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Optical Diagnostic for Index of Refraction Measurements across Shock Waves

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Motivation

- Dissociation at high temperatures will affect optical properties of air
- Constant Gladstone-Dale (GD) coefficient cannot be assumed
- GD has a temperature and pressure dependance
- No experimental validation

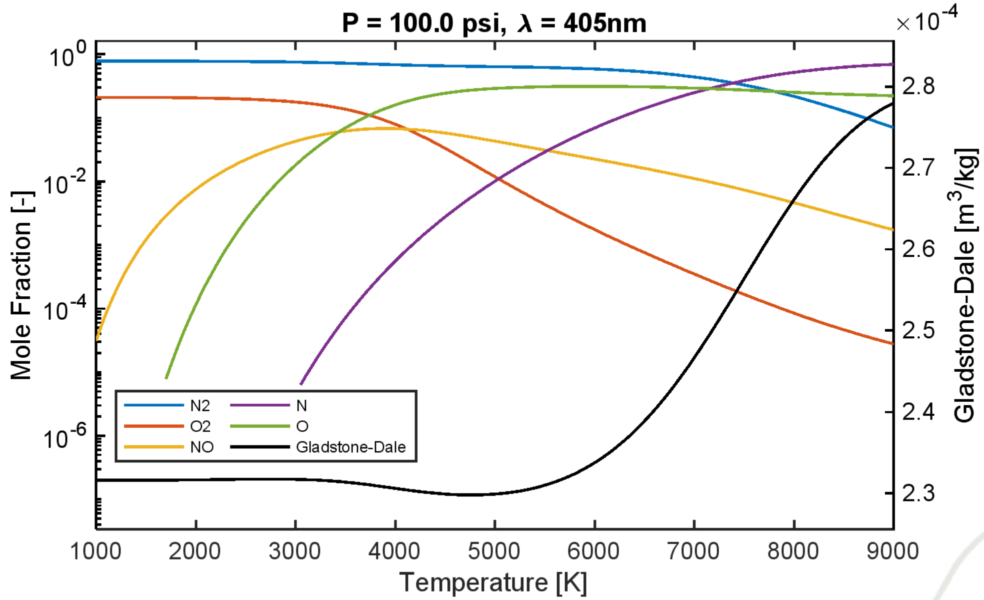
index of refraction

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

density

Gladstone-Dale Coefficient

- High temperature conditions can be reached with modern shock tubes
- New diagnostics are needed to make this type of measurement



Motivation

- Interferometry is used to measure index of refraction, which has wavelength and species dependence
- Composite index for gas mixtures are well tabulated values for common gas species

Post shock conditions introduces challenges

- Density changes are nearly discrete
- Low pressure → small fringe shift number and lower uncertainties
- Moderate densities are necessary to produce measurable index change

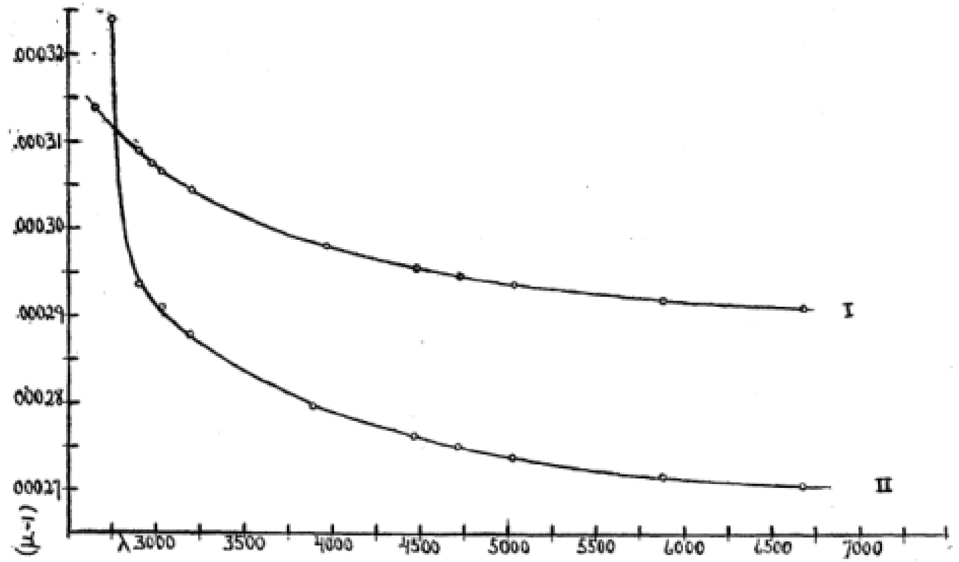
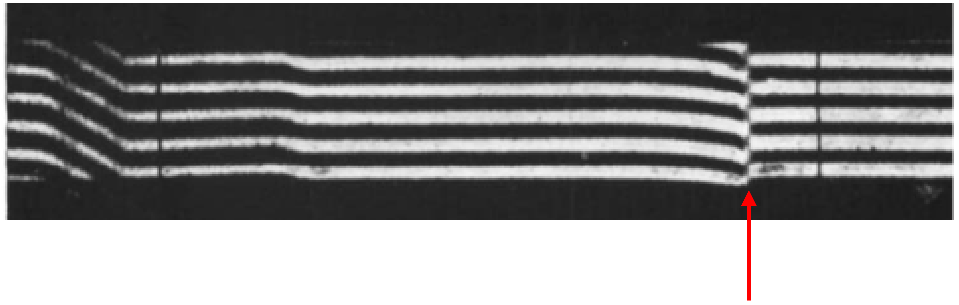


Fig. 3.

Dispersion Curves: I., Air; II., Oxygen. Abscissae: λ in Ångstrom units. Ordinates: $(\mu - 1)$.



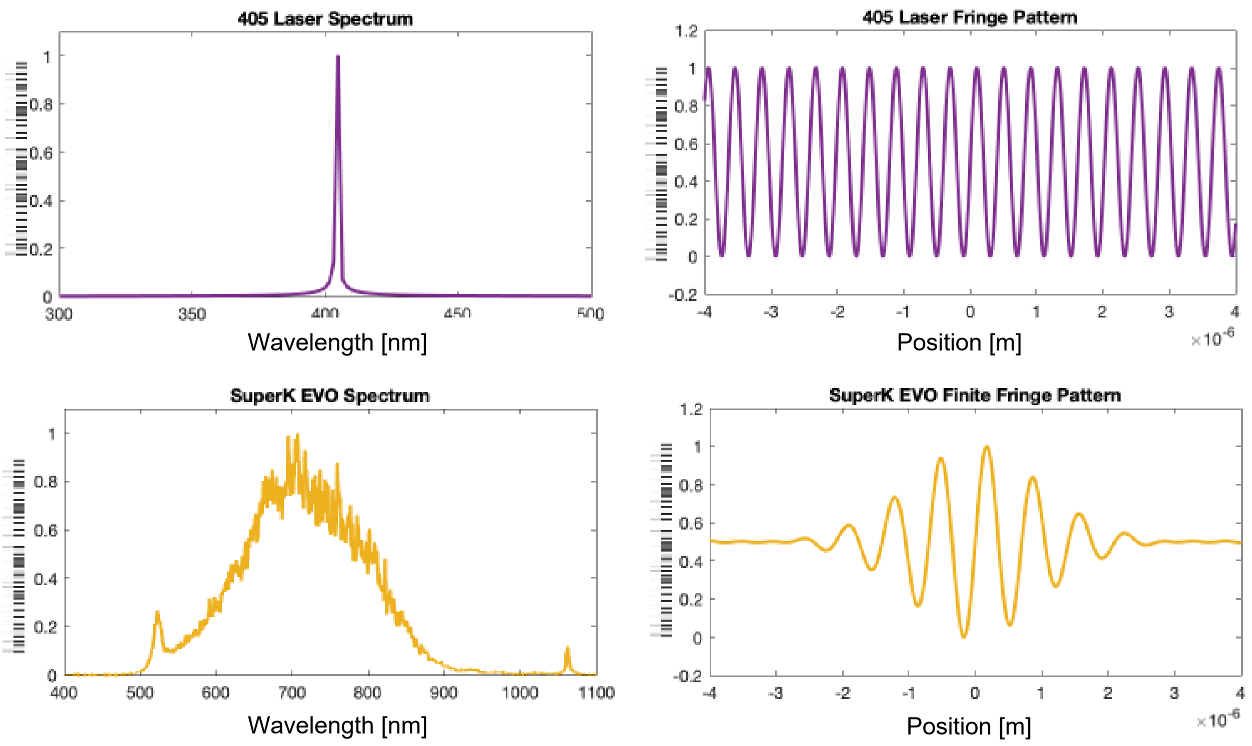
Interferometer capable of resolving large discrete density gradients is needed

Howell, Physical Review 6.2 (1915)

Blackman, Journal of Fluid Mechanics, 1(1), 61-85. 1956

Quadrature Fringe Imaging Interferometer (QFII)

- Develop a diagnostic to resolve large discrete density changes
- Use narrowband and broadband source
  - Narrowband for analog quadrature
  - Broadband for absolute reference
- Broadband sources tested
  - LED bulb
  - Halogen bulb
  - Xenon flash lamp
  - SuperLED
- SuperK EVO supercontinuum laser is the only source that provides enough power for ultra-high-speed frame rates



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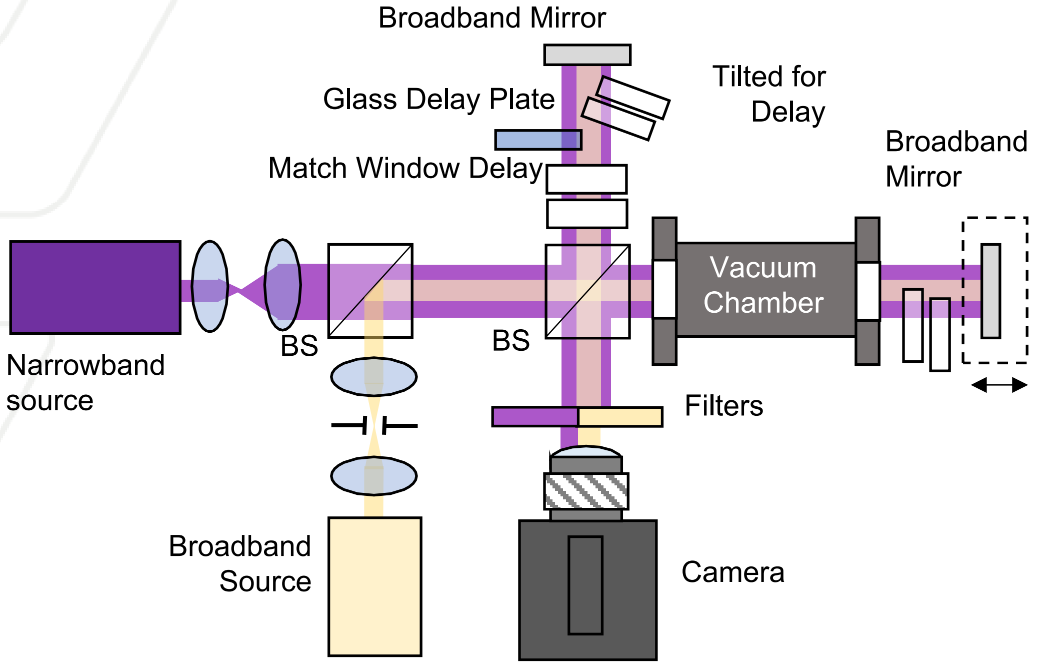
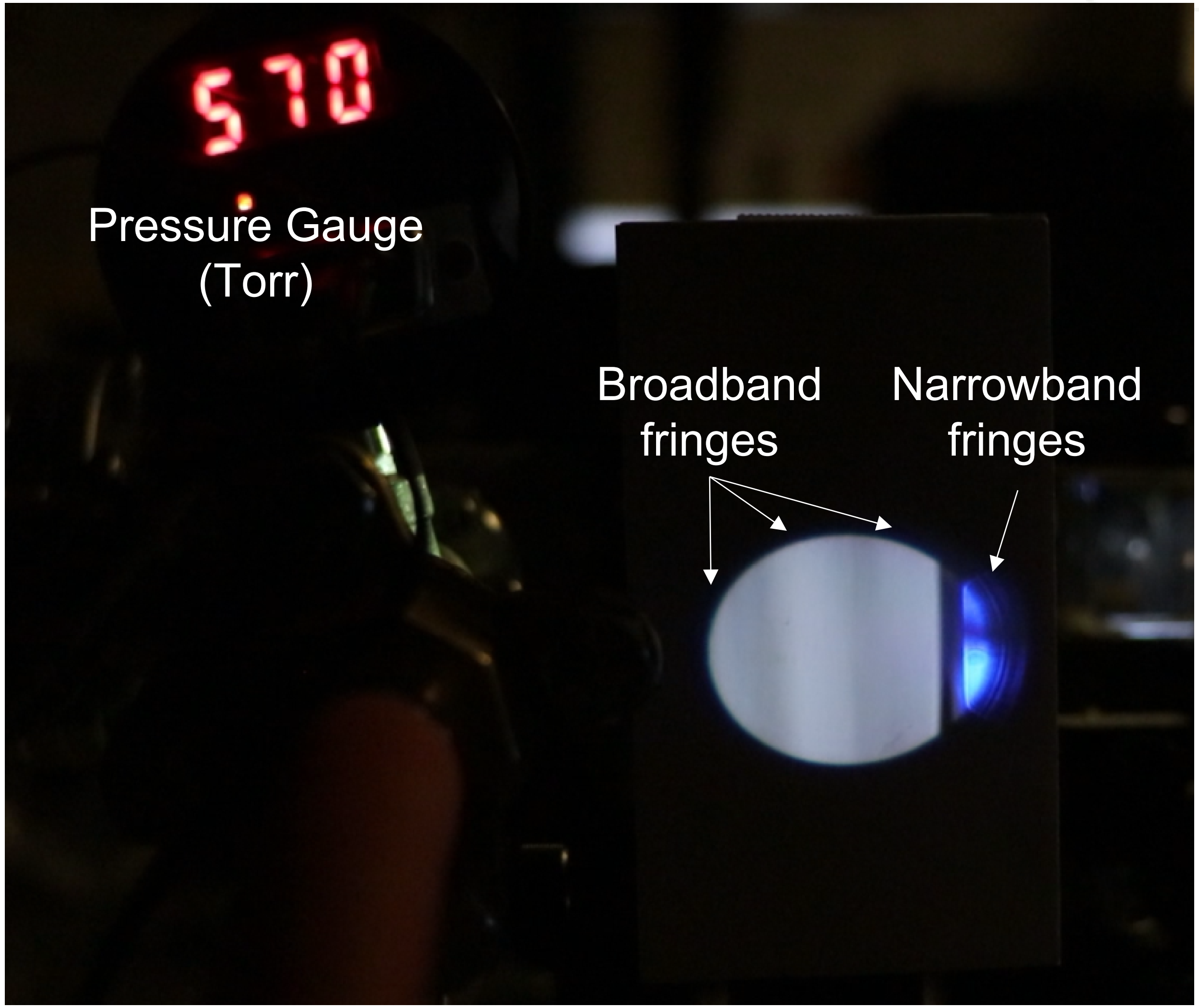
Early Development





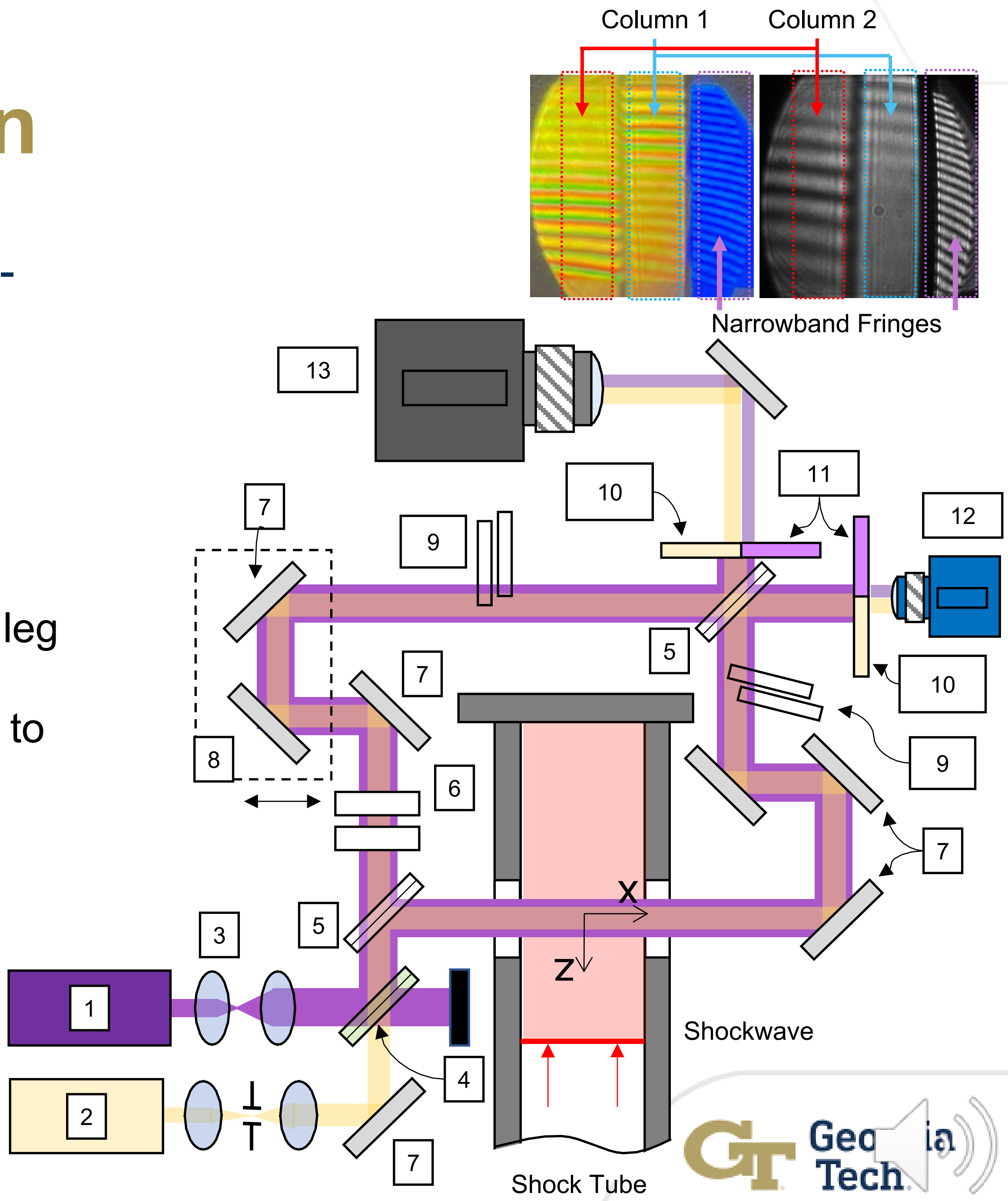
- Michelson interferometer with vacuum cell
  - Micrometer stage to balance and offset center
  - Glass delay plates to increase dynamic range
- Developed a calibration method for narrowband measurement using an analog quadrature

Mach-Zehnder Configuration

- For a Shock Tube implementation, we use a Mach-Zehnder configuration, which gives more flexibility and degrees of freedom for alignment than a Michelson configuration

- Filters and dichroic mirrors are used to combine and separate beams
- Windows of same thickness are placed in the reference leg to match divergence
- Glass delay plates create columns of broadband fringes to increase the dynamic range of measurement

1. 405 nm Laser
2. Broadband Source
3. Lenses
4. 425 nm Long Pass Dichroic
5. Beam Splitter
6. Windows to Match Delay
7. Broadband Mirrors
8. Adjustable Leg
9. Glass Delay Plates
10. 420 nm Long Pass Filter
11. 425 nm Short Pass Dichroic
12. Calibration Camera
13. High Speed Camera



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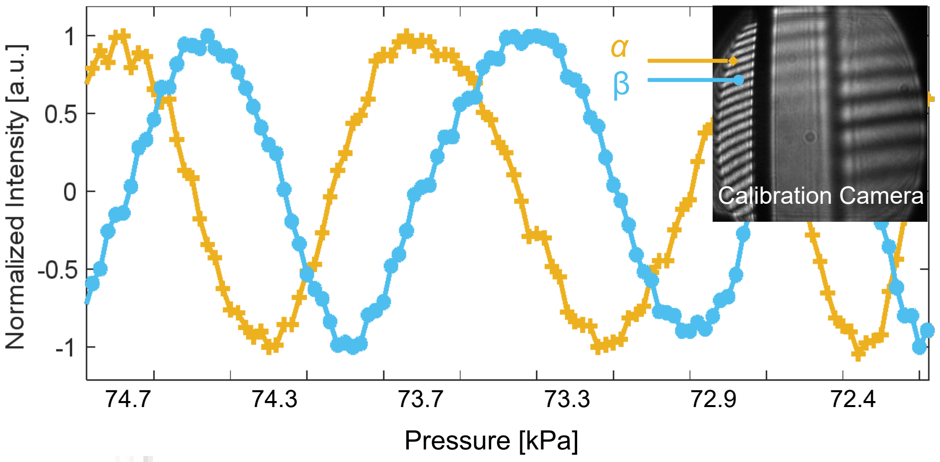
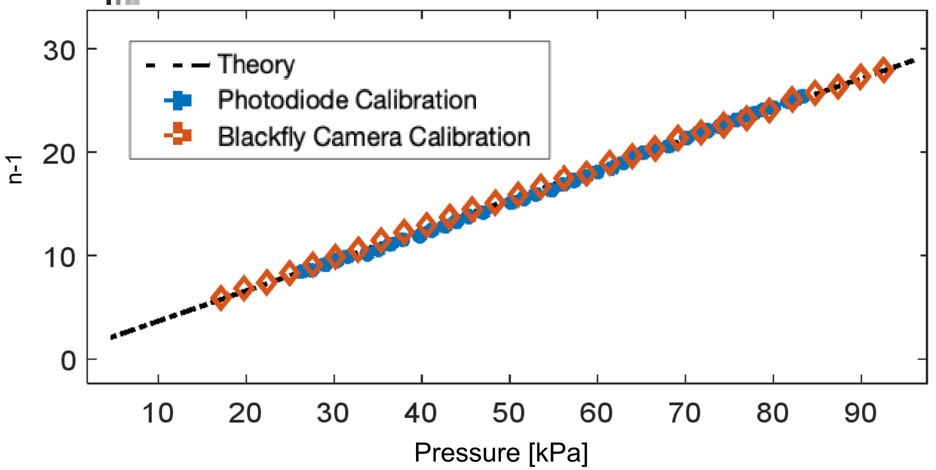
Calibration





- Calculate absolute index with narrowband analog quadrature
  - High resolution and automated tracking
  - Photodiodes or camera can be used
  - Camera provides more flexibility
- Calibration verified with constant GD relationship at ambient conditions

For two sinusoidal signals α, β with phase shift $\phi_{\alpha\beta}$, the change in index is:

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

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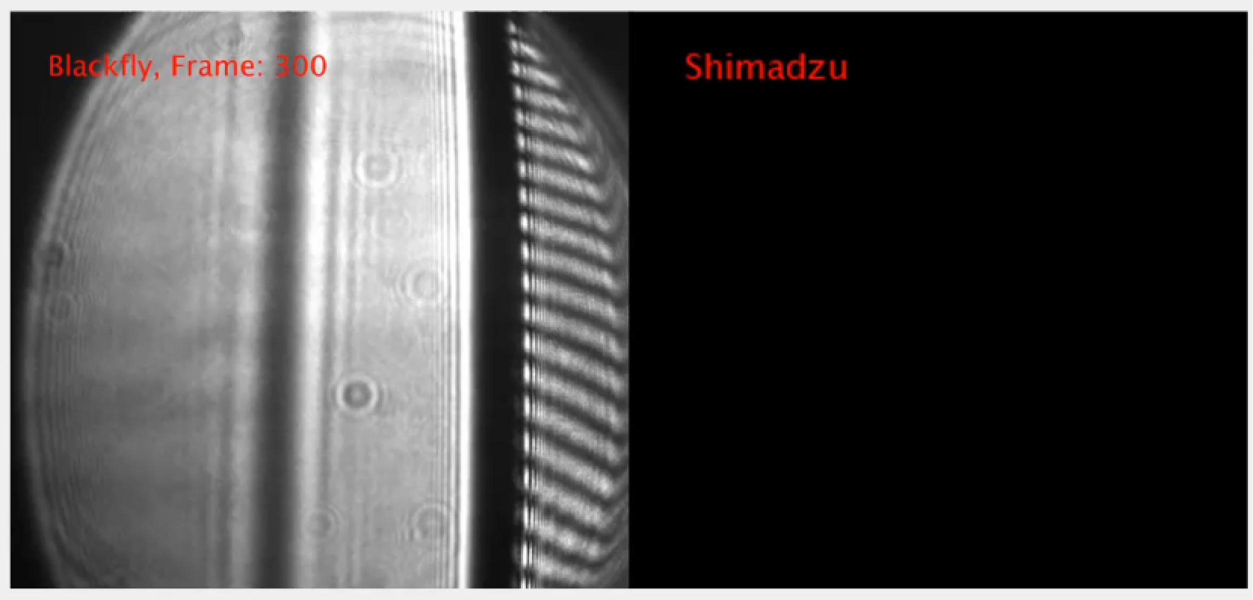
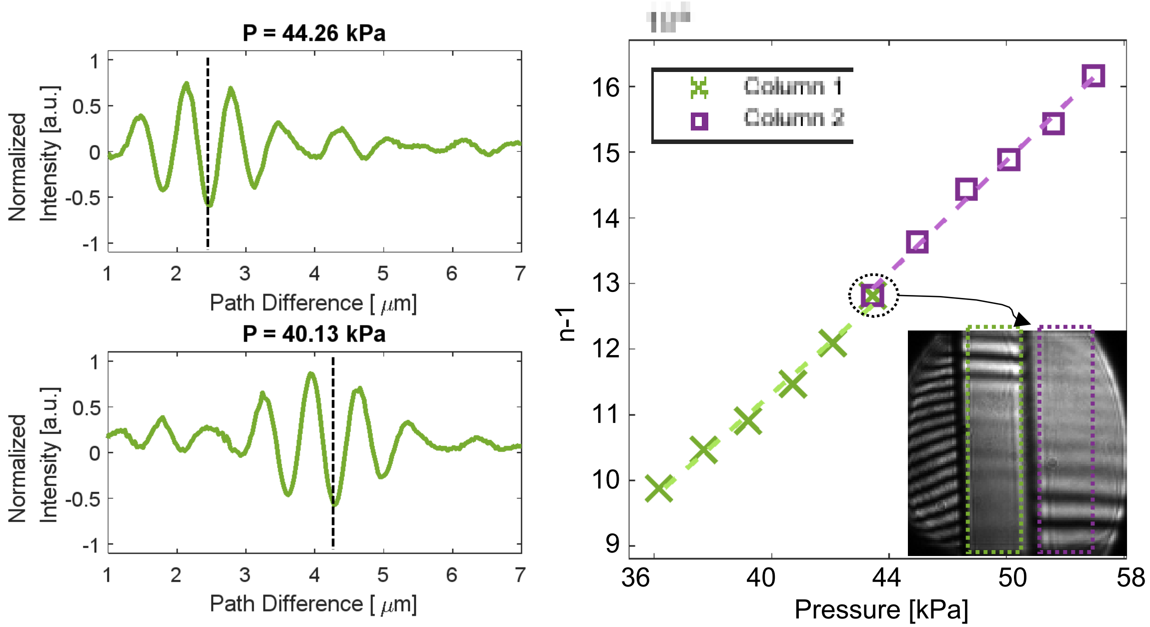
Calibration

- Relate broadband fringe center to absolute index
- Simultaneously trigger calibration camera and high-speed camera, note difference in quantum efficiency for different cameras
- Track center fringe





- Highest resolution with narrowband calibration
  - In presence of large external vibrations, calibration can be modified to use broadband for index calibration
  - Narrowband quadrature then used to reduce uncertainty
  - Can be challenging if interference pattern is not clear

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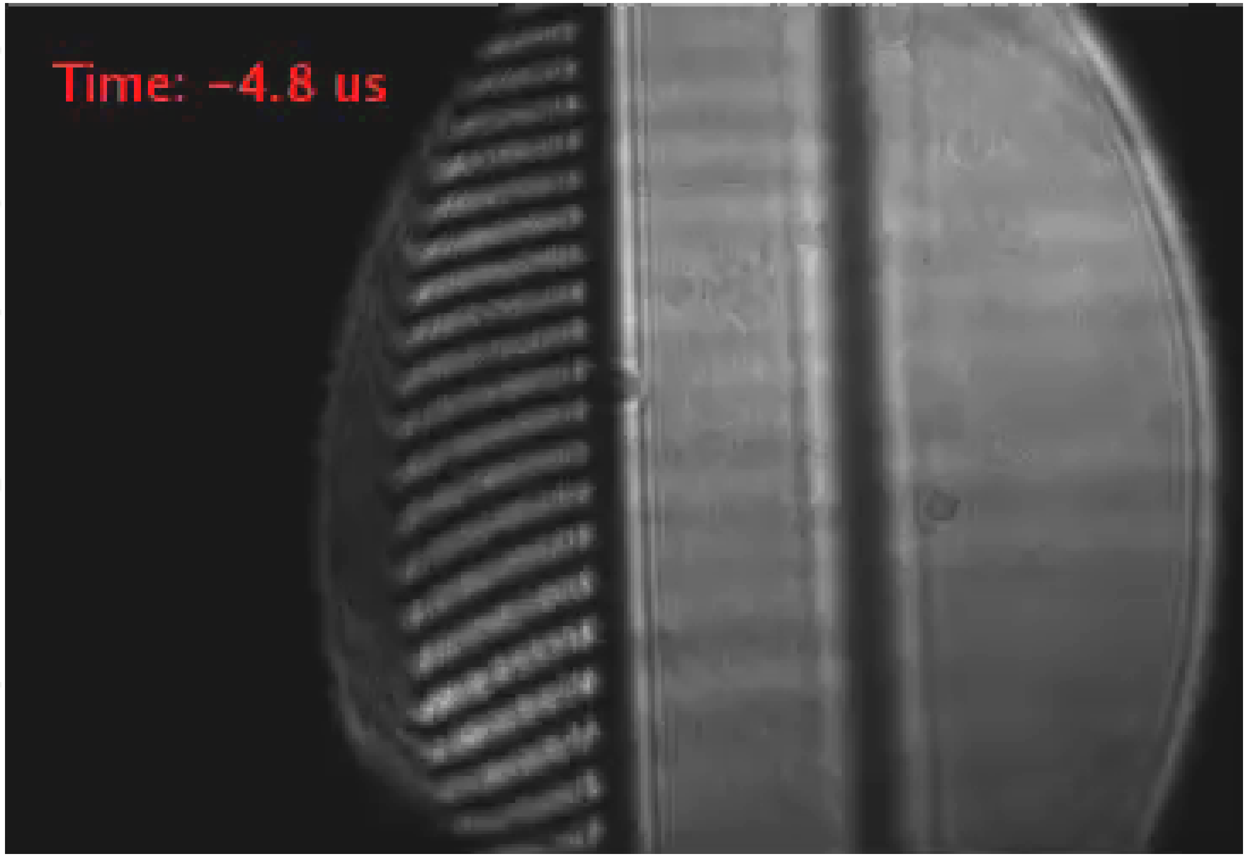
Experiments: Georgia Tech Shock Tube



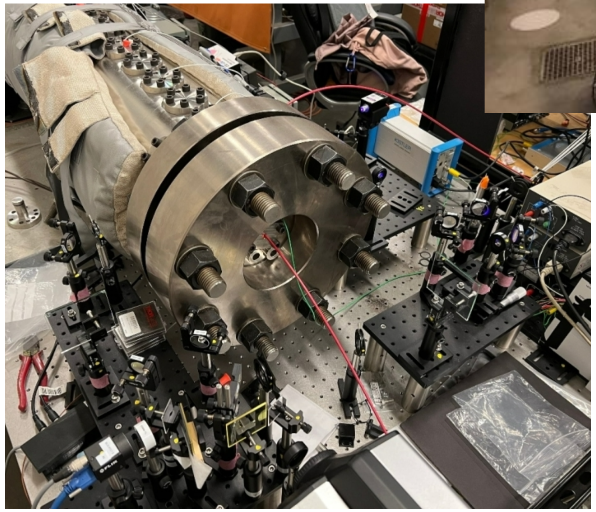
Direction of Incident Shock Wave

Incident Wave Speed: M2.92

Shimadzu HPV-X2

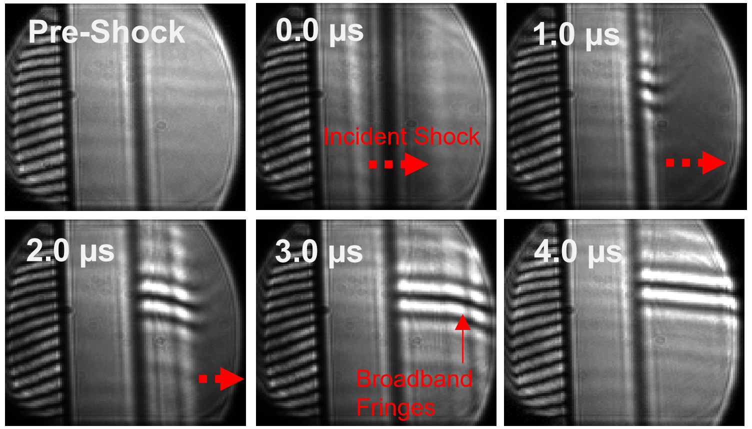
- 5 MHz frame rate
- 200 ns exposure
- Centered triggered on frame 64

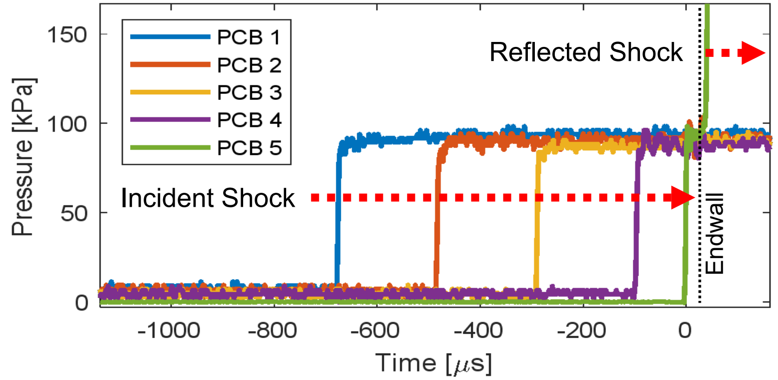
T2 = 749 K
P2 = 1.05 atm

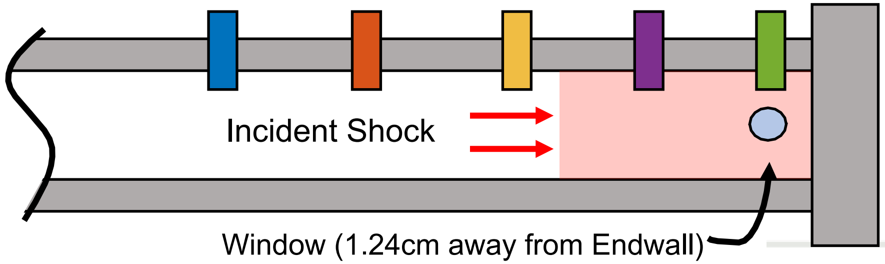


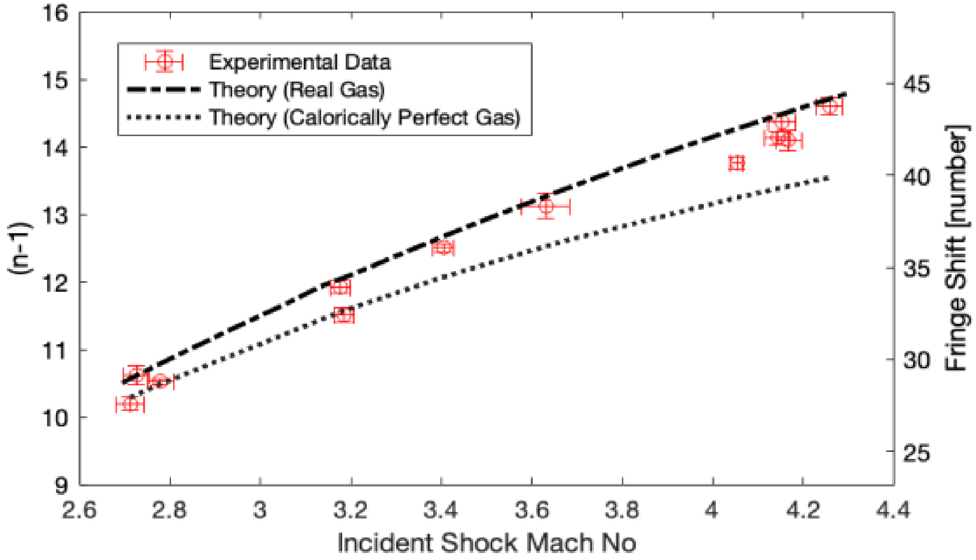
Experiments: Georgia Tech Shock Tube

- 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%









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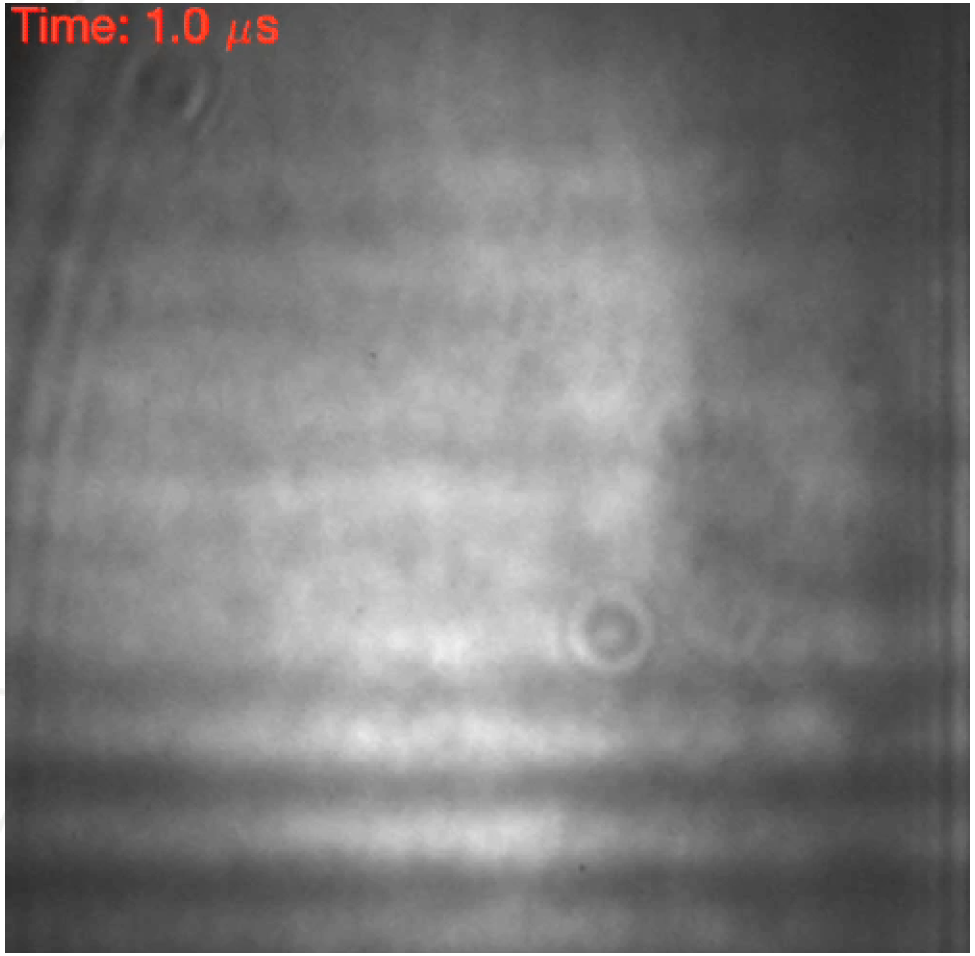
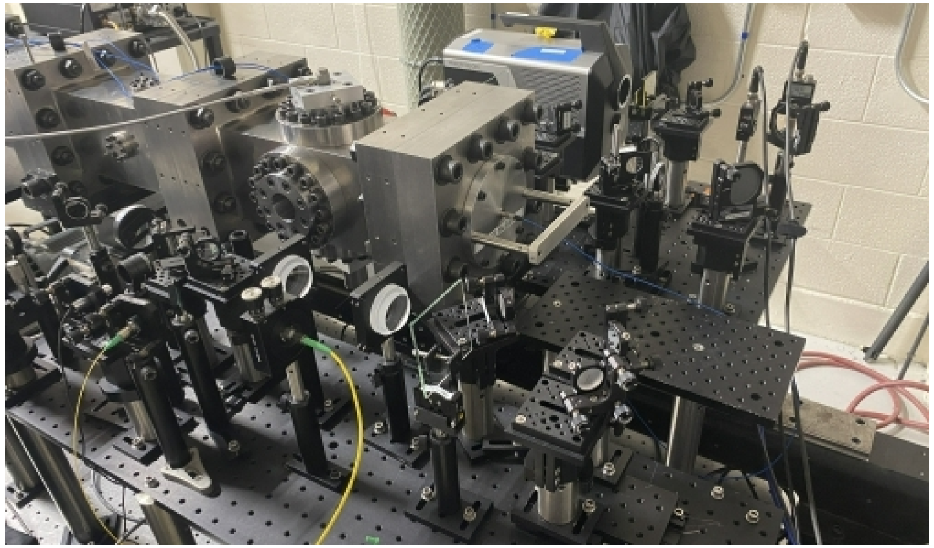
Experiments - Sandia HST



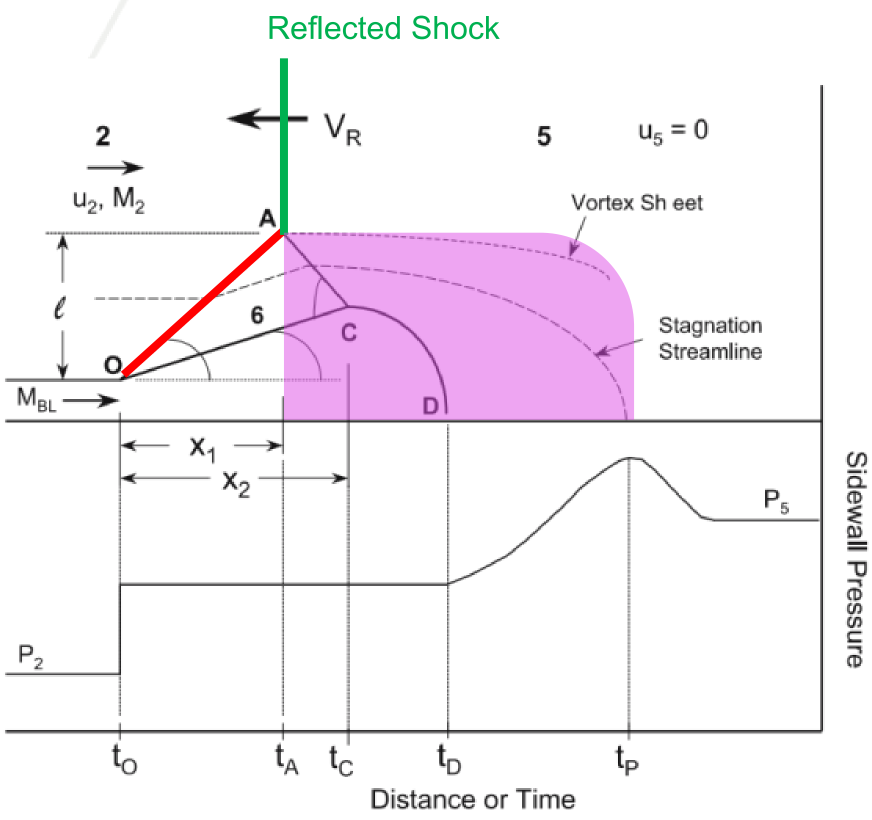
Direction of Reflected Shock Wave
(Incident Shock M13.95)



Shimadzu HPV-X2
1MHz, 200 ns exposure

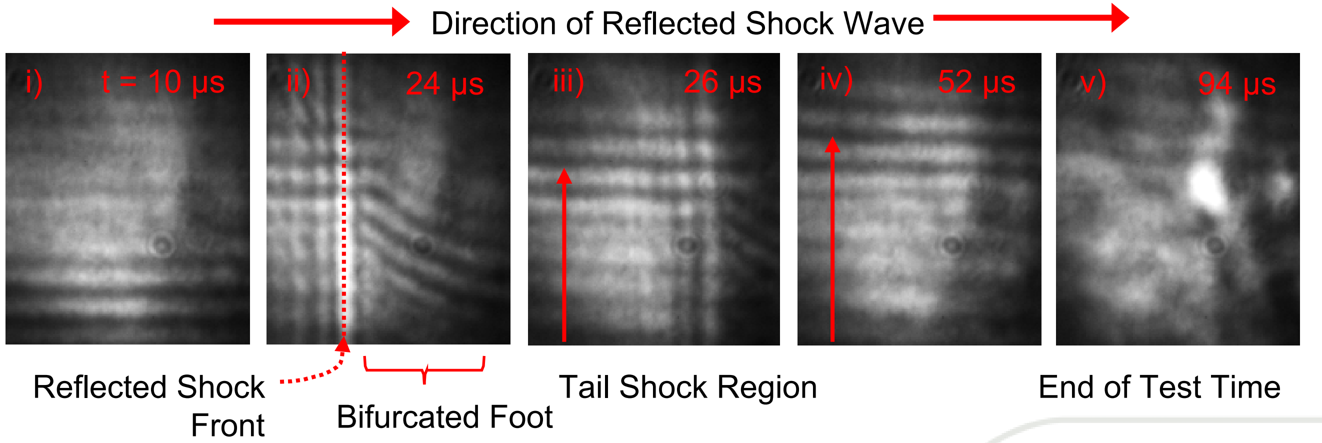
State 5		State 2	
P5	7.87 Bar	P2	0.63 Bar
T5	7653 K	T2	5343 K
ρ5	0.24 kg/m3	ρ2	0.03 kg/m^3

Reflected Shock 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



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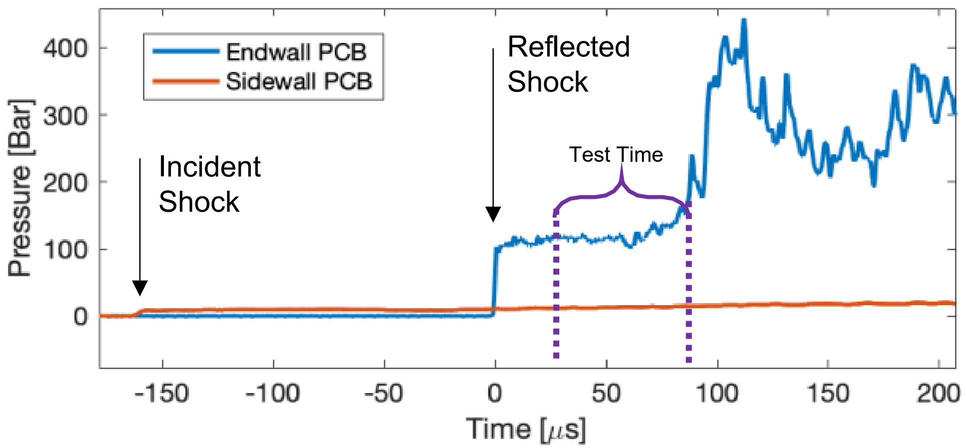
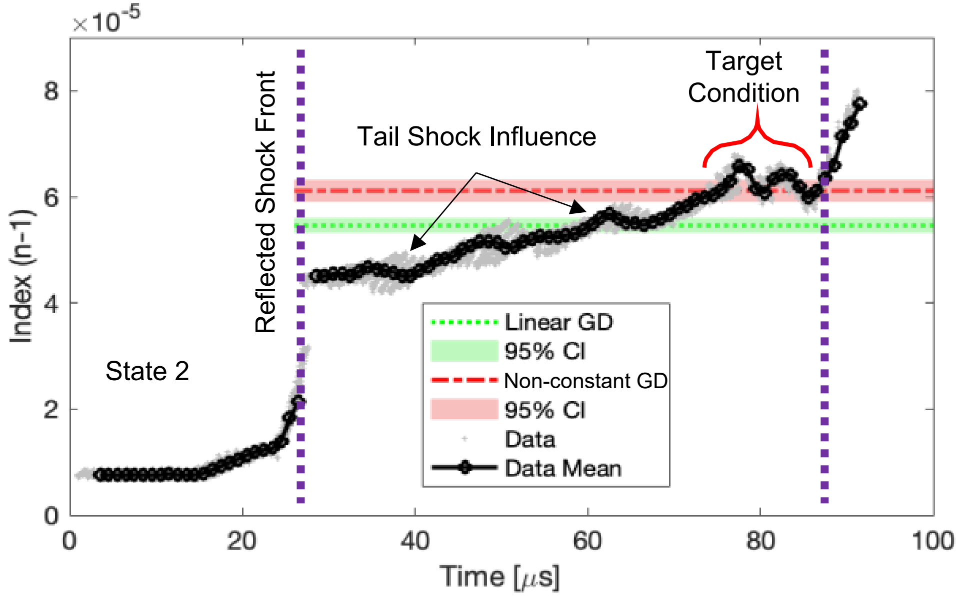
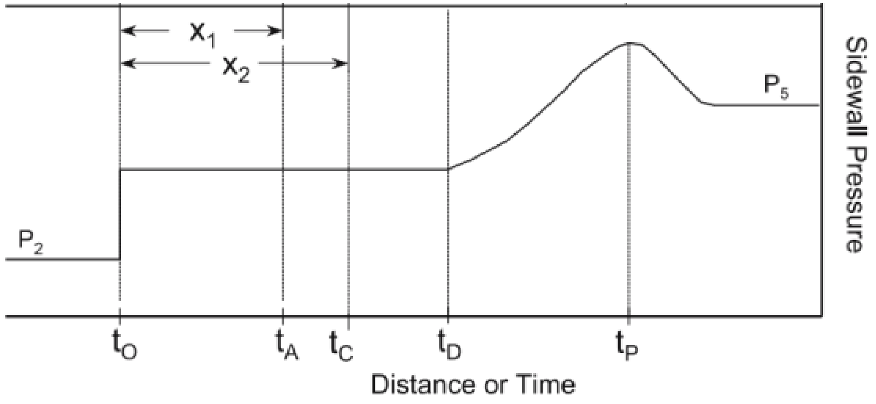
Results - Index of Refraction

- 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







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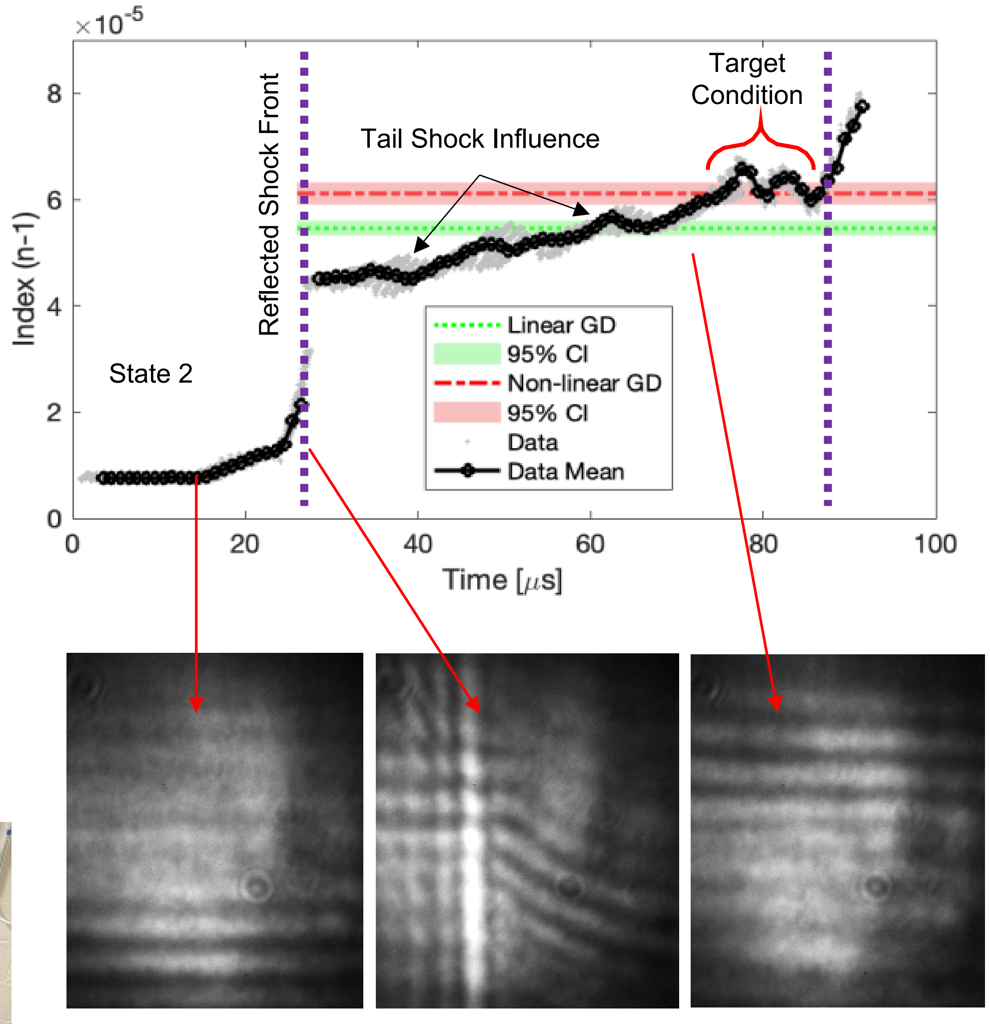
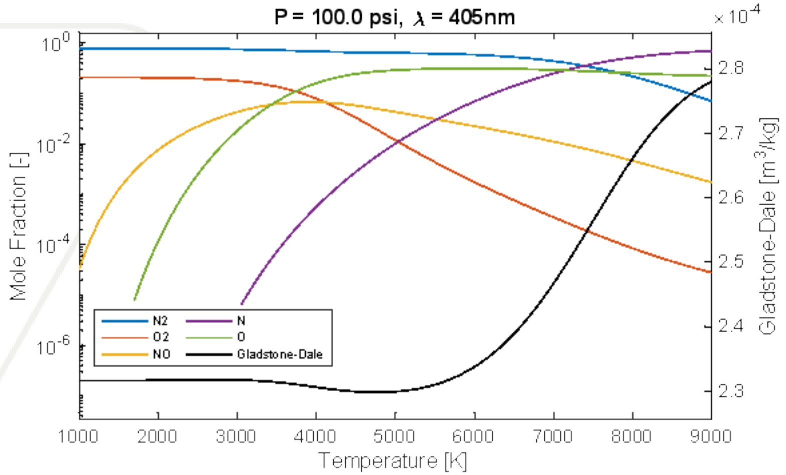
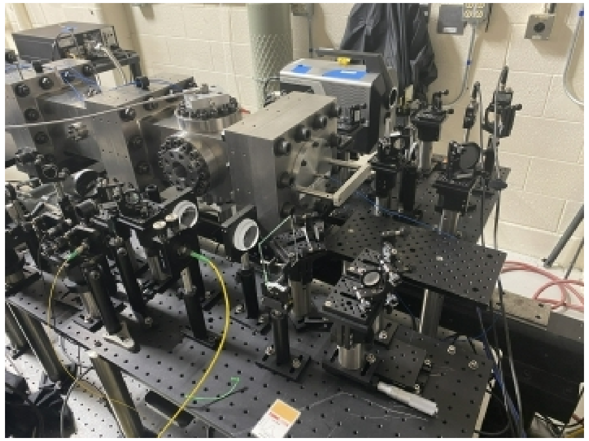
Summary and Conclusion

- Development of optical diagnostic capable of measuring large discrete index of refraction changes
- Free-piston facility combined with QFII diagnostic to measure high pressure, high temperature incident and reflected shock conditions
- Reflected shock flow has complex bifurcation features
- Higher density conditions are necessary to generate better validation data







Thank you for listening!

Questions?

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