Using PDV to measure transverse and off-axis velocity

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Org. 1647 – Solid Dynamic Experiments

Shock Thermodynamics Applied Research Facility - (STAR)

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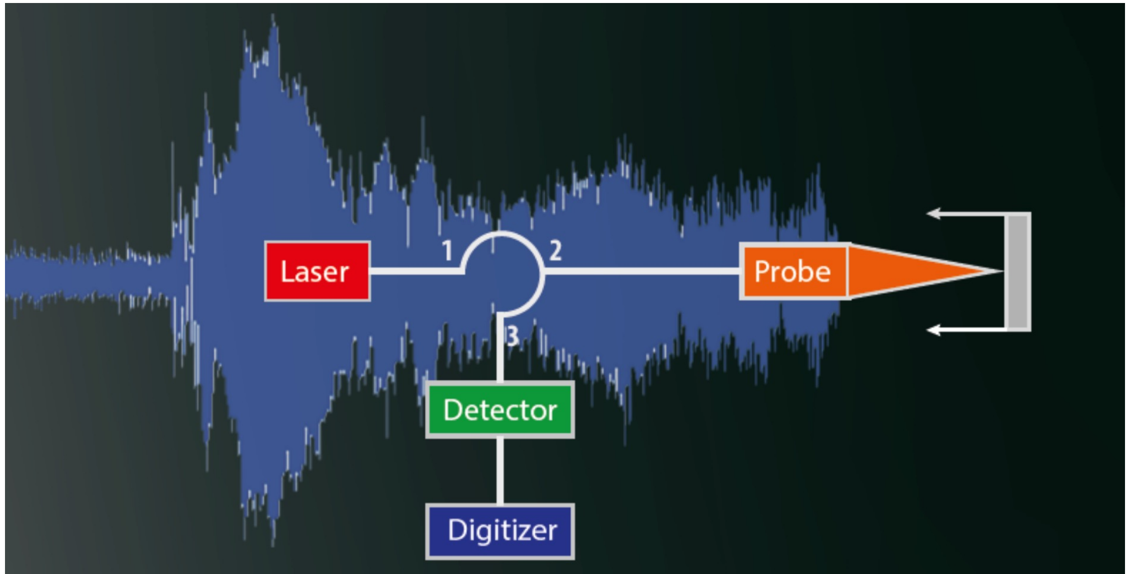
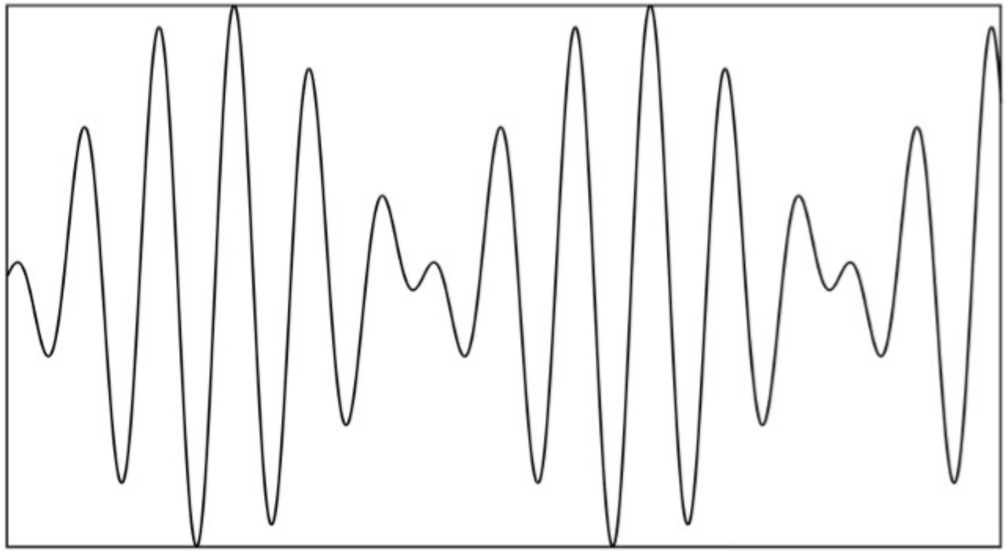
Introduction - PDV



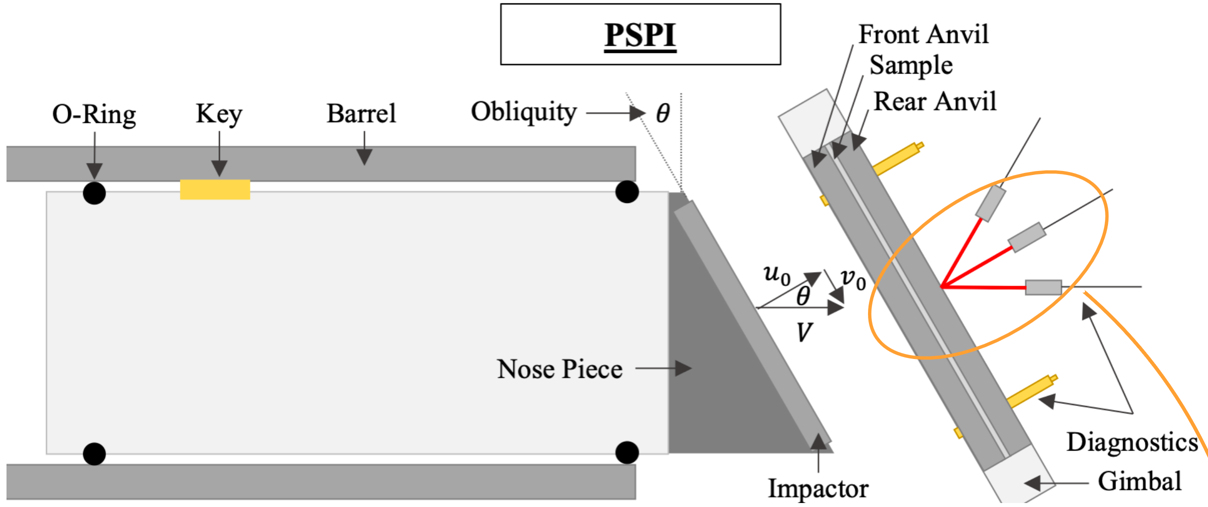
O.T. Strand, *Handbook for the Photonic Doppler Velocimeter*, 2020



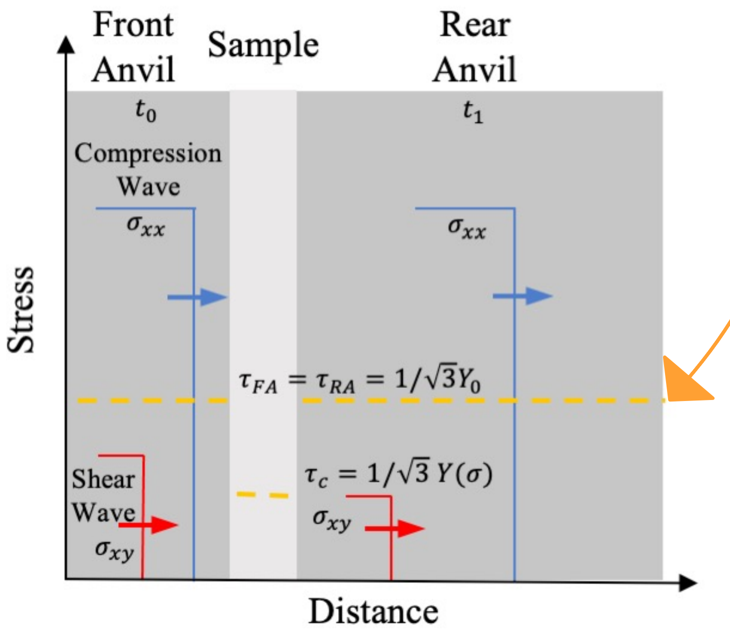
- Photon Doppler Velocimetry (PDV)
  - Michelson interferometer
  - Developed by Strand et al. in 2006
  - System components leverage modern telecommunications technologies!
  - Heavily adopted by the dynamic compression community.
  - Numerous configurations have been built.

Pressure-shear plate impact experiments

- General experiment:
  - Skewed, planar impact
  - Sample sandwiched between anvils
- What do you measure?
  - Longitudinal & shear stress wave
  - Flow strength vs. pressure
- Why do we need XPDV?
  - 1D waves
    - (i.e. need to measure off of the rear anvil)
  - Shear wave velocities are small ~0-50 m/s
  - Window of measurement is small ~0.5-2 us

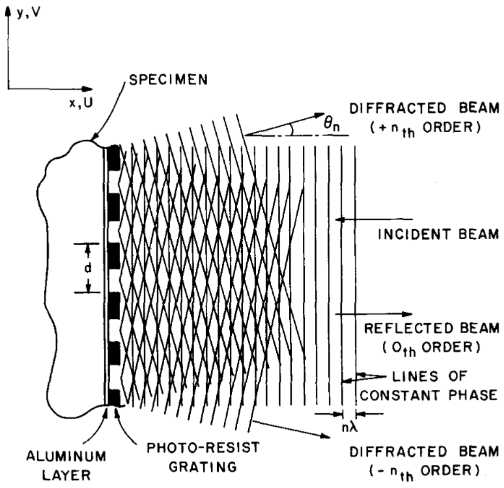


We need to measure the shear wave!

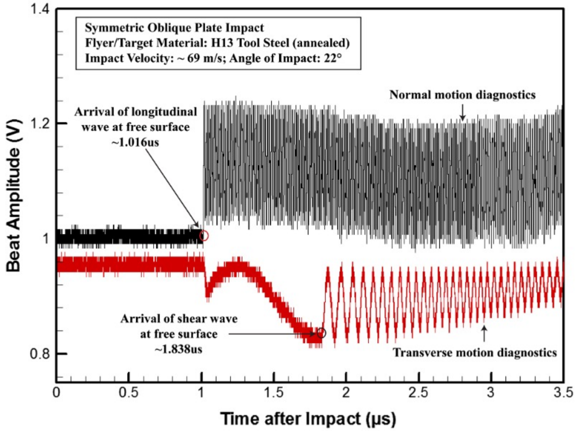


Previous methods for measuring transverse velocity

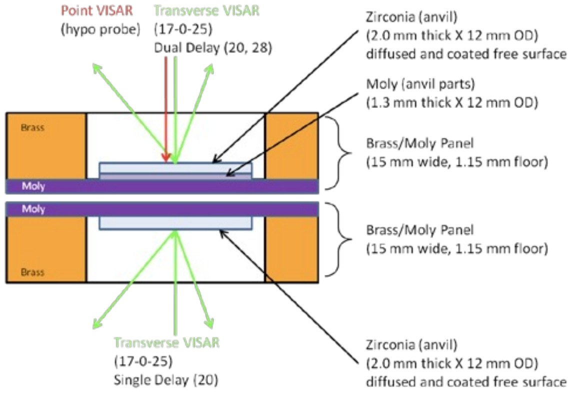
- What were the methods previously attempted?
  - NDI/TDI, VISAR, PDV
- What was found?
  - Difficult measurement
  - Need expensive diffraction gratings
  - Alignment is hard
  - Need high temporal resolution
  - Large measurement uncertainties.



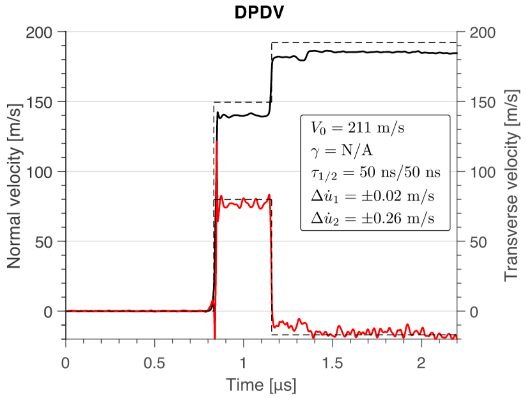
K.S. Kim, *JAP*, 1977



Zuanetti, *RSI*, 2017



Alexander, *JAP, 2010*

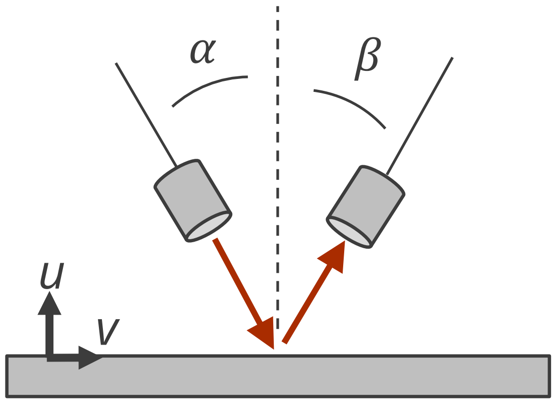


Kettenbeil, *JAP*, 2018

- A diagnostic and reflector is needed to overcome the difficulties of **light return**, **expense of diffraction gratings**, and **reduces measurement uncertainties**.

XPDV

- Theory
- Probe setup
  - 3 – collimating probes
  - Diffuse reflector
- XPDV overview
  - A modified frequency multiplexed heterodyne system
- Light Return
  - Back end amplifiers
- Frequency multiplexing
- Measurement



α = Send Angle

β = Receive Angle

u = Longitudinal Velocity (compression)

v = Transverse Velocity (shear)

V^* = Apparent Velocity

$$V^* = \frac{u}{2}(\cos\alpha + \cos\beta) + \frac{v}{2}(\sin\alpha + \sin\beta)$$

Dolan, *Foundations of VISAR Analysis*, 2003

Solve for u → If $\alpha, \beta = 0$ & $v = 0$

$$V^* = u$$

(Normal PDV operation)

Solve for v →

$$v = \frac{2V^* - u(\cos\alpha + \cos\beta)}{(\sin\alpha + \sin\beta)}$$

- We are solving for a small transverse velocity
- Small uncertainties are **vital** in the analysis.
- Therefore, we need high fidelity measurements of:
  - Apparent & longitudinal velocities
  - Probe angles

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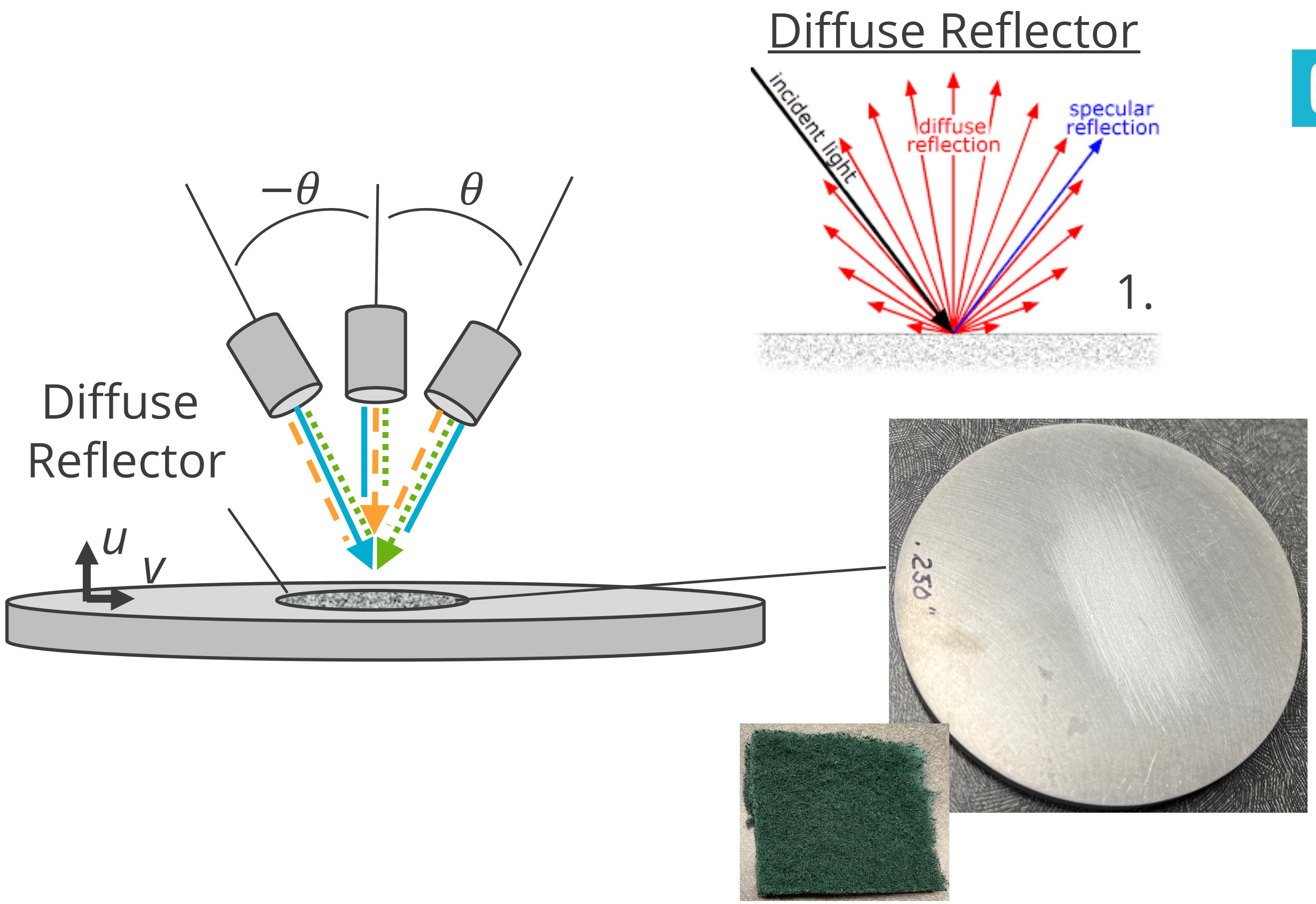

- Diffuse reflector is forgiving for optical alignment & easy to produce
- Light originates from one probe and is scattered to all three probes.

1. https://en.wikipedia.org/wiki/Diffuse_reflection

XPDV

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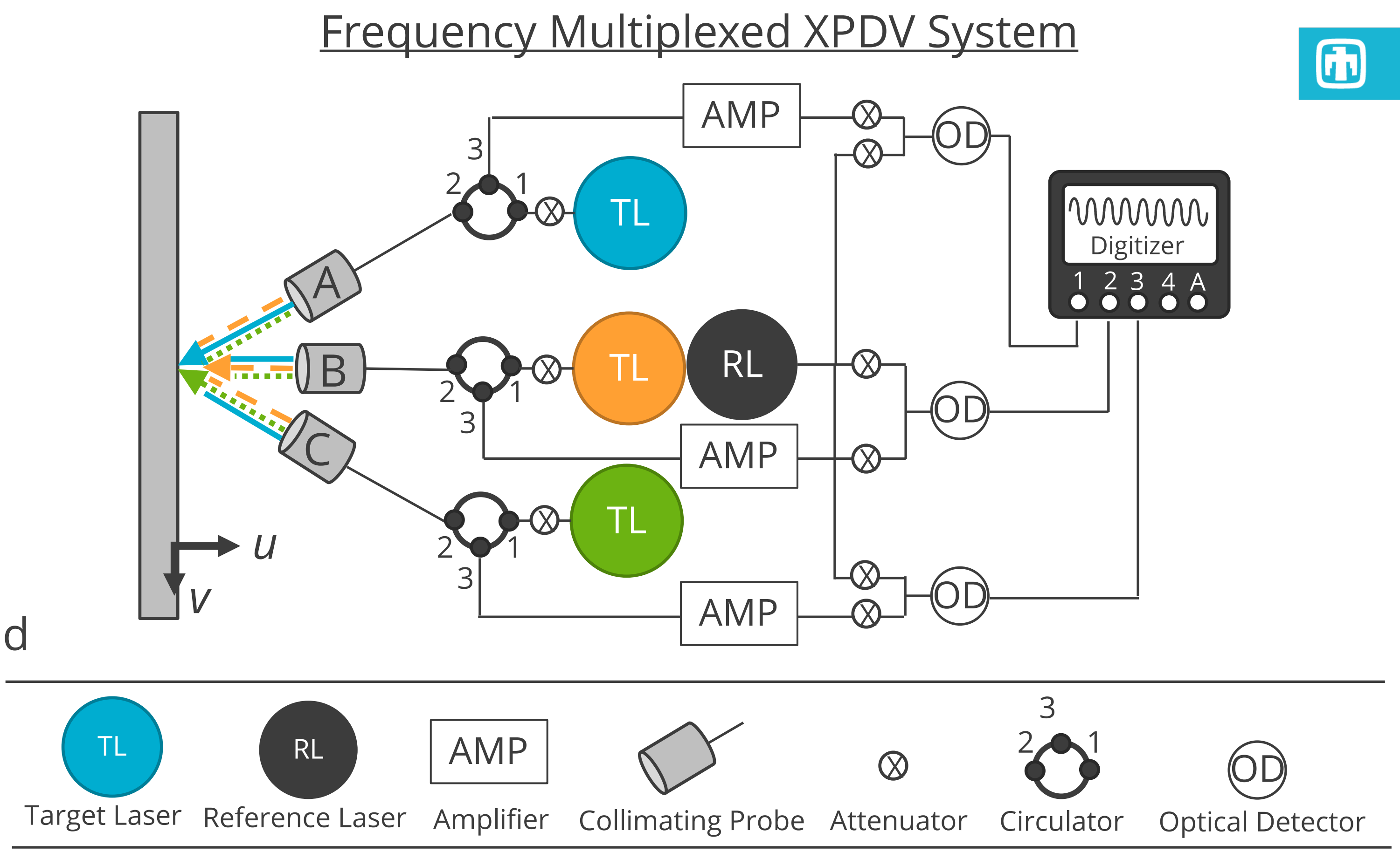

- 3 target laser wavelengths
  - (i.e. 3 multiplexed signals on each probe)
- Tune lasers for baseline frequencies of 3, 5, 8 GHz
- We can identify each optical path because of the distinct frequencies.
  - (i.e. we know which probe sent the light!)

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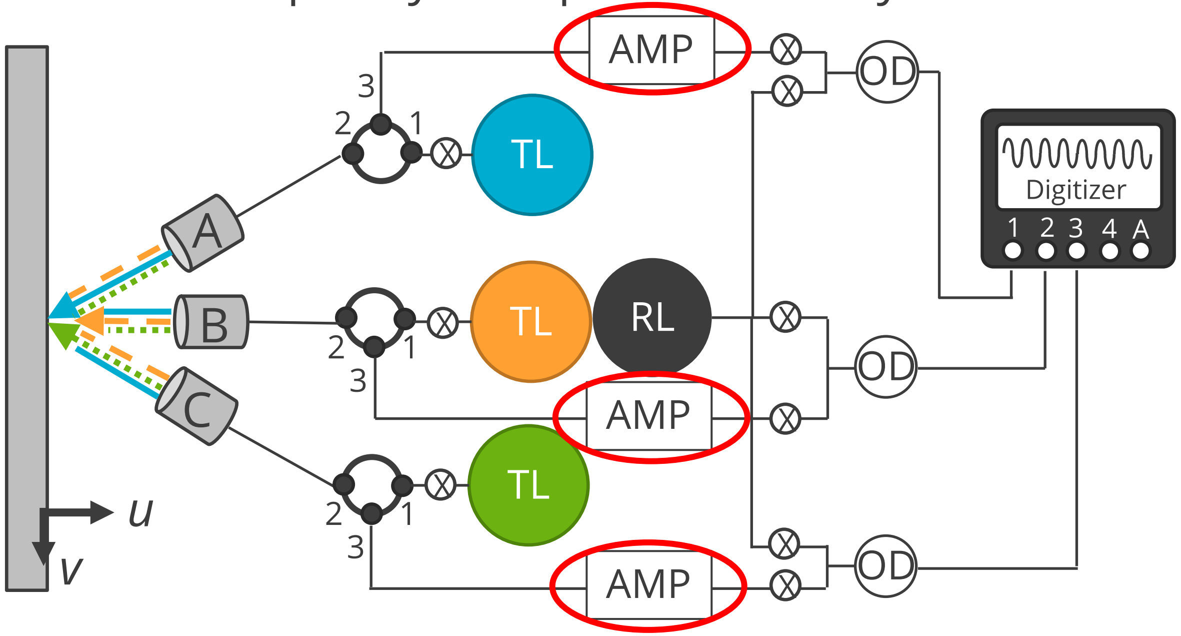
Frequency Multiplexed XPDV System



- Low light return levels
  - 40 mW laser -> -60 to -40 dBm of return
- Back end amplifiers amplify return light.

XPDV

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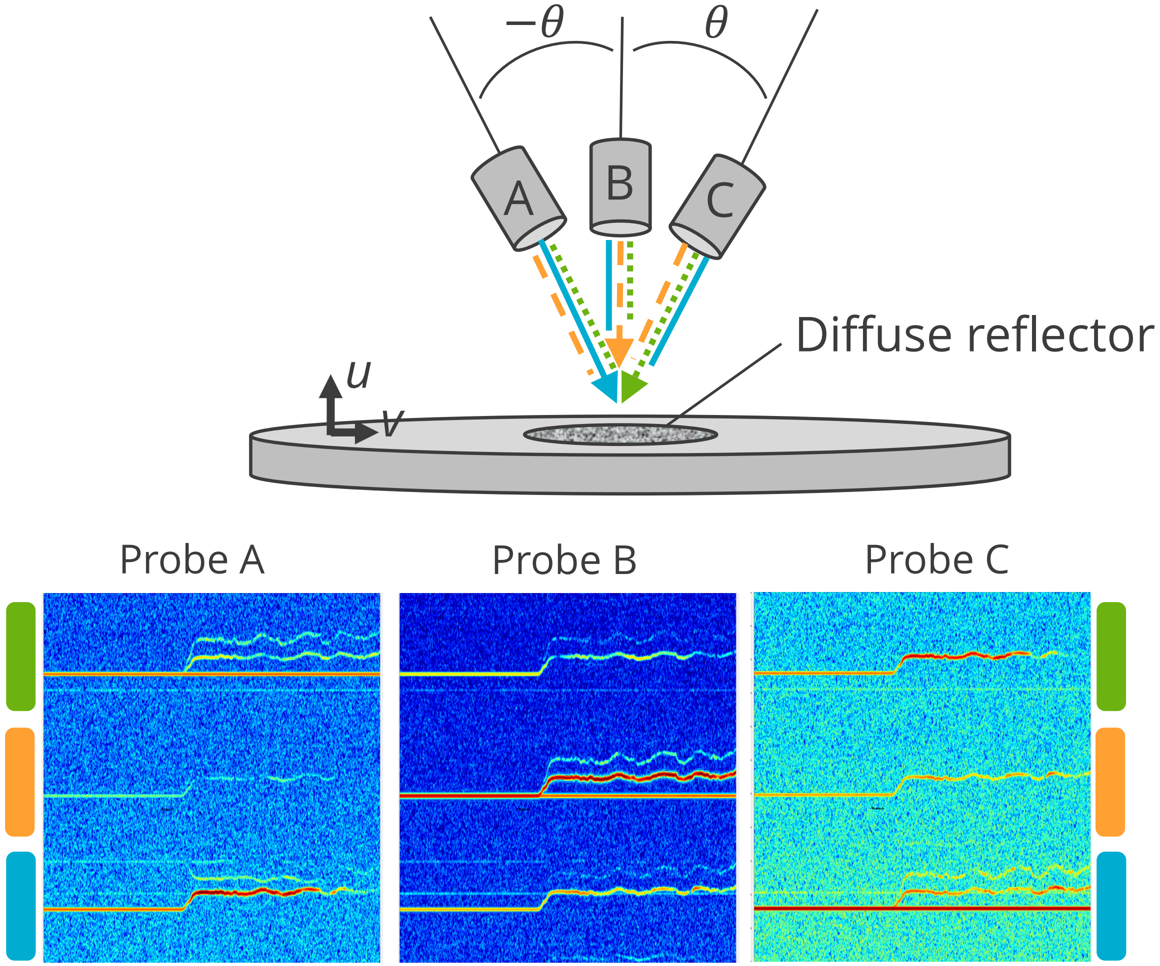

- Many measurements made via frequency multiplexing.
- Each measurement has a characterized optical path.

XPDV

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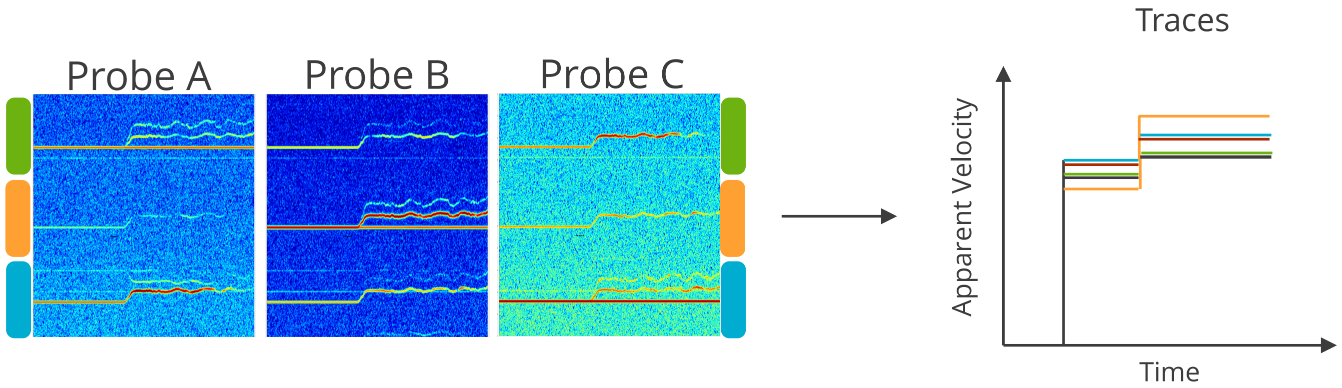
- Light Return
  - Back end amplifiers
- Frequency multiplexing
- **Measurement**



Weighted Average

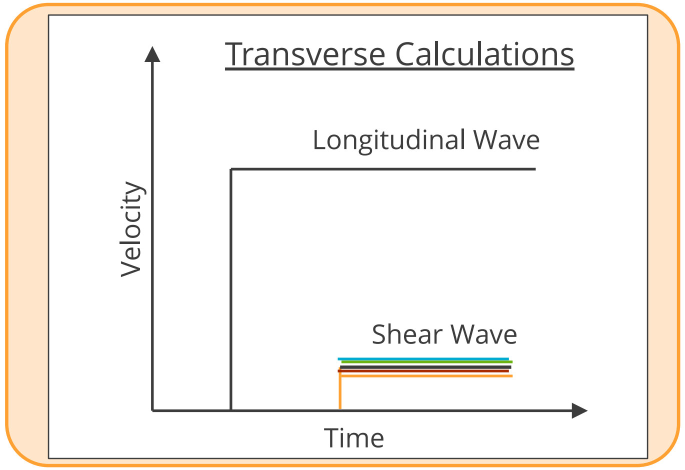
$$v_{i,j} = \frac{2V_i^* - u_j(cos\alpha_i + cos\beta_i)}{sin\alpha_i + sin\beta_i}$$

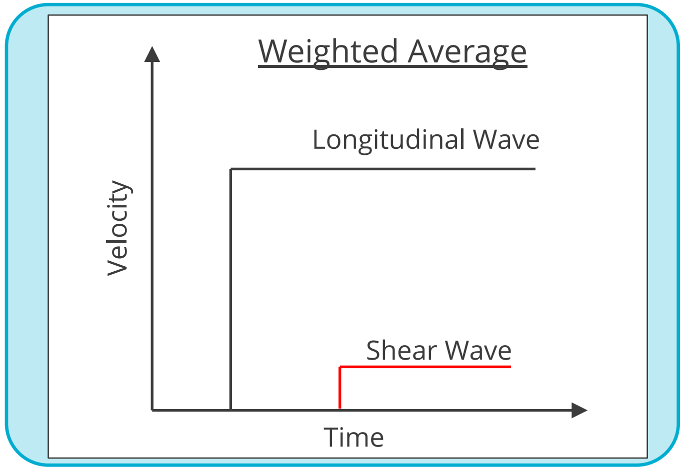
$$\partial v_{i,j} = \sqrt{\left[\frac{\partial v_{i,j}}{\partial V_i^*}\partial V_i^*\right]^2 + \left[\frac{\partial v_{i,j}}{\partial V_N}\partial V_N^2\right]^2 + \left[\frac{\partial v_{i,j}}{\partial \alpha_i}\partial \alpha_i\right]^2 + \left[\frac{\partial v_{i,j}}{\partial \beta_i}\partial \beta_i\right]^2}$$

$$\bar{v} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M} w_{i,j} v_{i,j}}{\sum_{i=1}^{N}\sum_{j=1}^{M} w_{i,j}}$$

$$w_{i,j} = \frac{1}{(\partial v_{i,j})^2}$$

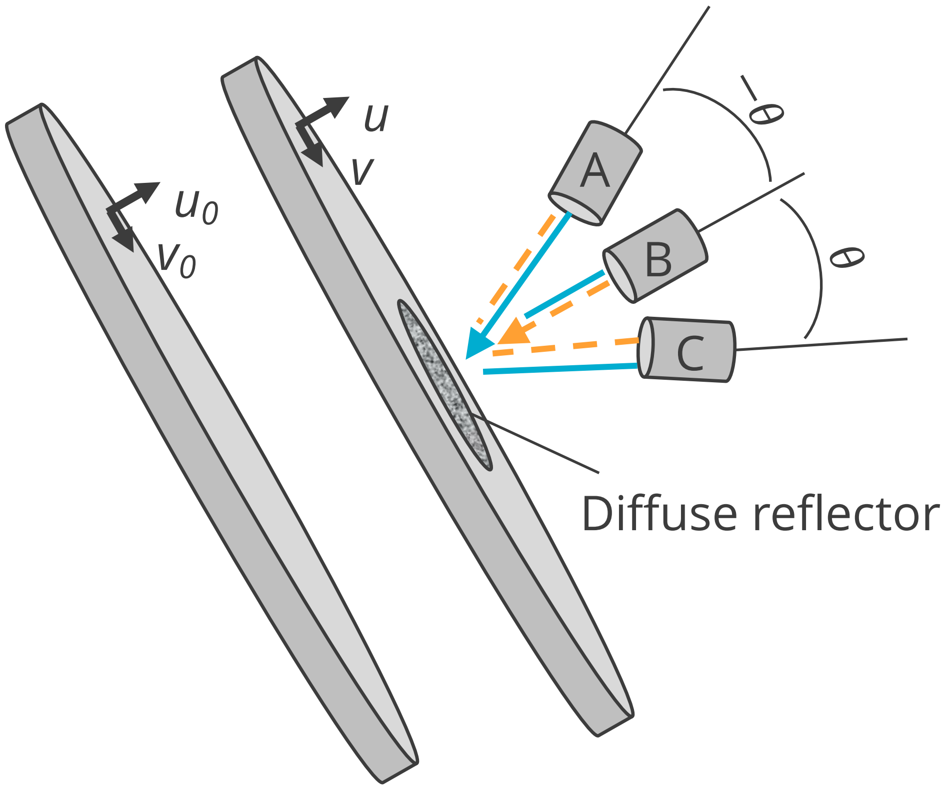
$$\partial \bar{v} = \left(\sum_{i=1}^{N}\sum_{j=1}^{M} w_{i,j}\right)^{-1/2}$$



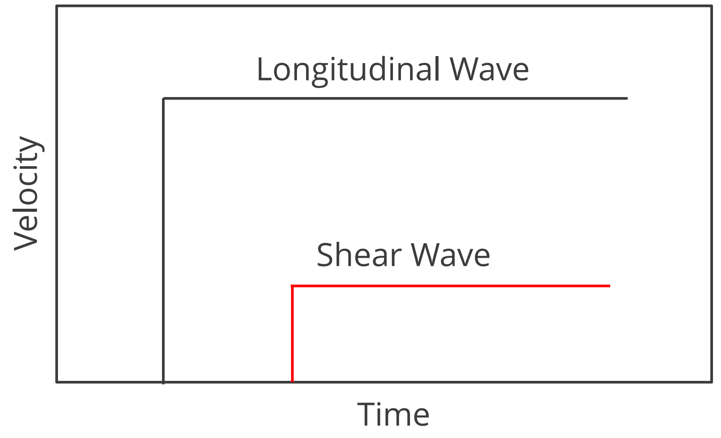


Validation Experiment

- A validation experiment was designed for the XPDV system.
- Impact between 2 – 6061-T6 aluminum disks.
  - 75 m/s impact
  - Skew angle = 15^0
- XPDV was fielded
  - Only **two** laser sources in this example…

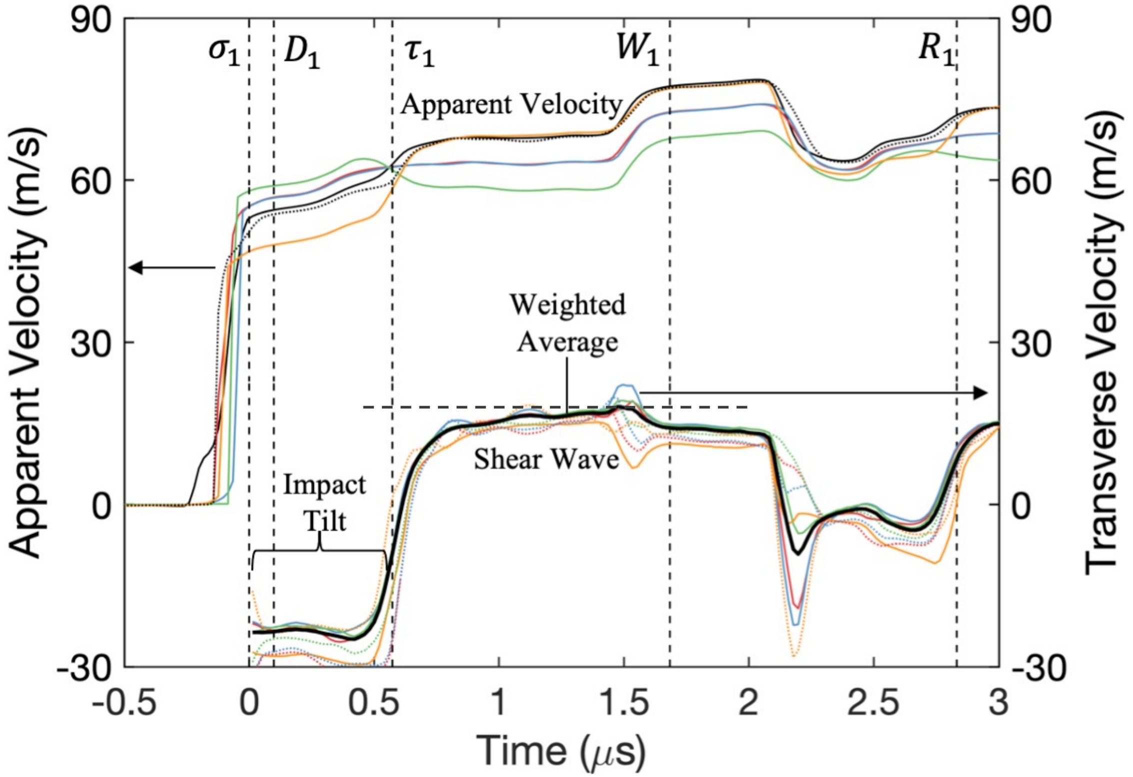


Expected Wave Profile



Validation Experiments: Results

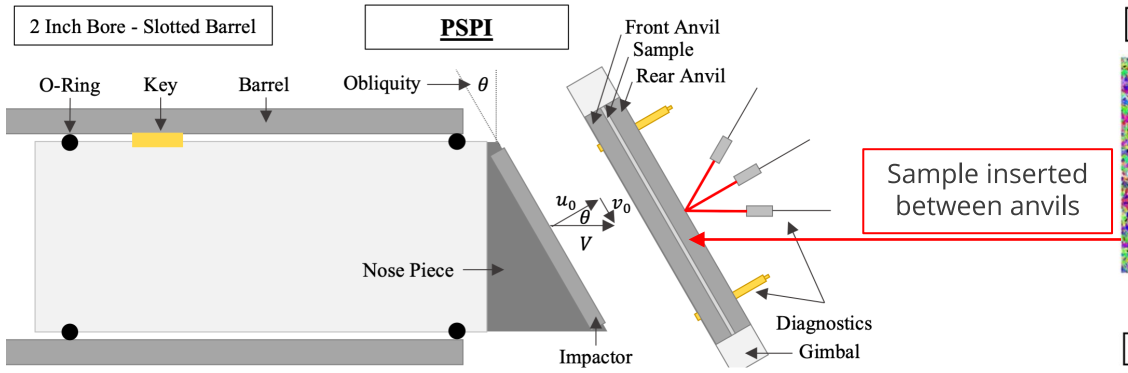
- Waveforms:
  - 6 apparent velocities
  - Timing agrees well with theory
  - Tilt effects
  - Structure changes when shear wave arrives
- Analysis:
  - Yields 8 transverse velocity measurements.
  - Weighted average used to determine statistical best.
- How does this compare with theory?
  - Impact velocity was 75 m/s
    - i.e. u_0=72 m/s, v_0=19 m/s
  - v within shear window was 18 ± 3 m/s.
    - Agrees well with theoretical of 19 m/s!

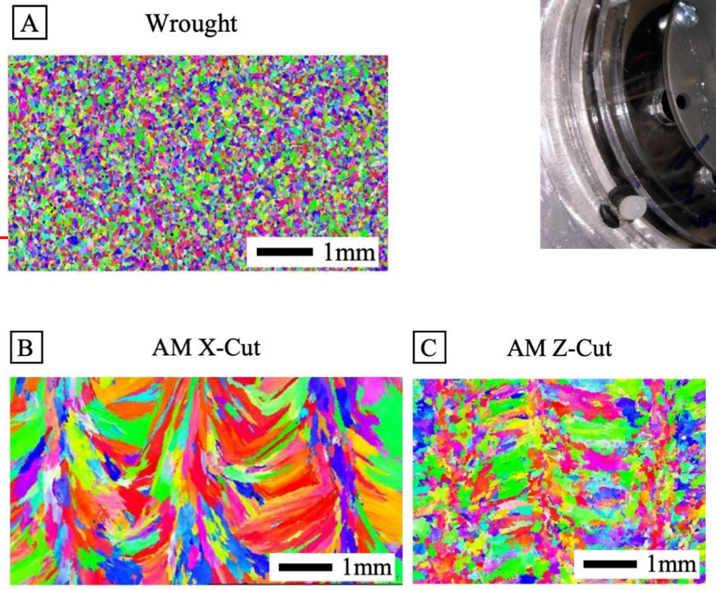


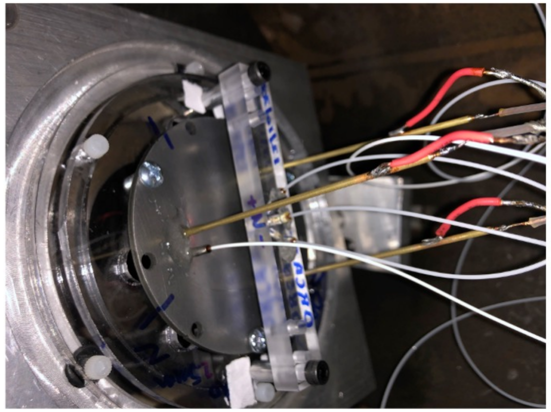
	Theory (m/s)	Exp. (m/s)
u	72	70
v	19	18 ± 3

$$v = \frac{2V^* - u(\cos\alpha + \cos\beta)}{(\sin\alpha + \sin\beta)}$$

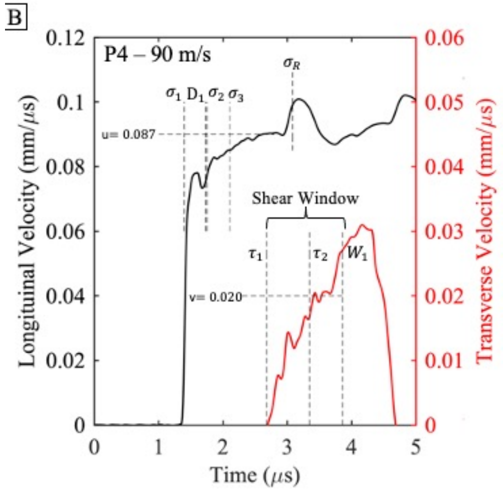
Use of XPDV in an Experimental Series

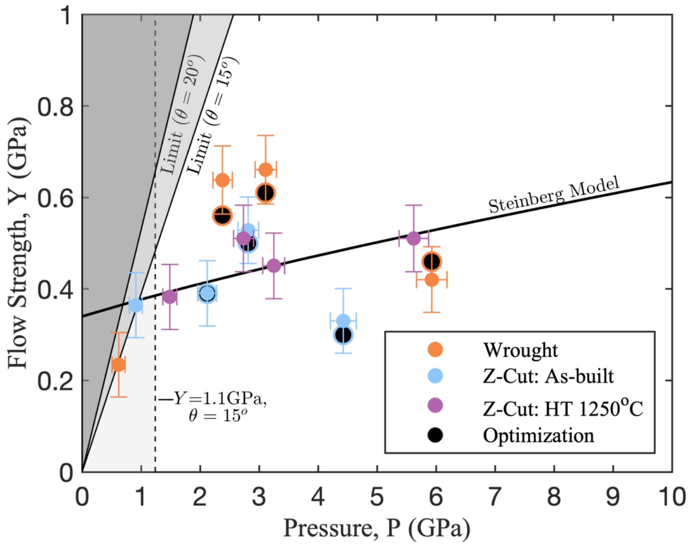






- Experiments were performed to compare dynamic behavior of SS304L.
  - Wrought, as-built AM, & heat treated AM
- Does fabrication process influence strength?
- Loading conditions: P = 0-6 GPa
- Results are compared between varieties and to existing strength model.
- XPDV is highly effective for these measurements.

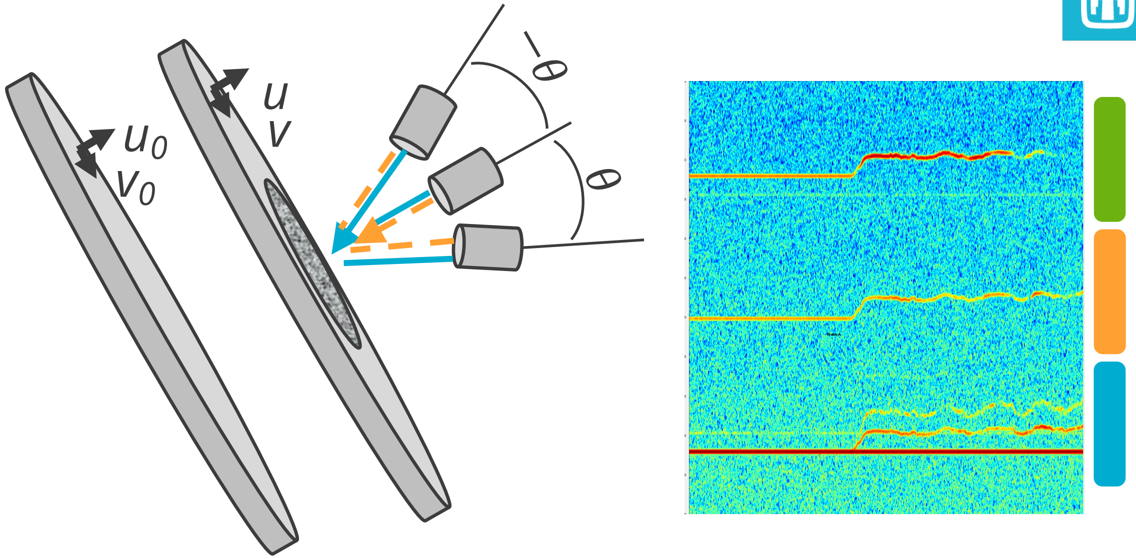




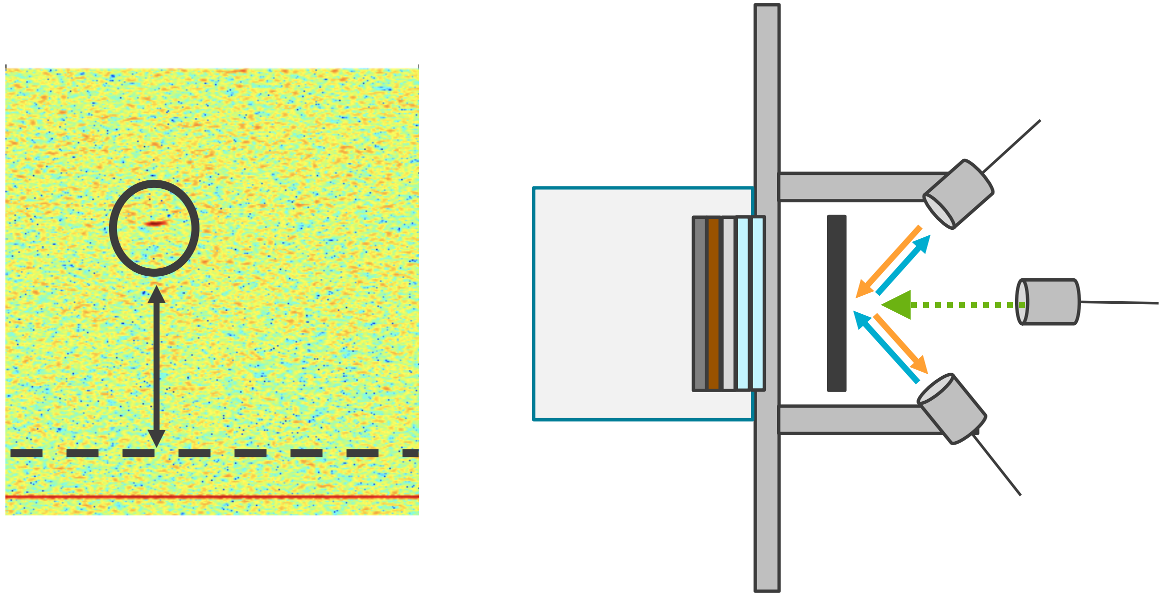
Summary

- XPDV was developed for the measurement of off axis velocities.
- The system overcomes many difficulties:
  - Light return issues
  - Reflectors
  - Measurement uncertainties
- Highly functional diagnostic for pressure shear plate impact experiments
- Other applications: Hyper velocity launches

Pressure Shear Plate Impact Experiments



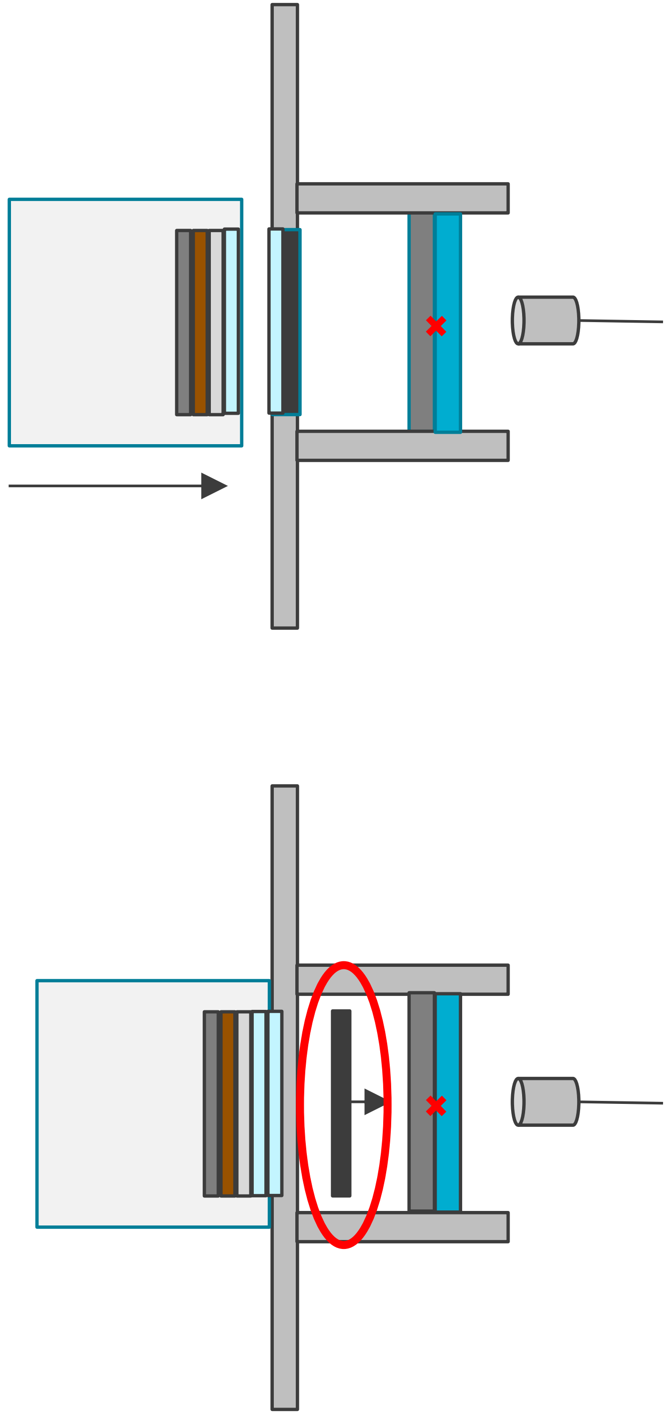
Hypervelocity Launches



Extras

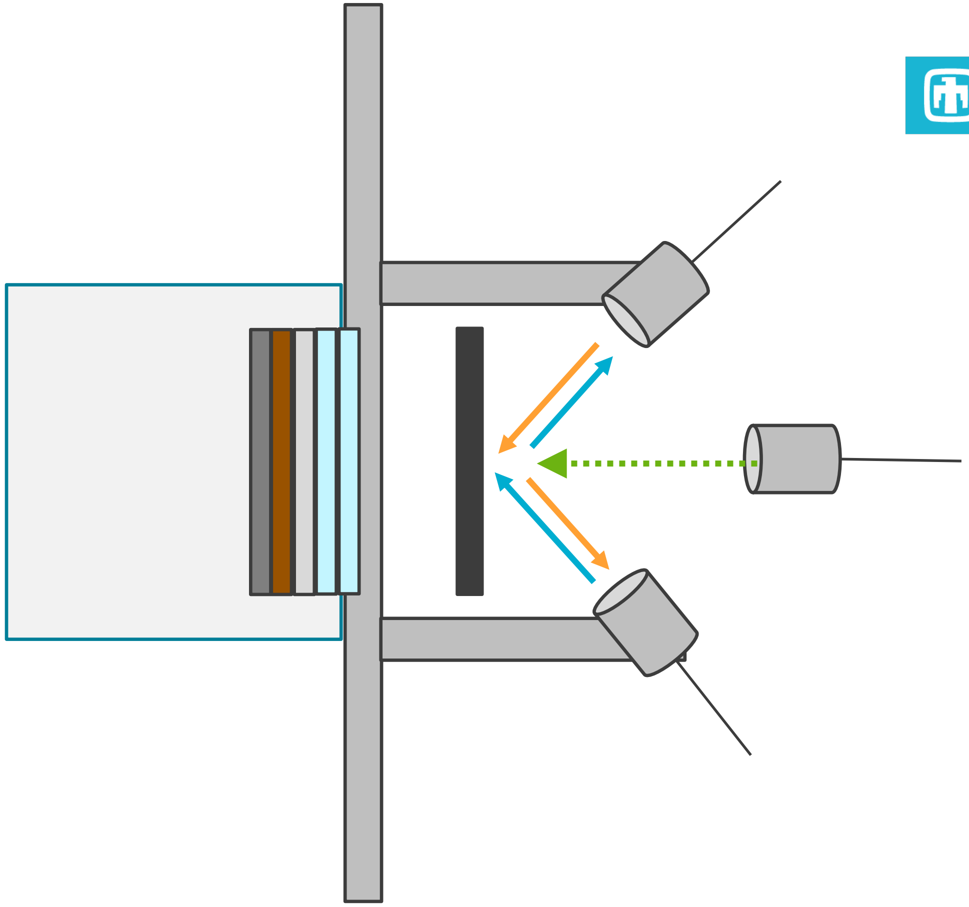
Other applications - HVL

- STAR developed GDI techniques for hyper velocity launches in the 1980's.
- A plate is launched at velocities ranging between 7-13 km/s.
- It is difficult to measure the flyer velocity due to geometric limitations.



Can XPDV be used to measure the flyer velocity?

Validation Experiment



- Hyper velocity launch using GDI into Ti flyer.
- XPDV techniques are compared to a normal PDV probe.
  - Two off axis probes are placed symmetric about the flyer. (55 degree skew angle)
    - Cosine correction for the velocity
  - A normal probe to measure 'true velocity'.
- Results are compared to assess validity of results.

$$V^* = \frac{u}{2}(\cos a + \cos \beta) + \frac{v}{2}(\sin \alpha + \sin \beta)$$

→

$$u = \frac{2V^*}{(\cos a + \cos \beta)}$$

Results

- GDI impact of 5.122 km/s into flyer.
- Normal PDV: 7.85 km/s
- Off-axis PDV: $(\alpha, \beta = \pm 55^{o})$
  - XPDV 3:
    - Apparent: 4.45 km/s
    - Corrected: 7.75 km/s
  - XPDV 4:
    - Apparent: 4.46 km/s
    - Corrected: 7.78 km/s
- Measurement accuracy within 2% of true velocity