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Optical diagnostics in dynamic compression research

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Outline

- Part I: An overview of optical diagnostics
  - Motivation and historical examples
  - Diagnostic limitations and their impact
    - Detectors/optics, windows
  - Survey of techniques

- Part II: Optical velocimetry
  - Photonic Doppler Velocimetry (aka HetV)

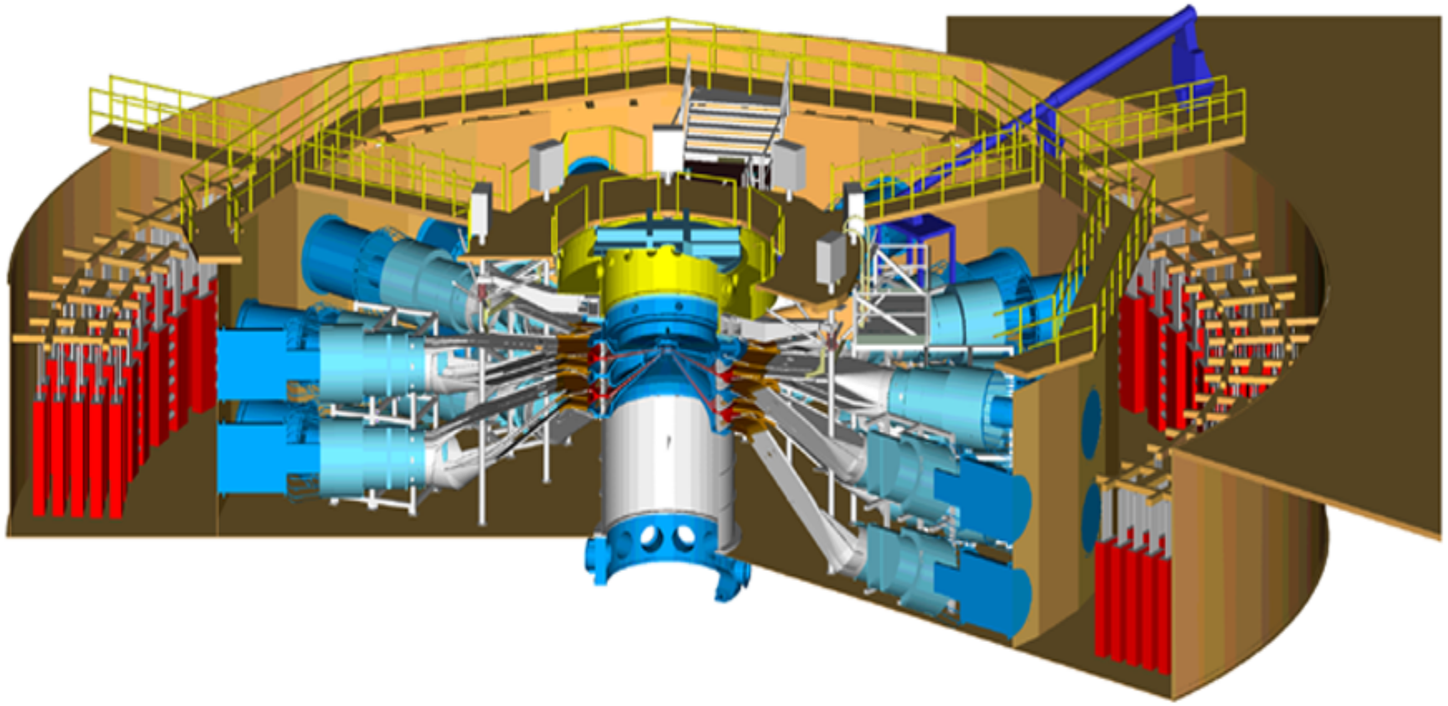
- Part III: Optical spectroscopy and imaging
  - Transmission, emission, reflection
  - Detecting phase transitions
  - Measuring temperature

Part I: An overview of optical diagnostics

Motivation

- Dynamic compression involves harsh conditions:
  - Explosives
  - High-speed impact
  - Pulsed power
  - Lasers
- On short time scales:
  - 10^{-10} to 10^{-4} seconds
- That are costly to repeat!
- How does one monitor a single-event experiment in real time?

Sandia Z machine



Shock wave experiments

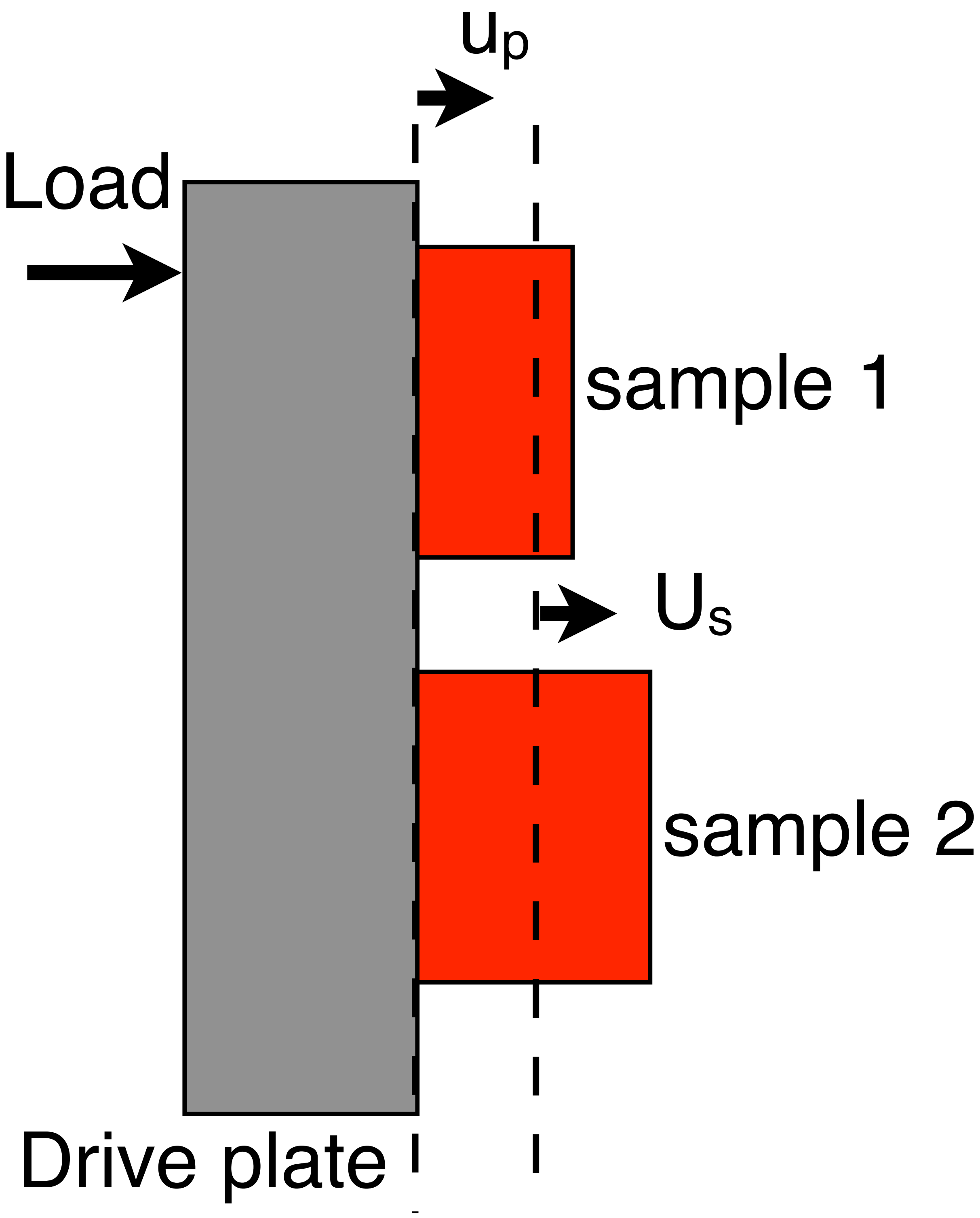
- Mechanical variables:
  - Pressure
  - Density
  - Shock velocity
  - Particle velocity

  are related by jump conditions

$$\frac{\rho}{\rho_0} = \frac{U_s}{U_s - u_p}$$

$$P = \rho_0 U_s u_p$$

Measure two things (usually U_s and u_p)



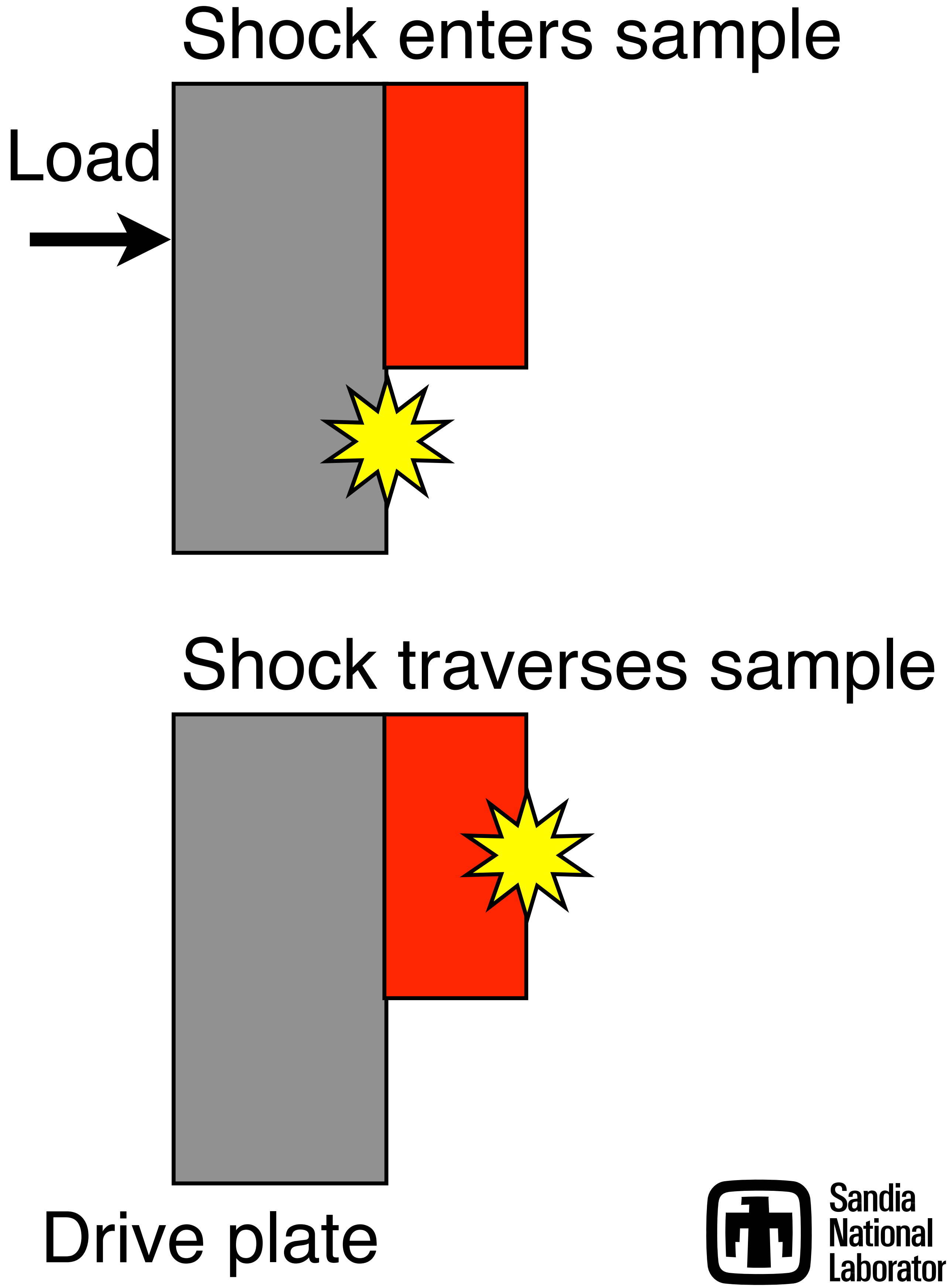
Basic velocimetry (transit time)

- Electrical or optical shock breakout measurements

$$U_s = \frac{\Delta x}{\Delta t}$$

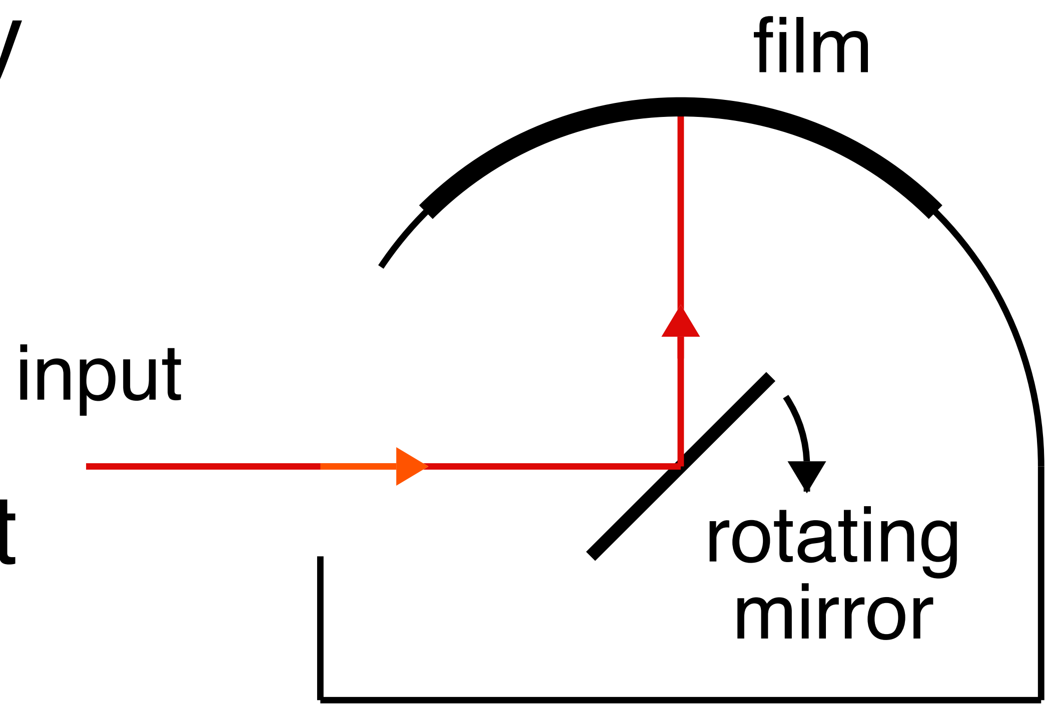
- Lots of data extracted from U_s
  - u_p inferred from impedance matching
  - LASL shock tables

- Optical methods usually superior
  - Noise isolation
  - Time resolution



Fast optical measurements

- High time resolution achieved by spatial dispersion
  - Rotating mirror streak cameras
- Alternatives exist (digitizers), but streak cameras remain in use
  - Highest time resolution
  - Continuous horizontal data
    - Position
    - Wavelength
- Framing cameras use similar techniques
  - 2D images at discrete times



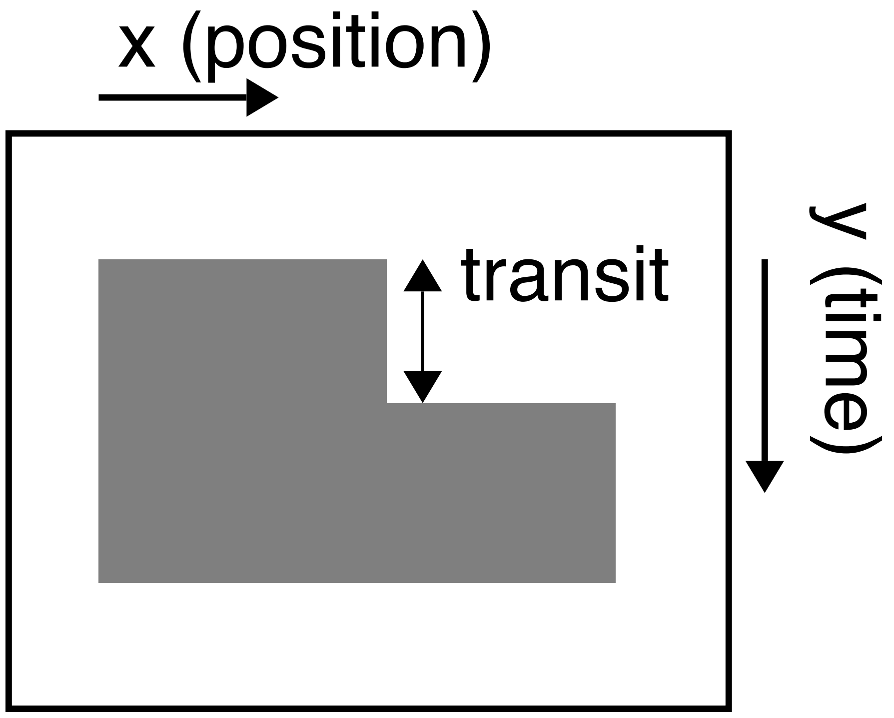
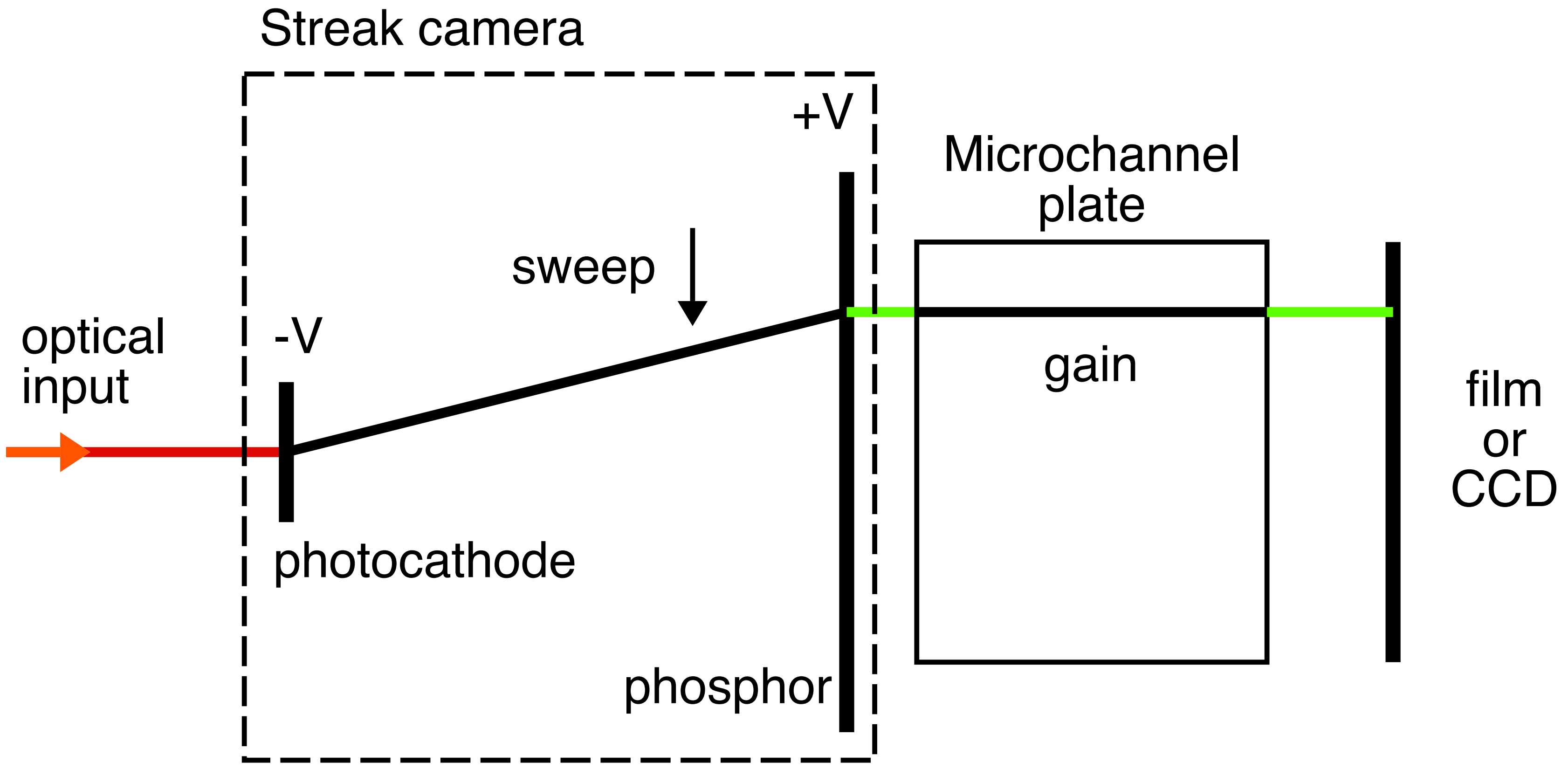


Image conversion cameras



- Spatial dispersion by electron deflection (E or B)
  - Photocathode: photons → electrons
  - Phosphor: electrons → photons
  - Optional MCP: photons → electrons → more electrons → photons
  - Final output recorded on film or CCD

- http://learn.hamamatsu.com/tutorials/java/streakcamera/

Technical/economic limitations

- Optical transparency
  - ~350-2000 nm (silica optics and **fiber**)
  - Limited dynamic window selection (LiF, Al_2O_3, SiO_2, CZ, NaCl, MgO, diamond?)

- Efficient photon conversion
  - <1000 nm (film)
  - 300-1800 nm (photocathodes/photodiodes)
  - Longer wavelengths (low band gap) require cooling and are not as well developed

- Measurements are predominantly visible to near-infrared
  - Traditionally film based
  - Electronic systems are more common now

Survey of techniques

- Passive : sample generates light
  - Shock breakout (argon flash gaps)
  - Emission spectroscopy
    - Temperature (**pyrometry**) and chemistry
- Active: sample modifies light
  - Optical velocimetry (VISAR and **PDV**)
    - Wave and particle velocity measurements
  - **Transmission/reflection spectroscopy and imaging**
    - Inelastic behavior, phase transitions, temperature?
  - Fluorescence/Raman spectroscopy
    - Electronic and vibrational state information, sometimes used for temperature

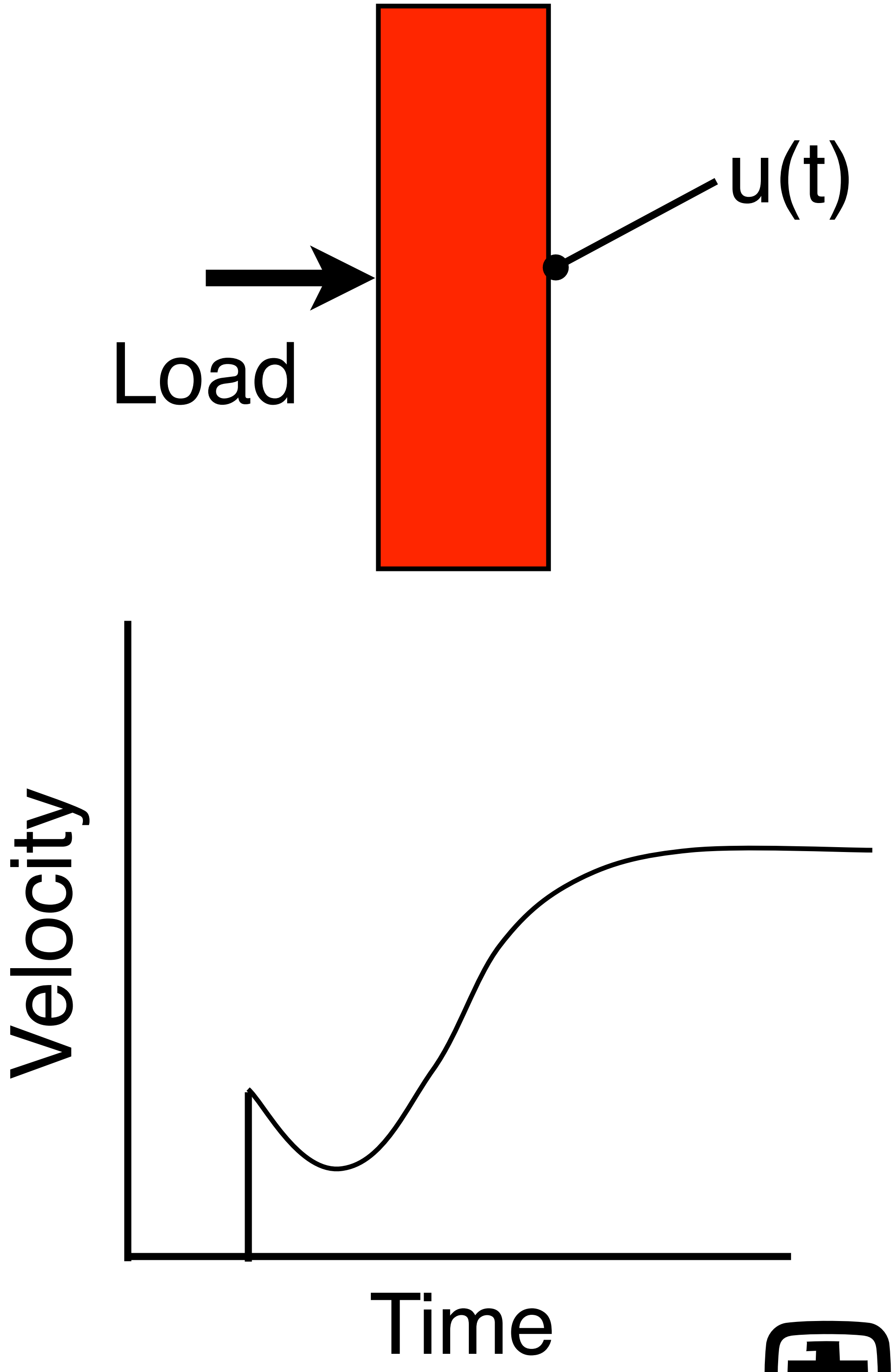
Part II: Optical velocimetry

Time-resolved velocimetry

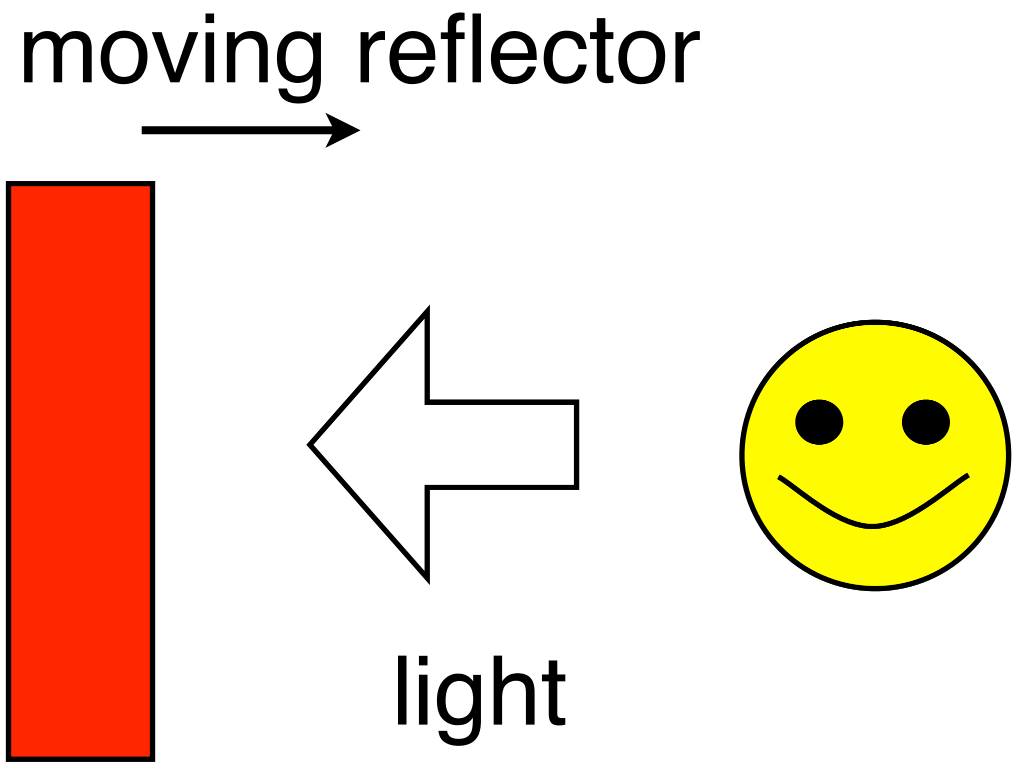
- Mechanical waves often contain a lot of structure
  - Inelastic compression
  - Phase transitions
  - Chemical reactions

- This structure is difficult, sometime impossible, to extract from transit time measurements

- Time-resolved measurements needed

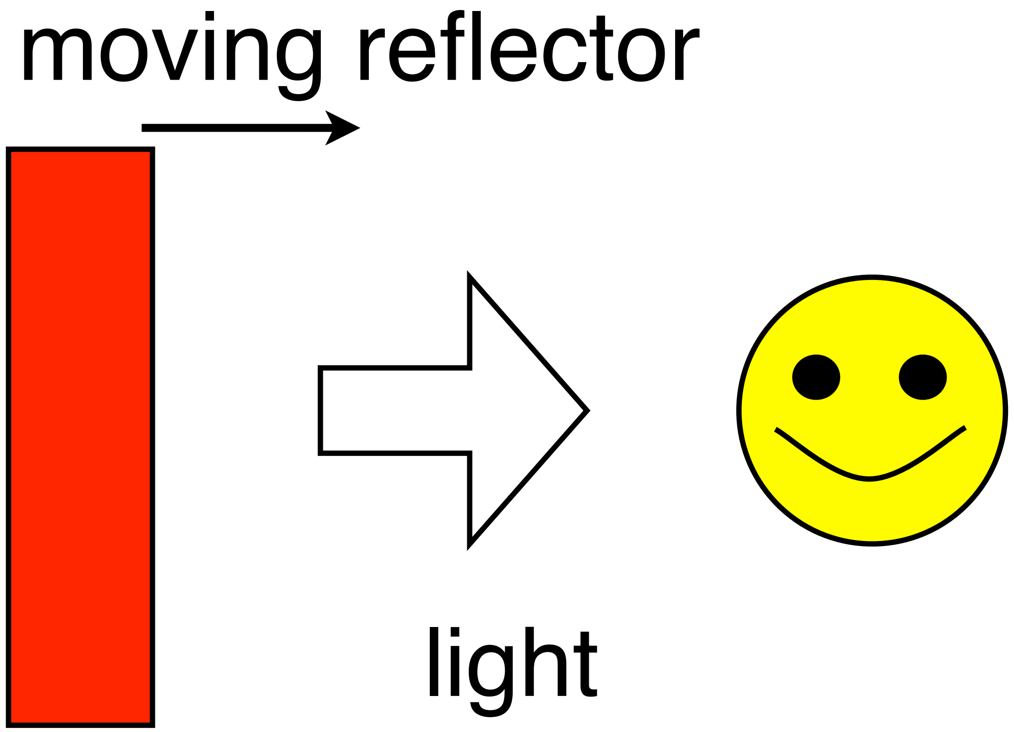


The Doppler effect



Observer sees: λ_0

Reflector sees: λ'



Reflected light: λ'

Observer sees: λ

$$\frac{\lambda}{\lambda_0} \approx 1 - \frac{2v}{c_0}$$

6-7 ppm change at 1 km/s
(0.004 nm at 532 nm)

Interferometry

- Wavelength changes are small for non-relativistic motion
  - Cannot by resolved by simple dispersion (i.e. prism)

- Two-beam interferometry:

$$I(t) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \underbrace{(\phi_1(t) - \phi_2(t))}_{\text{phase difference}}$$

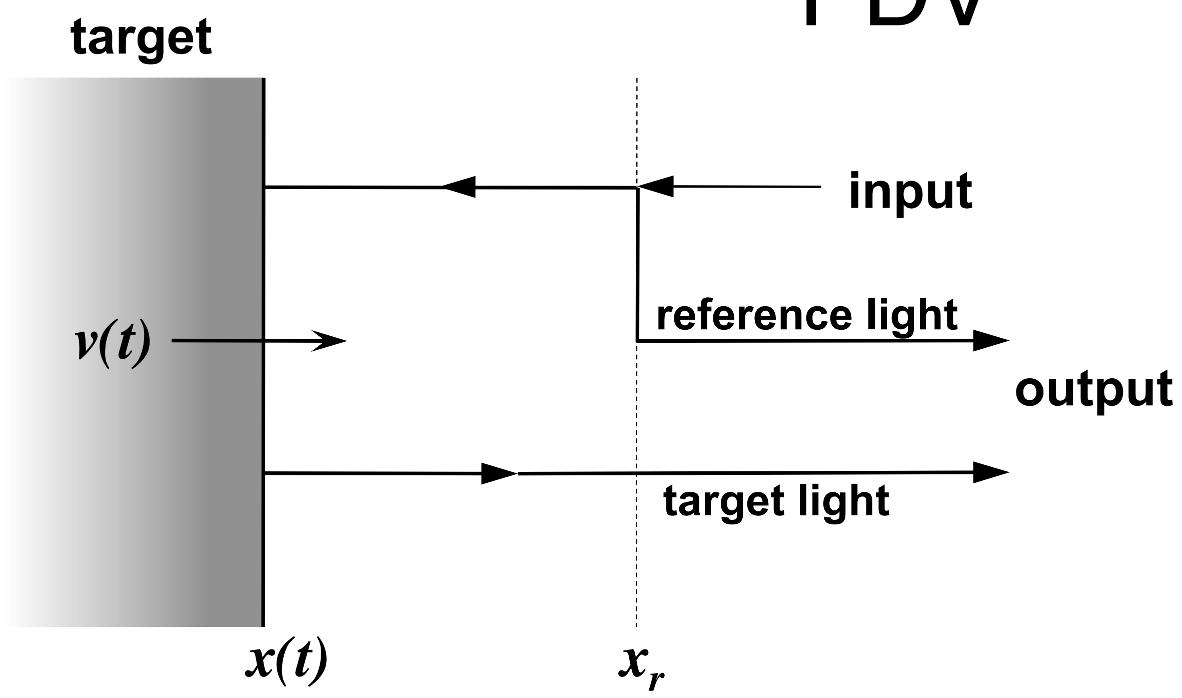
$$\boxed{f_B = \frac{2u}{\lambda_0}}$$

At 632.8 nm, 1 km/s velocity creates a 3.16 GHz Doppler shift

Interferometer approaches

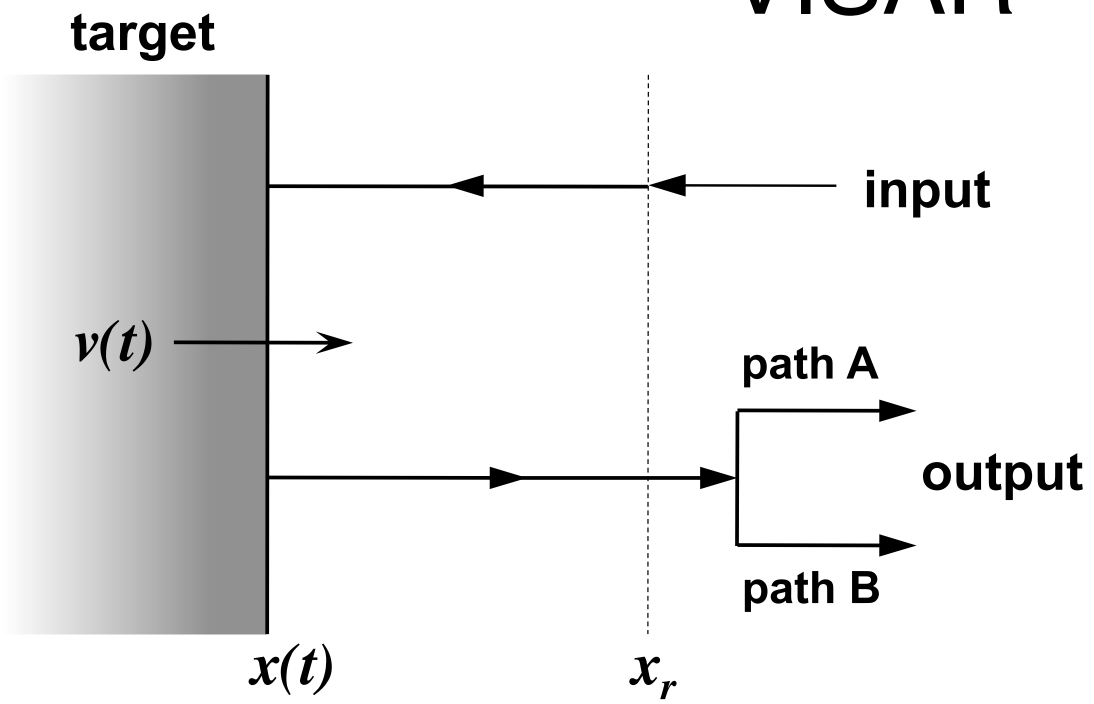
- "Displacement" approach
  - One output path contains target (Doppler)
  - Other output path does NOT contain the target
  - Mixes two different optical frequencies

PDV



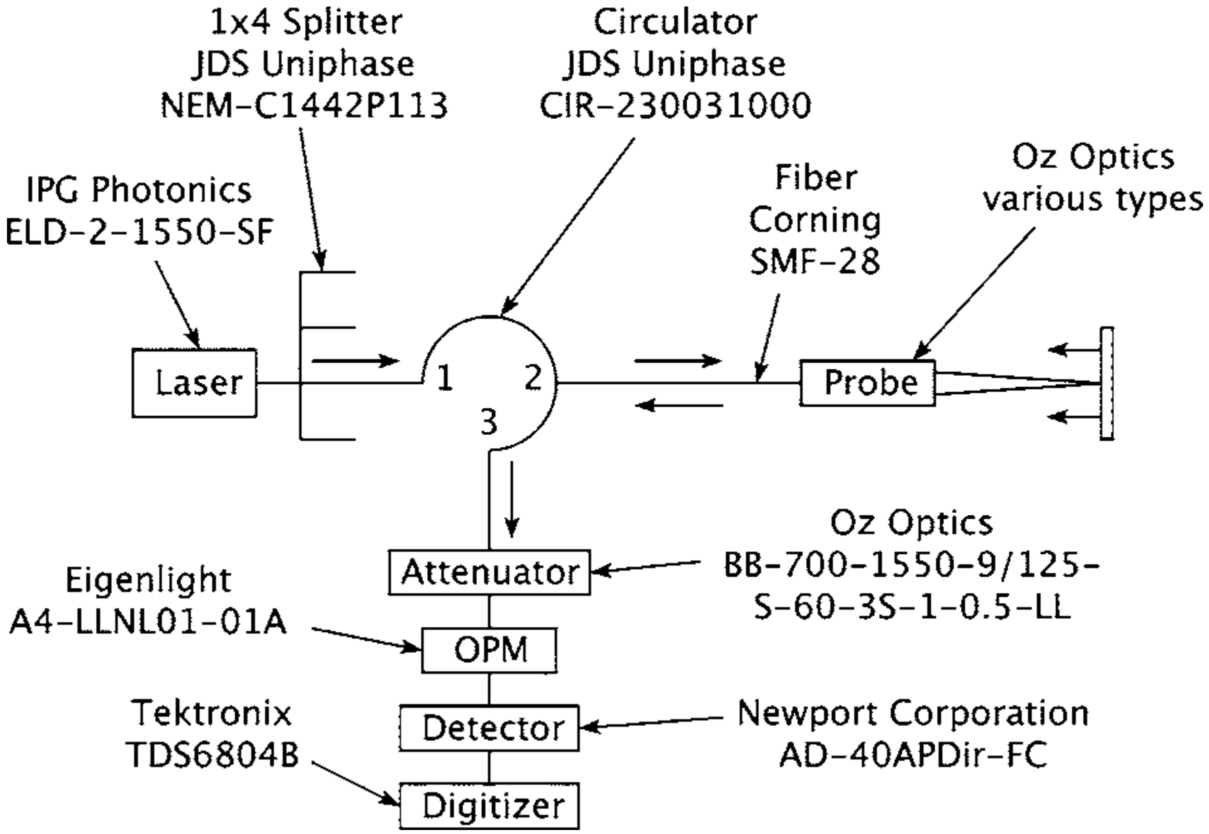
- "Velocity" approach
  - Both output paths contain the target (Doppler)
  - Mixes two copies of a single optical frequency

VISAR



PDV born at LLNL (2002-2003)

- Utilizes advances from the telecommunications industry (1550 nm)
  - Compact fiber lasers
    - 9 um core size (SMF)
    - Narrow line width
      - <10-100 kHz
  - Three-port circulator (magic!)
    - Port 1 input goes to port 2
    - Port 2 input goes to port 3
  - High speed detectors/ digitizers (>10 GHz)

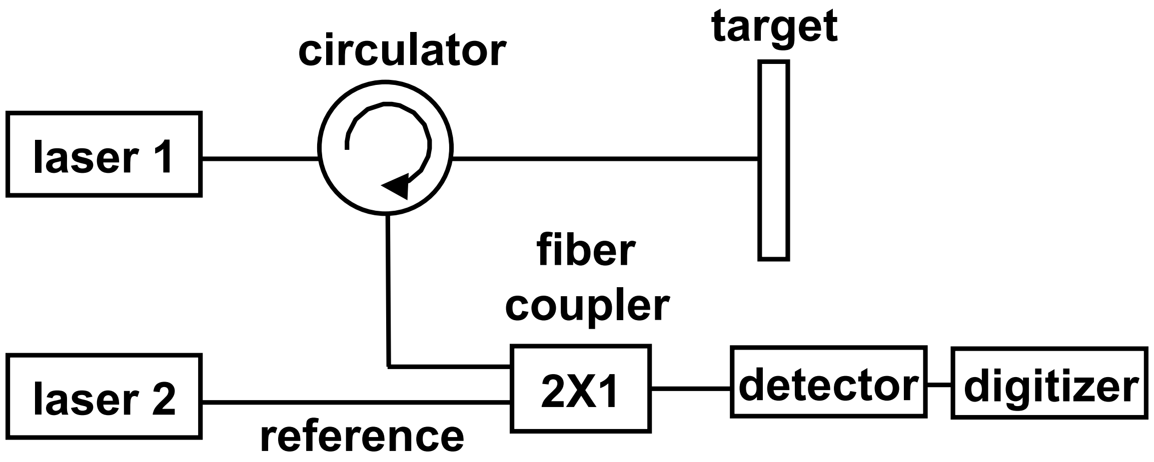


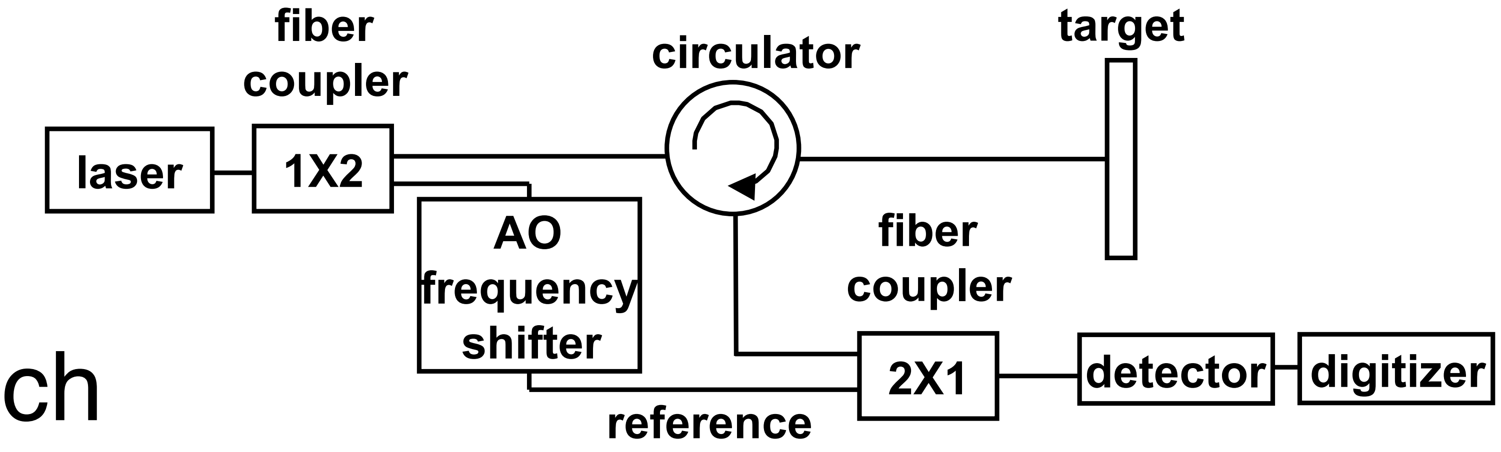
Strand et al, Rev. Sci. Instrum. **77**, 83108 (2006).

Generation 0: reference light comes from the probe's back reflection

Frequency-conversion PDV

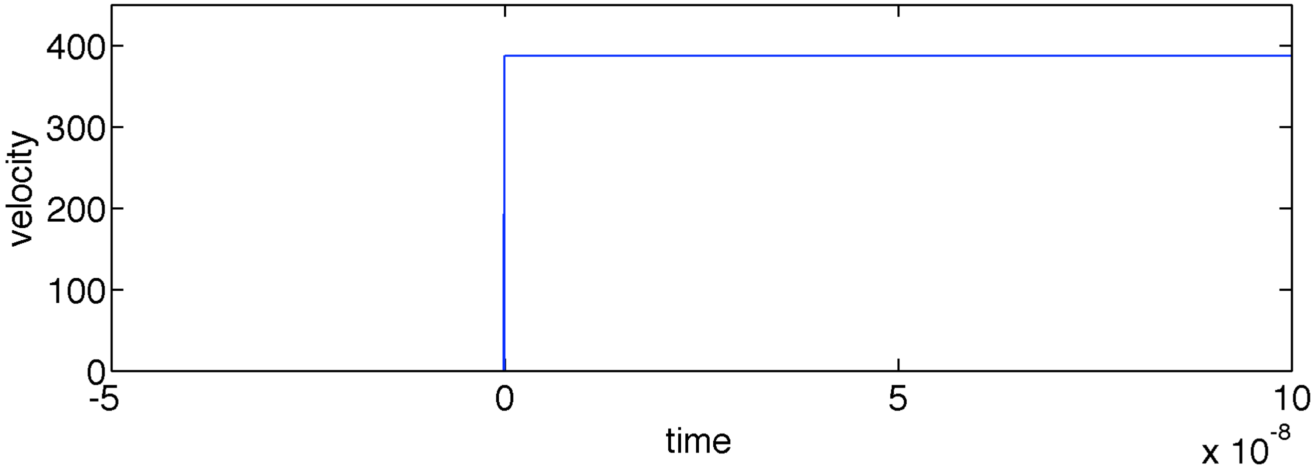
- Two wavelengths
  - One illuminates target
  - One serves a reference
- Up/down conversion
  - Frequency increases/ decreases with velocity, depending on configuration
  - Direction information
- This is my favorite approach
  - Works at any velocity
  - Utilizes the power of the FFT



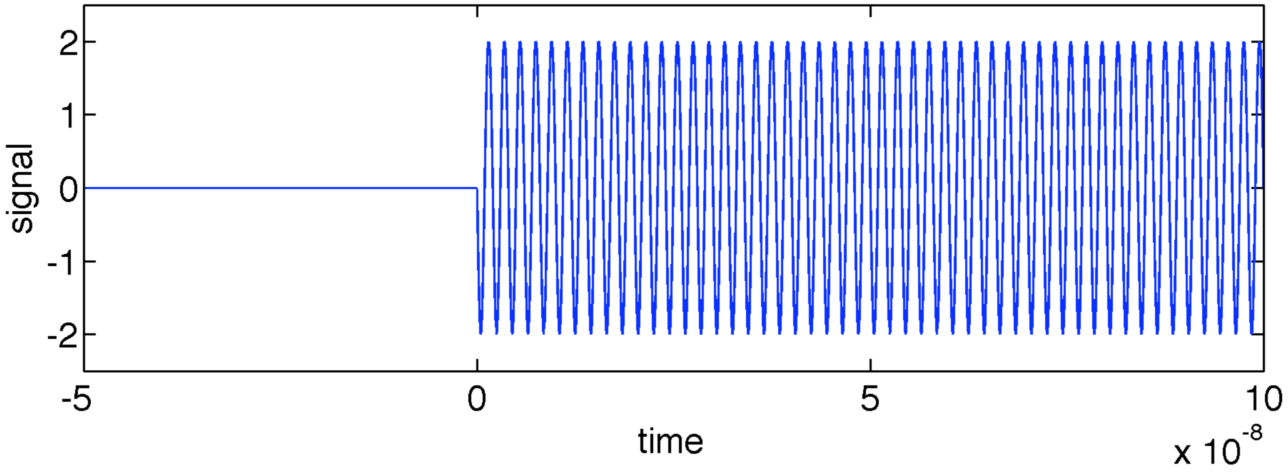


A simple example

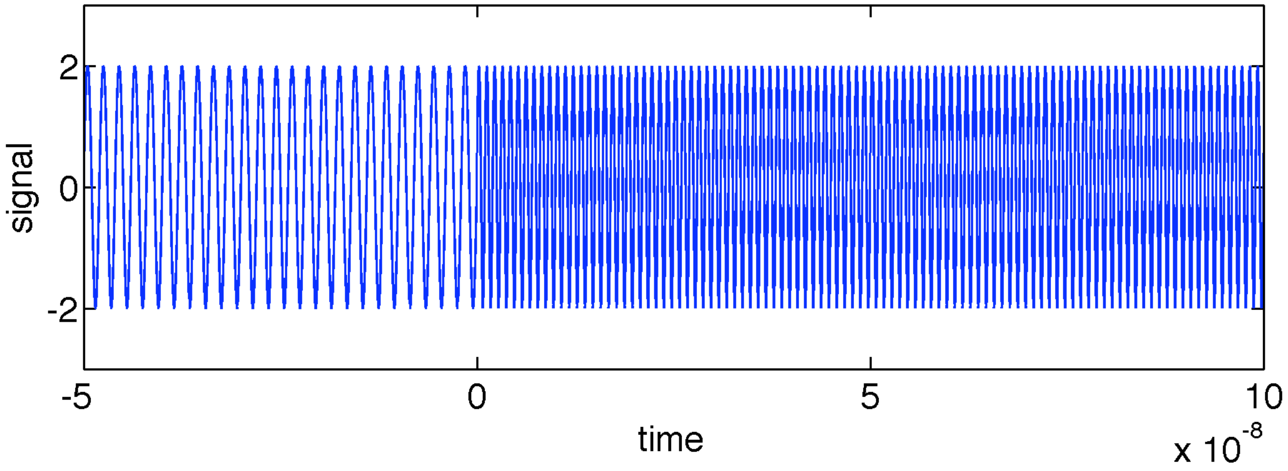
- Consider a velocity step



- Conventional PDV
  - Constant signal at rest
  - 775 nm motion= 1 fringe



- Frequency-conversion PDV



PDV approximation

Suppose velocity changes slowly over some small duration.

$$x(t) \approx x(\bar{t}) + \bar{v} \times (t - \bar{t})$$

The optical signal in this duration would be harmonic:

$$I(t) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left[\bar{\Phi} + 2\pi \left(\frac{2\bar{v}}{\lambda_0}\right) t\right]$$

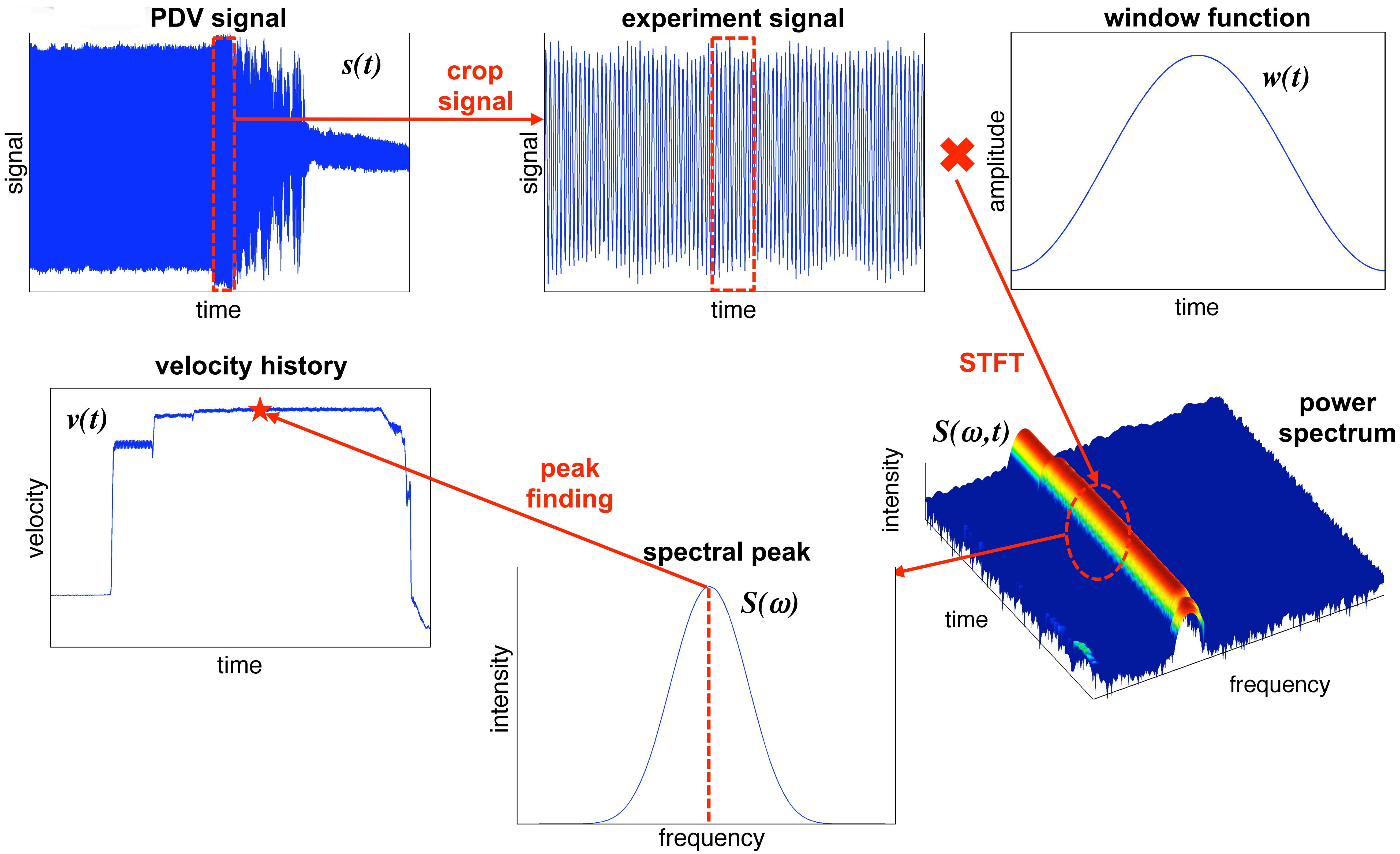
with a beat frequency proportional to velocity.

This frequency can be determined with a short-time Fourier transform (STFT).

$$S(f, \bar{t}) = \int_{-\infty}^{\infty} s(t) w(t - \bar{t})\ e^{-2\pi i f t}\ dt$$

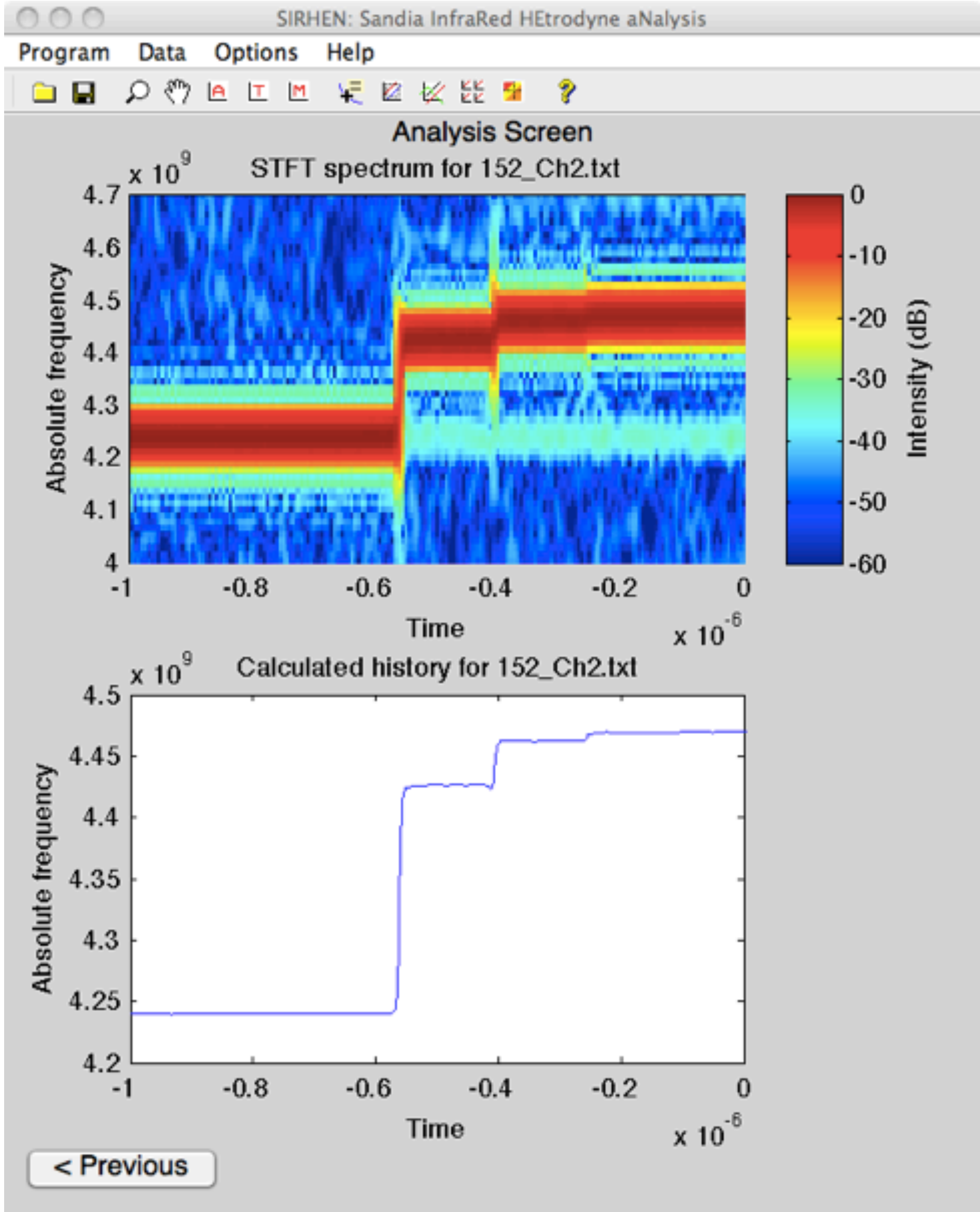
Window w(t) selects regions in signal s(t).

Analysis overview

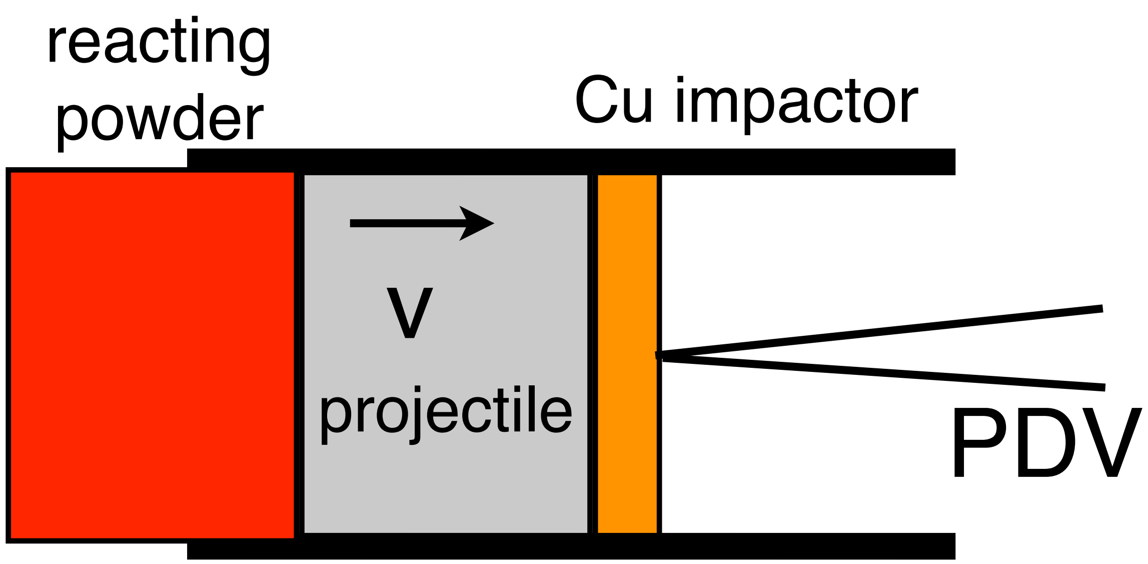


Data reduction

- STFT image (spectrogram)
  - Color represents spectral intensity at a particular time and frequency
  - Useful for qualitative inspection
- Velocity history
  - Extracted from spectral peak at different FFT locations
  - Takes a bit more effort
  - Frequency bounding may be needed (refer to STFT)
- Some examples...

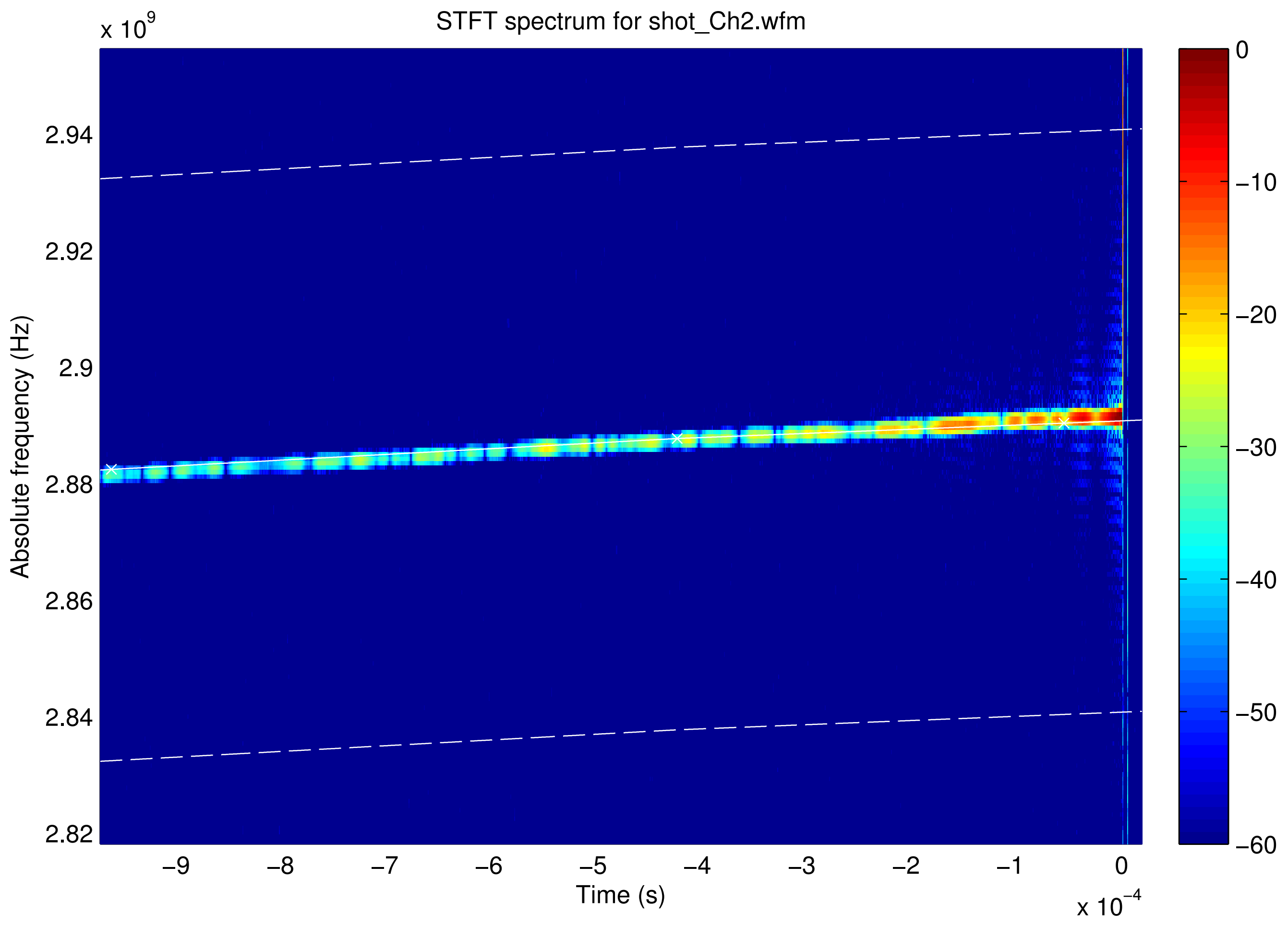


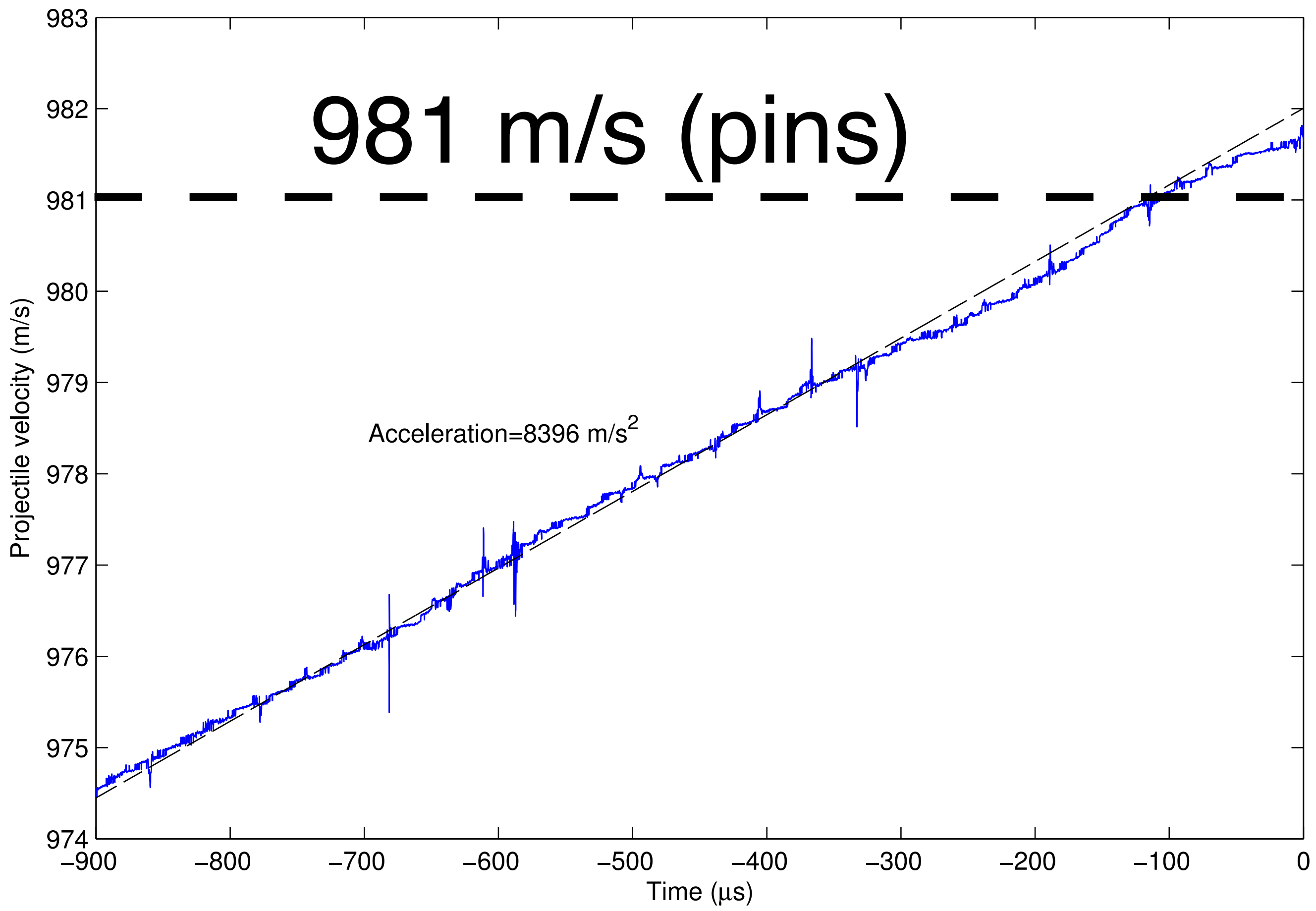
Projectile velocity monitor (STAR)



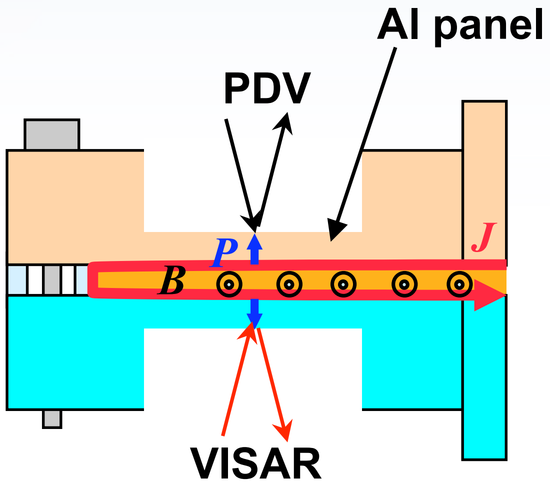
- Projectile tracked ~1 m prior to impact

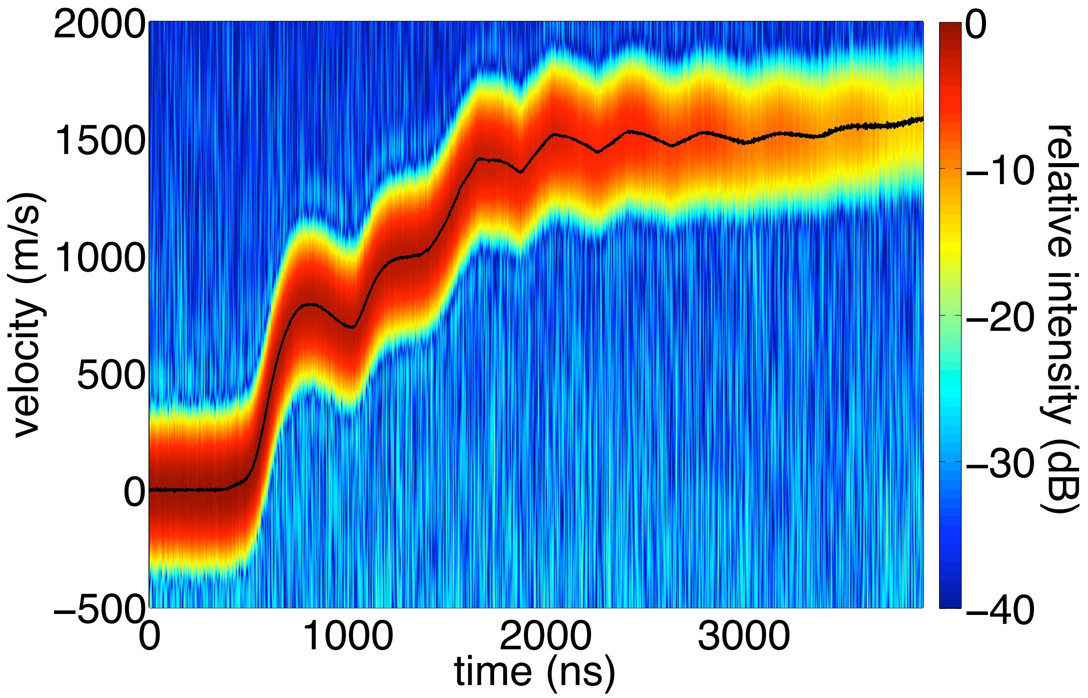
- Additional tracking possible with slight probe/ digitizer modifications

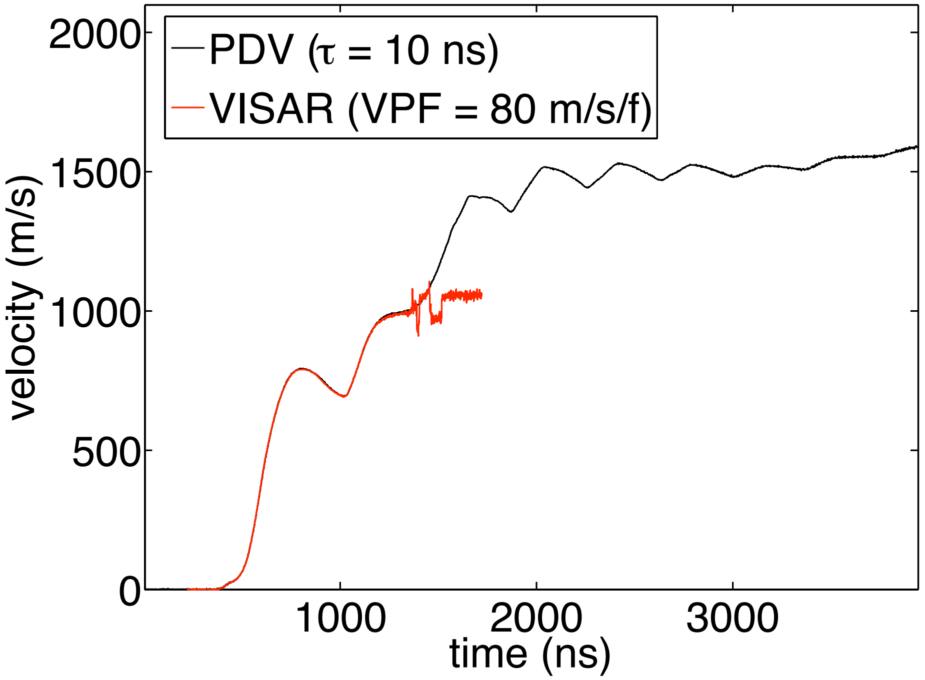




Ramp loading: free surface







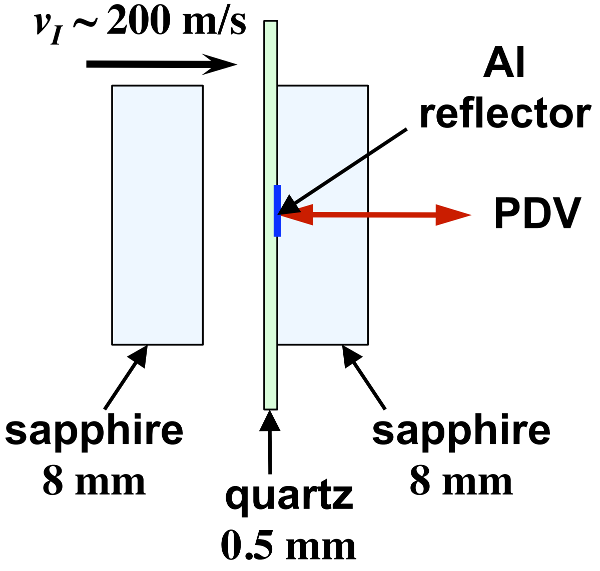
Validation between PDV and VISAR

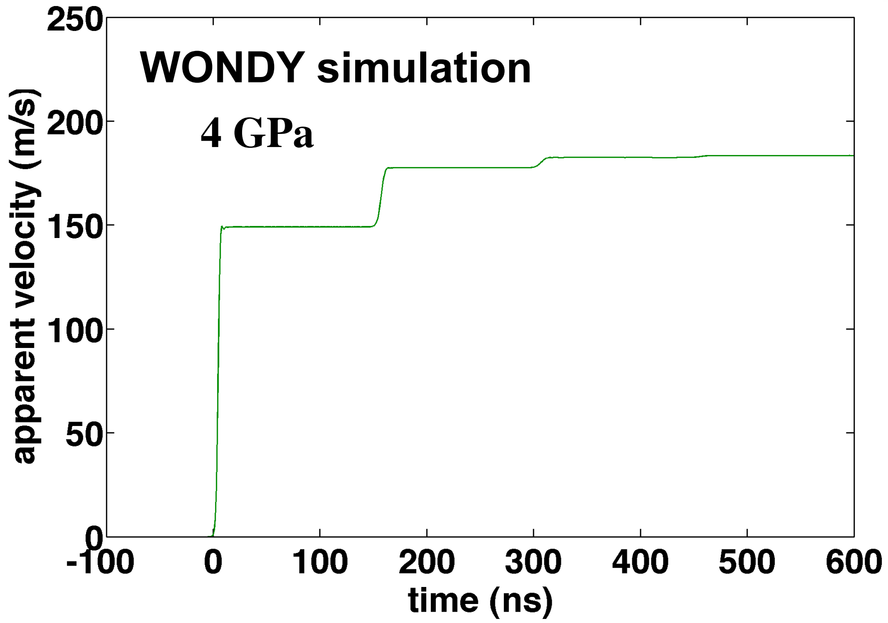
- PDV able to track free surface over considerable distance after VISAR loses signal
- VISAR's $\mathrm{VPF} = 80\ \mathrm{m/s/f}$ corresponds to and ideal risetime of $2.7\ \mathrm{ns}$ but detector risetime needs to be accounted for
- PDV's $\tau\ = 10\ \mathrm{ns}$ (Hamming window) corresponds to a risetime of $3.7\ \mathrm{ns}$

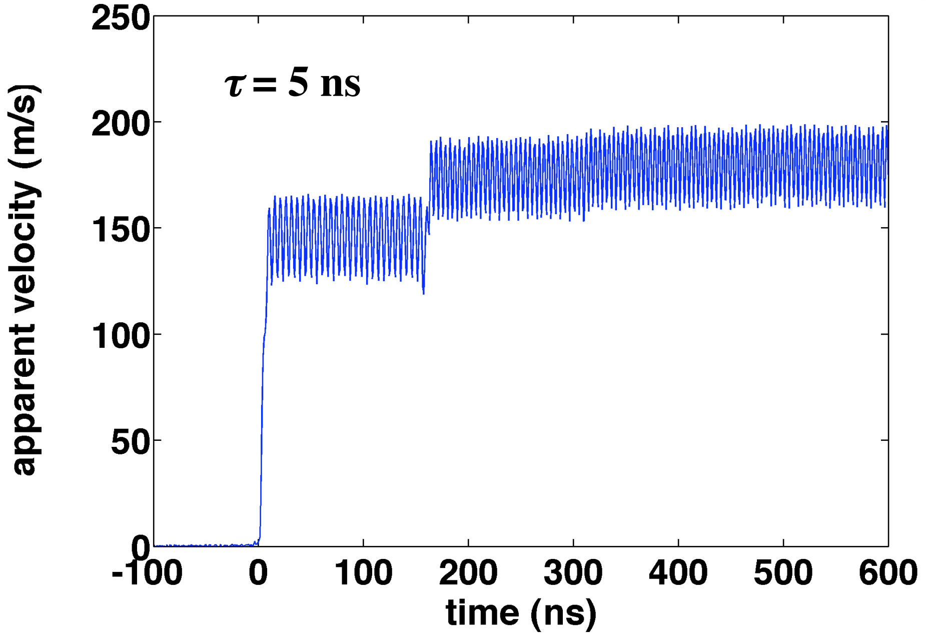
Shock reverberation experiment

Measurement of transient wave structure

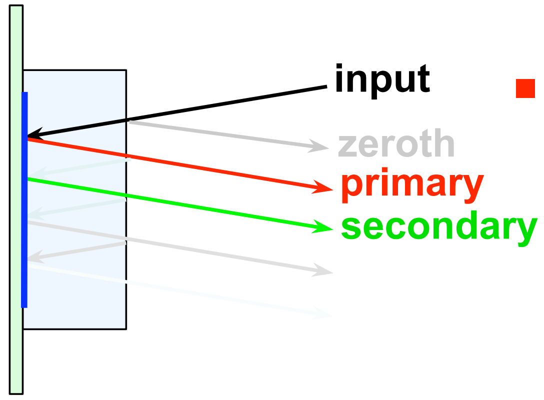
- Quartz sample sandwiched between sapphire impactor and sapphire window





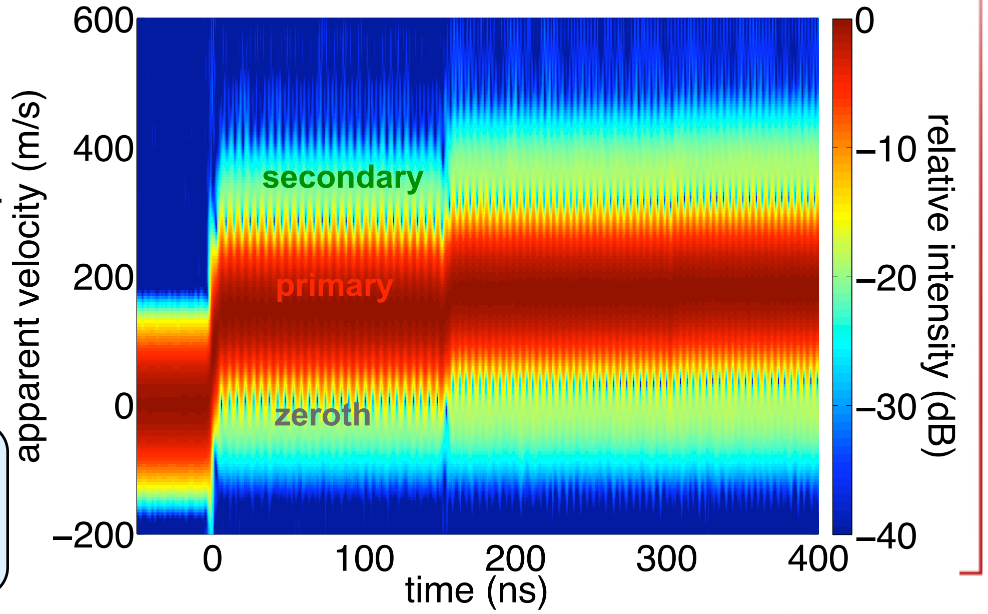


Multiple window transits due to reflections from free surface of window



- Oscillations within velocity profile due to other reflections perturbing primary

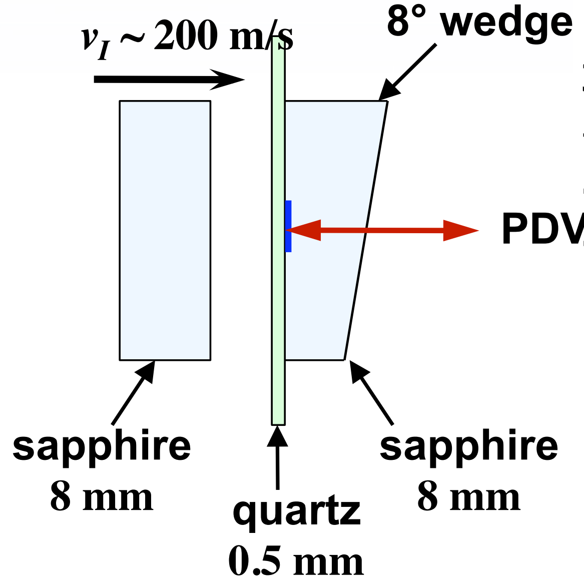
$$s(t) \propto \sqrt{I_R I_0(t)}\cos\Phi_0 + \sqrt{I_R I_1(t)}\cos\Phi_1 + \sqrt{I_R I_2(t)}\cos\Phi_2 + \ldots$$

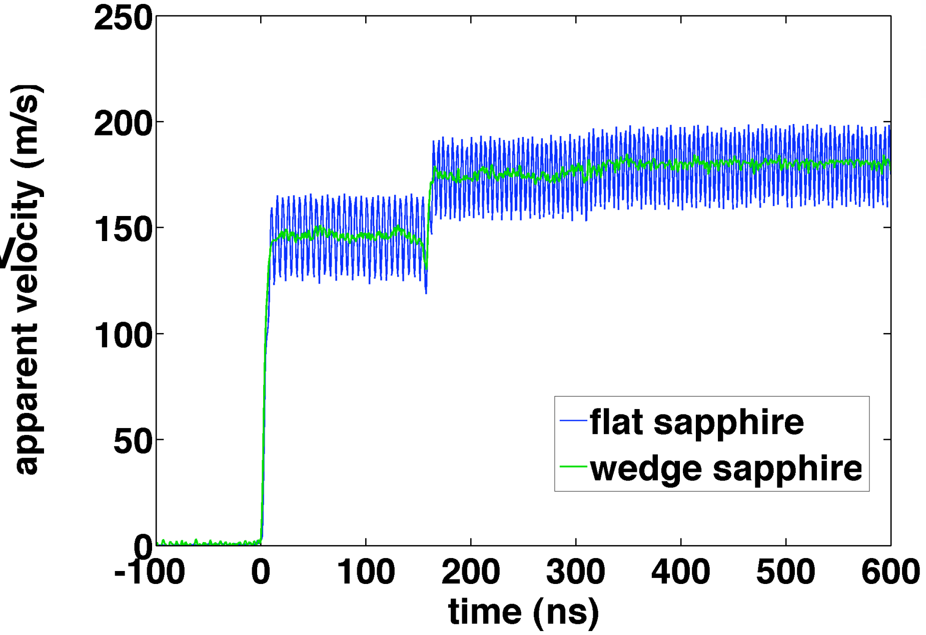


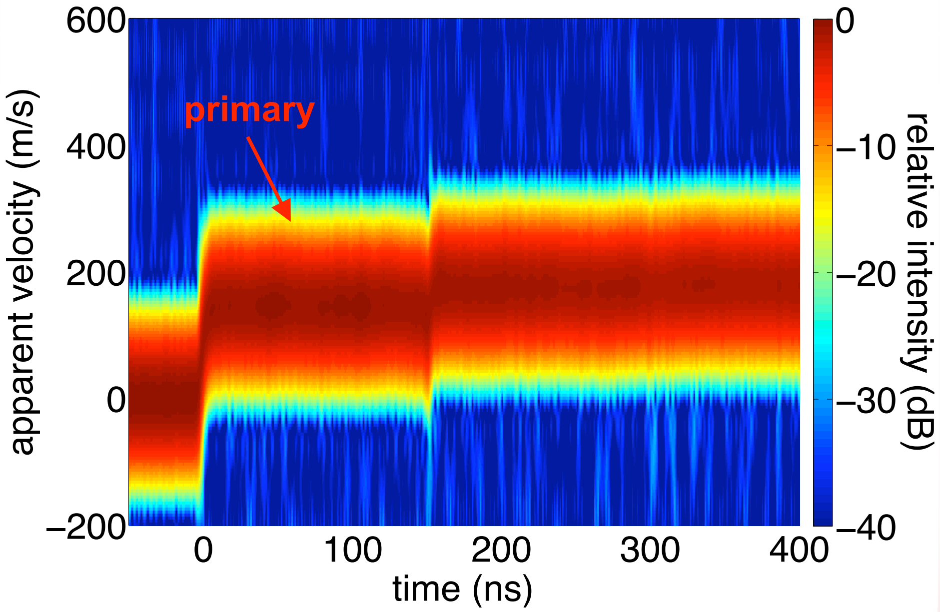
T. Ao and D.H. Dolan, Rev. Sci. Instrum., accepted (2011)

Mitigating window reflections

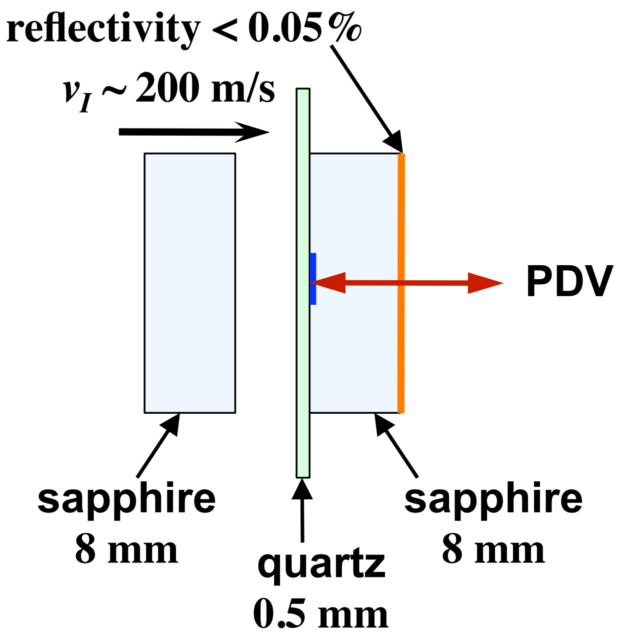
Wedge window deflect reflections from free surface

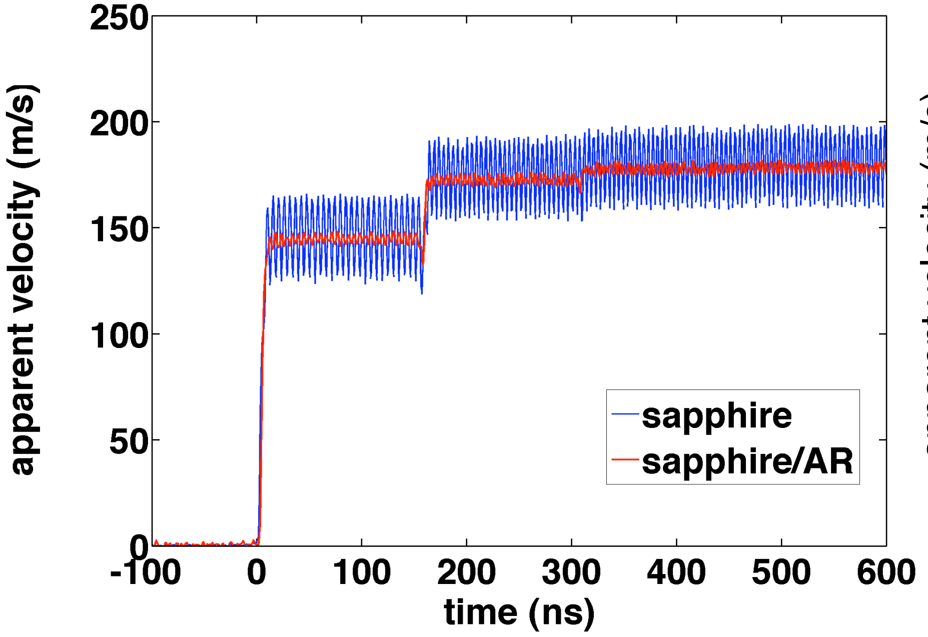


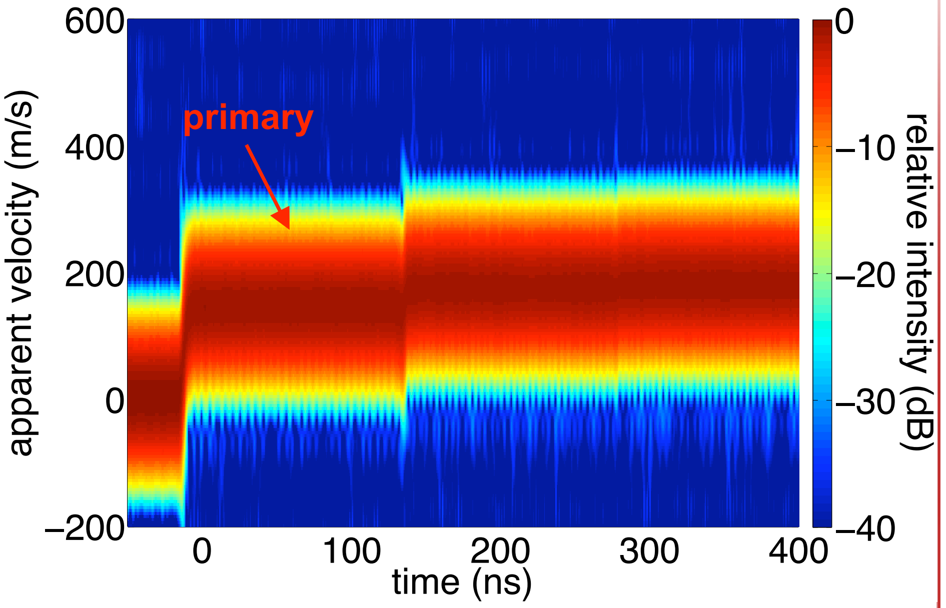




Anti-reflective coating attenuates reflections from free surface



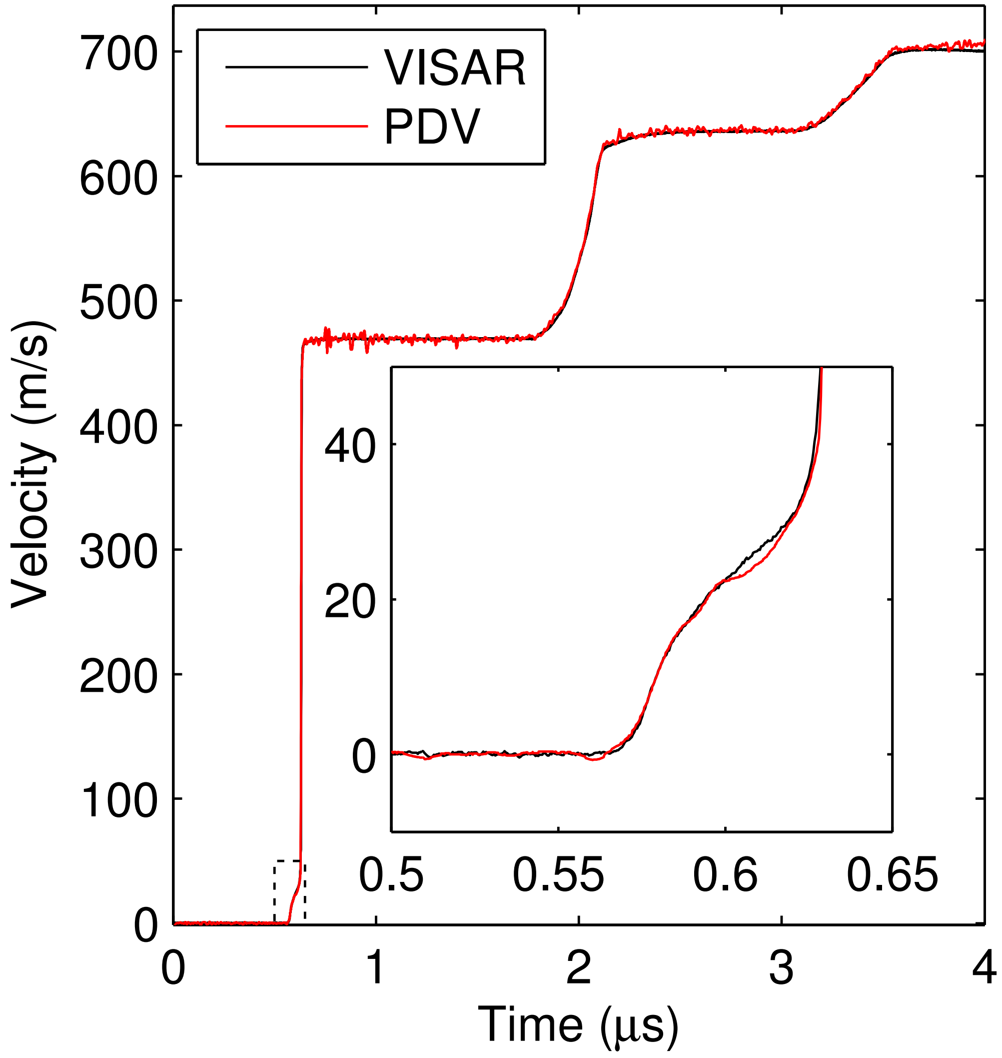




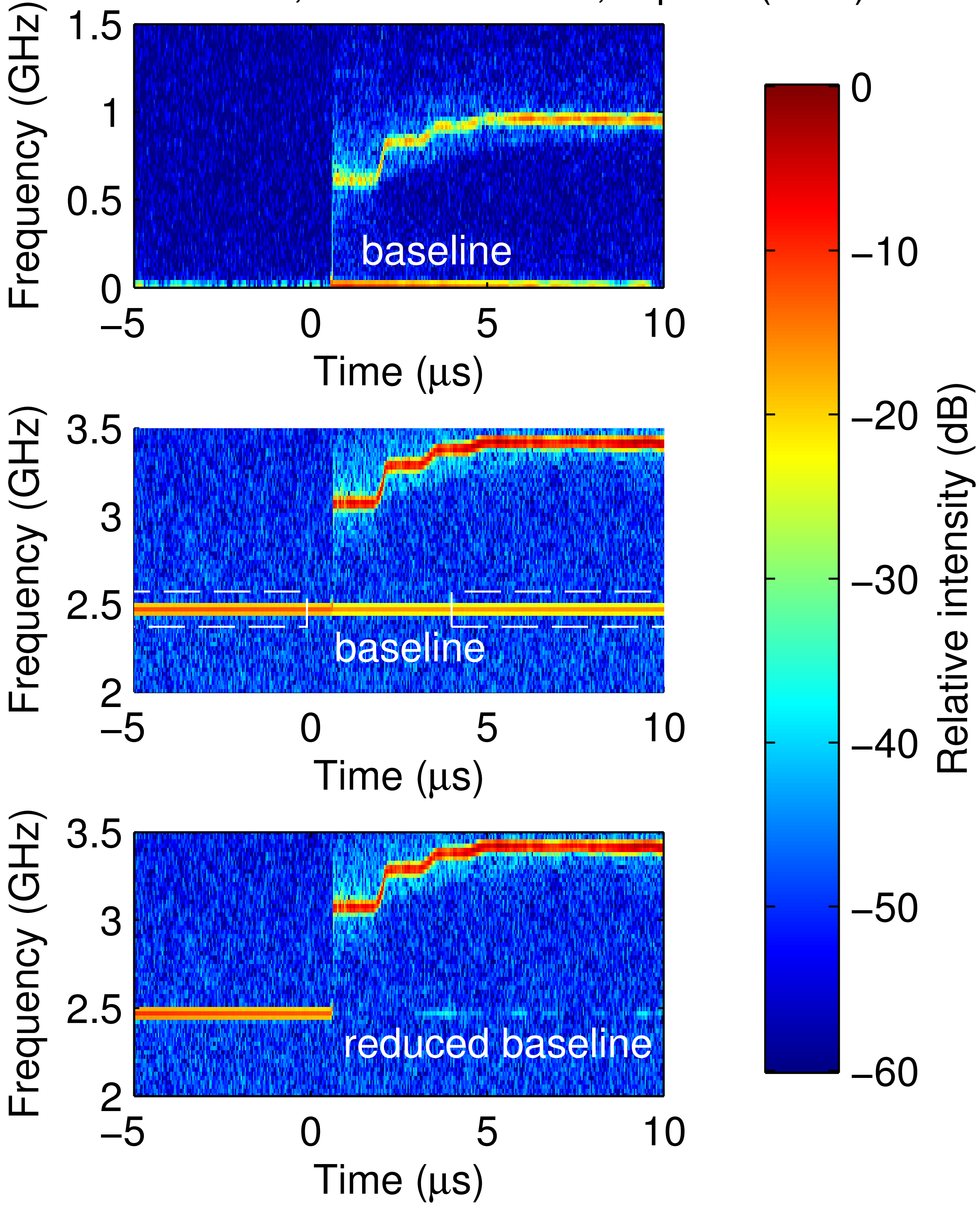
Velocity variations $\delta v/v \approx 1\%$ and analysis time duration $\tau = 5$ ns comparable to velocity and time precision of VISAR

Good news, bad news, good news?

- PDV can sense very weak reflections
- Weak signals can hinder extraction analysis
- Signal processing can remove “baseline” effects



Dolan et al, Rev. Sci. Instrum, in press (2012).



Part III: Optical spectroscopy and imaging

Overview

- Goal: obtain information beyond mechanical data of velocimetry
  - Phase transitions and inelastic deformation
  - Temperature

- Transmission spectroscopy and imaging
  - Isentropic freezing of water

- Emission spectroscopy (aka pyrometry)
  - Radiance measurements
  - The emissivity problem

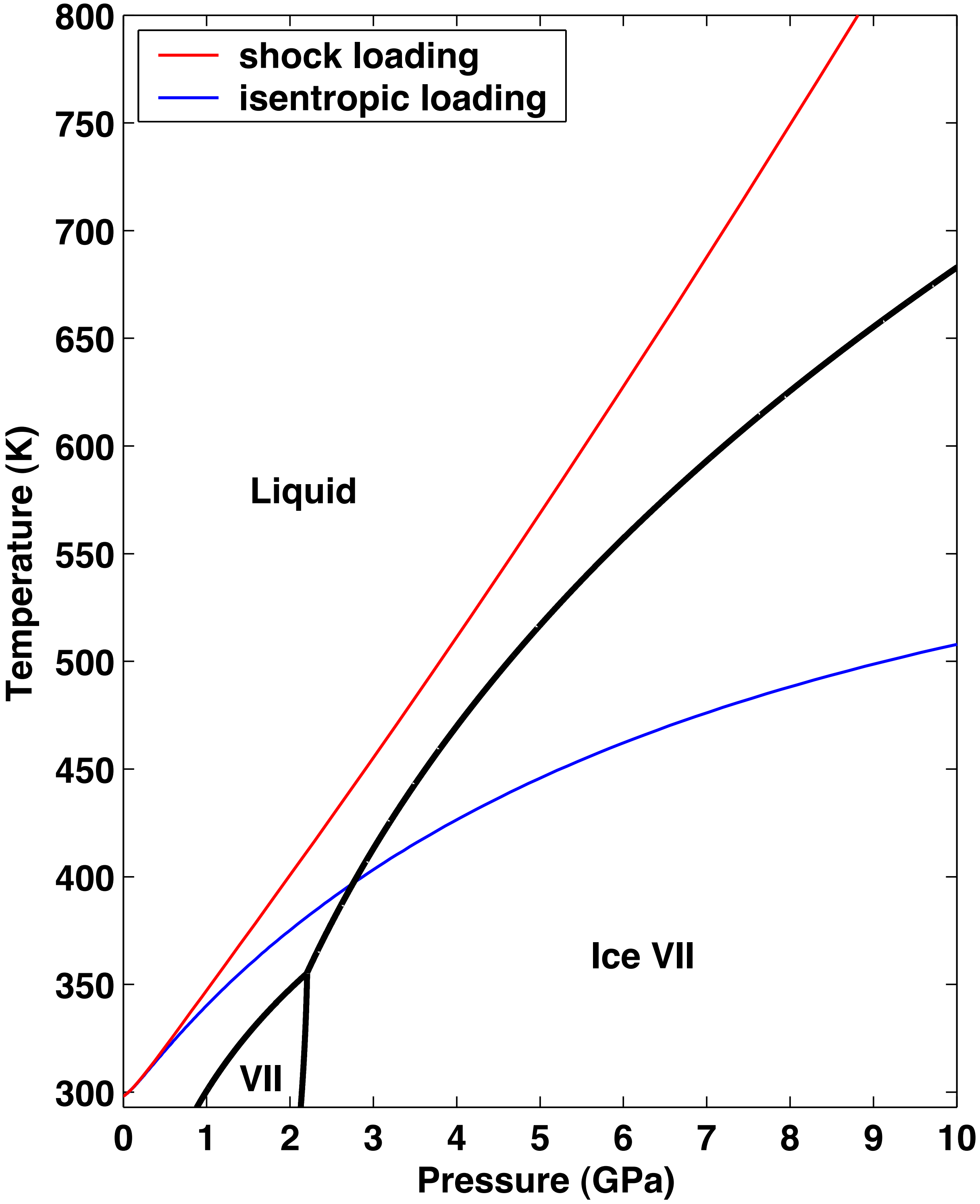
- Reflectance spectroscopy
  - Thermoreflectance of gold

Shock induced freezing

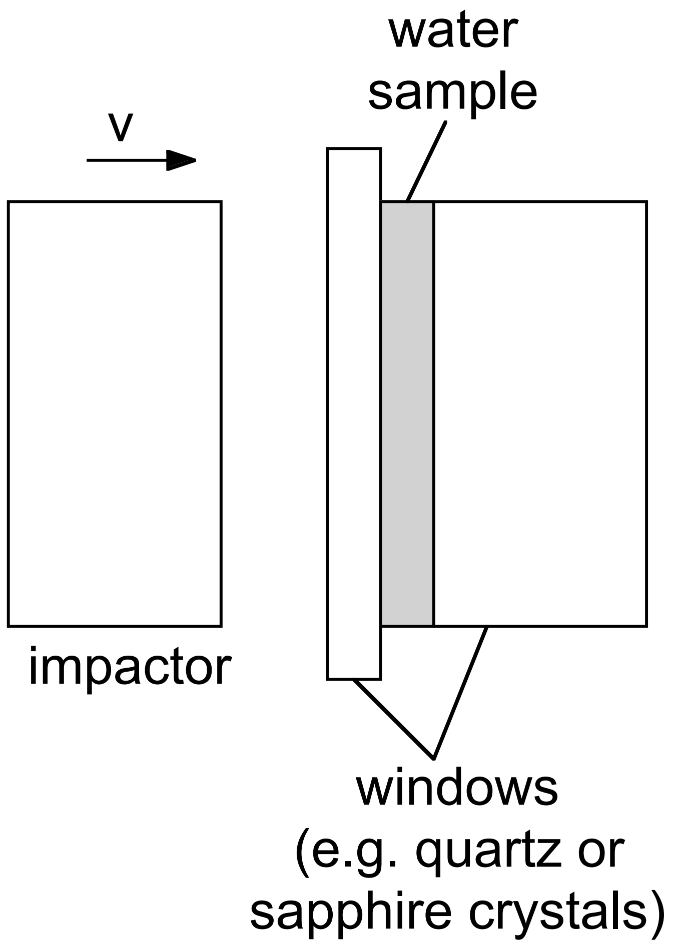
- Shock melting and solid-solid transitions observed for decades
  - G.E. Duvall and R.A. Graham, Rev. Mod. Phys. **49**, 523 (1977).

- Freezing inconclusive
  - High temperatures
  - Long metastable lifetime
  - Conflicting experimental results (subtle effects?)

- Isentropic compression may lead to freezing

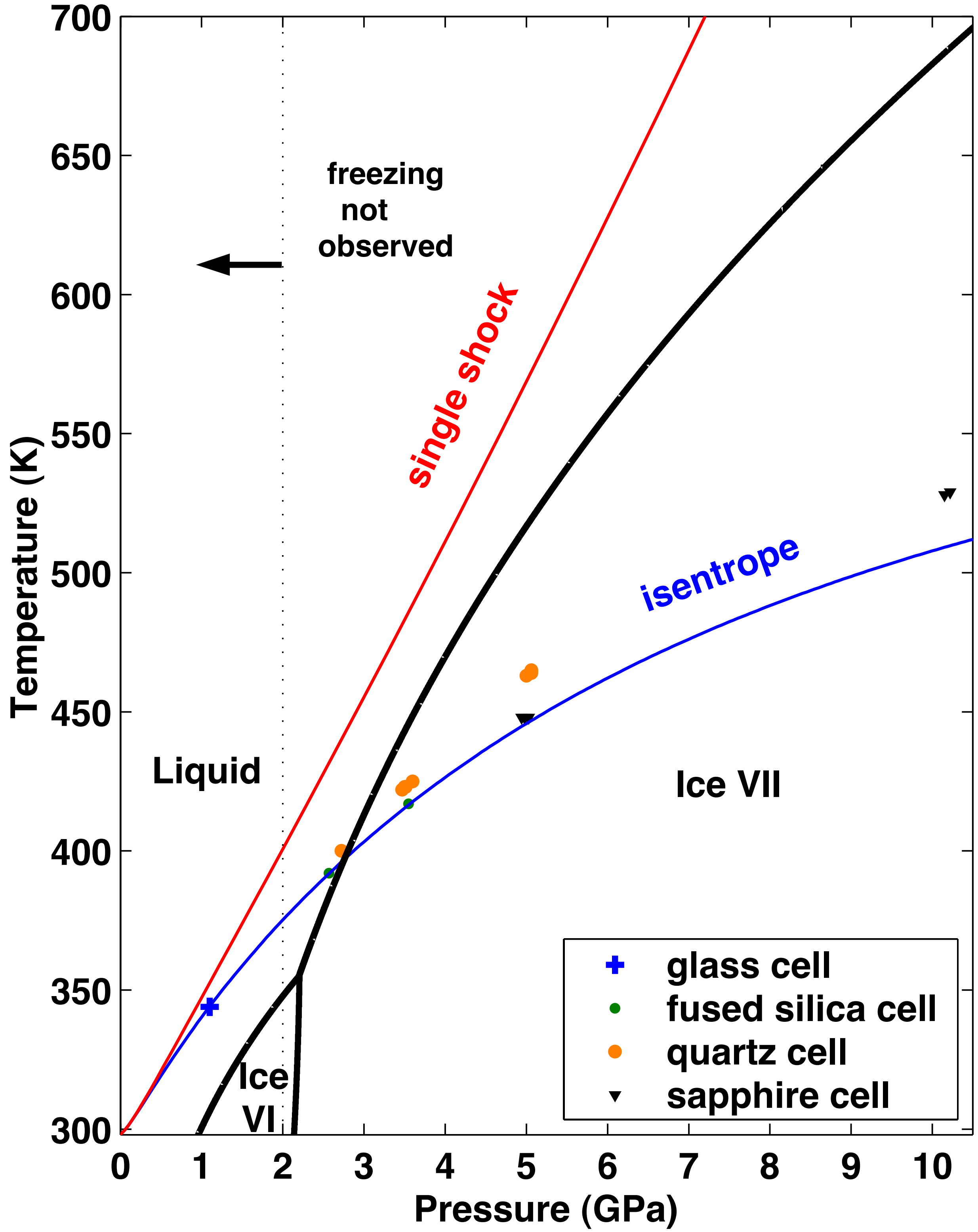


Multiple shock compression

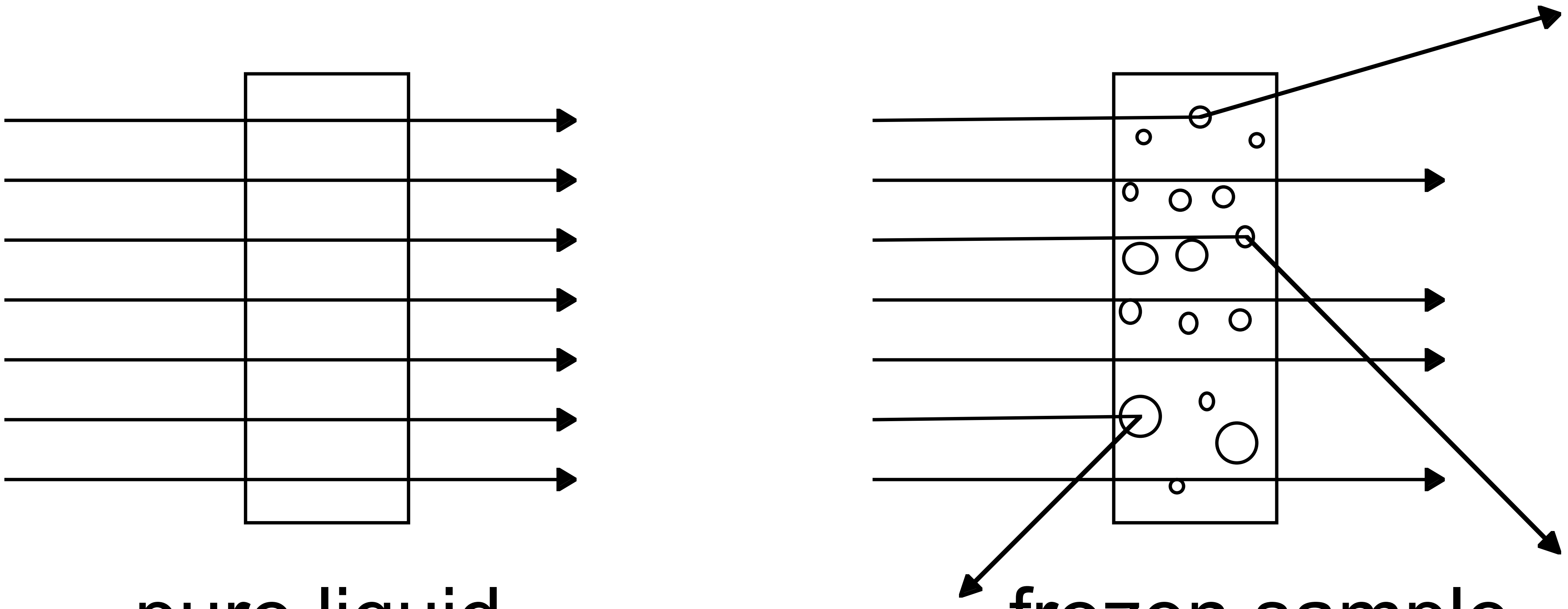


$$\Delta S = -\sum_{k=1}^{N} A_k \left(\frac{\Delta v}{N}\right)^3 \propto \frac{1}{N^2}$$

$$\Delta S \to 0 \text{ as } N \to \infty$$

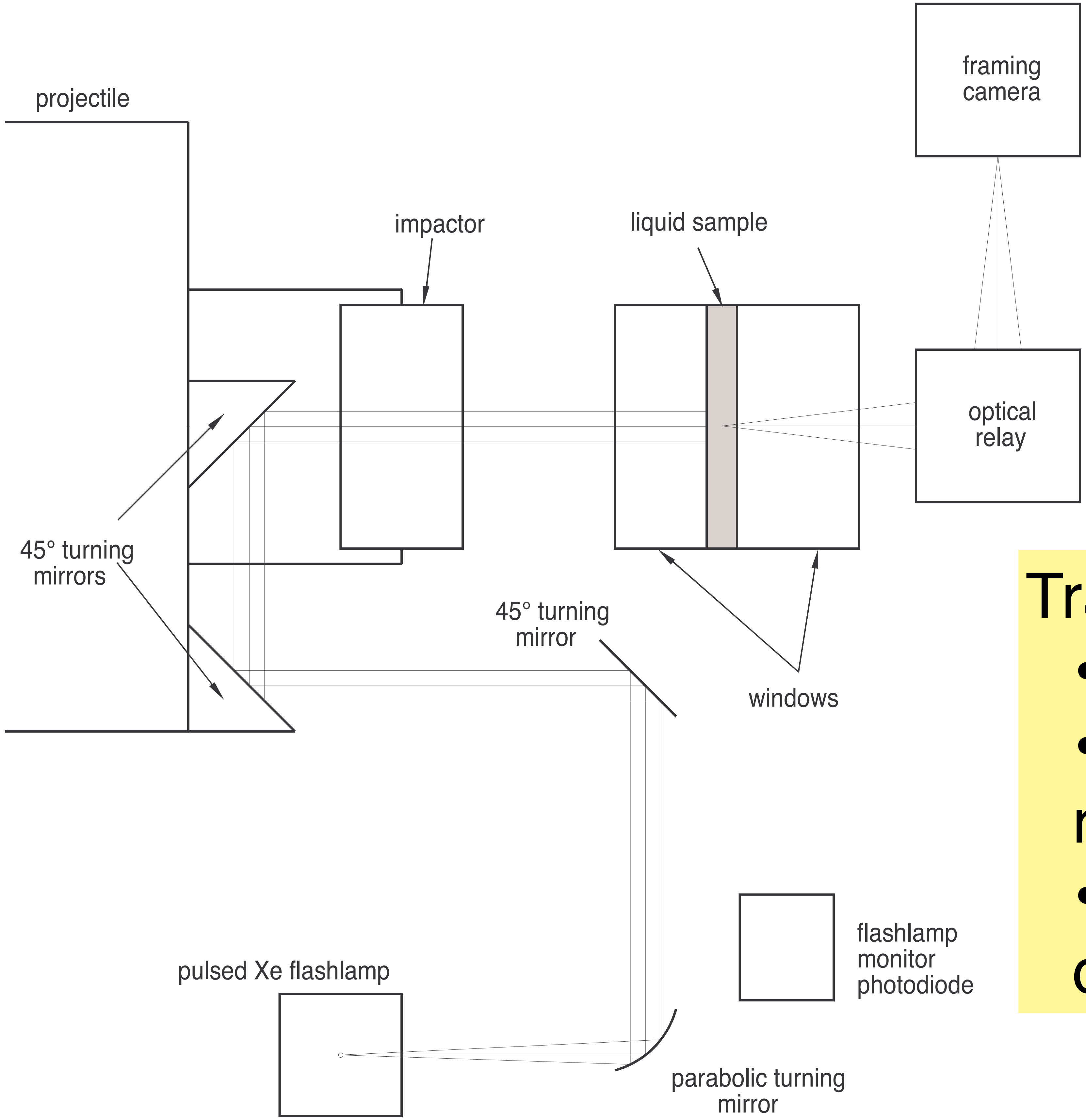


Optical transmission/imaging



- Water does not absorb visible (400-700 nm) light
- Liquid-solid coexistence leads to optical scattering
- Variables
    - Pressure
    - Sample thickness
    - Window material

Single pass transmission



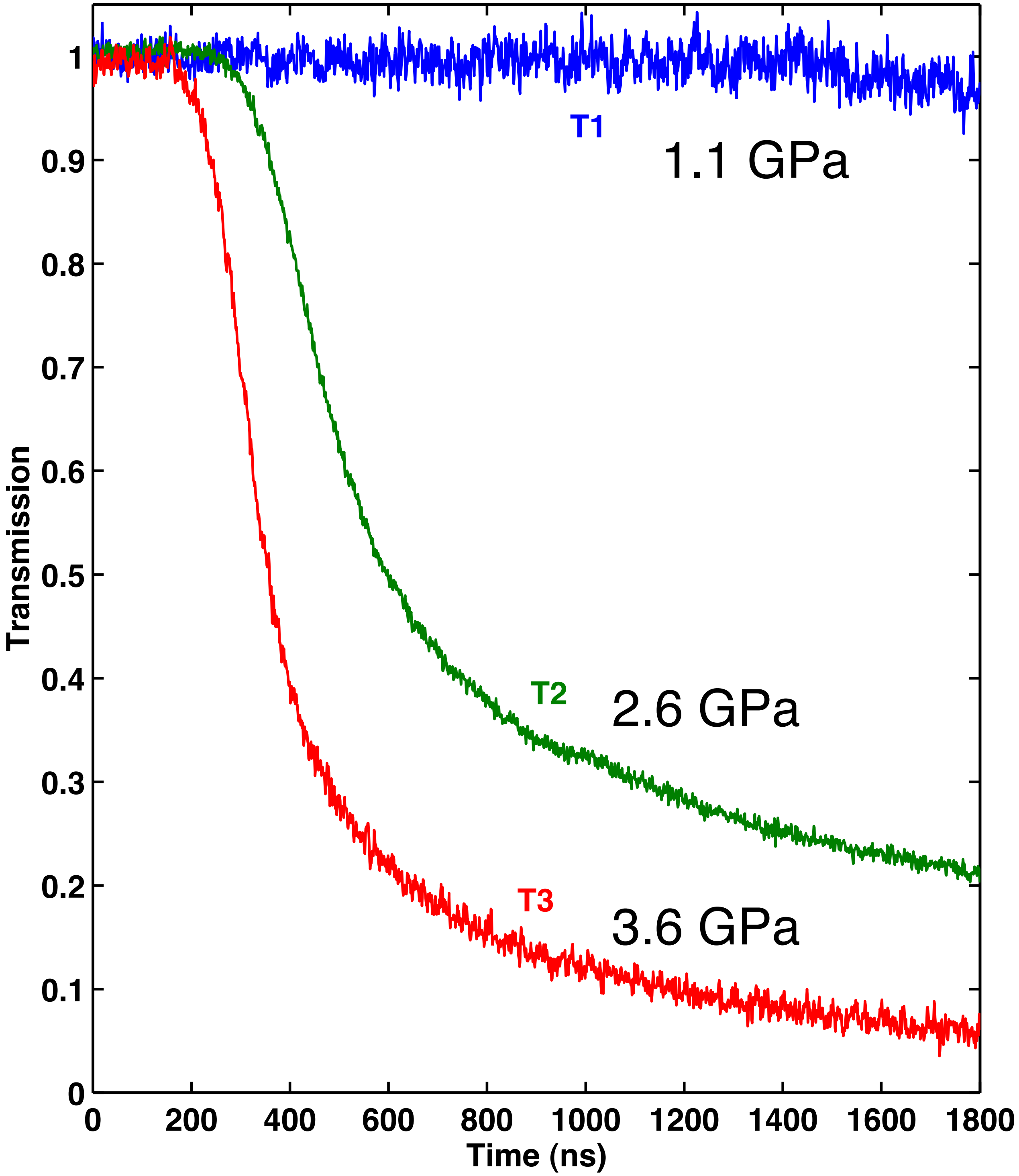
+ photodiode
+ spectrometer + streak camera

Transmission data:

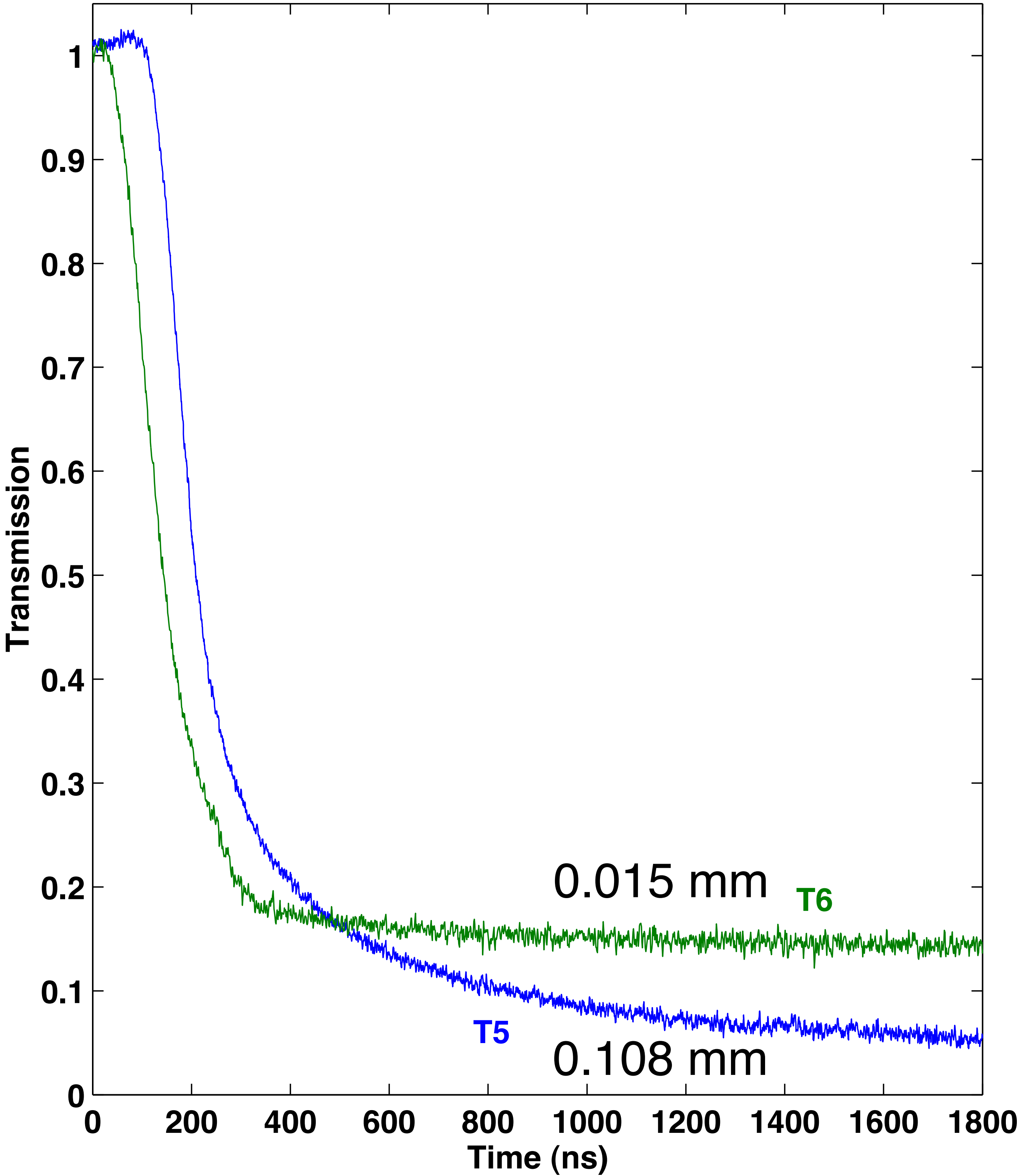
- Time resolved
- Time/wavelength resolved
- Spatially resolved at discrete times

Transmission results

Pressure effects (silica windows)



Thickness effects (quartz windows)



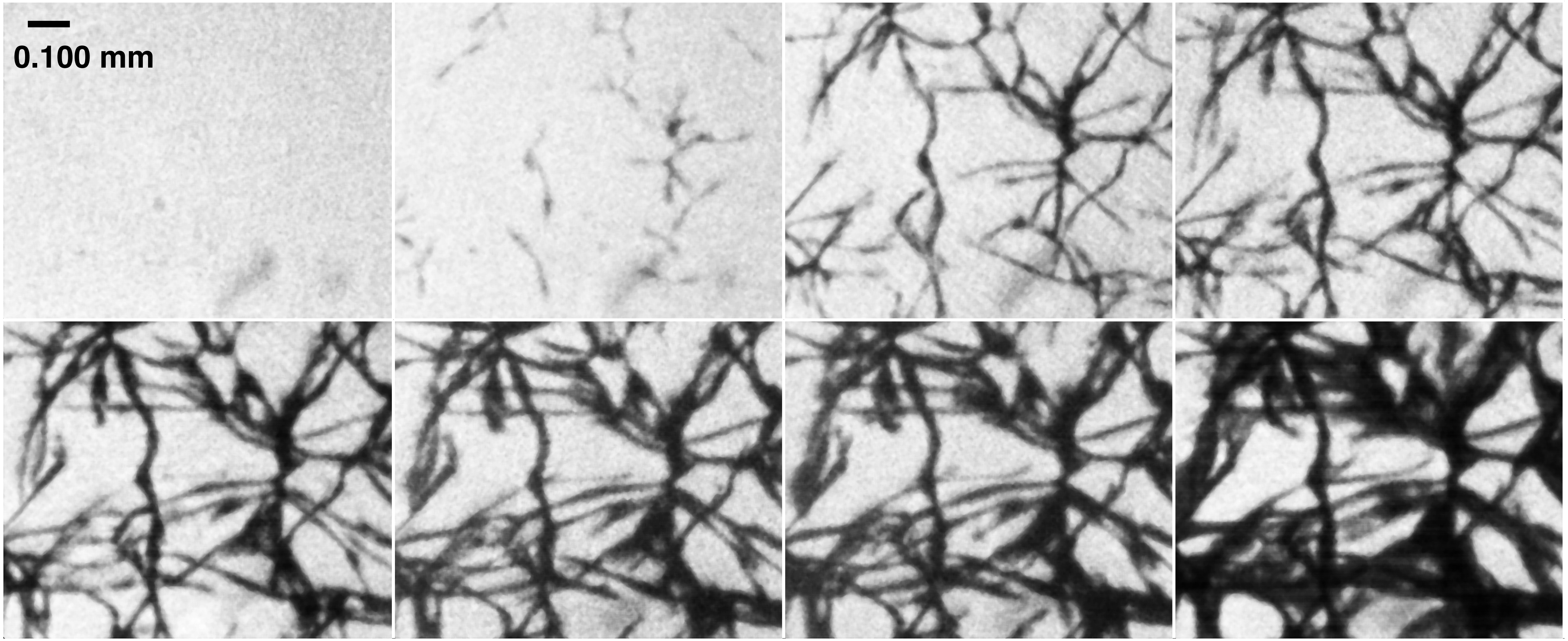
Imaging results

- **Multi-shock compression to 2.7 GPa in quartz windows**

t(ns) from shock arrival=

230	330	530	630
730	830	930	1530

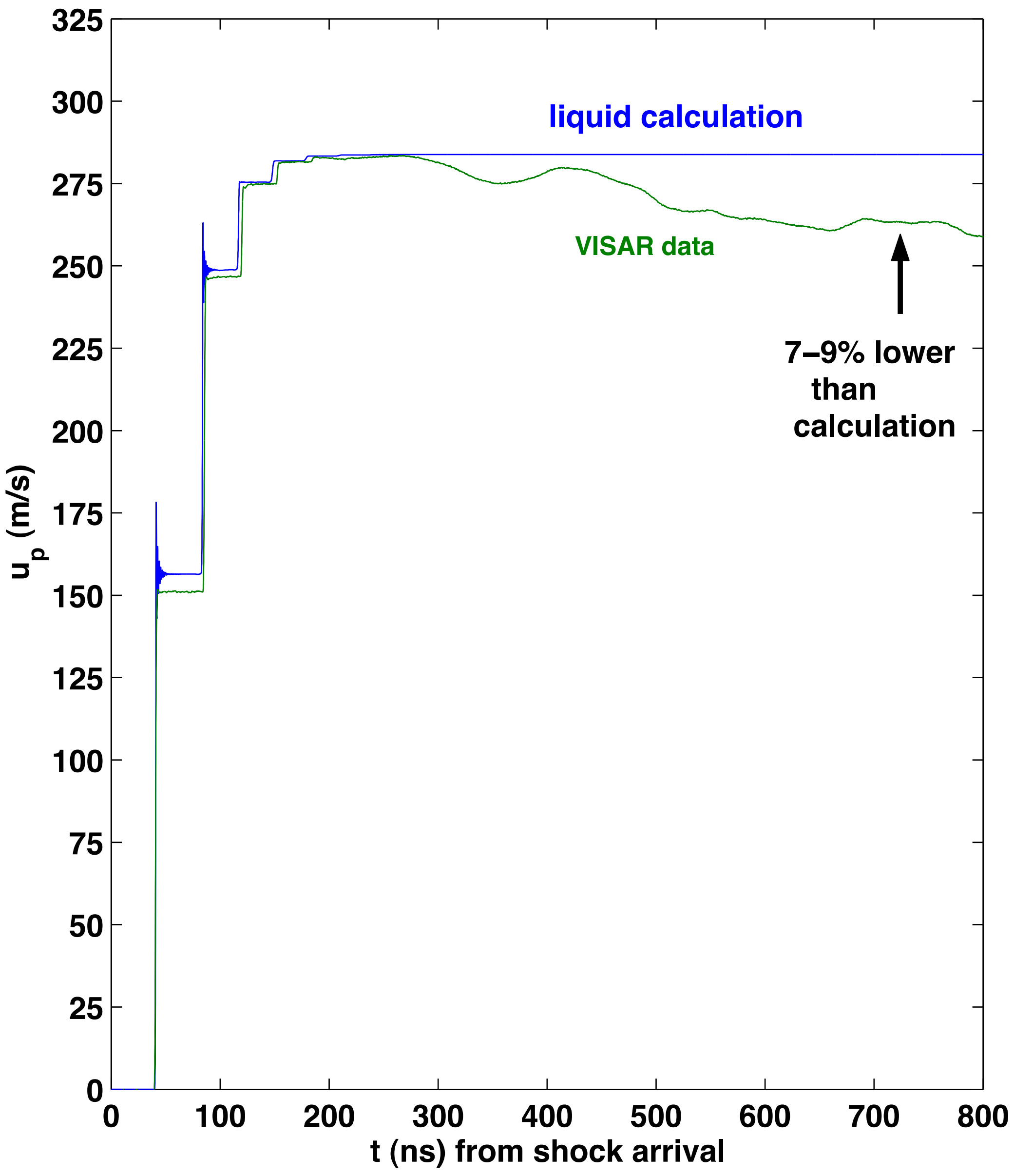
25 ns exposure



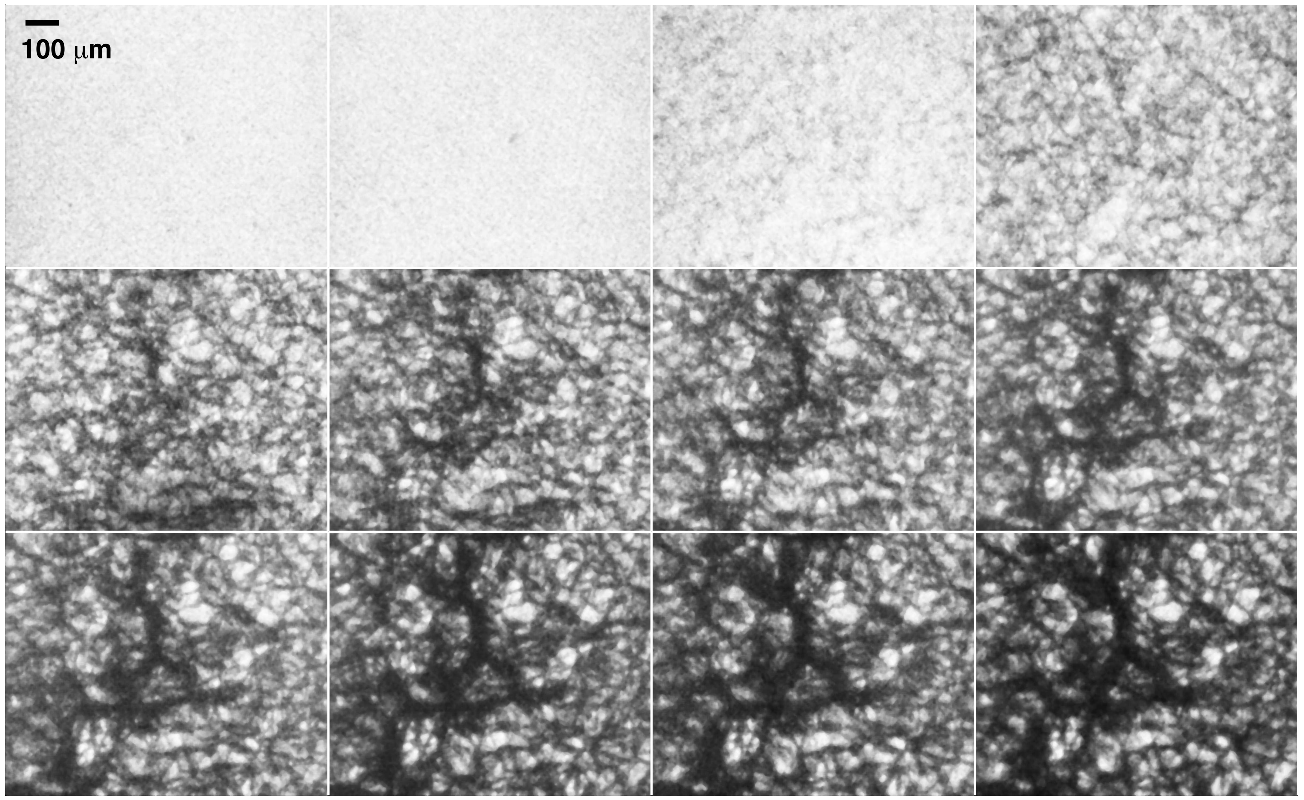
D.H. Dolan and Y.M. Gupta, J. Chem. Phys. **121**, 9050 (2004).

Velocimetry vs transmission

VISAR



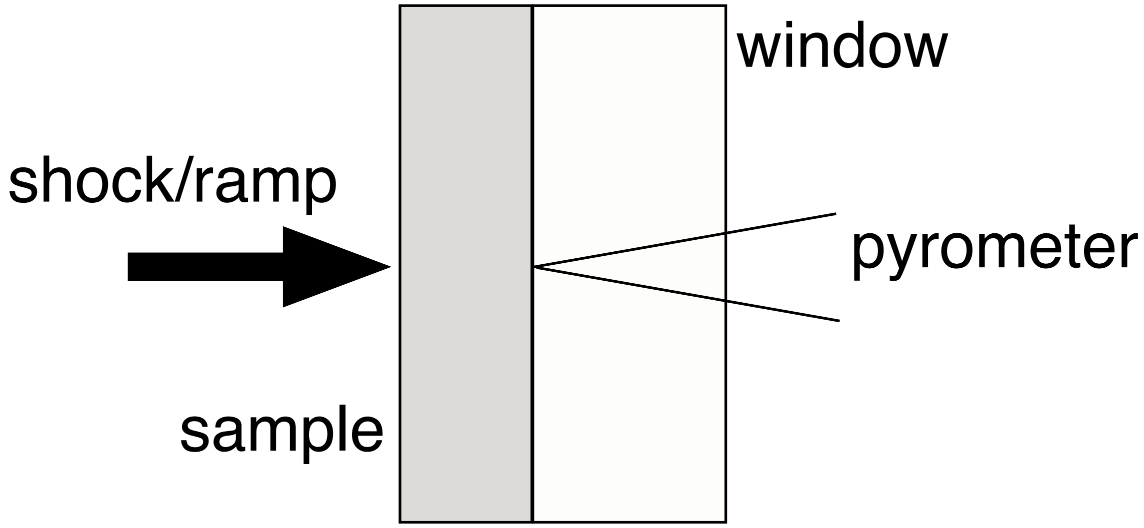
Transmission imaging



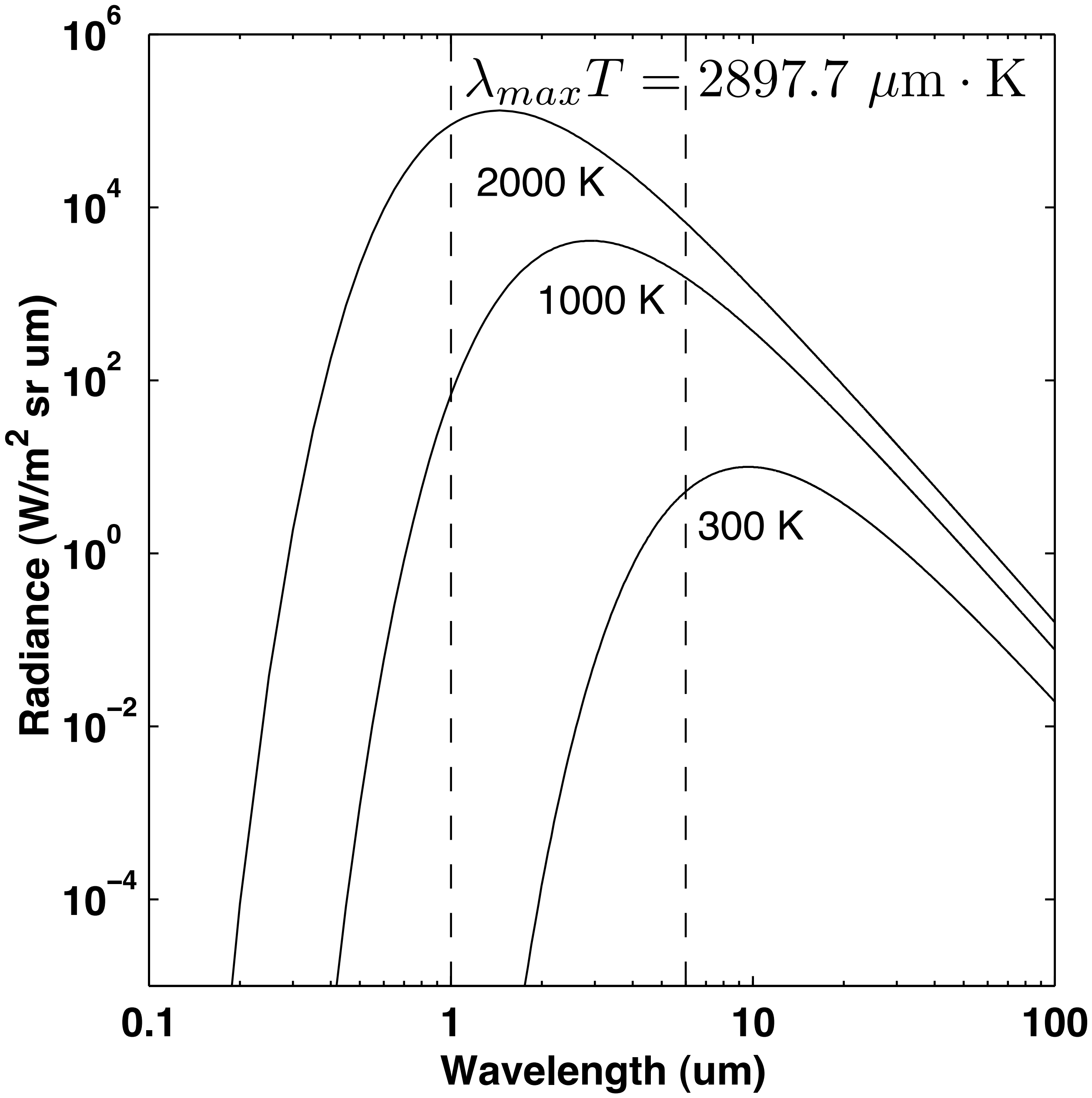
Water compressed to 5 GPa in quartz windows

- Velocimetry is more subtle, especially for very thin samples
- Imaging dramatically reveals the transition, but it's difficult to make quantitative comparisons

Emission spectroscopy



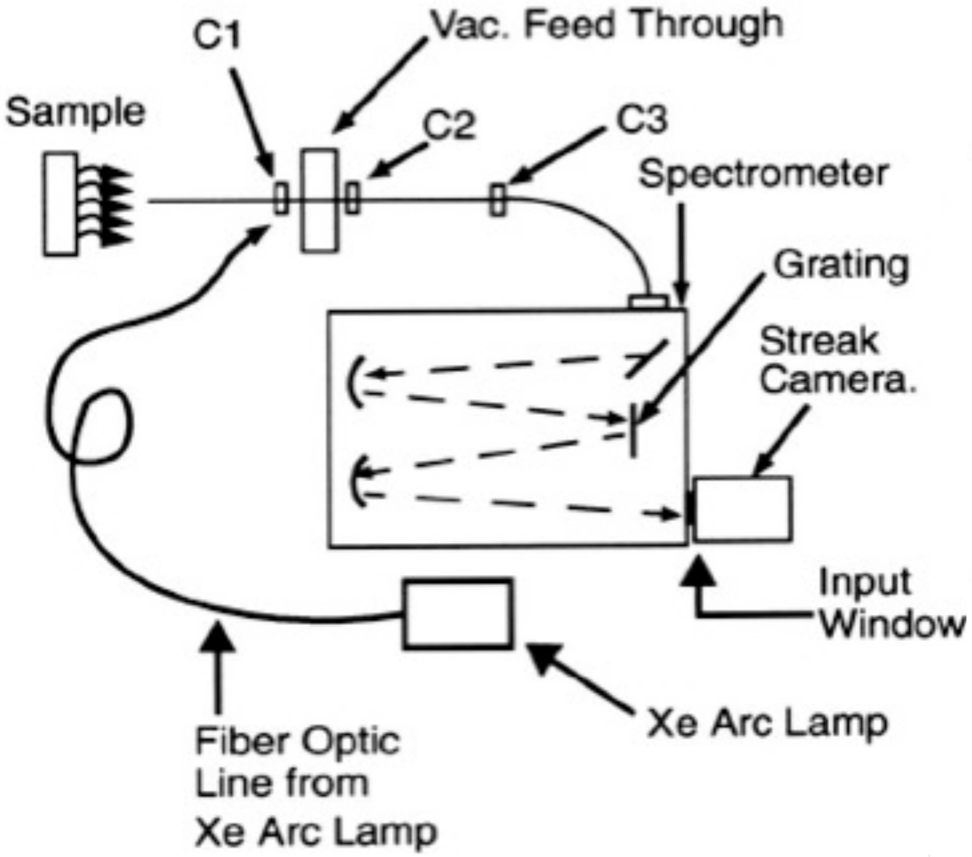
$$L = \frac{2hc^2}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)}$$

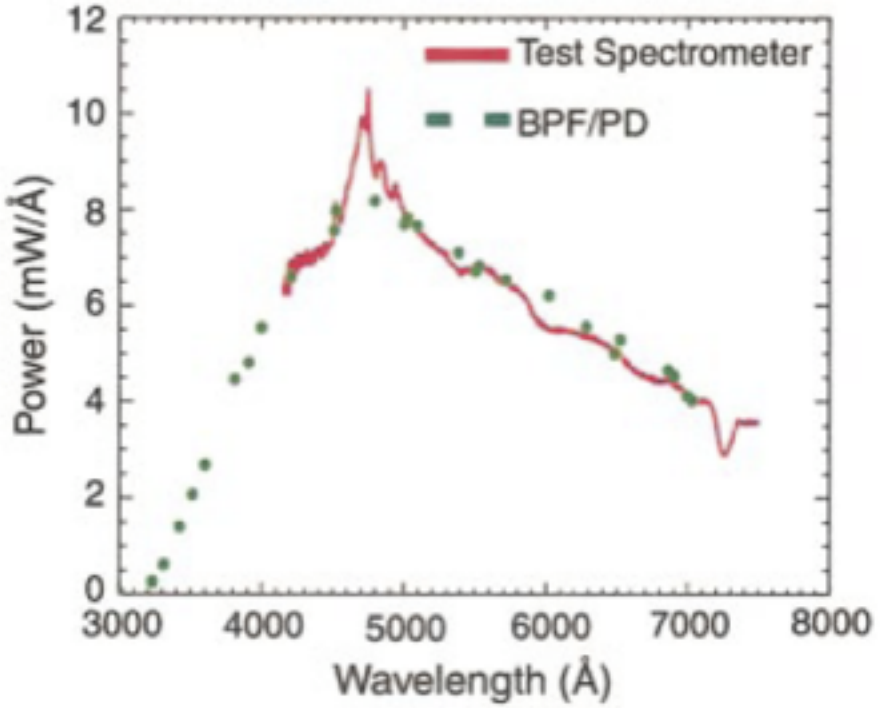


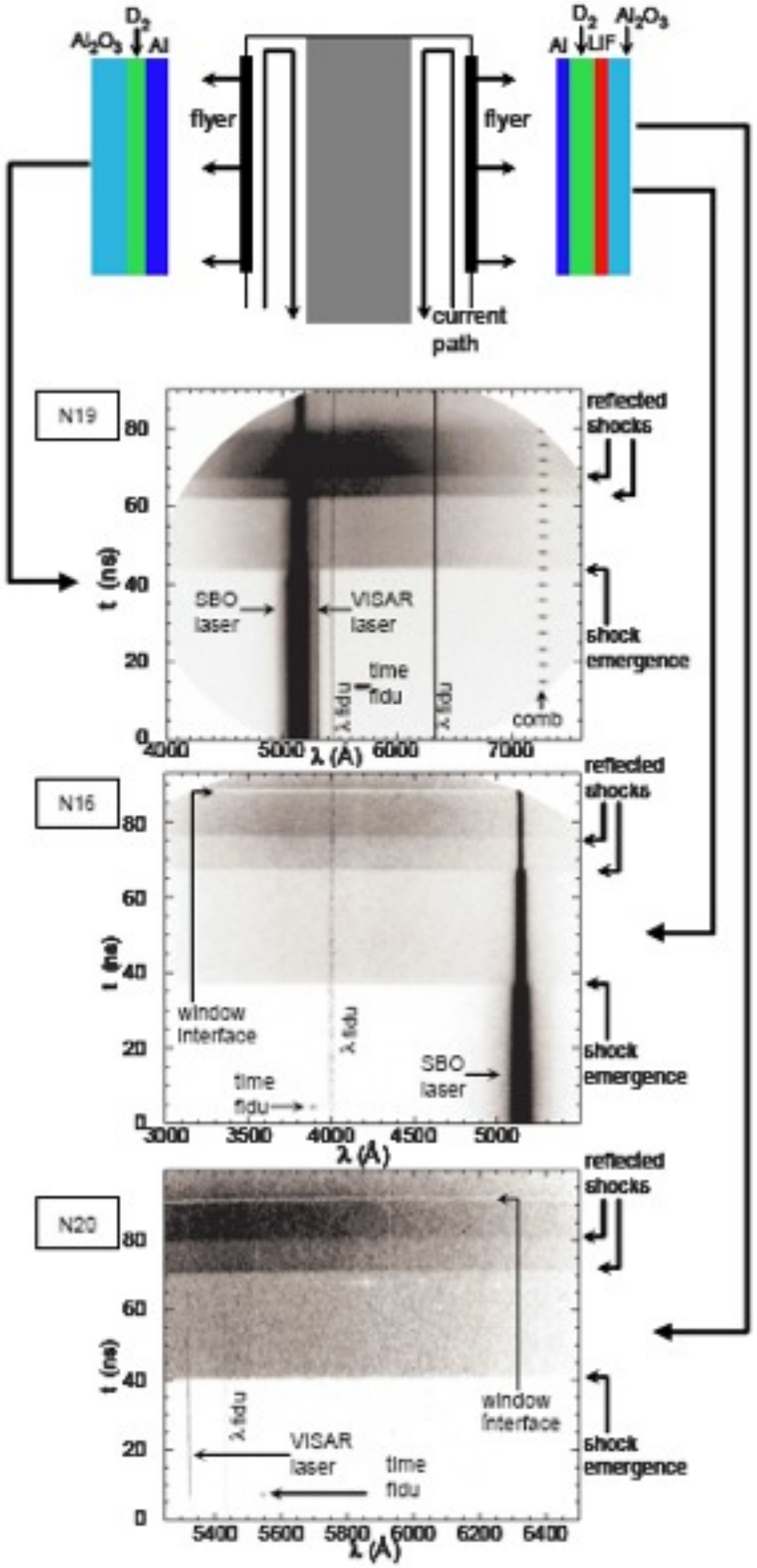
- Optical pyrometry
  - Sample temperature changes amount/distribution of radiance [power / area /solid angle/ wavelength]

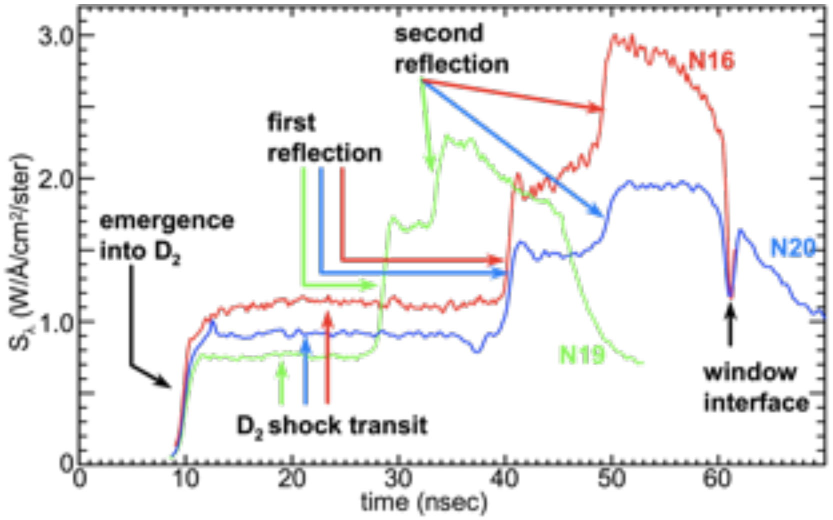
  - Challenging below 1000 K
    - Photon limited in the visible
    - Technically challenging in the infrared (>2000 nm)

Visible pyrometry available for much higher temperatures (0.5-2.5 eV)









- 2-3 spectrometer systems available at Z
- Spans the visible spectrum
- New calibration process under development

The emissivity problem

- Measurements depend on temperature AND emissivity
  - 0≤ emissivity ≤ 1
  - ~0.1 for metals (infrared)
- Emissivity changes with:
  - Temperature, pressure, phase
  - Surface geometry
- Without emissivity, only the minimum temperature is known
  - T uncertainty scales with emissivity uncertainty

The emissivity problem

$$L(\lambda, T) = \epsilon \times \left(\frac{2hc_0^2}{\lambda^5 \left(e^{hc_0/\lambda kT} - 1 \right)} \right)$$

$$\epsilon(\theta) = 1 - \rho(\theta; 2\pi) - \tau(\theta; 2\pi)$$

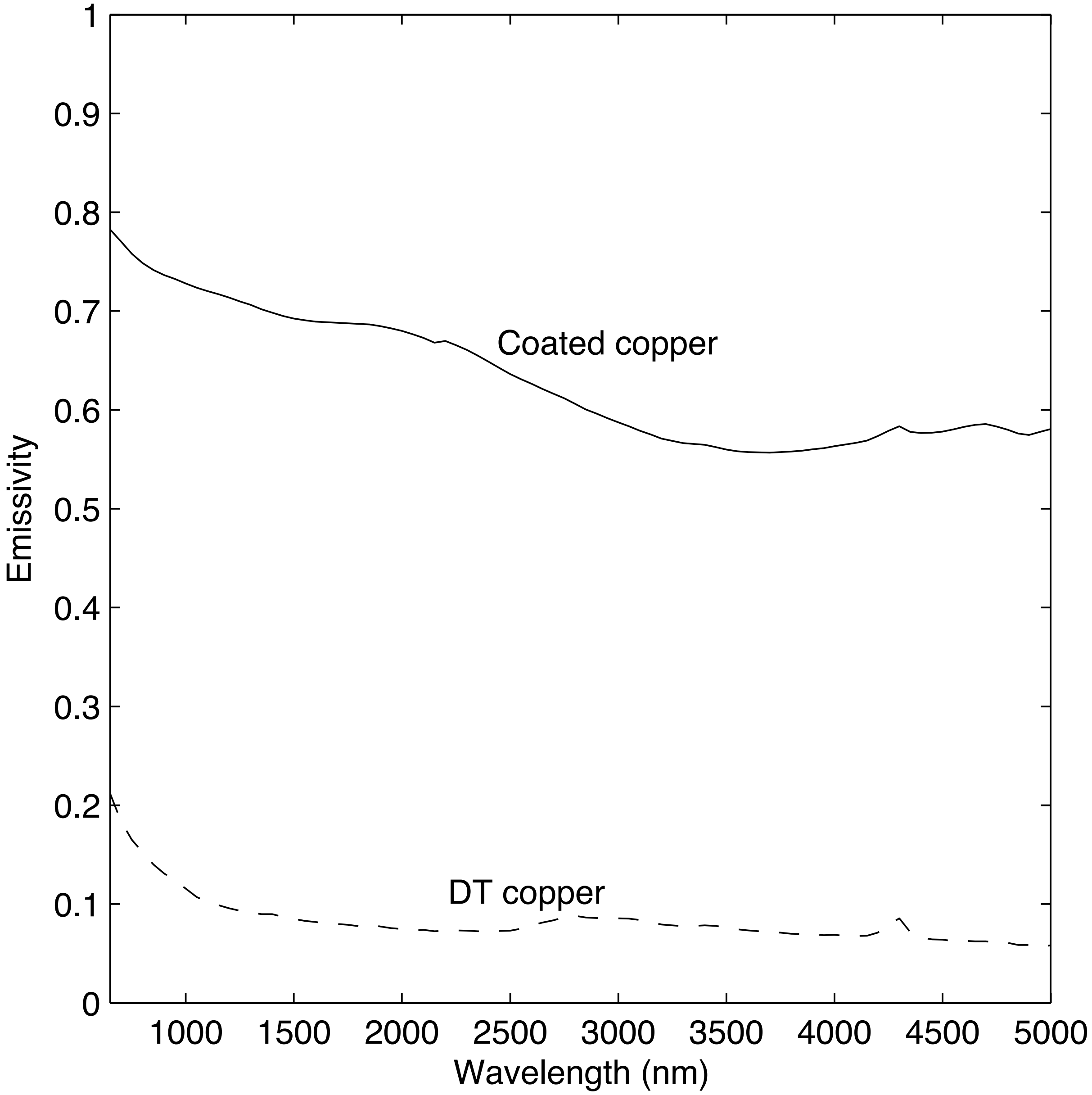
N measurements
N+1 unknowns

A solution or a dead end?

- Create emissivity standard for various (P,T) conditions
  - Thin for fast equilibrium
  - Opaque to hide substrate
  - Low reflectance is an added bonus

- We have been partially successful
  - Ambient emissivity well known
  - Moderate P shock experiments (NSLS) show no obvious failure
  - Doesn't solve other problems...

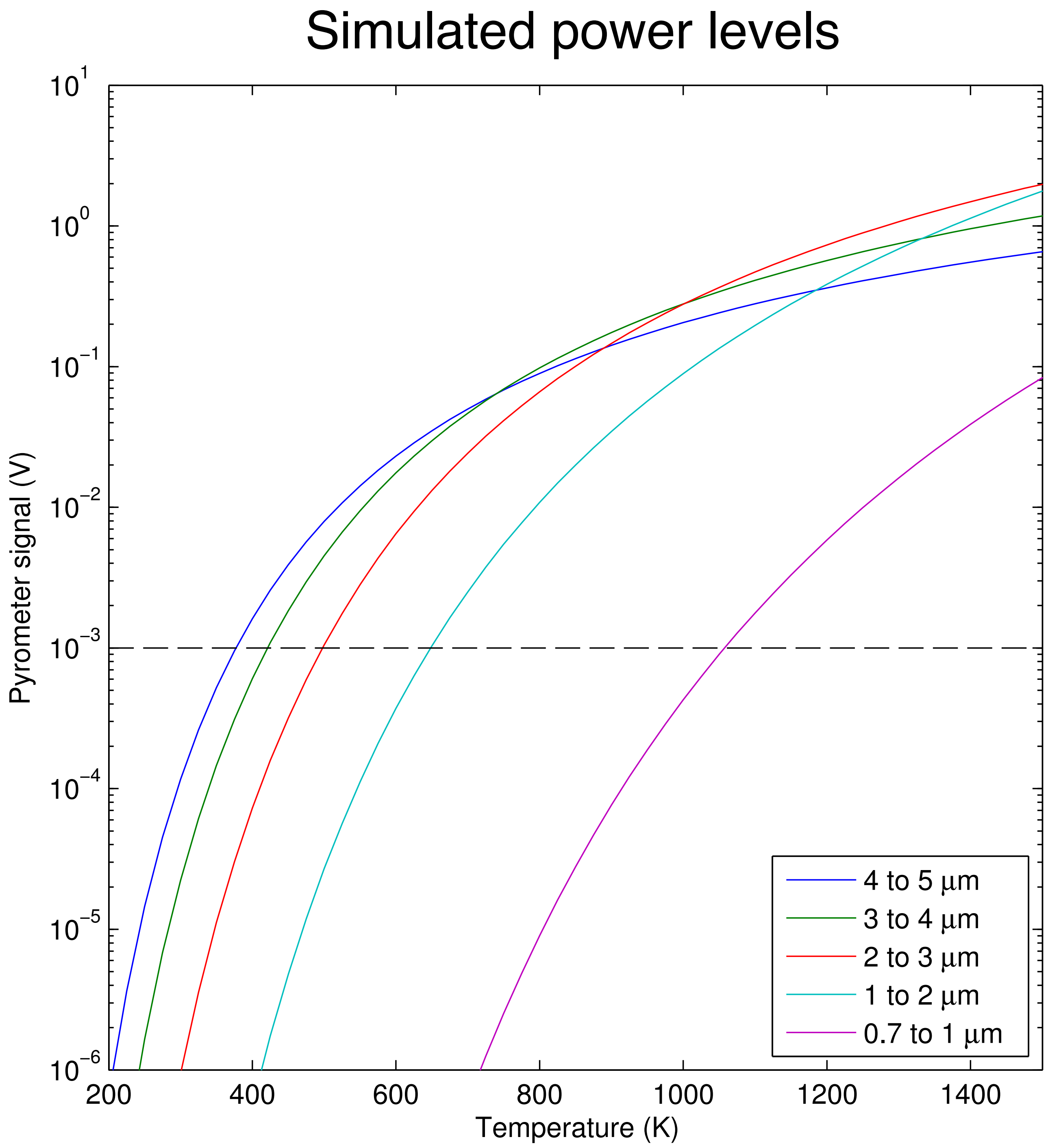
Sandia high emissivity coating (300 nm)



Is pyrometry viable below <1000 K?

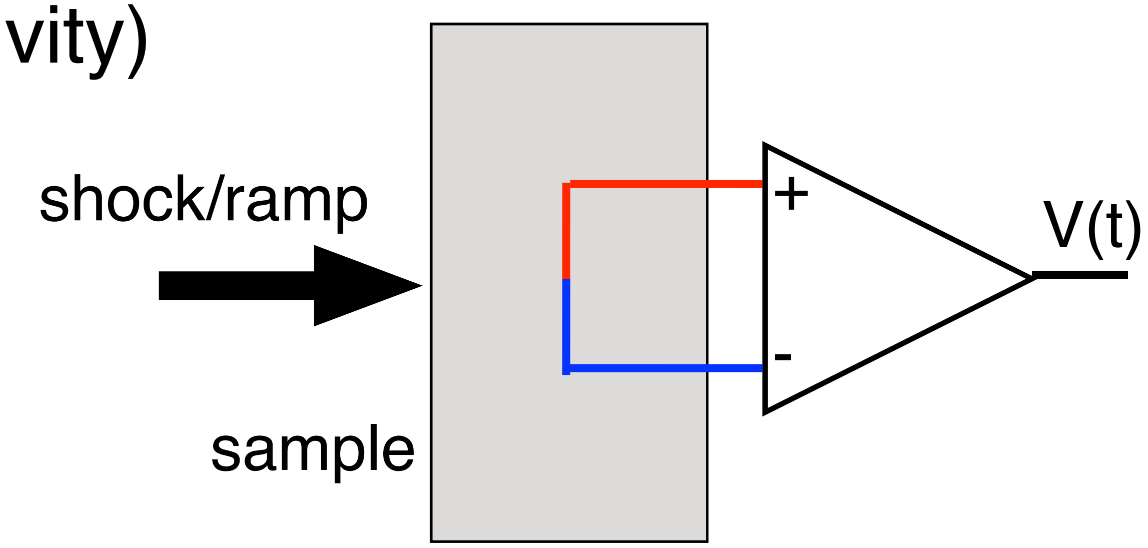
- Problems with pyrometry
  - Light levels are limited, even for a perfect black body
  - Mid-infrared detectors are slow
  - Optics are complicated (chromatic aberrations)
  - Fibers are expensive ($1000/m)

- Will this ever scale to multiple measurements on a platform such as Z?



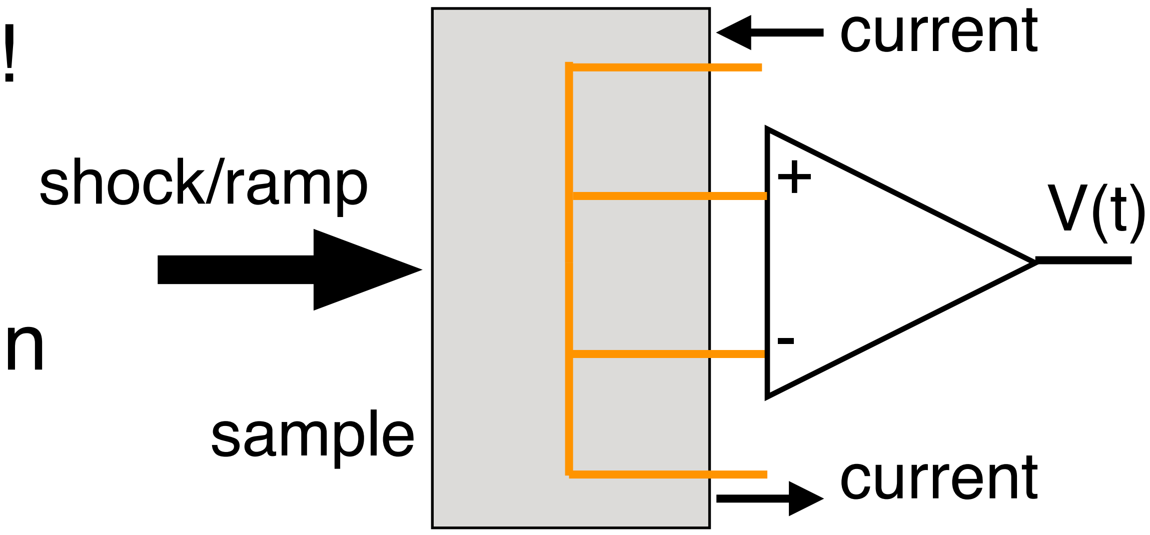
What about embedded gauges?

- Thermocouples/thermistors
  - Tied to material property (e.g., Cu resistivity)
  - Operate at modest temperatures
  - Difficult to use in metals
  - Thin (<25 um) connections are tricky to install and prone to failure



- Optical sensors avoid coupling issues
  - Not all techniques are viable
  - Example: ruby fluorescence is temperature sensitive, but the lifetime is milliseconds!

- Desirable features:
  - Thin (<1 um) for fast thermal equilibration
  - Visible operation, ns time resolution
  - Simple/reproducible fabrication
  - Compatible with optical velocimetry

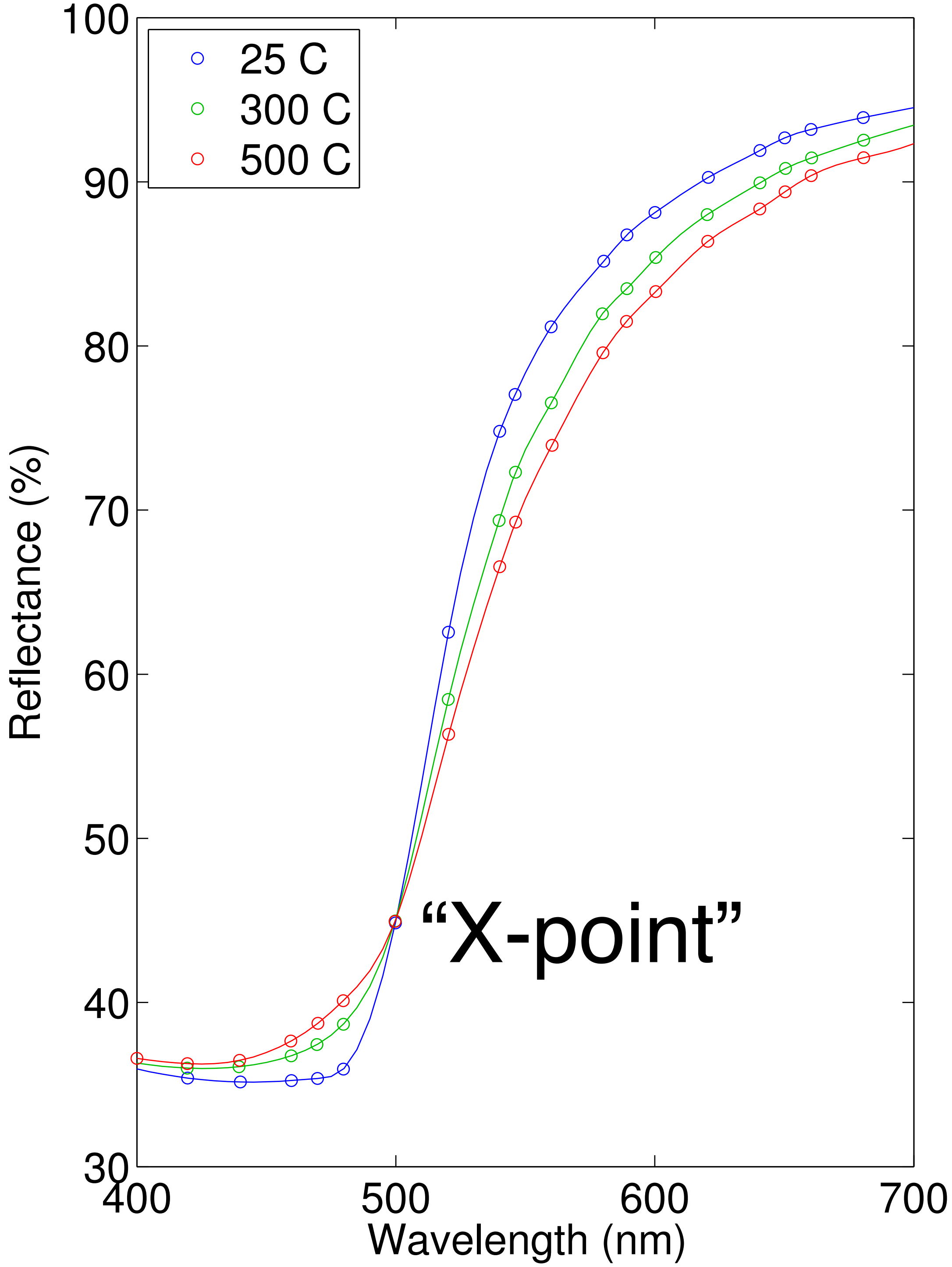


Gold reflectivity

- Gold reflects red light well and blue light poorly
  - This is why it looks yellow
  - VERY good reflectivity at 1550 nm (PDV)

- The reflectivity curve is known to vary with temperature
  - Blue reflectivity increases
  - Red reflectivity decreases

- Local changes are small, but the overall shape change is noticeable
  - This effect could serve as an optical thermometer
  - Absolute uncertainty estimated to be ±15-20 K, perhaps less

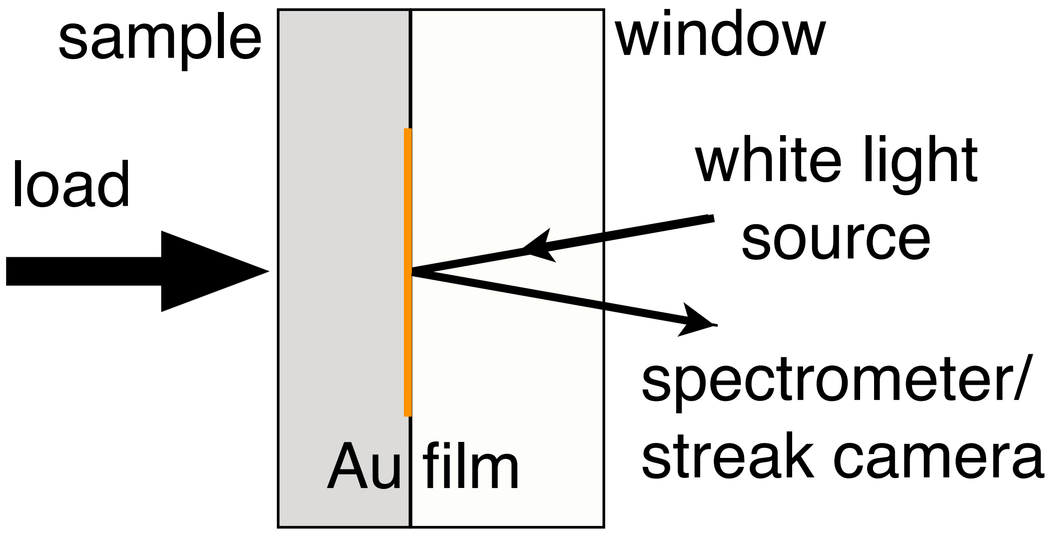


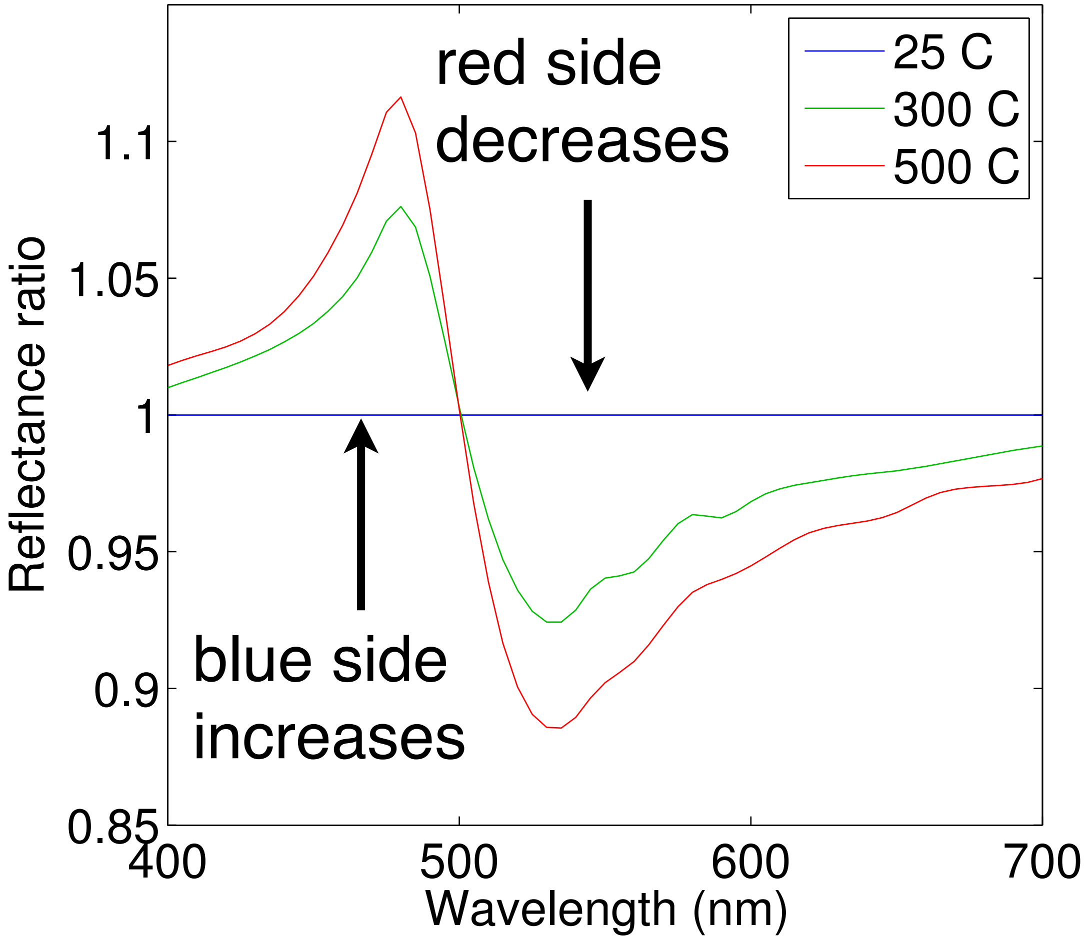
Dynamic reflectivity measurements

- Deposit 300 nm of gold onto the optical window
  - Equilibration time is ~1 ns
  - Sensor is completely opaque

- Illuminate the Au with a bright, white light source
- Measure the specular reflection (near-normal)

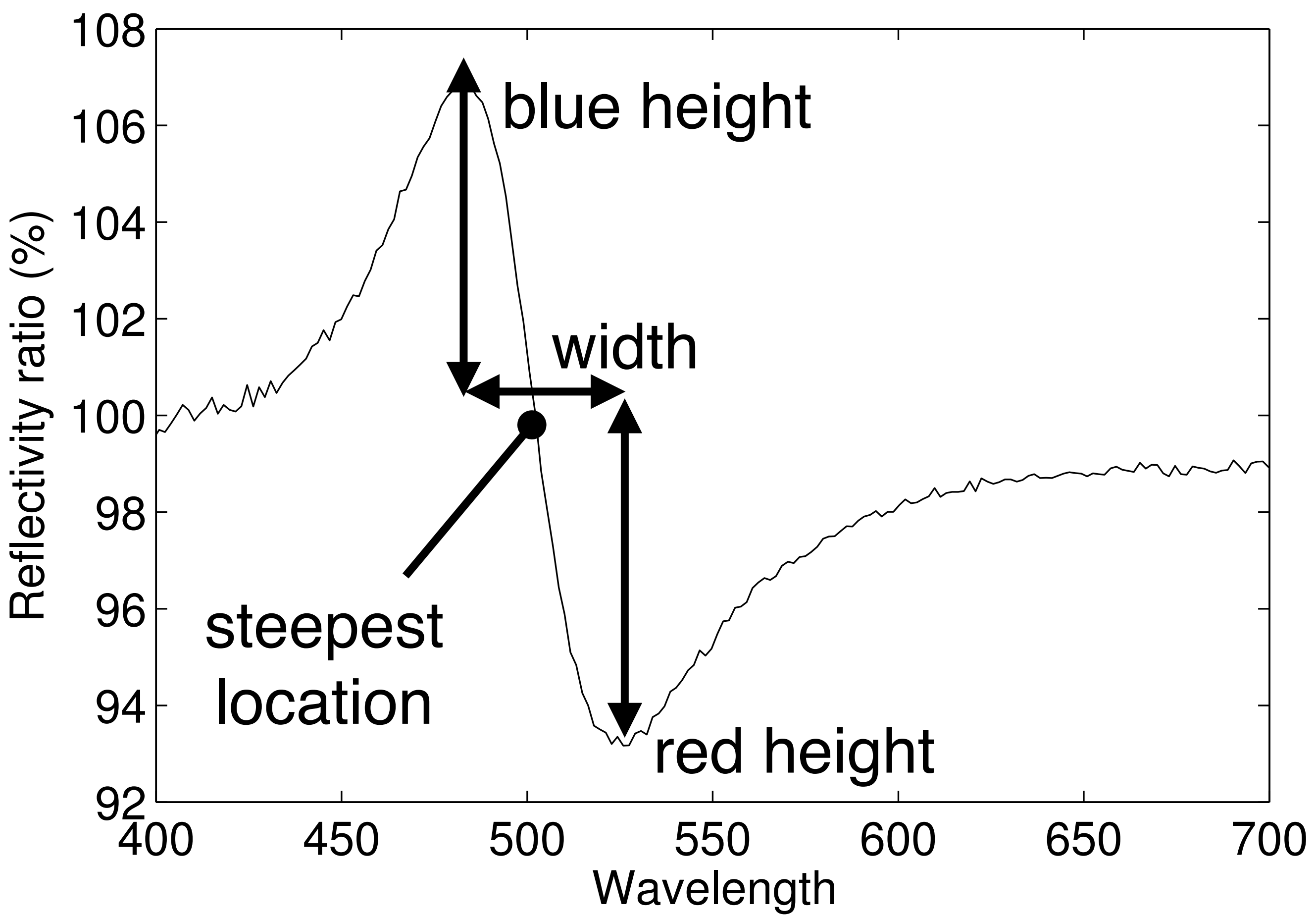
- Compare the dynamic state to the ambient
  - Reflectance ratio avoids the need for absolute system calibration
  - Peak/trough changes ~2% for each 100 K

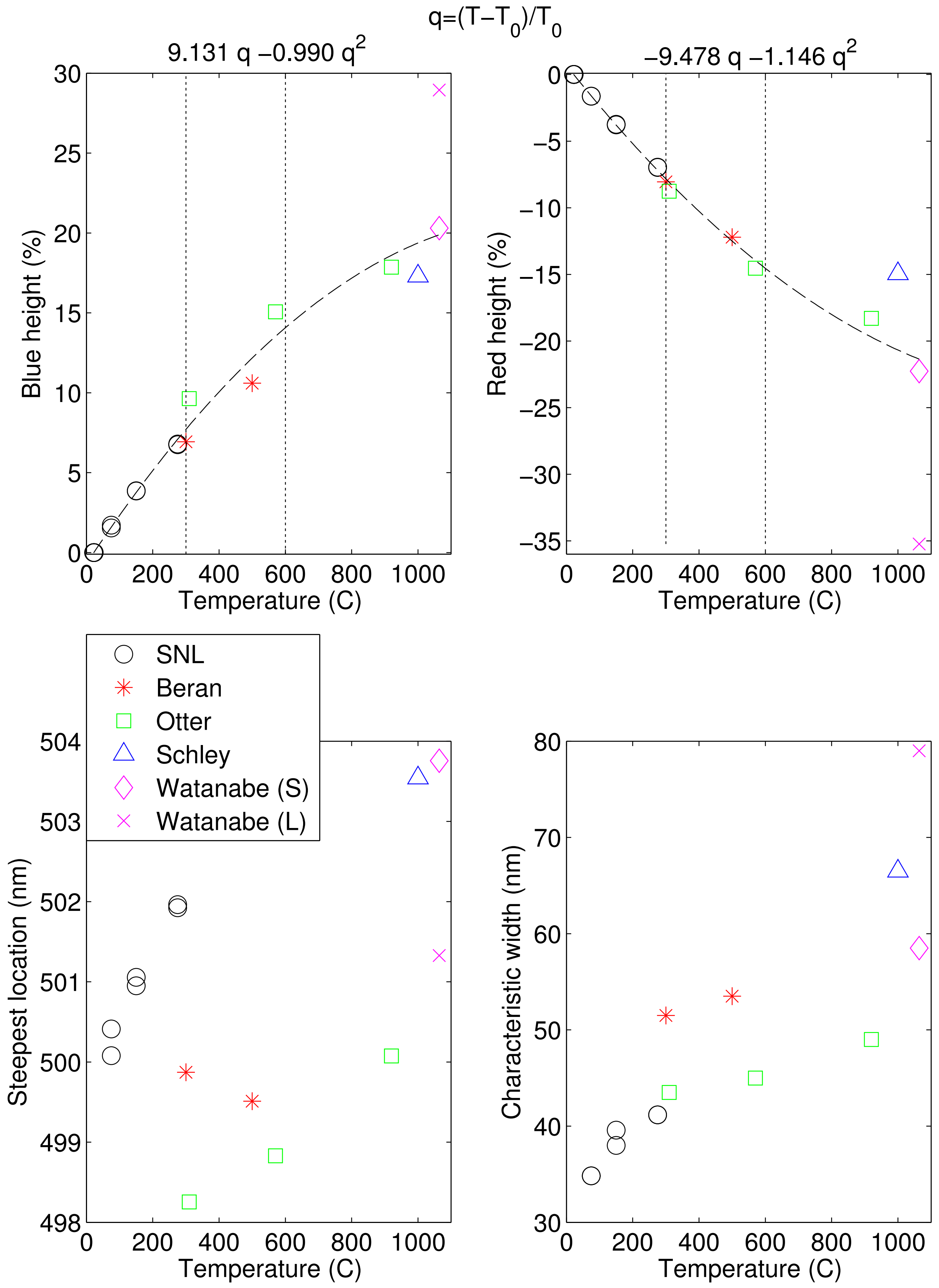




P=0 temperature trends

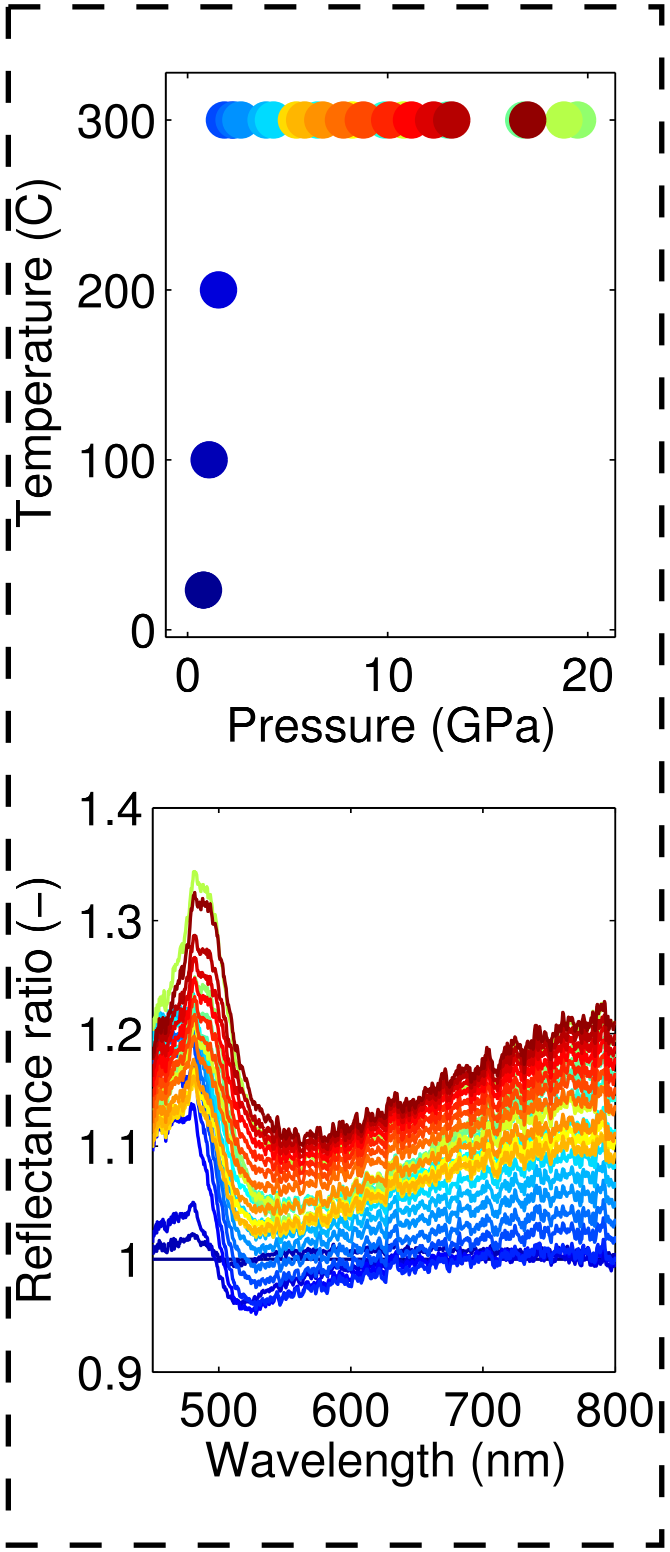
- Ratio spectrum attributes
  - Steepest location
  - Blue/red height
  - Characteristic width

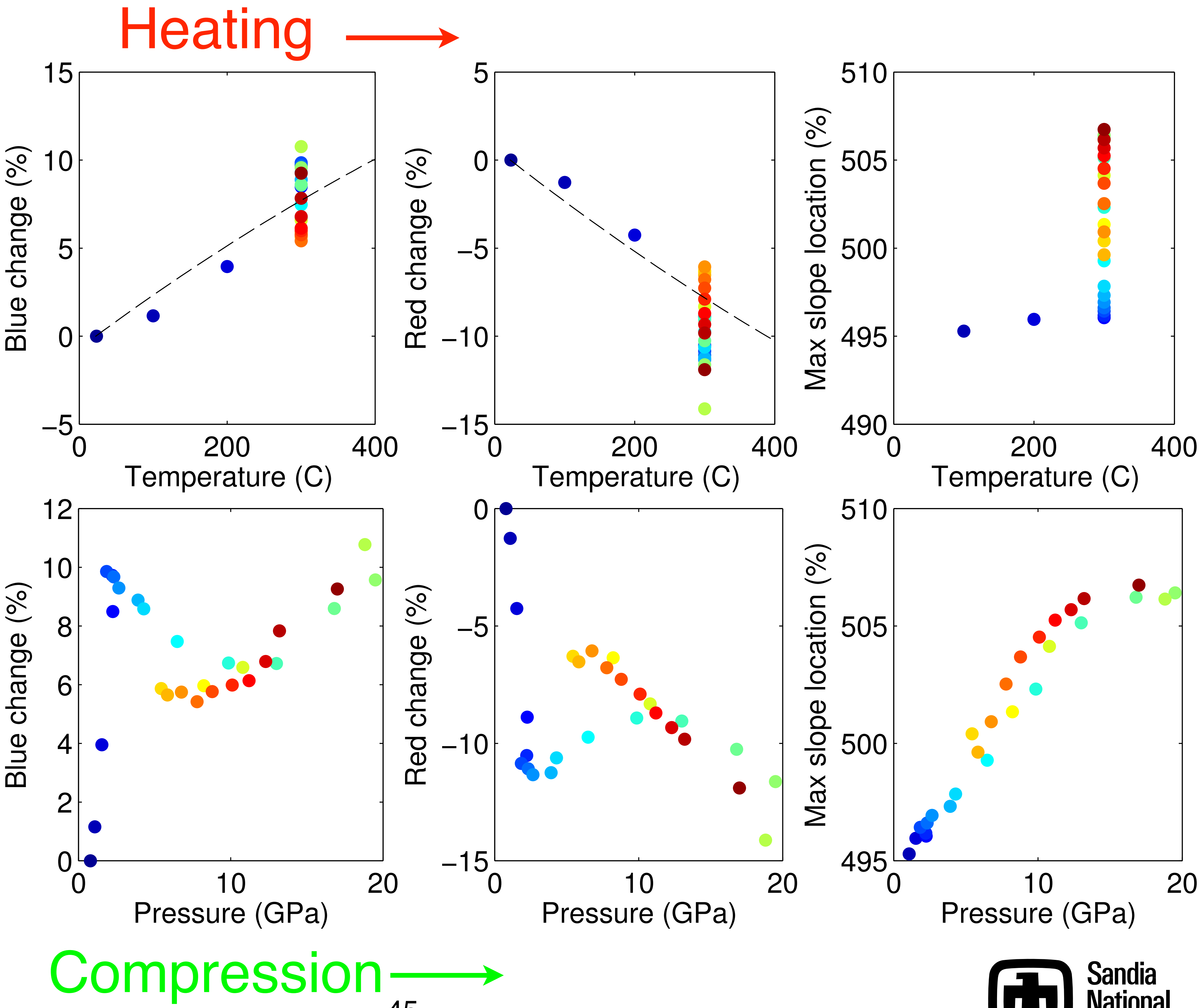




Height trends persist to the melt point!

P>0 characterization (static)





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Thermoreflectance challenges

- Pressure effects
  - DAC measurements indicate reduced blue/red peaks AND a shift in the steepest location
  - Dynamic calibration underway

- Window effects
  - Refractive index >1
    - Model dielectric function (Drude + interband) with temperature and density of gold

- Thermal diffusion in the mechanical bond (glue)
  - Initial experiments place gold in direct contact with sample (direct impact or liquid samples)
  - Metallic bonding (sample-Au-Au-window) under development

Summary

- Optical diagnostics provide a wealth of information
  - Velocimetry (PDV)
    - Mechanical state (pressure, density)
    - Mature, widely used diagnostic
  - Transmission/imaging
    - Phase transition onset and progress
    - Mature but material specific diagnostic
  - Pyrometry and reflectance thermometry
    - Thermal state (equation of state and phase boundaries)
    - Potentially universal, but a lot of work remains
- There are many other options...

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