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Quantification of Explosively Driven Shock Wave Propagation and Attenuation in Polymethyl Methacrylate (PMMA)

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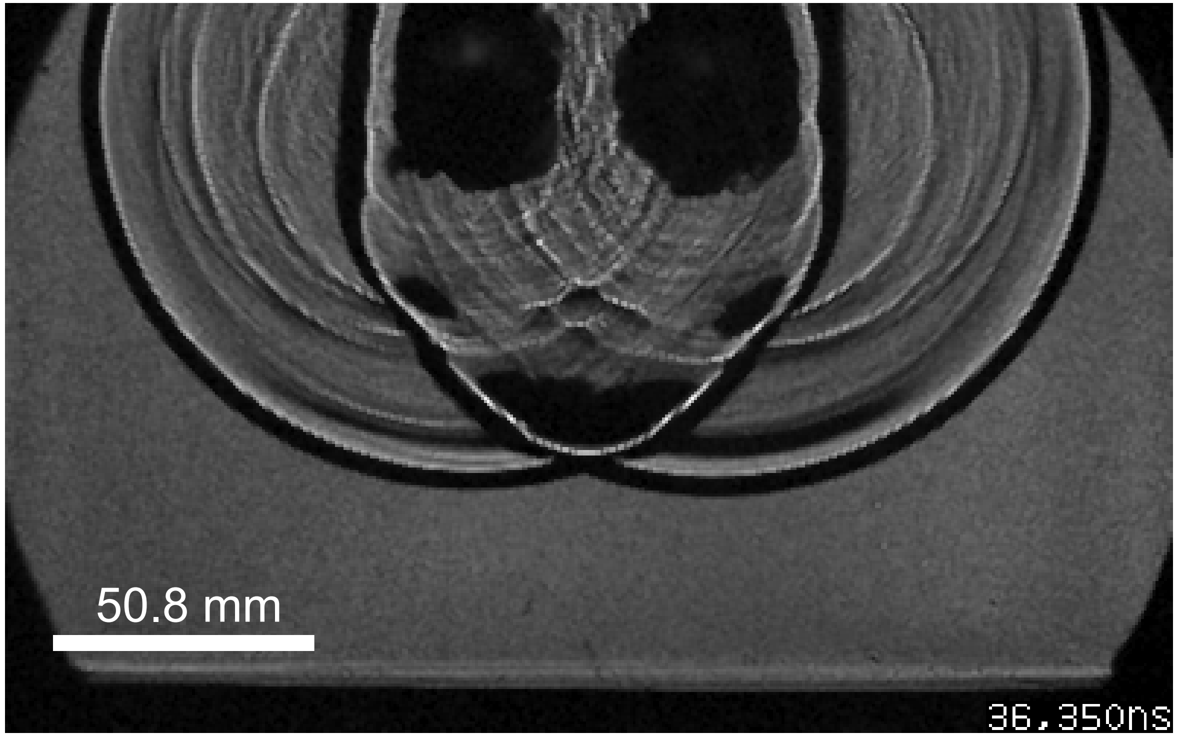
Explosively-driven fracture is a complex process involving varied physical processes and multiple timescales

- Characterizing explosively-driven fracture propagation requires understanding shock response, gas production, and material state
- Many applications for explosively-driven fracture are for geologic applications including oil/gas extraction and geothermal well formation
- In optically transparent materials shock propagation can be measured using high-speed imaging
  - PMMA is a good substitute for geologic materials



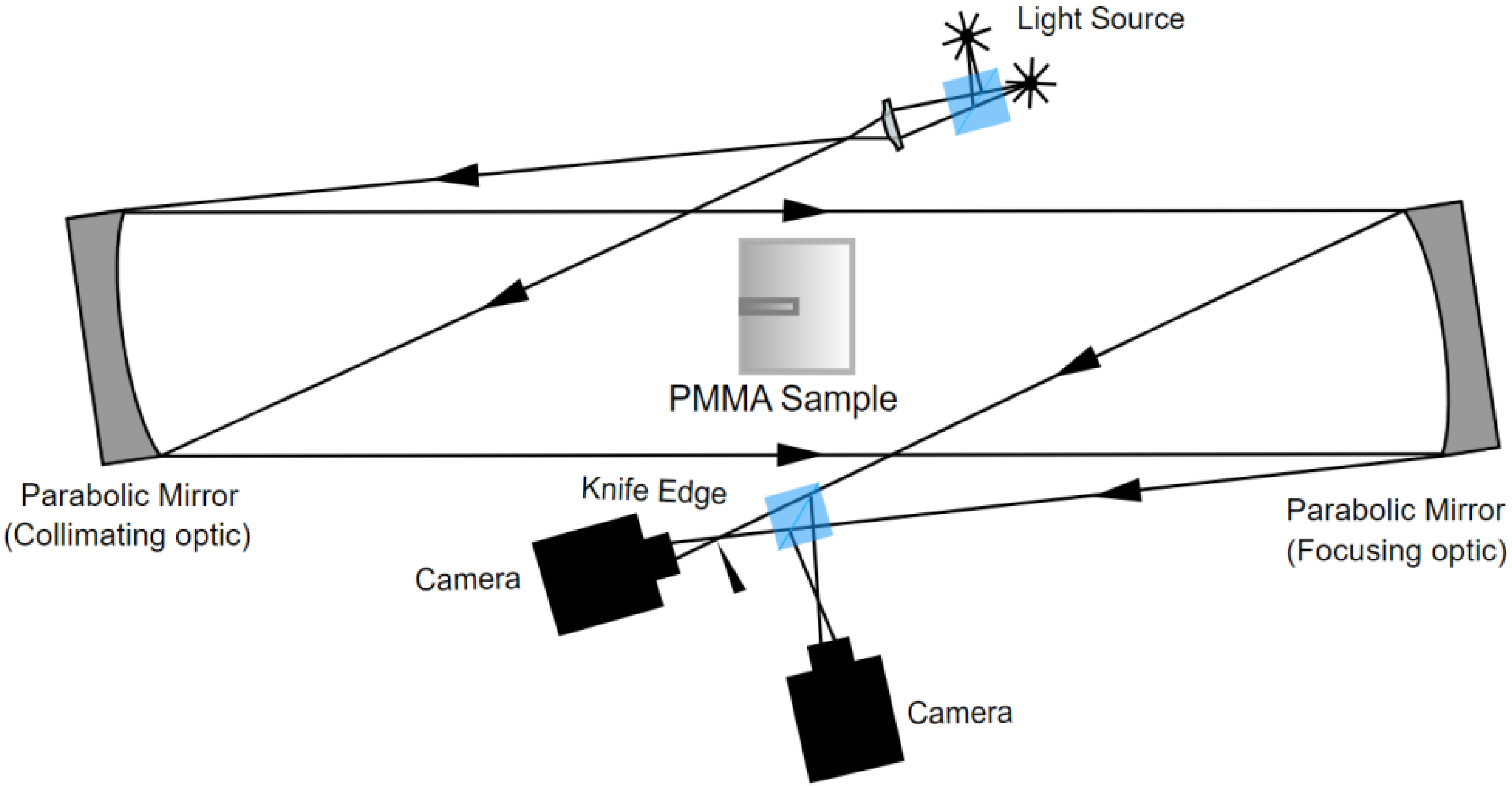
PMMA is a well characterized material for experimental impact studies

- Interferometry methods such as Velocity Interferometer System for Any Reflector (VISAR) [1] and Photon Doppler Velocimetry (PDV) [1,2] are widely used for impact studies
- Schlieren and shadowgraphy have been implemented to study shock Hugoniots in transparent materials [5]
- Impact experiments impart a square pulse whereas an explosive source will decay
  - Spherical elastic waves decay with a r^{-1} behavior [4]
- Murphy et. al explored the pressure decay of PMMA under explosive loading [3]
  - PMMA explosively driven shock-attenuation exhibits a complex-decay trend
- PMMA can be used as a surrogate material for understanding the fracture process of rock allowing for optical techniques to for studying dynamic fracture growth [6]

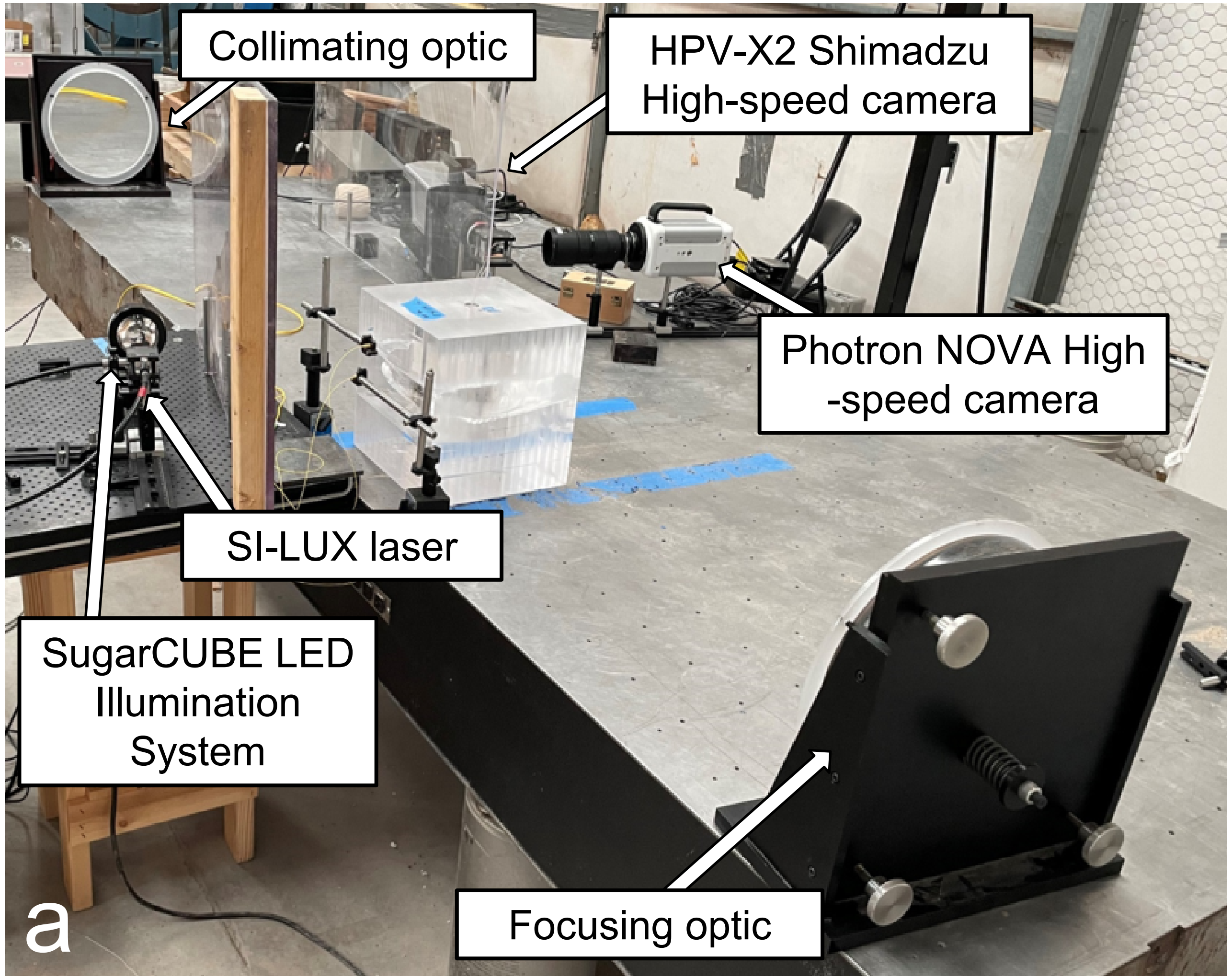
[1] Barker, L. M, and R. E Hollenbach. 1970. “Shock-Wave Studies of PMMA, Fused Silica, and Sapphire.” Journal of Applied Physics 41 (10): 4208–26. https://doi.org/10.1063/1.1658439.
[2] Jordan J.L, Casem D, and Zellner M. 2019. “Shock Response of Polymethylmethacrylate.” Journal of Dynamic Behavior of Materials 2 (3): 372–78. https://doi.org/10.1007/s40870-019-00185-z.
[3] Michael J. Murphy, Mark A. Lieber, and Matthew M. Biss , "Novel measurements of shock pressure decay in PMMA using detonator loading", AIP Conference Proceedings 1979, 160020 (2018)
[4] Meyers Dynamic Behavior Materials,1994-09,John Wiley & Sons, Inc.
[5] Svingala, F. R., Hargather, M. J., Settles, G. S. Optical techniques for measuring the shock Hugoniot using ballistic projectile and high-explosive shock initiation 2012-12 International Journal of Impact Engineering , Vol. 50 Elsevier BV p. 76-82
[6] Rossmanith, H. P, R. E Knasmillner, A Daehnke, and L Mishnaevsky. 1996. “Wave Propagation, Damage Evolution, and Dynamic Fracture Extension. Part I. Blasting.” Materials Science 32 (4): 403–10. https://doi.org/10.1007/BF02538964.

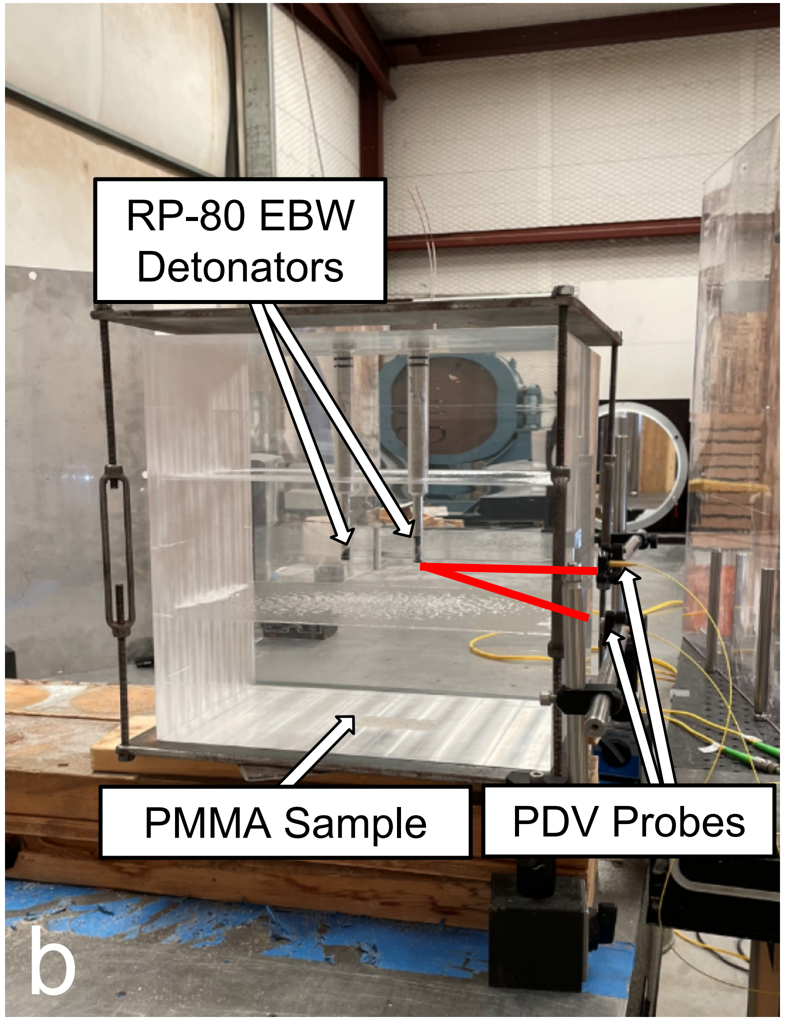
Schlieren imaging is a technique allowing for the visualization of the density gradient field in transparent material

- Light from a point source is collimated, and refocused down to a point
- Knife edge is placed at the focal point visualizing the first derivative of the refractive index



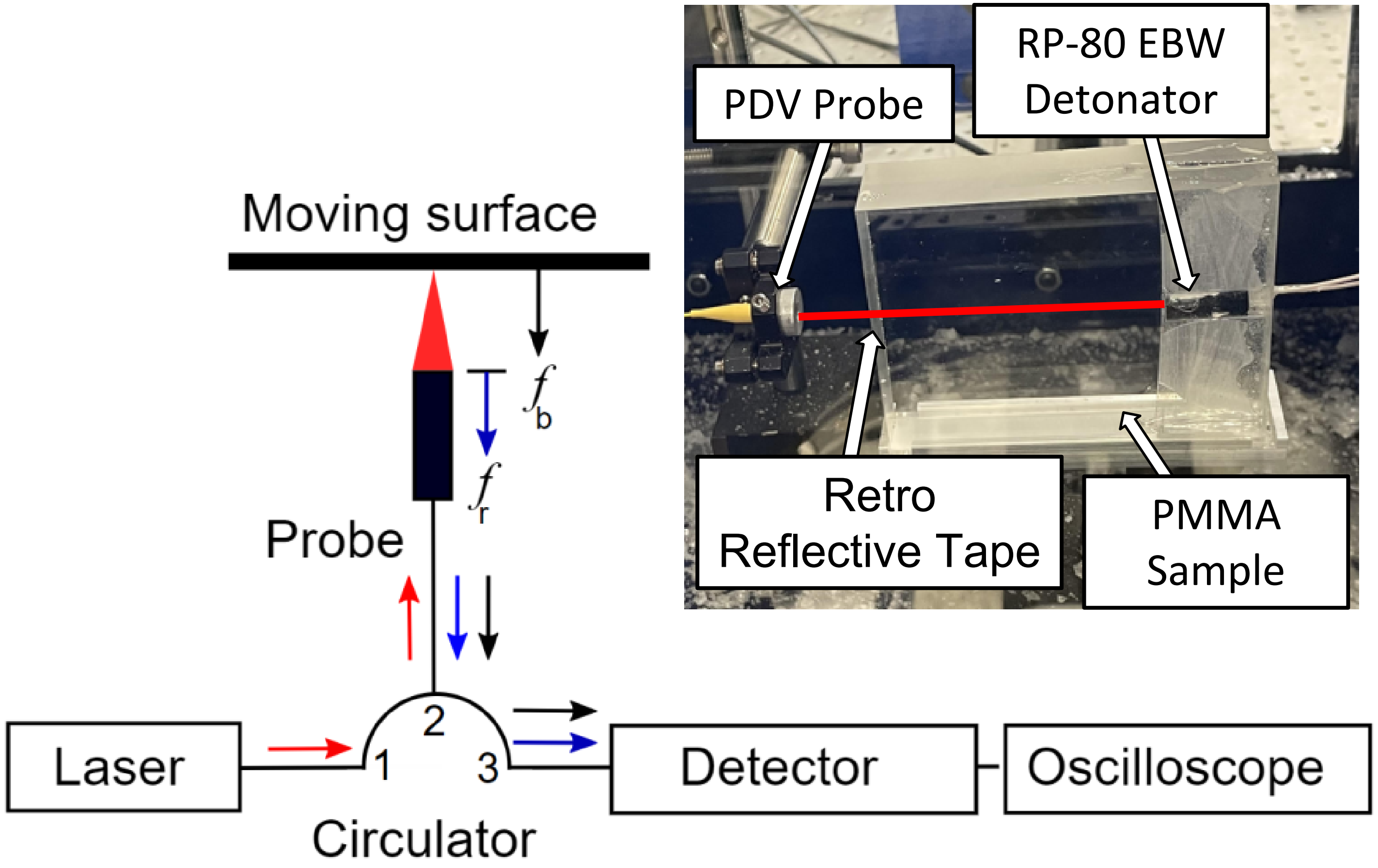
Small scale and large scale explosive testing have been preformed





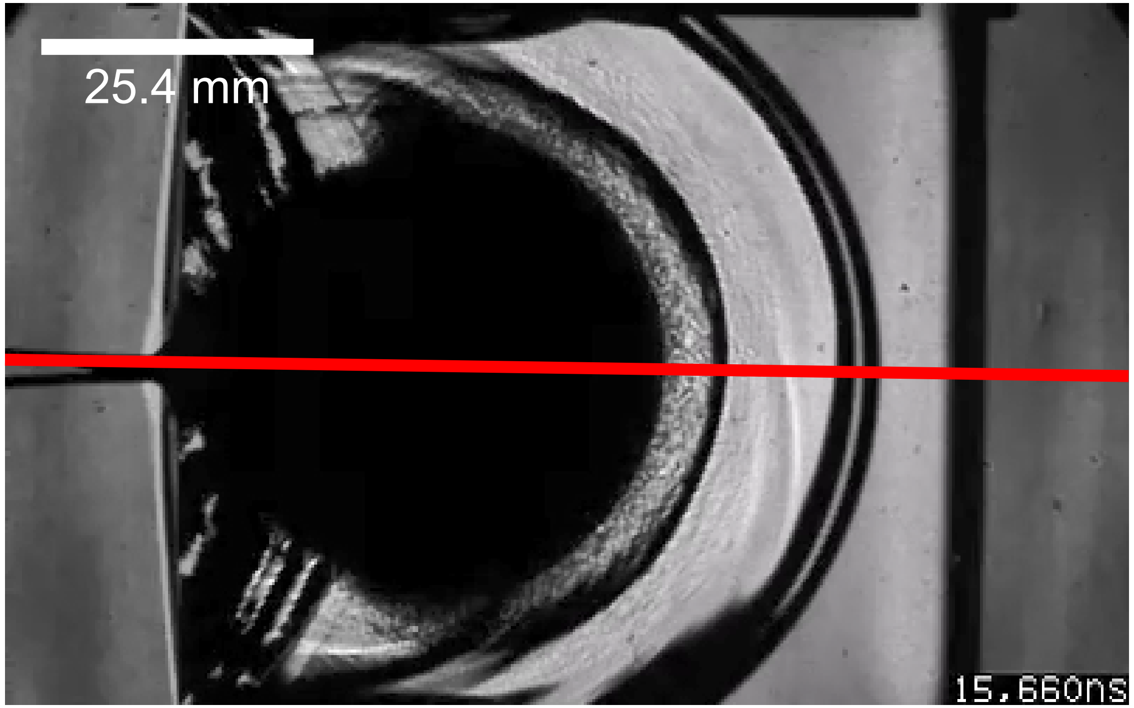
PDV is an interferometry technique used for measuring surface movement

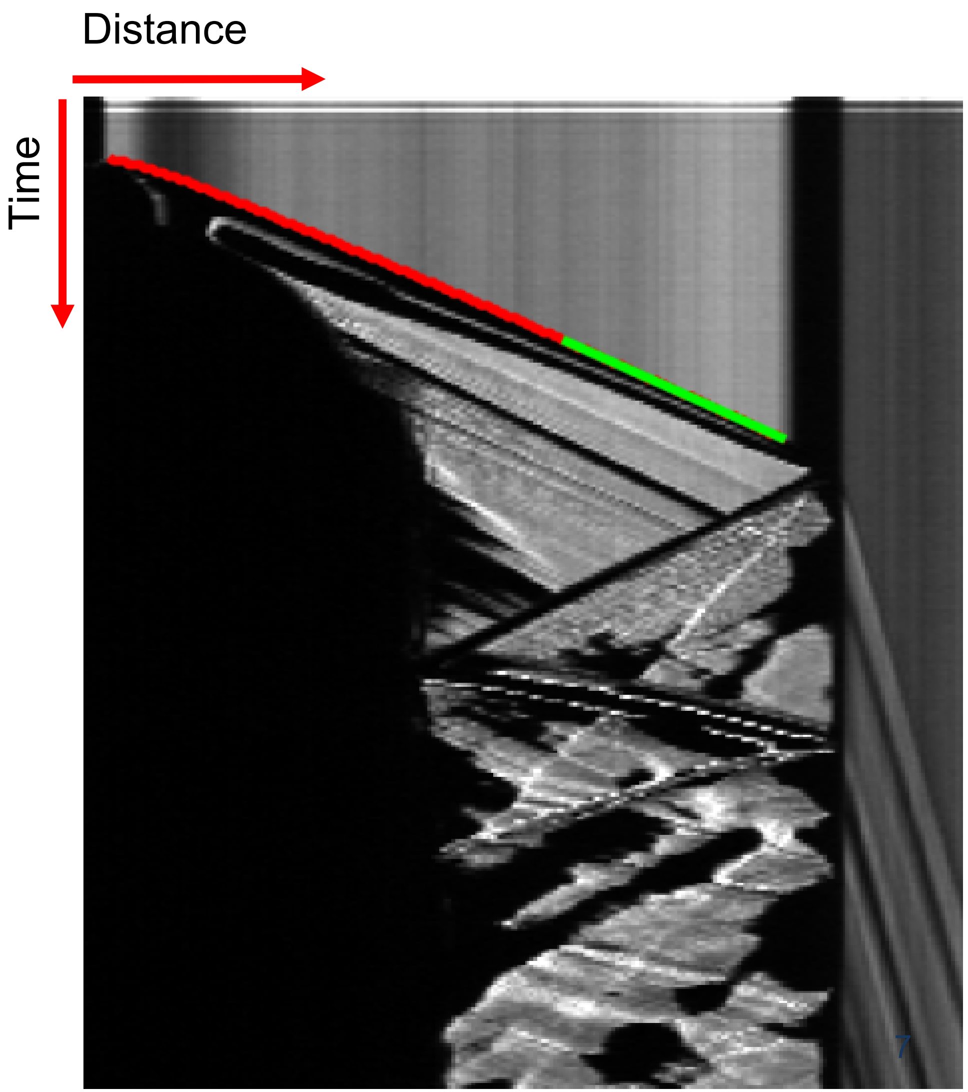
- Experimentally determine particle velocity at a free surface or an interface
- Surface movement Doppler shifts light
- Doppler shifted light is combined with the reference laser light producing an interference pattern
- The interference pattern is represented as a beat frequency which is converted to particle velocity



Shock wave propagation is characterized from the high-speed images through digital streak images

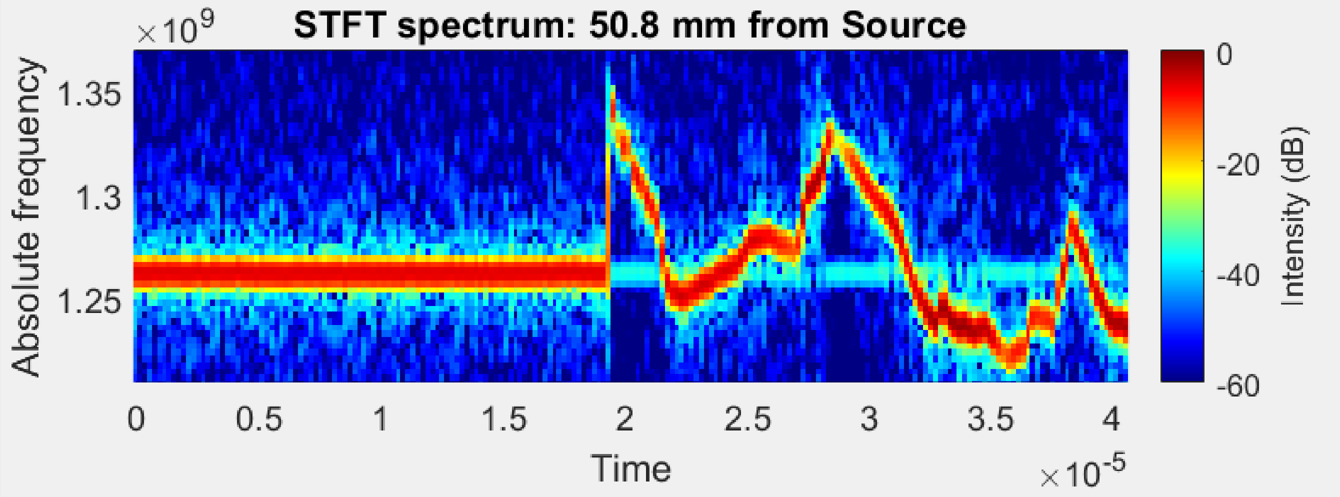
- Shock boundary is extracted using MATLAB
- The inverse of the slope is the shock velocity

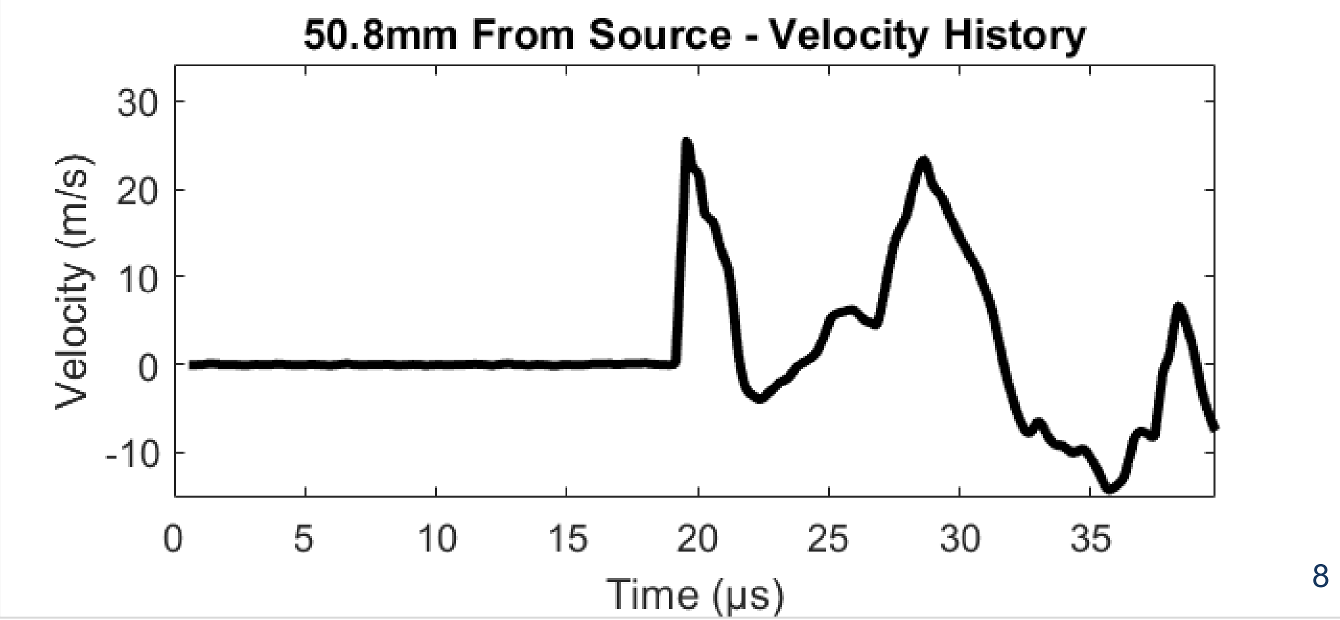




PDV signals were processes using SIRHEN (Sandia InfraRed HEtrodyne aNalysis) a data reduction software developed by Sandia National Labs [6]

- The recorded signal is analyzed using a short-time Fourier transform
- Peaks in the power spectrum are found through a peak finding algorithm
- The peak frequencies are converted to velocity

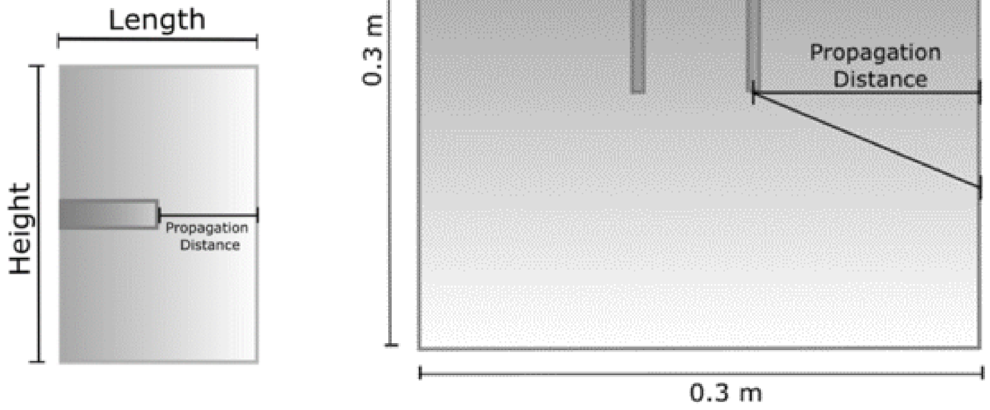


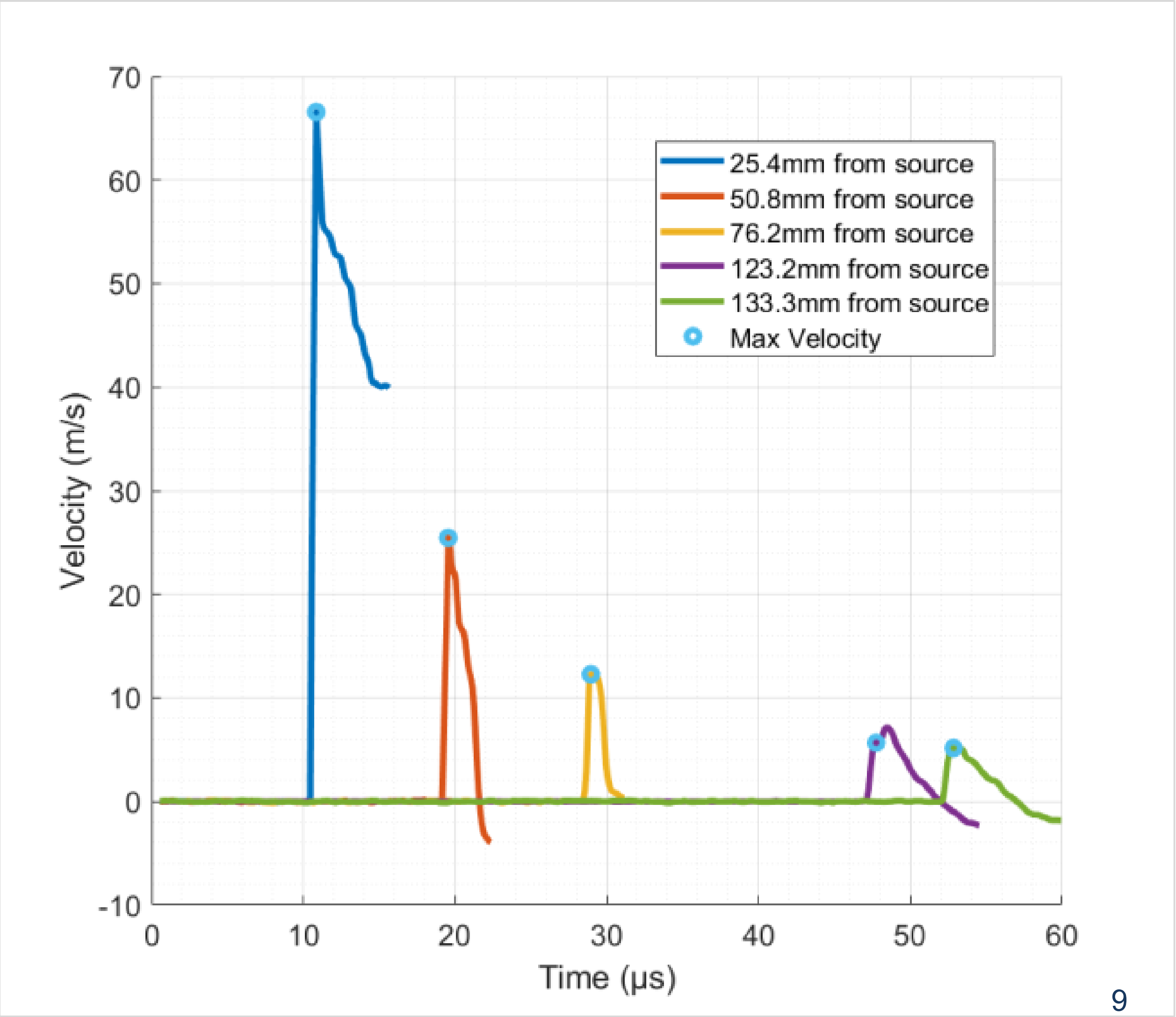


[6] Dolan, III, D. H., and Ao, T. *SIRHEN : a data reduction program for photonic Doppler velocimetry measurements.*. United States: N. p., 2010. Web. doi:10.2172/989357

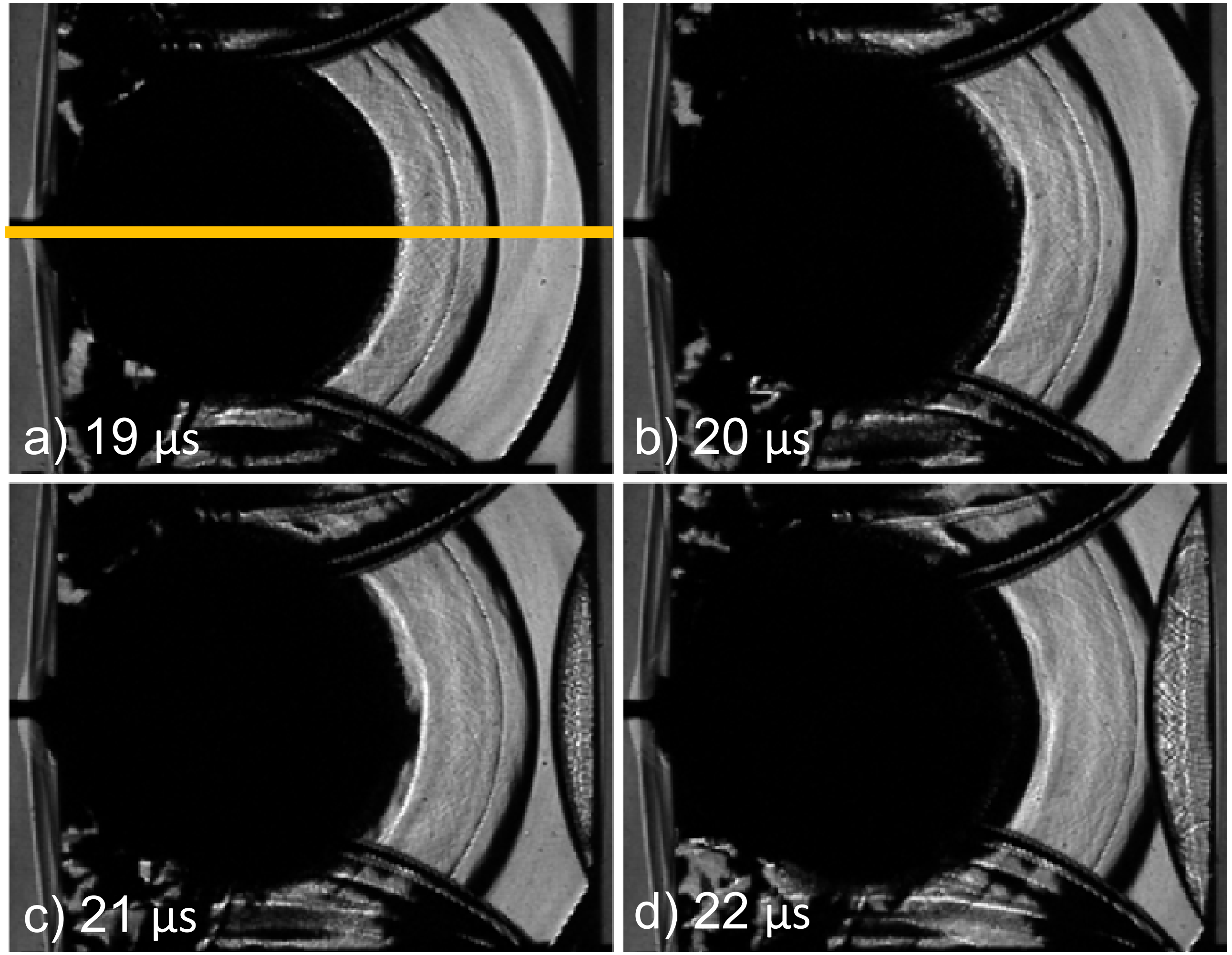
Explosively driven shock attenuation behavior of PMMA was experimentally determined

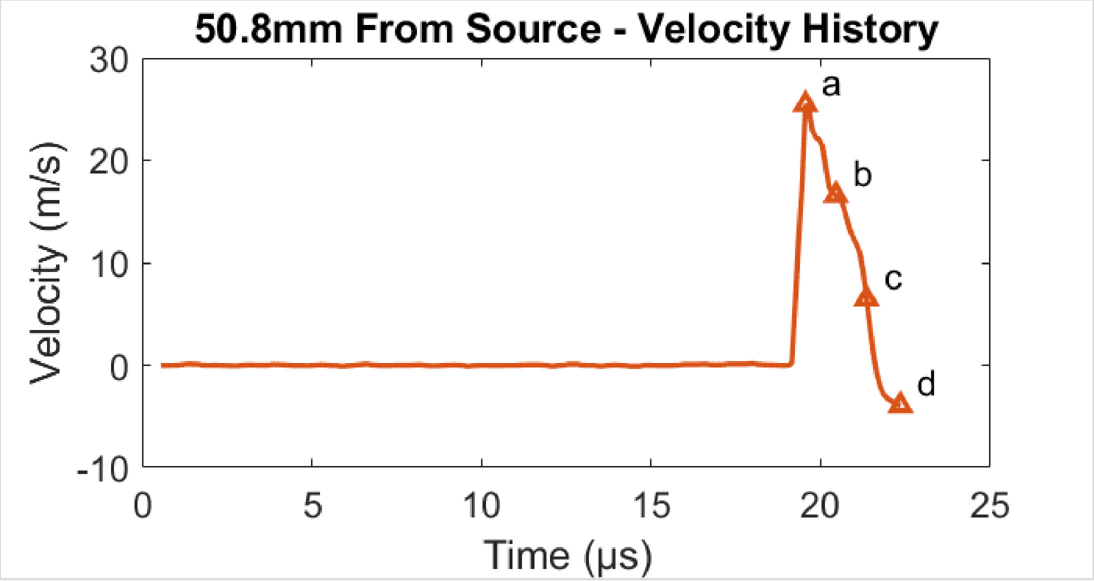
- Both near and far field data was collected

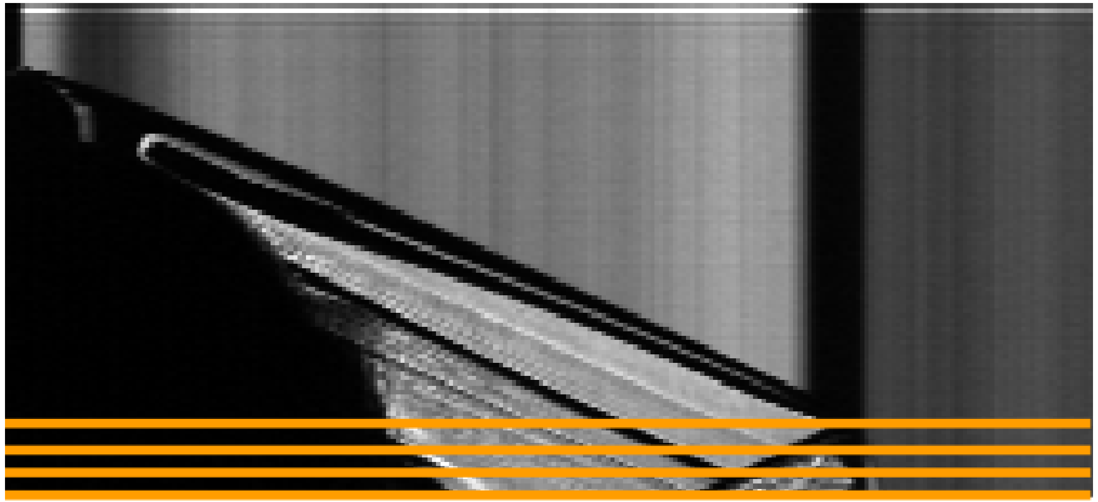




PDV data compared to the high speed schlieren images

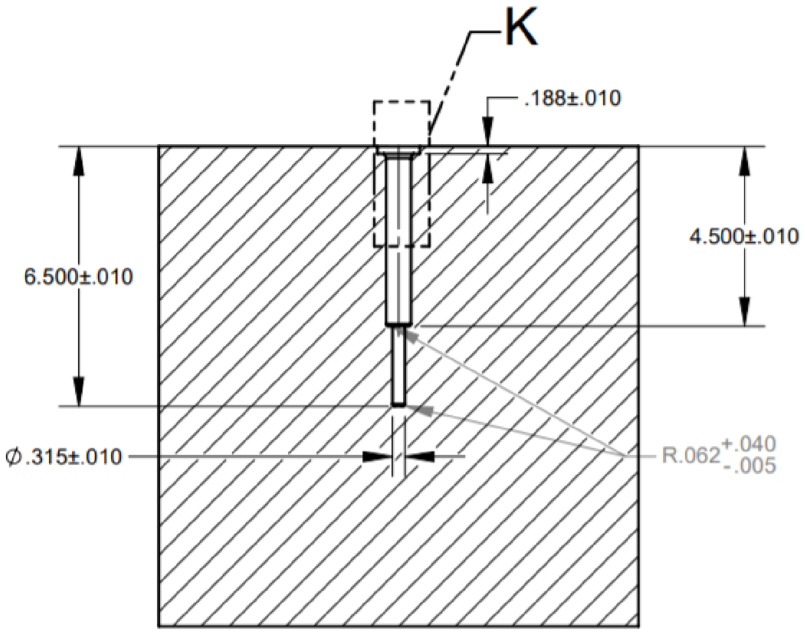


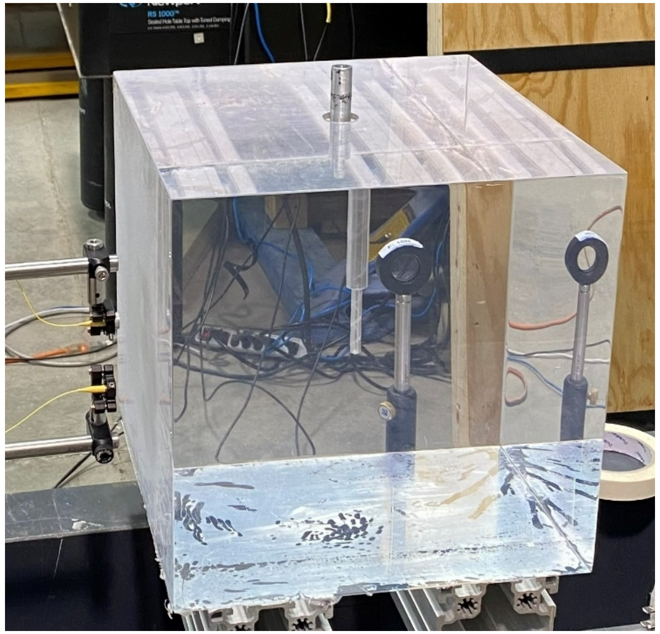


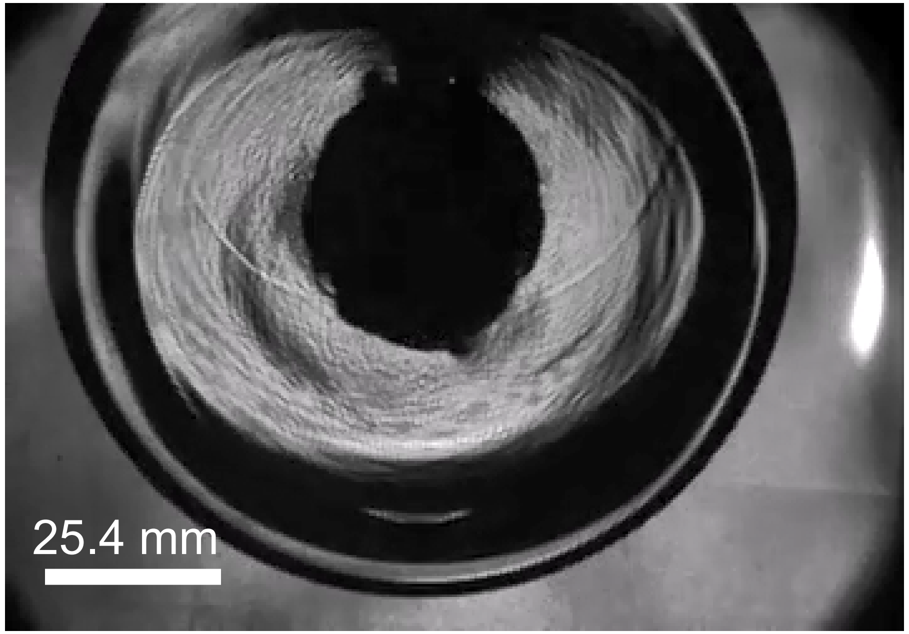


Large scale tests allow for understanding how confined explosive gases drive fracture growth

- Small scale test define the stress state imparted by the explosively driven shock wave
- High speed schlieren and shadowgraph were implemented in the large scale testing

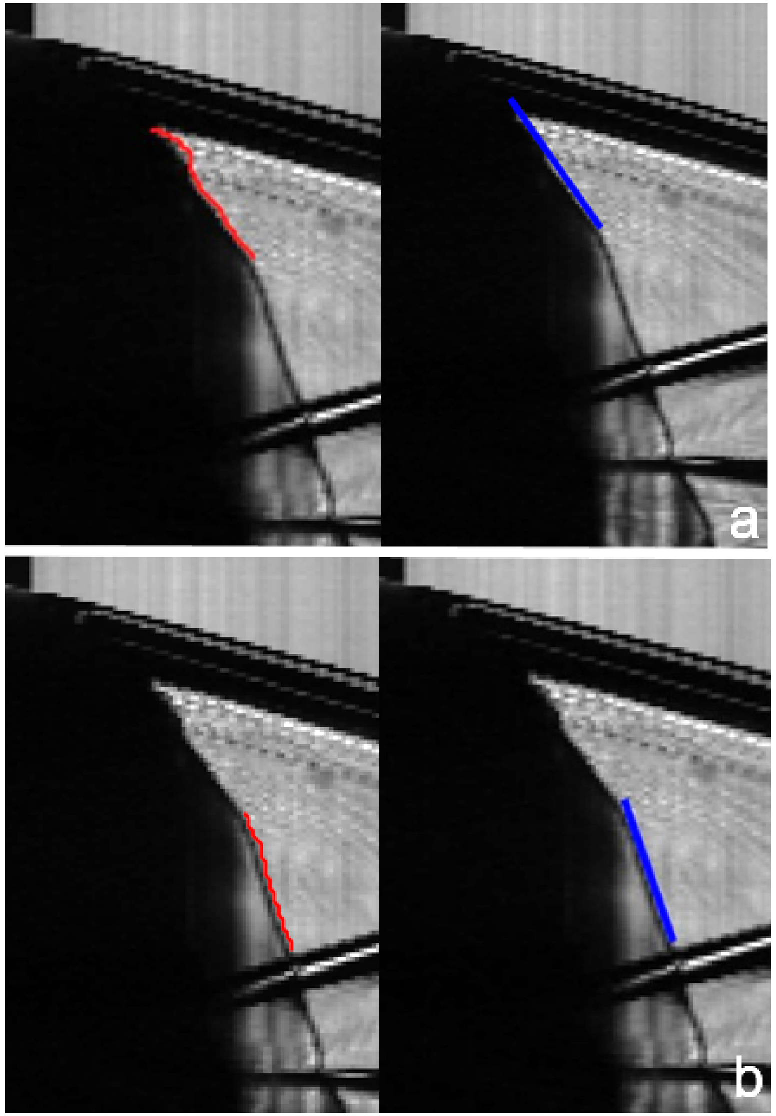




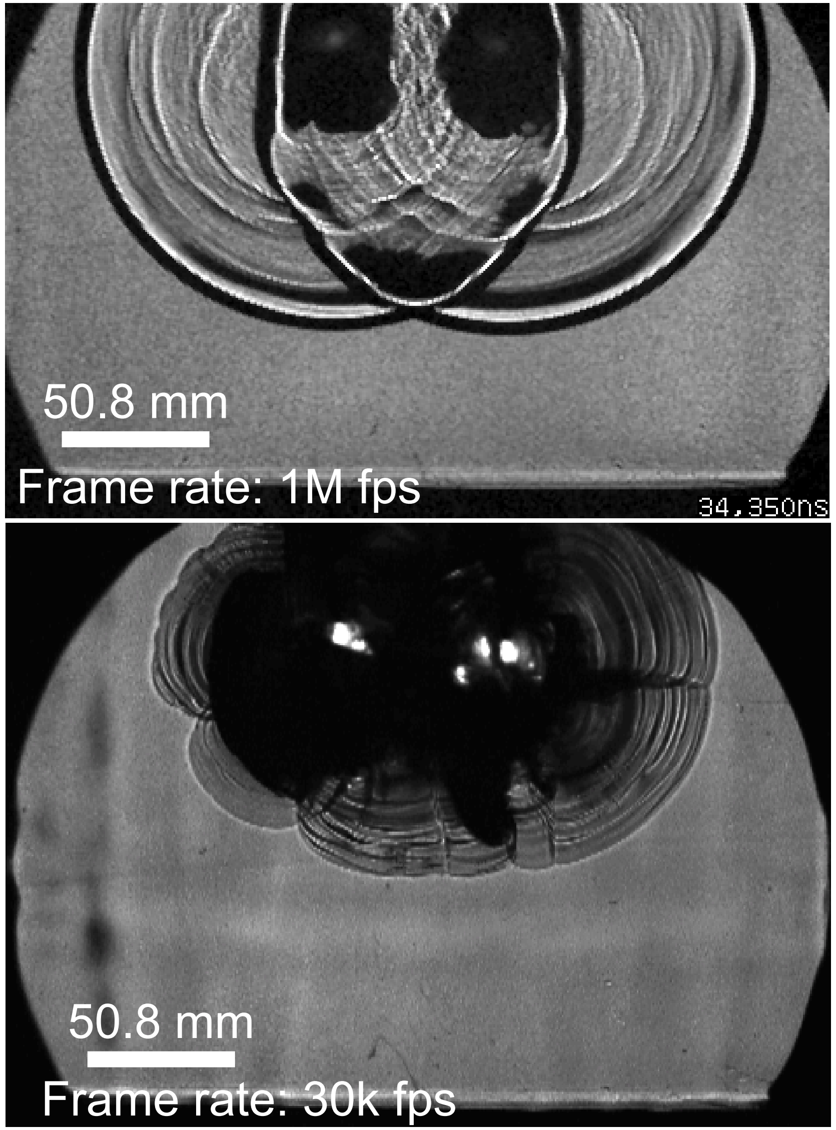


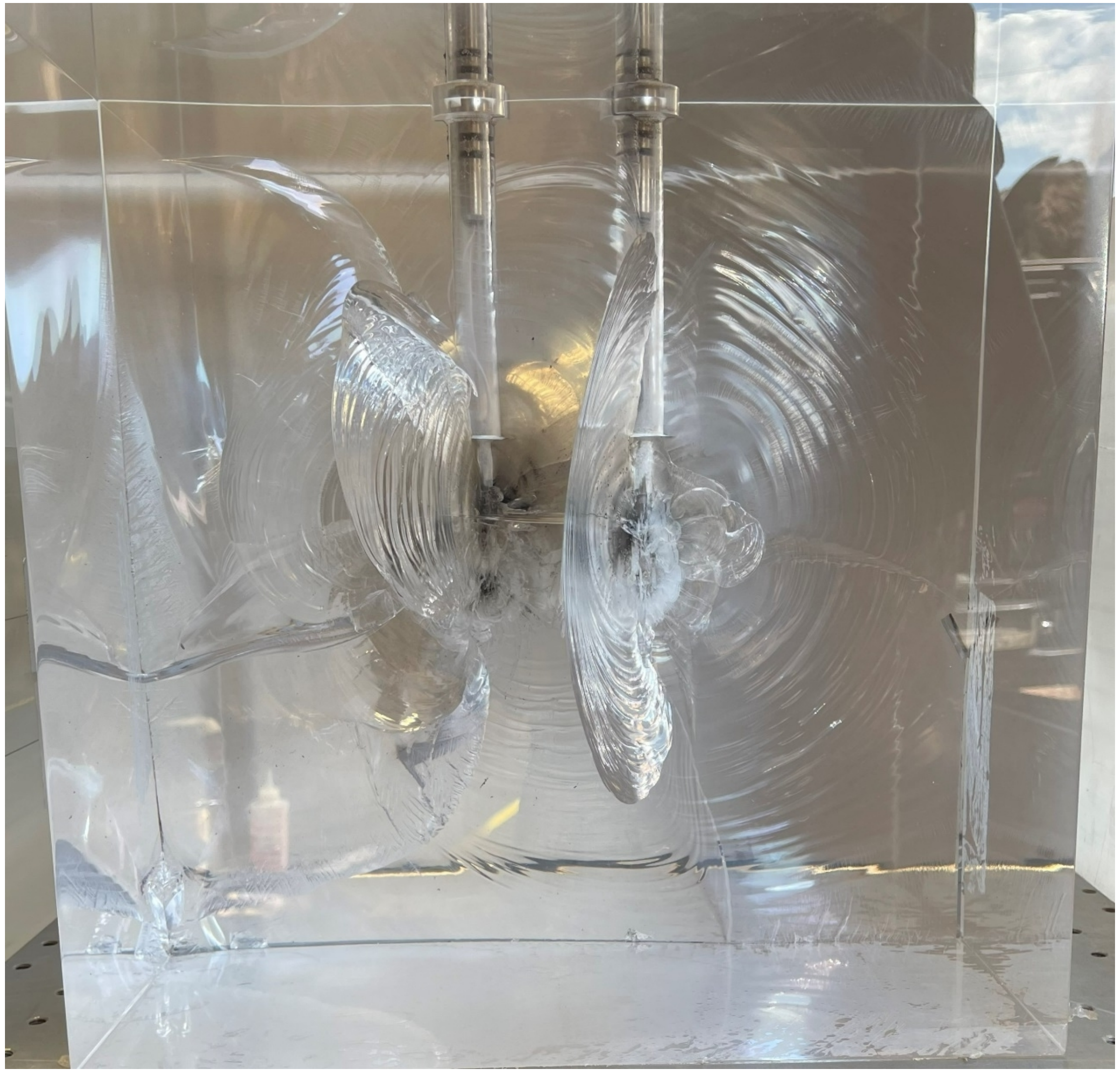
The fracture growth behavior indicates there is more than one mechanism driving fracture growth

- Shock wave velocity: 2.8 km/s
- Initial fracture growth
  - Hard to quantify due to shock wave
- Early time fracture growth
  - Time duration: 30.4 μs – 59.4μs
  - Velocity: 510 m/s
- Later time fracture growth
  - Time duration: 60.4μs – 90.4μs
  - Velocity: 250 m/s
- Velocity after reflected shock wave
  - Hard to quantify due to PMMA distortion



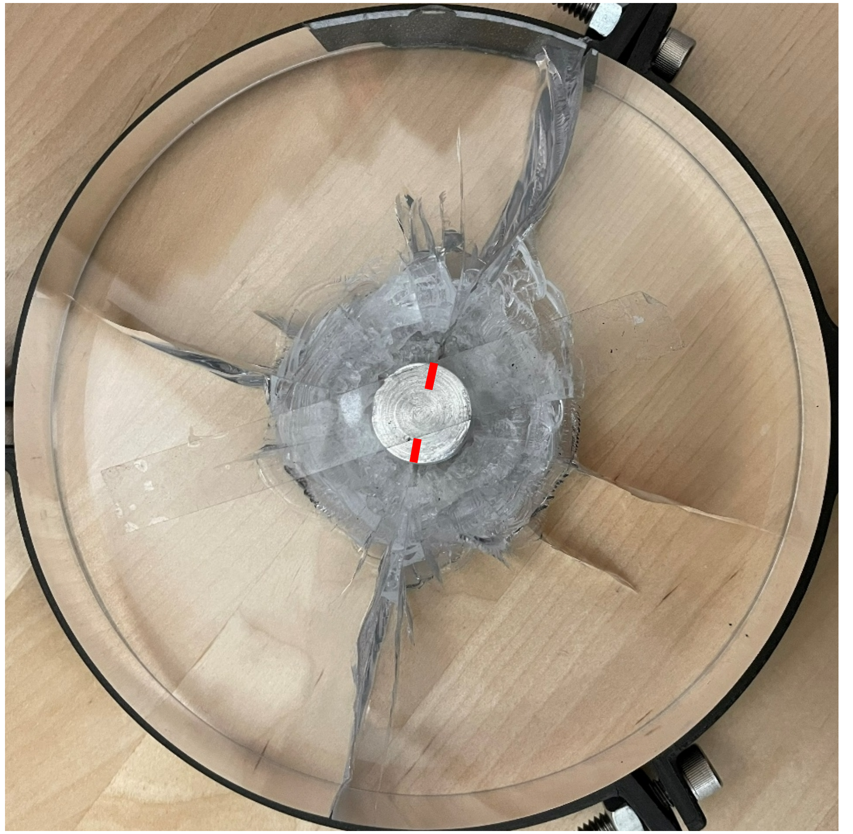
Simulations show that an RP-80 has a damage radius of about 80 mm





Future work

- Reduce the propagation distance to collect attenuation behavior closer to the explosive source
  - Attenuation behavior prior to elastic wave decay
  - 10mm, 5mm, 2mm gap
- Define the attenuation behavior with increased explosive weight
- Repeat the tests
- Explore fracture growth in disk-shaped PMMA samples



Questions?

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