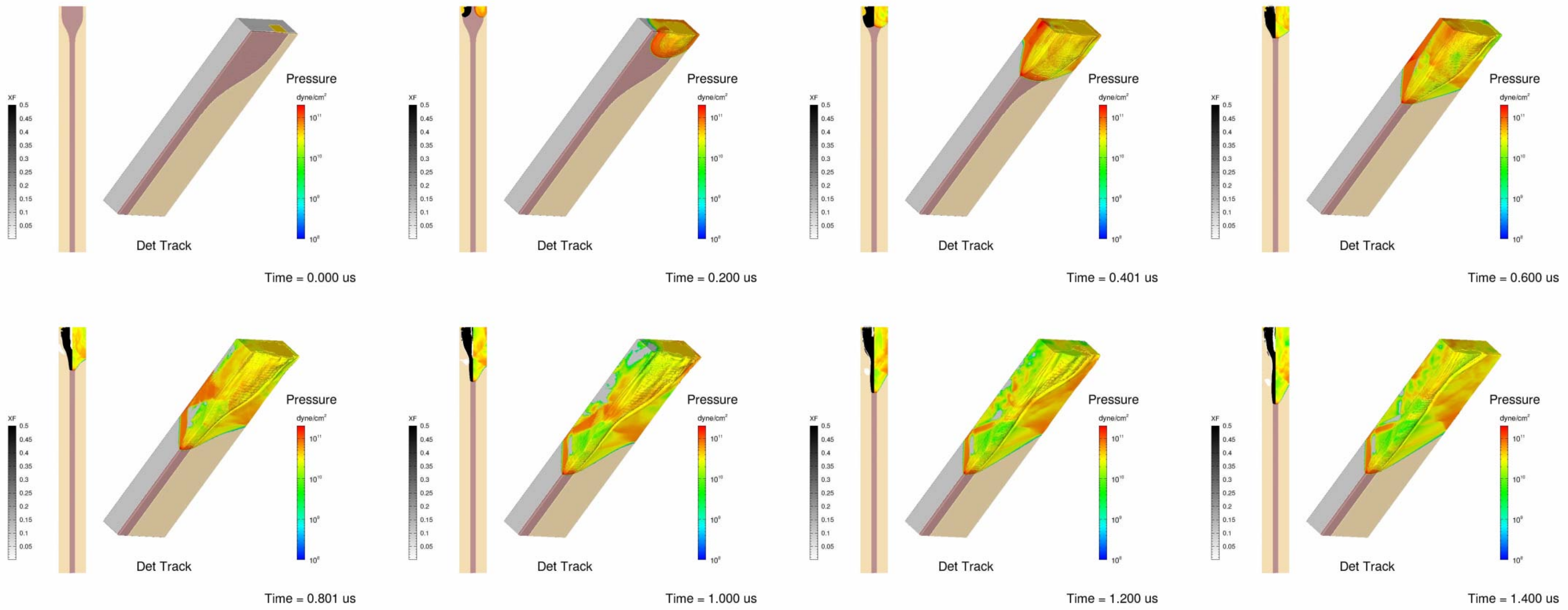
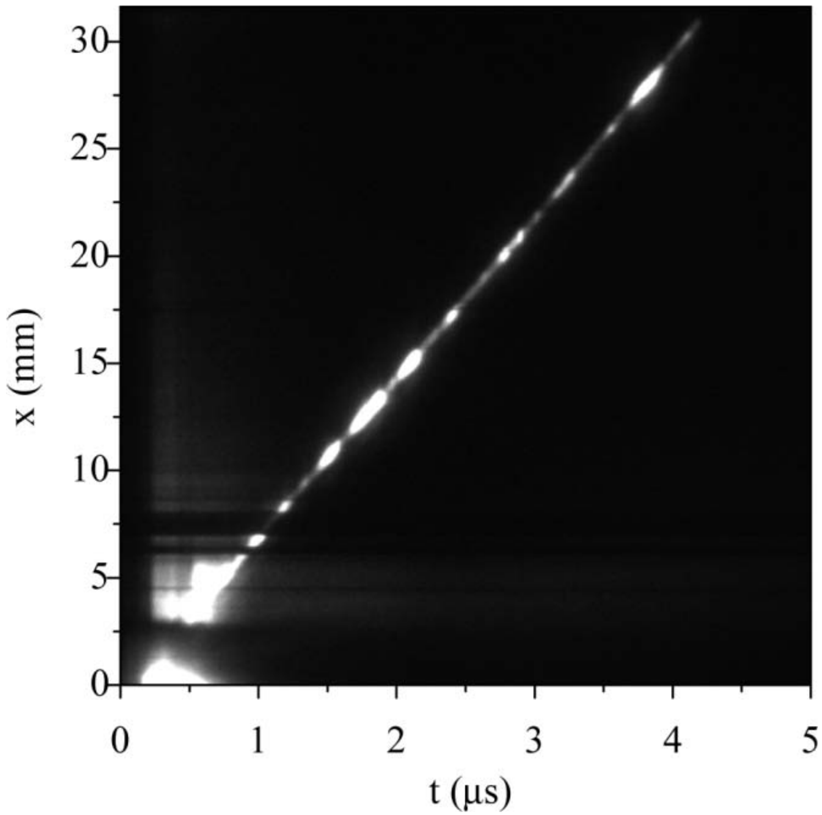
CTH Simulation of Deposited PETN
Frames from Movie

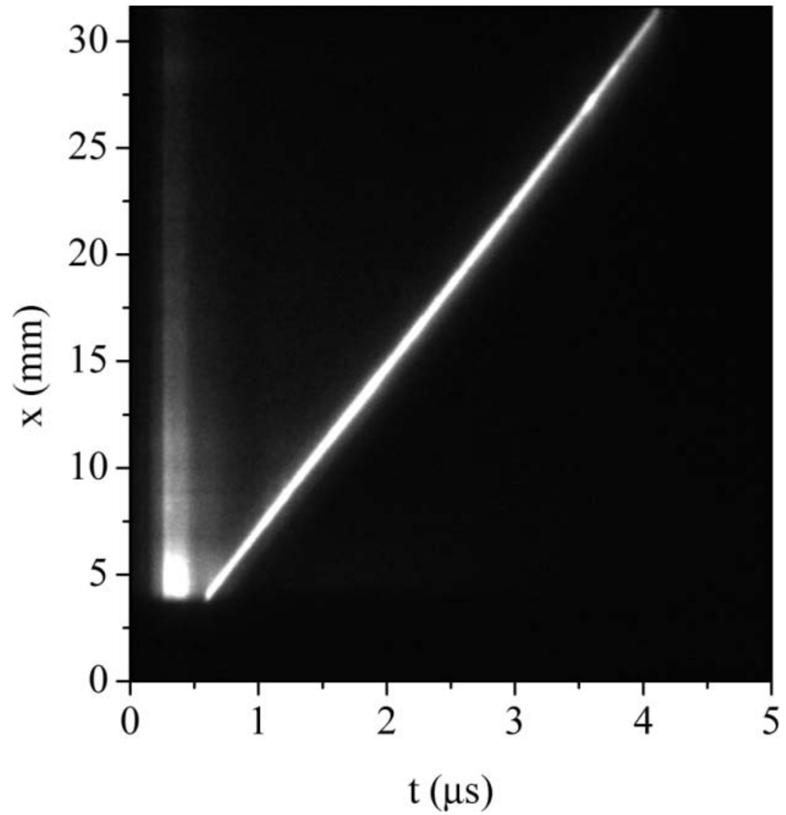


Evidence of Unsteady Detonation Near the Critical Thickness

- Thinner PETN films produced fluctuations in streak camera light intensity
- Not observed in thick films or thin films that were also wide
- No effect on velocity stability



Unsteady light intensity,
0.14   0.001 mm thick, 0.80 mm wide,
7.429   0.004 mm/µs, Shot018.



Steady light intensity,
0.132   0.004 mm thick, 1.00 mm wide,
7.691   0.002 mm/µs, Shot036.

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Conclusions

- Physical vapor deposition used to produce high-density PETN samples with small geometries
- Density and surface roughness change with film thickness
- Critical thickness shows dependence on PETN film width
  - 0.206 mm (0.40 mm wide)
  - 0.131 mm (0.80 mm wide)
- Critical thickness less than 0.13 mm for films at "infinite width"
- Unsteady light intensity in thin, narrow films

- Funding: Joint Department of Defense/Department of Energy Munitions Technology Development Program
- Thanks to: Marc Basiliere, Rosa Montoya, Adrian Casias, David Saiz, Thomas Gutierrez , M. Barry Ritchey

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