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High Power Laser and Explosive Driven Shock Wave Characterization in Solids Using Fiber Optic Probes

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Invited Talk

Scaled Experiments on Shock Propagation in Solid Media

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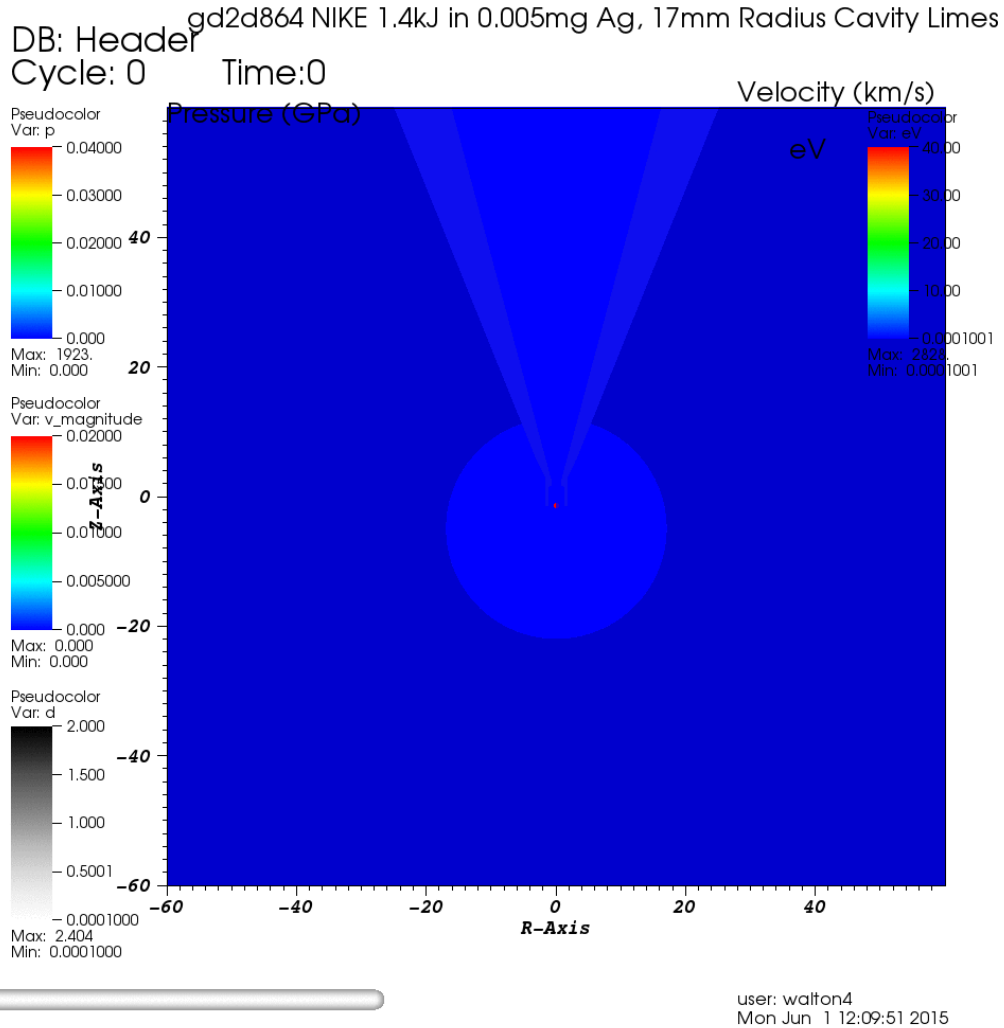
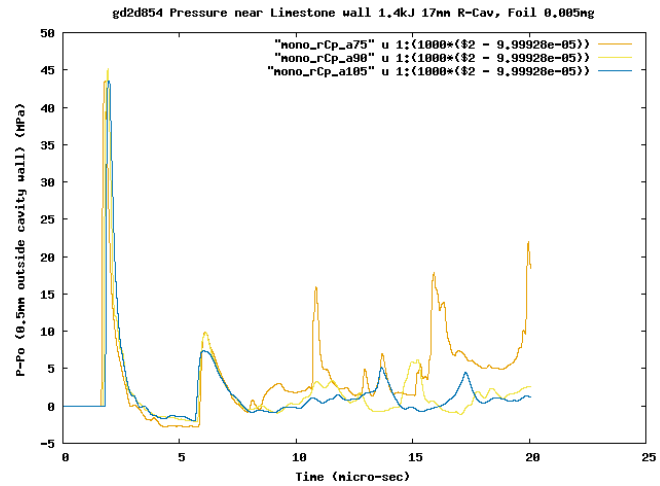
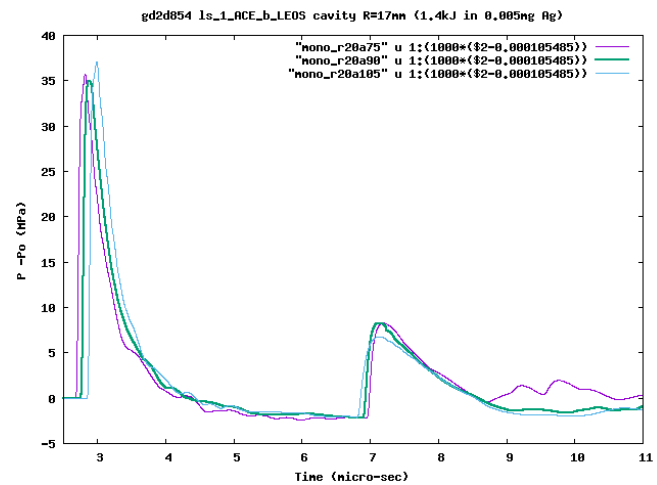
Objectives

- **Scaled experiments are used to study interaction of shock waves with solid media and propagation through solid materials**
- **Scaled experiments supplement full scale experiments (which are expensive)**
- **Scaling must be understood**
- **Shock generation:**
  - High power laser generated shocks
  - Explosive shocks (PETN)

How we understand shock propagation -Geodyne Simulation-







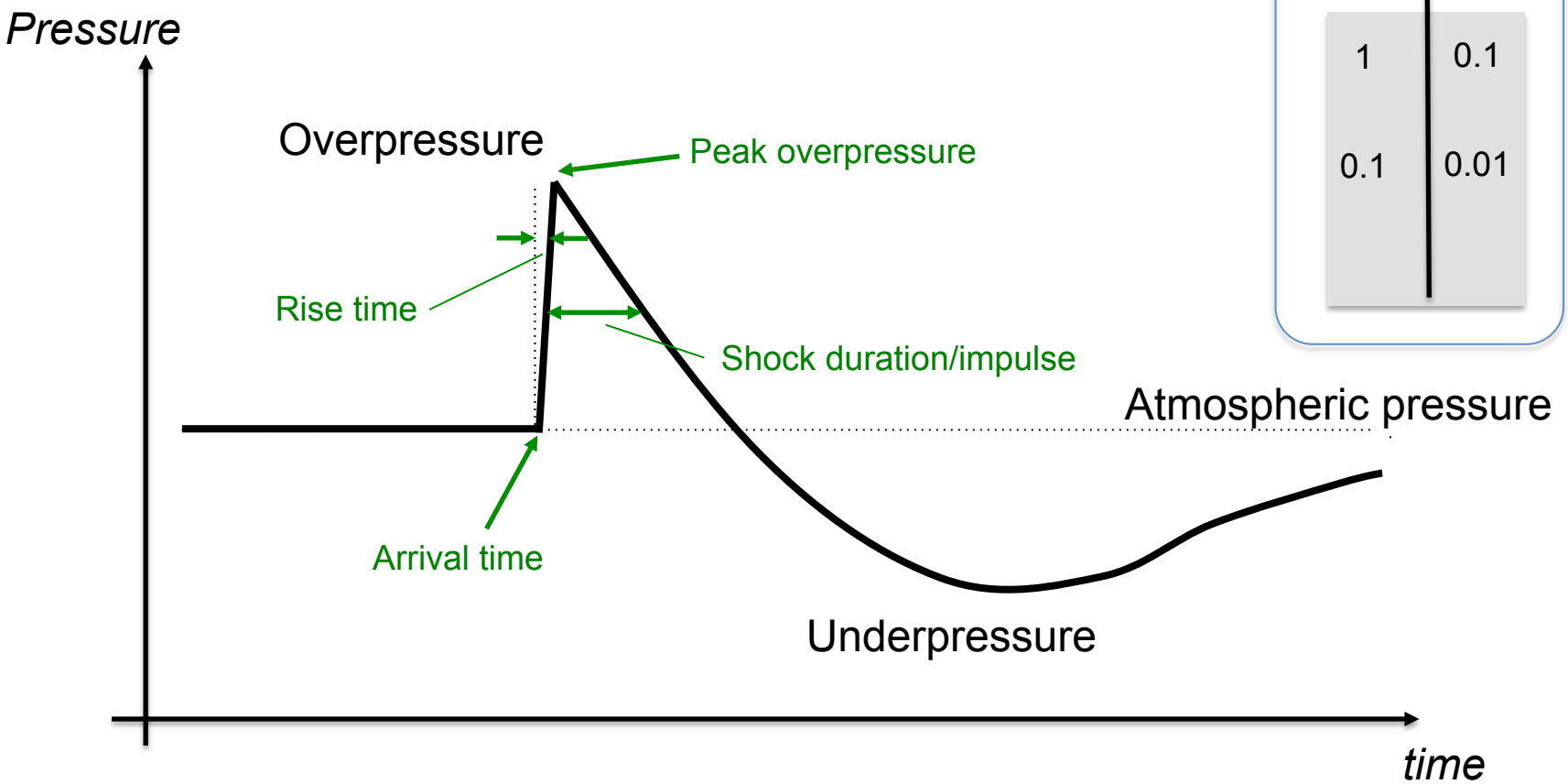
Simulation provided by **Otis Walton**, Lawrence Livermore National Laboratory, US

Definition of Terms/Requirements of Sensor

<u>Target performance</u>
Rise time: < 10 nsec
Max pressure: 1 GPa (10 kbar)
Dynamic range: >10^4

<u>Sensor requirements</u>
- Small/fast
- Immune to EMI
- Withstand shock

kbar	GPa
100	10
10	1
1	0.1
0.1	0.01



Scaling

What scales?

1. **Air hydrodynamics**
2. **Pressures/mass velocities**
3. **Shock velocities**
4. **Impulse**

Scaling laws are commonly used in hydrodynamic problems to enable scaled tests to be performed:

- Ocean hydrodynamics
- Aerodynamics

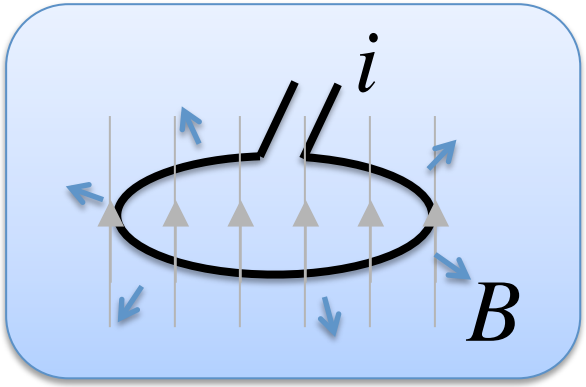
What doesn't scale and do they matter?

1. **Grain sizing**
2. **Compressibility/Strain rate**

Existing Characterization Techniques

Electrical:

- **Piezo-electric sensors**
  - Fairly large –time response?
  - Sensitive to EMI (much higher in laser gen shocks)
- **Dremin loops**
  - Sensitive to EMI
  - Require external magnetic field
    - Impractical for laser generated shocks



Fiber optic:

- **Ruby gauge**
  - Reliability
  - Temperature sensitive
  - Difficult to interpret signal

New fiber optic diagnostics

- **Fiber optic shock wave sensors developed for air blast measurements and medical ultrasound in liquids**

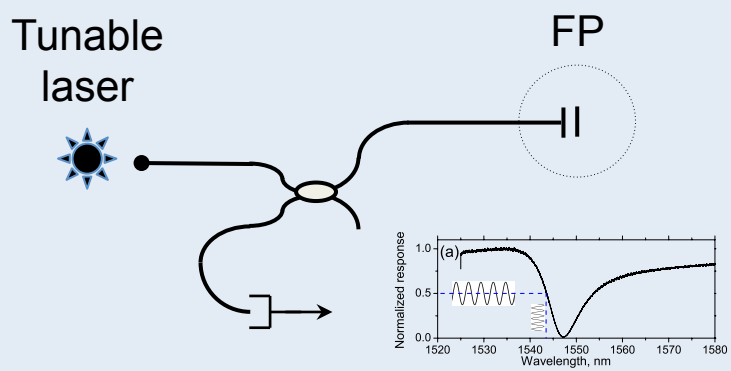
- **Fiber optic pressure sensor**
  - Fabry-Perot fiber tip sensor (solid cavity)

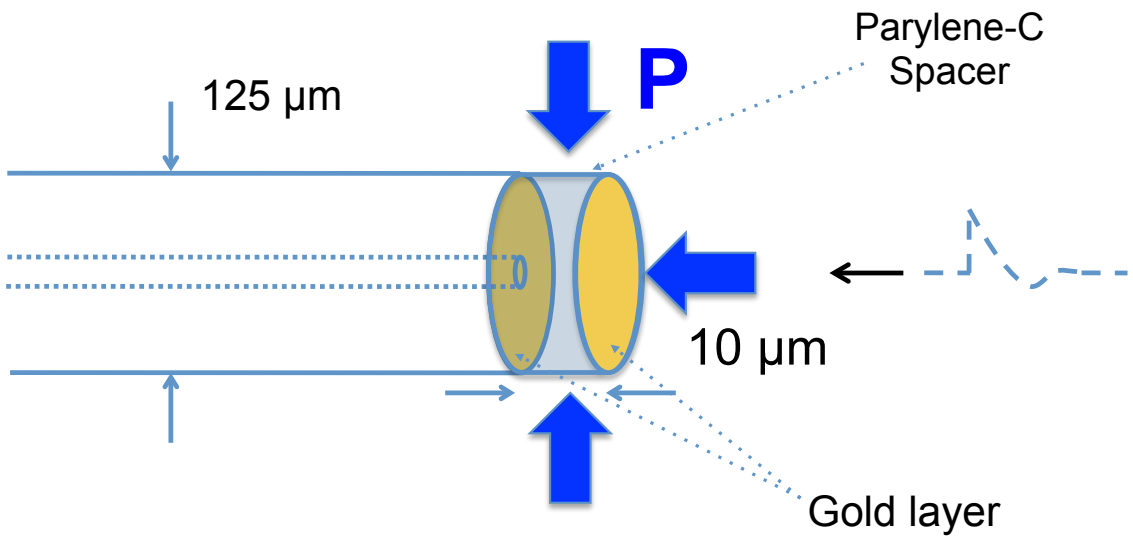
- **Fiber optic displacement/velocity sensor**
  - Interferometric fiber tip sensor (mirrored end)

Pressure (P) probe

- Fabry-Perot cavity on fiber tip
- Shock compresses Fabry-Perot
- Response proportional to pressure
- Calibrated in water: 250 nm/GPa
- Measurement range:
  - 0.1 MPa – 0.1 GPa

Interrogation system

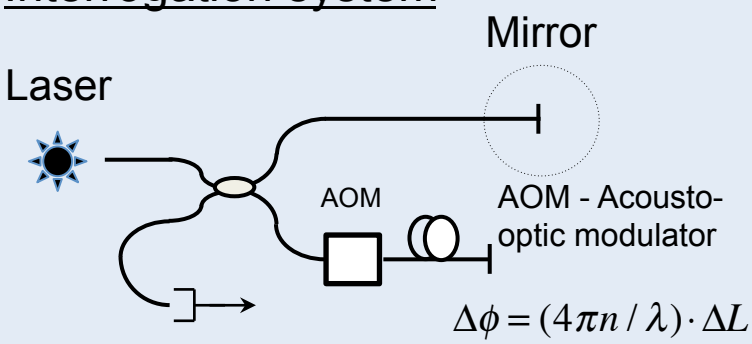




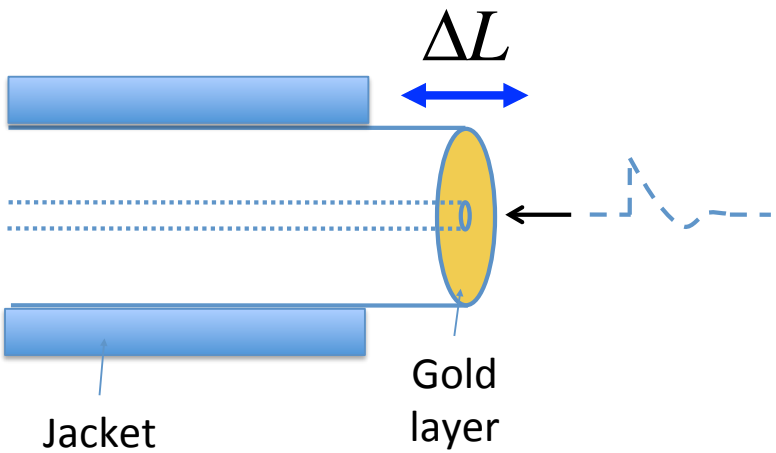
Displacement/Velocity (V) Probe

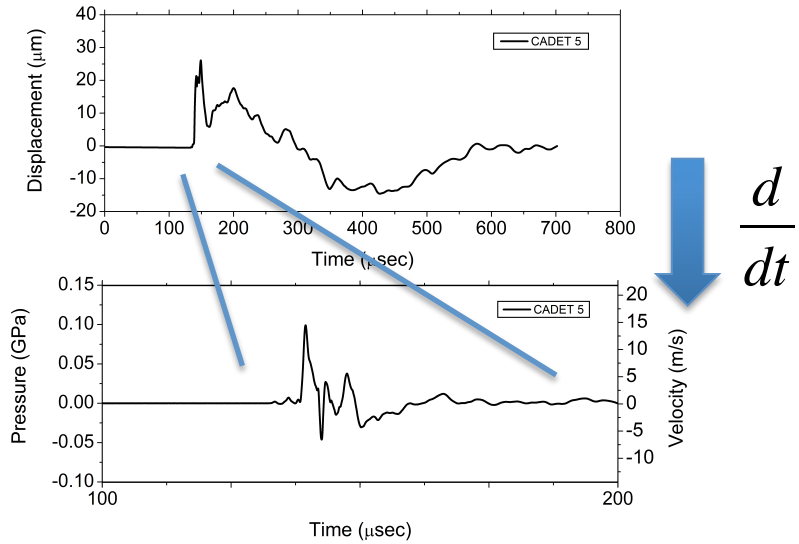
- Tip displacement measured with interferometer
- Mass displacement moves mirror
- Displacement measured along fiber axis
- Velocity obtained by differentiation
- Self-calibrated: depends only on wavelength
- Measurement range:
  - 0.01 m/s to >> 1500 m/s
  - 80 kPa to >> 10 GPa

<u>Interrogation system</u>



$$\Delta\phi = (4\pi n / \lambda) \cdot \Delta L$$

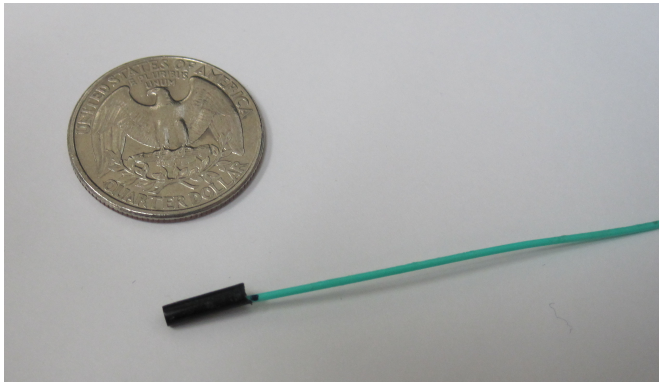




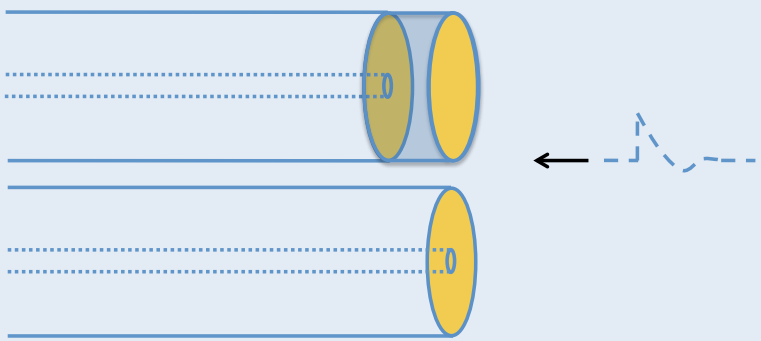
P-V Probe

- P probe and V probe in one sensor head
- Simultaneous measurement of pressure and velocity
- Measures shock energy transport (P+V)
- Provides cross calibration between probes

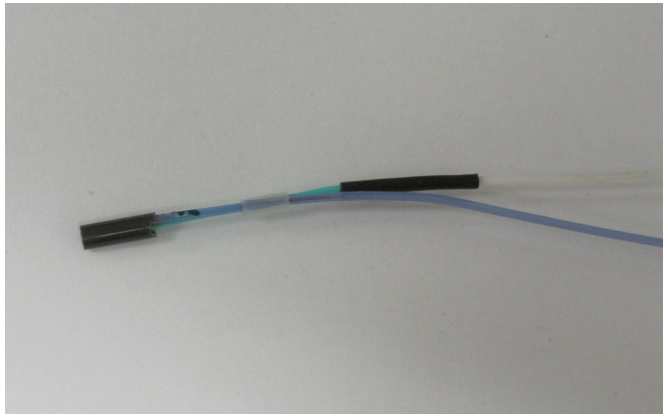
Single probe



Velocity sensor head (mirror)

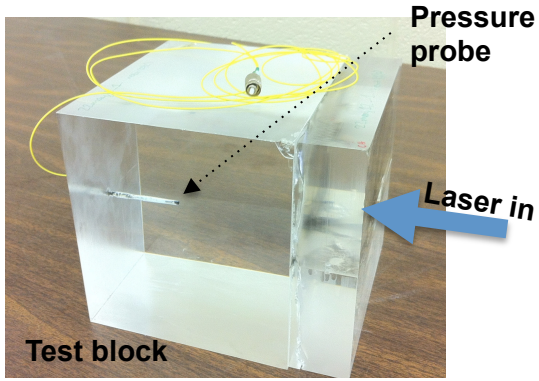


Dual probe

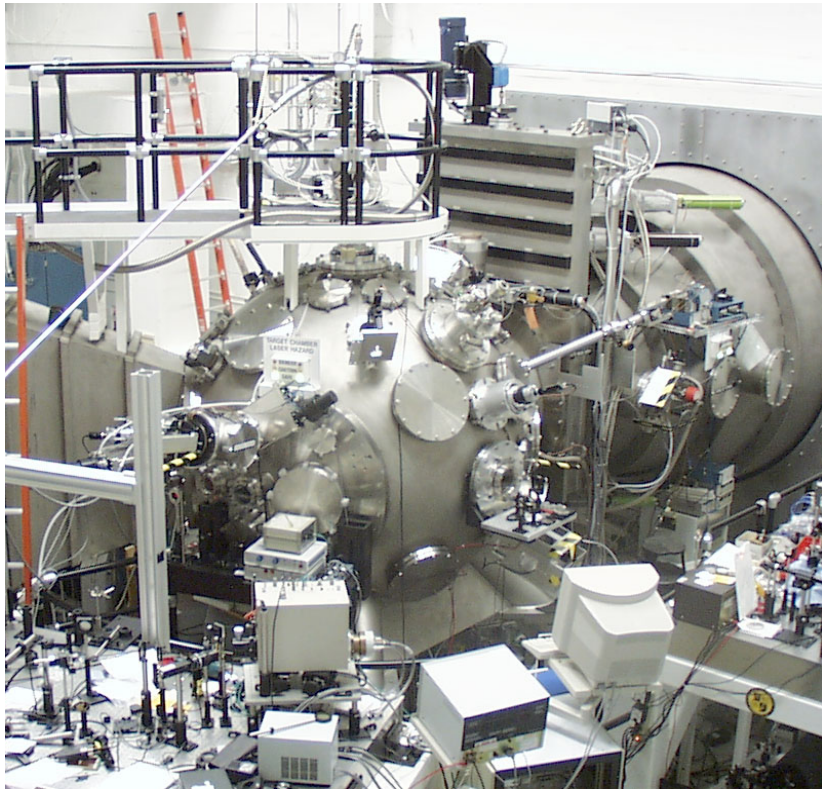


Example 1: Laser Driven Shock Waves

Targets

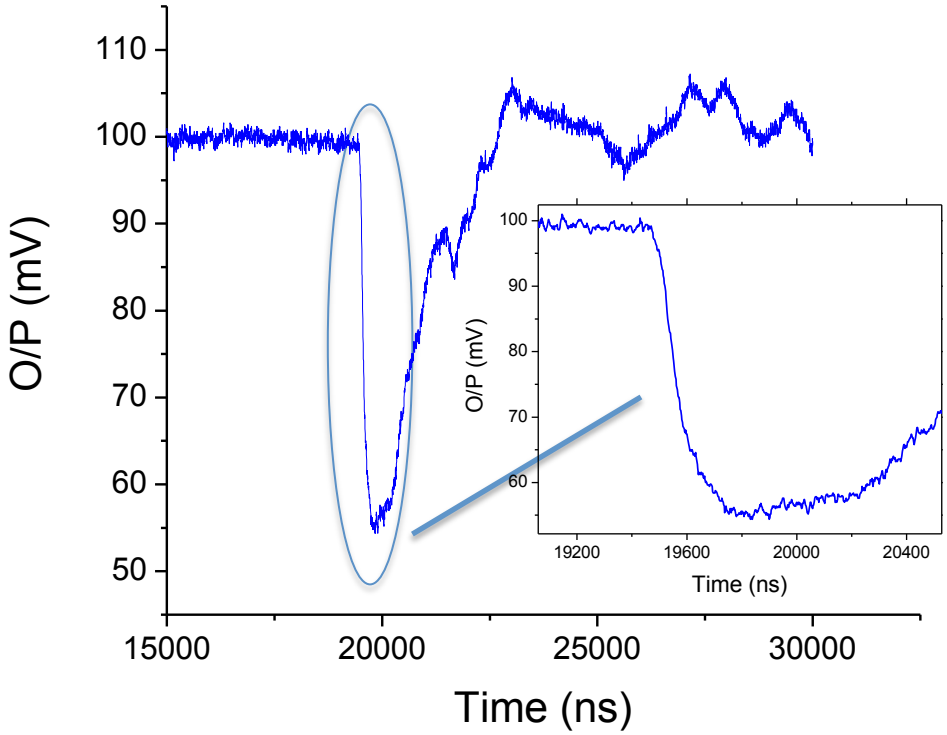


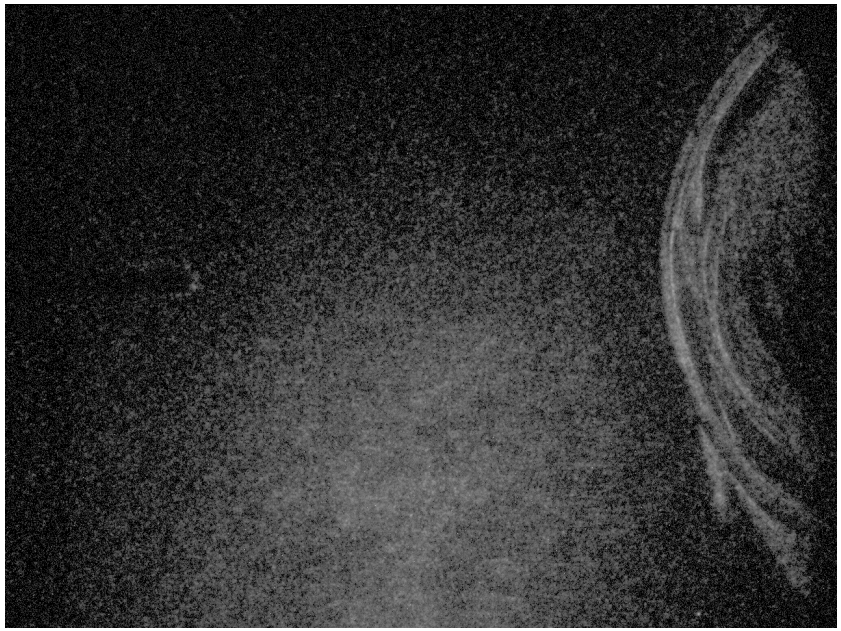
NIKE (2KJ, 4ns, 500um diameter)



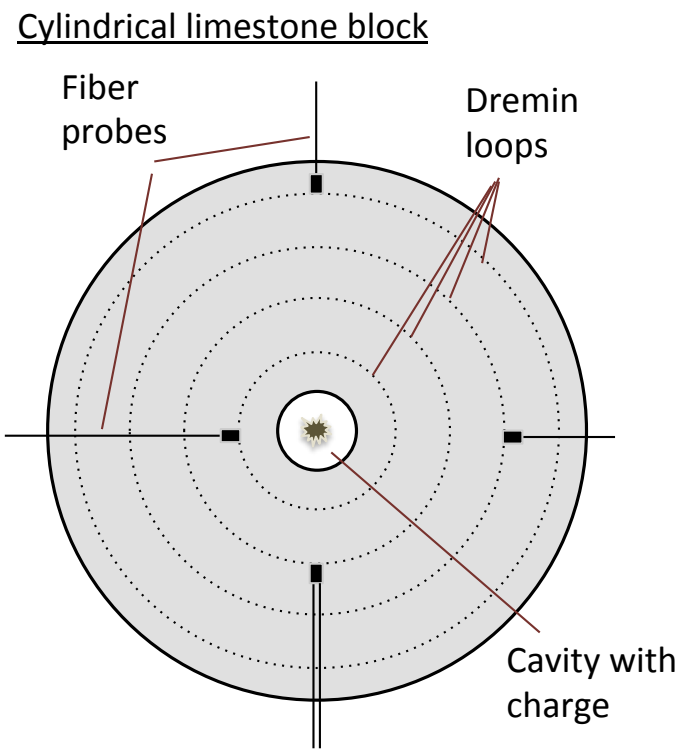
Imaging the shock

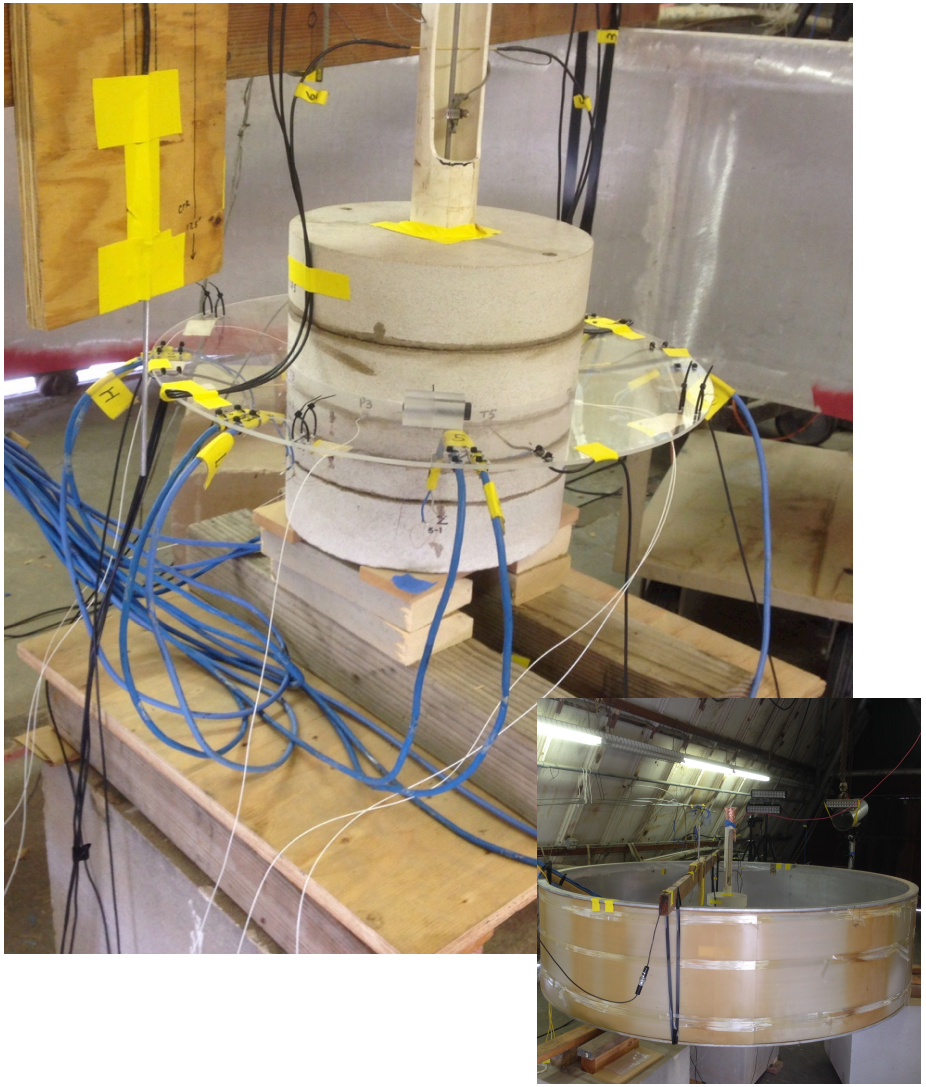
Schlieren/dark field shadowgraphy



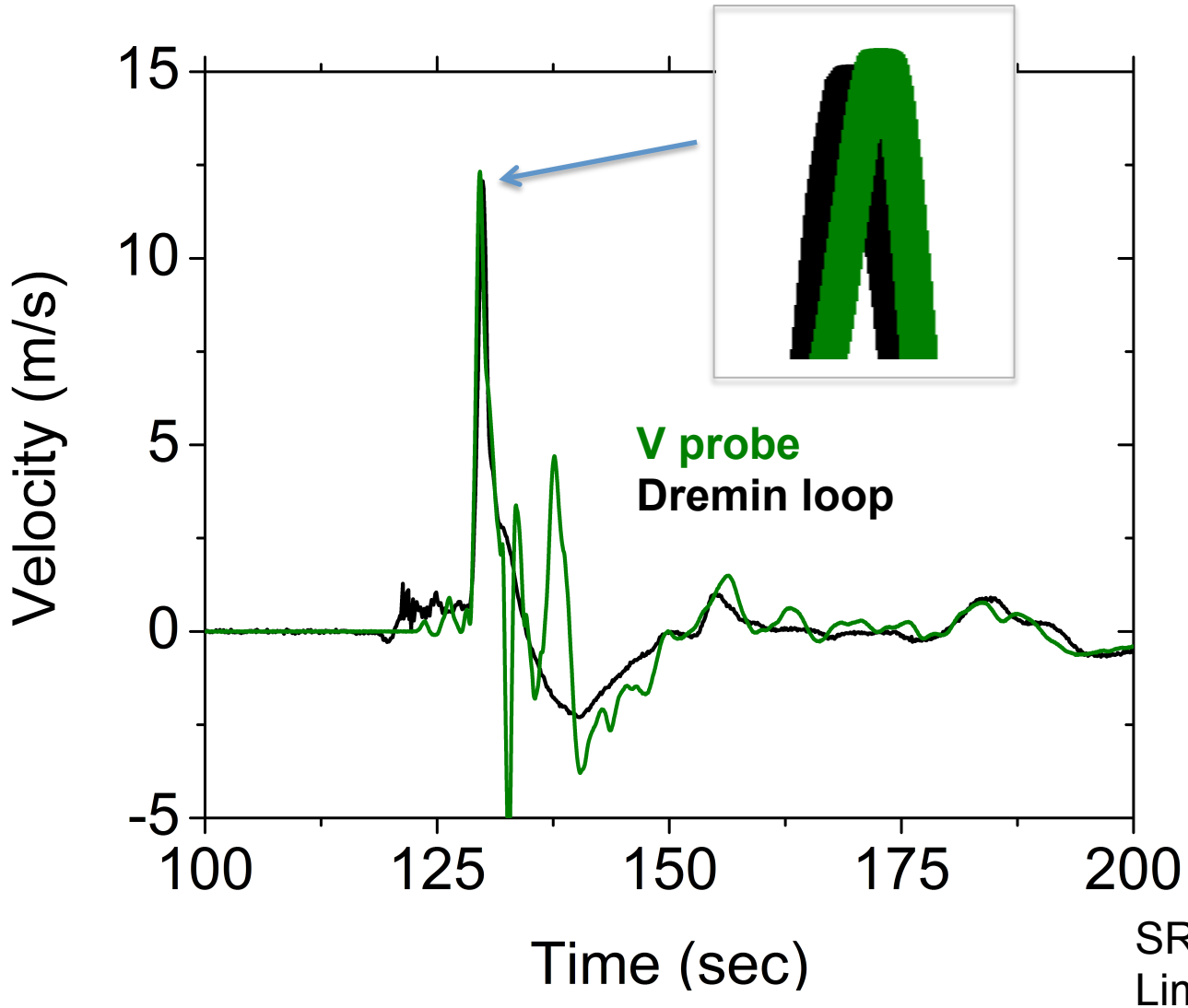


Example 2: Explosive Driven Shock Wave



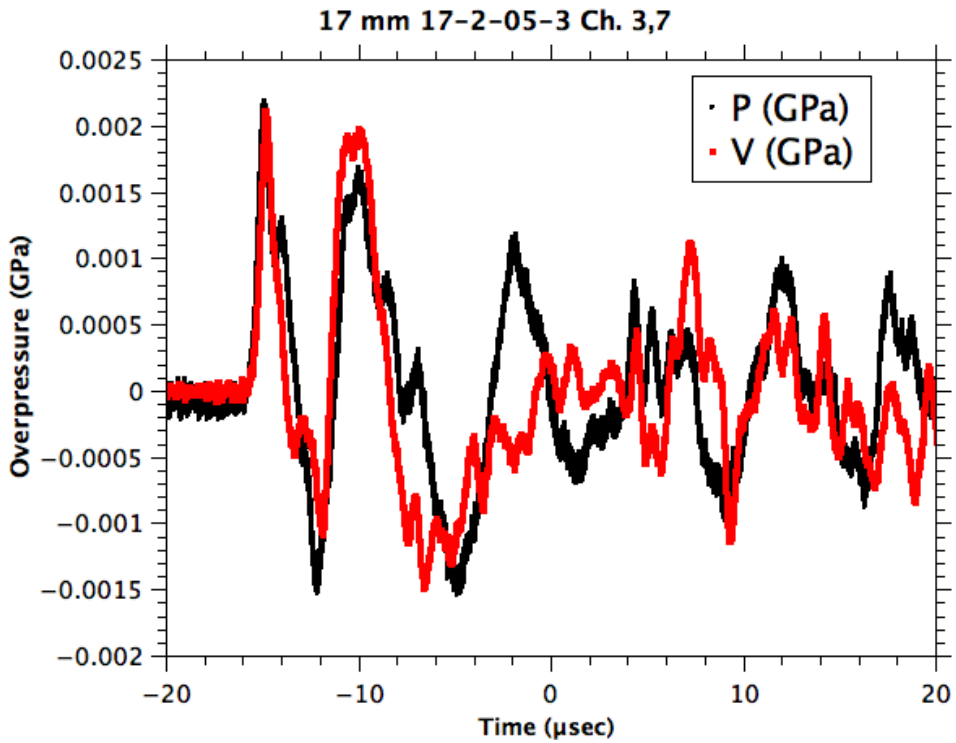


Fiber optic V probe and SRI Dremin loop agree



SRI 2014 tests
Limestone

Calibration of pressure probe against velocity probe



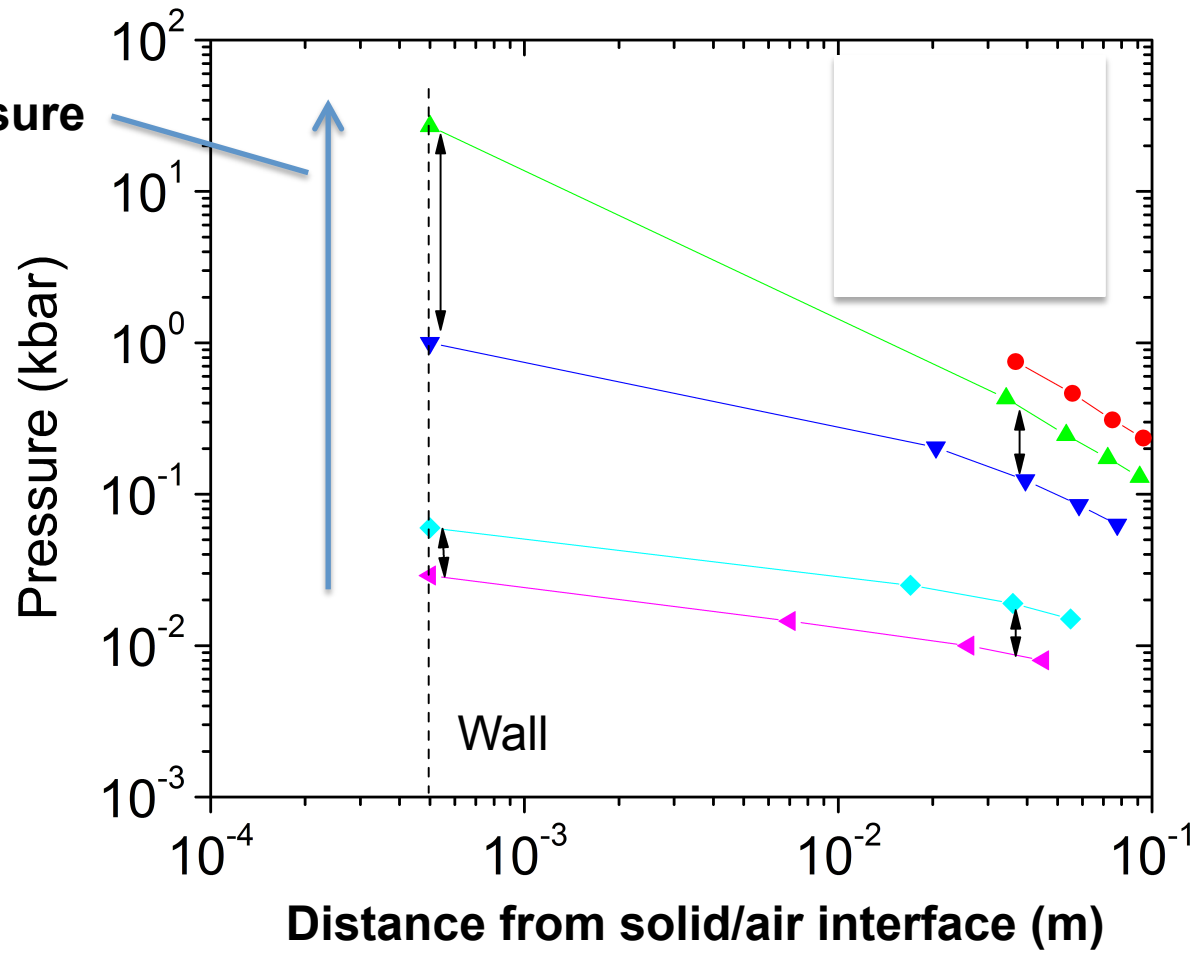
- Plane wave approximation applied to shock velocity to obtain shock pressure

Shock pressure $\cdots$ $$P_s = \rho c_s U_s$$ $\cdots$ Shock mass velocity

Example application:

Shock transmission in solid media (explosion resistance)

Increasing shock pressure at interface



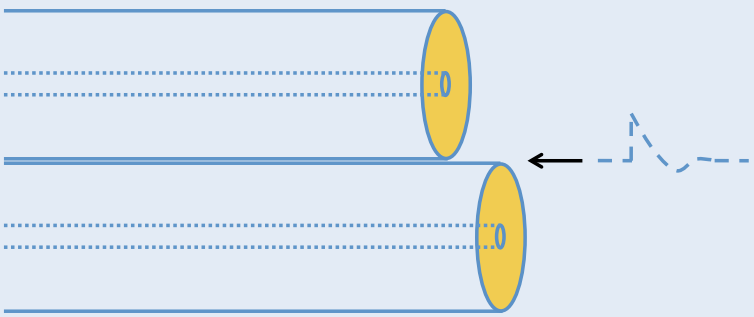
Can also plot mass velocity

(GEODYNE simulation data)

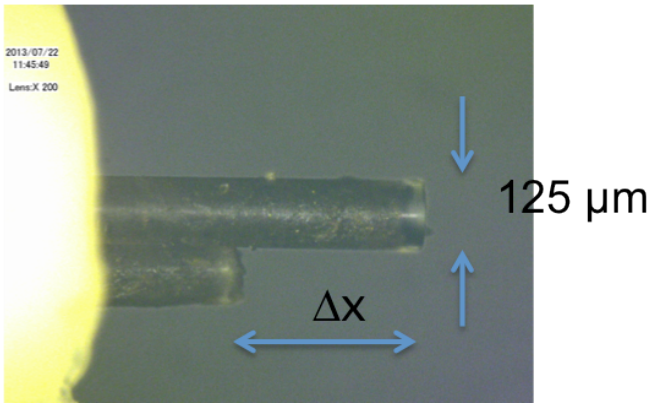
Velocity sensor (V2)

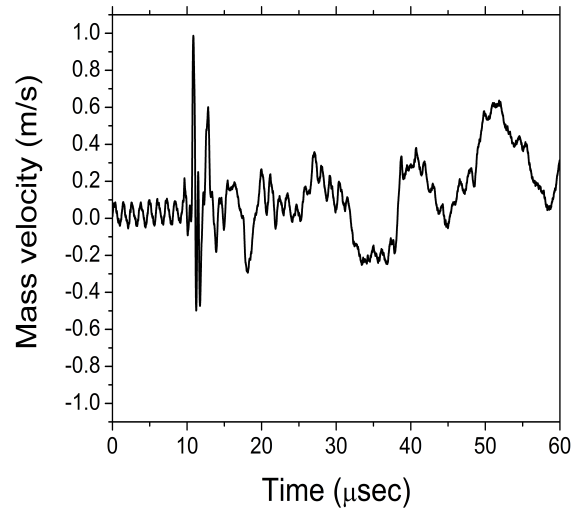
- Measures difference in displacement between two fiber ends
- Measures mass velocity directly (not displacement)

Velocity sensor head 2



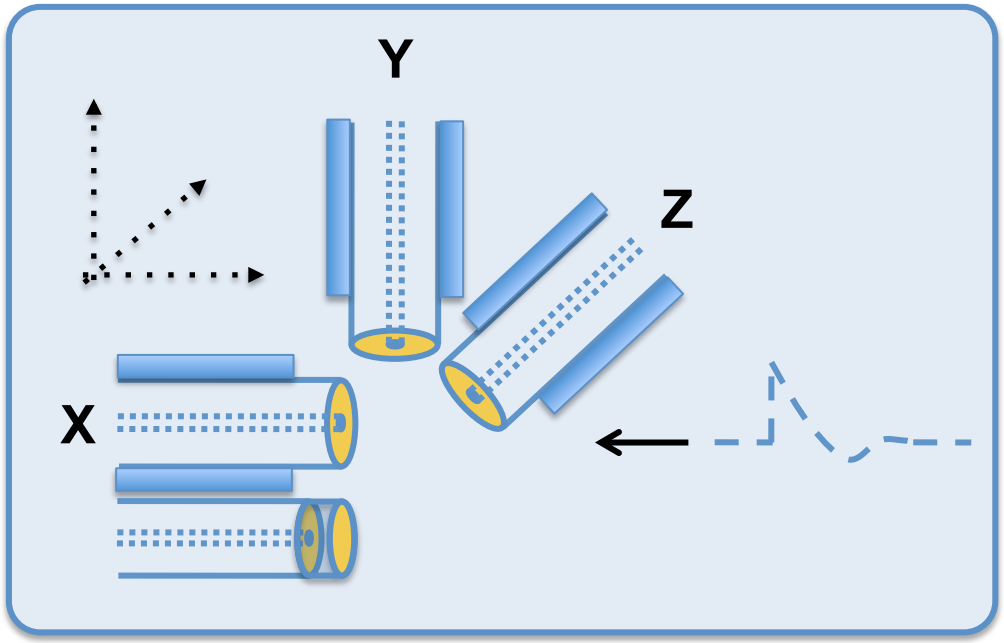
Prototype Directional Sensor





Other probes configurations

- **3-axis mass velocity/pressure measurement**



- Provides 3 components of mass velocity and pressure
  - direction of energy flow

Characterization of strong shocks?

- **Pressure sensor (Fabry-Perot)**
  - Max shock pressure ~0.1 Gpa
  - Need stiffer cavity material
  - Sensitive to shock induced temperature

- **Velocity sensor (Interferometric)**
  - Max velocities >> 1.5 km/s
  - Velocity measurement independent of shock induced temperature change
  - ($\sigma.c_s$) deviates substantially from linear acoustic value for shock pressure above GPa
    - Unreliable conversion to pressure (data may be available in tables)

- **Measurement of shock velocity viable for higher shock pressures**

Conclusions

- **Scaled experiments enable study of explosive energy propagation and coupling at much lower cost than full scale experiments**

- **Fiber optic pressure and mass velocity probes demonstrated to characterize shock waves in solids**
  - Measured shocks in range 100 kPa - > 10 GPa
  - Determine ***energy flow*** from P and V

- **Example applications:**
  - Basic studies on materials under extreme conditions
  - Synthesis of new materials for blast protection

Acknowledgements

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  - David Kehne, Young Chang, Steve Krafsig
- **Otis Walton, Lawrence Livermore National Lab, USA**
- **Janet Lou (NRL), Robert Lunsford (formally NRL)**

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