SAND2022-16480C

# High Temperature Gladstone-Dale Coefficient Measurements in a Free-Piston Shock Tube

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AIAA SciTech 2023, Jan 23-27

Georgia Tech

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# Motivation

- Dissociation at high temperatures will affect optical properties of air
- Composite GD is species dependent
- Constant Gladstone-Dale coefficient cannot be assumed
- Temperature and pressure dependance
- No experimental validation currently exists

index of refraction

s - denotes species

$$\frac{n-1}{\rho} = GD = \sum GD_s \frac{\rho_s}{\rho}$$

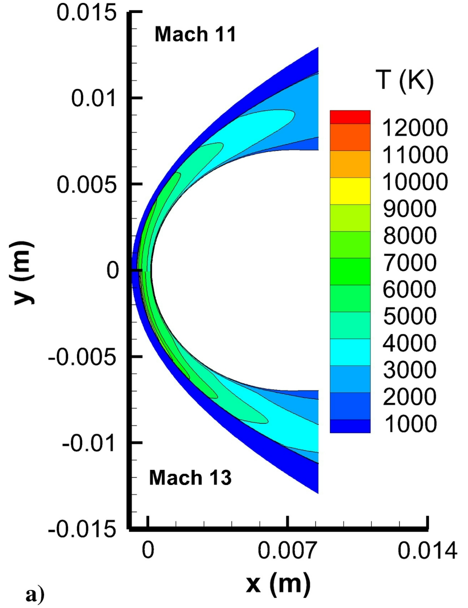
density

Gladstone-Dale Coefficient

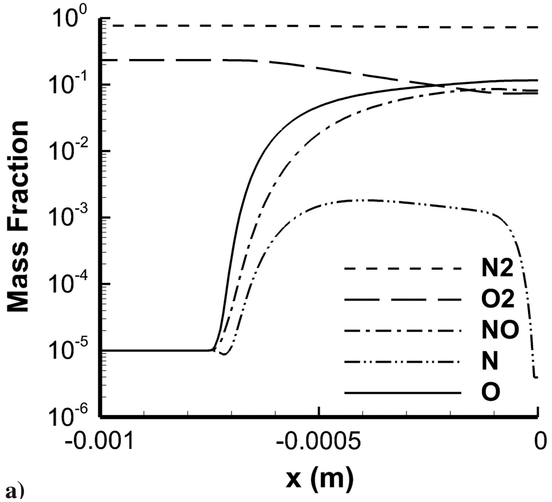
To make this measurement, we need:

1. Experimental facility capable of generating 5000K and above at moderate to high pressure
   → Shock Tubes
2. Diagnostic to resolve large discrete density changes

Example: Stagnation flow over a blunt body causes dissociation




a)




a)

Mackey, Lauren E., and Iain D. Boyd. *AIAA Journal* 57.9 (2019)

# Gladstone-Dale Simulation

- Wavelength dependence of gas species
  - $N_2$, $O_2$, NO are well tabulated
  - N and O from experimental data
  - Carbon species and electrons are not considered here

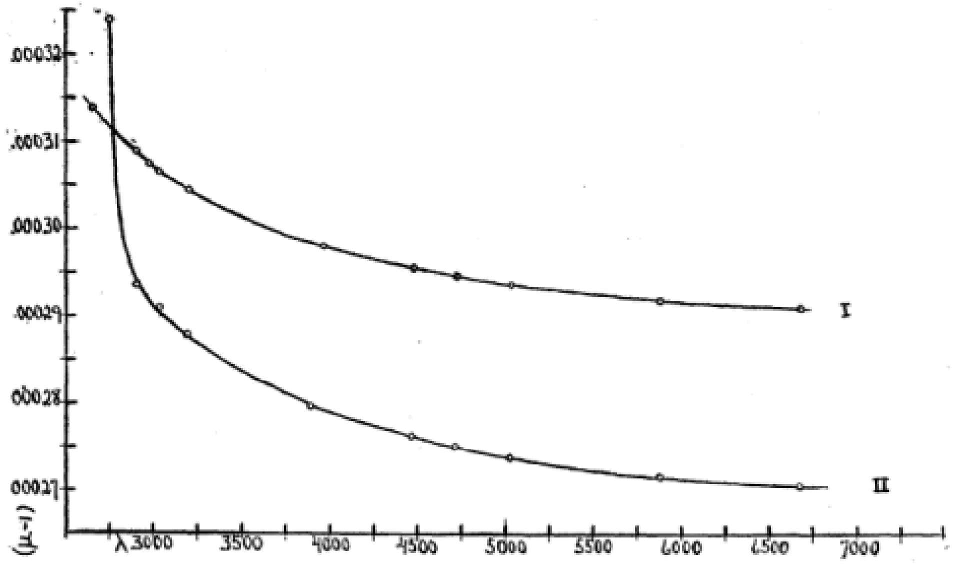
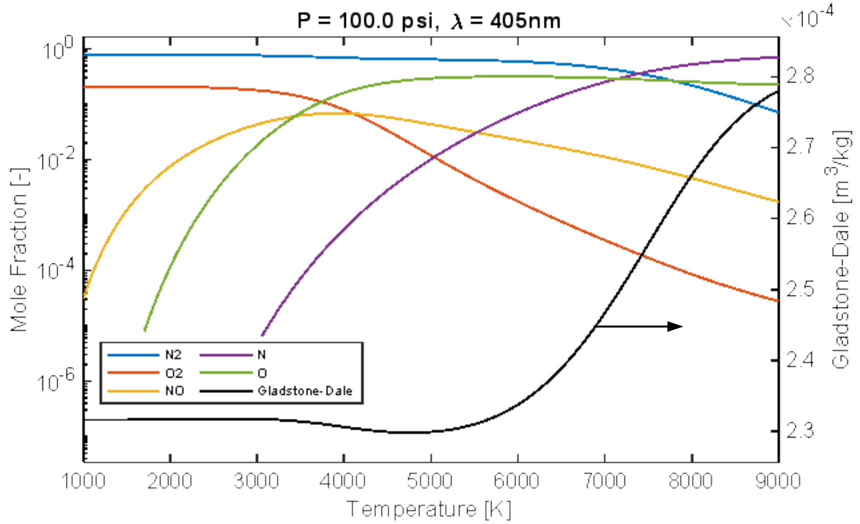
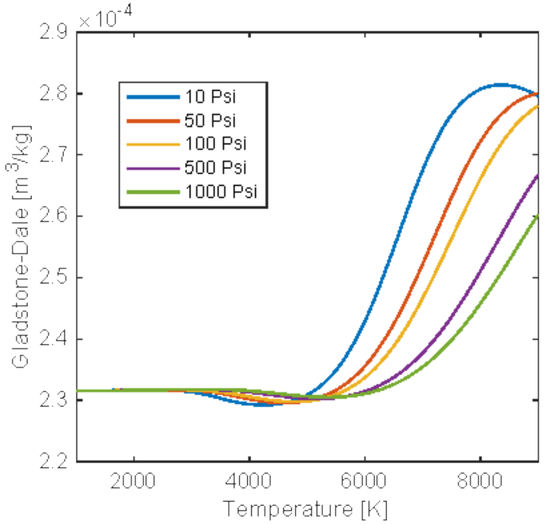



Fig. 3.

Dispersion Curves: I., Air; II., Oxygen. Abscissae: λ in Ångstrom units. Ordinates: (μ − 1).

Howell, Janet Tucker. *Physical Review* 6.2 (1915)



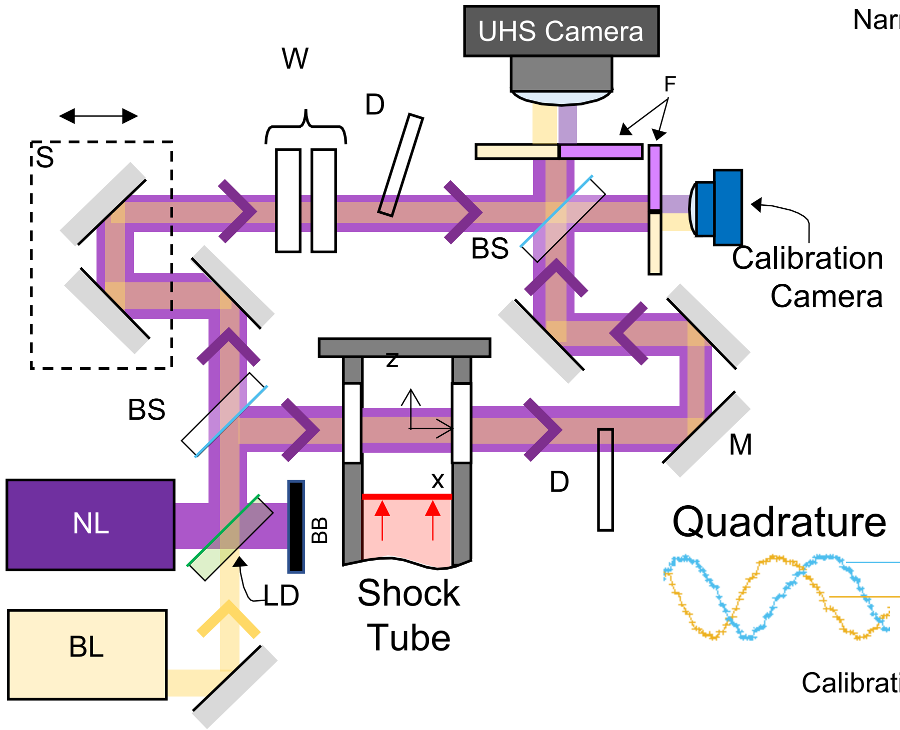



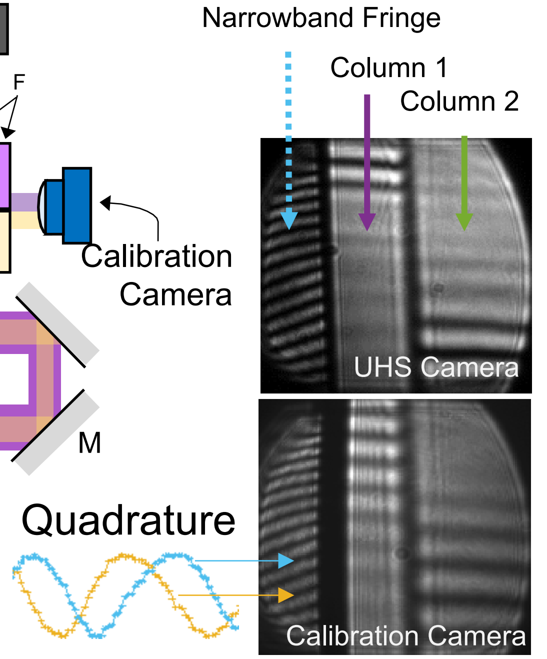

- Equilibrium composition of air at constant P varies with T
  - Presence of N and O significant past ~3500K

# QFII Diagnostic

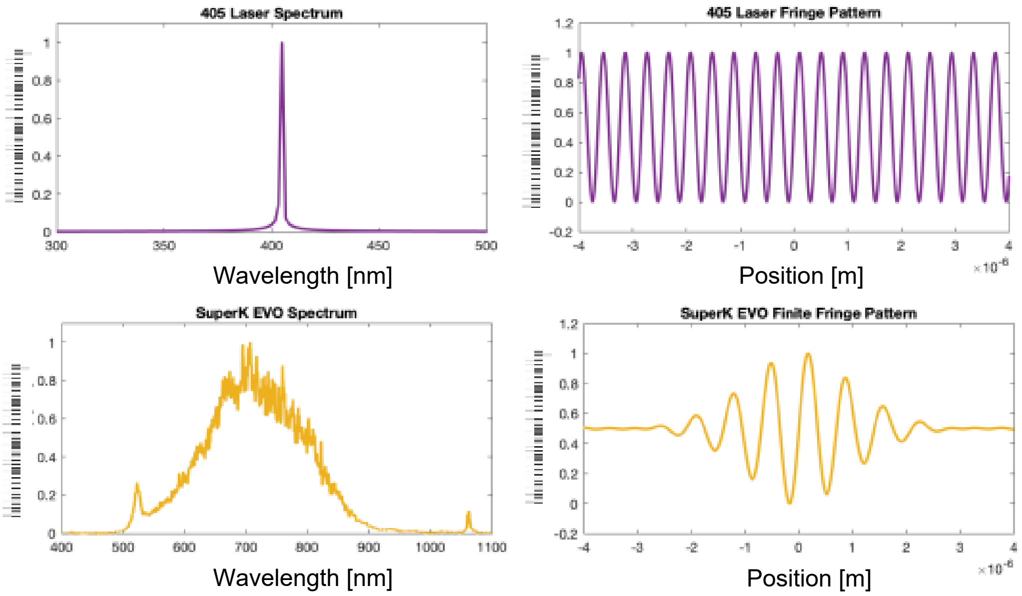
## Quadrature Fringe Imaging Interferometer

Hybrid broadband and narrowband technique for measuring large and discrete density gradients




Calibration camera is LR flipped

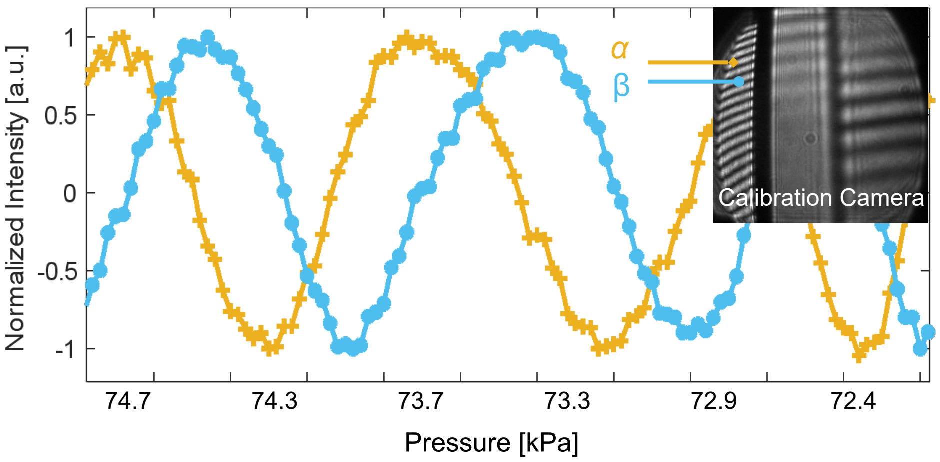



- Narrowband analog quadrature to automate tracking for high resolution
  - 405 nm laser diode
- Balanced broadband pattern for absolute reference
  - SuperK EVO supercontinuum source

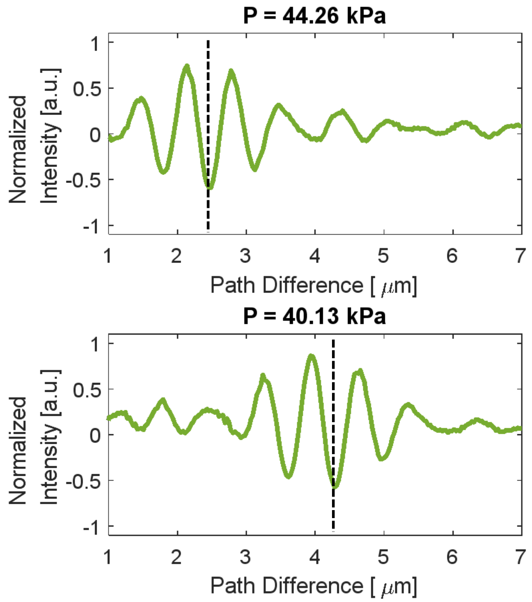

Wang, Y. Peng, W. Sun, and Y. C. Mazumdar, AIAA SciTech, paper AIAA 2022
Wang et al. *Optics Letters*, vol. 47 (16), 47, pp. 4159-4162, 2022

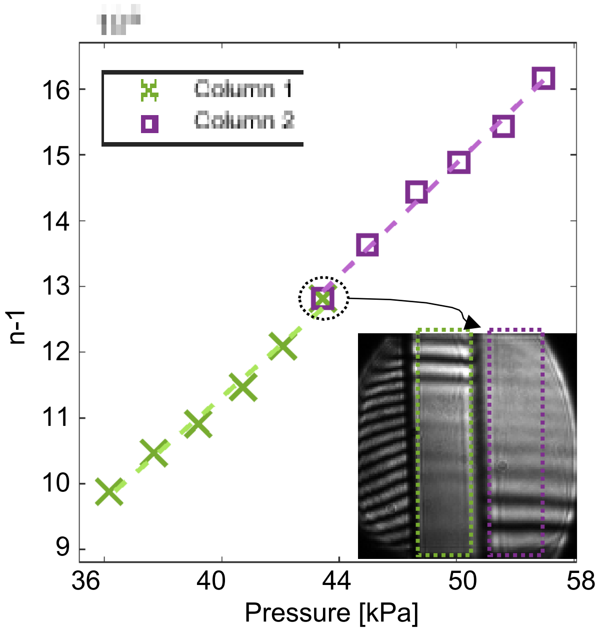
# Calibration

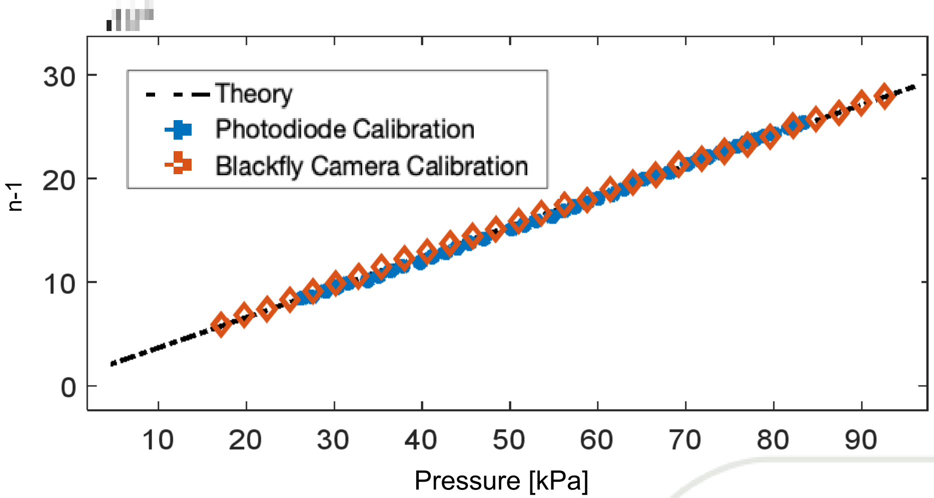
- Calculate absolute index with narrowband analog quadrature
- This technique leads to the highest resolution and automated tracking
- Calibration verified with linear GD relationship at ambient conditions
- Location of center fringe also related to index




$$\Delta n = \frac{\lambda}{\pi W} tan^{-1}\left(\frac{\beta(\Delta n) + \alpha(\Delta n)sin(\phi_{\alpha\beta})}{\alpha(\Delta n)cos(\phi_{\alpha\beta})}\right)$$



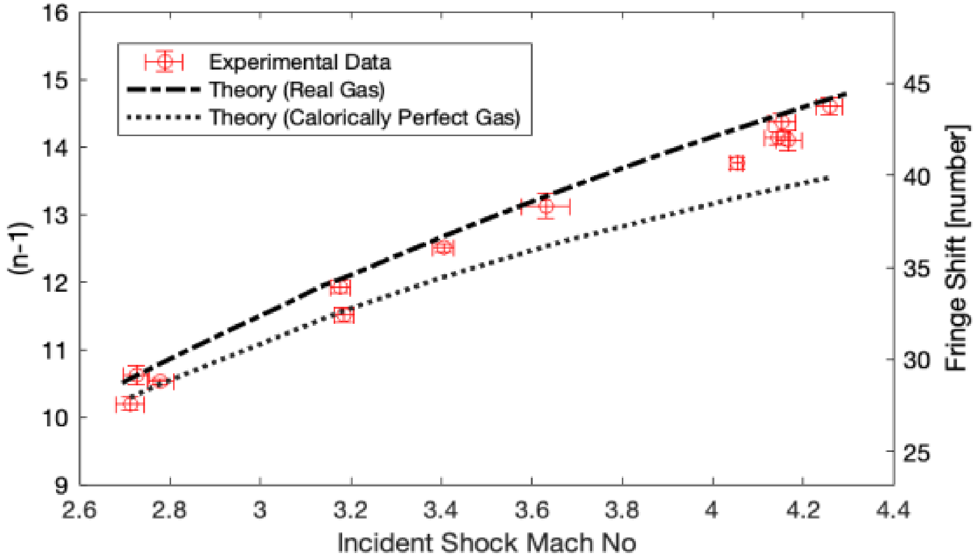



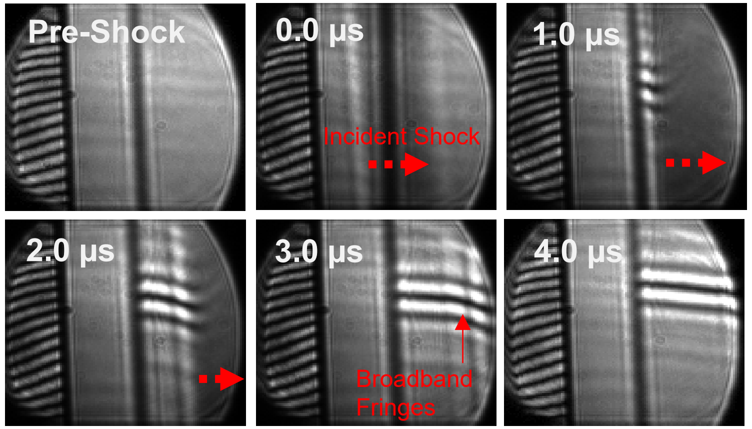



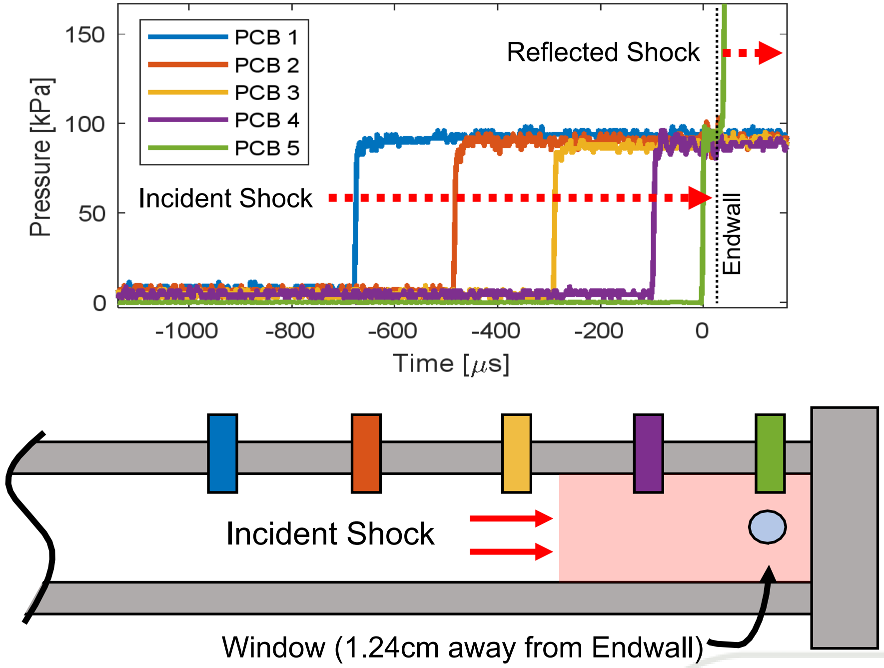

Wang et al. *Optics Letters*, vol. 47 (16), 47, pp. 4159-4162, 2022

# Shock Tube Experiments at Georgia Tech

- Post incident-shock conditions measured with QFII
  - M2.7 - M4.3
  - Constant P1 = 10.7 kPa = 80 Torr
  - He driver gas and air driven gas
- Results agree with theory within 2%



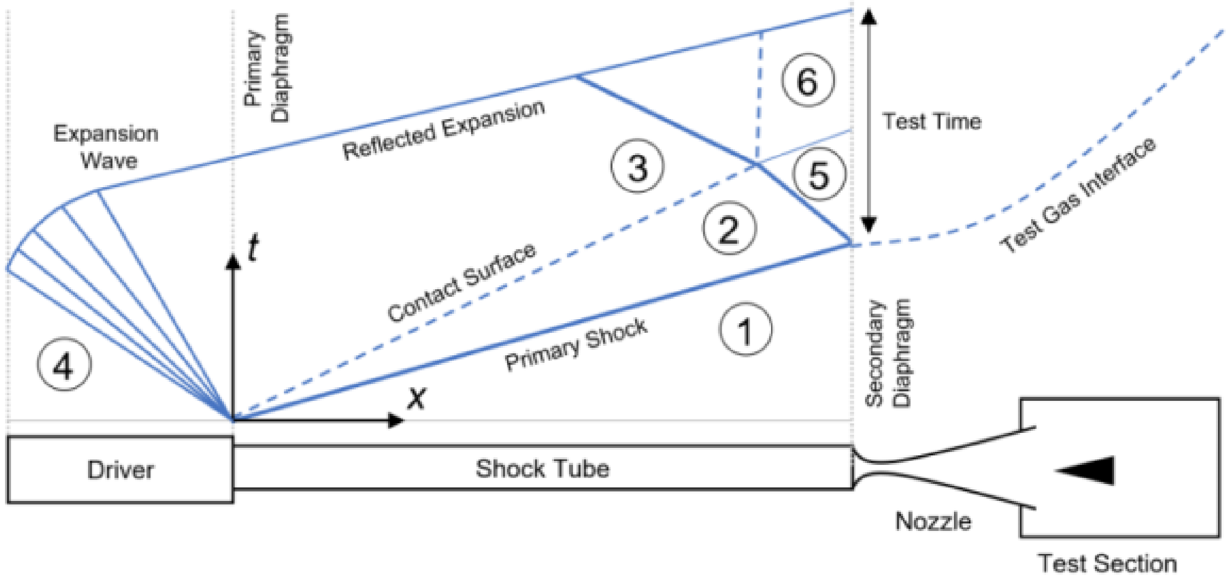



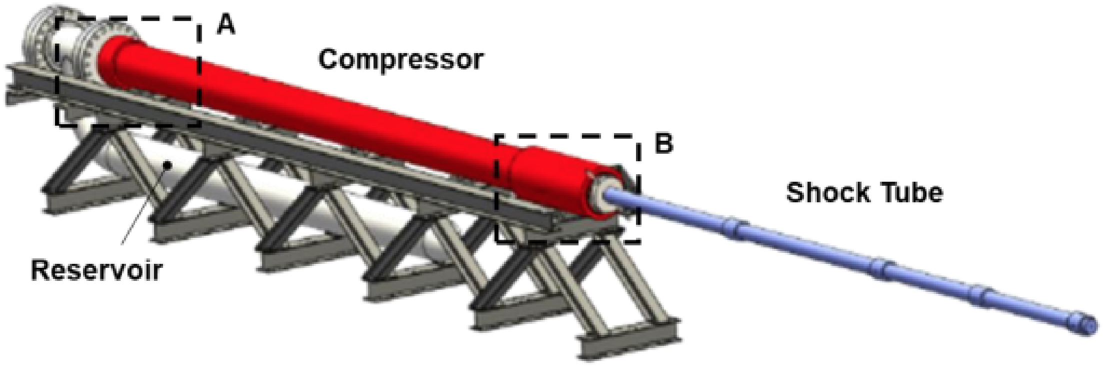



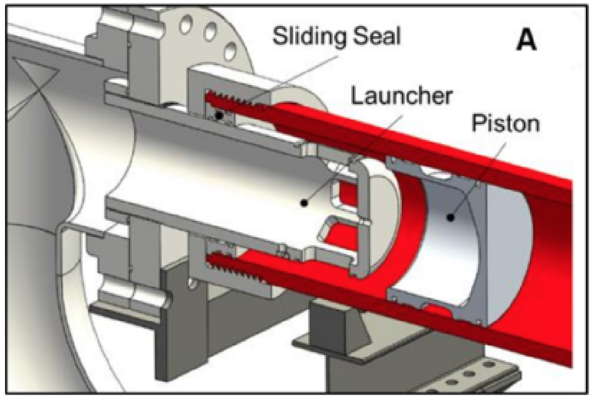

Wang et al. *Optics Letters*, vol. 47 (16), 47, pp. 4159-4162, 2022

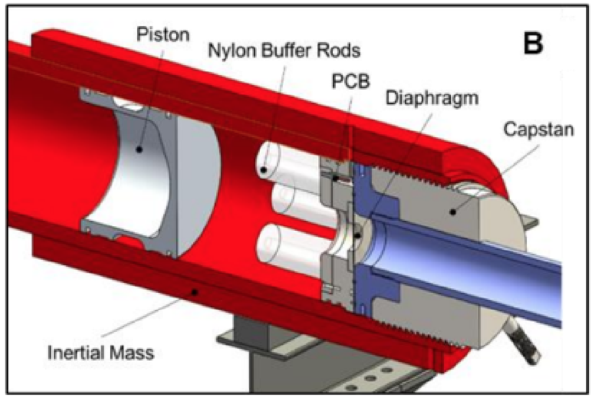
# Sandia Free-Piston HST

- Capabilities beyond traditional shock tubes
  - 35kg piston compressed driver gas more efficiently
  - Post reflected shock conditions able to reach 6000-8000K at pressures > 100 psi
- Conditions calculated with wave speed and NASA CEA



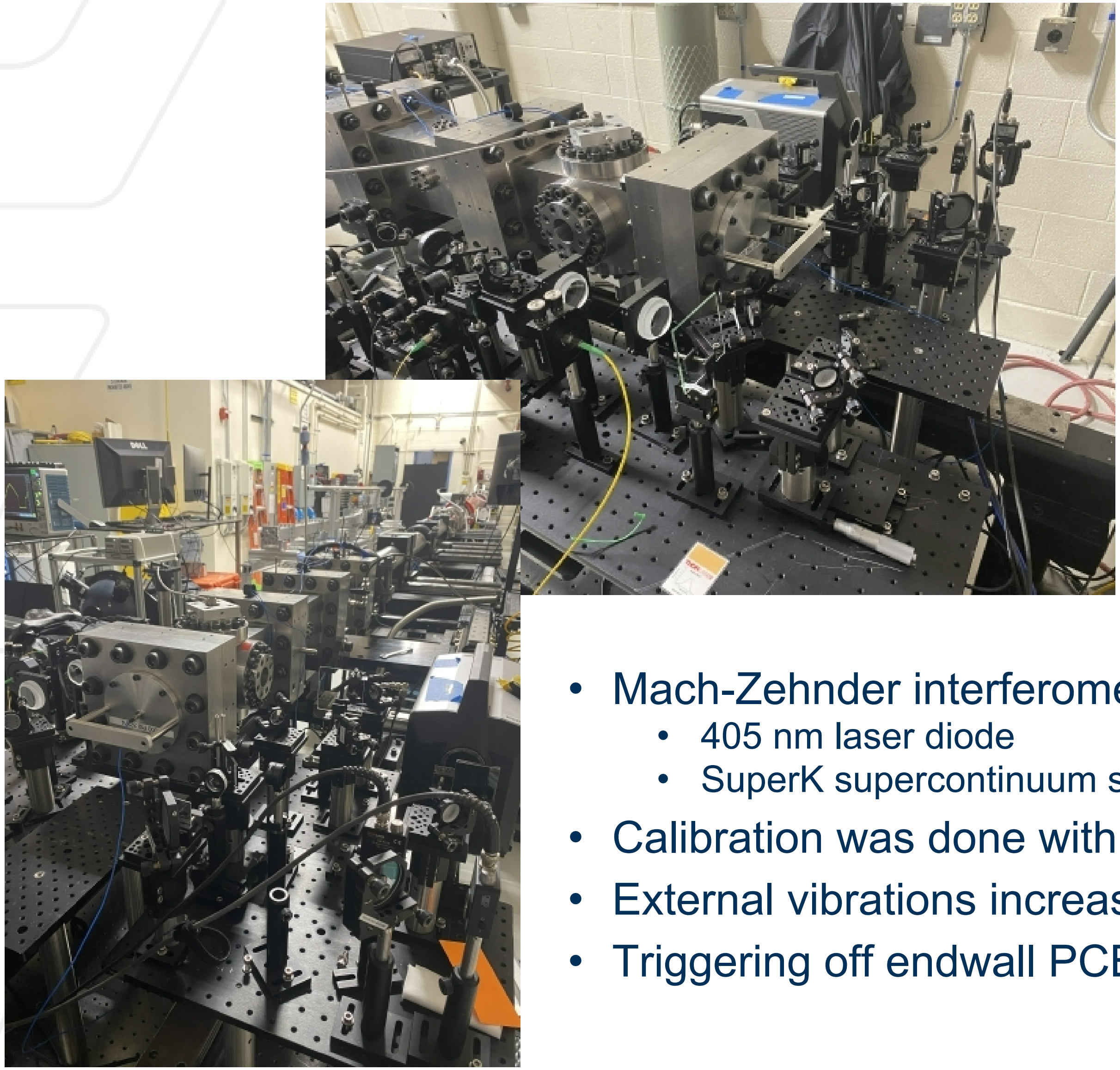



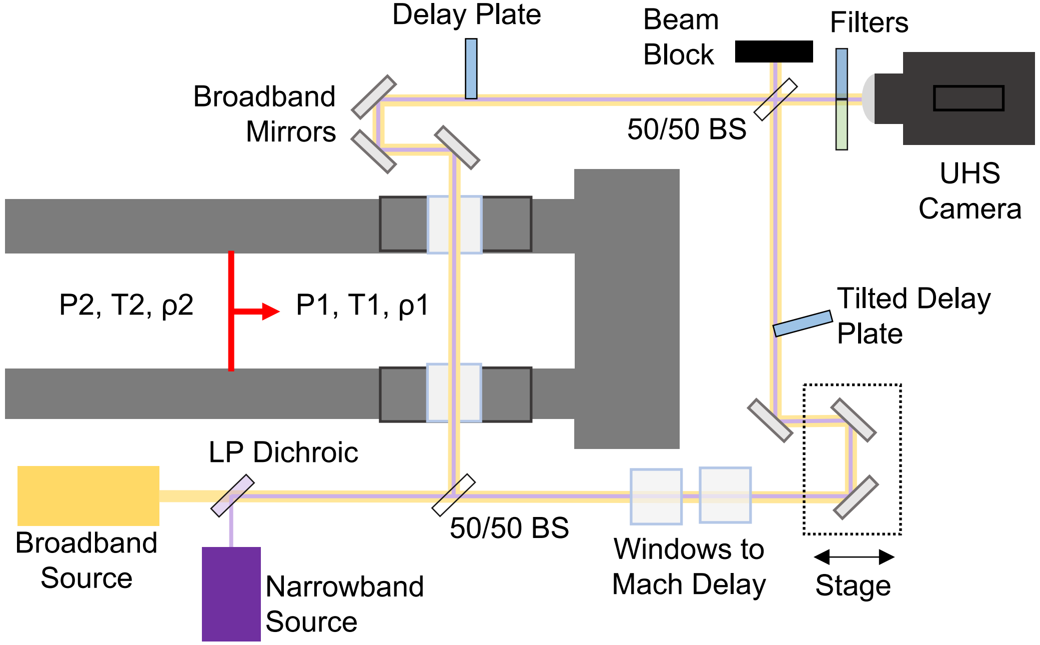





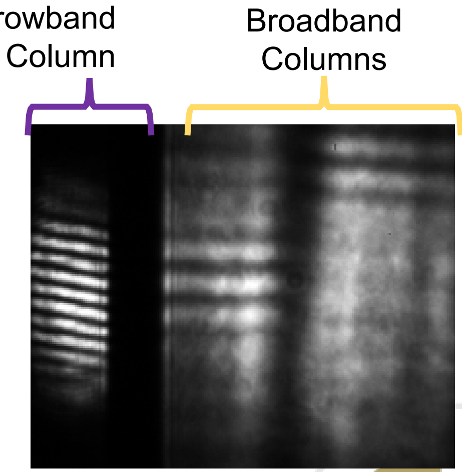
Lynch, Kyle P., et al. *AIAA SciTech 2022 Forum*. 2022.
Petter, Samuel J., et al. *AIAA Scitech 2020 Forum*. 2020.

# Experimental Setup

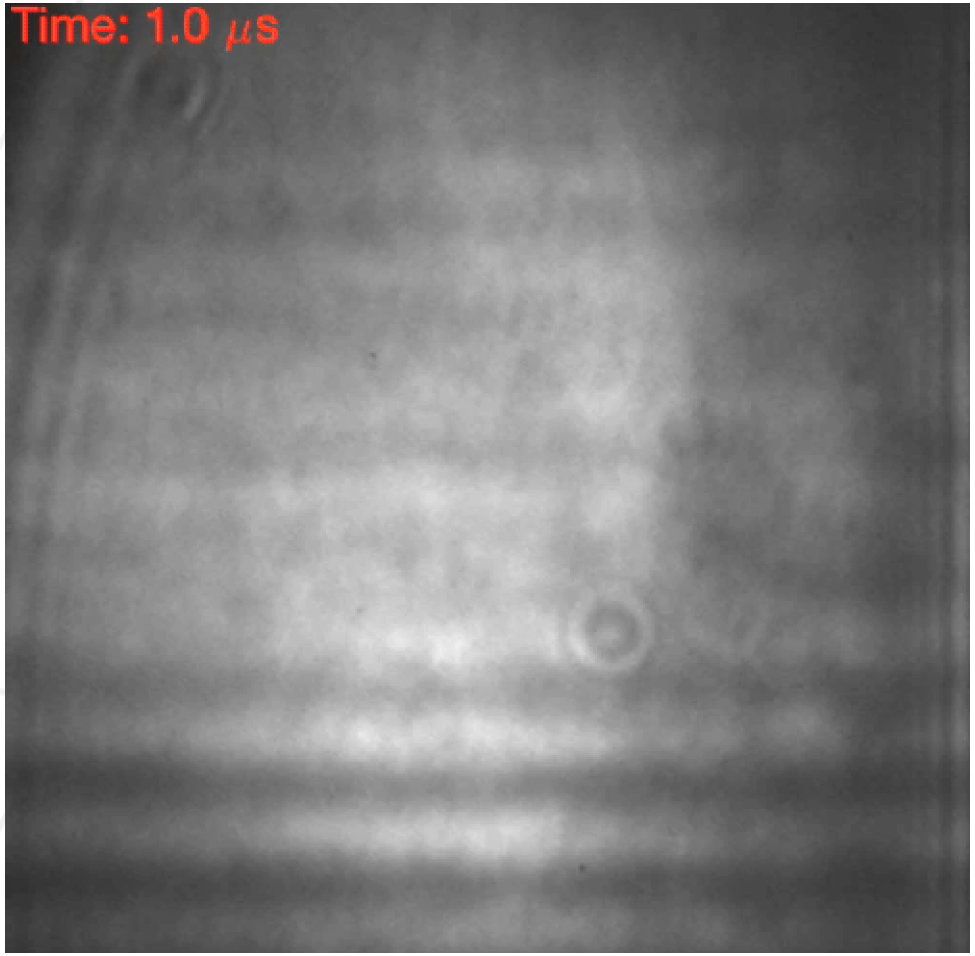





- Mach-Zehnder interferometer
  - 405 nm laser diode
  - SuperK supercontinuum source
- Calibration was done with UHS Shimadzu camera
- External vibrations increased uncertainty
- Triggering off endwall PCB



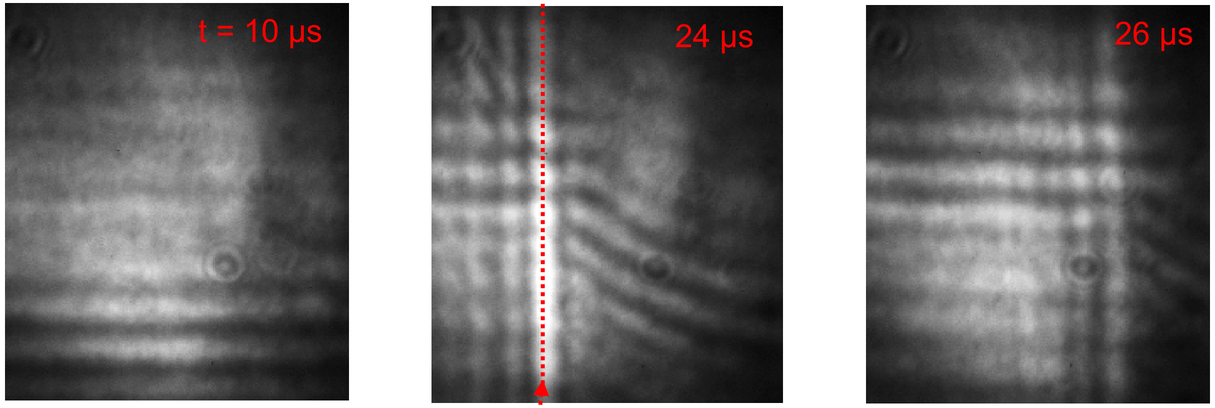
# Results - Video




Direction of Reflected Shock Wave
(Incident Shock M13.95)

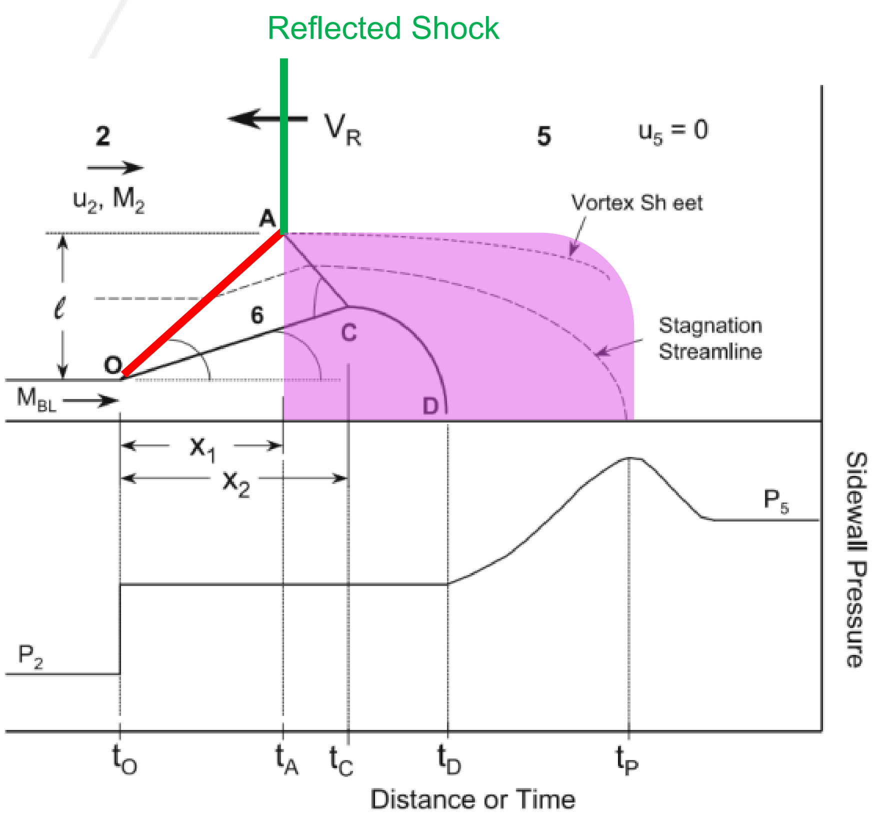
Shimadzu HPV-X2
1MHz, 200 ns exposure

| State 5 | | State 2 | |
|---|---|---|---|
| P5 | 7.87 Bar | P2 | 0.63 Bar |
| T5 | 7653 K | T2 | 5343 K |
| ρ5 | 0.24 kg/m3 | ρ2 | 0.03 kg/$m^3$ |



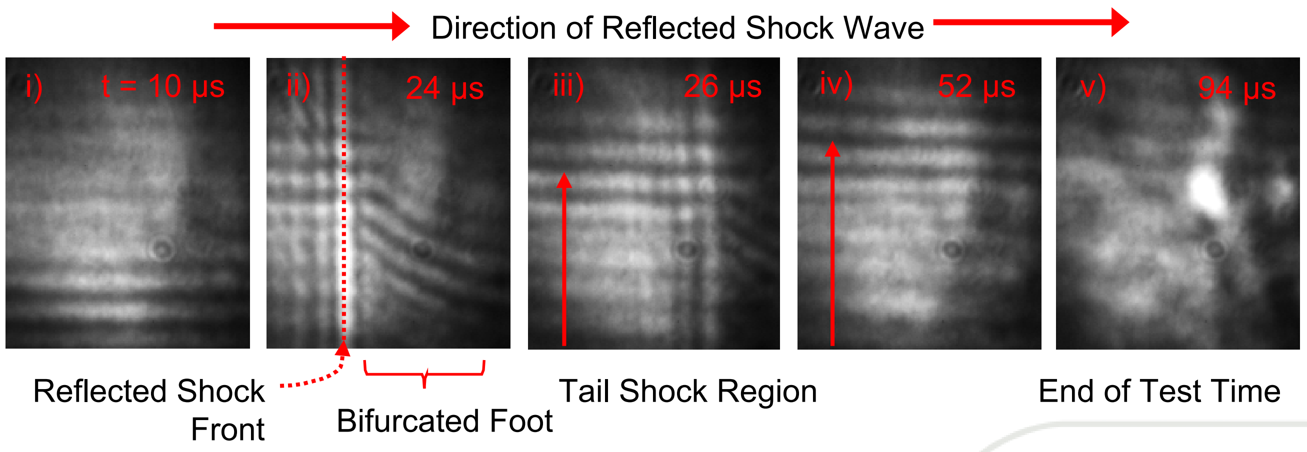

Reflected Shock Front

# Reflected Shock Flow Bifurcation



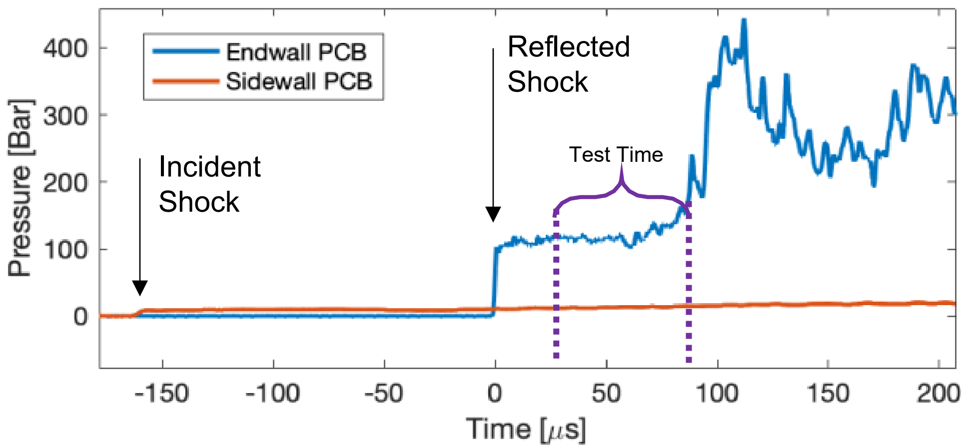

Petersen, E.L., Hanson, R.K. *Shock Waves* **15**, 333–340 (2006).

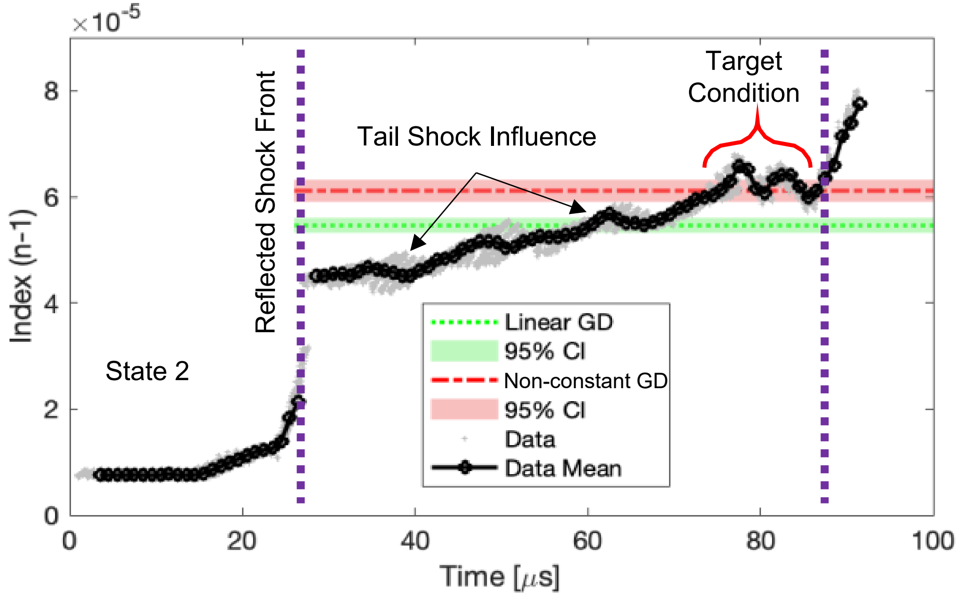
- In GT experiments, post-incident shock flow shows a nearly discrete index change
- Boundary layer interaction with reflected shock front causes bifurcation
  - Foot
  - Tail Shock (Vortex sheet and stagnation streamline)
- Petersen and Hansen reported similar time scale
  - 20-30 us before actual P5, T5 conditions

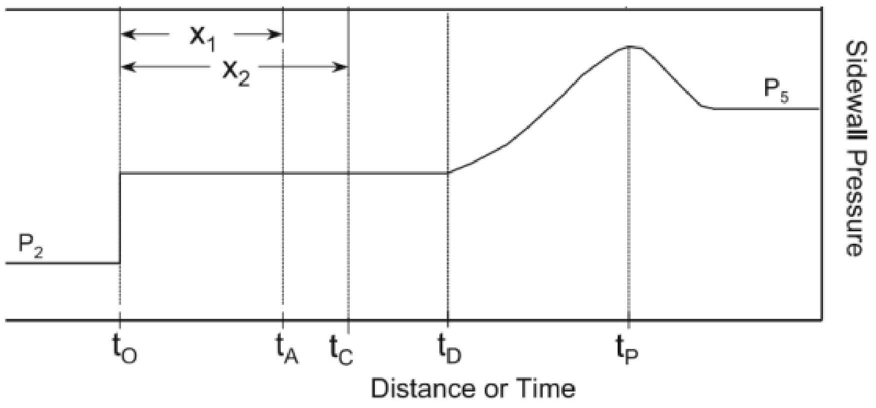


# Results - Index of Refraction

- Post-incident and post-reflected shock were within the measurement range
- Rising index right before shock front captures the bifurcation foot
- Index continues to rise due to tail shock influence before measurement time ends
- Bifurcation produces additional challenges to extract index measurement at a single condition



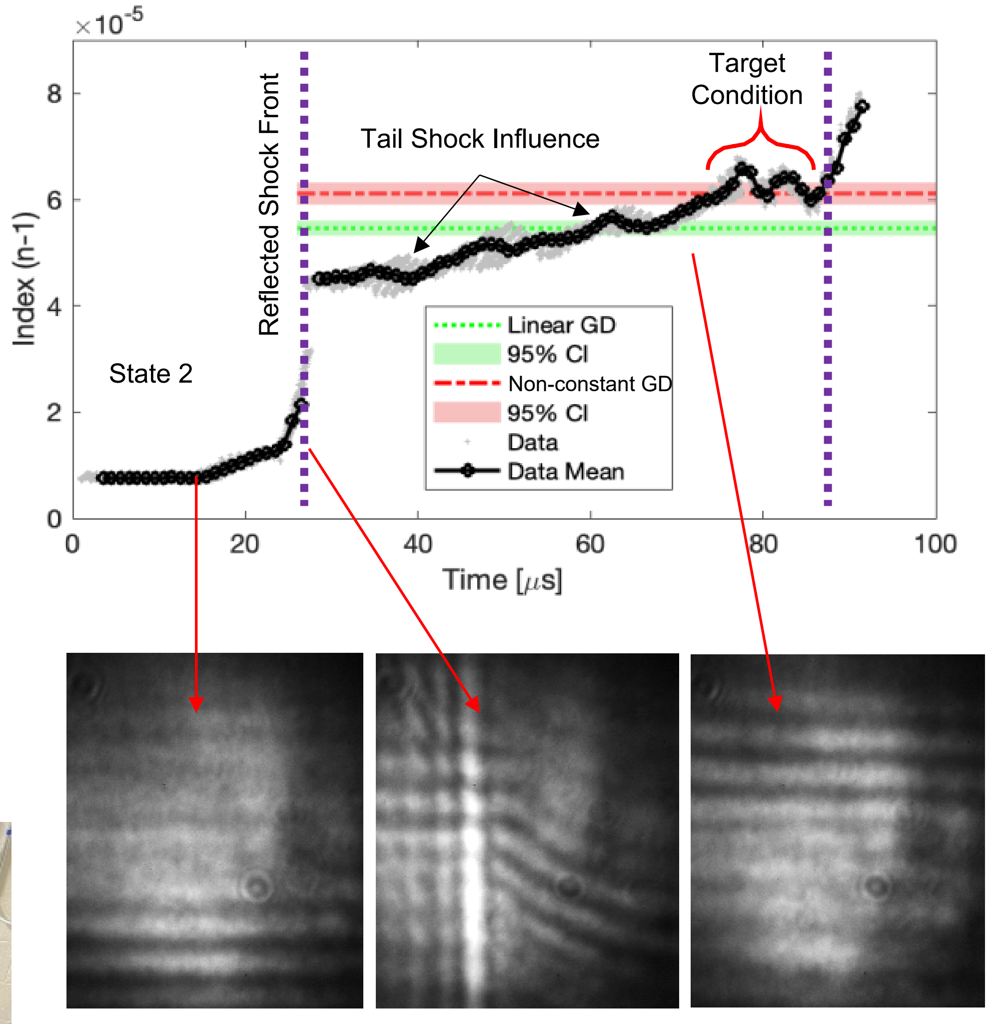



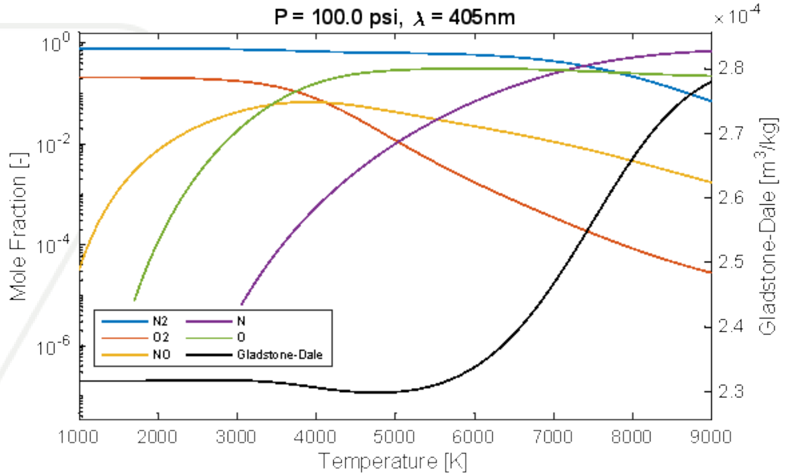



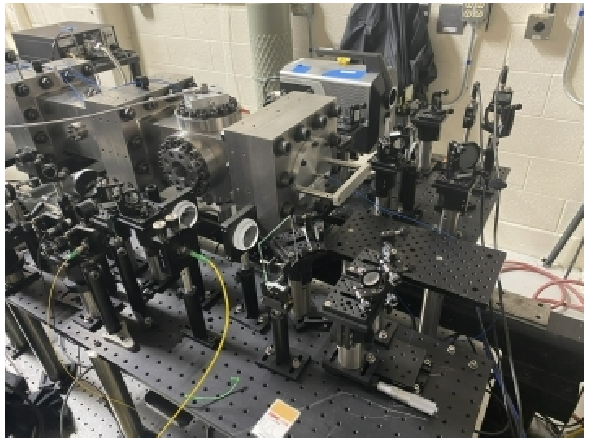

Petersen, E.L., Hanson, R.K. *Shock Waves* **15**, 333–340 (2006).

# Summary and Conclusion

- First known Gladstone-Dale coefficient measurements above 5000K at high pressures
- Free-piston facility combined with QFII diagnostic in a high pressure, high temperature reflected shock conditions
- Reflected shock flow has complex bifurcation features
- Higher density conditions necessary to generate better validation data



# Thank you for listening! Questions?

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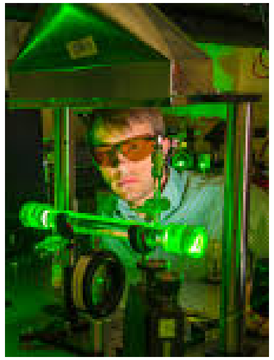

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## Acknowledgements

Thanks to the Sandia National Laboratories Academic Alliance Laboratory Directed Research and Development (LDRD) program for funding this research.

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