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Detonation in vapor-deposited explosives

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Ryan R. Wixom, Cole Yarrington, and Robert Knepper

PSEMC Technical Interchange Meeting,

Chandler, AZ,

September 7, 2017.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Geometry effects in HNAB (hexanitroazobenzene)
- Corner turning in HNAB and PETN (pentaerythritol tetranitrate)

Introduction

- Detonation failure
  - Occurs when size (diameter or thickness) of explosive is decreased
  - When surface losses dominate behavior
- Data for small-scale behavior of high-density pure explosives are scarce
  - Difficult to prepare small-scale samples
  - Failure length scales are often sub-millimeter

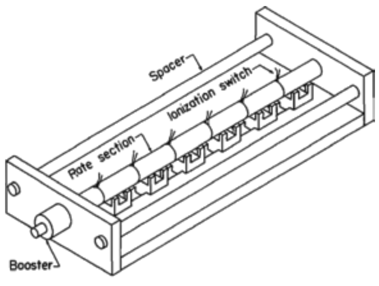
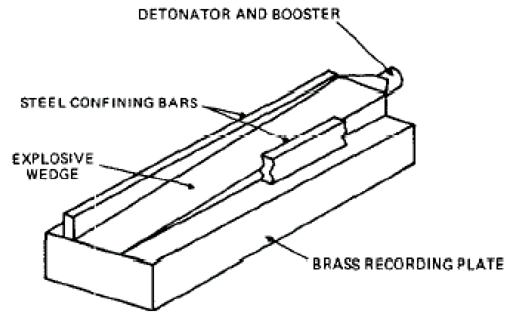
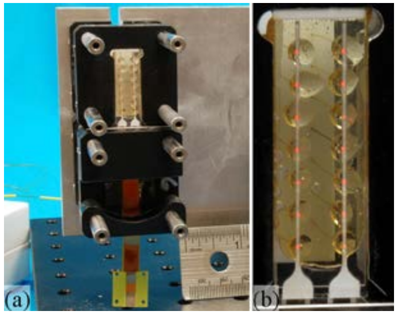


Fig. 1. Schematic of a typical rate-stick assembly.

Rate stick experiment.



Detonation failure experiment.



Critical thickness experiment.

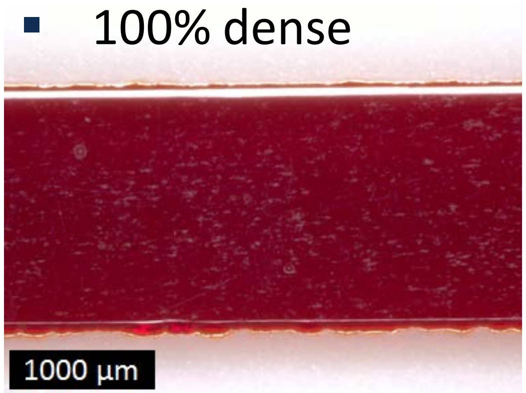
Campbell, A.W. and Engelke, R., "The Diameter Effect in High-Density Heterogeneous Explosives," 6th Symposium (International) on Detonation, Coronado, CA, August 24-27, 1976, pp. 642-652.

Gibbs, T.R. and Popolato, A., LASL Explosive Property Data, Detonation Failure Thickness, pp. 289-290. Berkeley, Los Angeles, London: University of California Press, 1980.

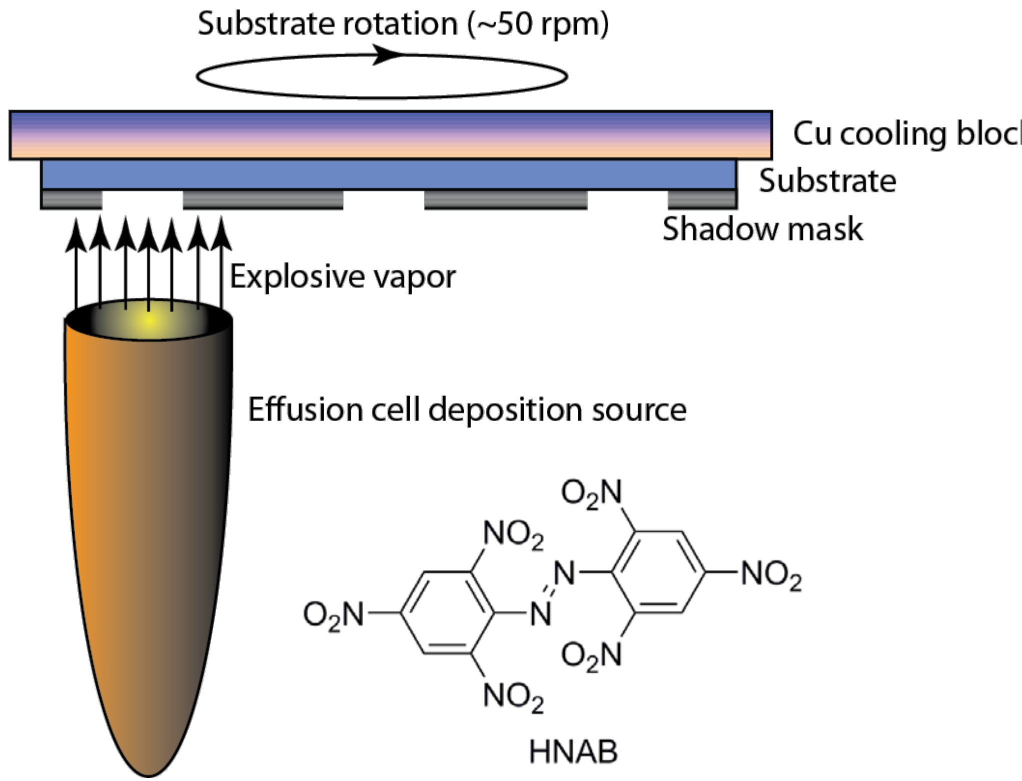
Tappan, A.S., Knepper, R., Wixom, R.R., Marquez, M.P., Miller, J.C., and Ball, J.P., "Critical Thickness Measurements in Vapor-Deposited Pentaerythritol Tetranitrate (PETN) Films," 14th International Detonation Symposium, Coeur d'Alene, ID, April 11-16, 2010.

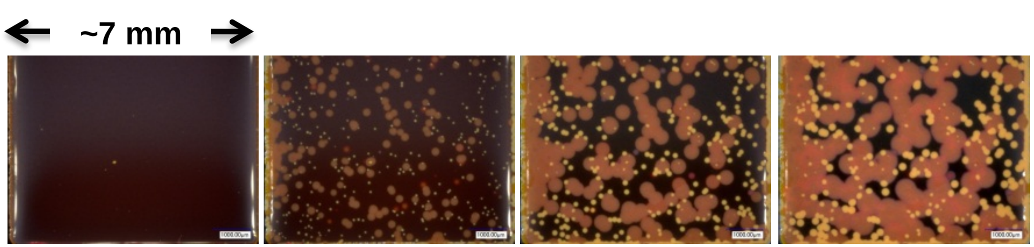
HNAB physical vapor deposition

- Polycarbonate substrates
- Amorphous HNAB films
- 100% dense



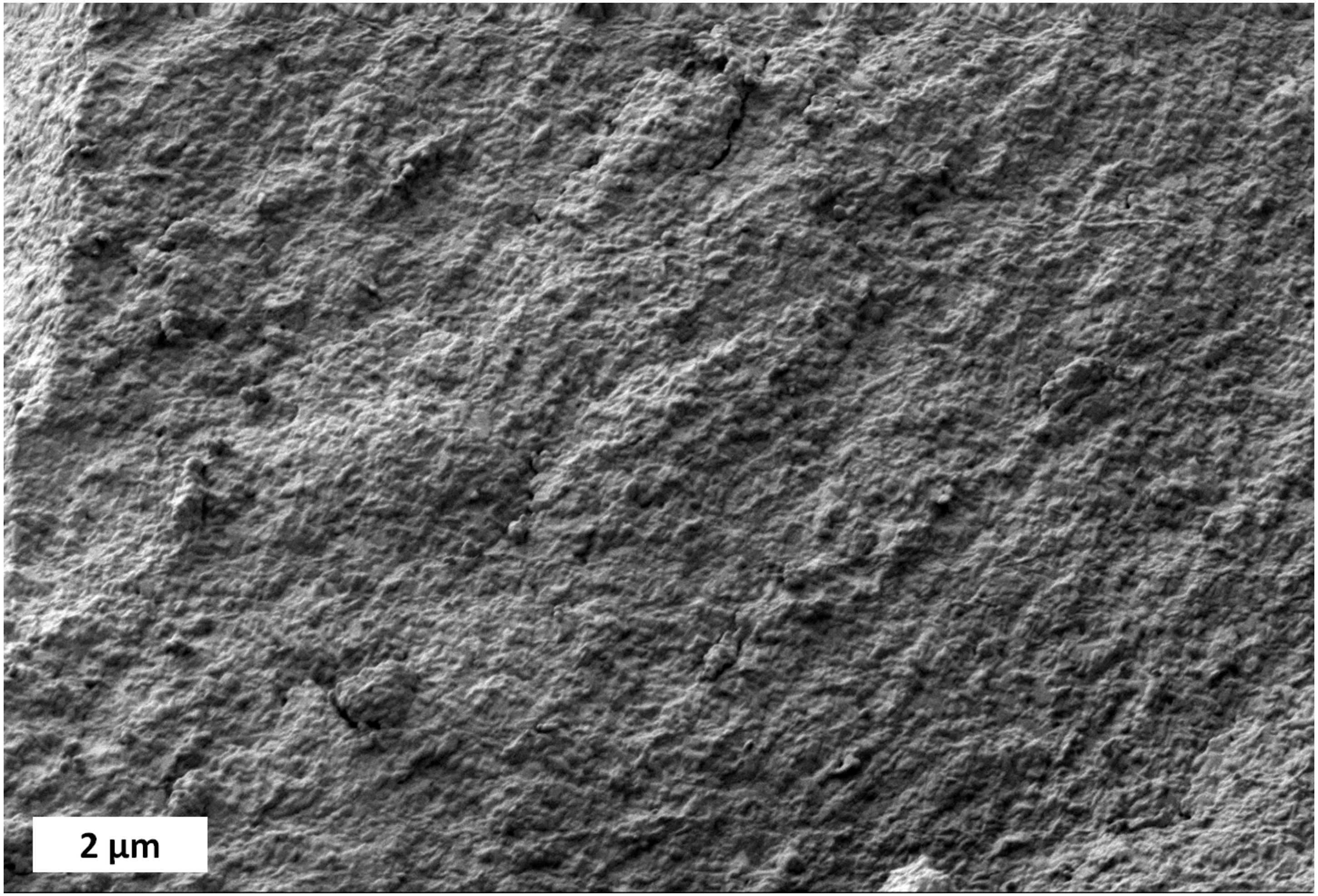
Optical micrograph of as-deposited HNAB.





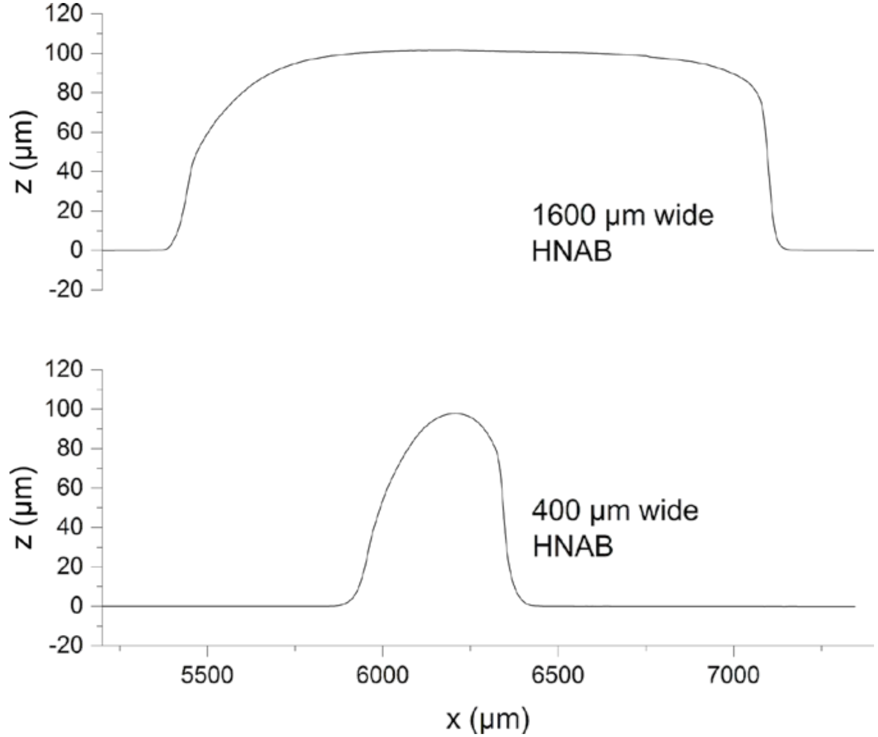
HNAB crystallization, time-lapse 65 °C, 24 min./image.

Fracture cross-section micrograph of 35 °C crystallized HNAB

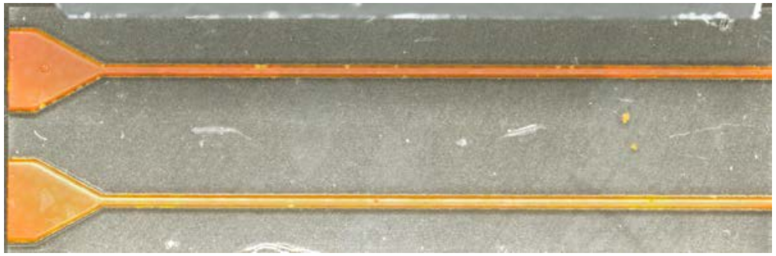


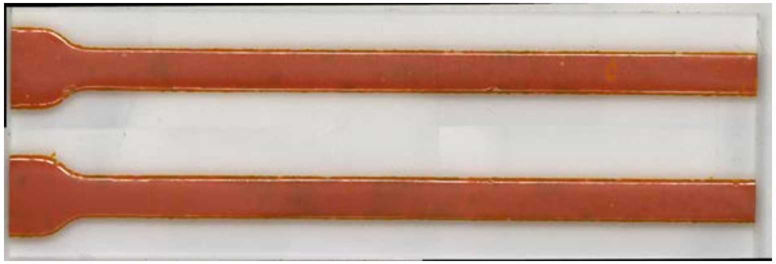
HNAB samples

- Polycarbonate substrates
  - 1 × 3 cm
- Two film widths
  - 400 µm
  - 1600 µm
- One crystallization condition
  - 35 °C



Surface profile of 400 and 1600 µm wide HNAB.





Photograph of HNAB films on 1 × 3 cm polycarbonate substrates. During deposition, a mask was used to define two film widths of 400 and 1600 µm.

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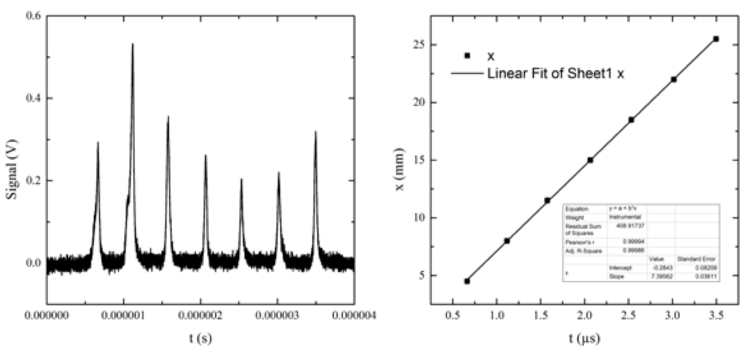
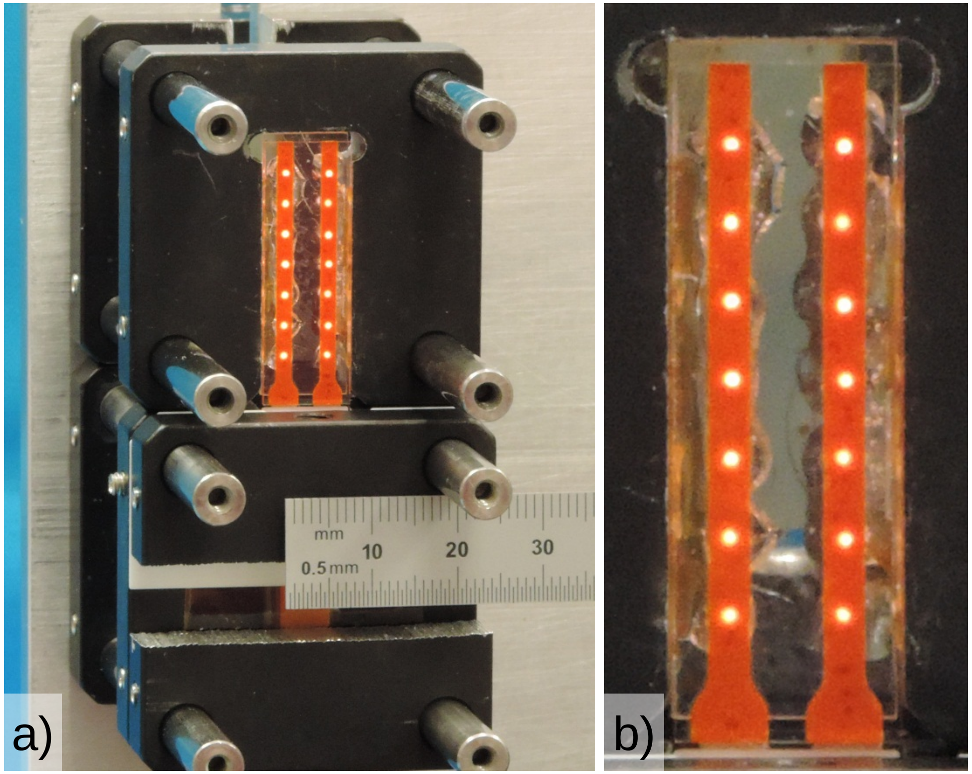
Critical detonation thickness experiment

- Two experiments (HNAB lines) each shot
- Optical fibers deliver detonation light to photodetector

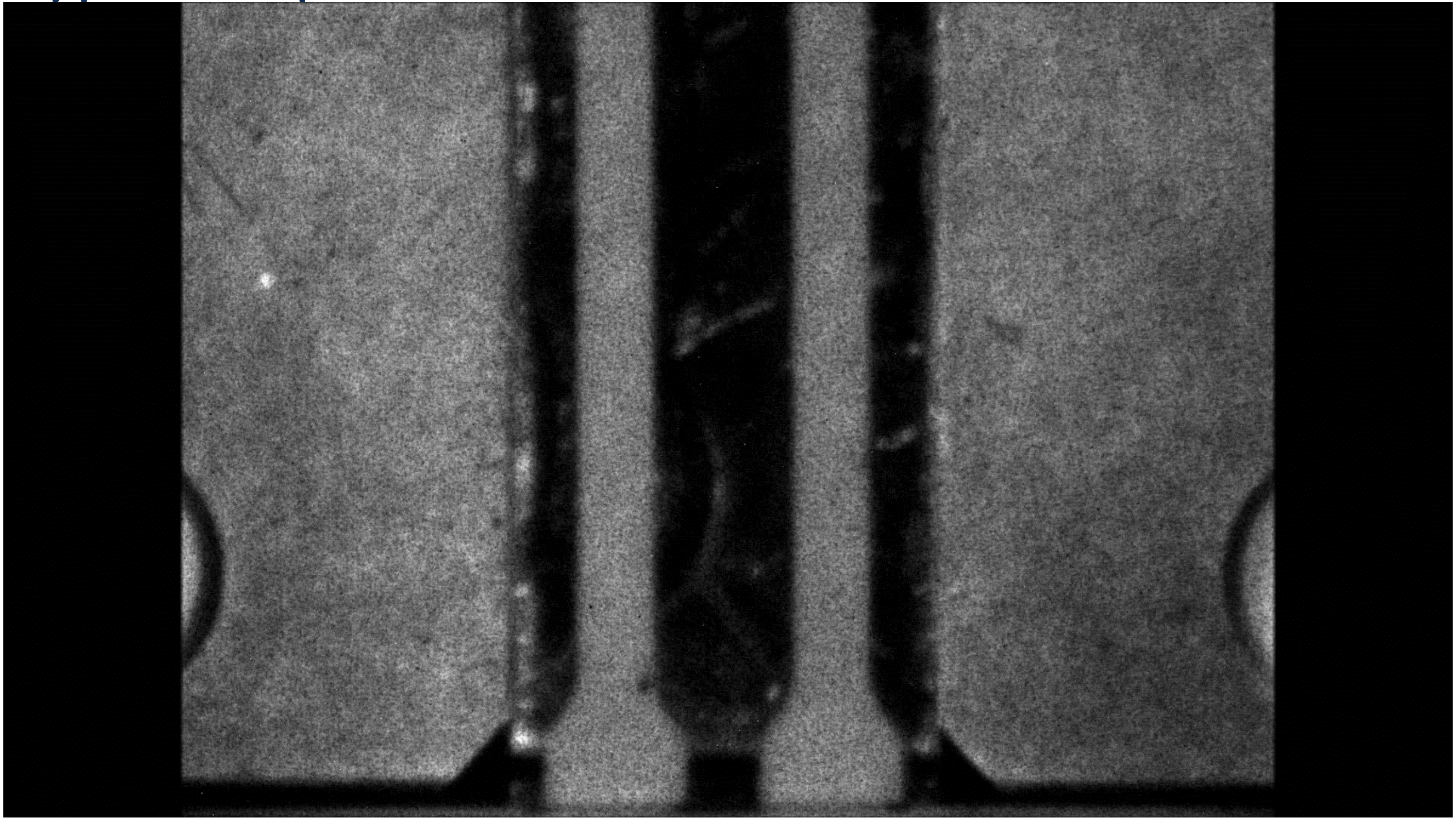


Optical fiber data is used to produce a linear fit to position versus time, where the slope is the velocity.



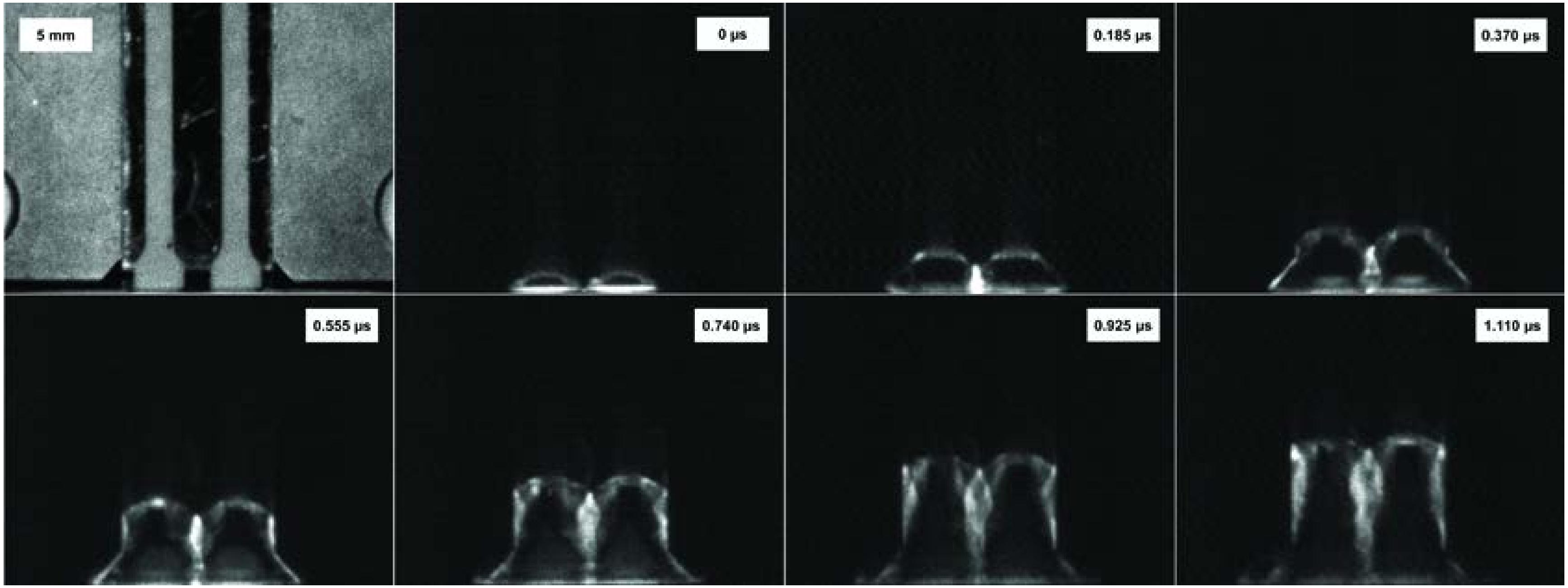
Photographs of critical detonation thickness experiment. Optical fibers illuminated to highlight position.

Framing camera video of a typical experiment



Framing camera images of detonation in the two lines of a single HNAB sample crystallized at 45 °C. These images were taken at 5.4 million frames-per-second (1/185 ns) with an exposure time of 15 ns.

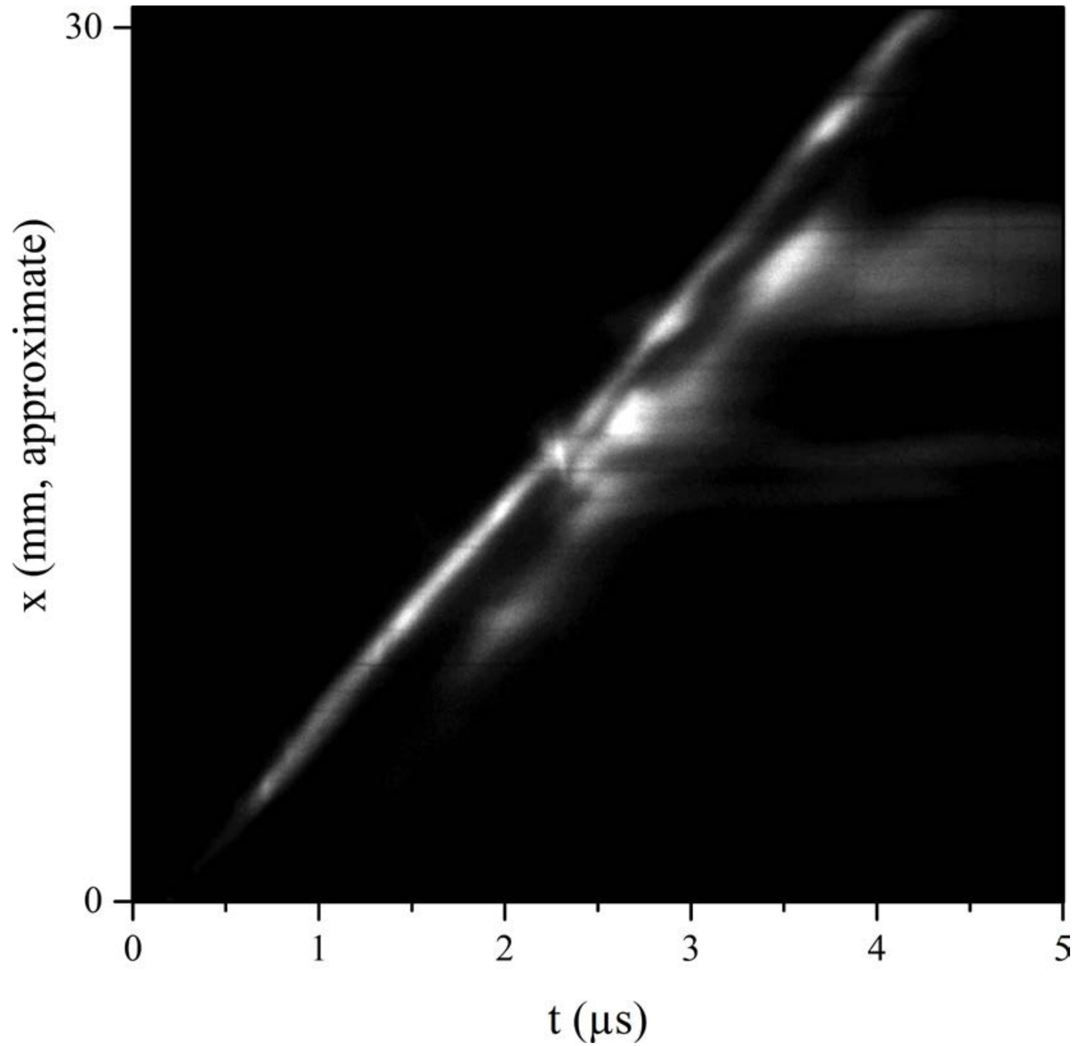
Framing camera images of a typical experiment



Framing camera images of detonation in the two lines of a single HNAB sample crystallized at 45 °C. These images were taken at 5.4 million frames-per-second (1/185 ns) with an exposure time of 15 ns.

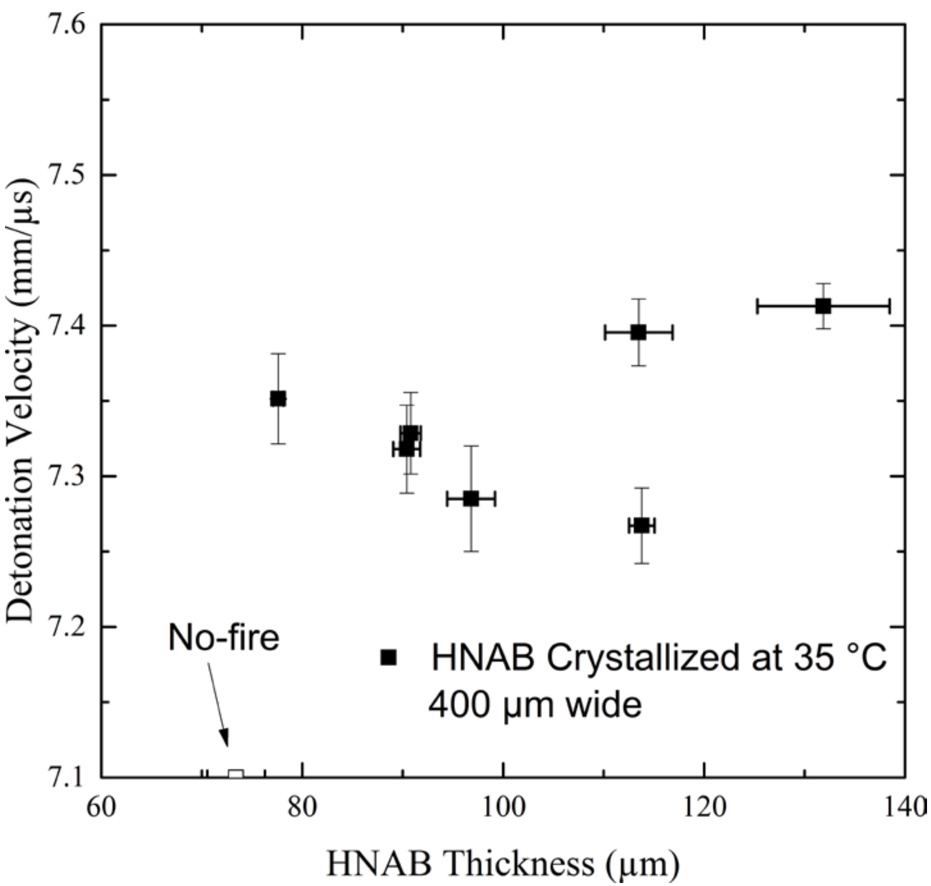
Streak camera image of a typical experiment

- HNAB, 1600 μm wide line
- 93.5 ± 0.9 μm wide
- 7.442 ± 0.043 mm/μs
- Steady detonation with late reaction or light output



Failure thickness for 400 µm wide HNAB

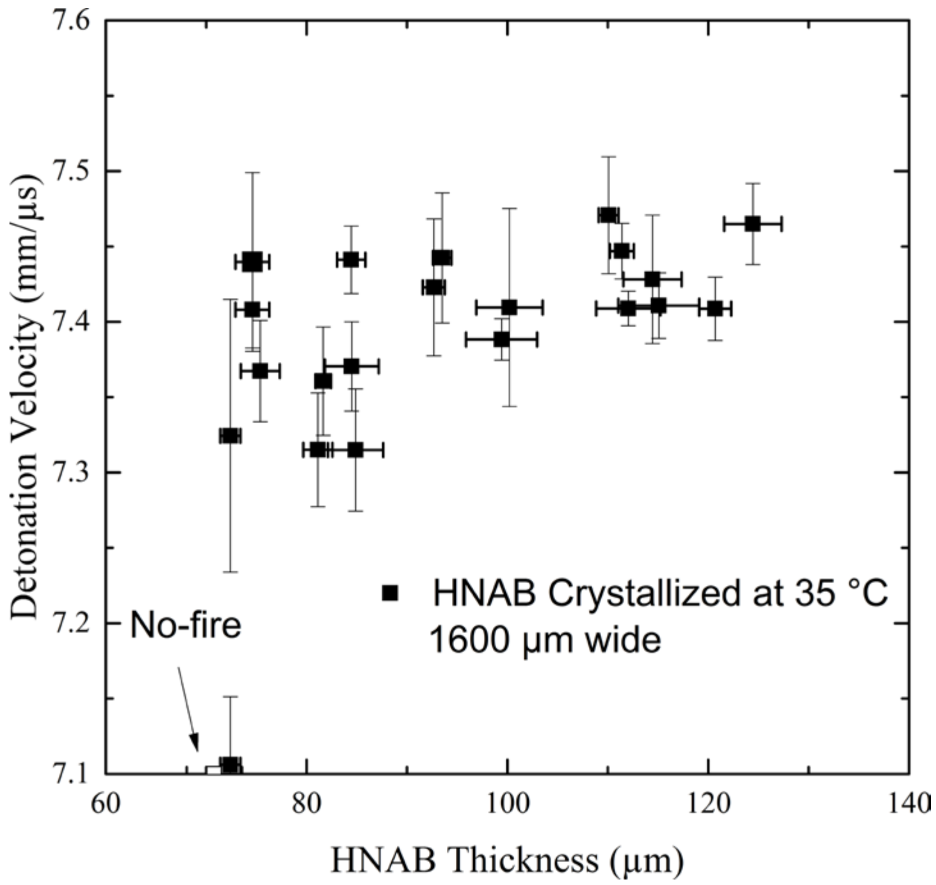
- Detonation velocity relatively consistent approaching failure
- Failure thickness = (thinnest Fire + thickest No-Fire)/2
  - 75.5 µm



Detonation velocity versus thickness. One failure point is included.

Failure thickness for 1600 µm wide HNAB (infinite width)

- Detonation velocity relatively consistent approaching failure
- Failure thickness = (thinnest Fire + thickest No-Fire)/2
  - 71.6 µm



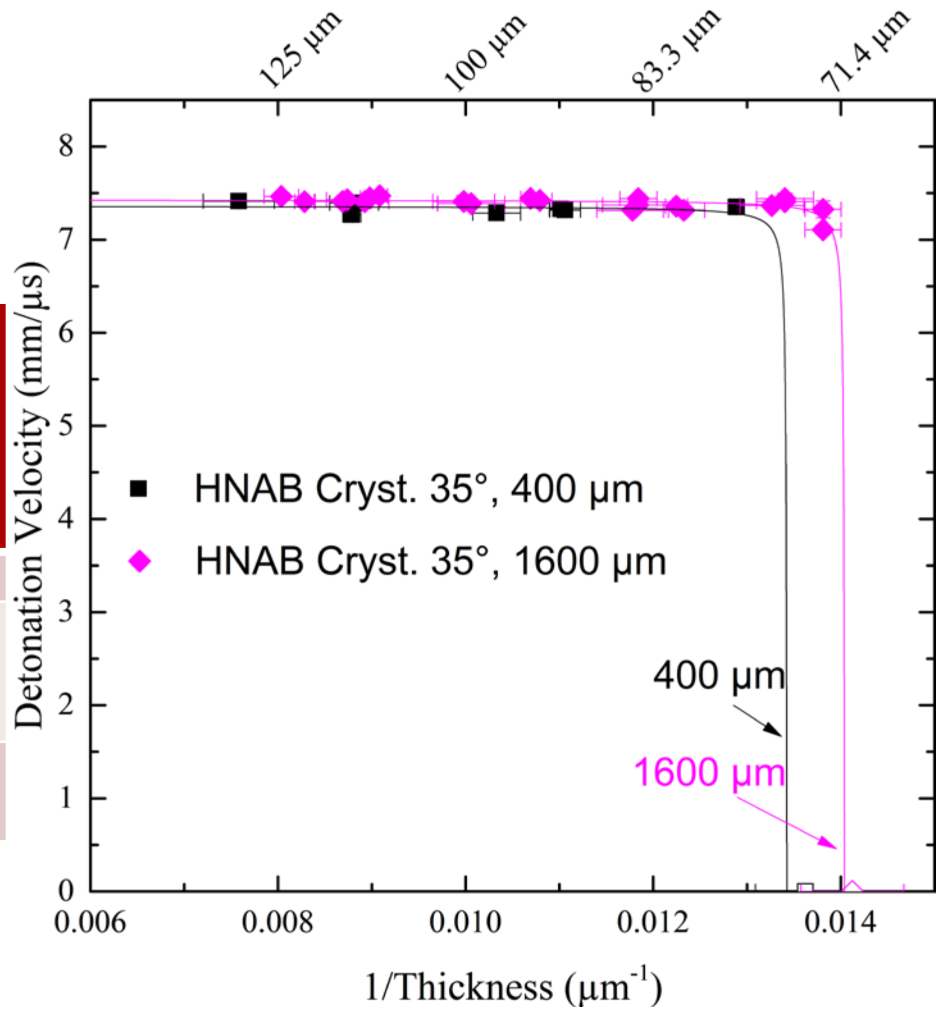
Detonation velocity versus thickness. One failure point is included.

Critical detonation thickness for HNAB at two deposition widths

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

Film Width	Detonation Velocity at Infinite Thickness, $D(\infty)$	Critical Thickness, t_c	Length Parameter, *A*
µm	mm/µs	µm	µm
400 µm	7.356 ± 0.026	74.5 ± 1.1	0.032 ± 0.01
1600 µm	7.424 ± 0.016	71.2 ± 0.4	0.032 ± 0.01

- For the 400 µm width, *A* had to be fixed at 0.032 µm for solution to converge



Detonation velocity versus 1/thickness.

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, pp. 642-652.

Conclusions

- Vapor-deposited HNAB infinite width likely bounded between 400 and 1600 μm
- Infinite width conclusively larger than 400 μm, width-to-critical thickness ratio of 5.4
- Detonation instabilities present near failure
- Acknowledgements

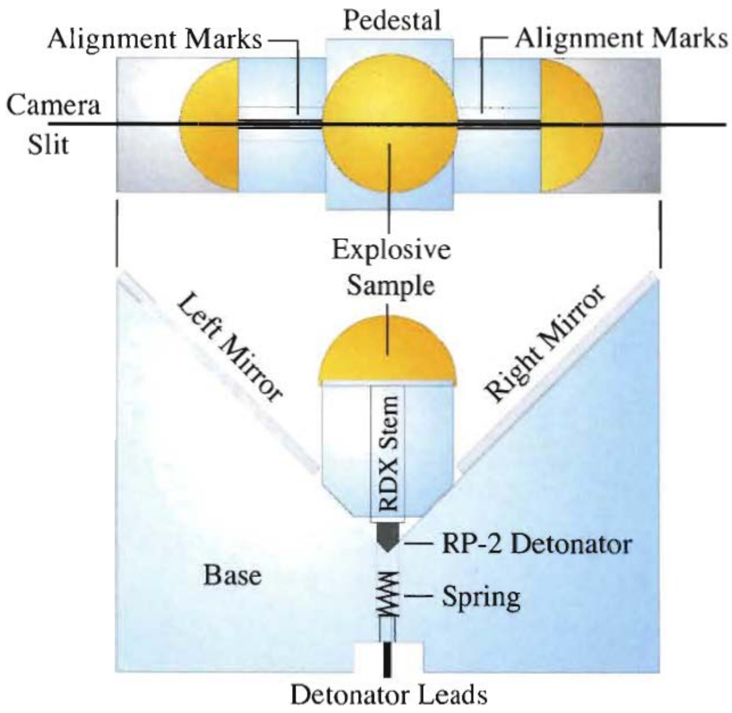
  - Michael P. Marquez, James Patrick Ball, Shawn Stacy, and M. Barry Ritchey
  - The Joint Department of Defense/Department of Energy Munitions Technology Development Program
  - Laboratory Directed Research and Development

Outline

- Corner turning in HNAB and PETN (pentaerythritol tetranitrate)

Introduction

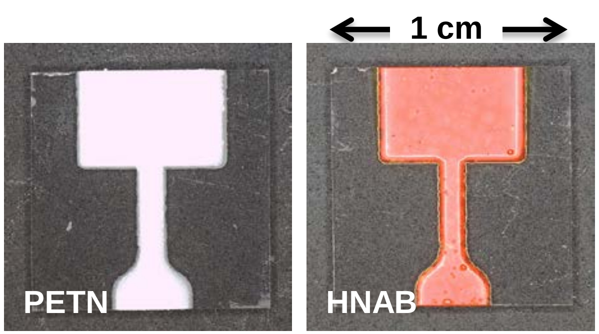
- Detonation corner turning
  - Ability of a detonation wave to propagate into unreacted explosive that is not immediately in the path of the detonation wave
- Dead zone
  - Unreacted explosive outside path of detonation wave
- Mushroom Test (LANL, Larry Hill)
  - Infers detonation corner turning from breakout at the explosive surface
- Motivation: to inform reactive burn models



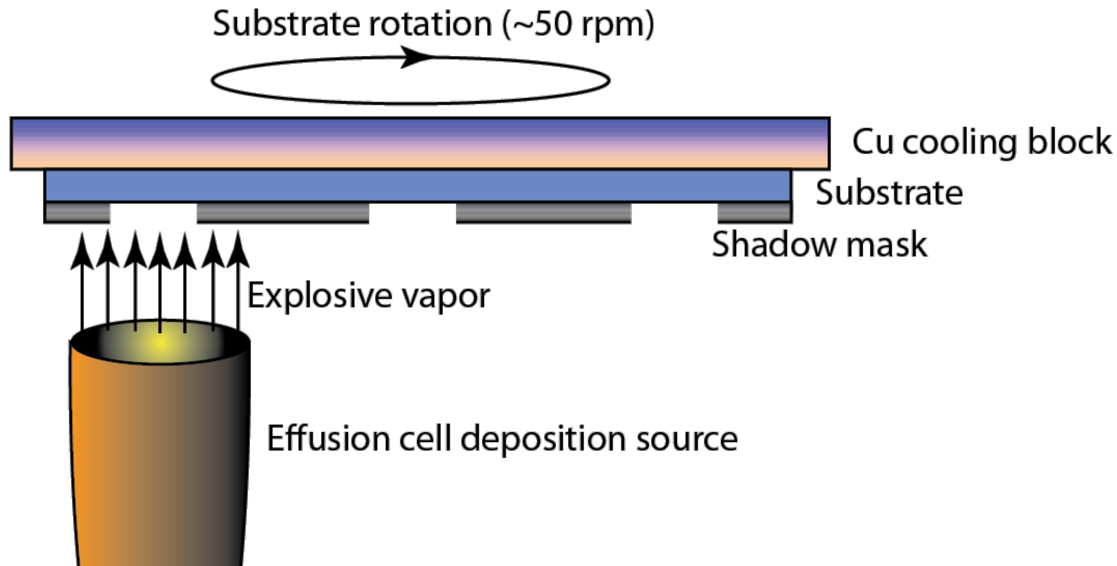
Hill, L. G., W. L. Seitz, et al. (1998). "High explosive corner turning performance and the LANL mushroom test." AIP Conference Proceedings **429**(1): 751-754.

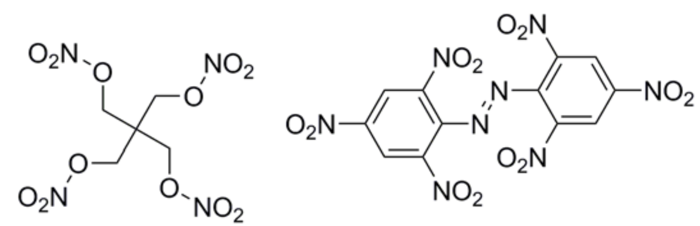
Micromushroom samples
Physical vapor deposition

- Polycarbonate substrates
- PETN and HNAB deposition
- Polycrystalline PETN films
- As-deposited HNAB films



Optical micrographs of deposited HNAB and PETN.

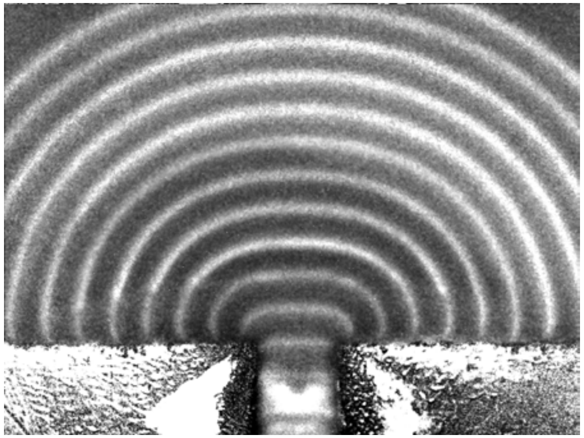




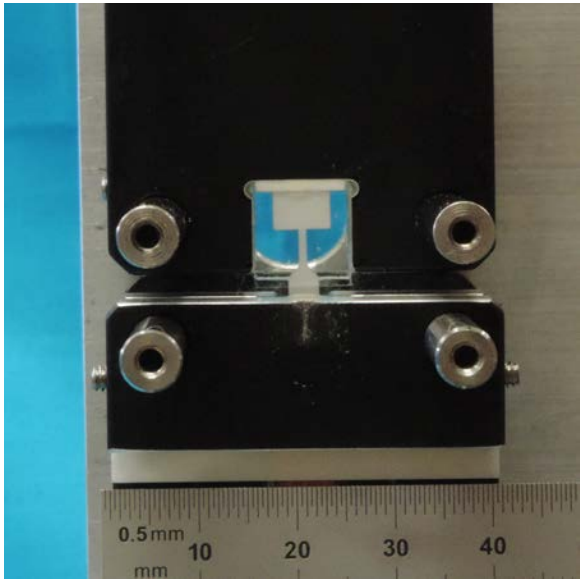
PETN (pentaerythritoltetranitrate)
HNAB (2,2',4,4',6,6'-hexanitroazobenzene)

Micromushroom test

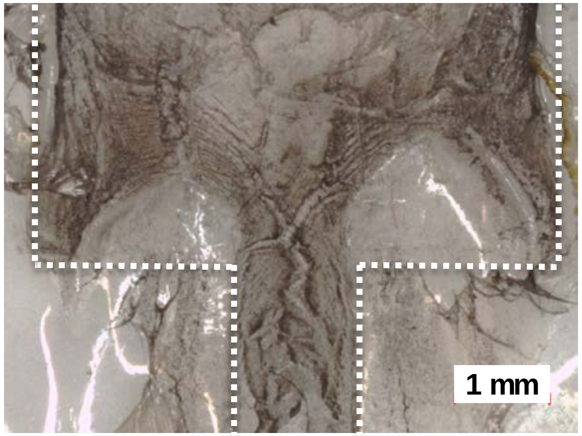
- Optical observation of corner turning
- Framing camera is principal diagnostic



Processed sum of framing camera images, PETN, 5 ns, 22 MHz (1/45 ns).

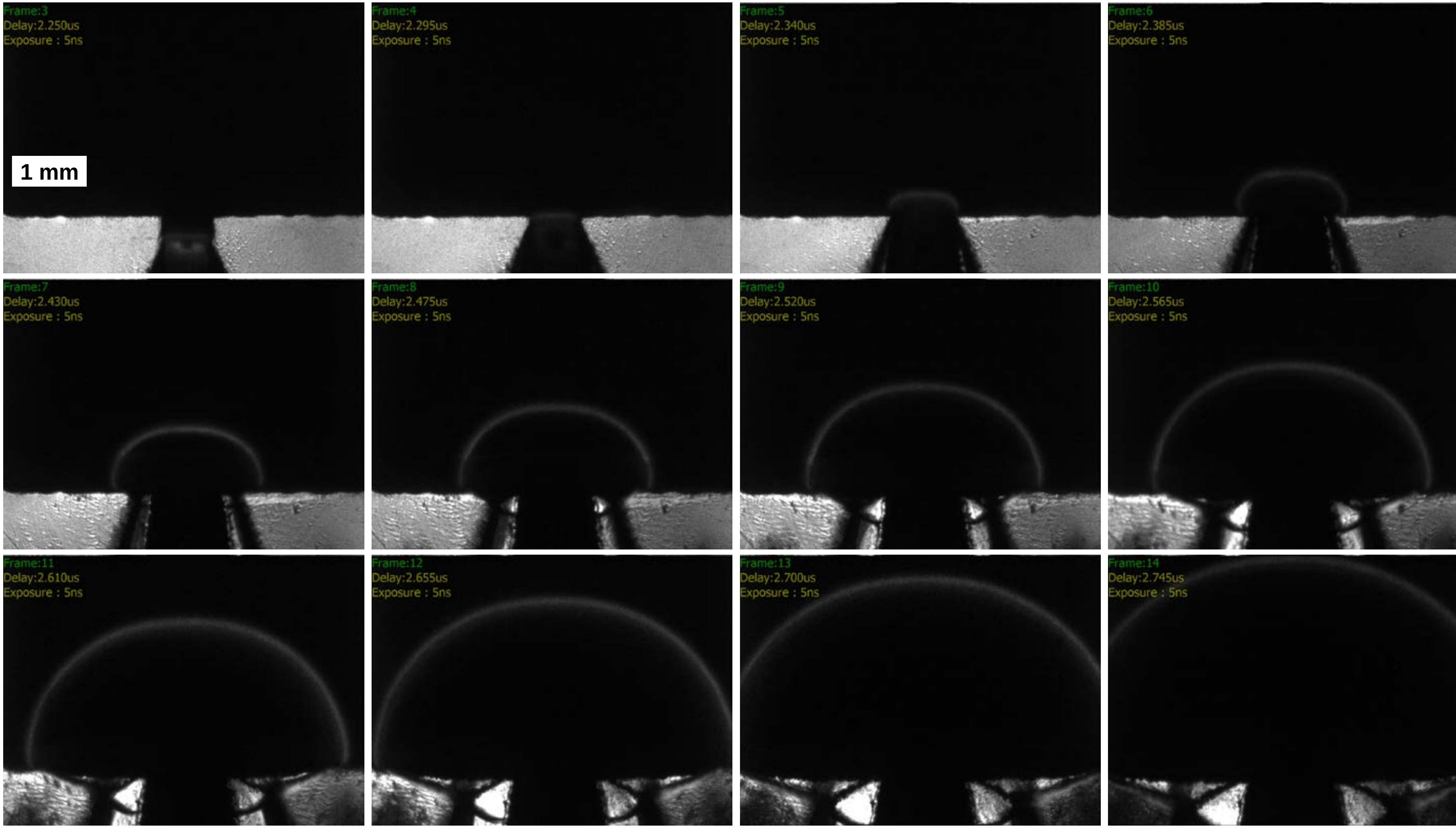


Photograph of micromushroom test with deposited PETN.



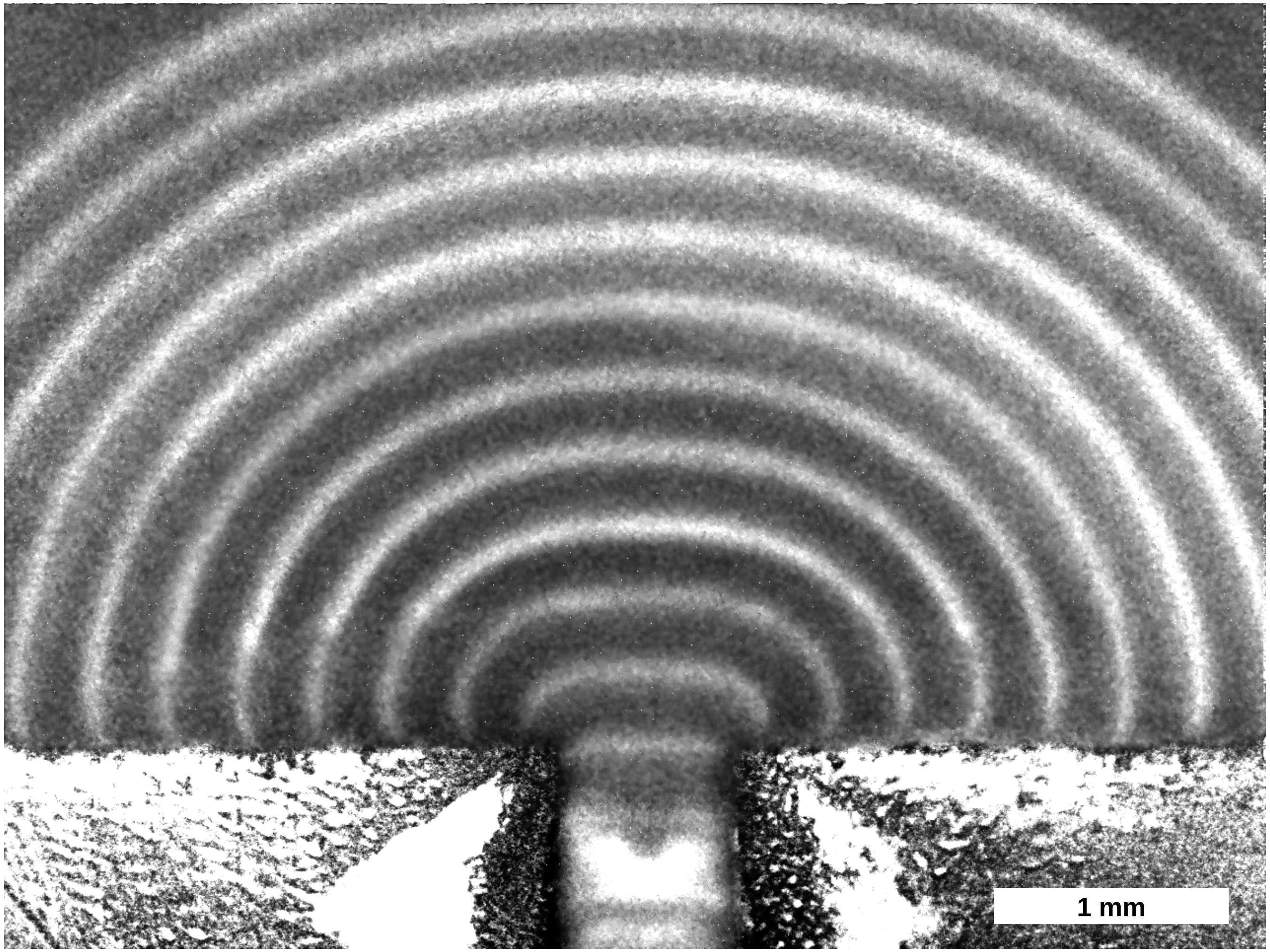
Postmortem image of polycarbonate substrate with HNAB dead zones.

Corner turning,
PETN, 0.75 mm stem, 277 µm thick



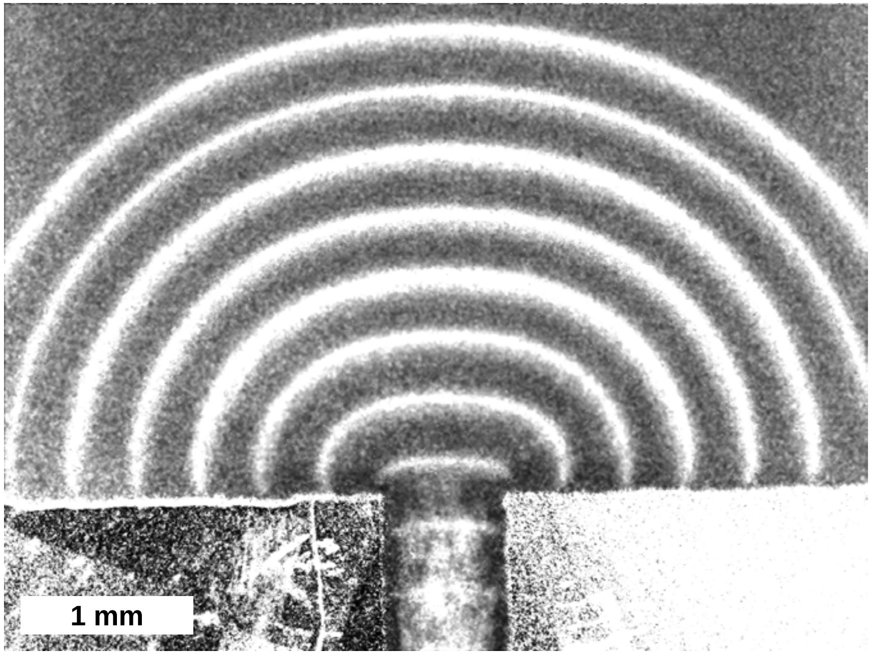
Framing camera images of PETN micromushroom, 5 ns exposure, 22 MHz (1/45 ns).

Corner turning, PETN, 0.75 mm stem, 277 µm thick

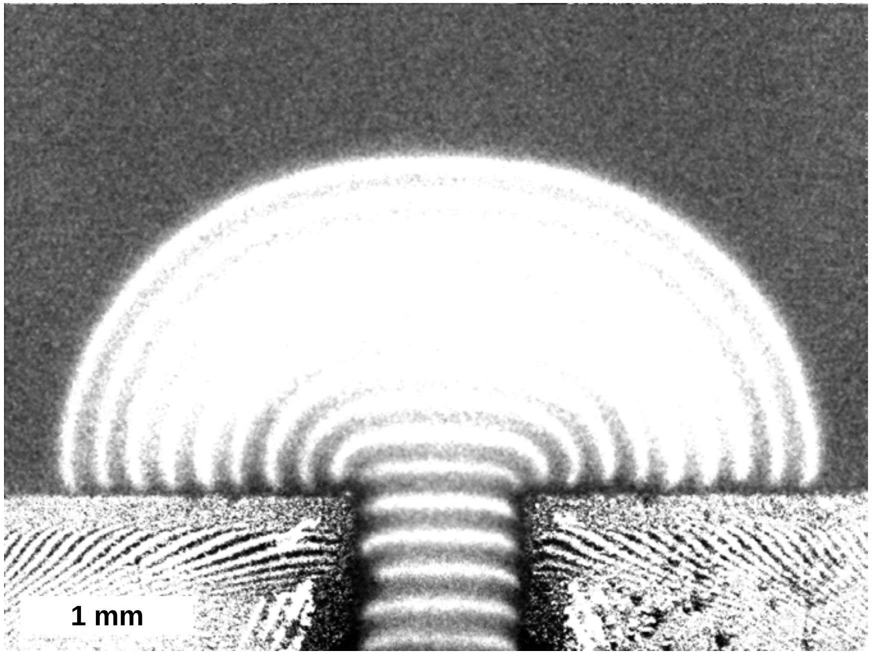


Processed sum of framing camera images, PETN micromushroom, 5 ns exposure, 22 MHz (1/45 ns).

Corner turning, PETN stem width and thickness has little effect



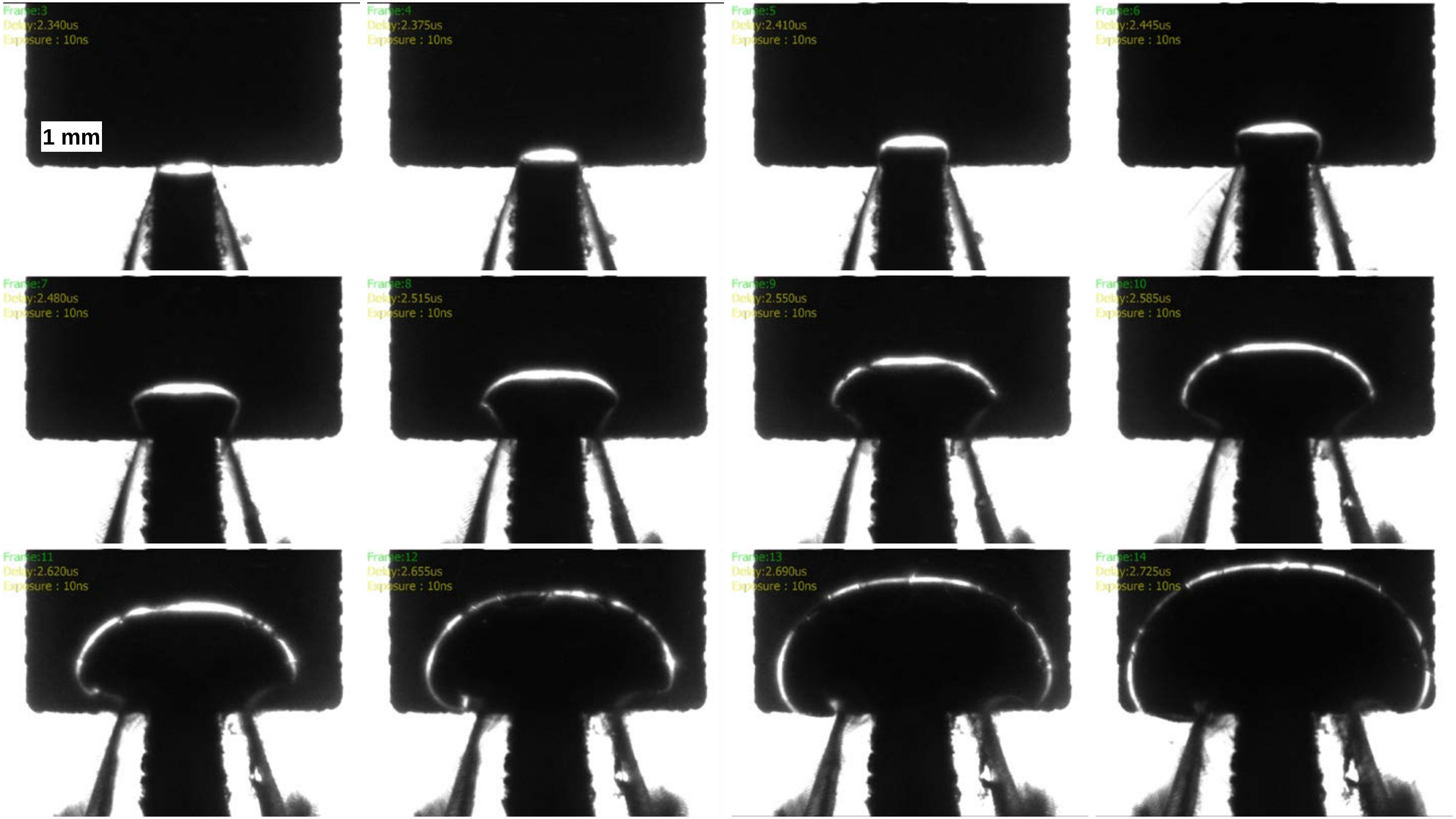
0.75 mm stem width, 173 µm thick.
5 ns exposure, 18 MHz (1/55 ns).



1.00 mm stem width, 277 µm thick.
5 ns exposure, 33 MHz (1/30 ns).

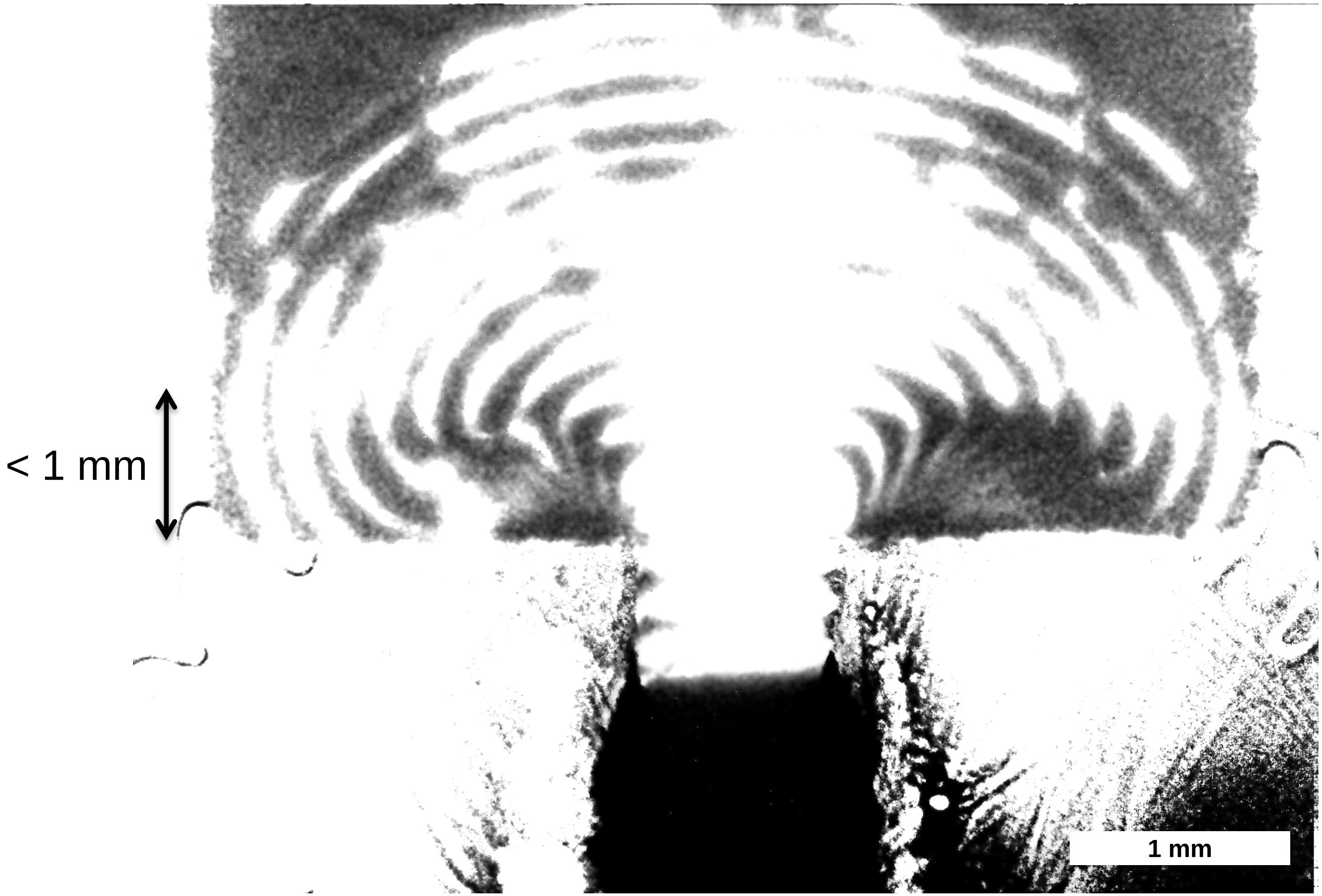
- No measurable corner turning difference in PETN with different stem widths of 0.75 mm, 1.00 mm, and 1.50 mm (1.50 mm not shown) or of different thicknesses.

Corner turning,
HNAB, 1.00 mm stem, 150 µm thick



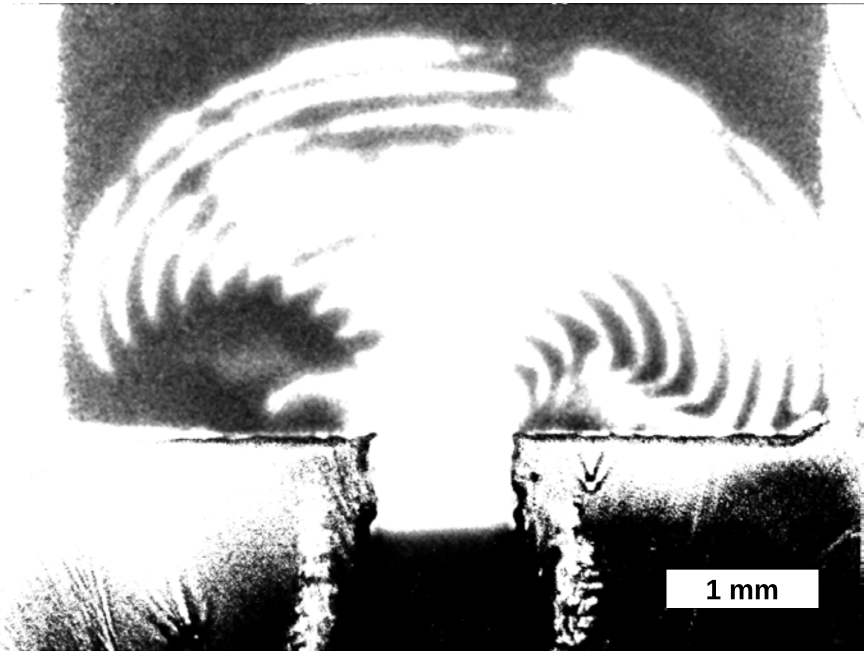
Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

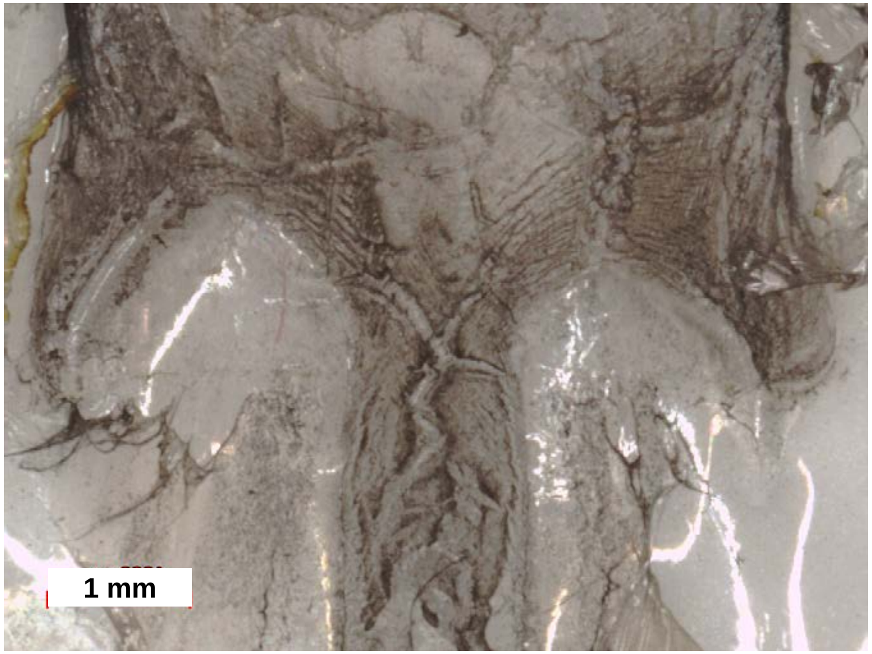
Corner turning,
HNAB, 1.00 mm stem, 150 µm thick



Processed sum of framing camera images, HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

Corner turning, HNAB postmortem



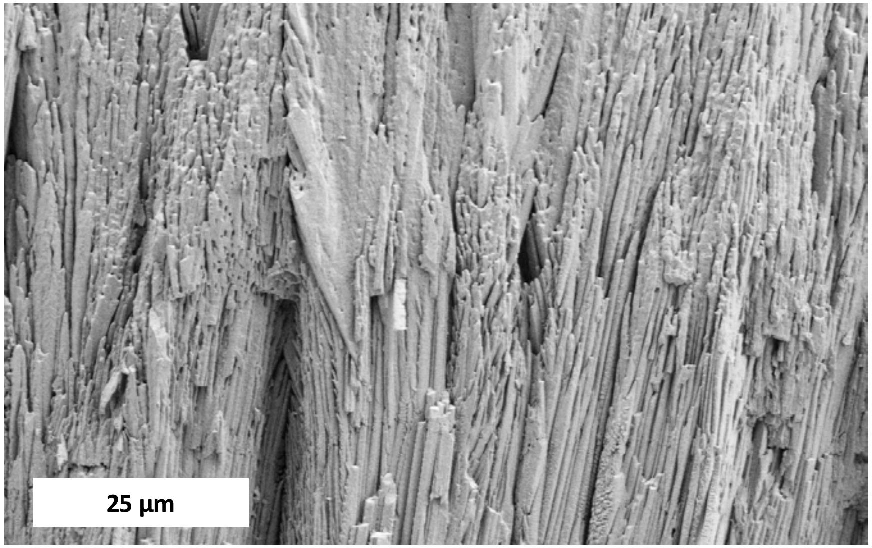


1.00 mm stem width, 150 µm thick. 5 ns exposure, 22 MHz (1/45 ns).

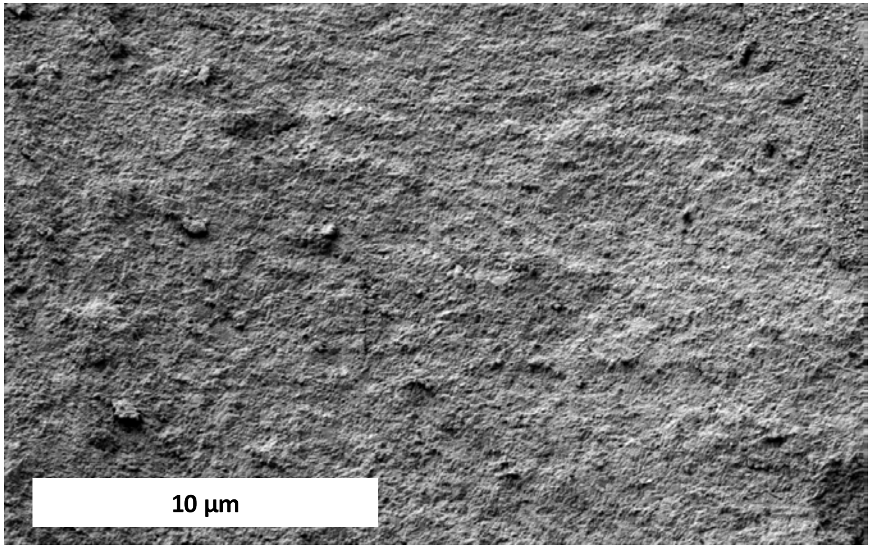
Photograph of polycarbonate substrate, reversed to match framing camera.

- Detonation recorded in polycarbonate substrate (flattened for analysis), showing dead zones

Microstructure and density



PETN scanning electron micrograph, 100 µm wide image.



HNAB scanning electron micrograph, 25 µm wide image.

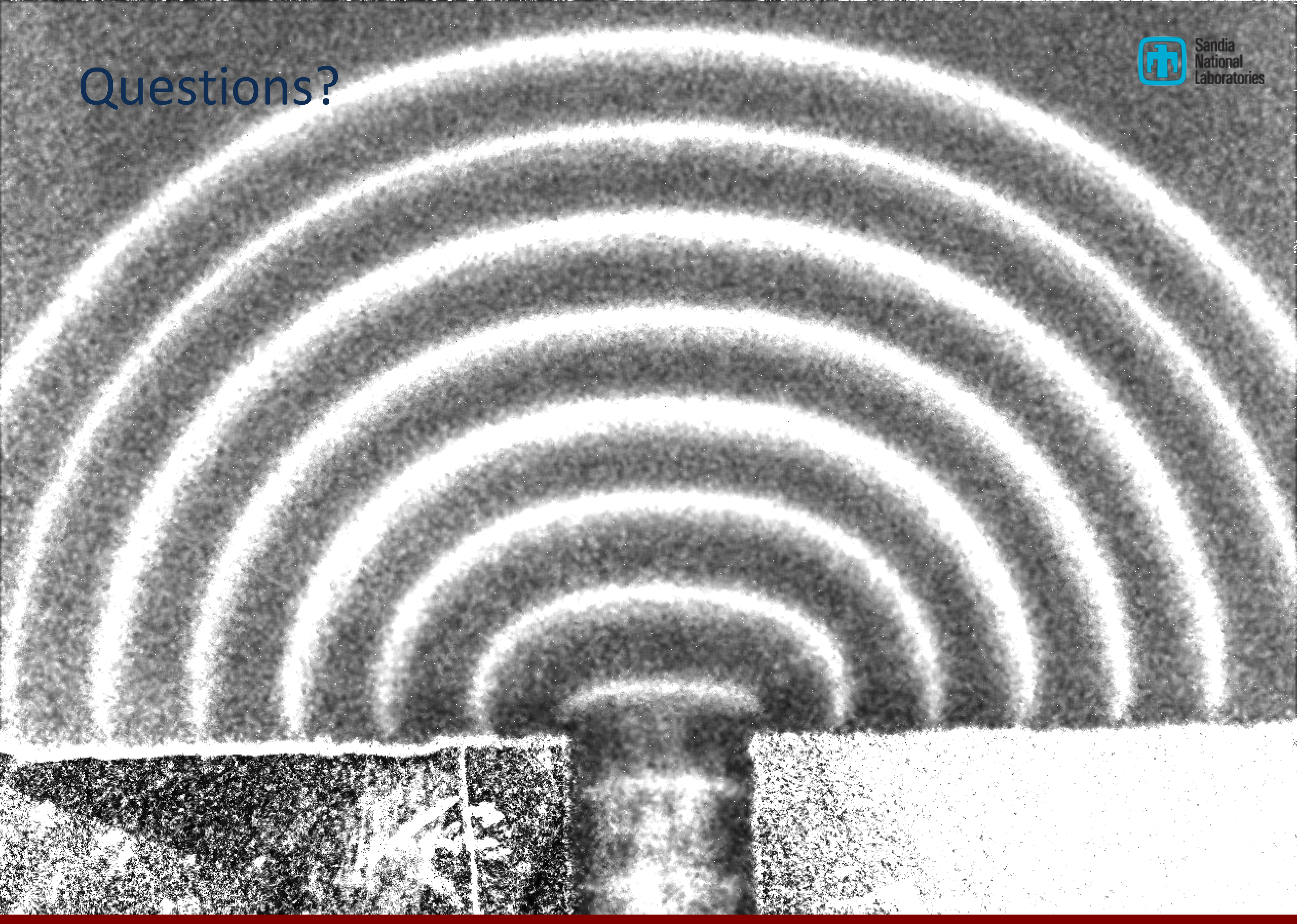
- PETN, micron-scale grains, 80 – 85% dense
- HNAB, sub-micron-scale grains, 99.5% dense
- Reaction zone of both materials is ~ 1 µm
- Microstructure appears to influence corner turning behavior

Conclusions

- PETN dead zone is sub-millimeter
  - Films are lower density with micron-sized grains
- HNAB dead zone is ~ 1 mm and highly variable
  - Films are high density with sub-micron-sized grains

- Acknowledgements:
  - Michael P. Marquez, Jon Vasiliauskas
  - Stephen Rupper, Tom Conwell
  - Caitlin O'Grady, James Erikson
  - M. Barry Ritchey
- Funding:
  - Sandia's Laboratory Directed Research and Development Program
  - Joint Department of Defense/Department of Energy Munitions Technology Development Program

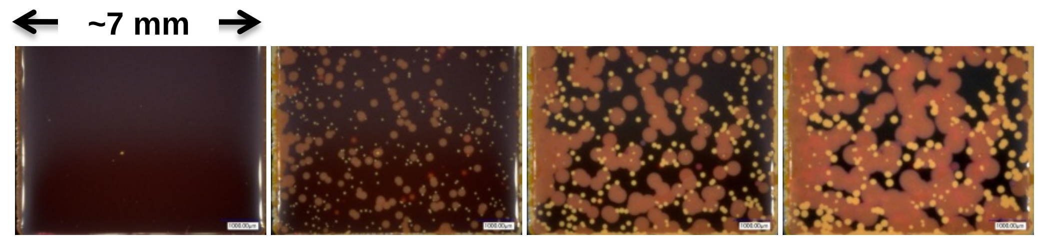
Questions?



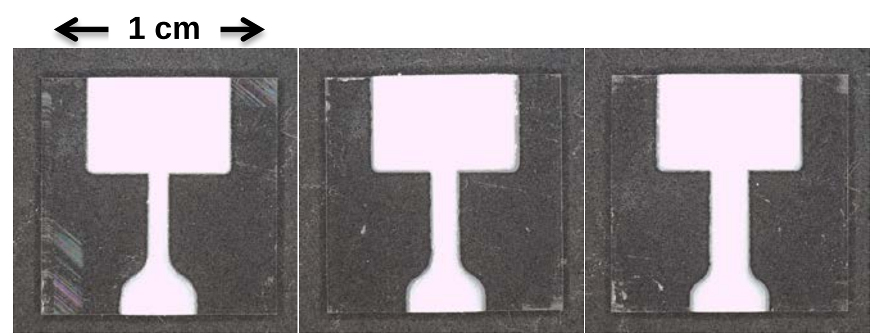
Backup slides

Micromushroom samples Characteristics

- PETN
  - 173 µm and 277 µm
- HNAB
  - 150 µm, crystallized at 35 ˚C
- Mushroom stem widths
  - 0.75, 1.00, 1.50 mm
- Mushroom cap width
  - 6 mm
- PETN Parylene C coated
- Polycarbonate lid, Sylgard® 184 encapsulated to prevent air shock



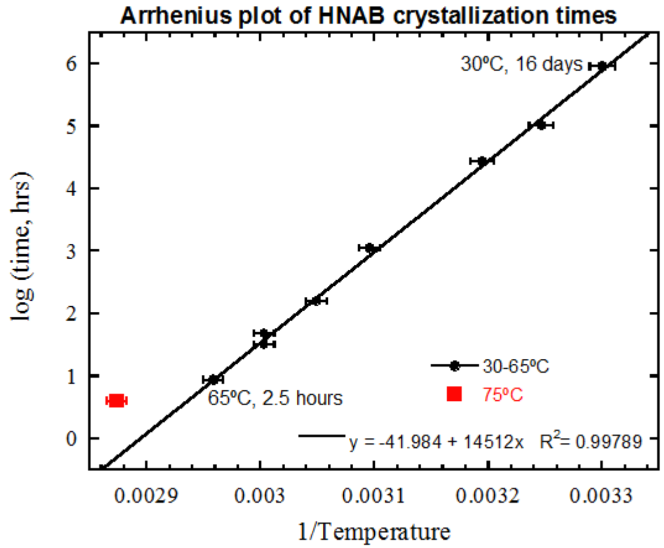
HNAB crystallization, time-lapse 65 °C, 24 min./image.

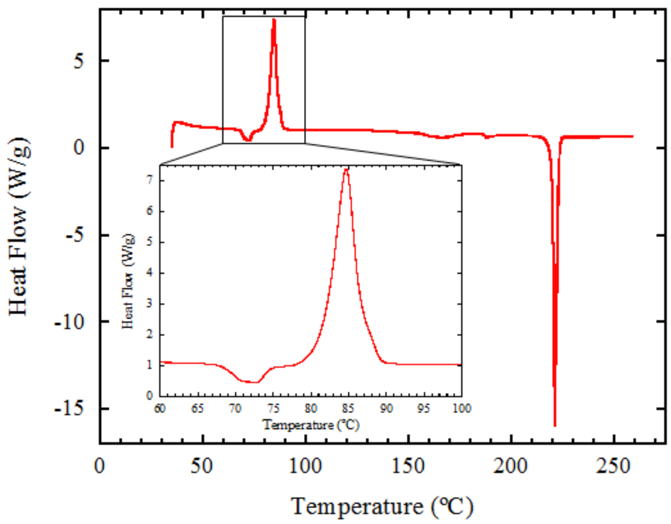


Optical micrographs of deposited PETN with stem widths of 0.75, 1.00, and 1.50 mm.

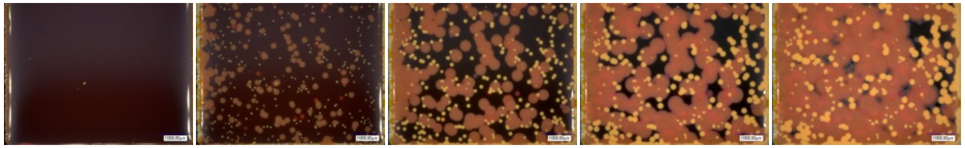
HNAB crystallization

- Amorphous HNAB films crystallize over time
- Pronounced difference in crystallization above glass transition temperature (T_g, ~70 °C)





DSC data from an amorphous HNAB film heated from 40–250 °C at 5 °C/min.



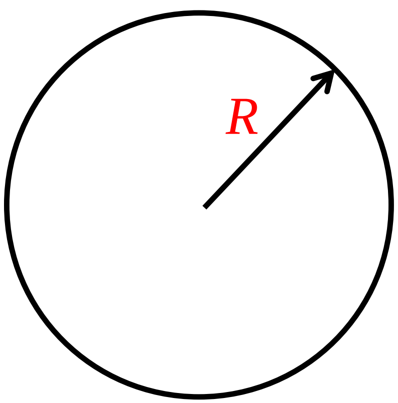
Time-lapse of HNAB crystallization, 65 °C, 24 min./image.

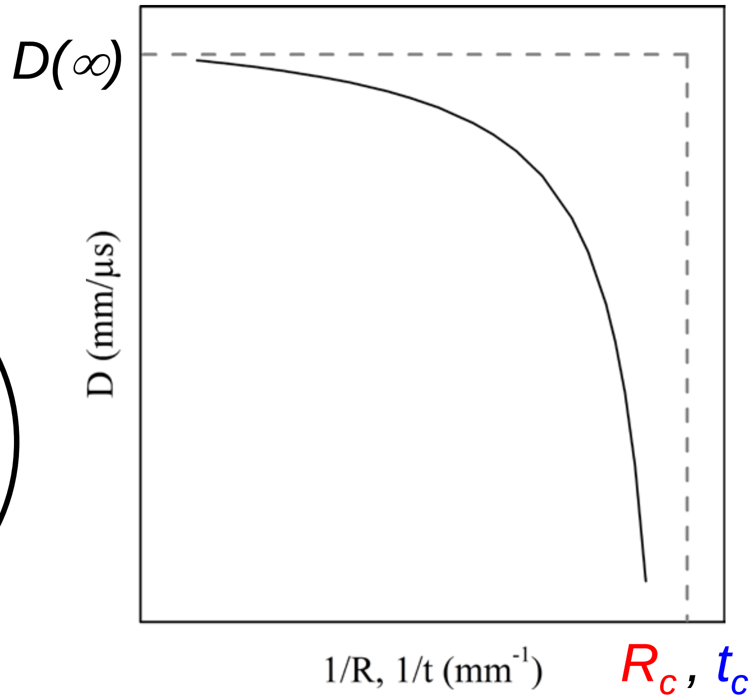
Knepper, R., Browning, K., Wixom, R.R., Tappan, A.S., Rodriguez, M.A., and Alam, M.K., "Microstructure Evolution during Crystallization of Vapor-Deposited Hexanitroazobenzene Films," *Propellants, Explosives, Pyrotechnics*, vol. 37, pp. 459 – 467, 2012.

Geometry effects on detonation failure

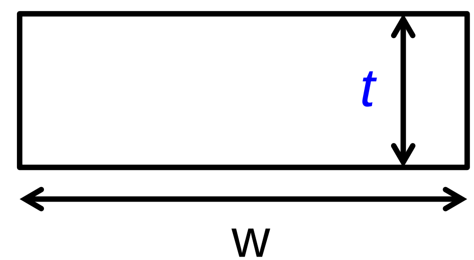
$$D(R) = D(\infty)\left[1 - \frac{1}{R}\left(\frac{A}{1-R_c\frac{1}{R}}\right)\right] \quad \Bigg| \quad D(t) = D(\infty)\left[1 - \frac{1}{t}\left(\frac{A}{1-t_c\frac{1}{t}}\right)\right]$$

Critical diameter configuration.





Critical thickness configuration.

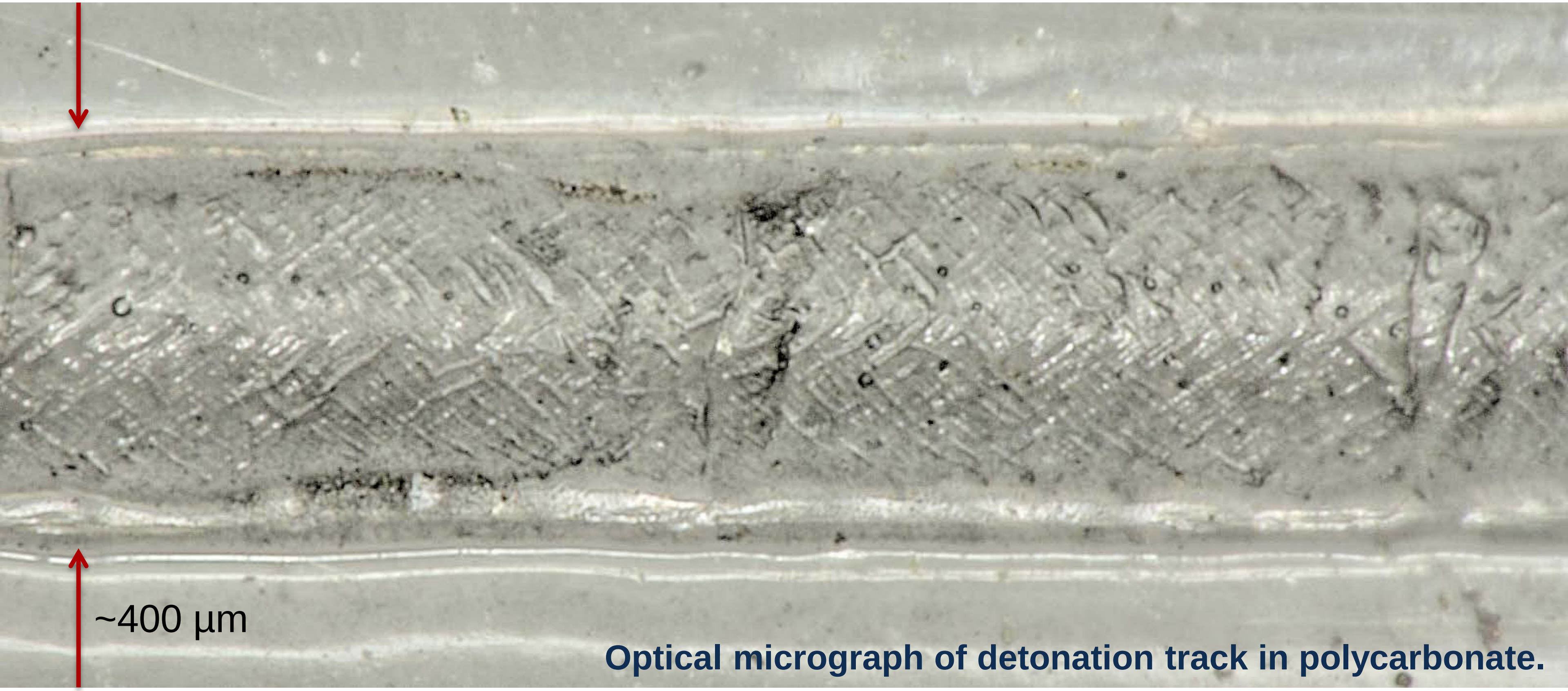


- How does width affect detonation failure?

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.*

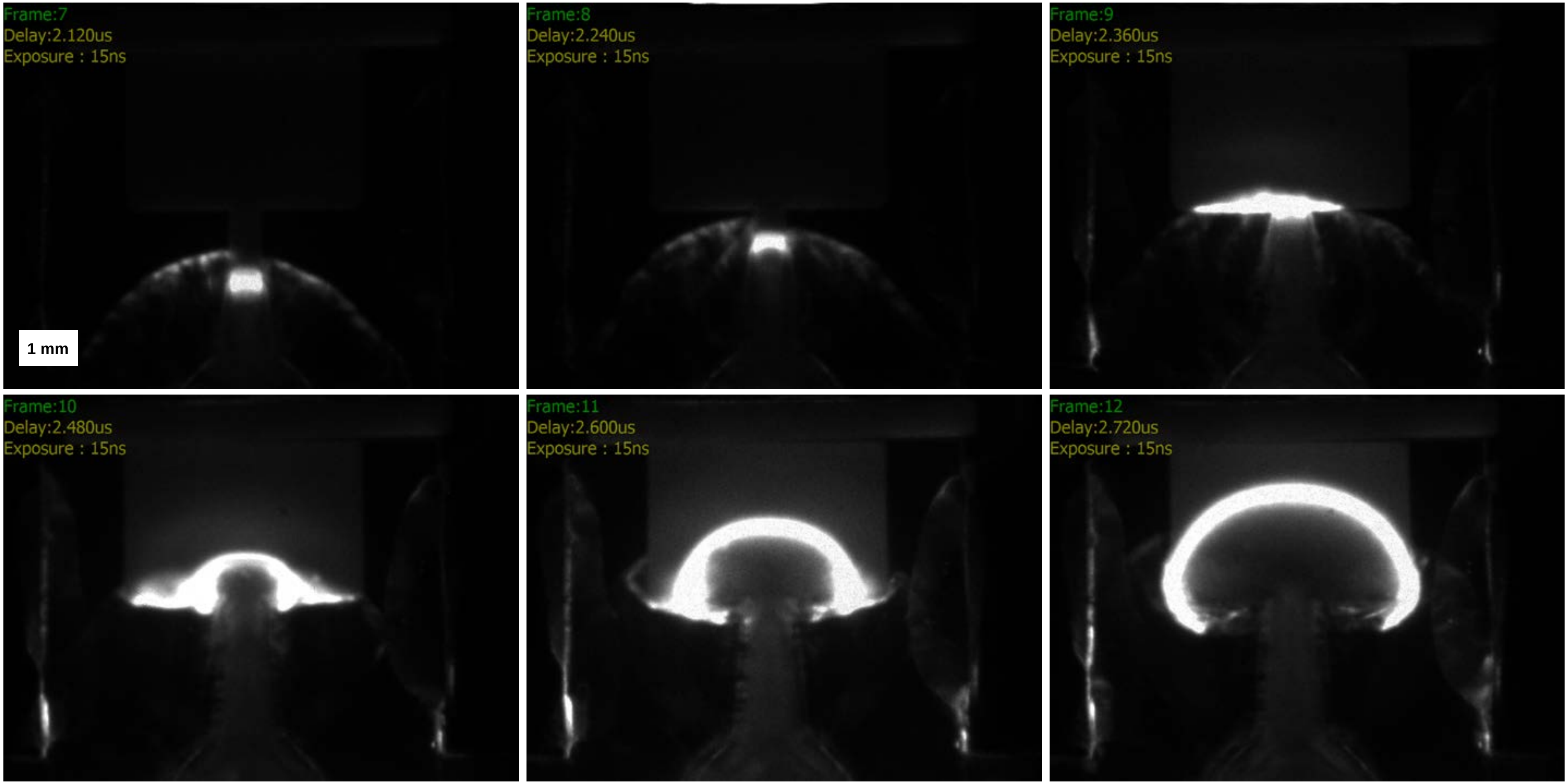
Detonation wave structure recorded in polycarbonate substrate

- Cellular structure observed frequently in HNAB especially near edges in films near failure



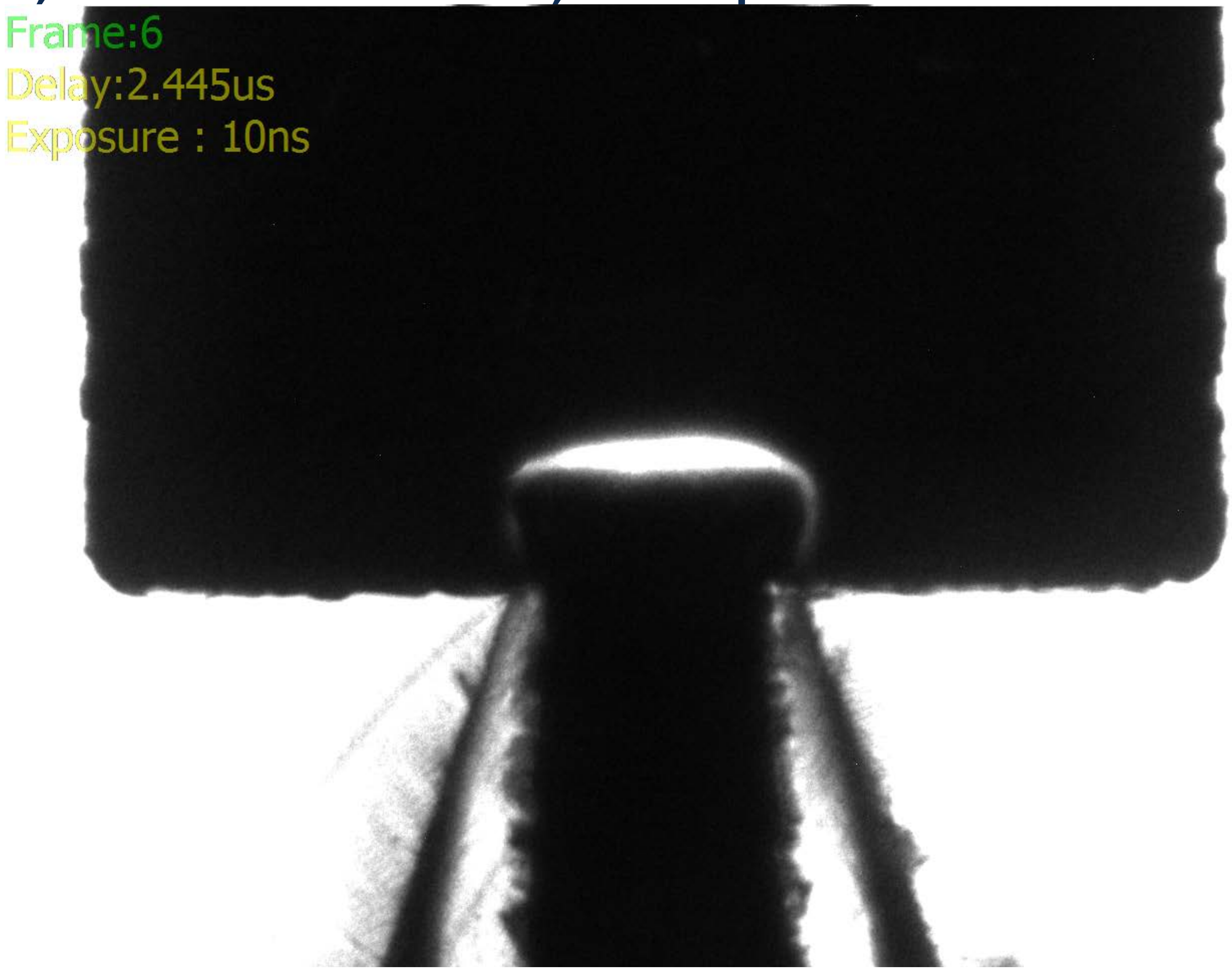
Optical micrograph of detonation track in polycarbonate.

Air shock preceding detonation wave



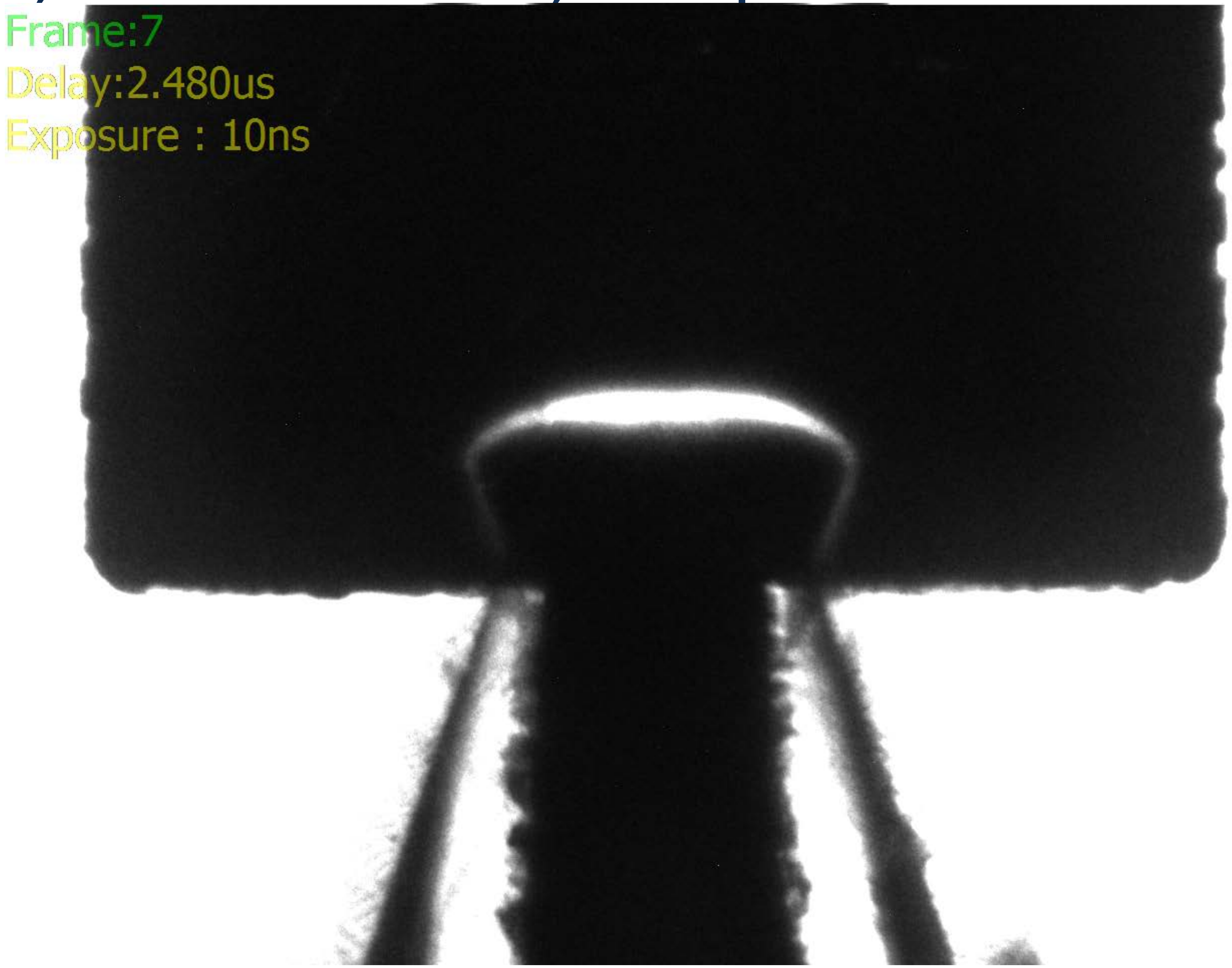
Framing camera images of PETN micromushroom, 15 ns, 8.3 MHz (1/120 ns). Some effect seen on corner turning. Possible dead-pressing.

Corner turning,
HNAB, 1.00 mm stem, 150 µm thick



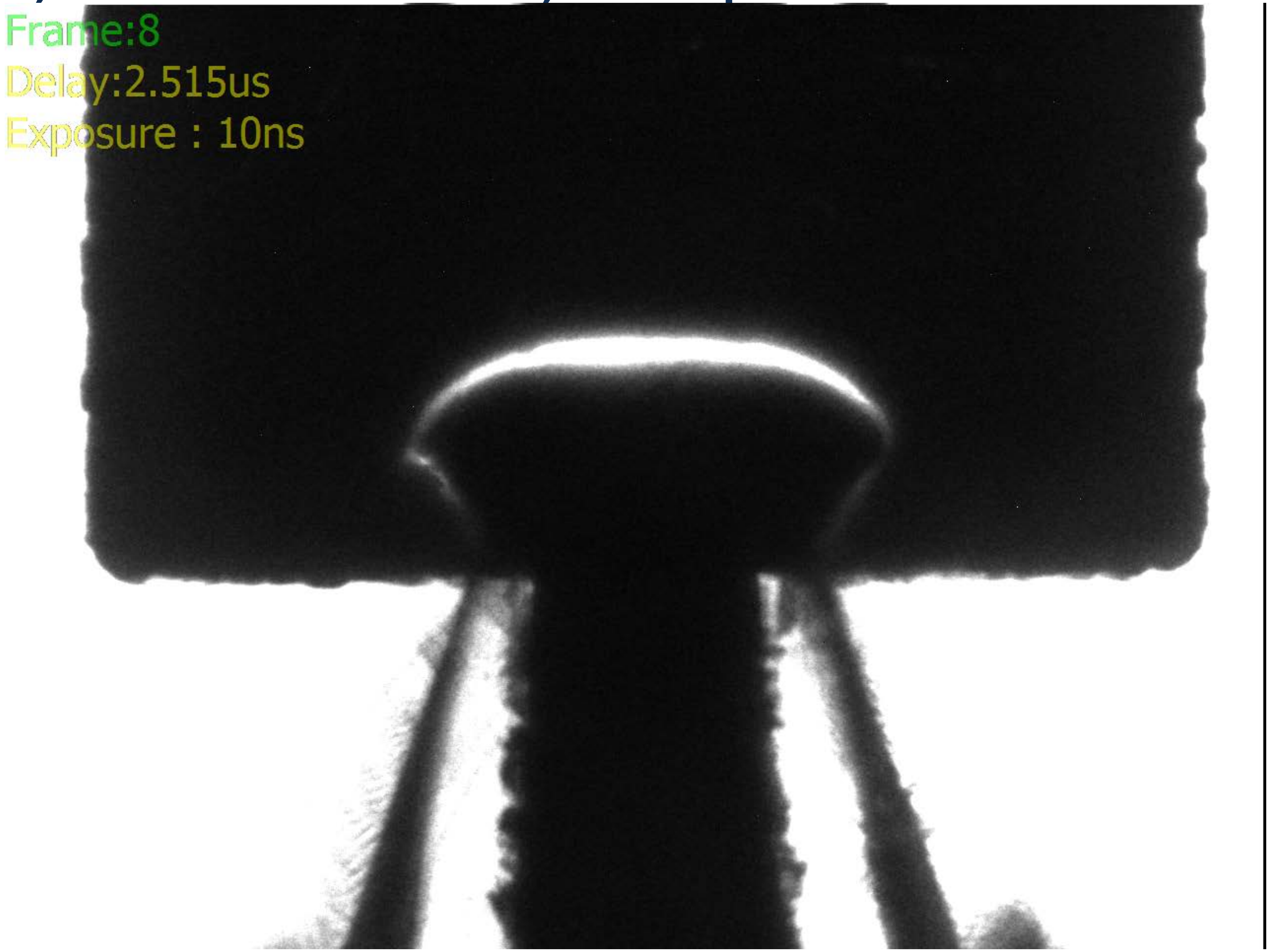
Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

Corner turning, HNAB, 1.00 mm stem, 150 µm thick



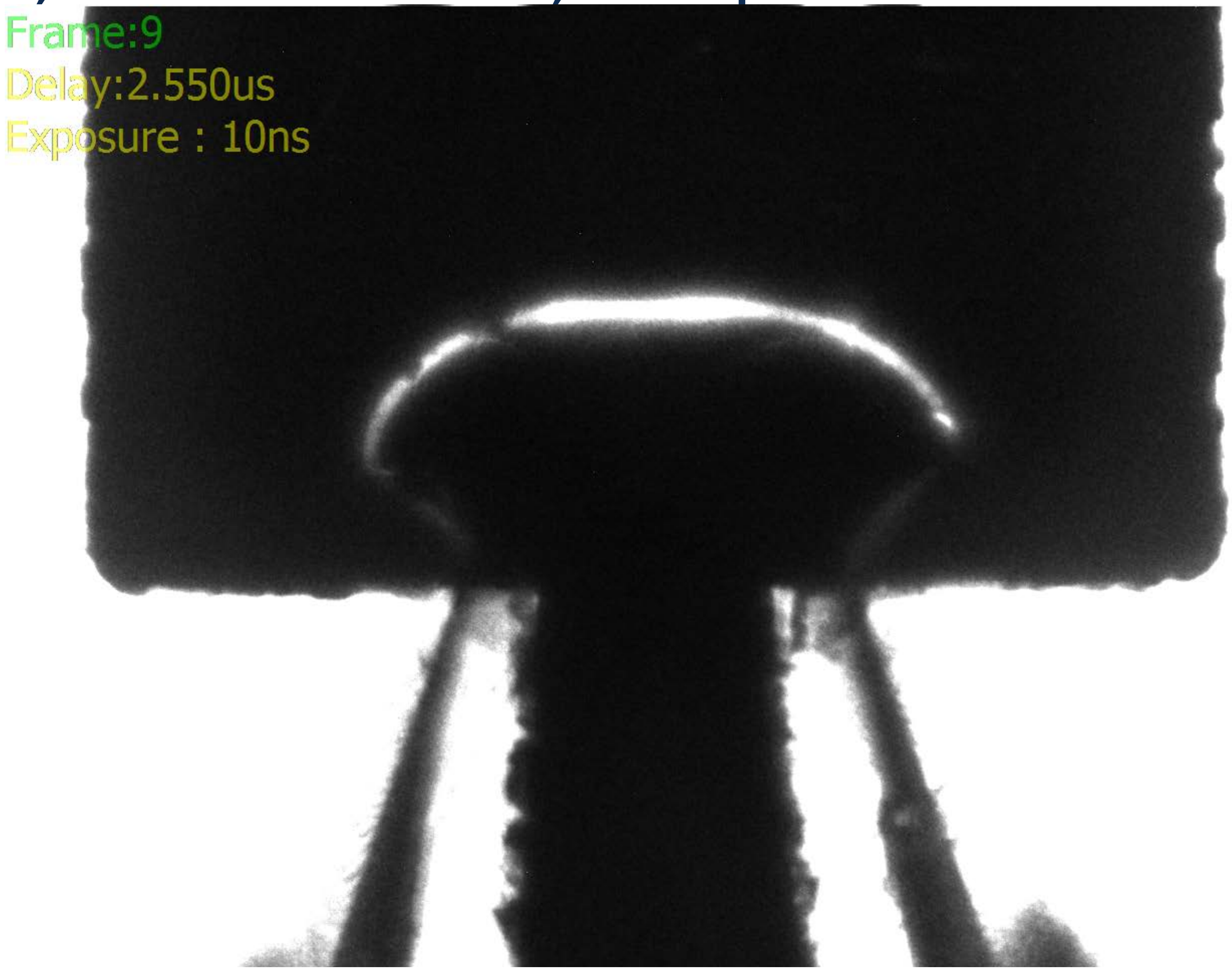
Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

Corner turning,
HNAB, 1.00 mm stem, 150 µm thick



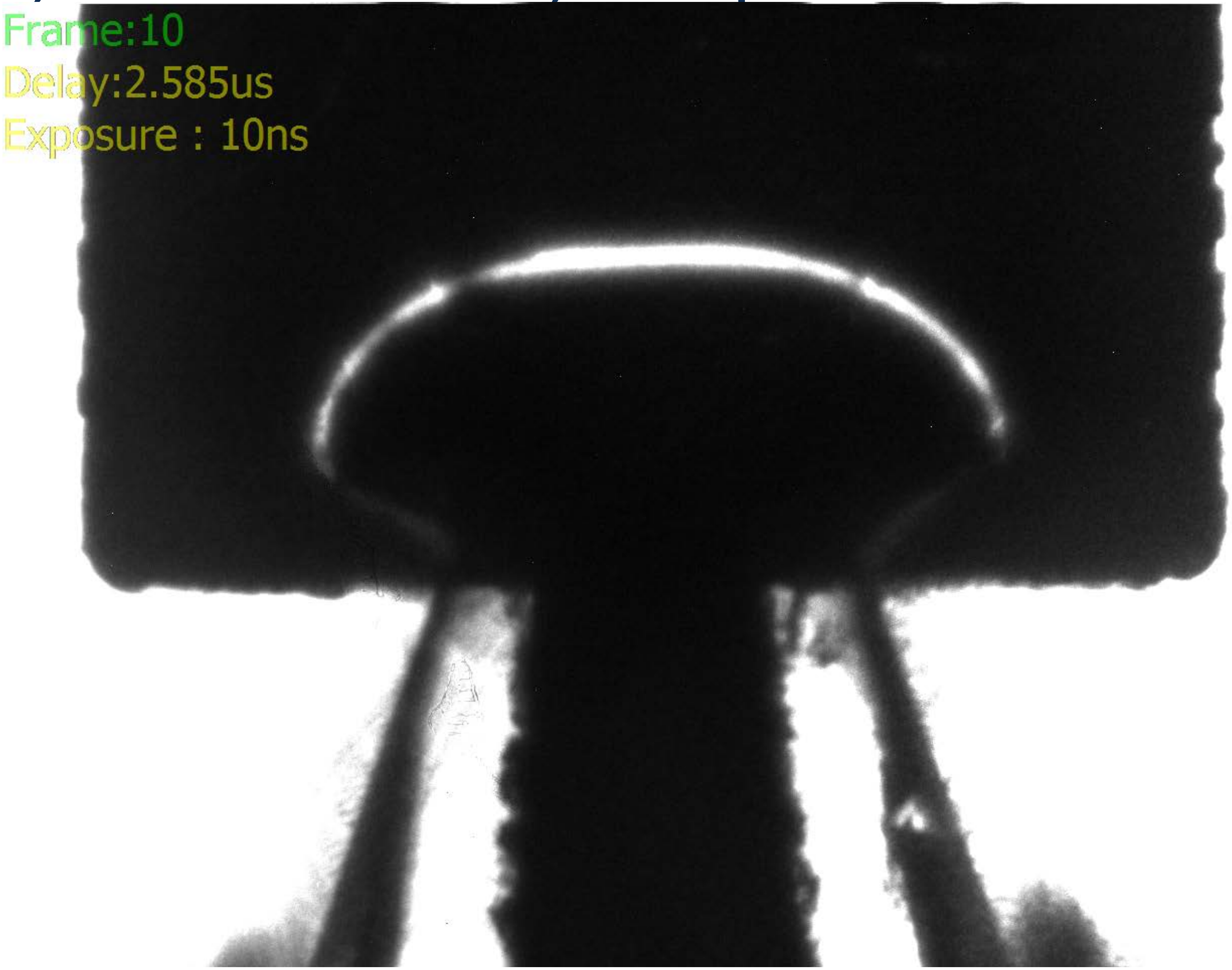
Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

Corner turning,
HNAB, 1.00 mm stem, 150 µm thick



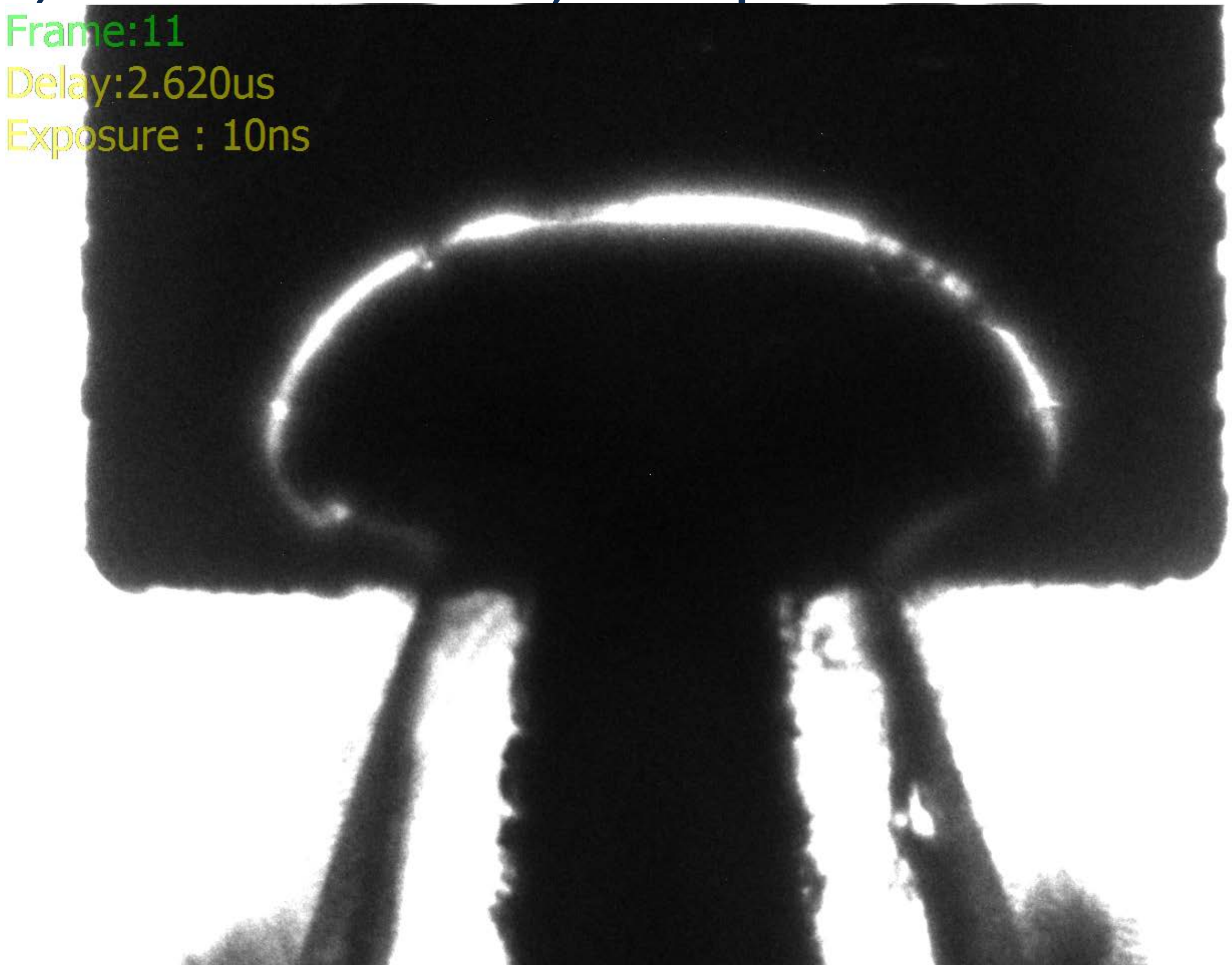
Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

Corner turning, HNAB, 1.00 mm stem, 150 µm thick



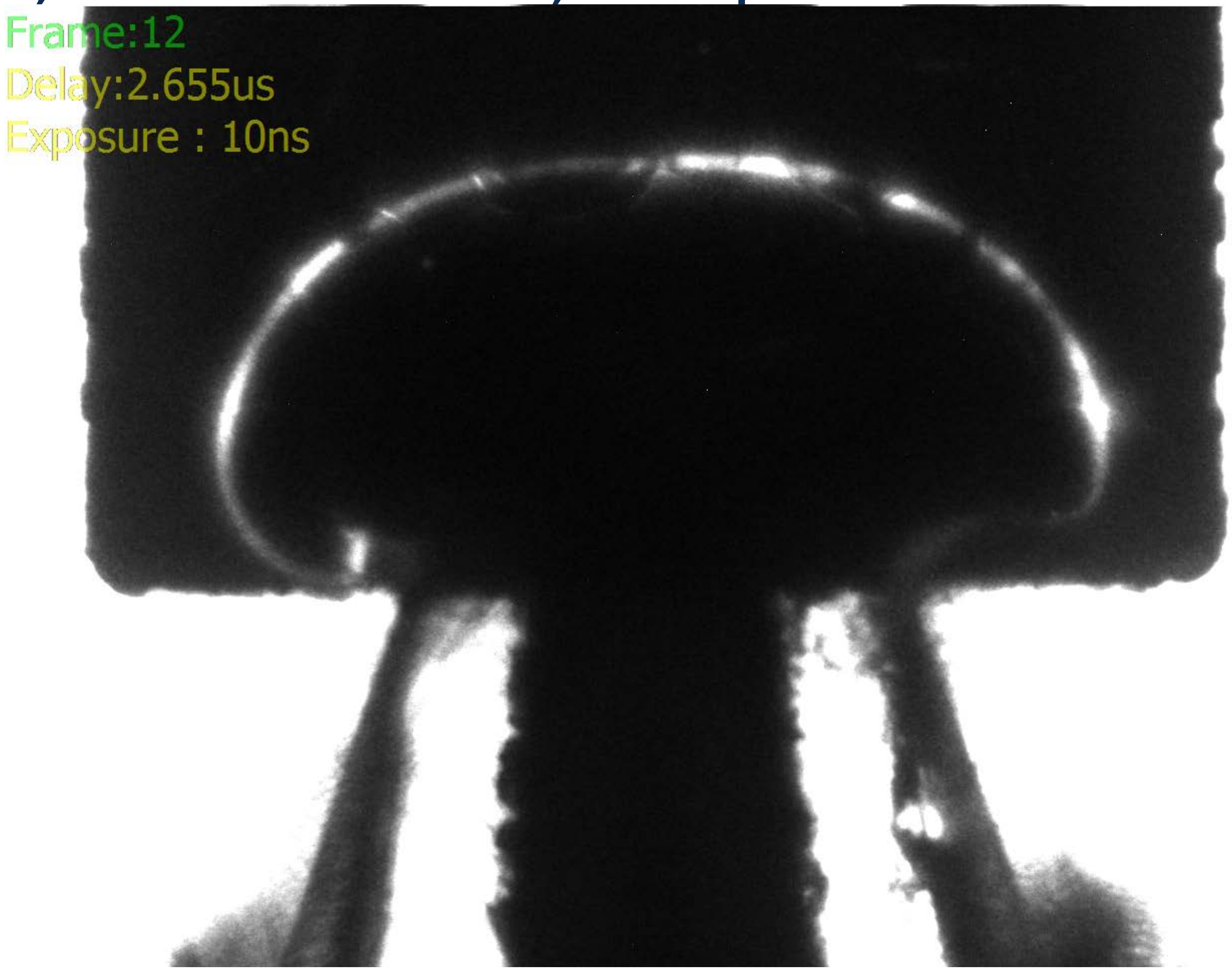
Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

Corner turning,
HNAB, 1.00 mm stem, 150 µm thick



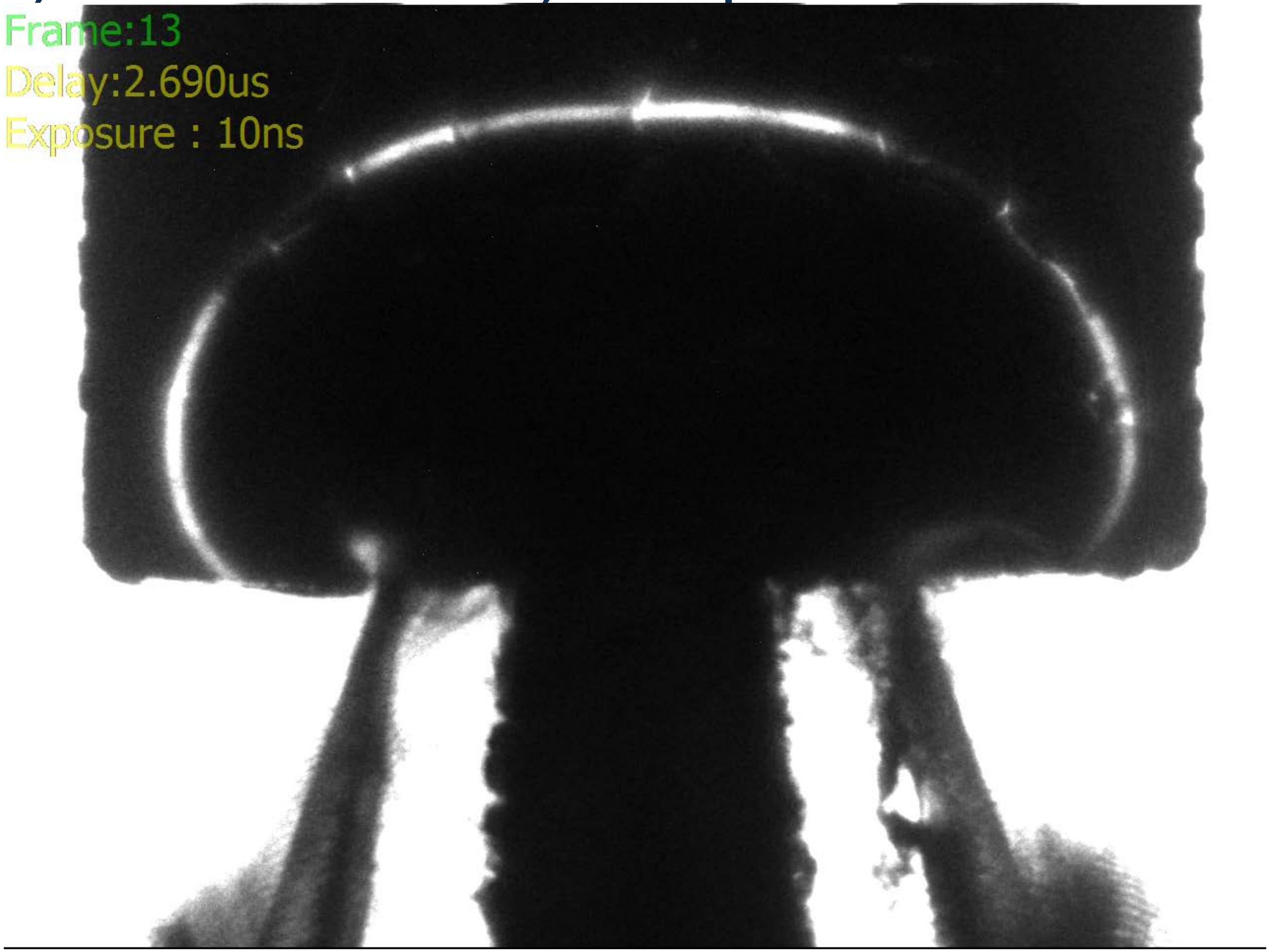
Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

Corner turning, HNAB, 1.00 mm stem, 150 µm thick



Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

Corner turning,
HNAB, 1.00 mm stem, 150 µm thick



Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).

Corner turning,
HNAB, 1.00 mm stem, 150 µm thick

Framing camera images of HNAB micromushroom, 10 ns, 22 MHz (1/45 ns).