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Title: Application of Photonic Doppler Velocimetry (PDV) to Shock and Detonation Physics Experiments

Author(s): R. Gustavsen, D. Dattelbaum, S. Sheffield, B. Bartram, D. Stahl, L. Gibson, N. Sanchez, D. Hooks

Intended for: Time Resolved Diagnostics Short Course: Measurements of Behavior at High Strain-Rates
February 16 - 18, 2011
Institute of Shock Physics
Imperial College, London, UK (via teleconference)

Los Alamos
NATIONAL LABORATORY
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APPLICATION OF PHOTONIC DOPPLER VELOCIMETRY (PDV) TO SHOCK AND DETONATION PHYSICS EXPERIMENTS

R. Gustavsen, D. Dattelbaum, S. Sheffield, B. Bartram, D. Stahl, L. Gibson, N. Sanchez, D. Hooks
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The Photonic Doppler Velocimeter (PDV) is a single mode fiber and fiber-laser based interferometer that has found a wide range of applications in shock and detonation physics. This lecture will review interferometer construction, its use to measure flyer plate velocity, shock velocity, and the particle velocity of surfaces. Additional topics include measurement of detonation wave profiles, measurement of profiles from multiple samples, and analysis of signals.

(Draft) Application of Photonic Doppler Velocimetry (PDV) to Shock and Detonation Physics Experiments

Time Resolved Diagnostics Short Course: Measurements of Behavior at High Strain-rates

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R.L. Gustavsen, Shock & Detonation Physics Group, LANL
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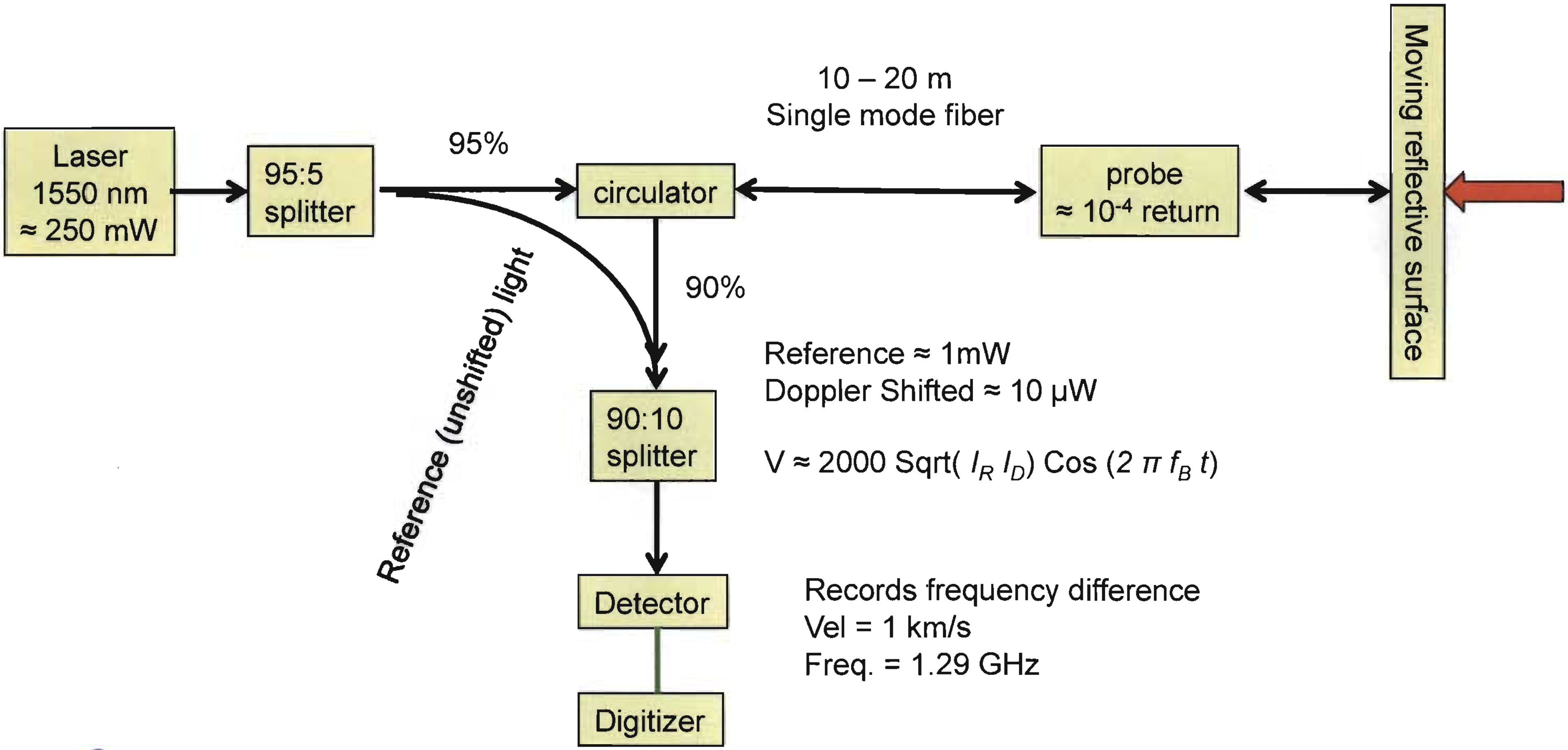
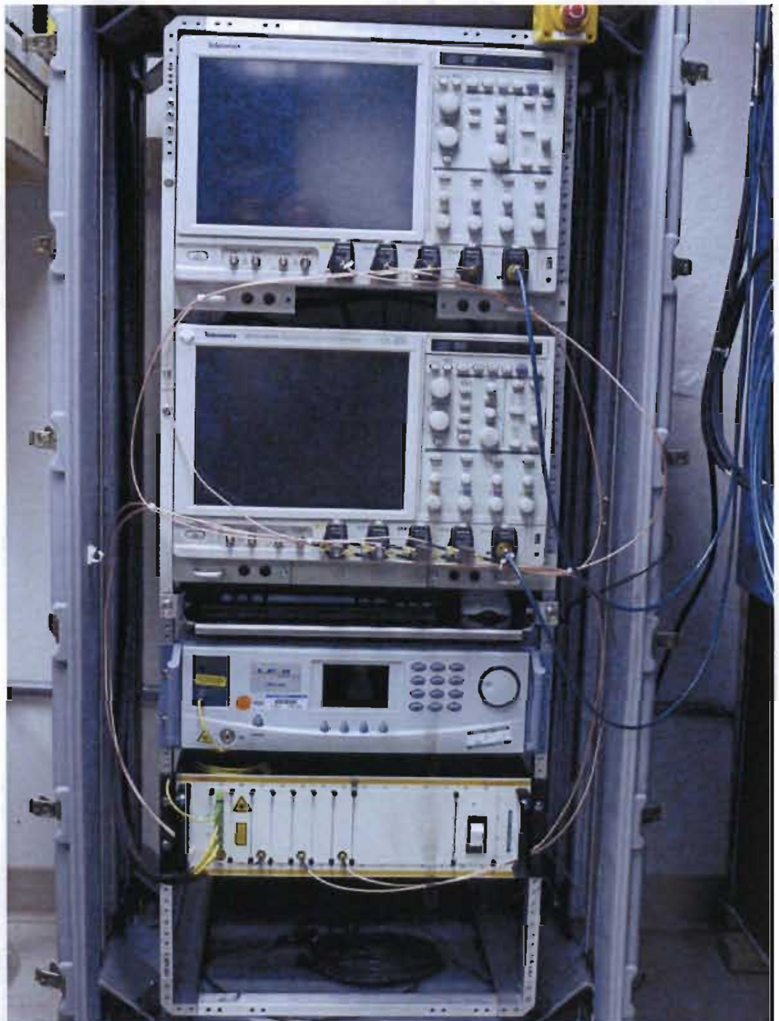
Part 1 – the PDV interferometer

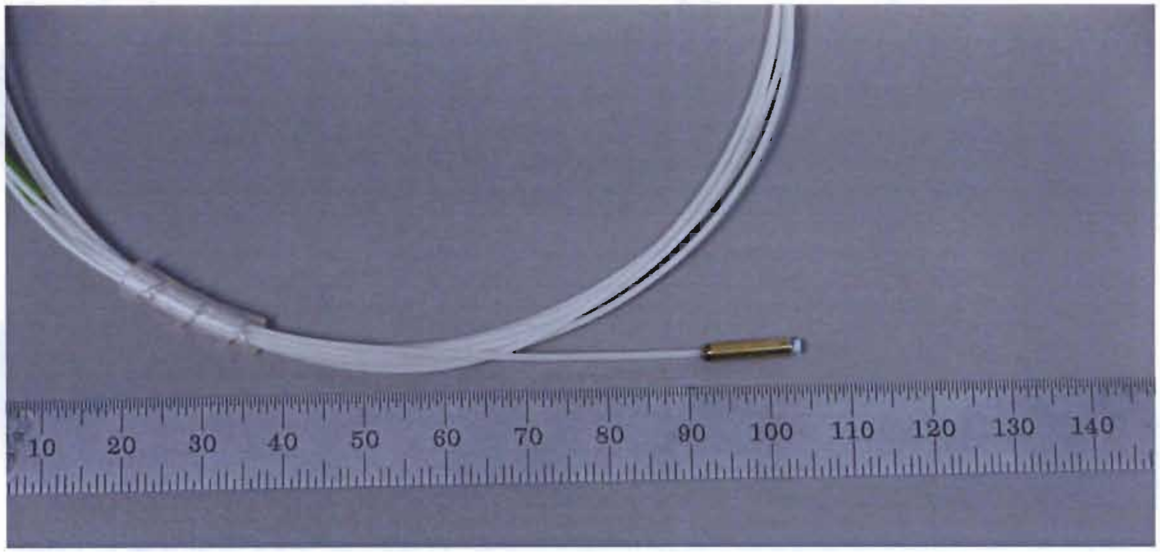
The PDV interferometer



PDV setup in Lab



Typical Probe



Typical Component, Cost, Manufacturer, etc.

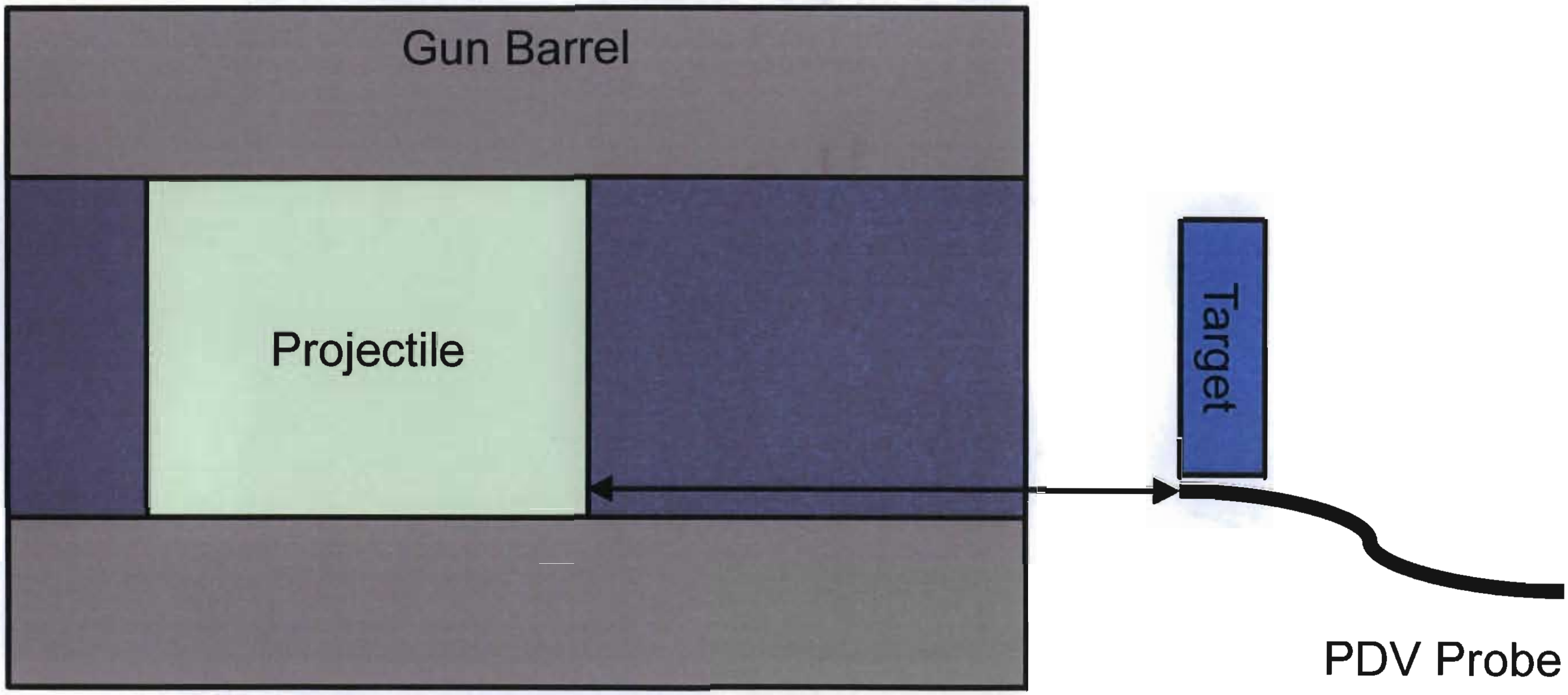
- **Digitizer - $60K (4 channels)**
  - Tektronix, DPO70604 (6 GHz → 4.65 km/s)
- **Laser - $19K (2 Watt)**
  - IPG Photonics, ELR-2-1550-SF
- **Detector - $1675 each**
  - Miteq, DR-125G-MV-FA (30 kHz - 13 GHz, internal power monitor)
- **Circulators, polarization insensitive - $330 each**
  - AC Photonics, PIOC315P2111
- **1 x 4 splitters - $170 each**
  - AC Photonics, SP15AV0104B2011

Typical Component, Cost, Manufacturer, etc.

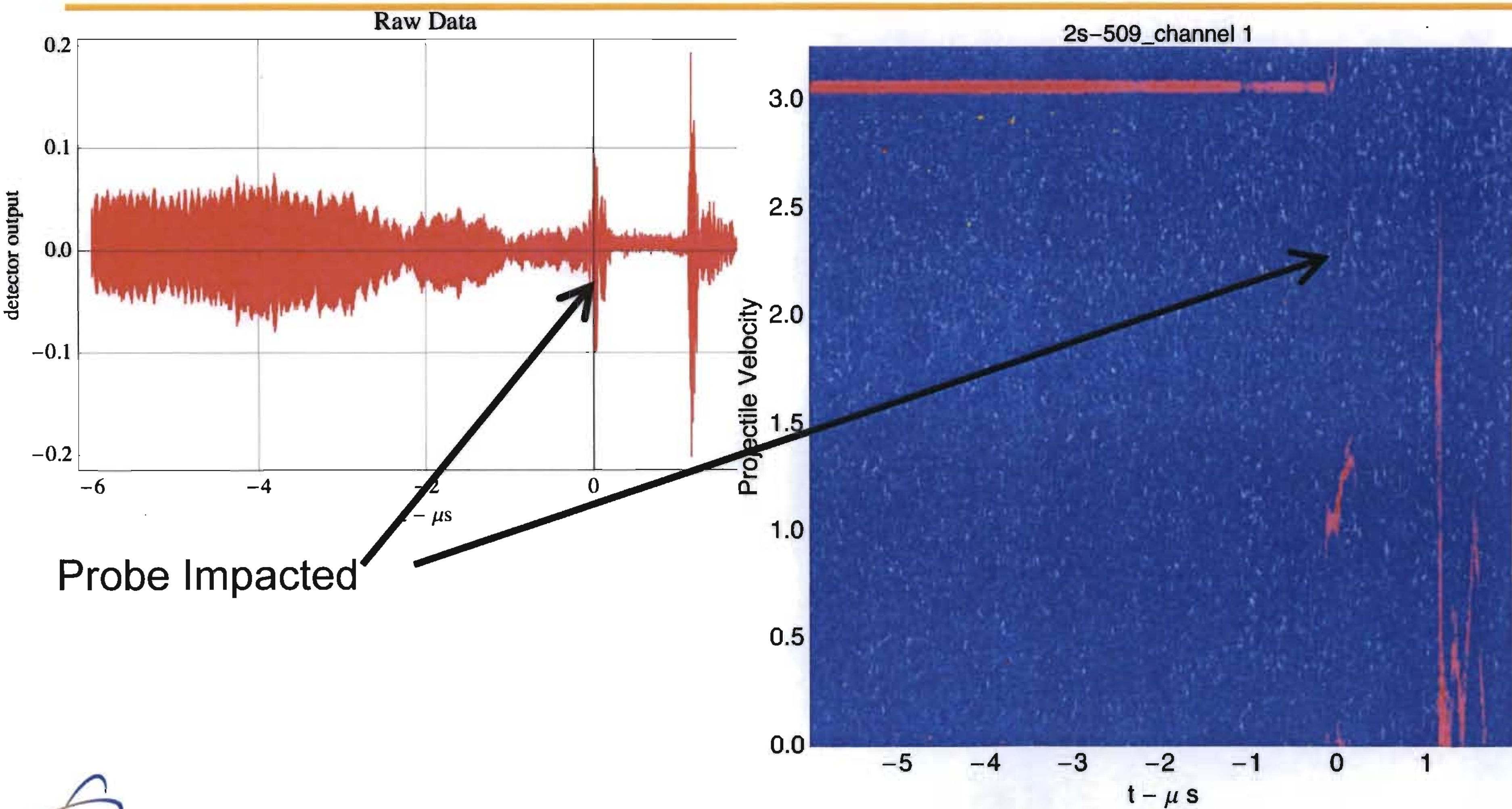
- **1 x 2 splitters - $75 each**
  - AC Photonics, SP15100102B2011
- **Connectors – FC/APC (angled physical contact)**
  - 3M, 8206FCAPC (reportedly the best
- **High Frequency Coax cable (SMA male – SMA male) - $15 each**
  - Thorlabs, CA2936
- **Misc. fiber optic components (jumpers, unions, fiber cleaners, etc.)**
  - Fiber Instrument Sales
- **Probes (disposable!) $23 - $40 each**
  - AC Photonics, 1CL15P020LCC01

Part II - Basic Applications

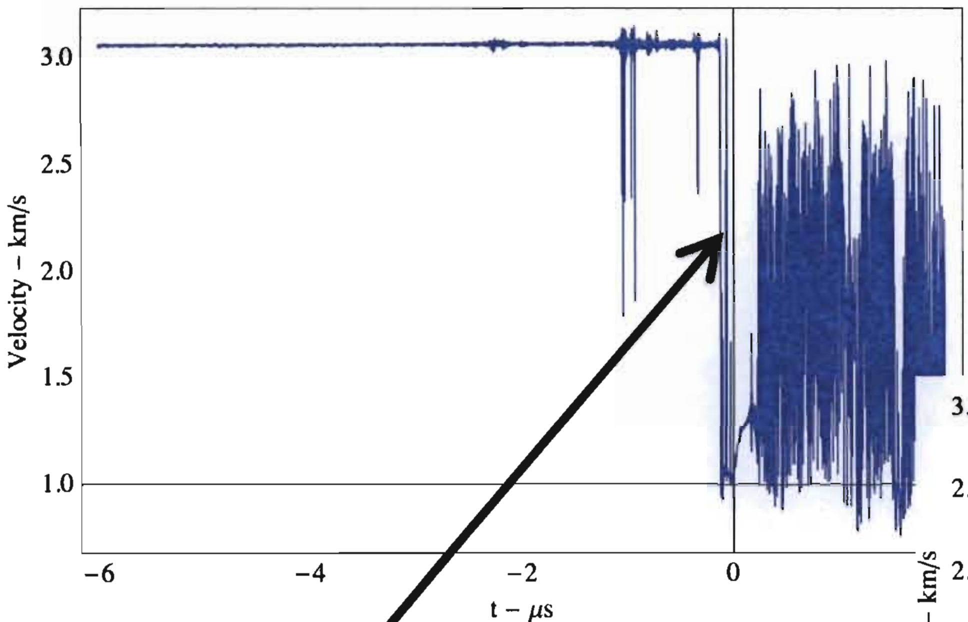
Projectile velocity (1 probe)



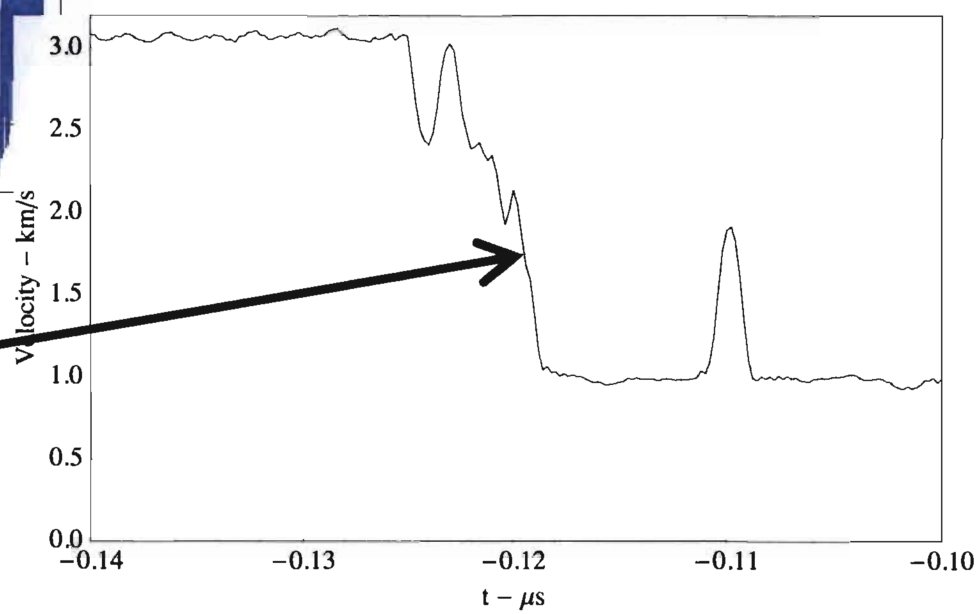
Projectile velocity PDV data



Projectile velocity PDV data (2)



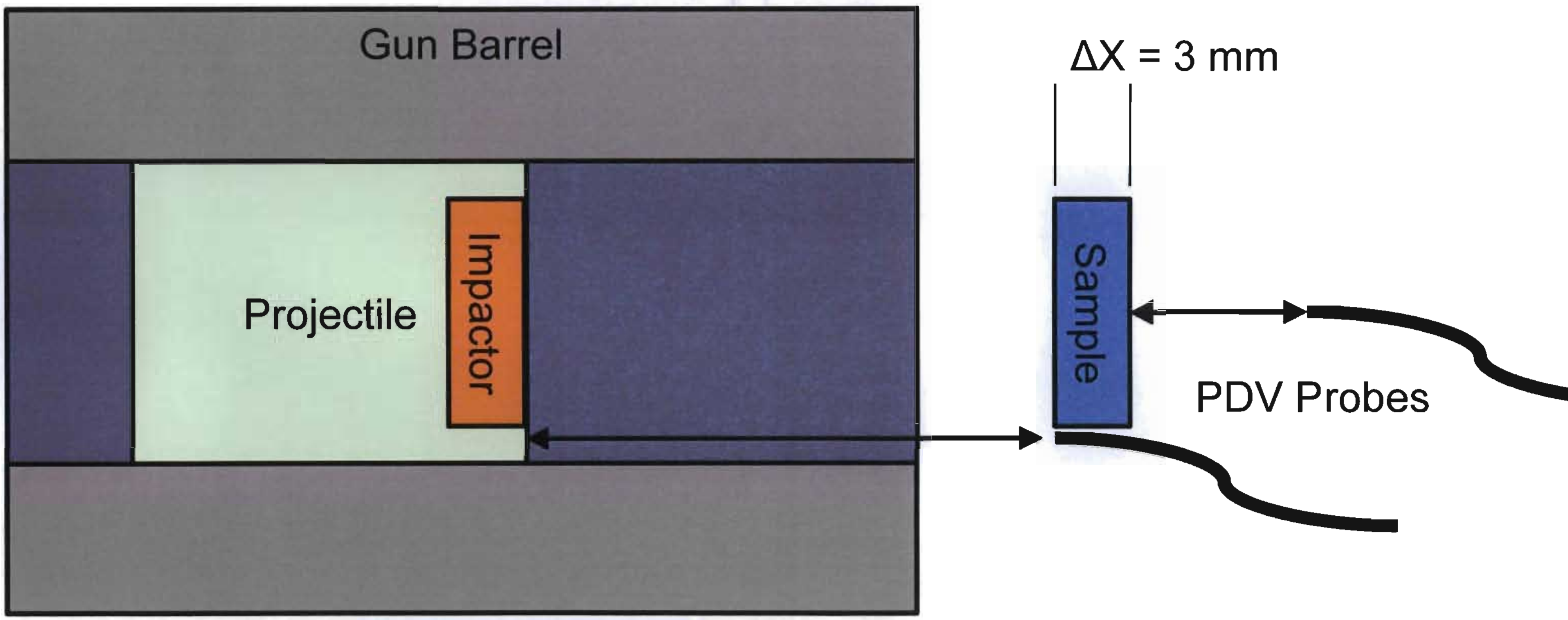
Vel. = 3.064 ± 0.003 km/s



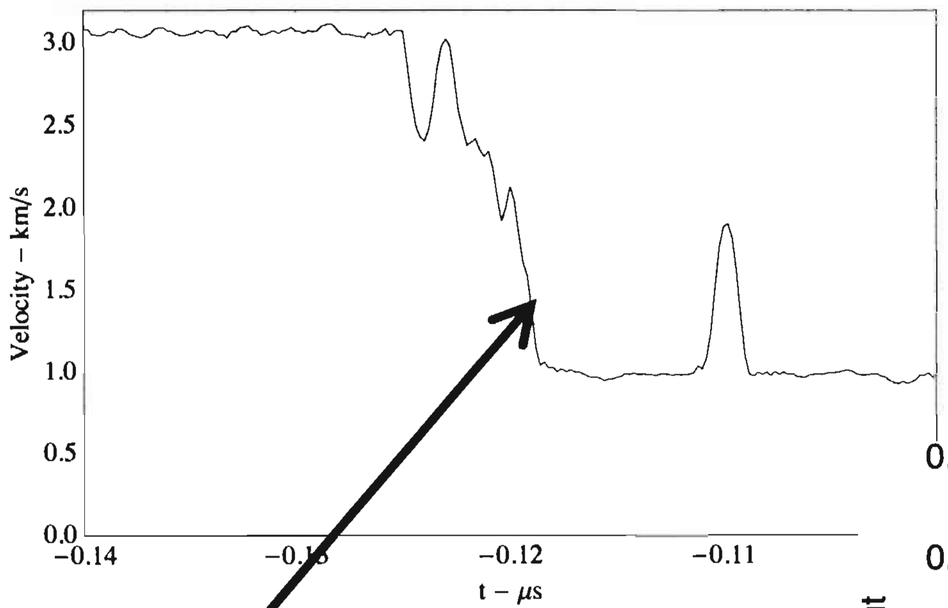
Probe Impacted
Impact time to 1 – 2 ns

Shock velocity (2 probes)

Δx/Δt



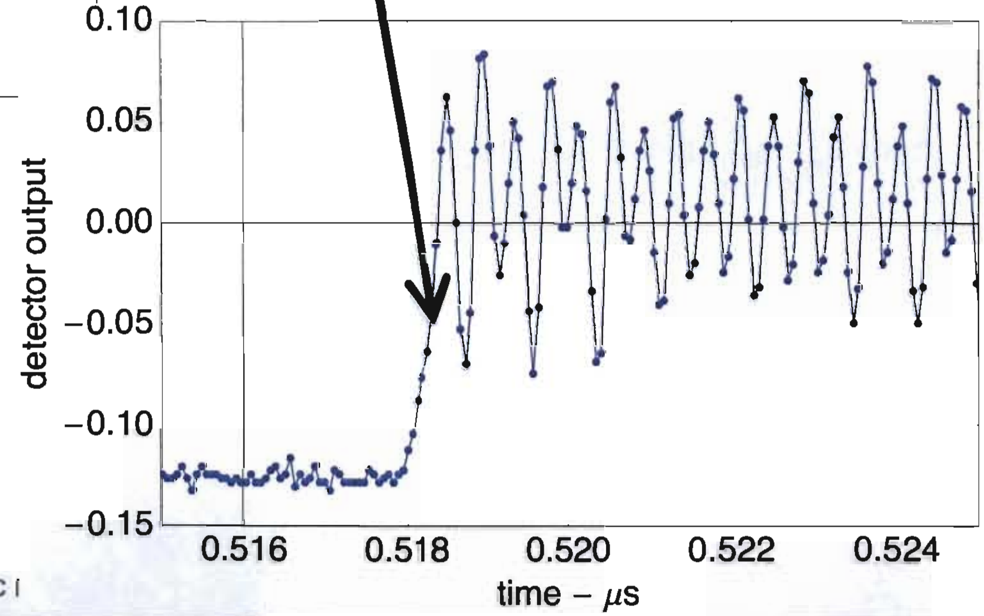
Shock Velocity (Δt)



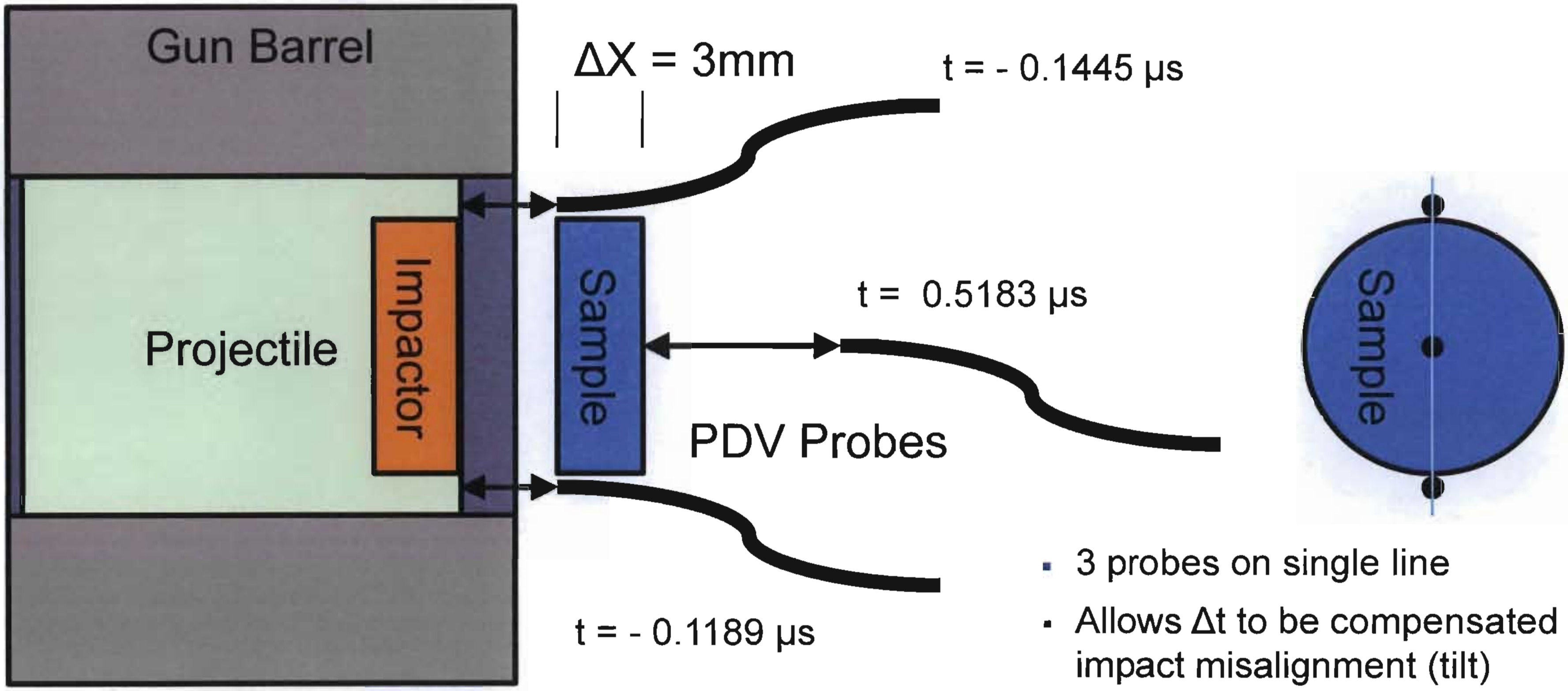
Probe Impacted
t = -0.1189 µs

Shock at back of sample
t = 0.5183 µs

Δt = 0.6372 µs
U_S = 4.71 mm/µs



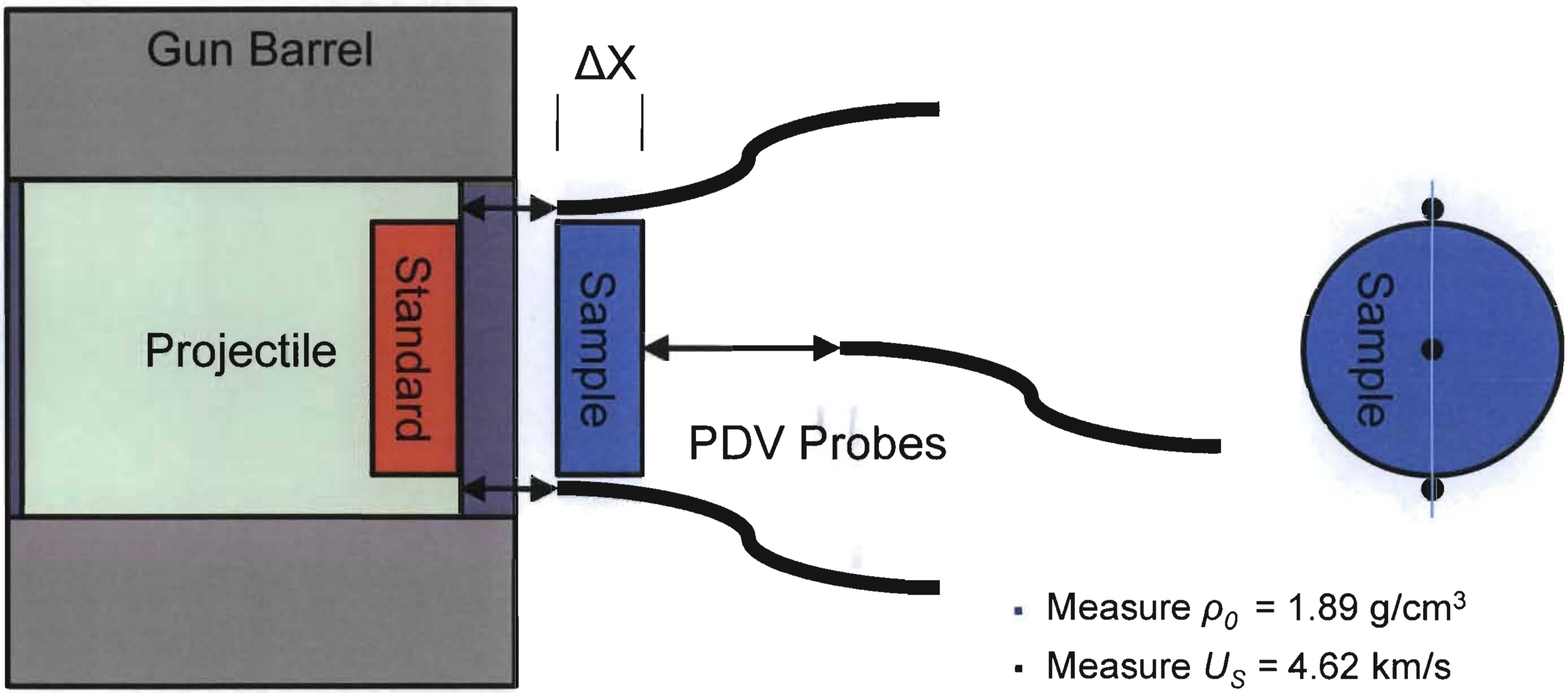
More accurate shock velocity (3 or more probes)



$\Delta t = 0.650$ μs
$U_S = 4.62$ mm/μs

- 3 probes on single line
- Allows Δt to be compensated for impact misalignment (tilt)
- Scopes started with piezo-electric (PZT) or electrical shorting pin

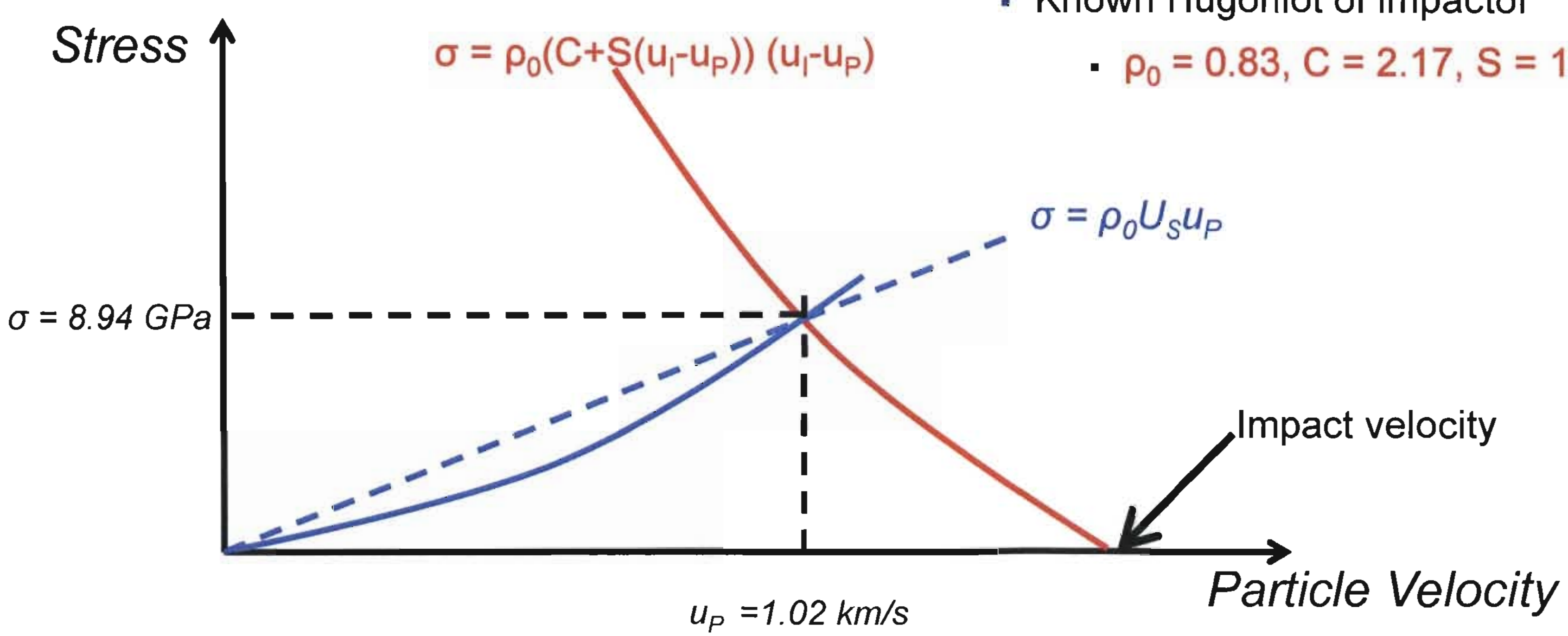
Measure a U_S - u_P Hugoniot point



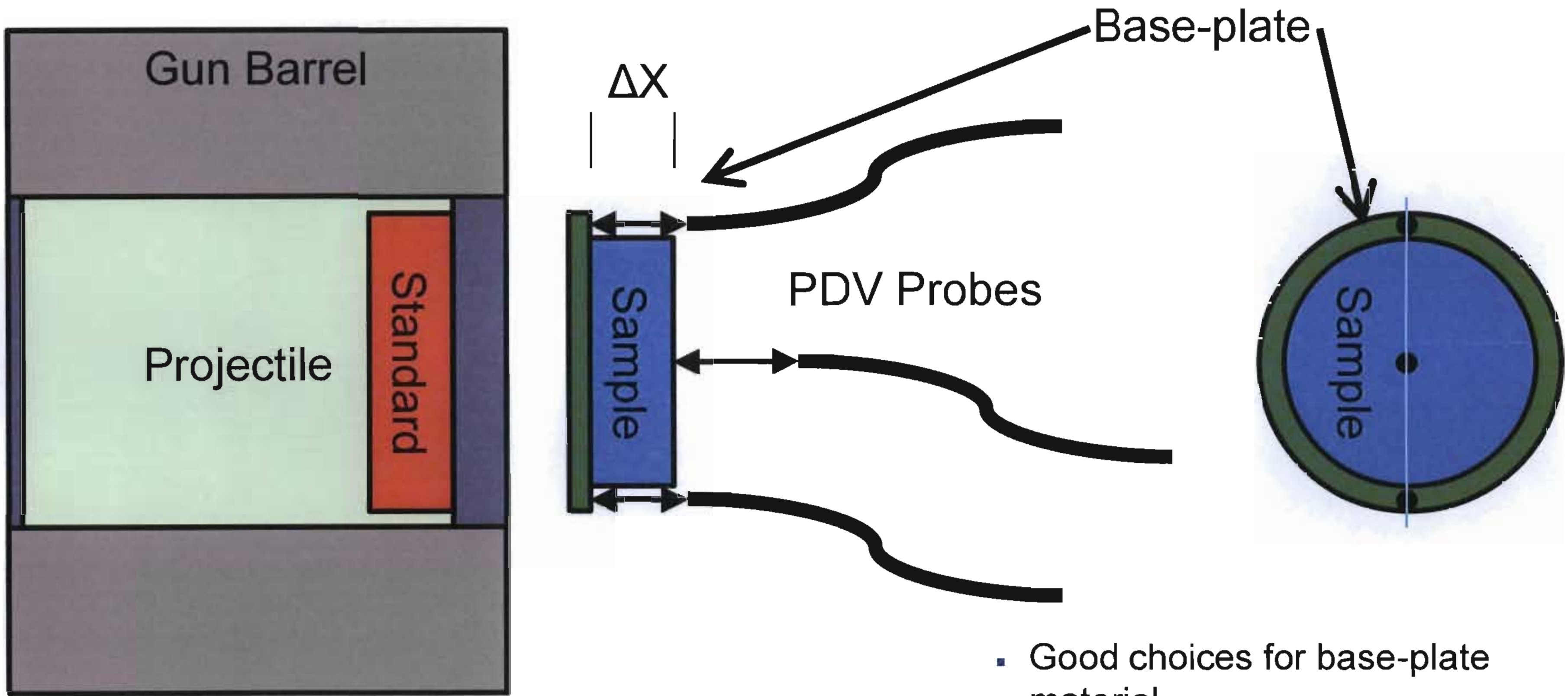
- Measure ρ_0 = 1.89 g/cm^3
- Measure U_S = 4.62 km/s
- Measure impact Vel. = 3.064 km/s

Measure a U_S - u_P Hugoniot point (cont.)

- Measured U_S = 4.62
- Measured impact Vel. = 3.064
- Known Hugoniot of impactor
  - $\rho_0 = 0.83$, $C = 2.17$, $S = 1.53$

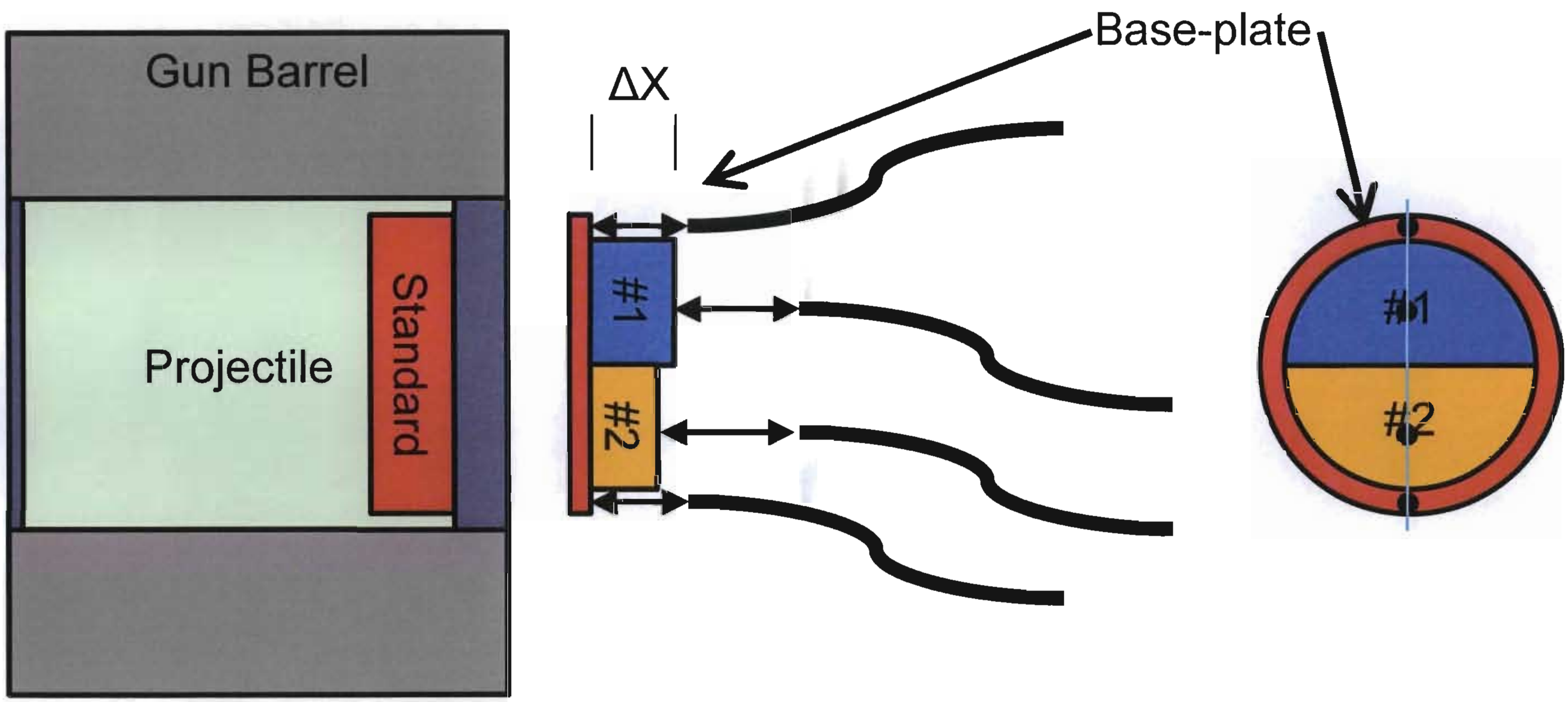


Base-Plate variant (projectile vel. not shown)

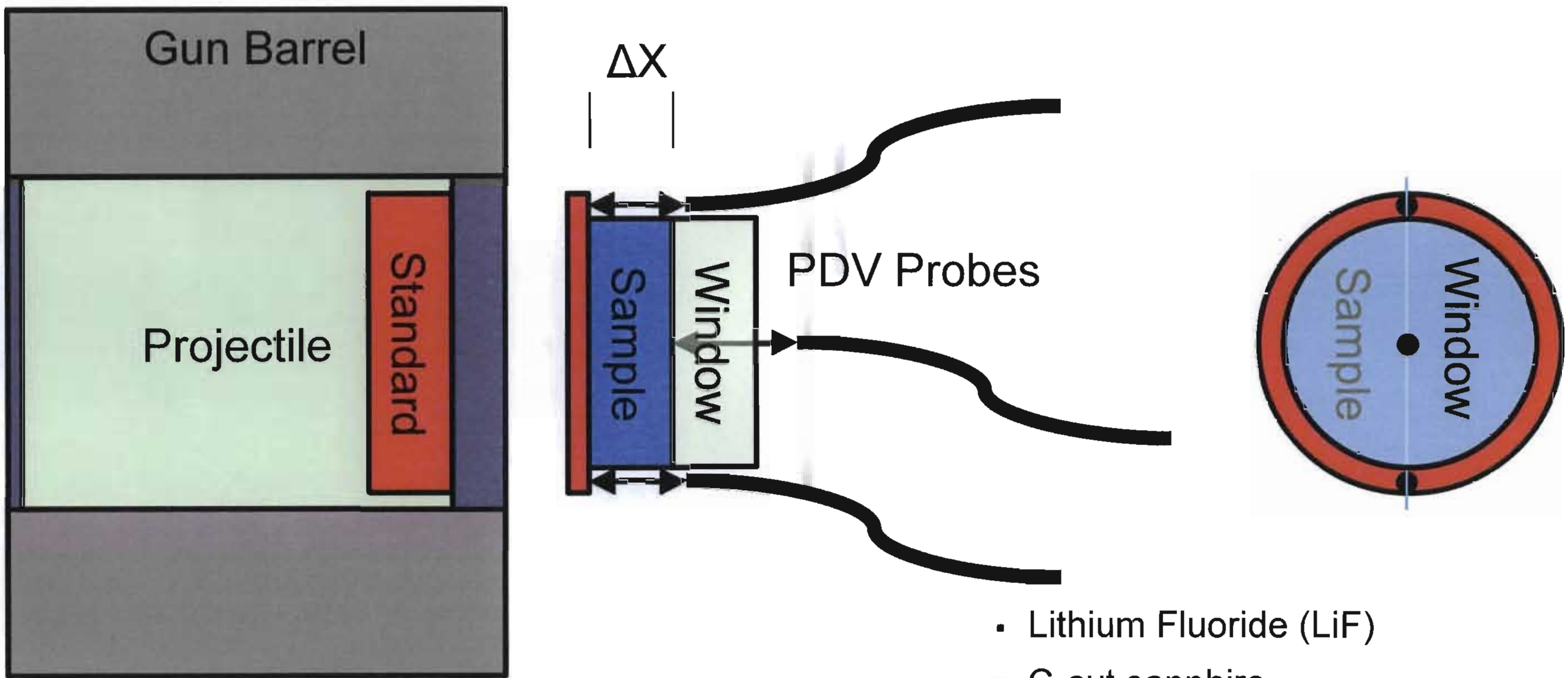


- Good choices for base-plate material
- Same as standard
- Same as sample

Base-Plate variant – 2 (or more) samples



Add a window to maintain stress at back of sample (projectile vel. not shown)



- Lithium Fluoride (LiF)
- C-cut sapphire
- Z-cut quartz
- PMMA

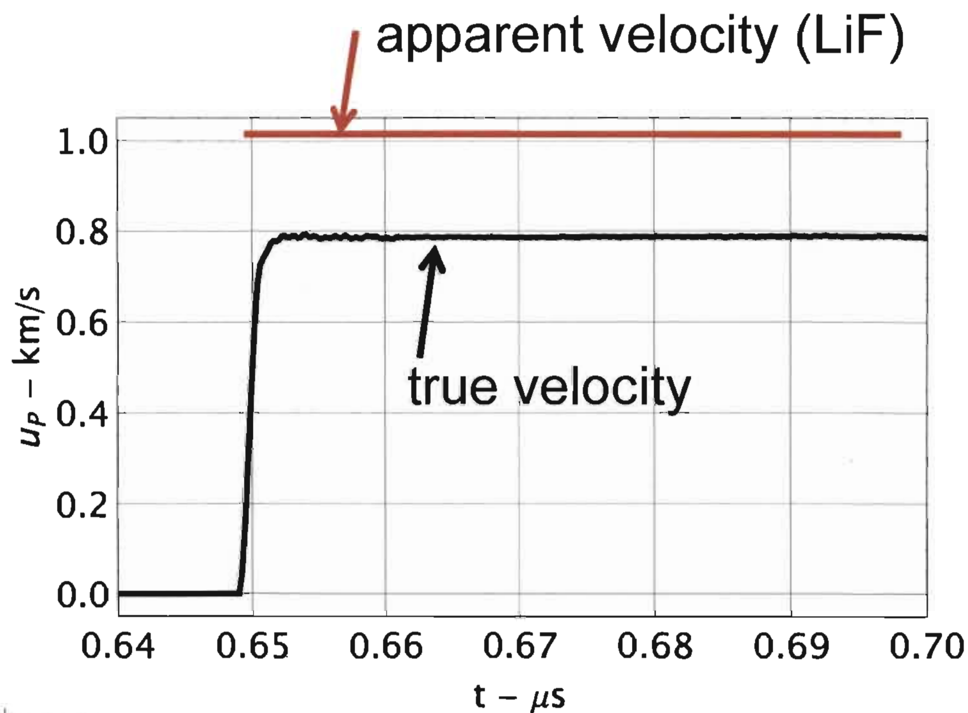
Jensen, Holtkamp, Rigg, & Dolan, JAP,**101**,13523 (2007)

Window "correction factors"

Apparent velocity = "correction factor" X true velocity

- Lithium Fluoride (LiF) = 1.2669
- C-cut sapphire = 1.7284
- Z-cut quartz = 1.0765
- PMMA = 1 (no published references)

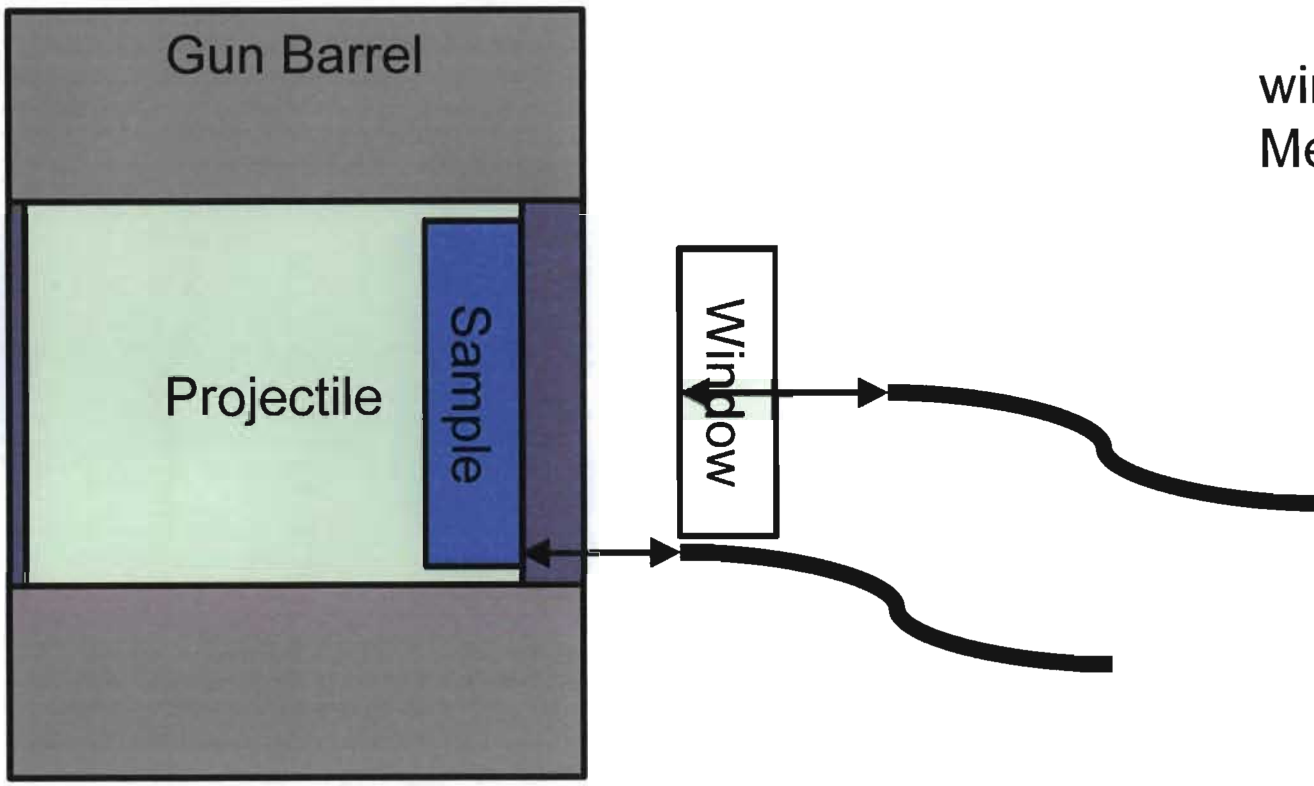
Jensen, Holtkamp, Rigg, & Dolan, JAP,**101**,13523 (2007)



Windows

- Lithium Fluoride (LiF) – high purity (100) orientation
  - Impedance similar to Al
  - Transparent to >100 GPA
  - HEL is very low
- C-cut sapphire
  - Impedance similar to Cu
  - Transparent until inelastic
  - Inelastic at 12 – 18 GPa
- Z-cut quartz
  - Inelastic at 6 – 9 GPa
- PMMA
  - Highly nonlinear (mechanical) < 4 GPa
  - Transparent until ~ 26 GPa (decomposition?)
  - Useable to > 30 GPa, but goes black over ca. 200 ns
  - Cheap, machinable

Front surface impact (reverse ballistic) experiment



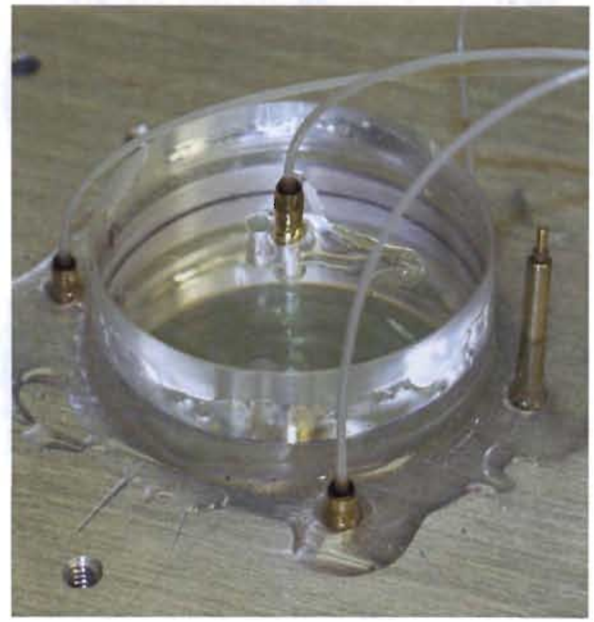
window is the “standard”
Measurements:
- projectile velocity
- interface velocity
- sample density

Front surface impact (reverse ballistic) experiment

Projectile w. sample as impactor

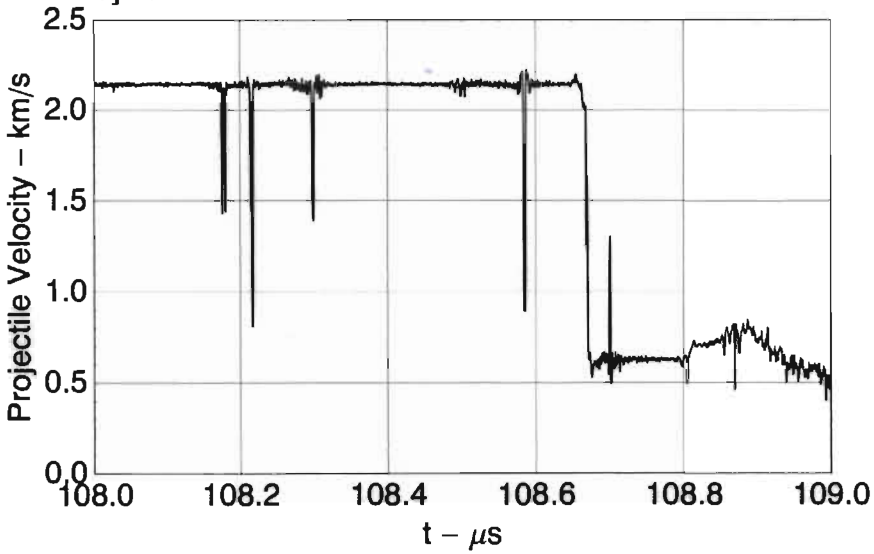
Impact face of window

Back of target

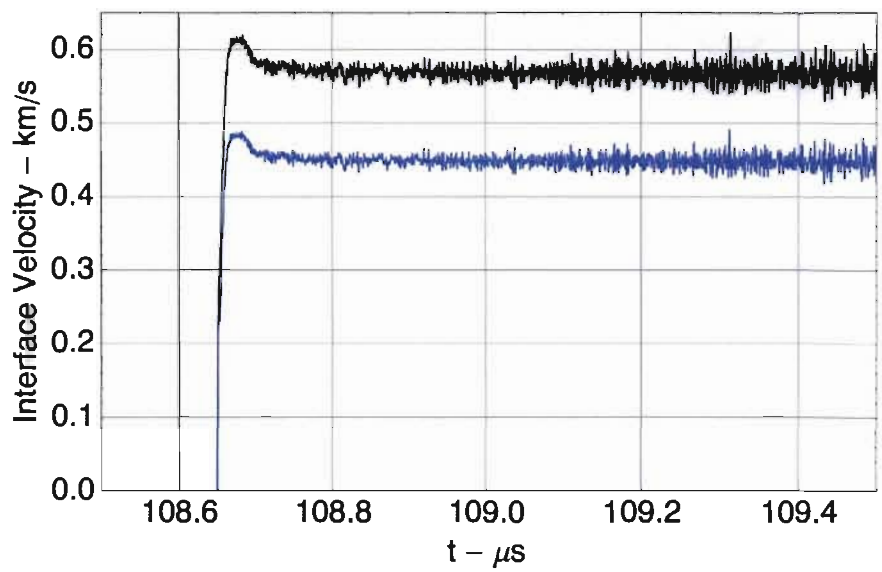


Front surface impact - data

Projectile vel. = 2.141 +/- 0.005 km/s

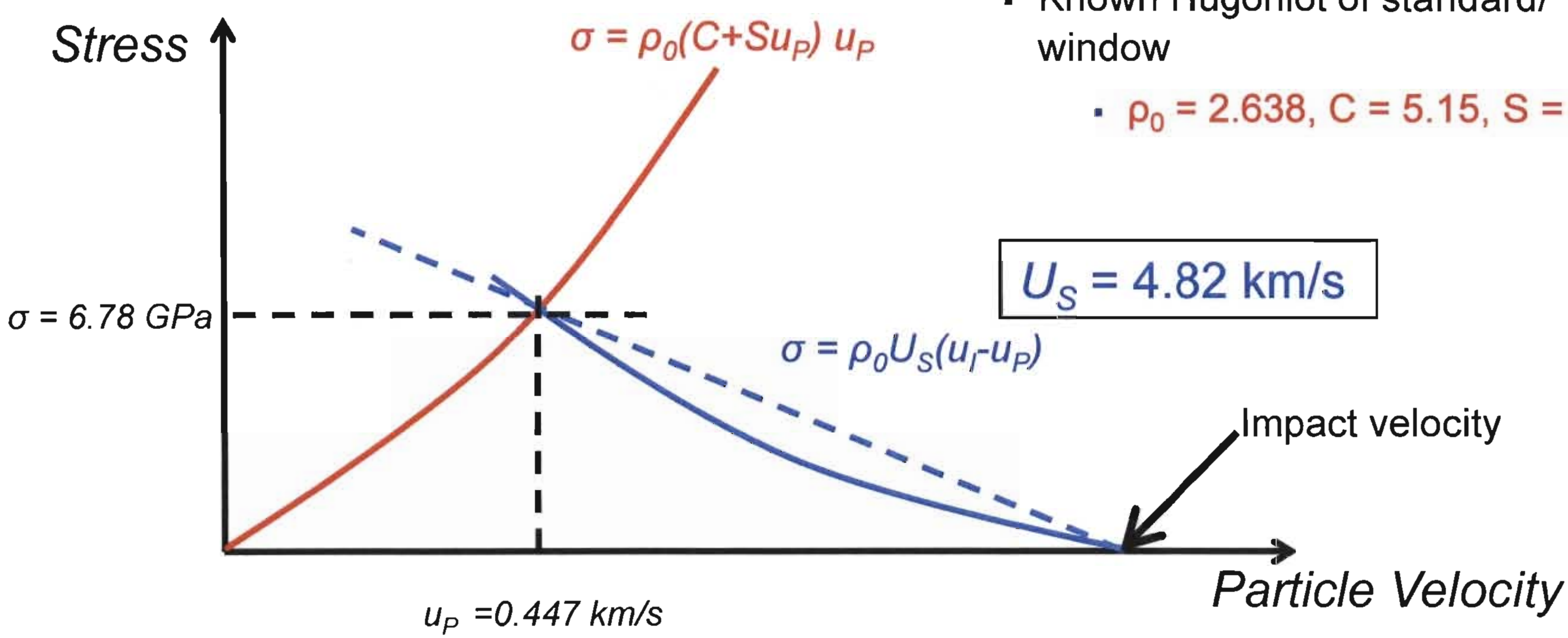


Black apparent vel.
Blue corrected interface vel.



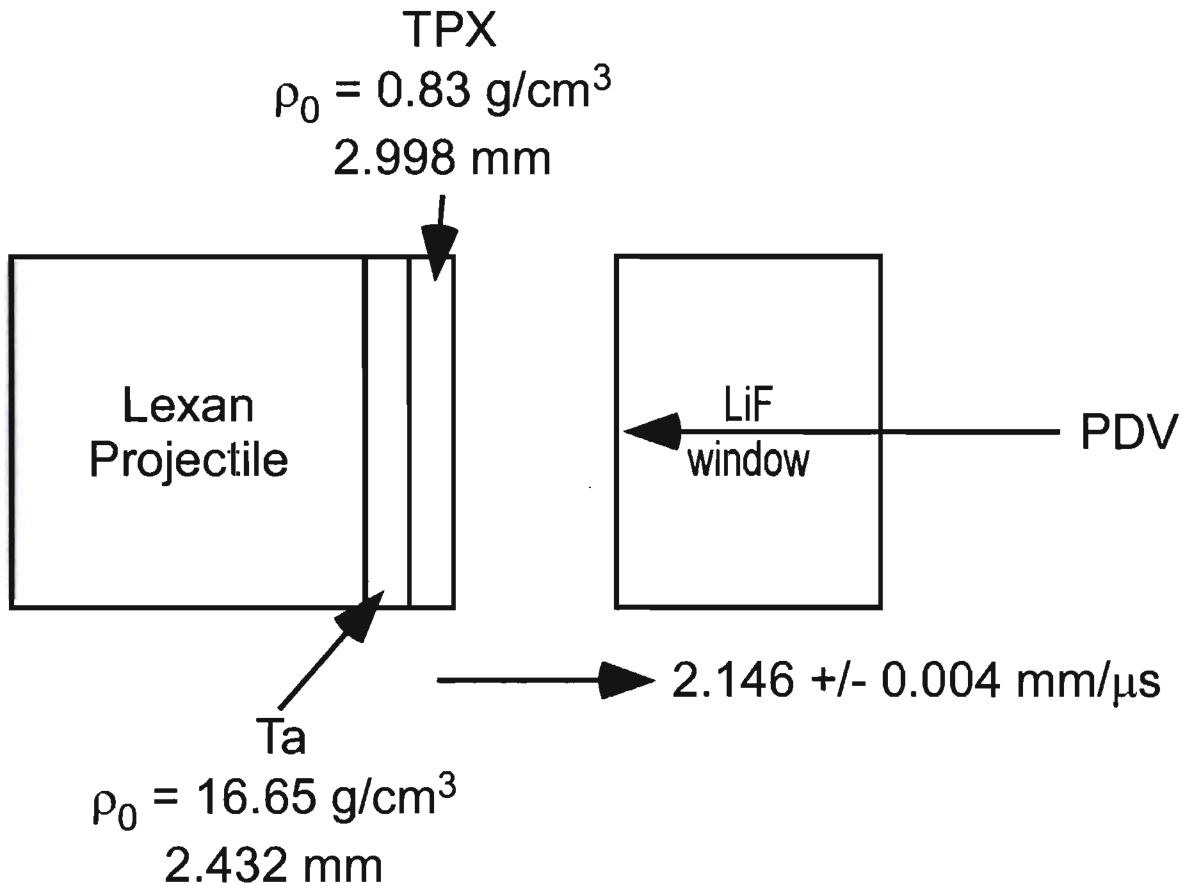
U_S - u_P Hugoniot point from front surface impact

- Measured u_p = *0.447 km/s*
- Measured impact Vel. = 2.141 km/s
- Known Hugoniot of standard/ window
  - ρ_0 = 2.638, C = 5.15, S = 1.35

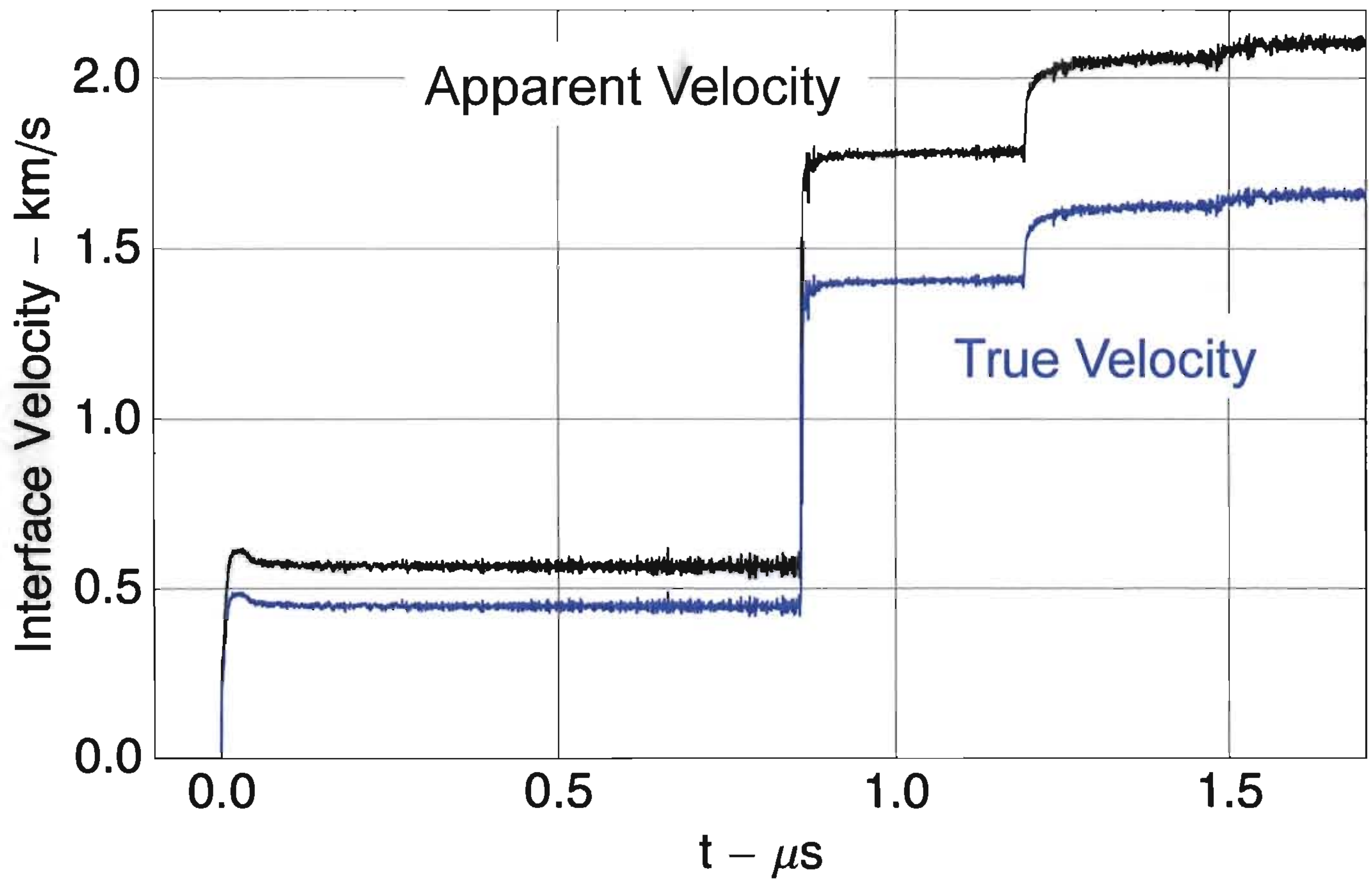


Double Shock - front surface impact

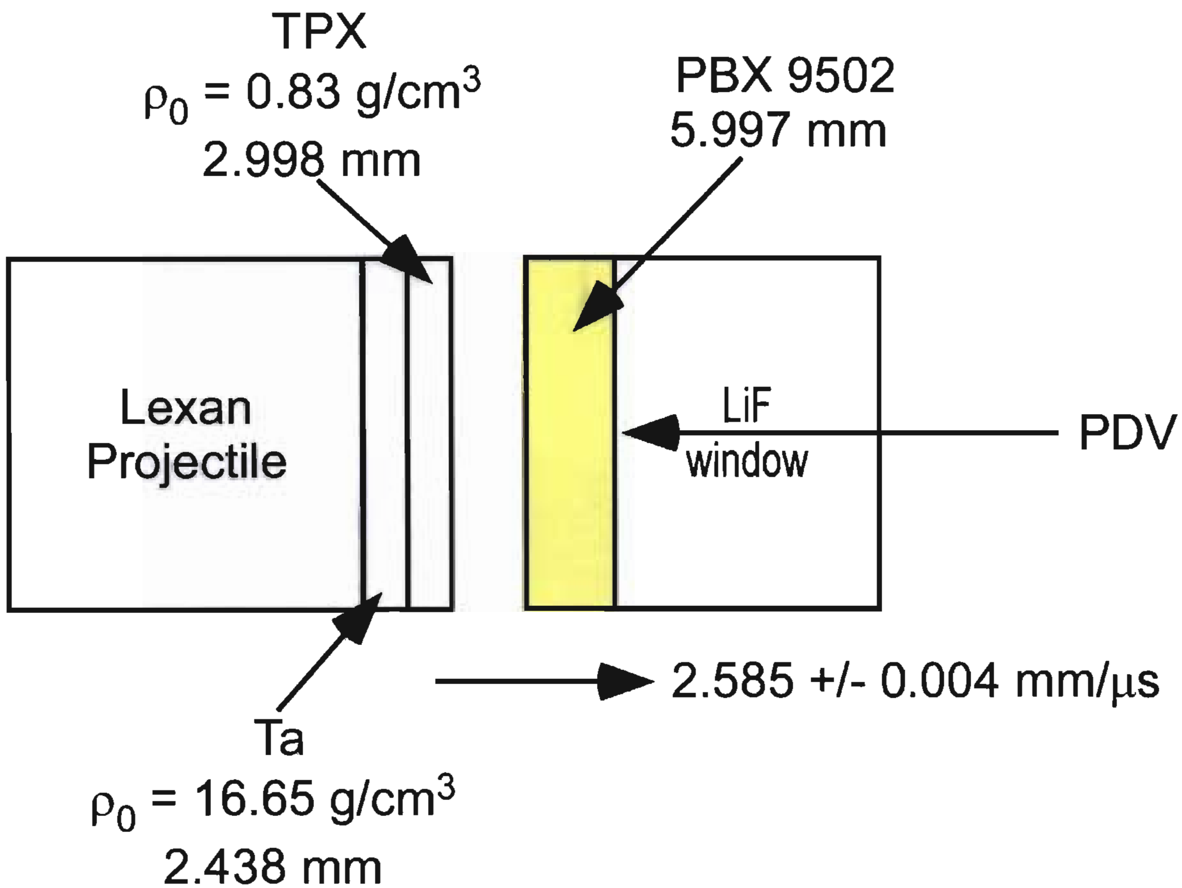
Double shocks result in lower temperature



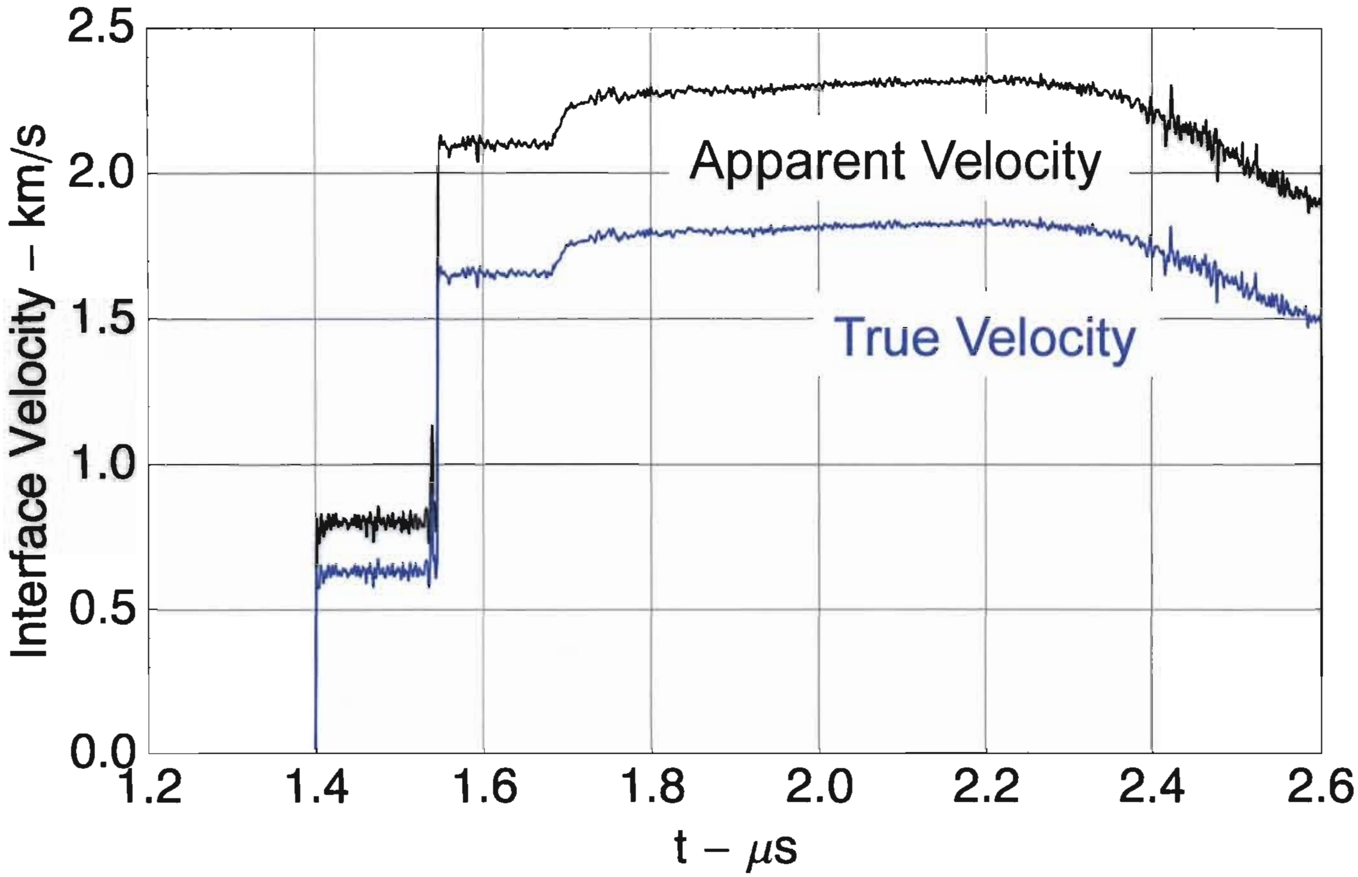
Double Shock: front surface impact



Double shock - transmitted

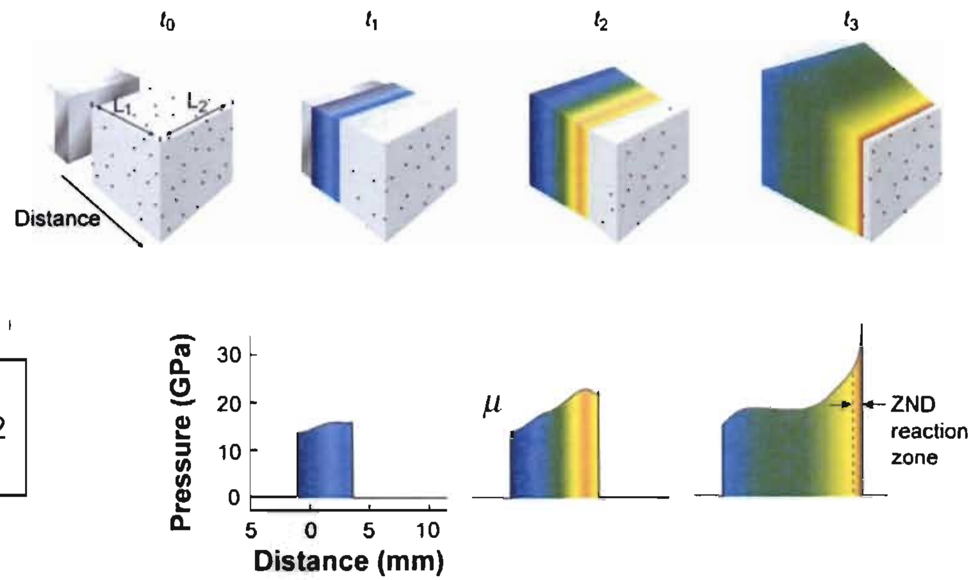


Double shock - transmitted

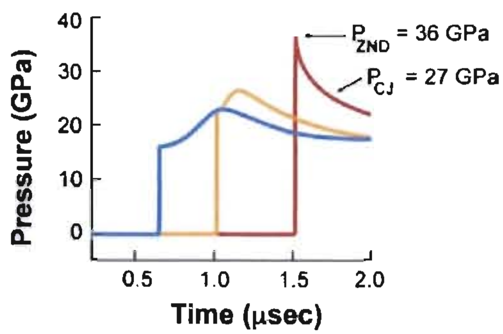


Part III – Measuring Detonation Wave Profiles

Background: Initiation and propagation of a Zeldovich-von Neuman-Doring (ZND) detonation wave



Bdzil & Stewart, Annu. Rev. Fluid Mech. 2007. 39:263-292 fluid.annualreviews.org



Reaction zone estimates are ≈ 1-2 mm (200 ns) in TATB based explosives, ≈ 200 microns (20 ns) in HMX based explosives.

Our group has a long standing interest in measuring detonation wave profiles

S. A. Sheffield, D. D. Bloomquist, and C. M. Tarver, *Subnanosecond measurements of detonation fronts in solid high explosives*, **The Journal of Chemical Physics**, 80**,** 3831 (1984).

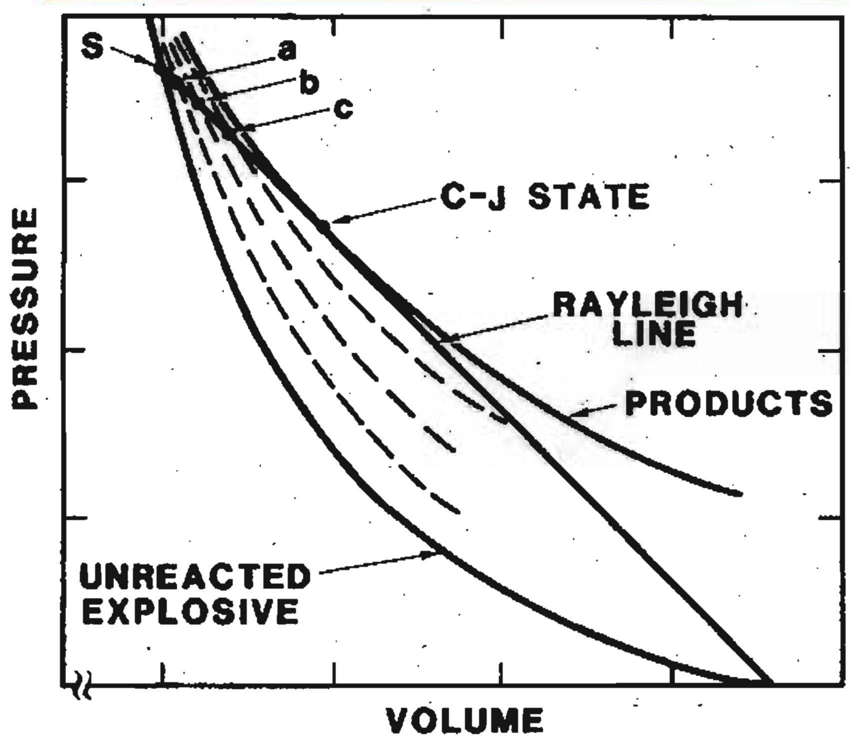
W.L. Seitz, H.L. Stacy, and Jerry Wackerle, *Detonation reaction zone studies on TATB explosives*, in **Eighth Symposium (International) on Detonation**; 1985, p. 123.

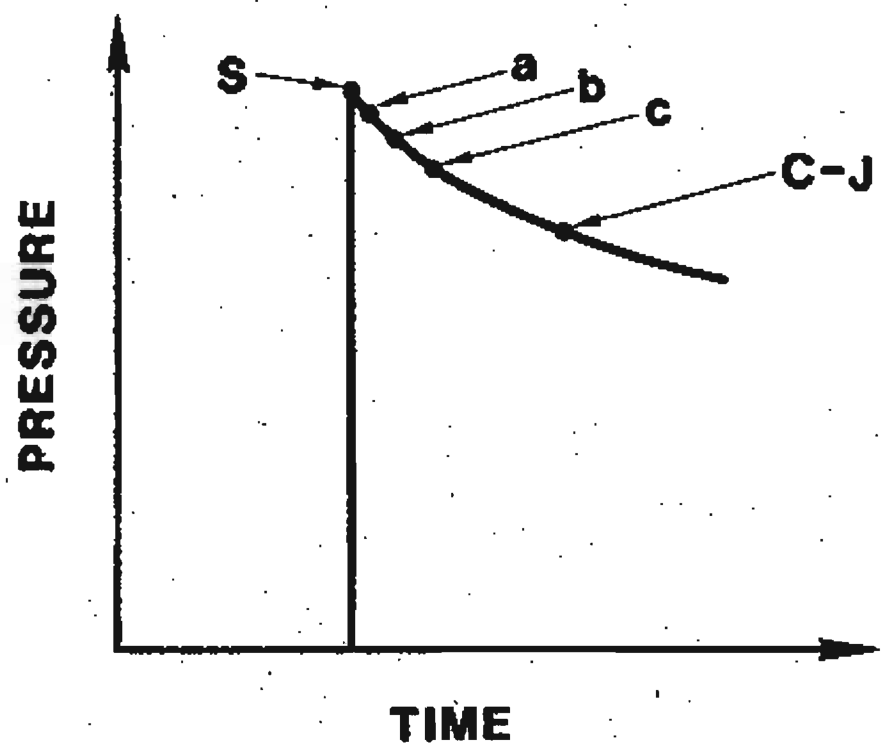
R. L. Gustavsen, S. A. Sheffield, and R. R. Alcon, *Progress in measuring detonation wave profiles in PBX 9501*, in **Eleventh International Detonation Symposium**; 1998, p. 821.

S. A. Sheffield, R. Engelke, R. R. Alcon, R. L. Gustavsen, D. L. Robbins, D. B. Stahl, H. L. Stacy, and M. C. Whitehead, *Particle velocity measurements of the reaction zone in nitromethane*, in **Twelfth International Detonation Symposium**; 2002, p. 159.

V. Bouyer, S.A. Sheffield, D. Dattelbaum et al., *Experimental Measurements of the Chemical Reaction Zone of Detonating Liquid Explosives*, in Shock Compression of Condensed Matter - 2009, p. 177.

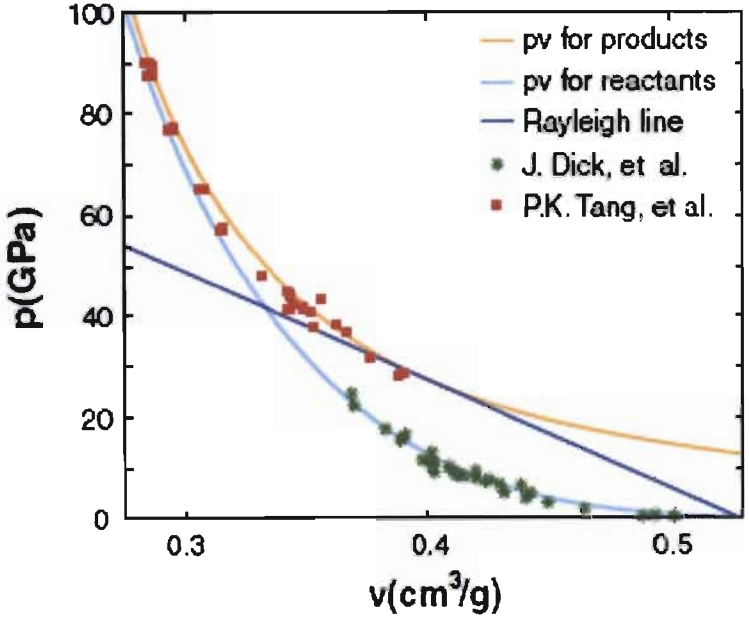
ZND Theory and Wave-Profiles

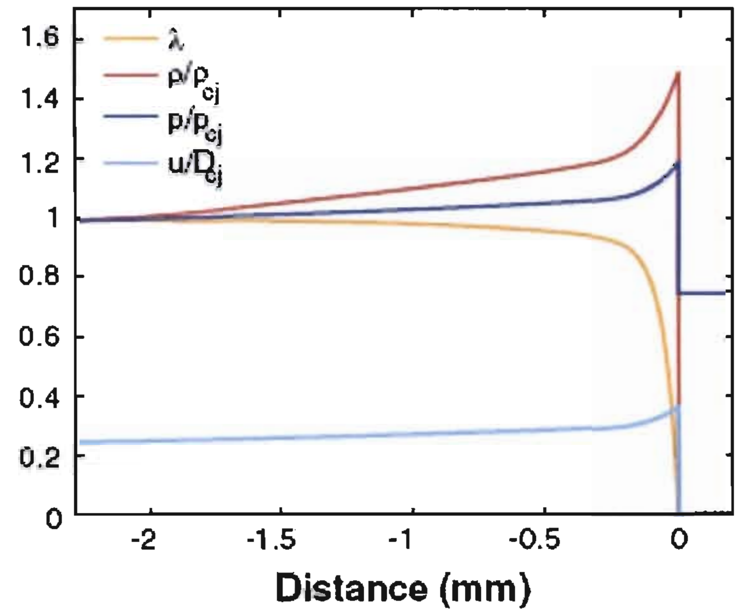




S.A. Sheffield, D.L. Bloomquist, and C.M. Tarver, J. Chem. Phys. 80, 3831 (1984).

Example: estimates of the ZND detonation wave in PBX 9502





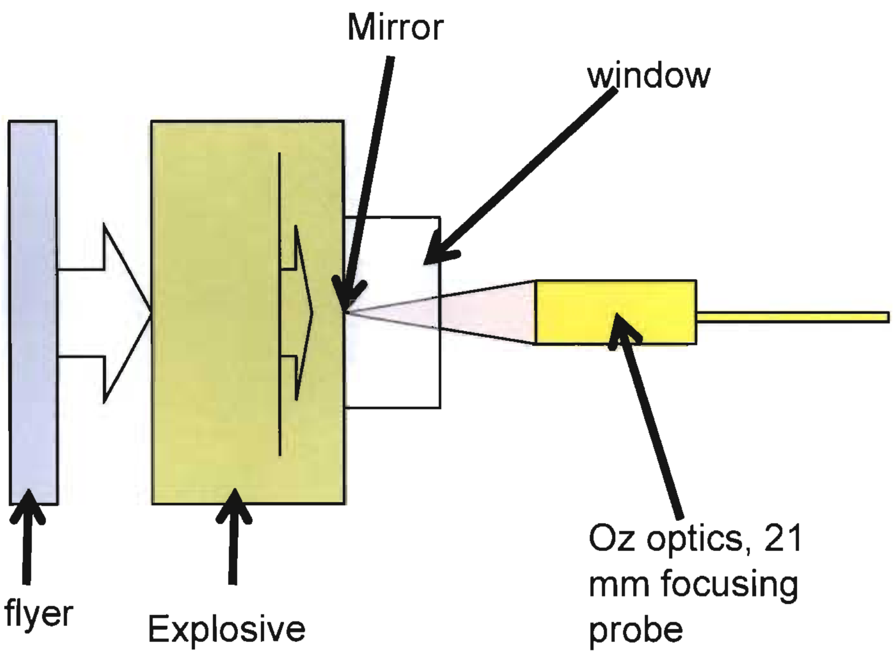
EOS for reactants has large uncertainties at high pressures, has large effect on some calculations.

Bdzil & Stewart, Annu. Rev. Fluid Mech. 2007. 39:263-292 fluid.annualreviews.org

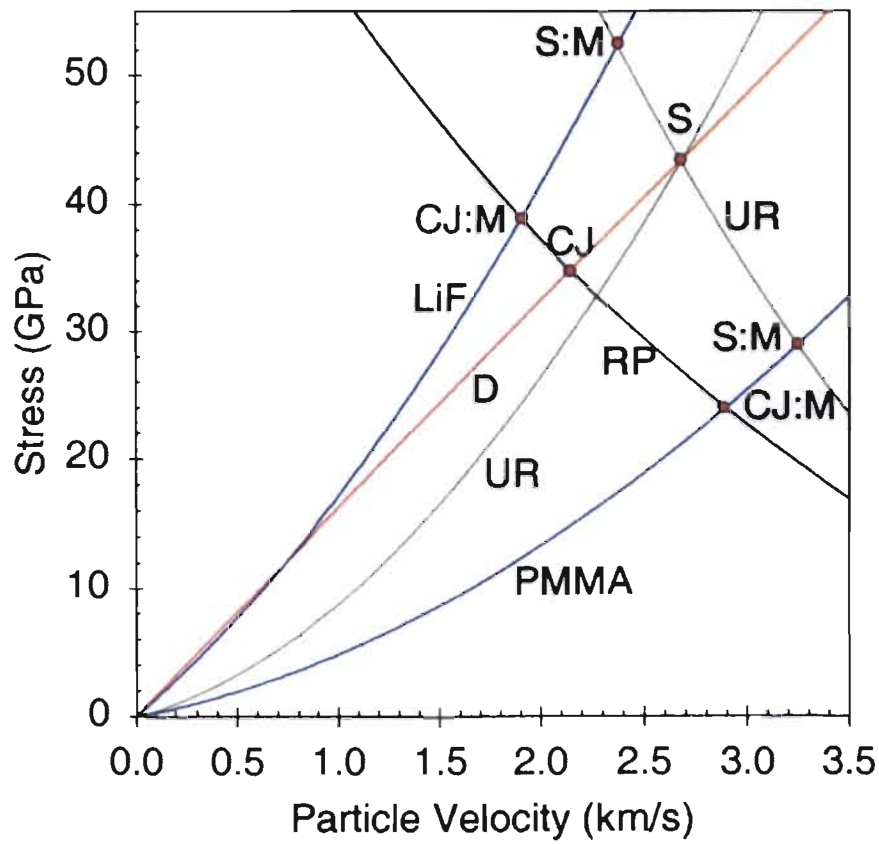
Time resolution of different experimental techniques

- **Entire reaction zone is ≈ 20 – 200 ns**
- **Gauges ≈ 20 ns**
- **Fabry Perot ≈ 10 ns**
- **VISAR (Valyn ca. 1997 ≈ 3 ns)**
- **ORVIS (line VISAR) < 1ns (depends on setup)**
- **PDV?**
  - But detectors are 13 – 20 GHz
  - Scopes sample at 0.05 – 0.02 ns/pt
  - A single fringe at 3 km/s is 0.25 ns
  - 1024 pt FFT windows represents 20 ns

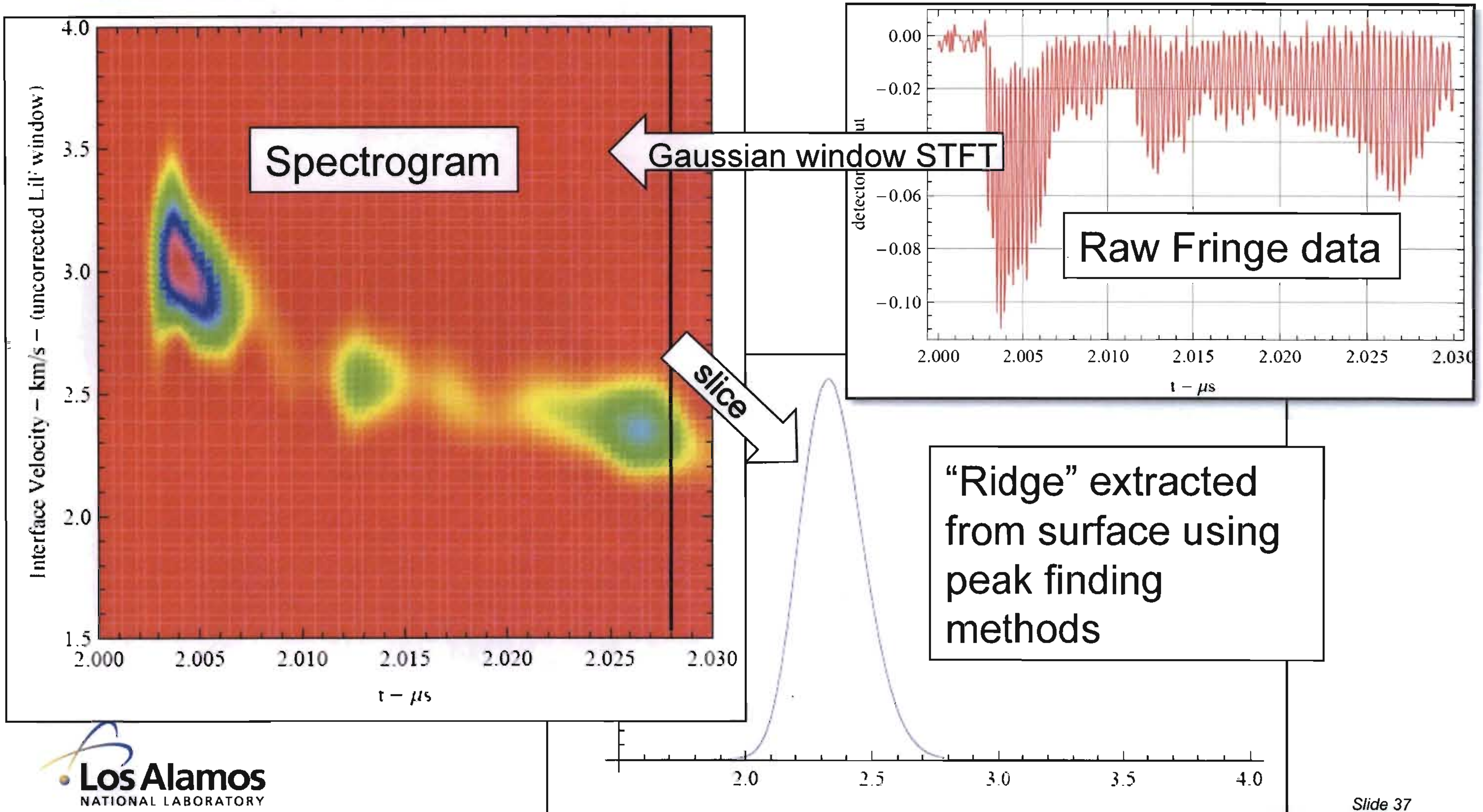
Shock physics experiment: window controls re-shock state & reaction rate



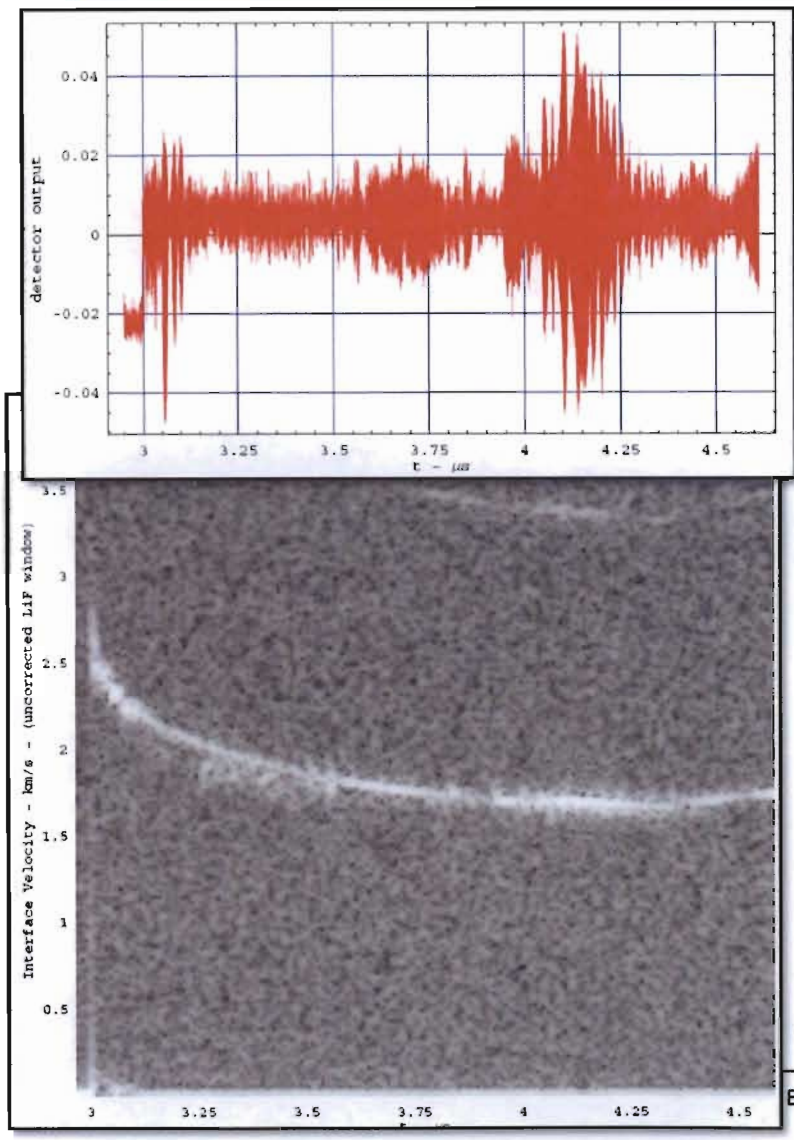
Hugoniot and Isentrope for a 95% HMX explosive

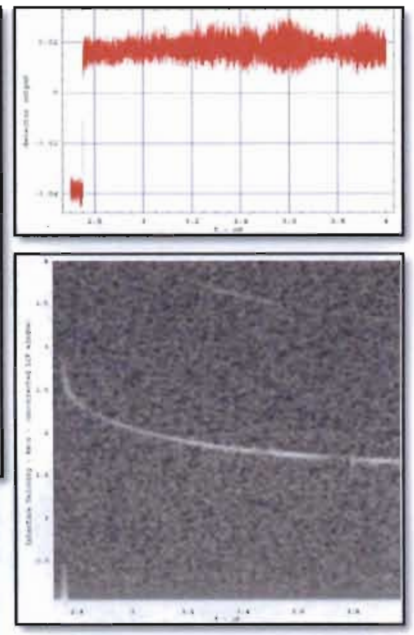


Time vs. Frequency Analysis: "Time resolution" defined by FFT window size.

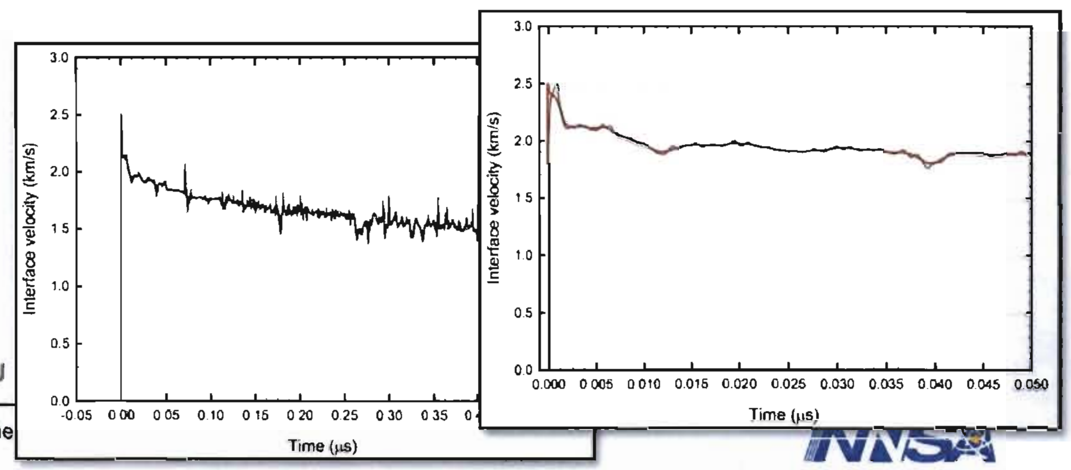


Explosive=TATB:Kel-F/ Window=LiF/ Mirror= vapor deposited Al, diffuse/ no barrier

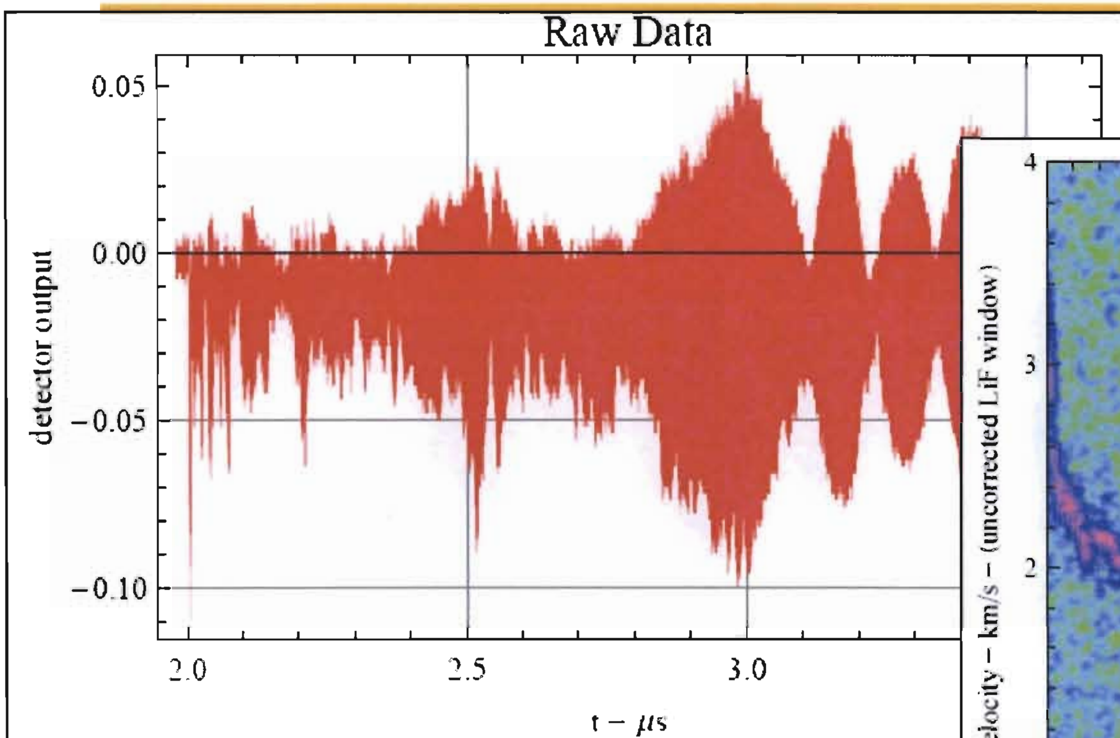


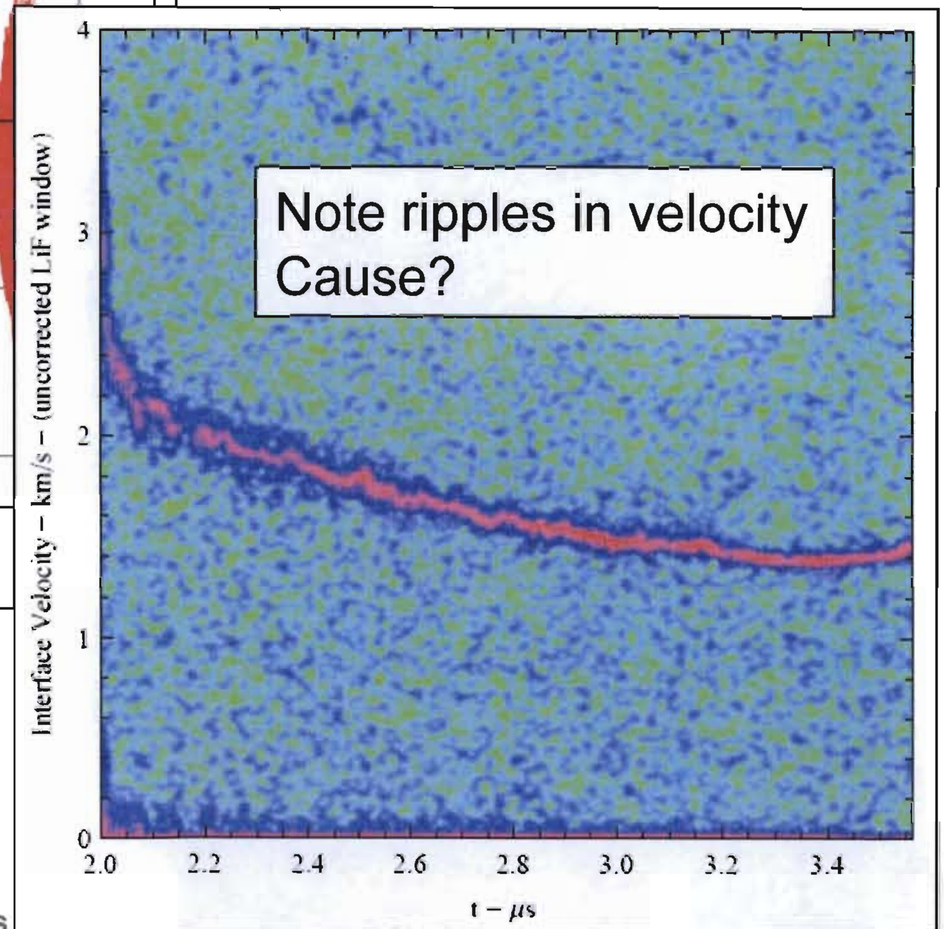


- Mirror surface roughened according to our best VISAR prescription
- Light levels drop dramatically when wave hits mirror
- Assume mirror is burning up
- best records are extracted below

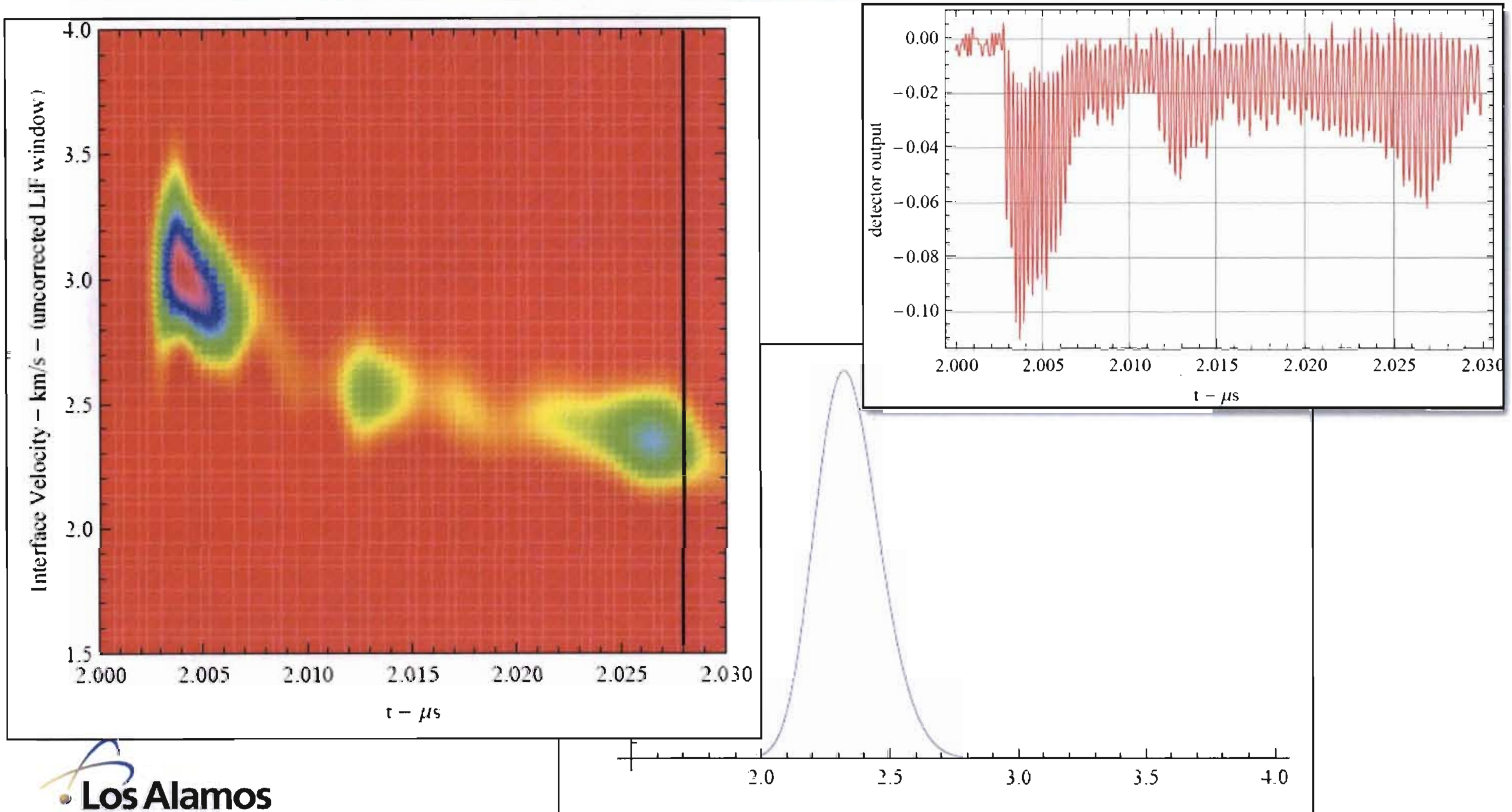


Raw Data & Spectrogram: Explosive=PBXN9/ Window=LiF/ Mirror= 6 μm thick, diffuse, Al foil

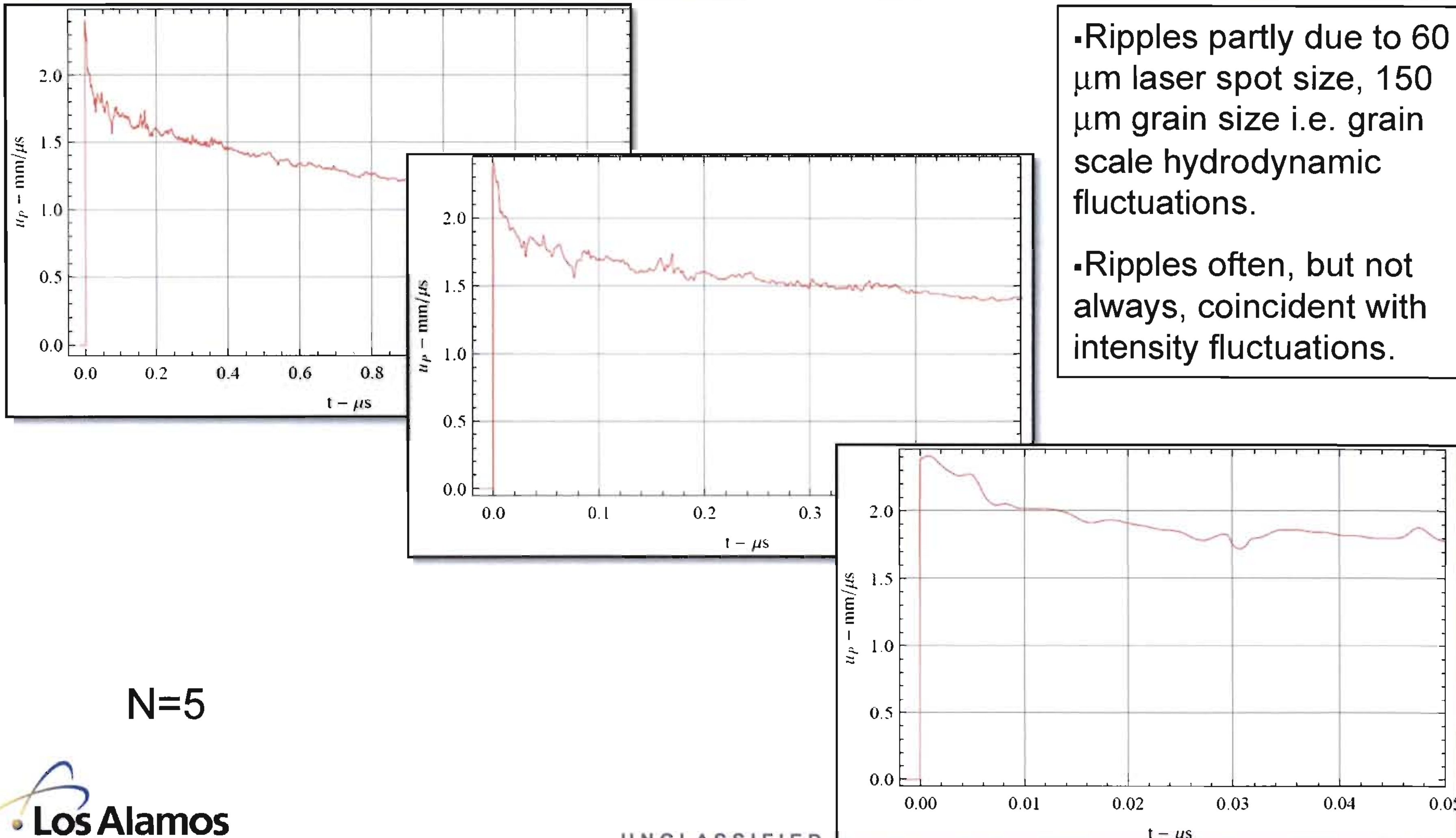




Detailed Spectrogram w. ca. 1 ns resolution: Explosive=PBXN9/ Window=LiF/ Mirror= 6 µm thick, diffuse, Al foil



Extracted/corrected wave profiles: Explosive=PBXN9/ Window=LiF/ Mirror= 6 μm thick, diffuse, Al foil

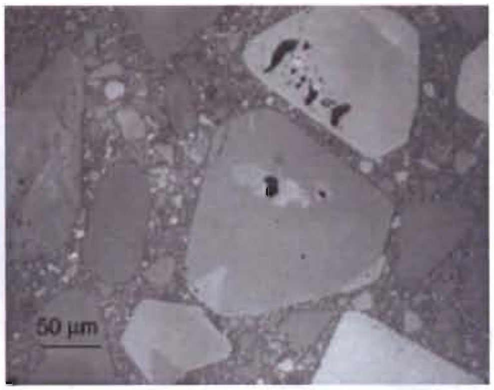


- Ripples partly due to 60 μm laser spot size, 150 μm grain size i.e. grain scale hydrodynamic fluctuations.
- Ripples often, but not always, coincident with intensity fluctuations.

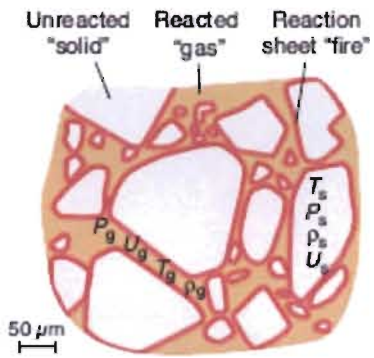
N=5

Micrograph of PBX 9501 and notional reaction process

(a)



(c)



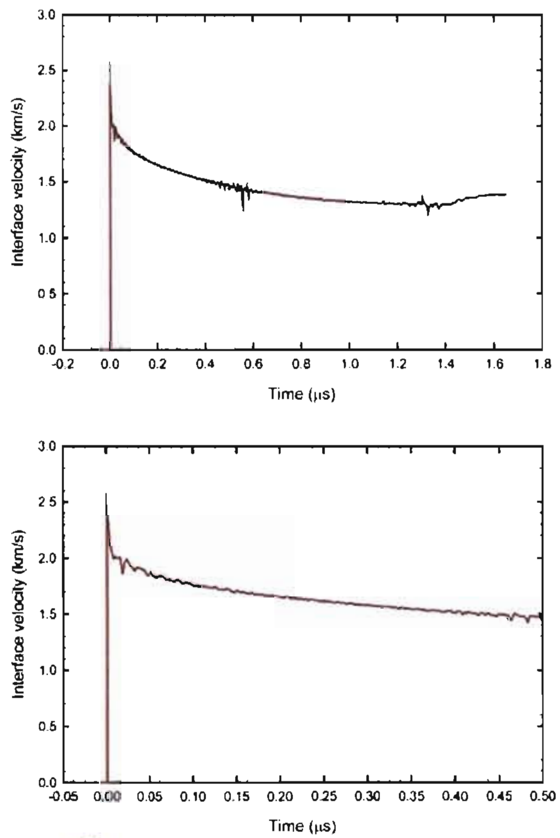
- Ripples partly due to 60 µm laser spot size, 150 µm grain size i.e. grain scale hydrodynamic fluctuations.
- Mel Baer et al. at SNL and Ralph Menikoff et al. at LANL are simulating shocks in composite explosives such as these.

Figure from Bdzil , et al., Los Alamos Science, No 28, 2003, page 96.

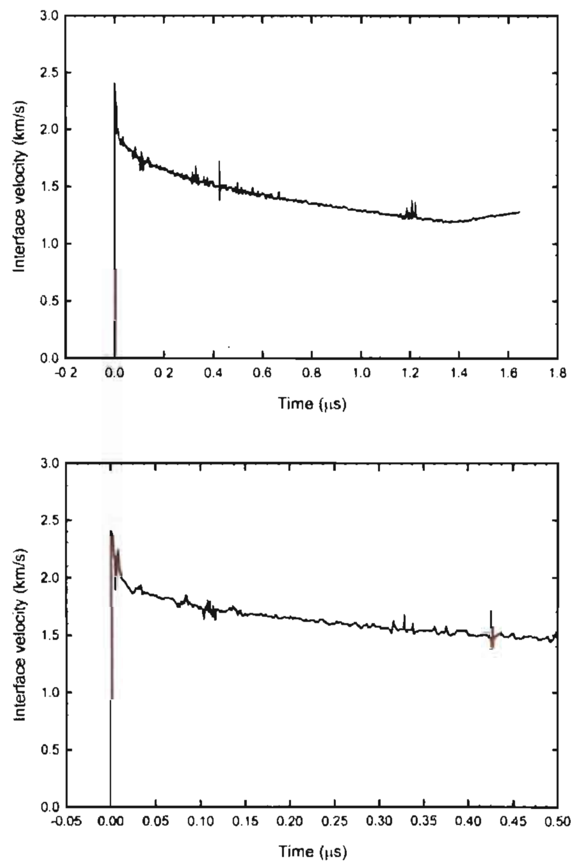
Micrograph originally from Skidmore et al. (LANL)

Explosive=TATB:Kel-F/ Window=LiF/ Mirror= 6 μm thick, diffuse, Al foil

Good

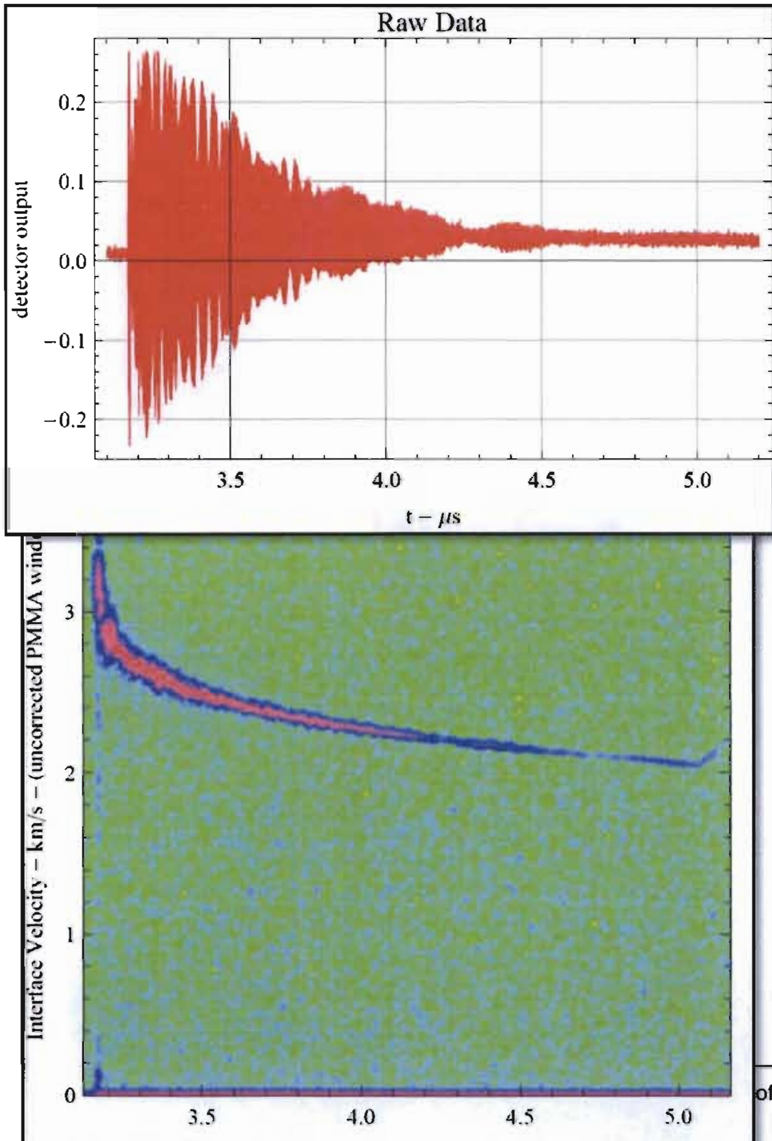


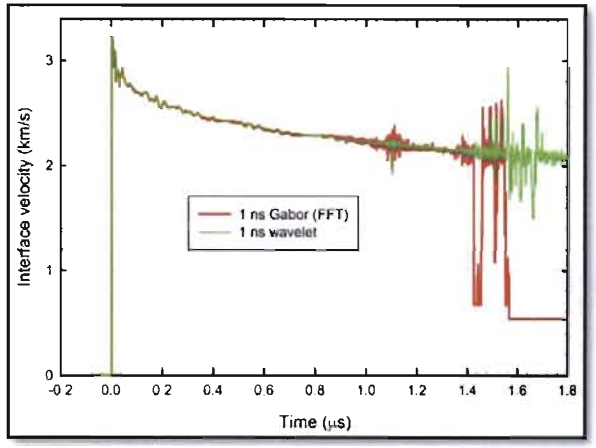
Not so good

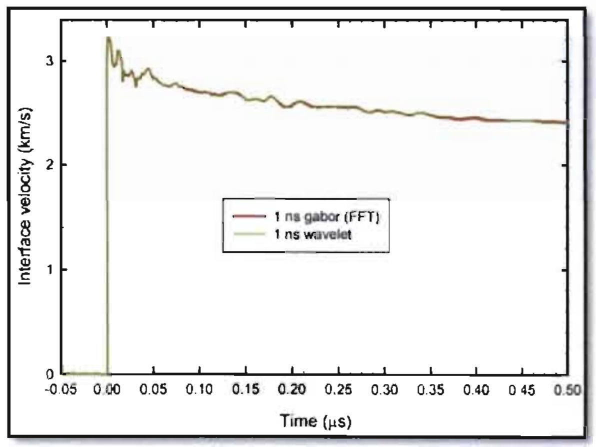


- 2 reactions observed: fast ≈ 20 ns, slow ≈ 200 ns
- LiF windows with diffuse Al foil mirrors are robust.
- Ripple (or noise) levels vary quite a bit from one experiment to the next.

Explosive=TATB:Kel-F/ Window=PMMA/ Mirror= 6 μm diffuse Al foil







Comments on PMMA windows

+ different impedance

+ inexpensive

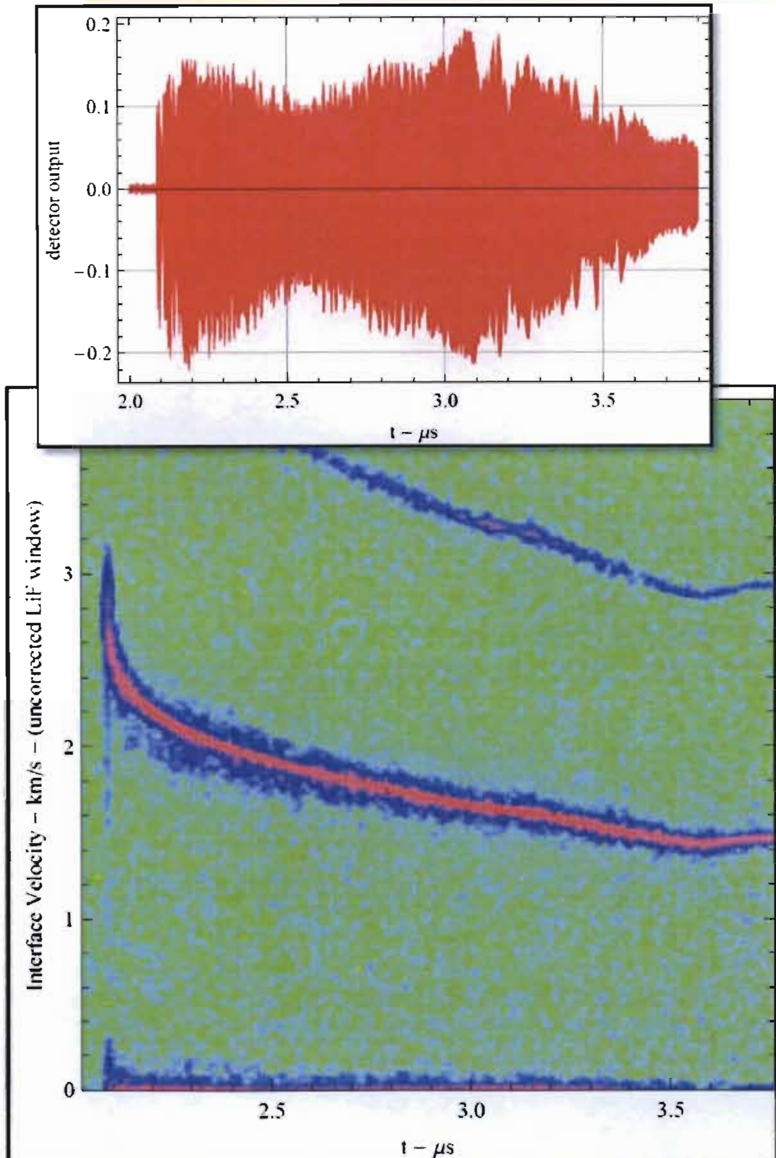
- do it yourself optical finish

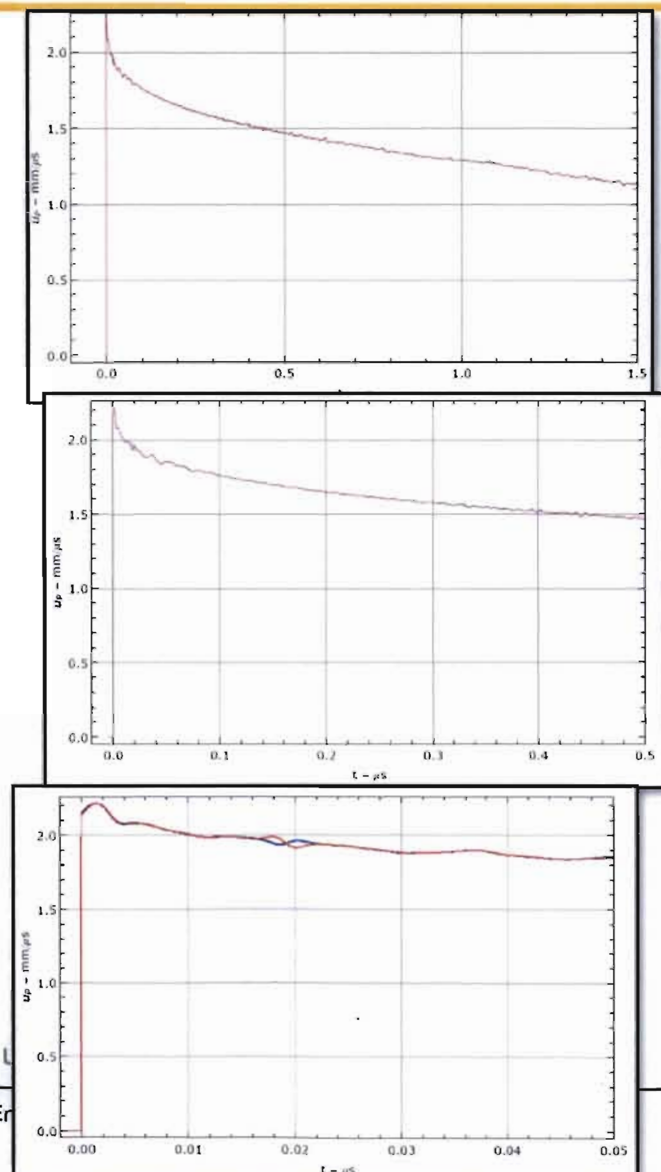
- no 1550 nm correction factor

- light goes out at high pressures

-Lots of noise in typical records

Explosive=TATB:Kel-F/ Window=LiF/ Mirror= vapor plated Al, specular, No barrier





Comments

- Best yet!
- Resolution shown 1ns
- As good as VISAR?
- What improvements can be made?
- Are there better analysis methods to apply if you have really good data?

Summary

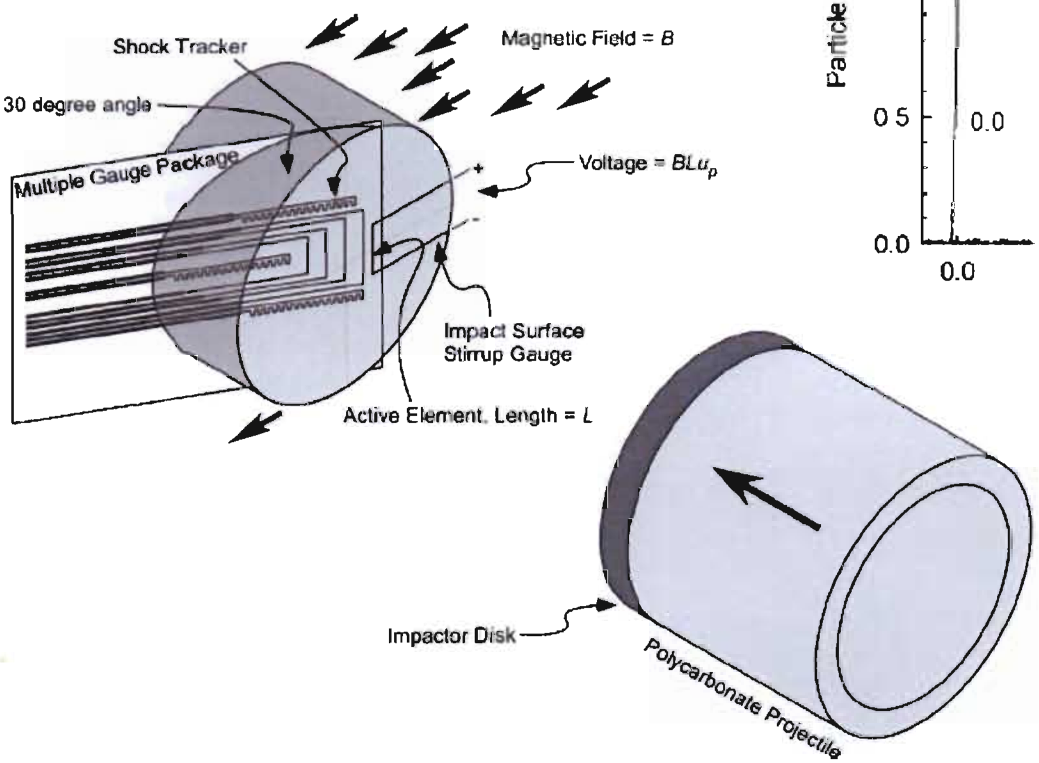
- Windows
  - LiF > PMMA
  - Still need correction factor for PMMA windows
  - Are the PMMA problems due to the do it yourself optical finish?

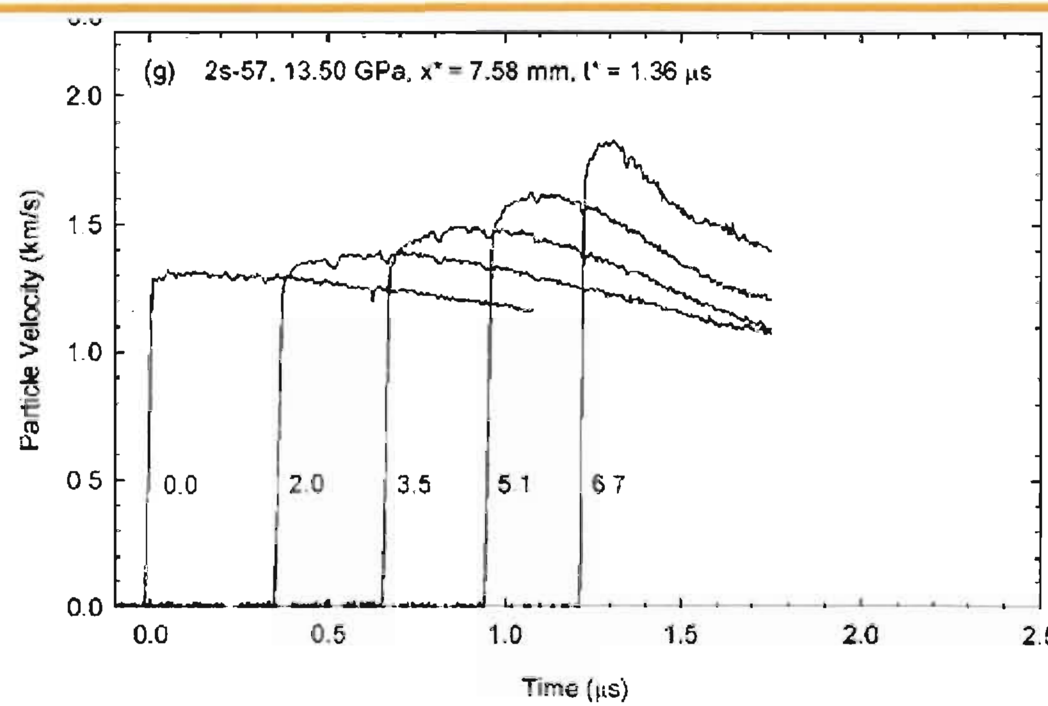
- Mirrors
  - Specular vapor plated Al > 6 mm Al foil > diffuse vapor plated Al
  - Barriers not needed (except maybe for diffuse vapor plated Al)
  - Ripples mostly correlated with intensity fluctuations. Intensity fluctuations likely due to laser speckle from diffuse mirrors (much reduced with specular mirrors).
  - Would an uncoated window work?
  - Should the explosive be polished? Currently just machined finish.

- General comments
  - Some ripples remain in the best data. These are likely due to grain scale hydrodynamic fluctuations. We need to look at profiles in homogeneous materials (nitromethane) where these are not expected.
  - ≈ 1 ns resolution can be achieved with good data.
  - Slowly varying intensities highly desirable.
  - With PDV you can always get something!

Part – IV: Shock Initiation Measurements Using Multiple Samples

Experiment we hoped to replicate





Gustavsen, Sheffield, and Alcon, J. Appl. Phys., 99, 114907 (2006)

Why PDV? Samples came in form of 25 mm diameter rods. Magnetic gauge experiments require 50 mm diameter cylinders.

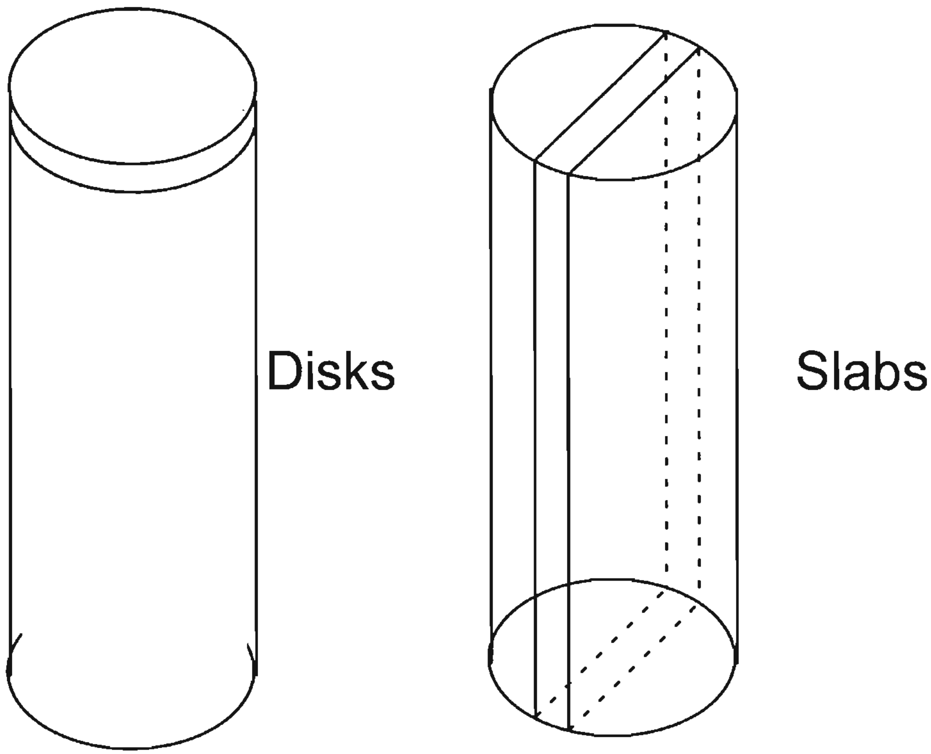
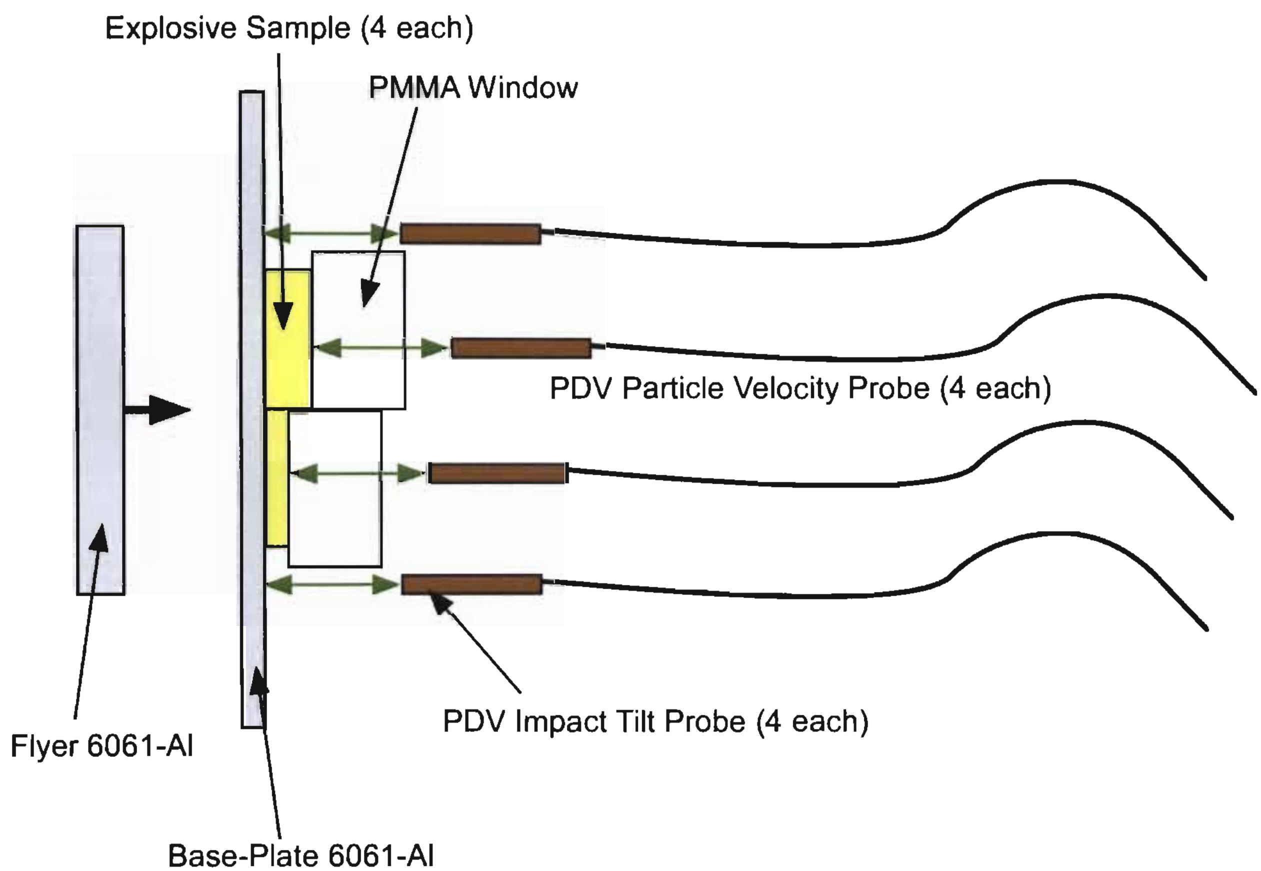
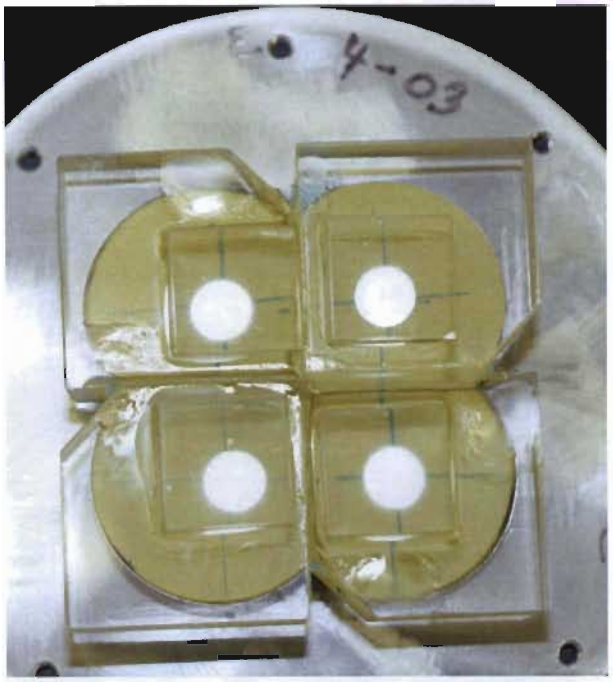
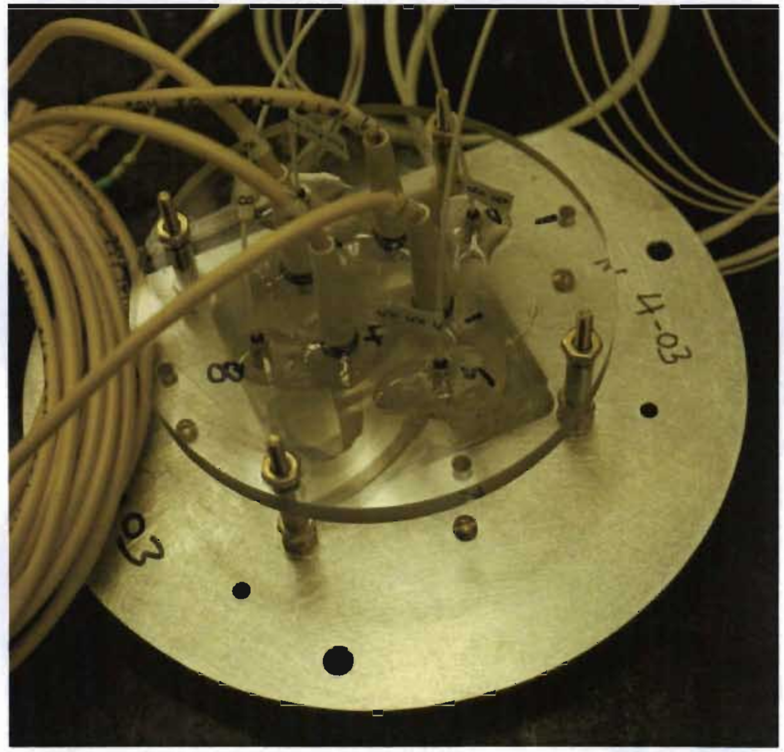


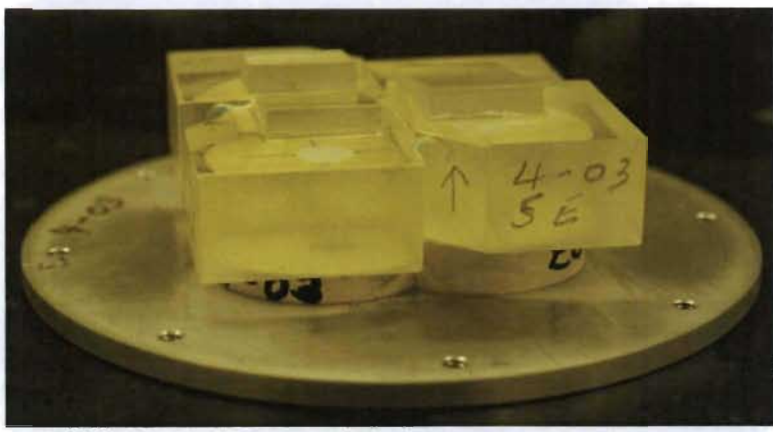
Plate impact experiment



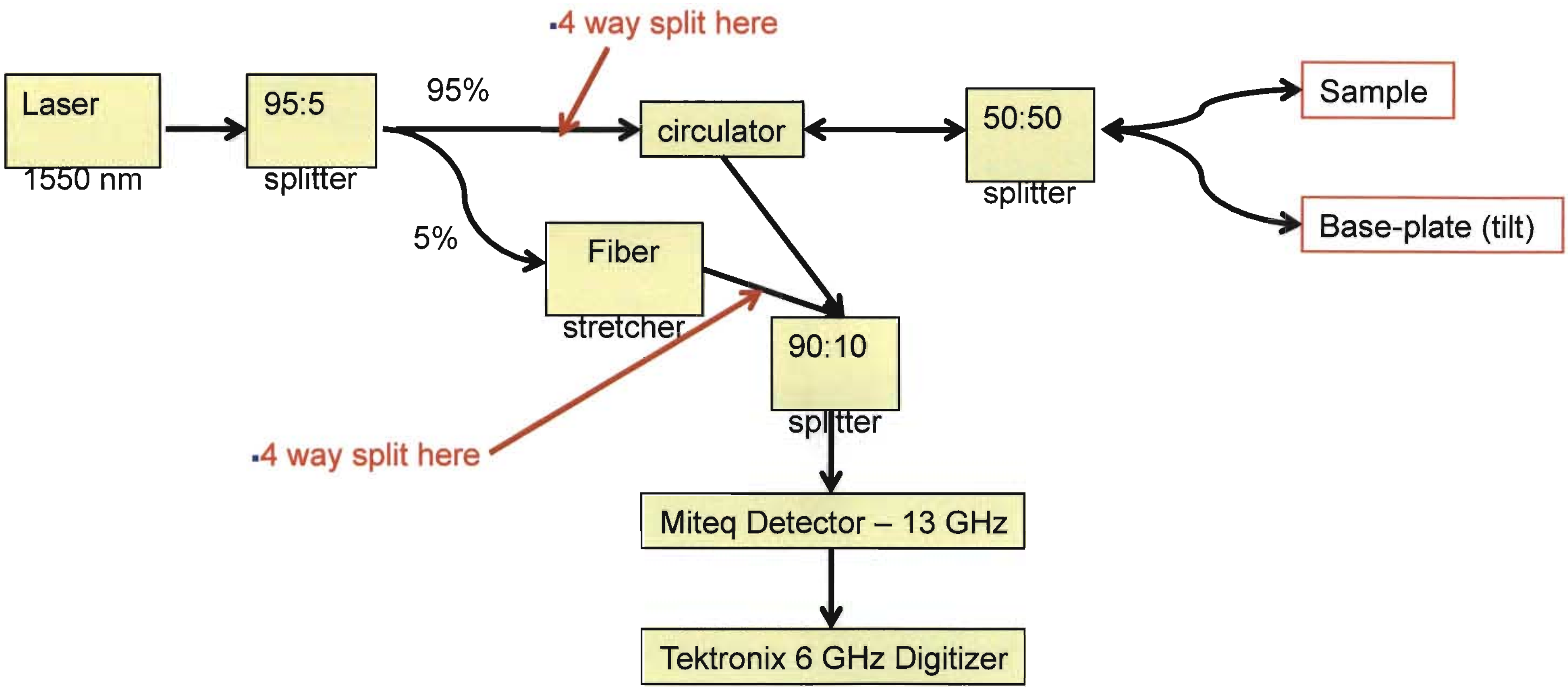
Impact Experiment – Photos



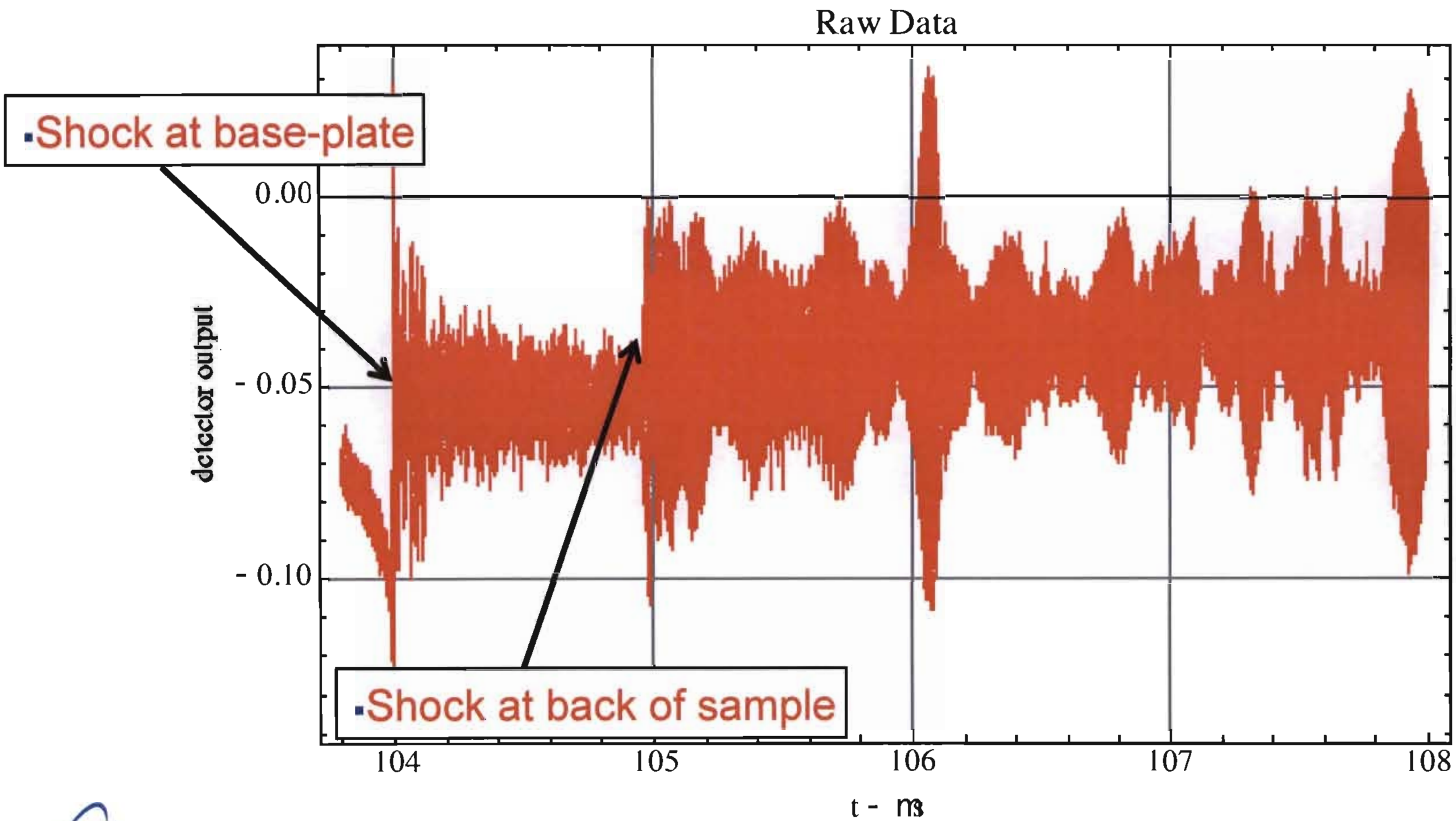




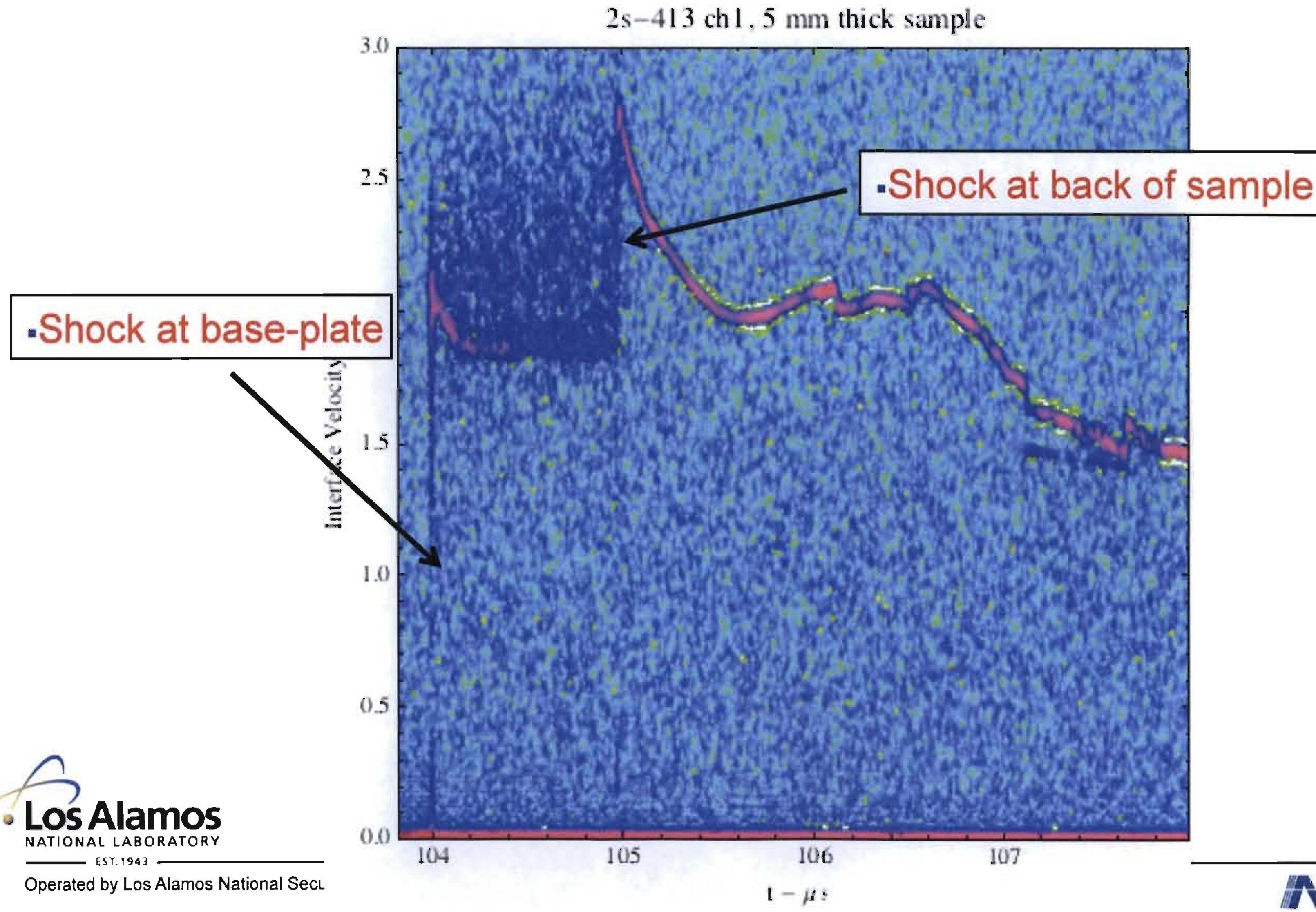
Optical layout and Interferometer setup



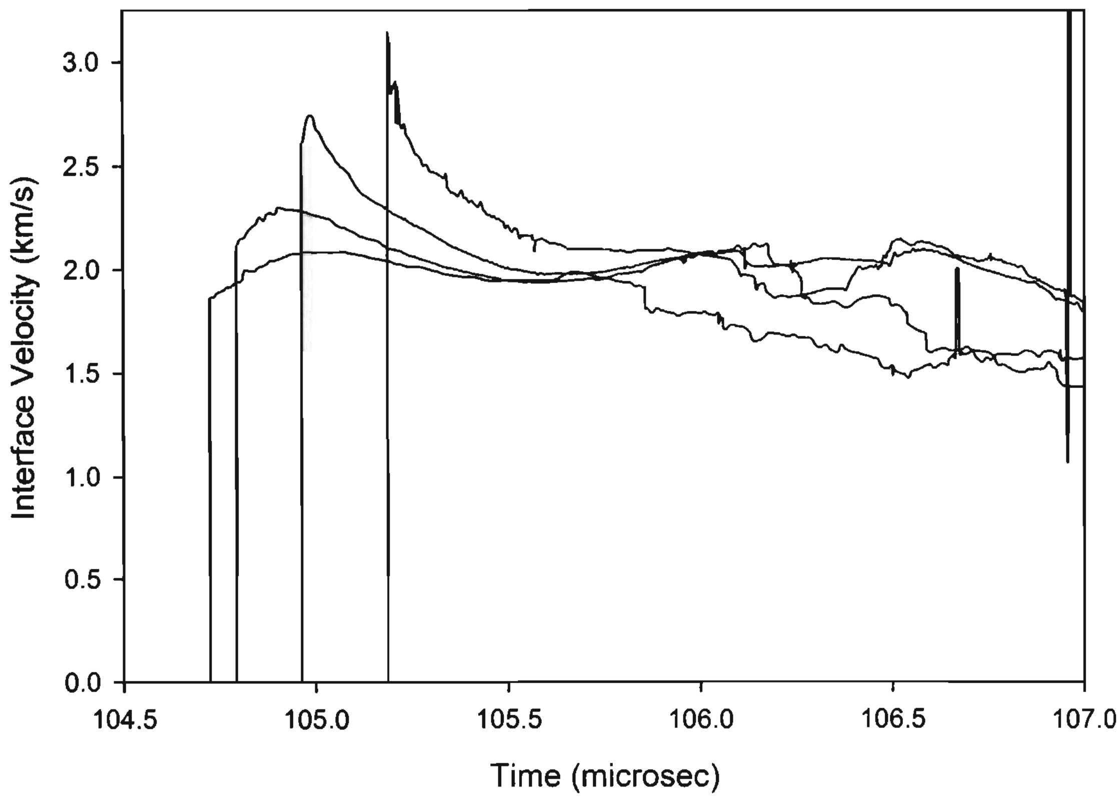
Raw Data (example)



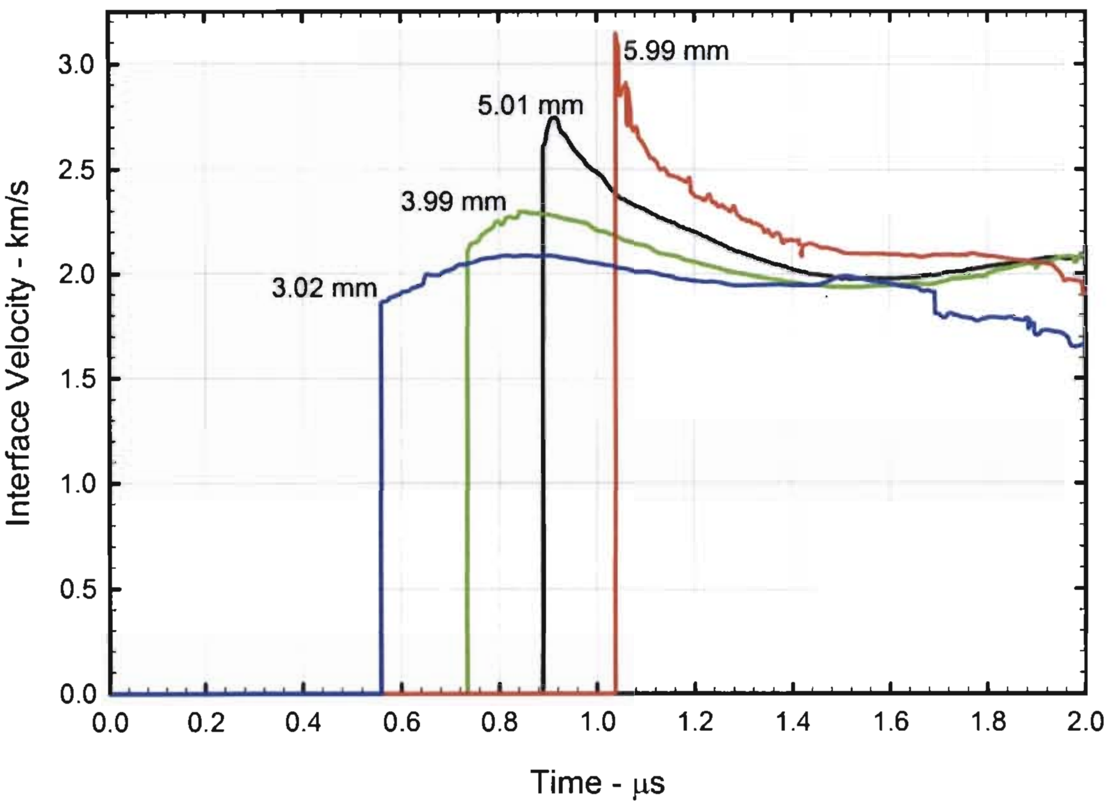
Spectrogram (example)



Shot 2s-413 data prior to correcting for tilt – raw time



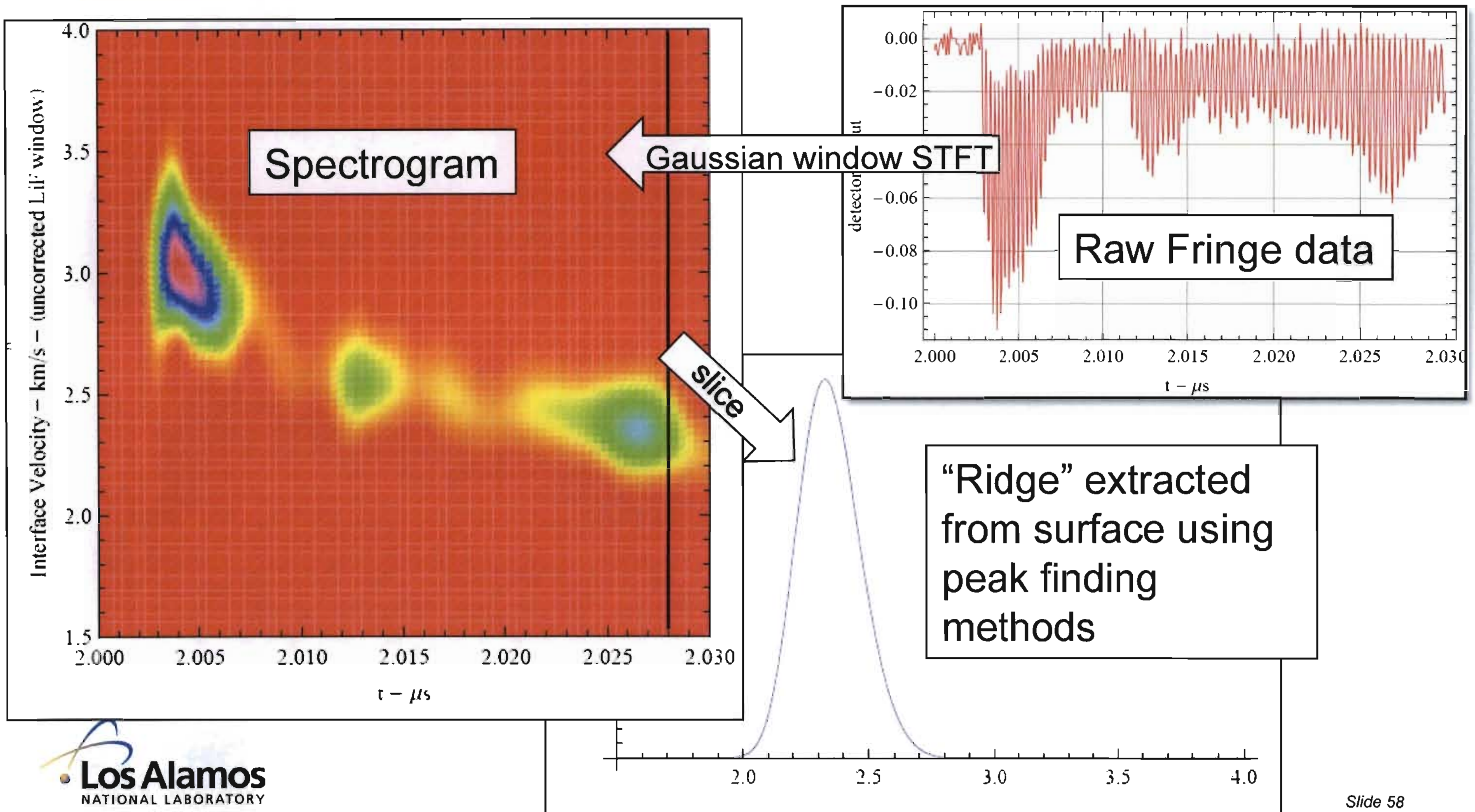
Shot 2s-413 corrected for tilt and time origin



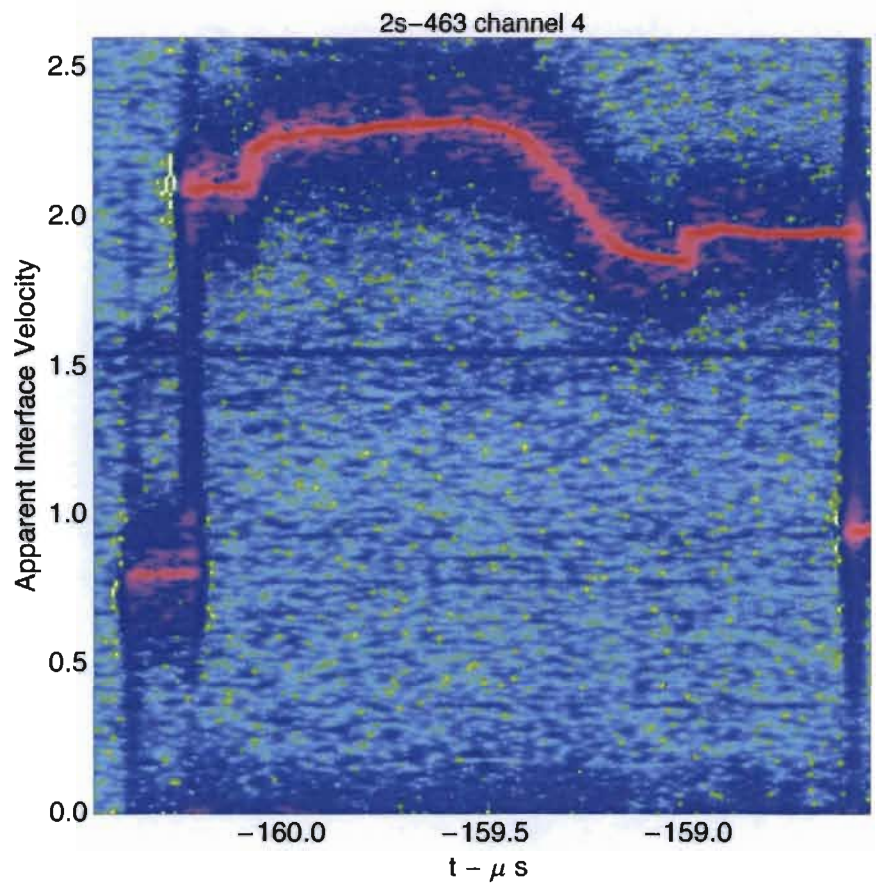
- Impact velocity 2.138 km/s
- Impact Pressure ~ 13.62 Gpa
- Tilt ~ 11 mrad. Top first.
- Nominal distance to detonation 6.2 mm

Part V: Phase unwinding, an alternative analysis method

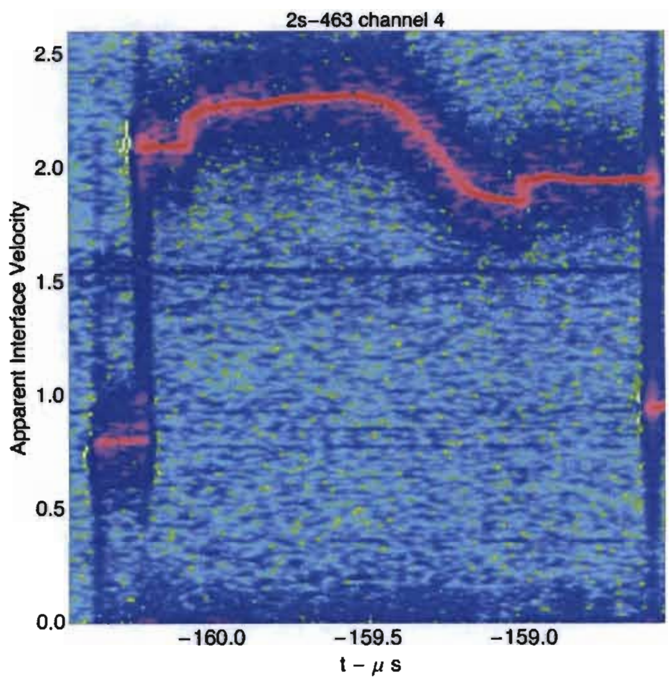
Time vs. Frequency Analysis: "Time resolution" defined by FFT window size.

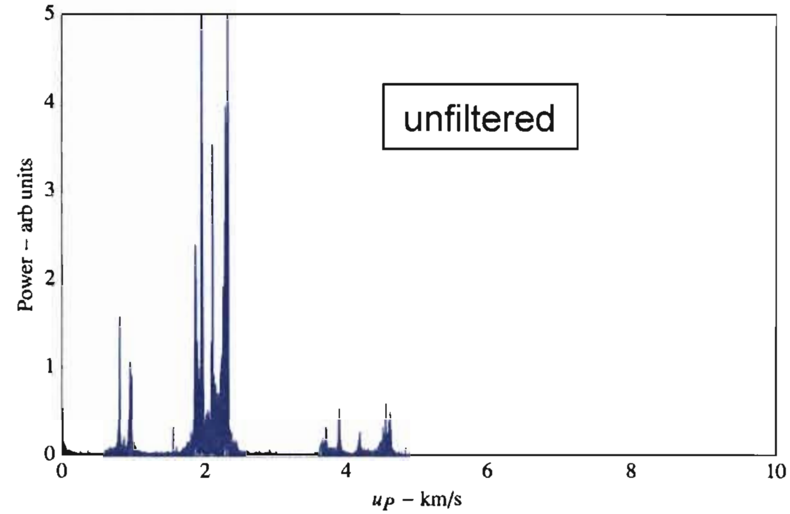


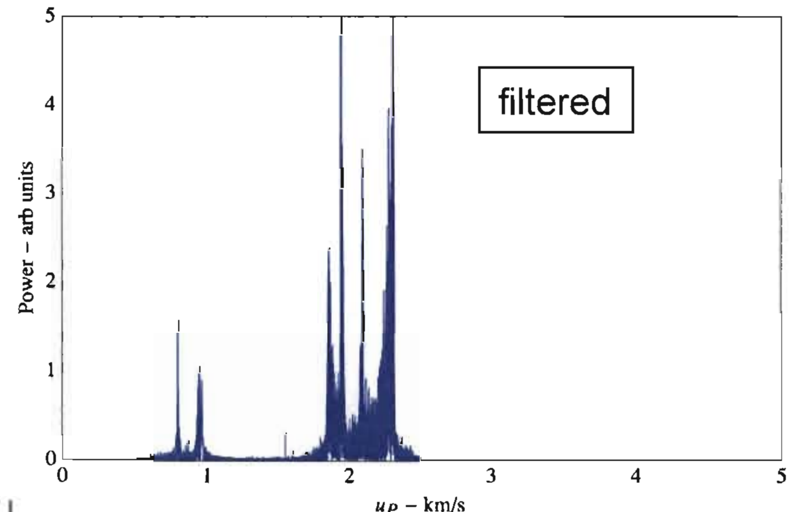
Data Analysis (phase unwinding method):
Step 1 - Examine the spectrogram



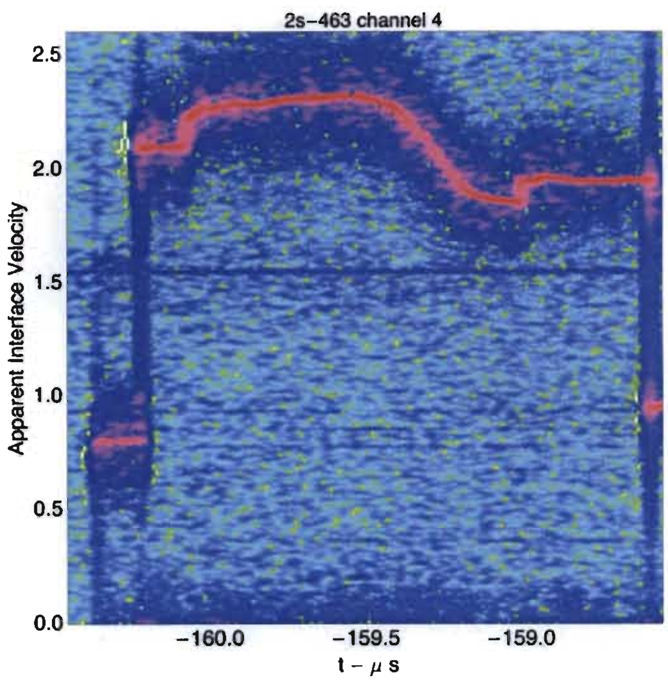
Data Analysis: Step 2 - Plot the Fourier power spectrum (all data)

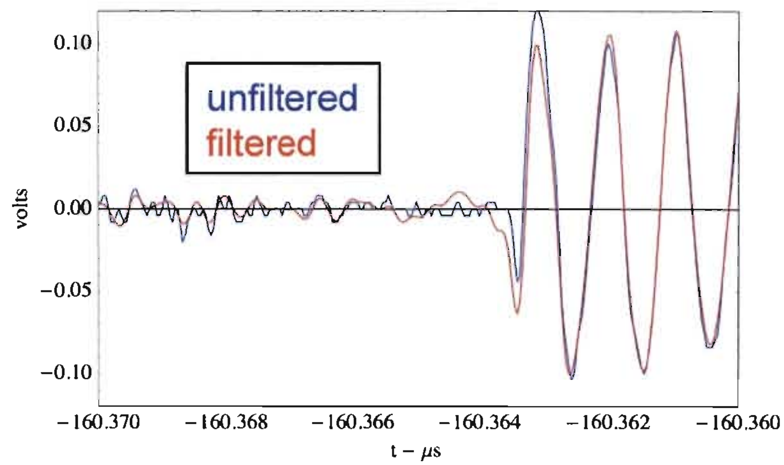


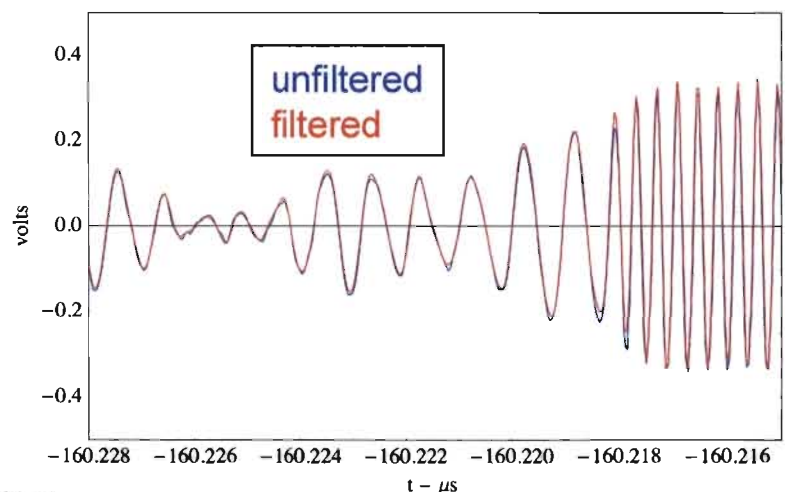




Data Analysis: Step 2 - effect of filtering the data

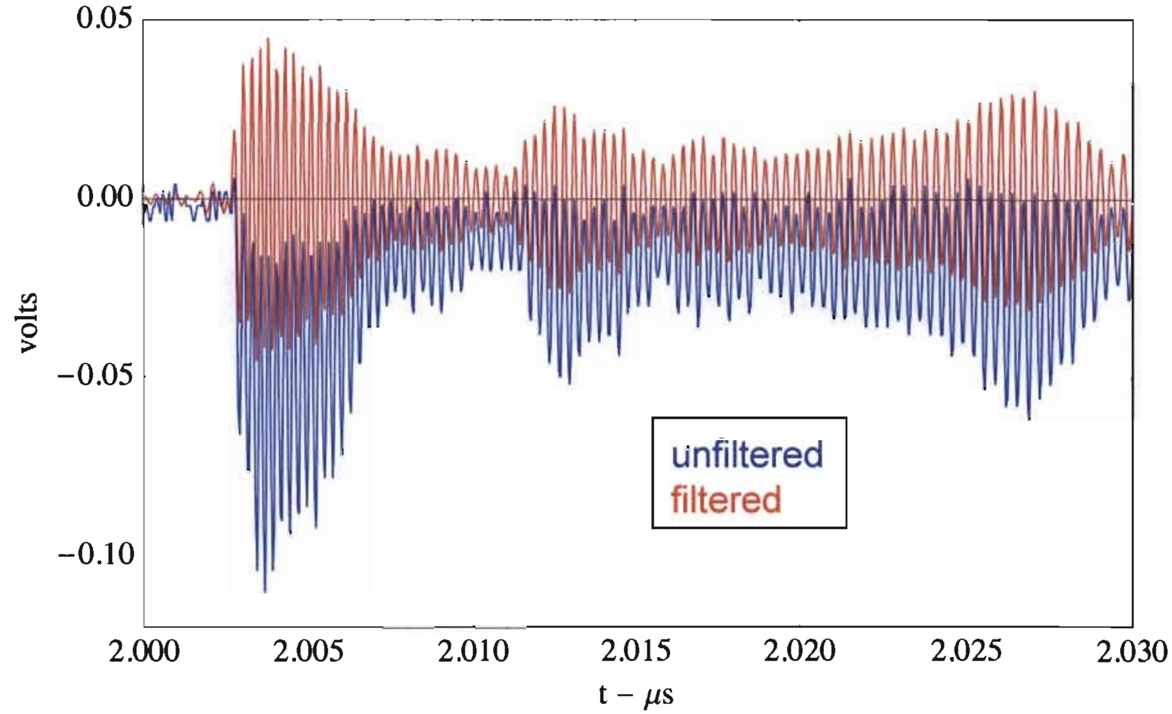






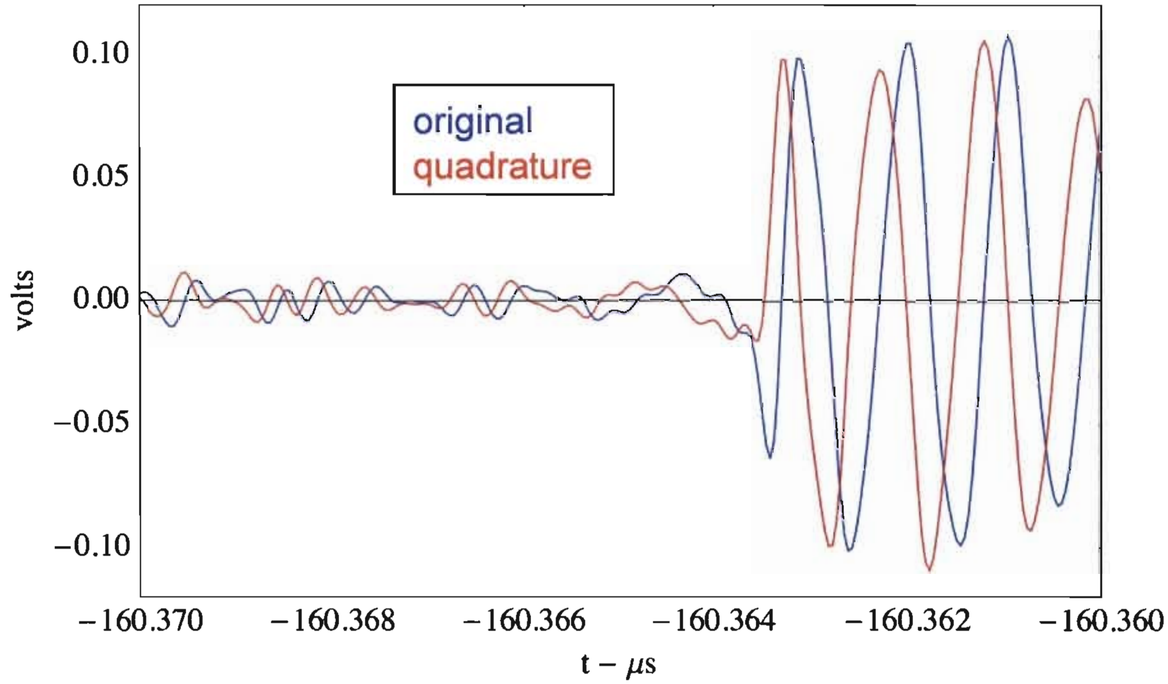
Data Analysis: Step 2 - effect of filtering the data

Low frequency blocking filter removes DC baseline

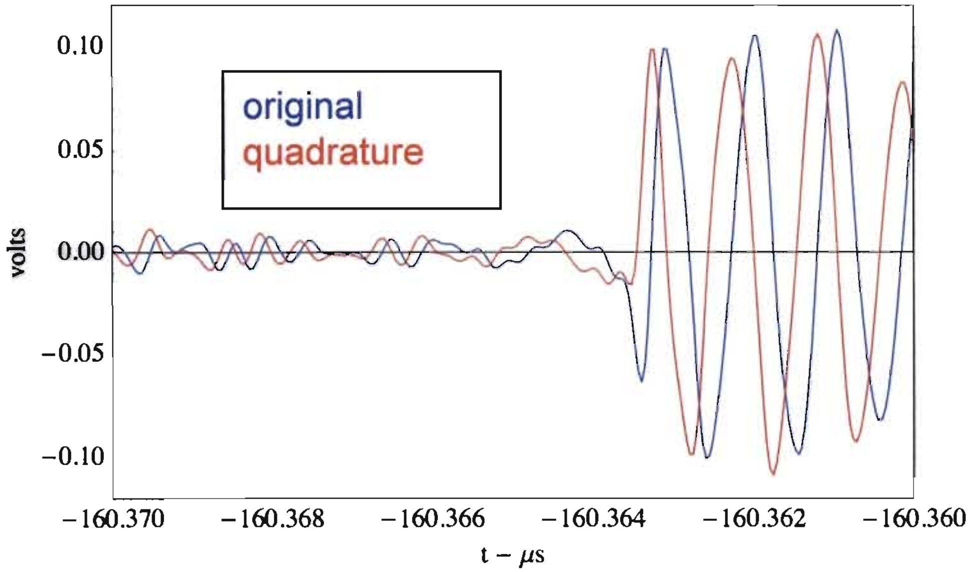


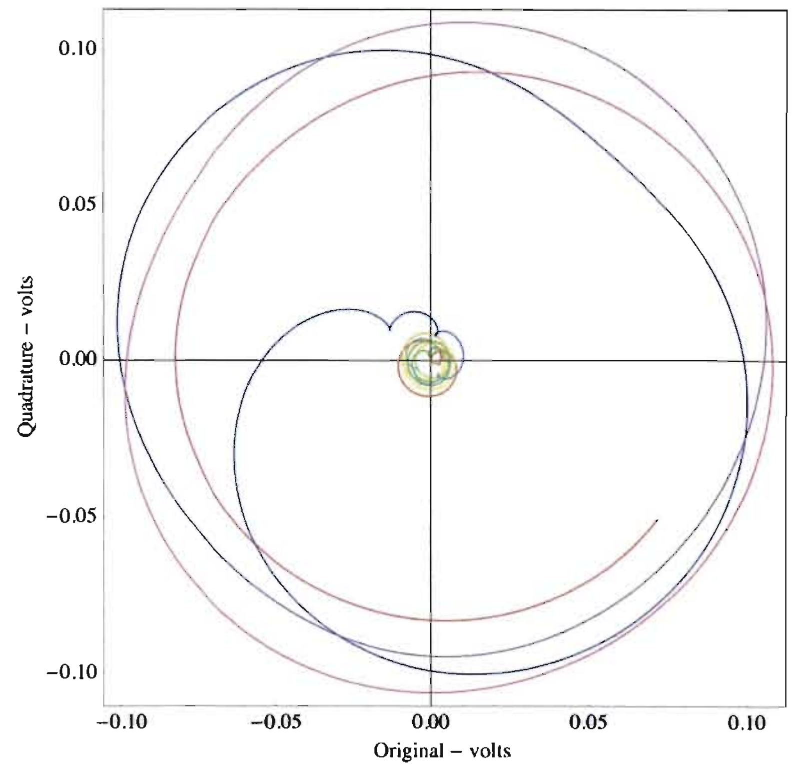
Data Analysis: Step 3 - form quadrature image of signal

1. Fourier transform signal
2. -1 x negative frequency coefficients
3. Inverse transform
4. Also called "Hilbert transform"
5. Quadrature pair called "analytic signal"

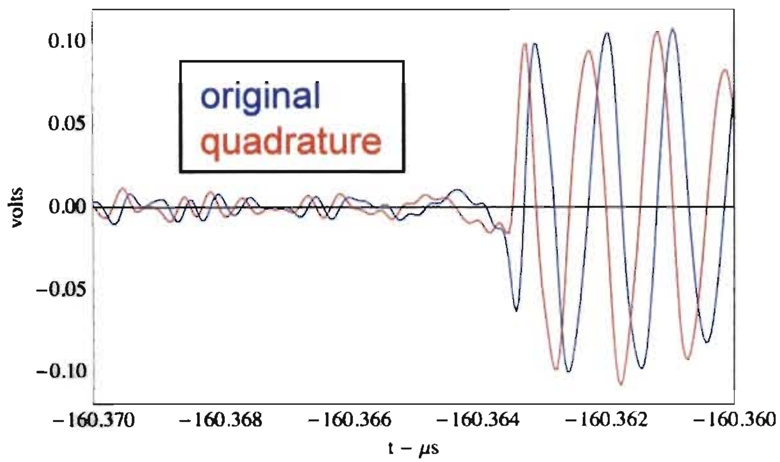


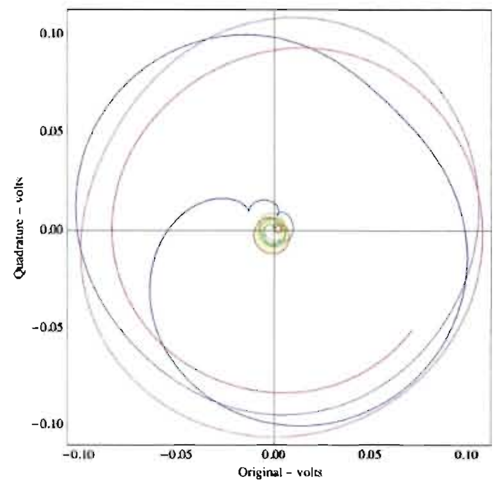
Data Analysis: Step 4 - plot quadrature vs. original signal

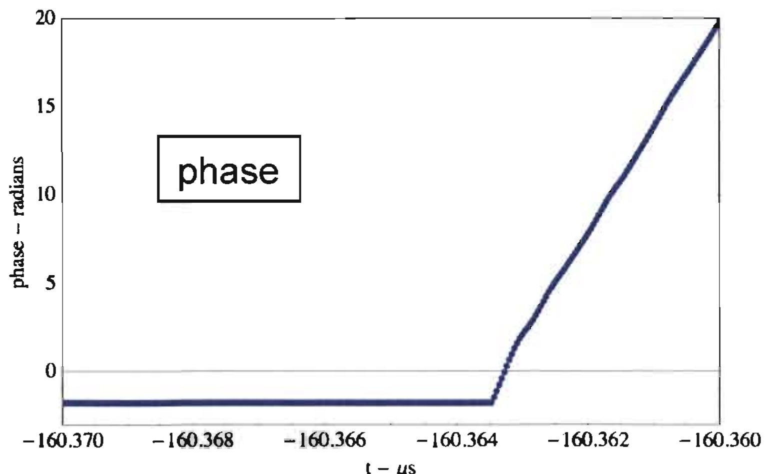




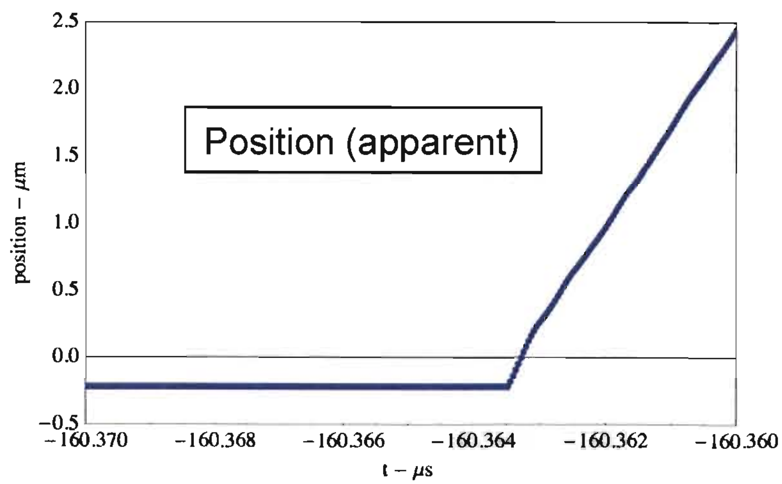
Data Analysis: Step 5 - phase vs. time



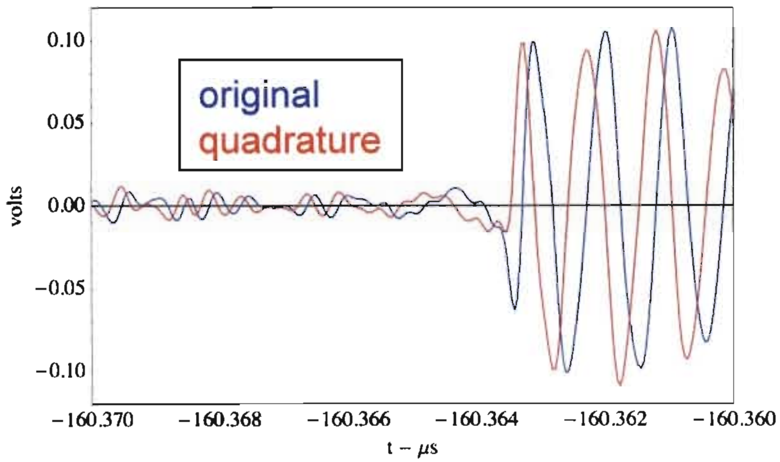


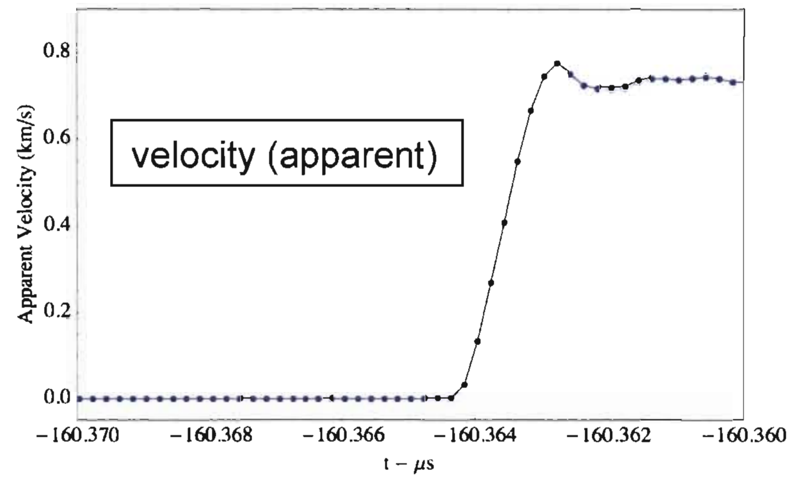


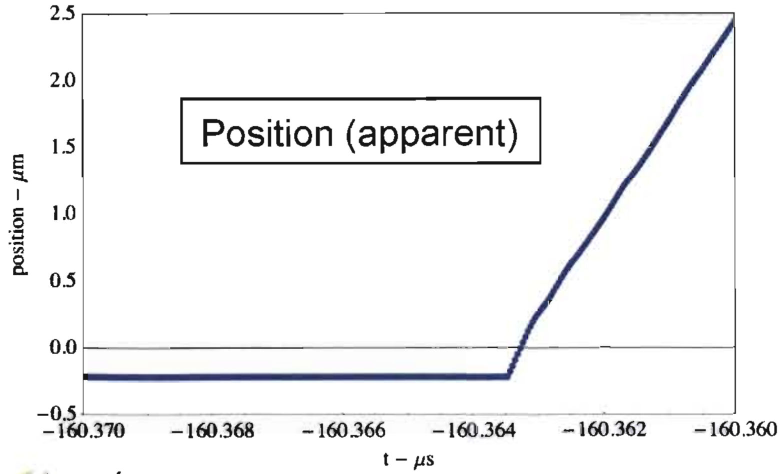
x λ/(4π)



Data Analysis: Step 6 - piecewise fit slope vs. time

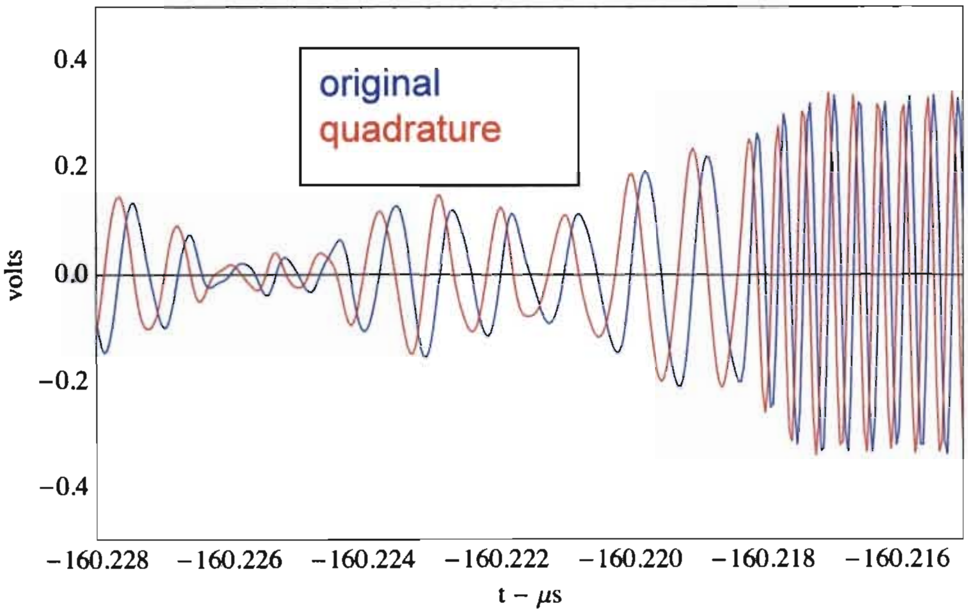


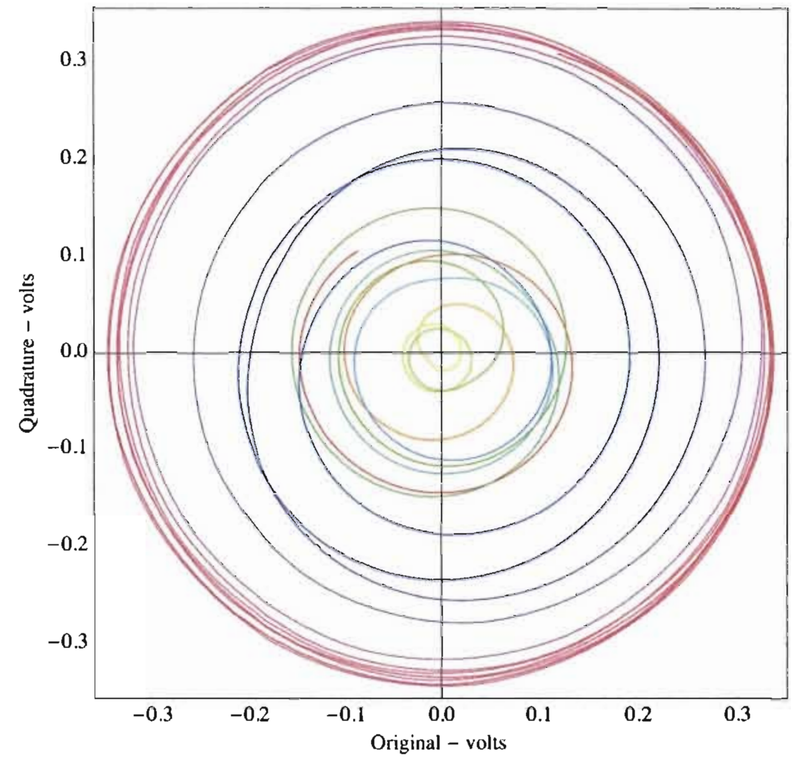




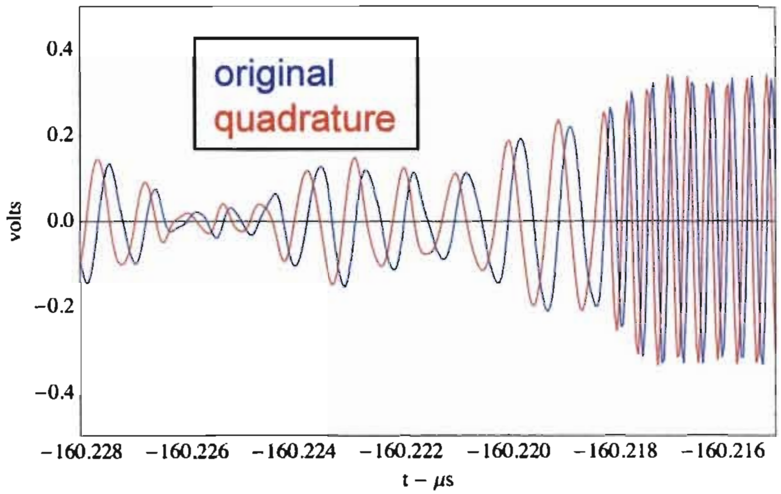
1 ns rise-time (10% - 90%) requires
1.66 ns piece length for fit

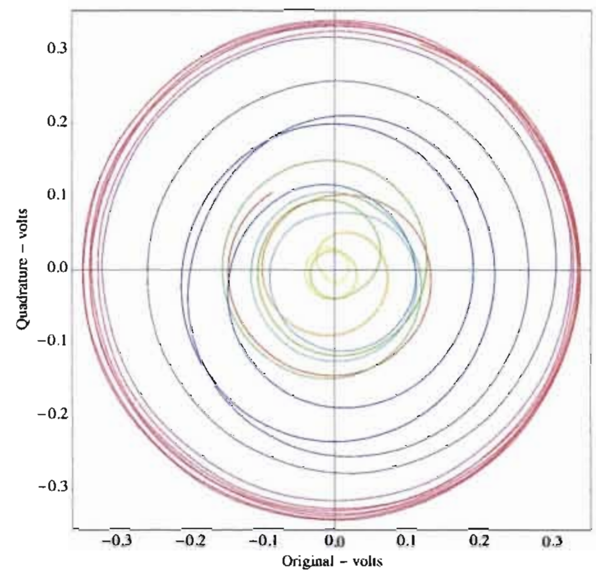
Data Analysis: Step 4 - plot quadrature vs. original signal

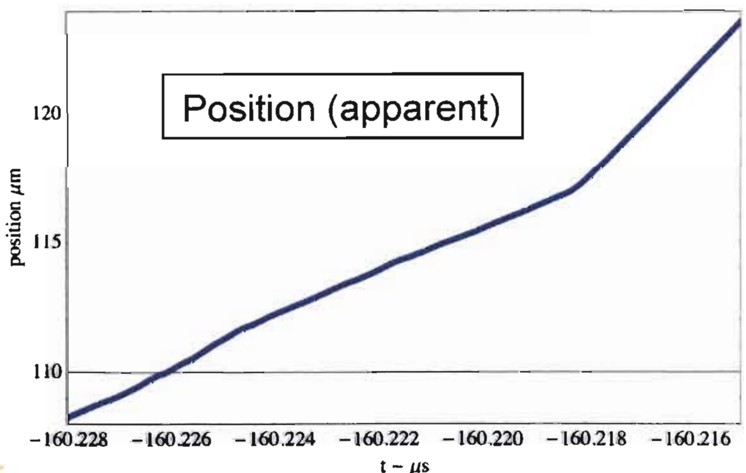




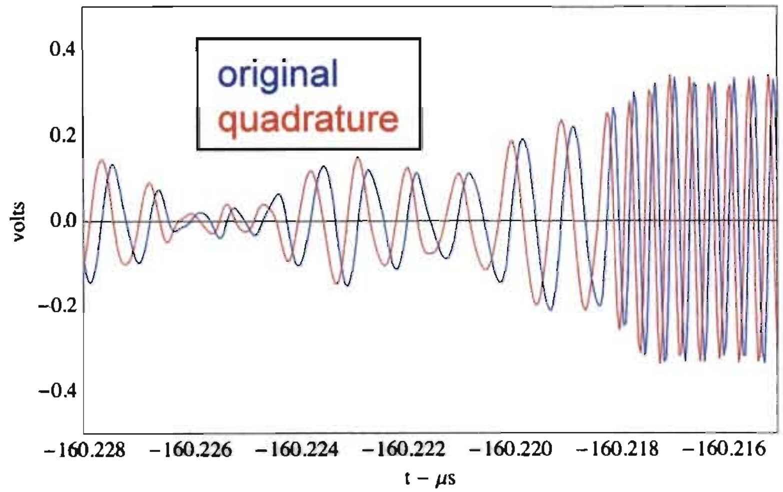
Data Analysis: Step 5 - phase vs. time



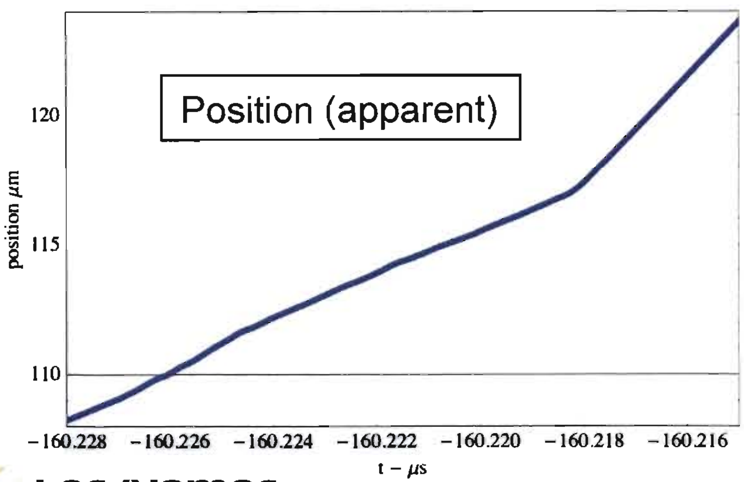


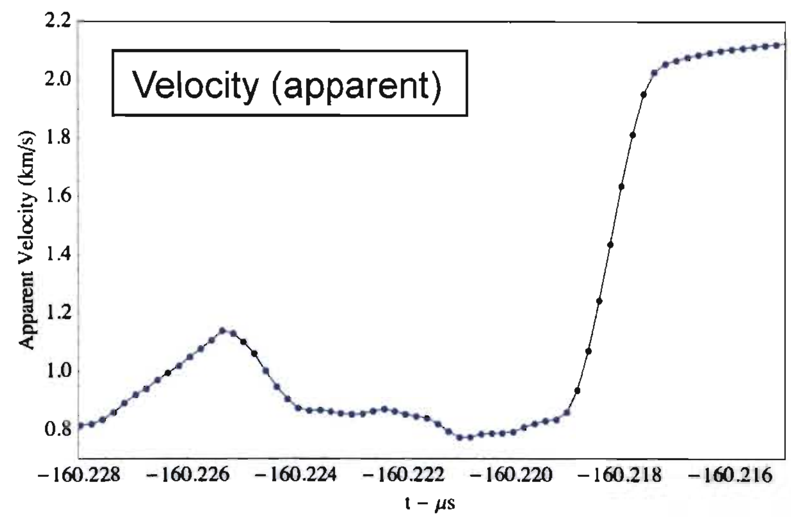


Data Analysis: Step 6 - piecewise fit slope vs. time



Wiggles in velocity correspond to times of low intensity in signal





Credits

- David Holtkamp, Brian Jensen & Adam Iverson for helping me get started.
- Dan Hooks for funding early work.
- Dana Dattelbaum for suggesting new (unique) uses
- Brian Bartram, Nate Sanchez, & Doug Hatch for making assemblies