THE UNIVERSITY OF RHODE ISLAND

Simulations and Experiments of PDV Diagnosed Wedge Tests

Robert T. Ichiyama, Noah Scarpelli, Madeleine Stanisha,
James L. Smith, Jimmie C. Oxley,
University of Rhode Island Energetic Materials Group

Paul E. Anderson
US Army DEVCOM ARDEC (Picatinny) Explosives Research Branch

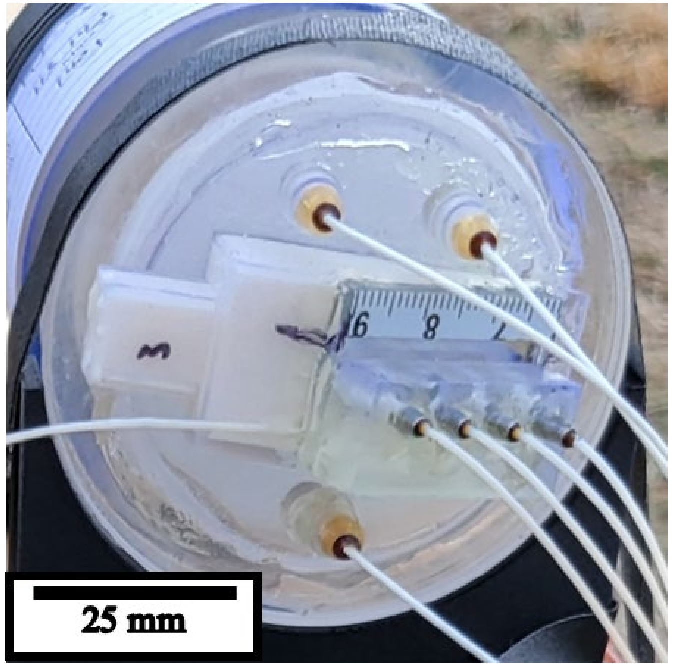
THINK BIG WE DO™

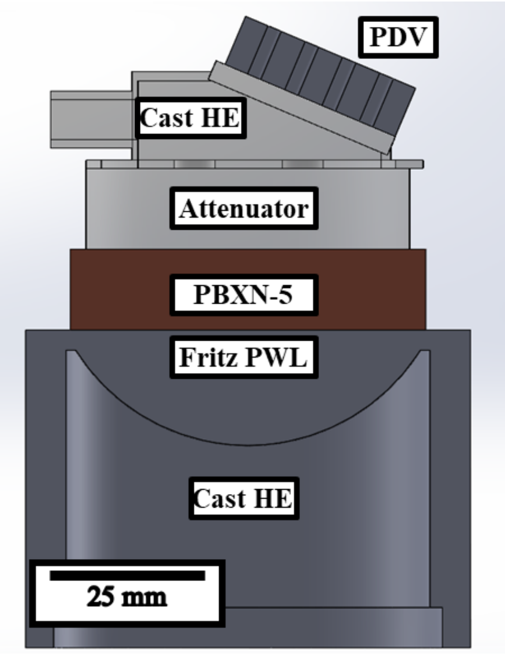
DEVCOM ARMAMENTS CENTER

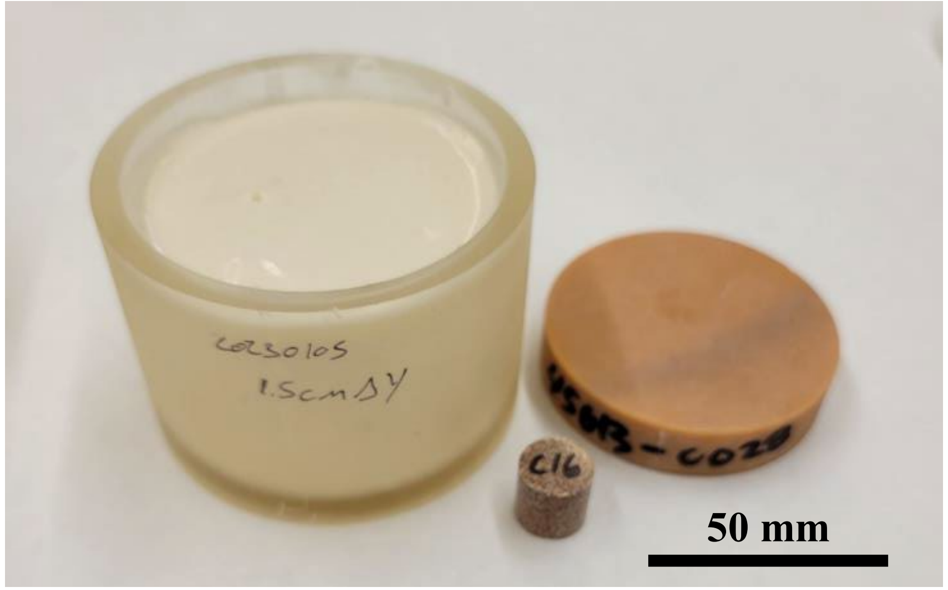
ENERGETICS LABORATORY UNIVERSITY OF RHODE ISLAND

Wedge Test Motivation

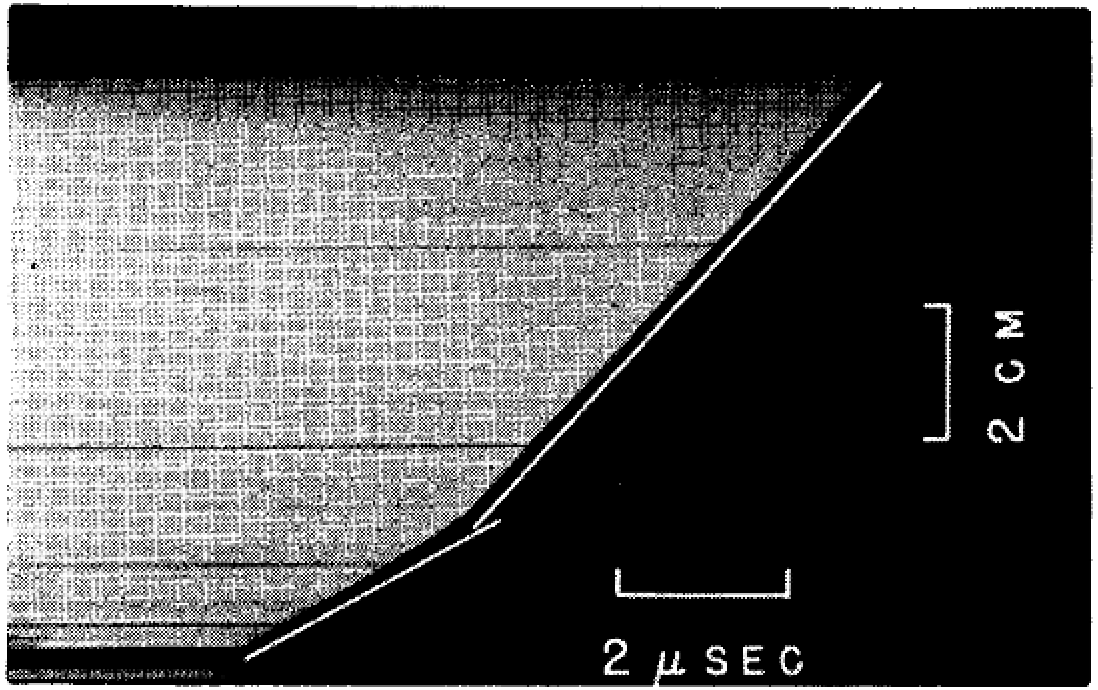
- Recent advances in PWL manufacturing allow for rapid testing of new formulations
- Wedge tests can provide a wealth of shock to detonation data for SDT measurements
- Dense PDV measurements provide a wealth of particle velocity data with minimal setup







Traditional Wedge Tests



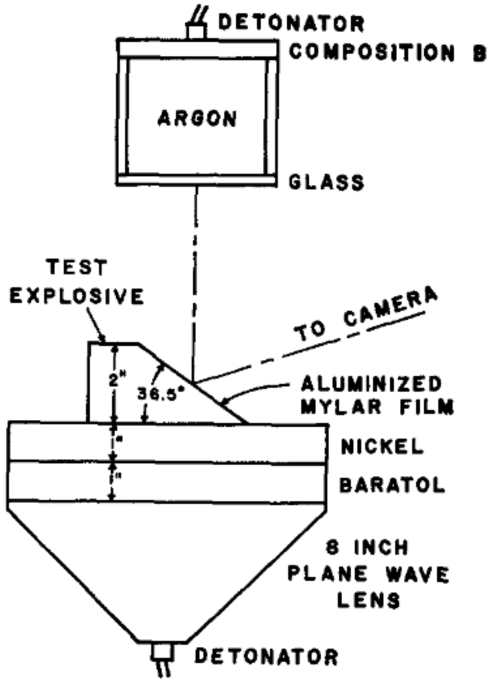


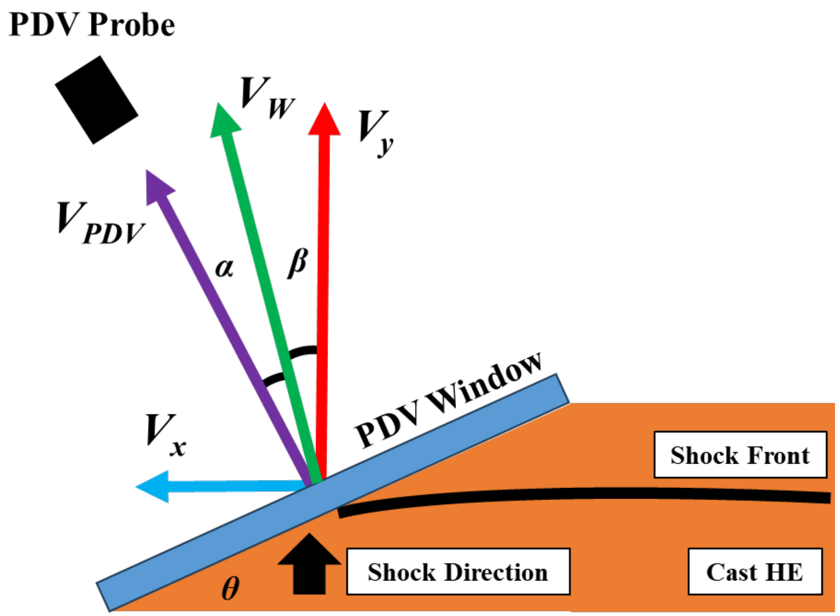
FIG. 2. Charge arrangement for type I experiments.

- Shock velocity tracking
- Bi-linear analysis to determine transition point
- Streak camera imaging, fiber Bragg gratings, timing pins

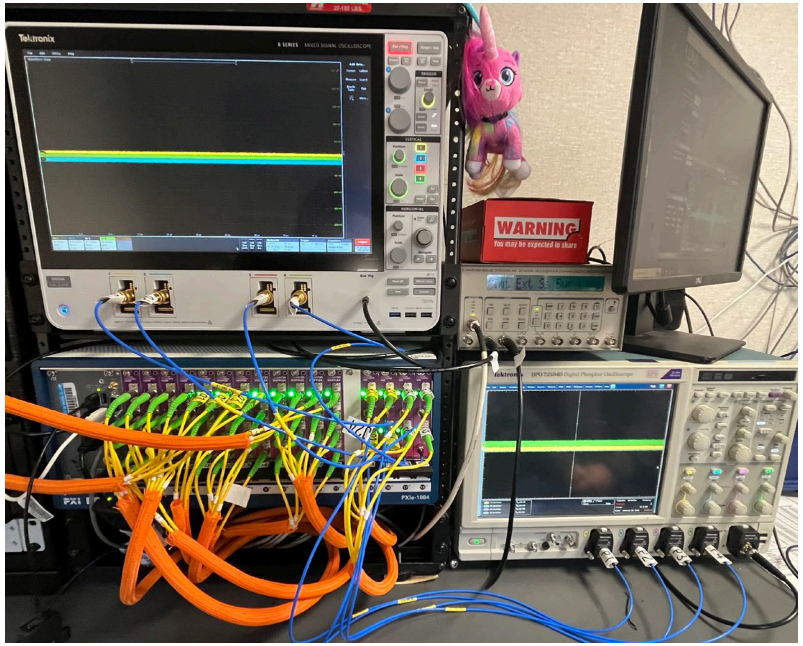
[1] A.W. Campbell, W.C. Davis, J.B. Ramsay, J.R. Travis, Shock Initiation of Solid Explosives, The Physics of Fluids 4 (1961) 511–521. https://doi.org/10.1063/1.1706354.

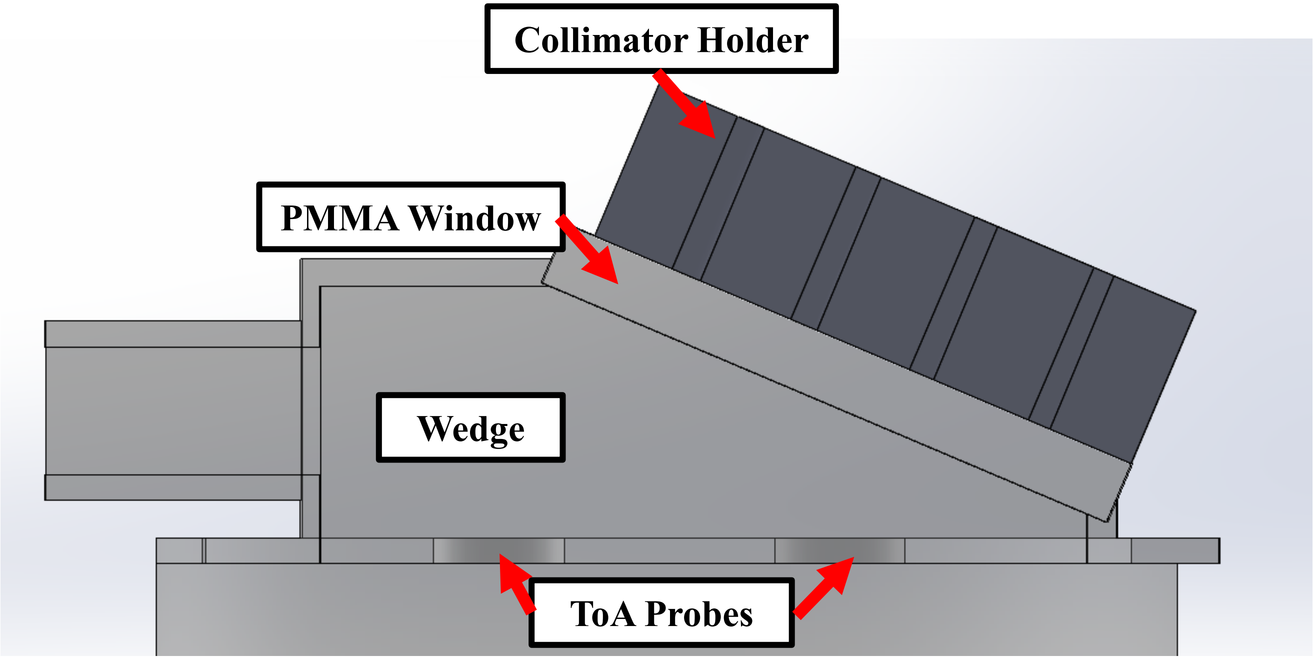
PDV Wedge Tests

- Very easy to field many PDV channels (8)
- Tilt measurements and analysis are robust
- Initial shock Hugoniot and shock sensitivity can be measured after 1 day of testing
- Challenge:
  - Data is taken normal to the wedge surface to increase light return
  - What does this mean in terms of angle?



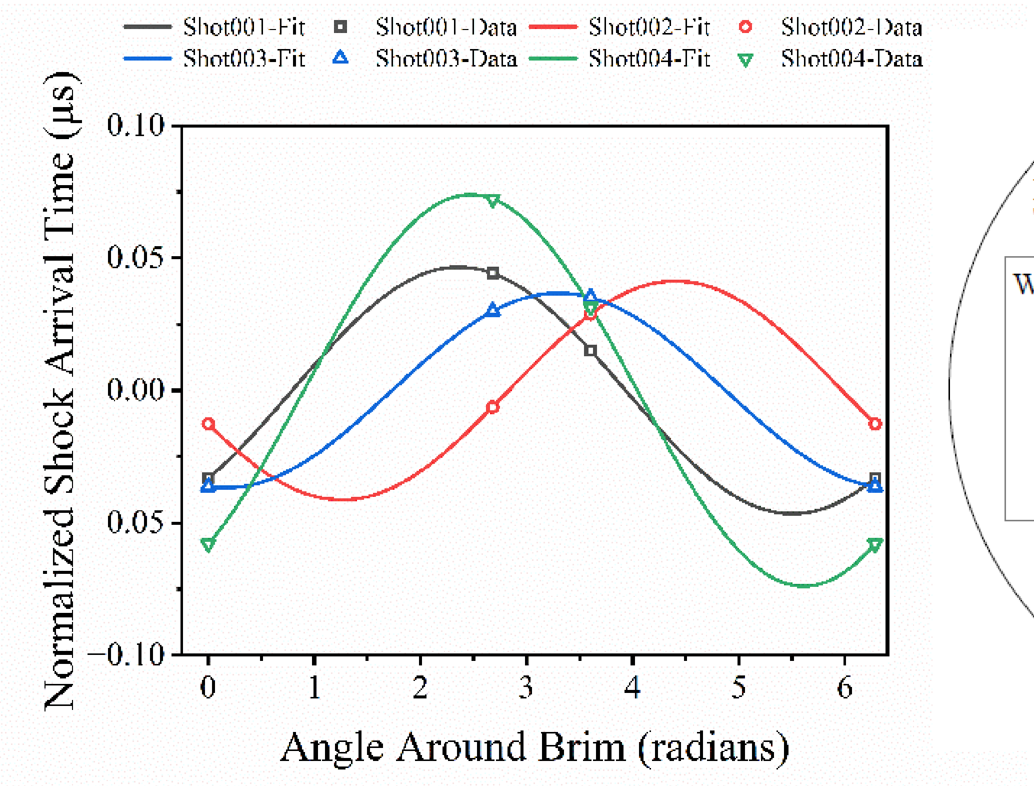
Photon Doppler Velocimetry

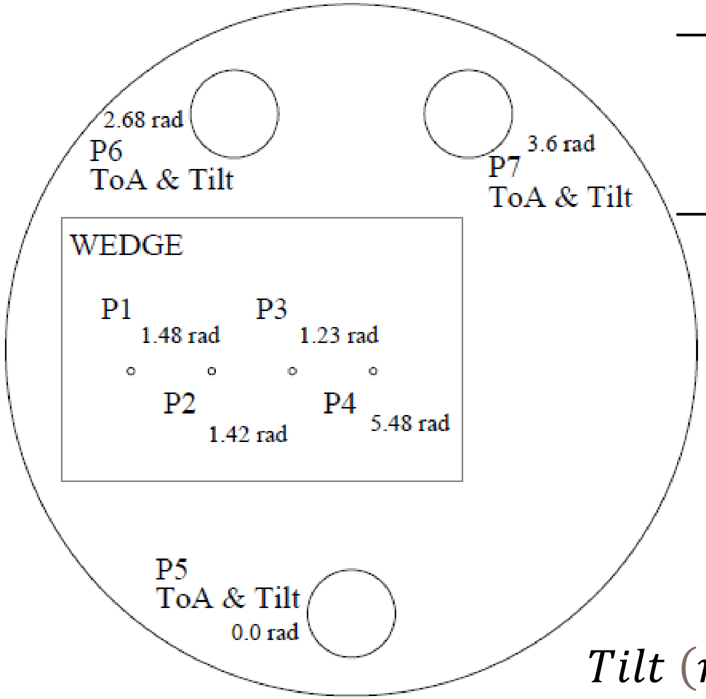




- High speed displacement interferometer
- Cast PMMA window with aluminized mylar reflector (< 50 µm)
- Used to measure ToA, wedge particle velocity, and shock velocity
- LUNA Optical Back Reflection measurements needed for time zeroing each channel

Tilt Measurements





	T_0 (μs)	A (μs)	φ (rad)	Tilt (mrad)
Shot 1	20.333	0.04658	5.493	3.6
Shot 2	21.024	0.04132	3.453	2.6
Shot 3	21.755	0.03677	4.551	2.0
Shot 4	20.580	0.07394	5.383	4.7

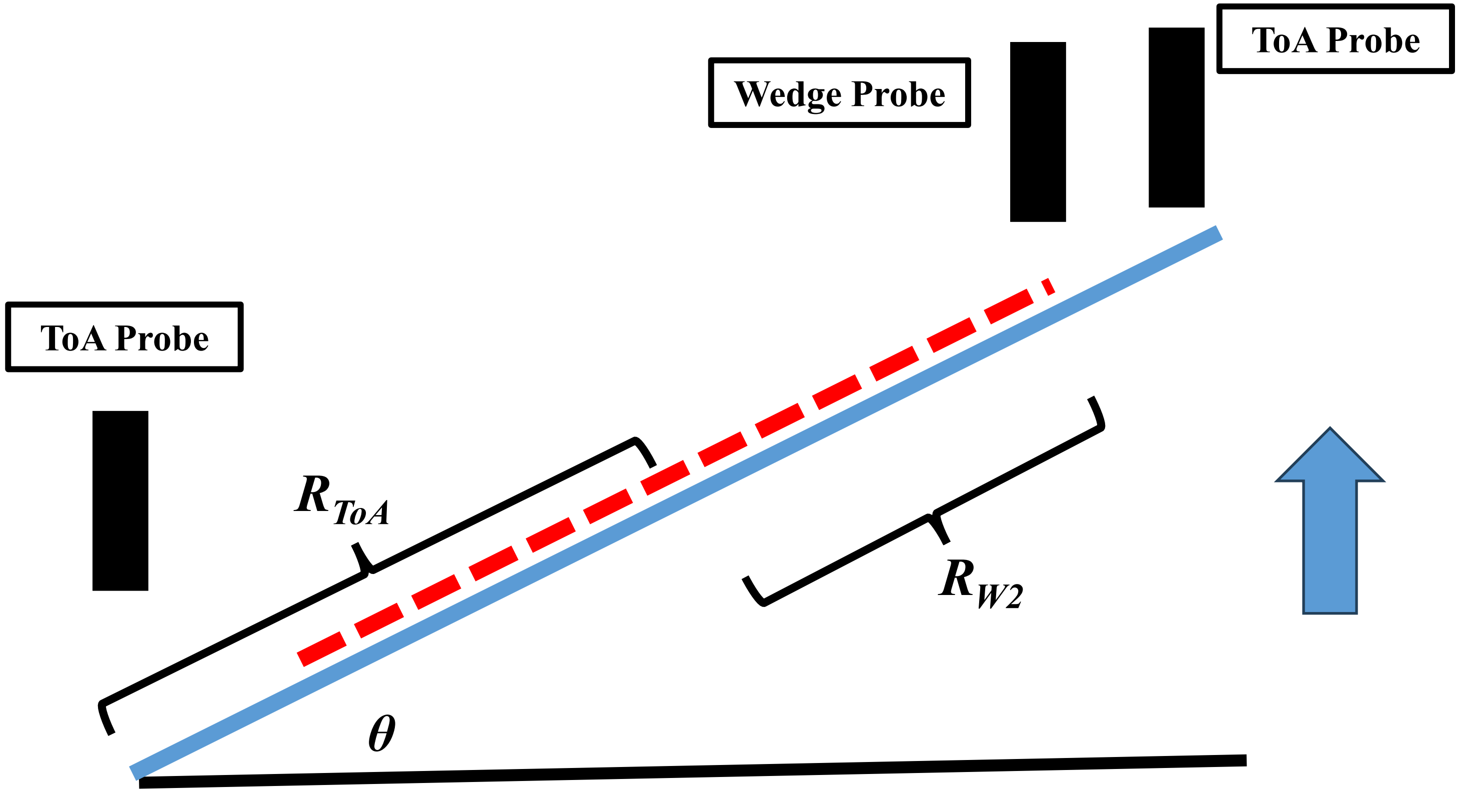
$$T(\theta) = T_0 + A\sin(f\theta + \varphi)$$

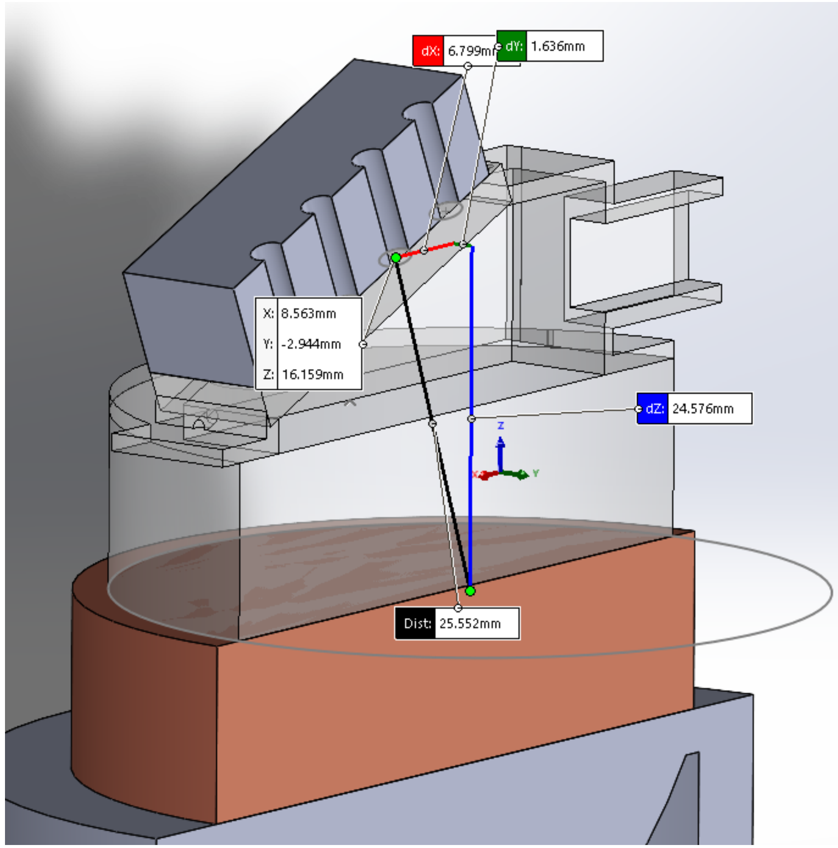
$$Tilt\ (mrad) = \tan^{-1}\left(\frac{Velocity * A}{Radial\ Distance}\right) * \frac{1}{1000}$$

- All lenses had below 5 mrads of tilt
- Bowing not accounted for due to wedge position
  - In-situ bow measurements underway

[1] O.T. Strand III, Handbook for the Photonic Doppler Velocimeter, second edition, United States, 2020. https://www.osti.gov/biblio/1722894.

Attenuated Shock Time of Arrival at Wedge





- Radial position of each PDV probe is different
- ToA function must be shifted for each new radial point

Tilt Scaling

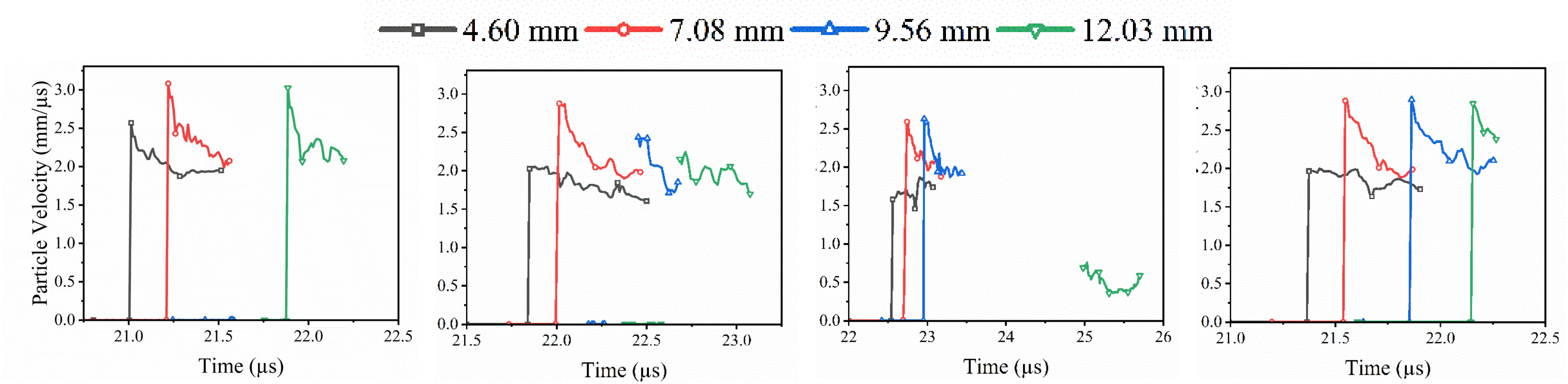
$$Tilt\ (mrad) = \tan^{-1}\left(\frac{Velocity * A}{Radial\ Distance}\right) * \frac{1}{1000}$$

$$A = \frac{\tan(Tilt\ *\ 1000)}{Velocity} * Radial\ Distance$$

Shot-Probe	R (mm)	*Θ* (rad)	*A* (µs)	Time of Arrival (µs)
Shot1-P1	16.02	1.476	0.03918	20.358
Shot1-P2	10.22	1.421	0.02499	20.348
Shot1-P3	4.52	1.227	0.01106	20.338
Shot1-P4	2.20	5.477	0.00538	20.327
Shot2-P1	16.02	1.476	0.03475	20.990
Shot2-P2	10.22	1.421	0.02217	21.002
Shot2-P3	4.52	1.227	0.00981	21.015
Shot2-P4	2.20	5.477	0.00477	21.027
Shot3-P1	16.02	1.476	0.03093	21.747
Shot3-P2	10.22	1.421	0.01973	21.749
Shot3-P3	4.52	1.227	0.00873	21.751
Shot3-P4	2.20	5.477	0.00425	21.753
Shot4-P1	16.02	1.476	0.06218	20.614
Shot4-P2	10.22	1.421	0.03966	20.600
Shot4-P3	4.52	1.227	0.01756	20.585
Shot4-P4	2.20	5.477	0.00854	20.571

- Each radial position gets a new *A*

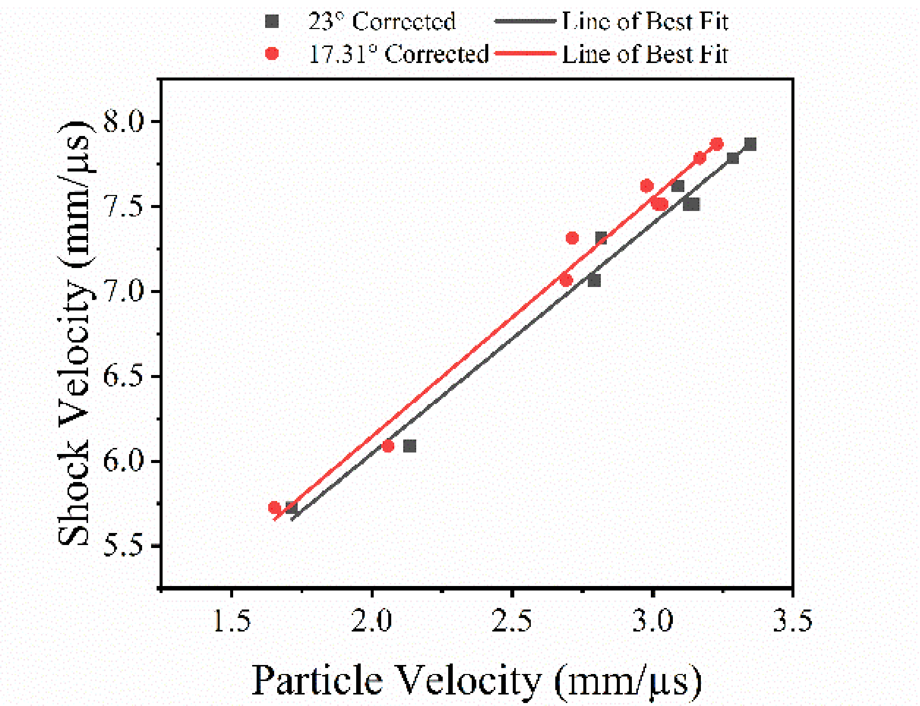
Wedge Output PDV Data



Shot 1 **Shot 2** **Shot 3** **Shot 4**

- Particle velocity data collected from wedge outputs
- Unreacted and reacted states captured
- Some inconsistency in data quality
  - PMMA window problem? Considering switching to LiF

Wedge Results



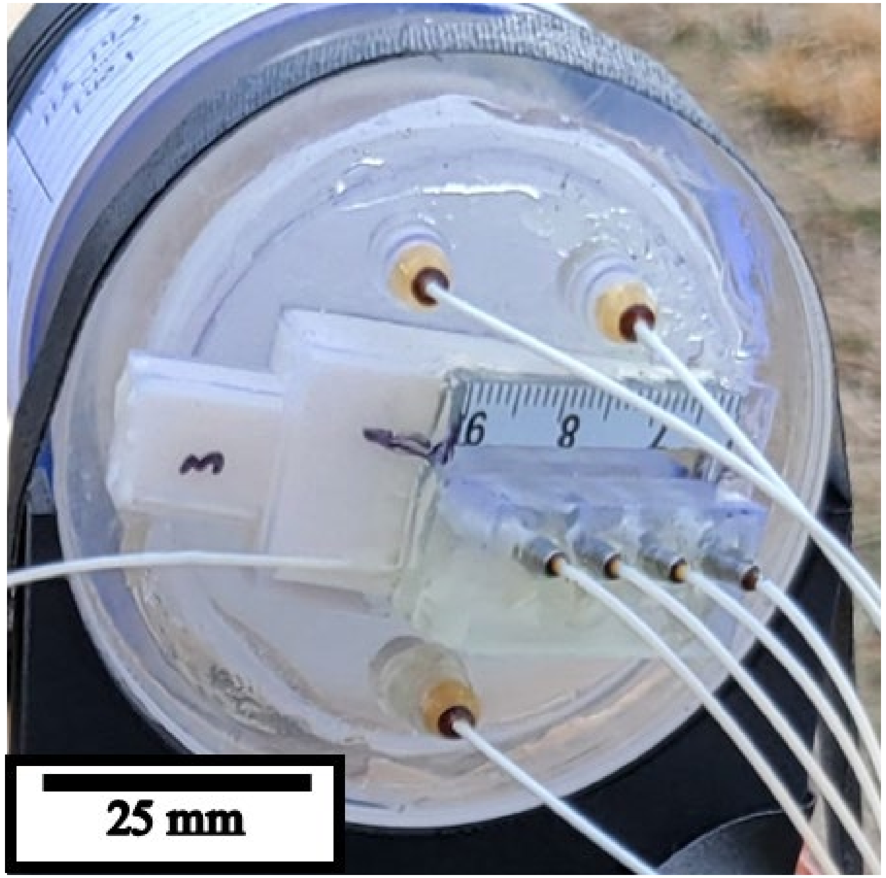
	Density (g/cc)	S (Dimless)	C_0 (mm/µs)
Acrylic	1.186 ± 0.005	1.54 ± 0.0535	2.57 ± 0.026
23°	1.60 ± 0.005	1.355 ± 0.066	3.332 ± 0.19
17.31°	1.60 ± 0.005	1.406 ± 0.068	3.332 ± 0.19

	23° (GPa)	17.31° (GPa)	X_d (mm)
Shot 1	4.04 ± 0.91	4.05 ± 0.91	2.3 ± 2.3
Shot 2	3.16 ± 0.89	3.12 ± 0.89	5.84 ± 1.2
Shot 3	2.66 ± 0.88	2.66 ± 0.88	5.84 ± 1.2
Shot 4	3.14 ± 0.89	3.15 ± 0.89	5.84 ± 1.3

- Established an initial shock Hugoniot and shock sensitivity
- Error is dominated by lack of independent C_0 measurement
- Angular correction from 23º to 17.3º is small, within error when C_0 error is large
  - Angle corrections motivated by ALE3D modeling

Conclusion

- Explosively driven wedge tests can be used to rapidly screen new explosive formulations
  - Especially cast cures
- PDV is an easy way generate a wealth of calibration data
- More work needs to be done on angular corrections at late time
  - High fidelity modeling will be needed



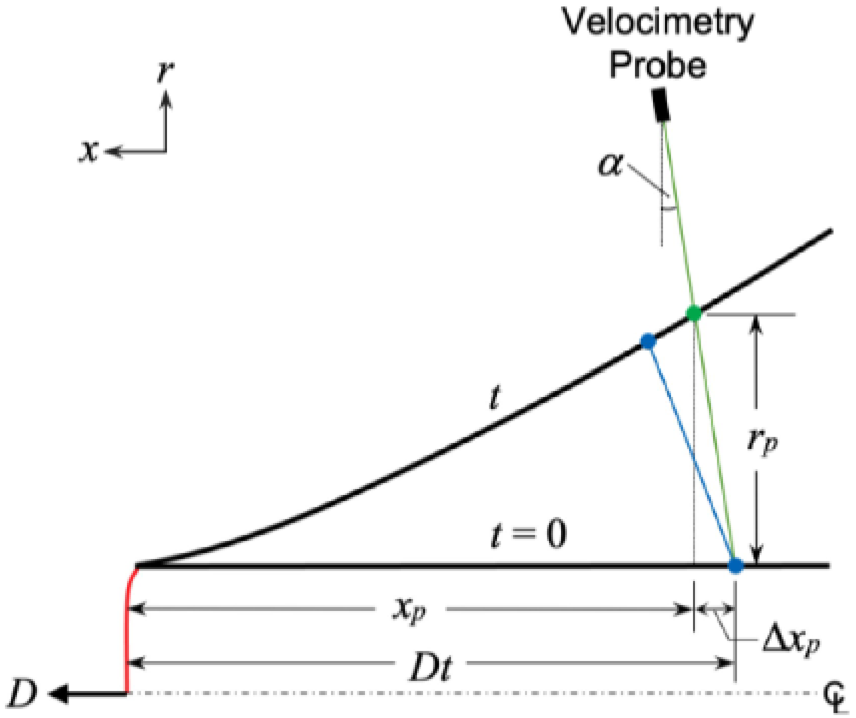
Seems like there's a lot of room there…

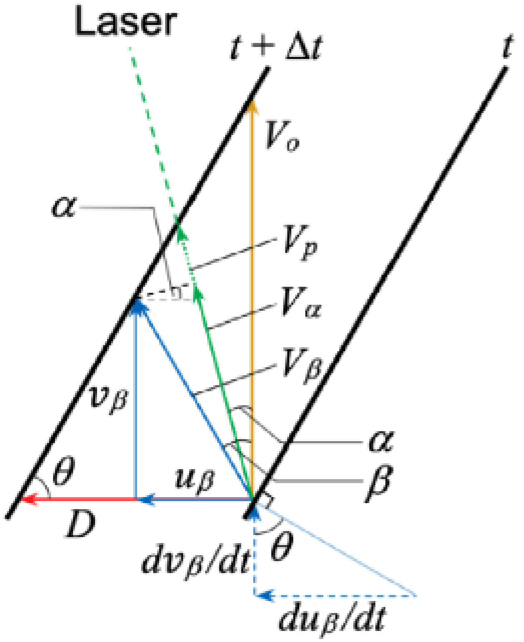
Conclusion

- Explosively driven wedge tests can be used to rapidly screen new explosive formulations
  - Especially cast cures
- PDV is an easy way generate a wealth of calibration data
- More work needs to be done on angular corrections at late time
  - High fidelity modeling will be needed

Wedge tests will return

A Question for You





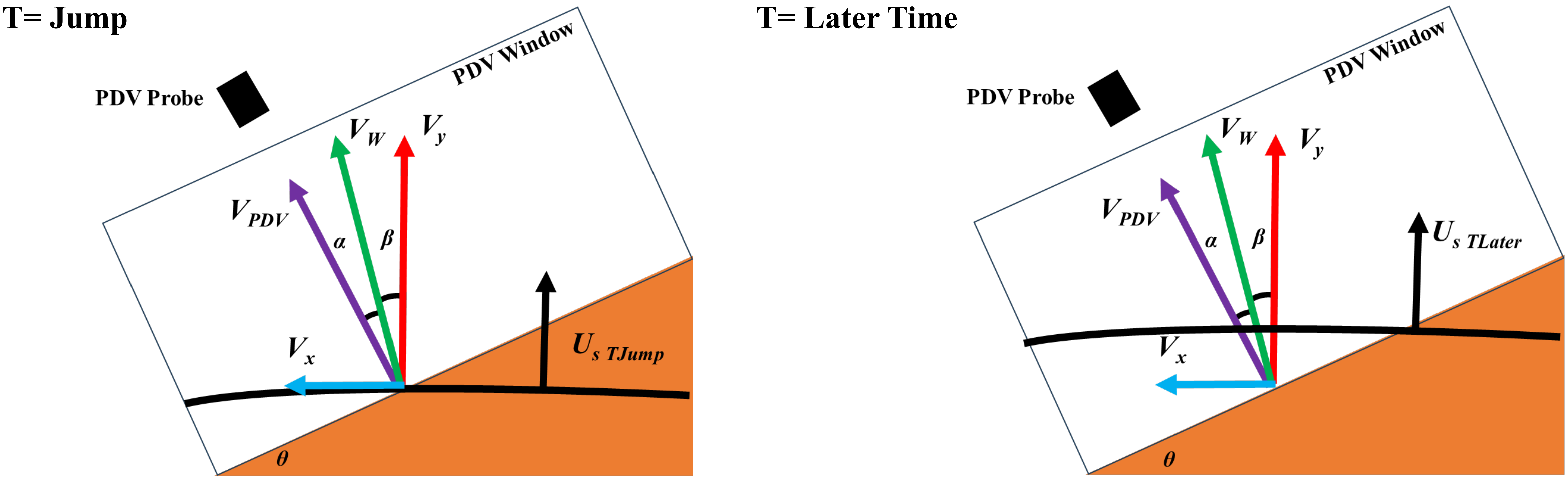
$$V_\alpha = v_\beta \cos\alpha + u_\beta \sin\alpha$$

$$\theta = \alpha + \sin^{-1}\left(\frac{V_\alpha}{D} - \sin\alpha\right)$$

- We have a well-defined descriptor of CYLEX kinematics thanks to Chaos[1]
- How should the wedge be approached??

[1] M. Chaos, Revisiting the Kinematics of the Cylinder Test, Propellants Explo Pyrotec 47 (2022). https://doi.org/10.1002/prep.202100349.

A Question for You



- How do we measure angular changes over time without a fixed velocity with only one probe?

Acknowledgements

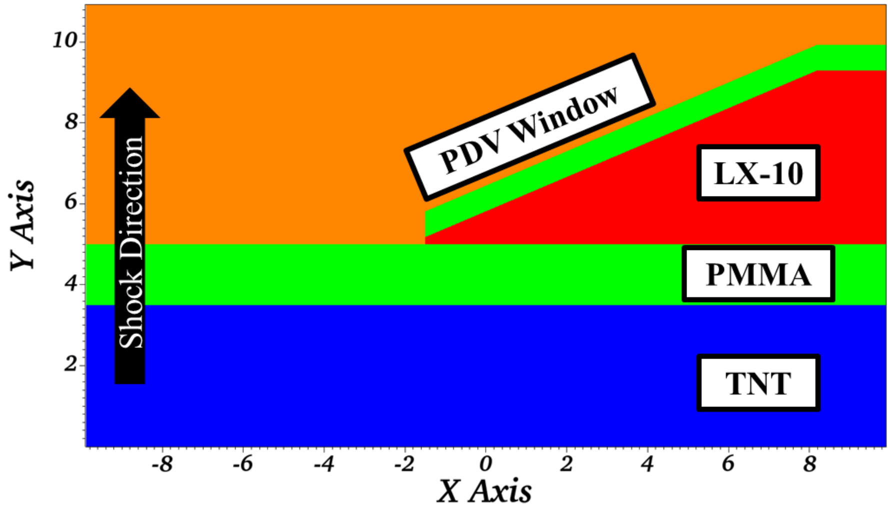
- Questions?

- Drs. Jimmie Oxley & James Smith, PIs
- Noah Scarpelli & Madeilene Stanisha, Graduate Students
- Alan Valliere, Site Manager & Ordinance Technician
- Dr. Paul Anderson, DEVCOM for funding (US Army APEX Program) and project insight
- Drs. Eric Beckel, Edward Cooke, & Jordan Steer, DEVCOM for formulation insight and development
- DURIP Awards from AFOSR & ONR

This work was funded by Picatinny DEVCOM under W52P1J-21-9-3000 P00005

Backup Modeling Slides

Wedge Modeling

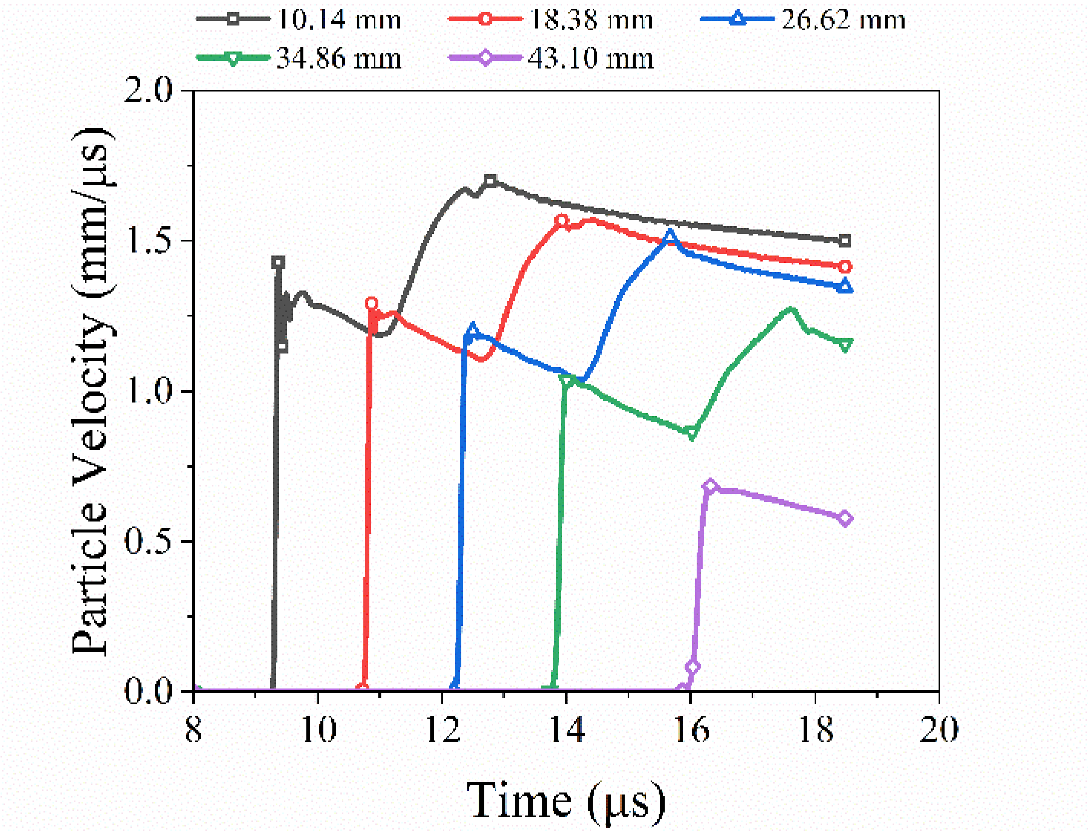


- ALE3D, arbitrary-Lagrange-Eularian 3D
- Multiphysics hydrocode developed by Lawrence Livermore National Lab
- Planar lighting TNT
- LX-10 either fully reacted or no reaction
  - Gave range of shock pressures that could be produced experimentally
  - Particle velocity tracers at wedge-PDV window interface

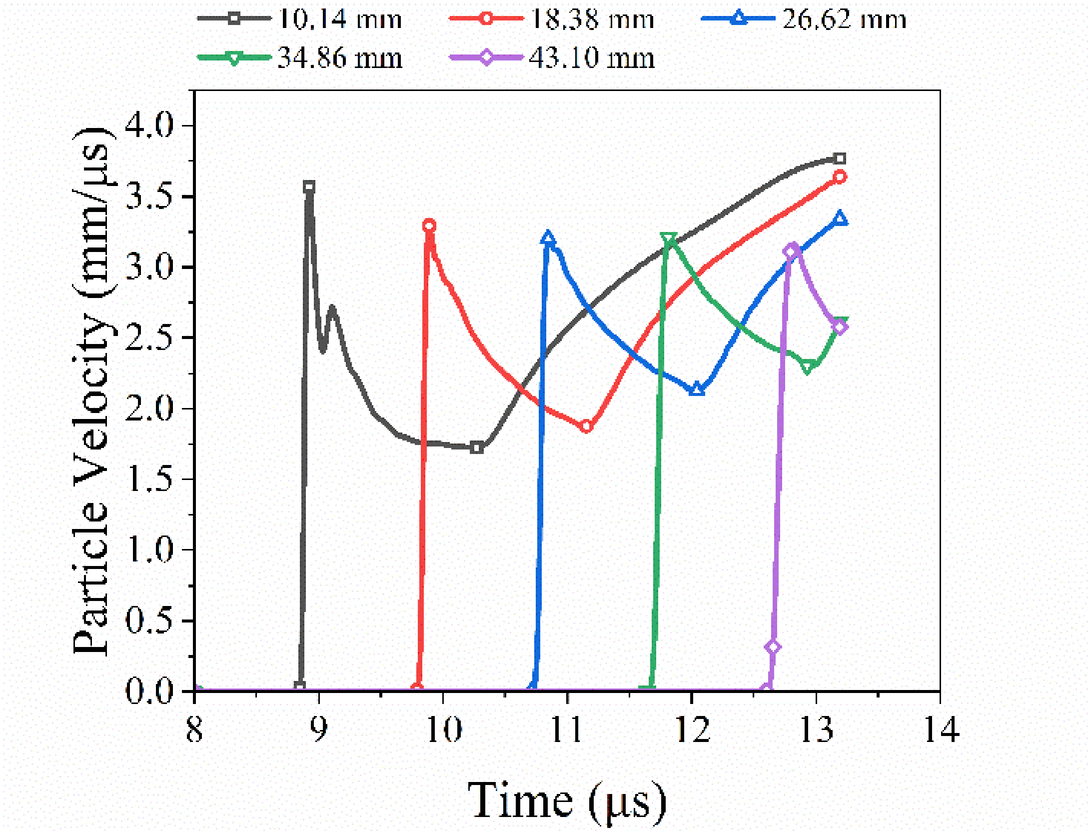
1. Noble, C.; Anderson, A.; Barton, N. ALE3D: An Arbitrary Lagrangian-Eularian Multi-Physics Code. LLNL.

Simulation Results

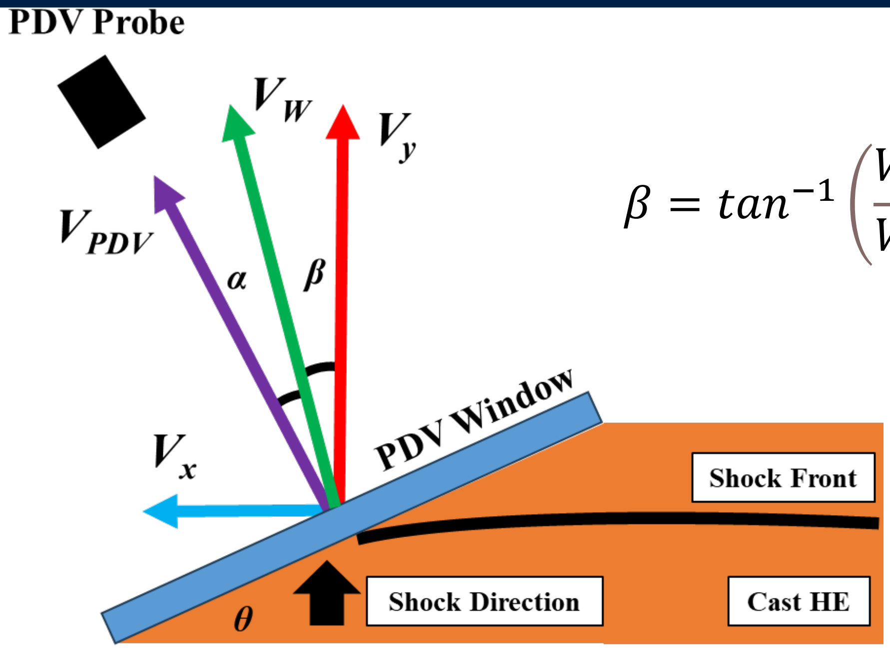
Unreacted Wedge



Reacted Wedge



Angled Shock Front

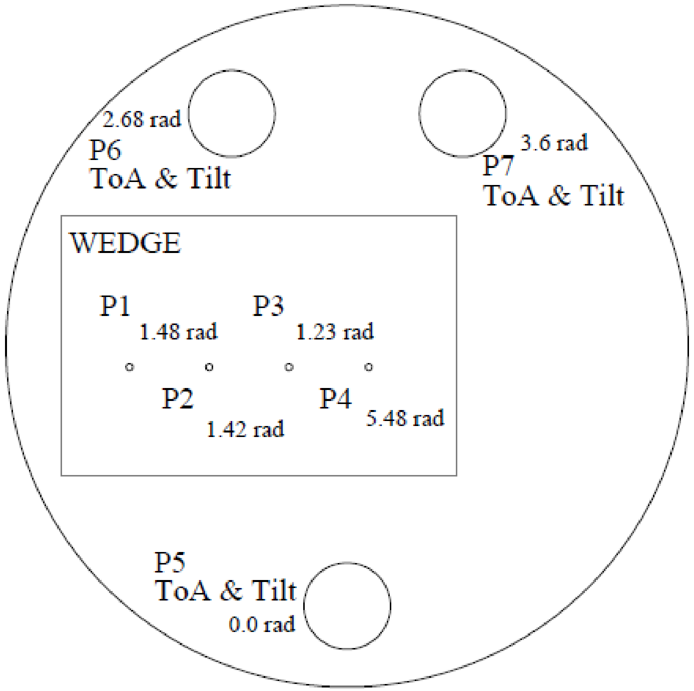


$$\beta = tan^{-1}\left(\frac{V_y}{V_x}\right)$$

Probe Location (mm)	β Unreacted (Degrees)	β Reacted (Degrees)
10.14	4.2	6.7
18.38	6.1	8.3
26.62	6.6	7.3
34.86	6.7	6.1
43.10	1.6	3.3

- Angle calculated by measuring x- and y- particle velocity at jump off
- Reacted wedge had larger angle on average
- Data should be corrected by less than wedge angle θ

Wedge Tilt Data



	Velocity (mm/μs)	ToA at 0 Radians (μs)	ToA at 2.681 Radians (μs)	ToA at 3.6022 Radians (μs)
Shot 1	1.478 ± 0.004	20.300 ± 0.010	20.377 ± 0.010	20.348 ± 0.010
Shot 2	1.216 ± 0.003	21.012 ± 0.010	21.053 ± 0.010	21.012 ± 0.010
Shot 3	1.057 ± 0.005	21.719 ± 0.010	21.785 ± 0.010	21.790 ± 0.010
Shot 4	1.211 ± 0.004	20.522 ± 0.010	20.652 ± 0.010	20.611 ± 0.010

- PWL tilt measurements to determine arrival time surface