

# Investigations in the Low Density Shock Tube (LDST)

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Radiation in High Temperature Gases Workshop

Bari, Italy

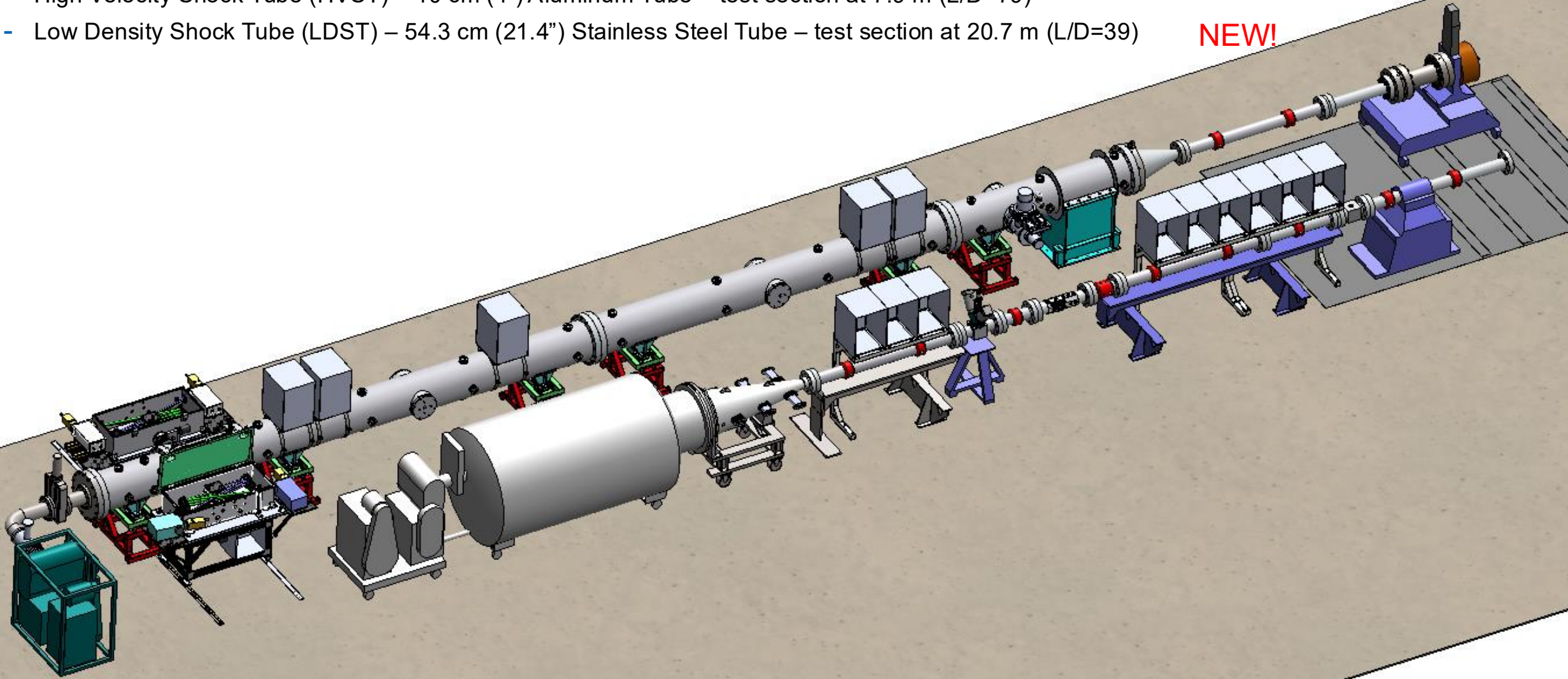
Sep. 23, 2026

# Electric Arc Shock Tube (EAST)



- The Electric Arc Shock Tube (EAST) is capable of simulating high speed flows relevant to entry problems
- Two shock tubes share the same driver:
  - High Velocity Shock Tube (HVST) – 10 cm (4") Aluminum Tube – test section at 7.9 m (L/D=79)
  - Low Density Shock Tube (LDST) – 54.3 cm (21.4") Stainless Steel Tube – test section at 20.7 m (L/D=39)

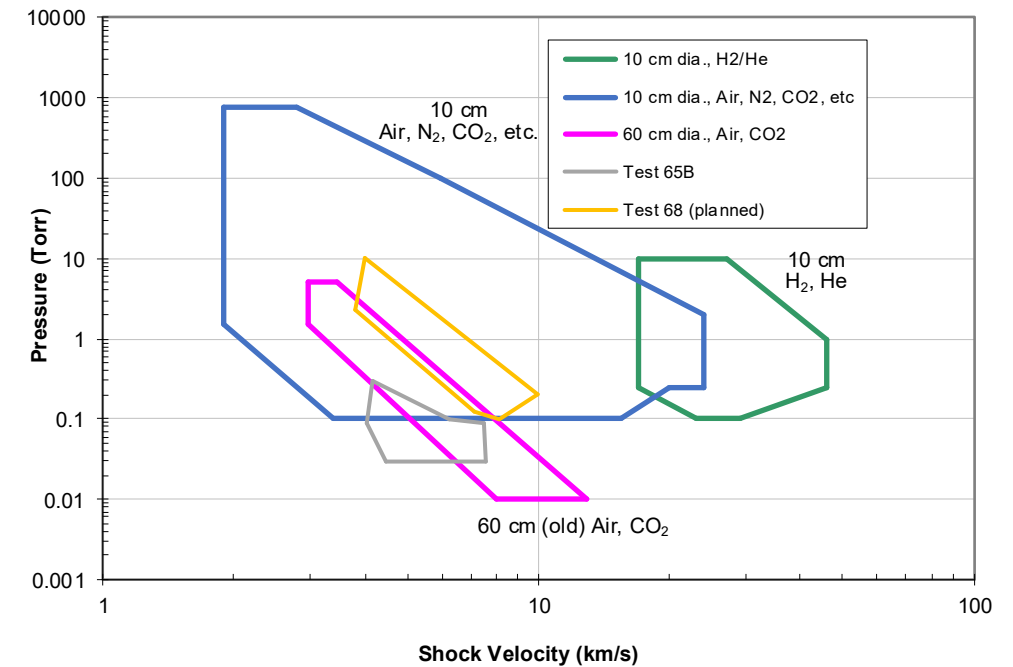
NEW!



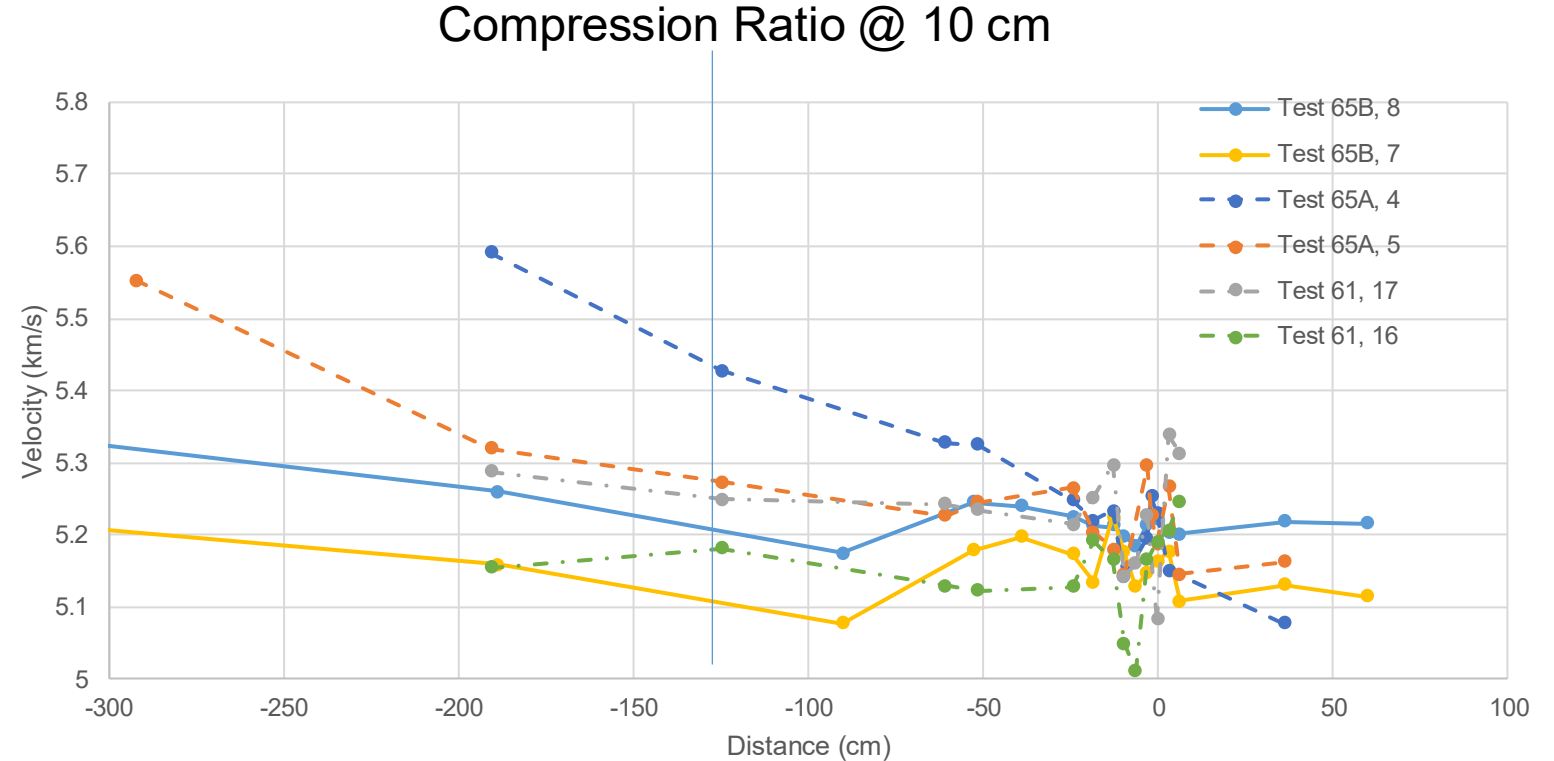
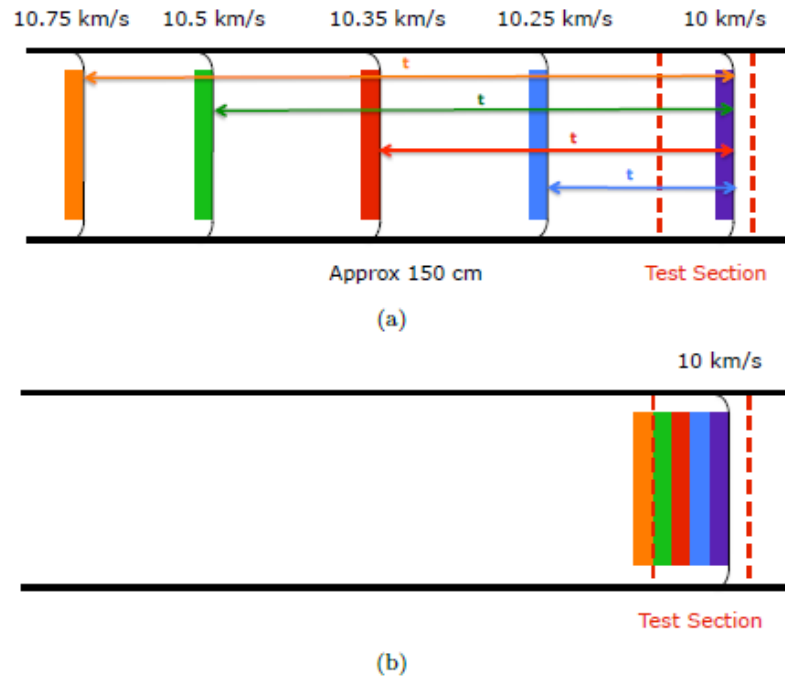
# Low Density Testing



- In 2024, we installed the Low Density Shock Tube (LDST) in the EAST Facility
- LDST diameter is 5.4x larger than EAST High Velocity Tube
- Increased diameter
  - Increases test time as  $PD^2$  (Roshko/Mirels)
    - Enables testing at low density, useful for high mass Mars landers
  - Increases S/N of optical measurements
  - Reduces boundary layer/core flow ratio
    - Reduced deceleration
- Test Series:
  - Test 65B (2024-25): Dragonfly (Titan) high altitude
  - Test 68 (2026-27): Air entries, overlap conditions

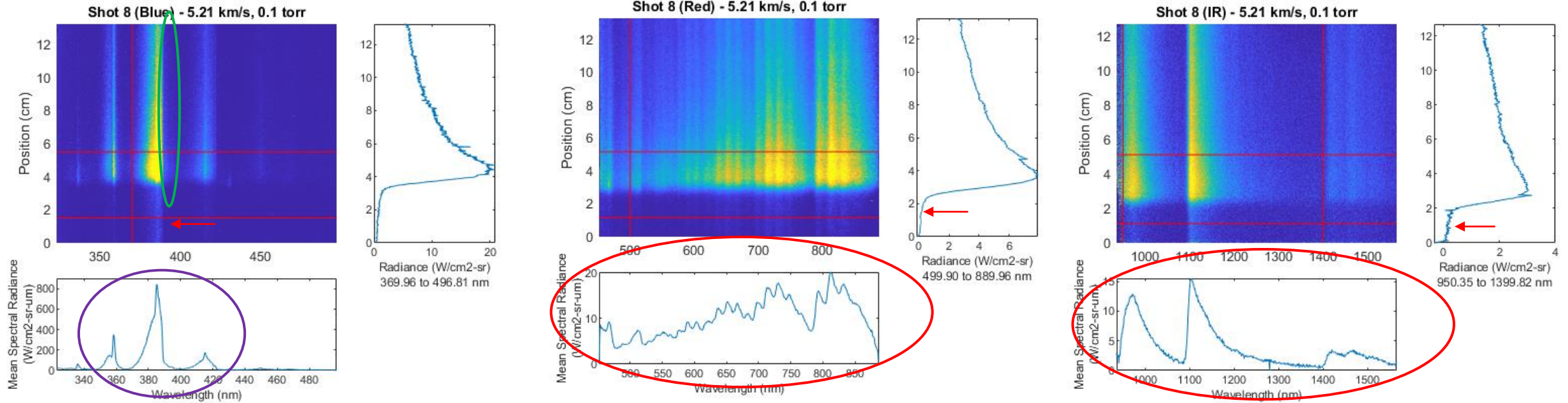


# Shock Velocity Profiles



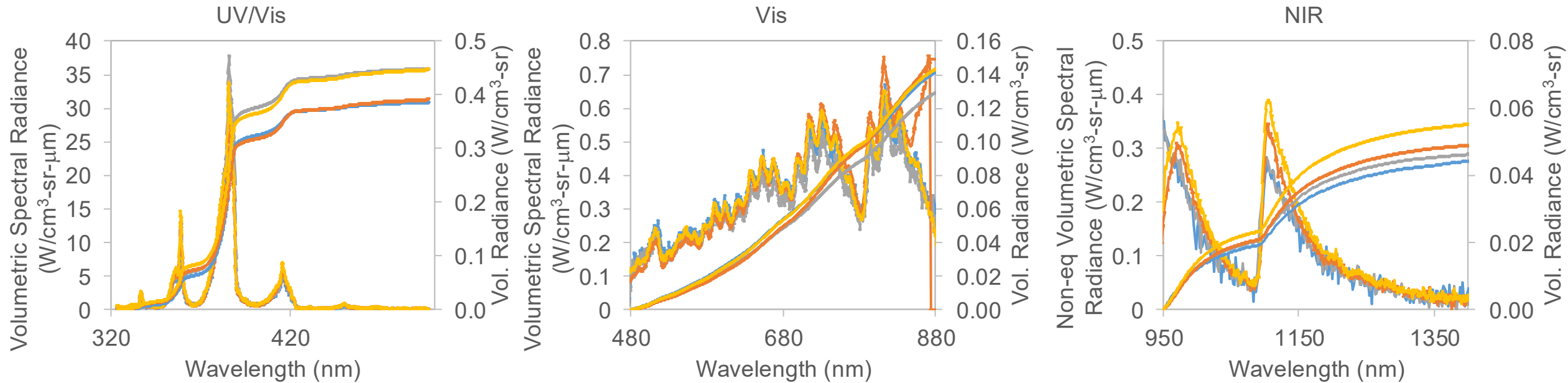
- Shock deceleration impacts the enthalpy profile of test gas in the test section
- Shown are three tests at 5.2 km/s in HVST (Tests 61,65A) and LDST (65B)
  - Noise in test section is due to proximity of sensors: average value reported
  - LDST shows less deceleration than Test 65A, but similar to Test 61

# Sample Data – 5.2 km/s



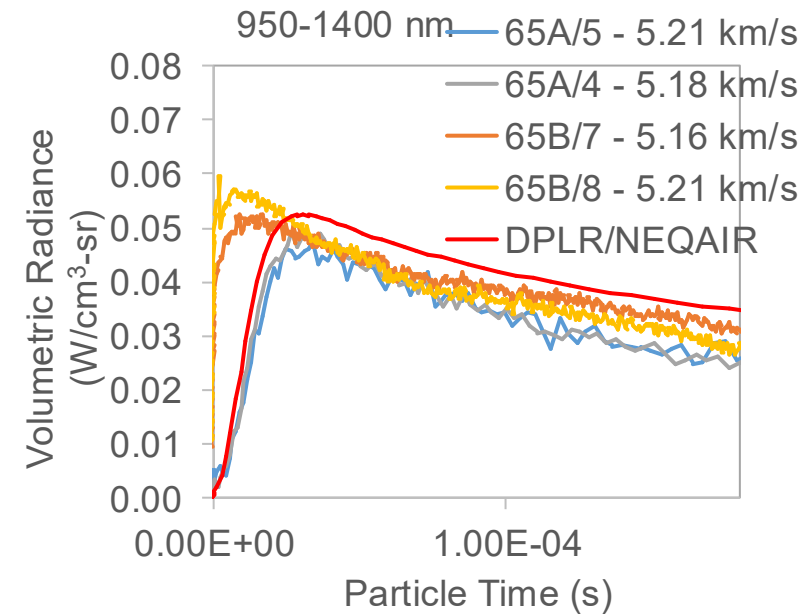
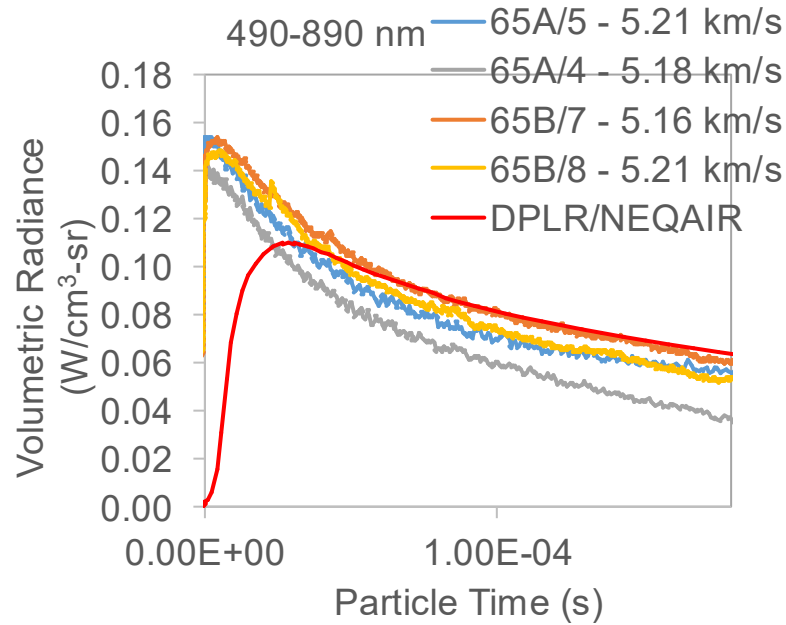
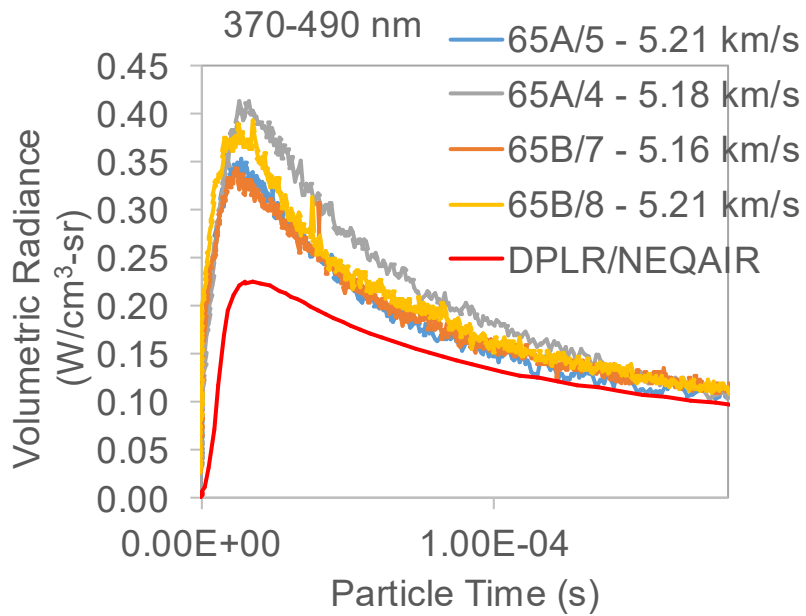
- Spectral and spatial radiance data collected on 4 spectrometers (UV not shown)
- Spectral features
  - CN Red
  - CN Violet
- No test gas contamination
  - Long test times realized
- Significant signal ahead of shock
  - Believed to be due to reflections from tube wall

# Spectral Comparison – LDST to HVST



- Mean spectral radiance within +/-0.5 cm of peak, normalized by Tube Diameter
- UV/Visible (330-490 nm)
  - Variation within test 15%, tube-to-tube comparisons overlap
- Visible (480-890 nm)
  - Variation within test series from 1-10%, mean values agree within 5%
- Infrared (950-1400 nm)
  - 5-13% variation within tests, Test 65B averages 12% higher than 65A
- Test 61 (2017, not shown) is in general agreement with these data

# HVST/LDST Comparison vs Time

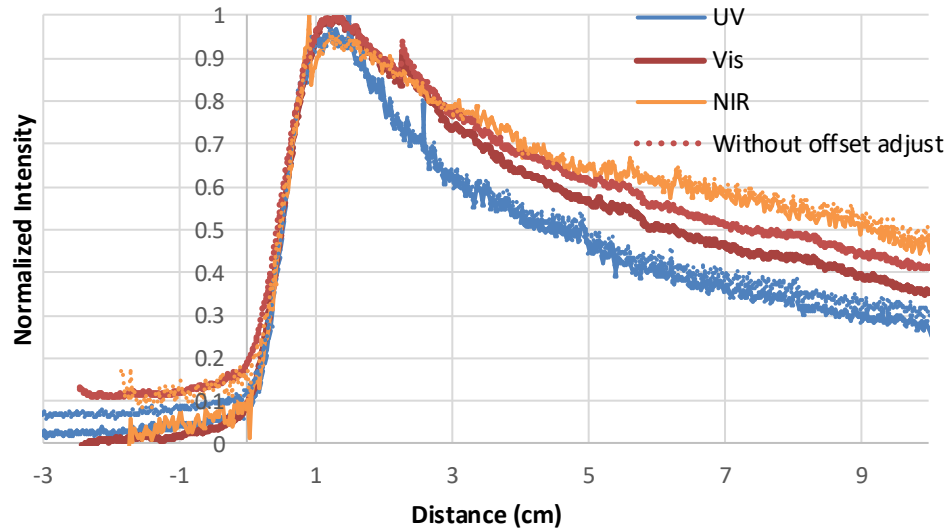


- Necessary to convert x-axis to particle time to compare
- Quantitative agreement obtained between LDST/HVST
  - Shot 65A/4 (greater deceleration) is somewhat an outlier
- DPLR/NEQAIR Comparisons:
  - Underpredicts peak radiance, except in IR
  - Decay rate slower in EAST than prediction
  - Cause of offset in shock location not yet determined
  - These inconsistencies are known from previous shock tube testing
  - Data will be used to improve modeling practices

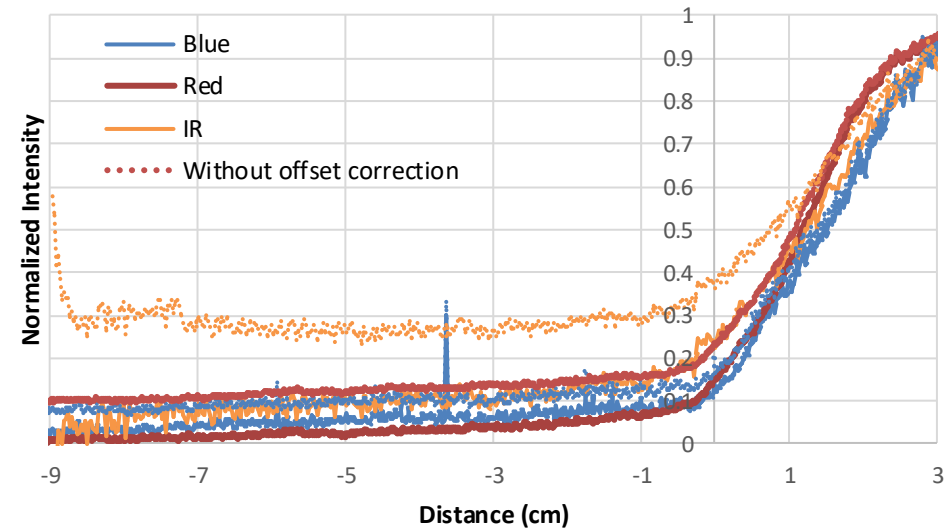
# Scattered Signal



Shot 8 – 5.21 km/s

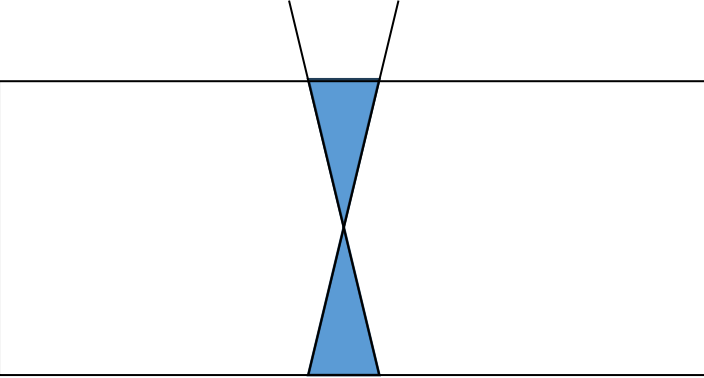


Shot 9 – 4.53 km/s



- All signals are normalized to maximum
- Raw signal shown as dotted lines
- Pre-shock signal can be due to dark charge or scattered light: Solid lines are corrected signal
- Shot 9 had early trigger : shows 10-15% of peak signal after subtraction
- Indicates pre-shock signal may be real – suggests scattering in the tube

# Specular reflectance

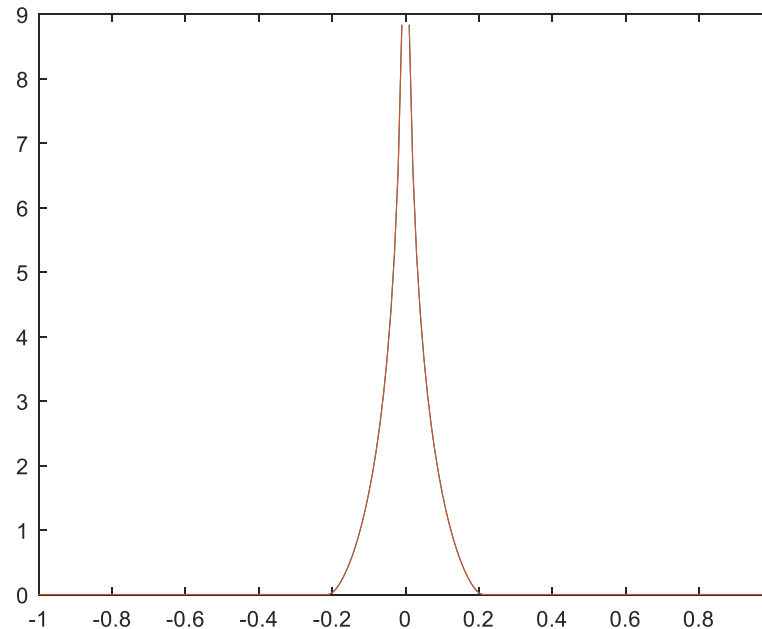


- Radiance Measured is a convolution of the actual radiance with a spatial resolution function (SRF):

$$I_{meas}(x) = \int_{-\infty}^{\infty} SRF(\Delta x) I_{true}(x + \Delta x) d\Delta x = SRF(x) \otimes I_{true}(x)$$

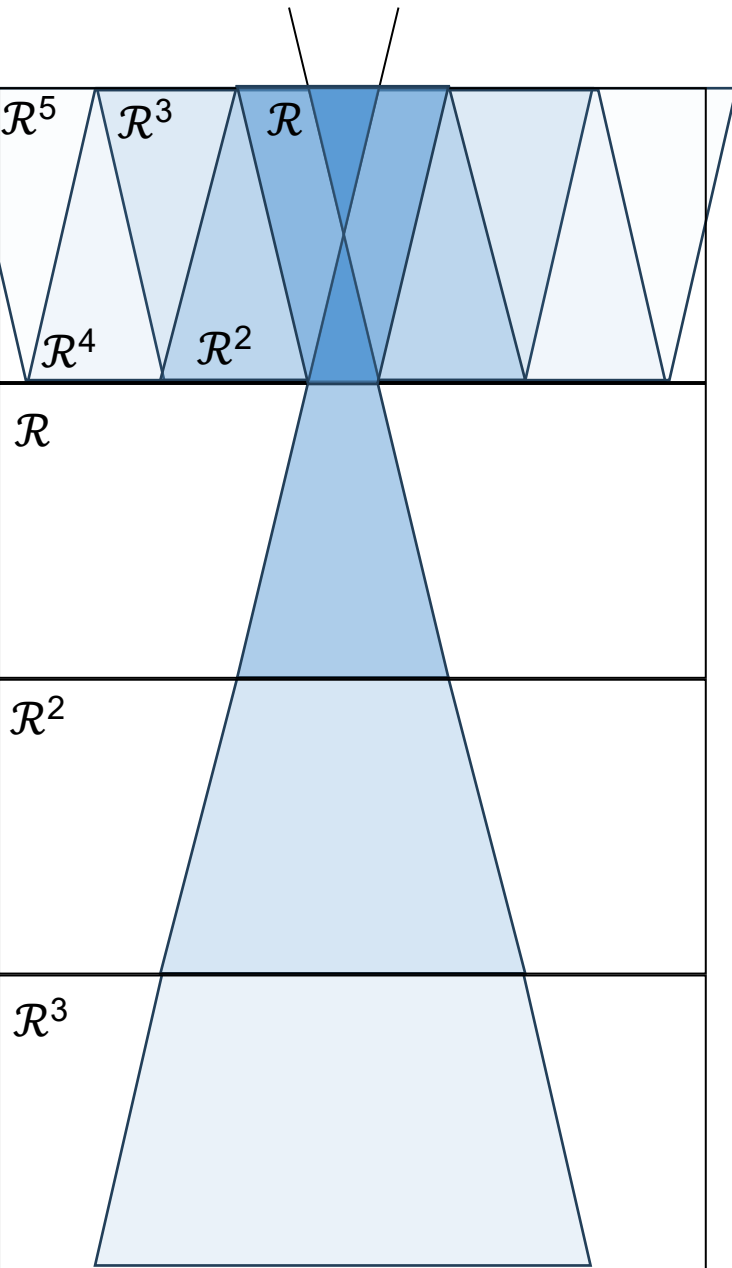
- The optics subtend a biconic volume, which produces the optical portion of the SRF (Cruden, 2014):

$$SRF_0(\Delta x) = \int_{\tan^{-1} \left| \frac{\Delta x}{R} \right|}^{\varphi_m} \frac{\tan \varphi_e R d\theta}{\sin \theta \cos^2 \theta}$$



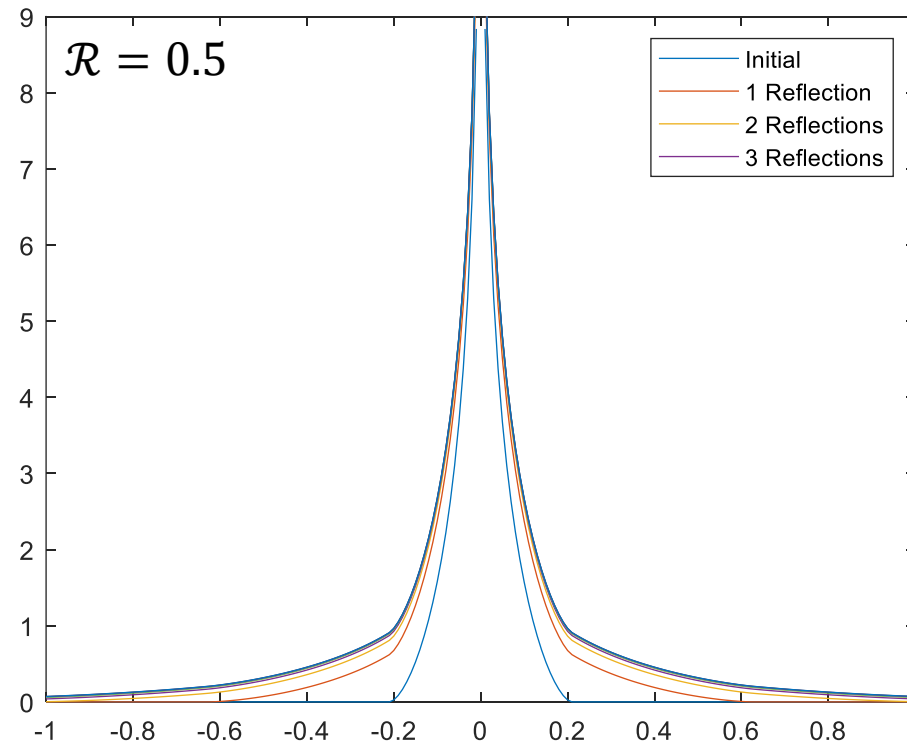
# Specular reflectance

- Each reflection extends the volume with reflectance  $\mathcal{R}$
- Equivalent to propagating the cone through successive tube diameters (ignoring wall curvature)

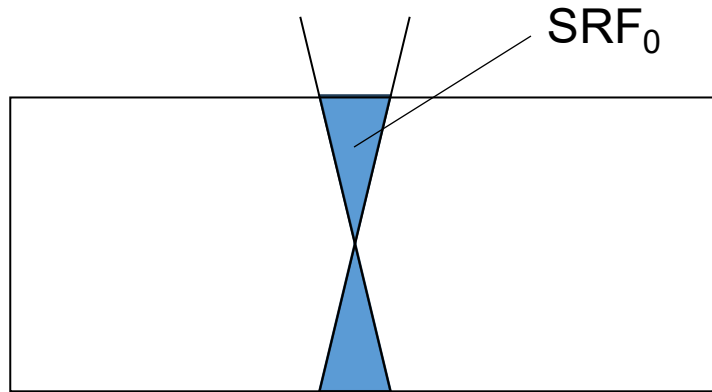


$$SRF(\Delta x) = SRF_0(\Delta x) + \sum \mathcal{R}^n SRF_n(\Delta x)$$

$$SRF_n(\Delta x) = \int_{\tan^{-1}\left|\frac{\Delta x}{(2n+1)R}\right|}^{\min(\varphi_m, \tan^{-1}\left|\frac{\Delta x}{(2n-1)R}\right|)} \frac{\tan \varphi_e R d\theta}{\sin \theta \cos^2 \theta}$$

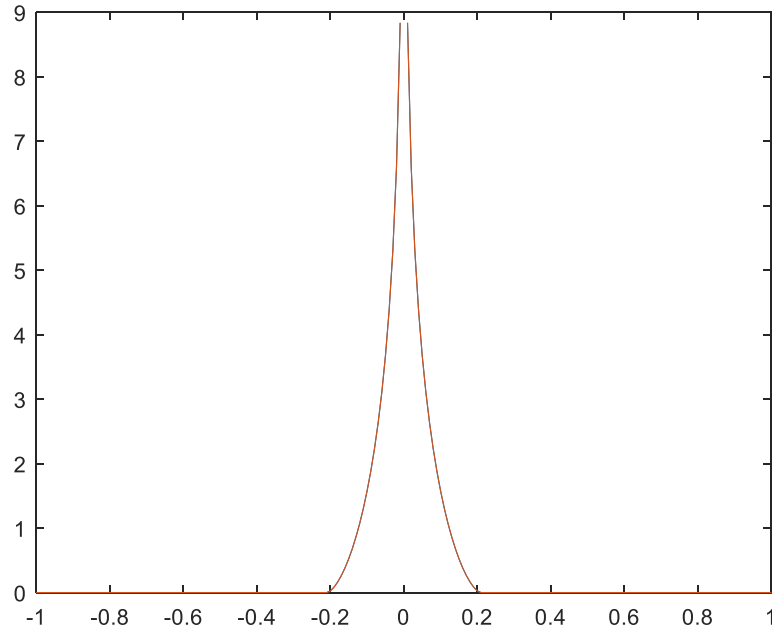


# Diffuse Reflectance

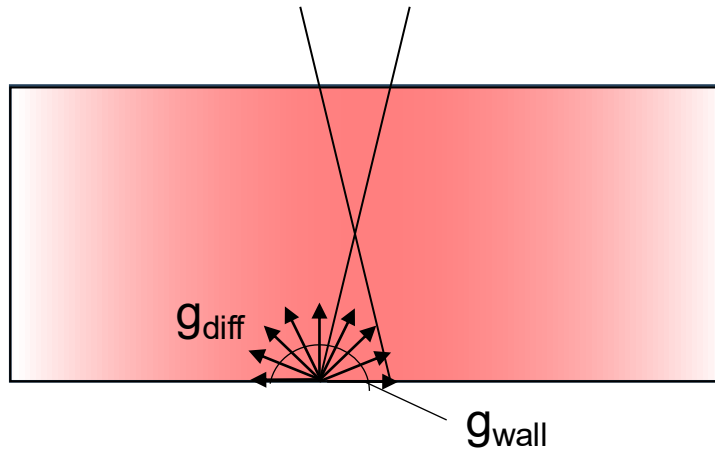


- For diffusely reflecting wall:  $SRF(\Delta x) = \sum \mathcal{R}^n SRF_n(\Delta x)$
- 0 reflections: bi-conic  $SRF_0$  as given previously

$$SRF_0(\Delta x) = \int_{\tan^{-1} \left| \frac{\Delta x}{R} \right|}^{\varphi_m} \frac{\tan \varphi_e R d\theta}{\sin \theta \cos^2 \theta}$$



# Diffuse Reflectance



- For diffusely reflecting wall:  $SRF(\Delta x) = \sum \mathcal{R}^n SRF_n(\Delta x)$
- 0 reflections: bi-conic  $SRF_0$  as given previously
- 1 reflection: Conical wall transfer function:

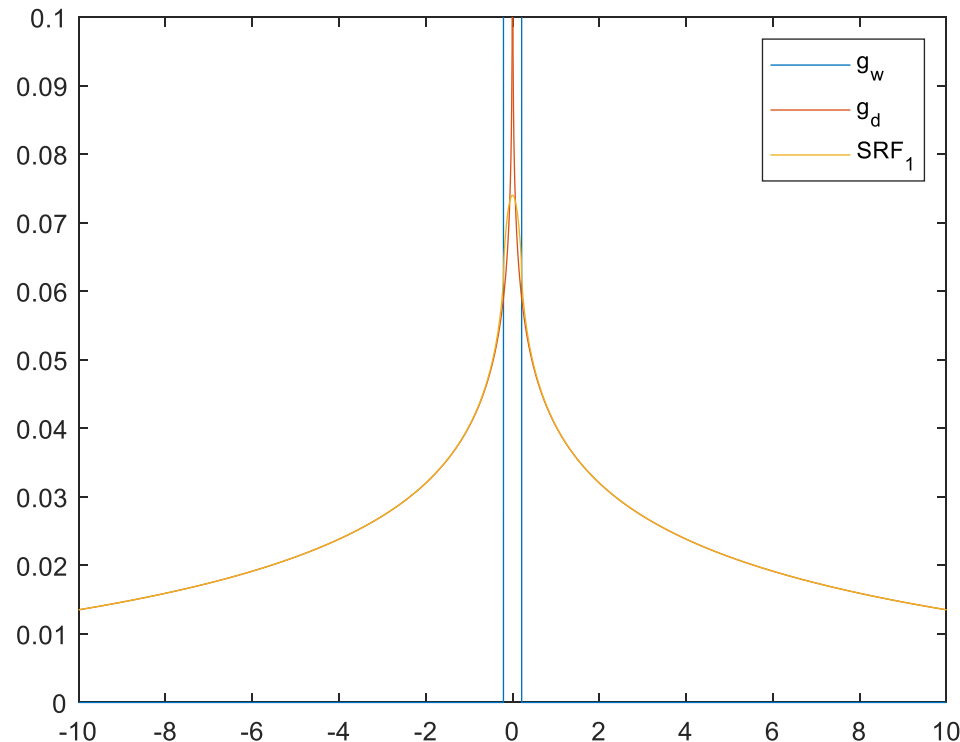
$$g_w(\Delta x) = (R^2 + \Delta x^2) \ln \left( \frac{1 + \sin \varphi_e}{1 - \sin \varphi_e} \right)$$

Diffuse transfer through medium to wall:

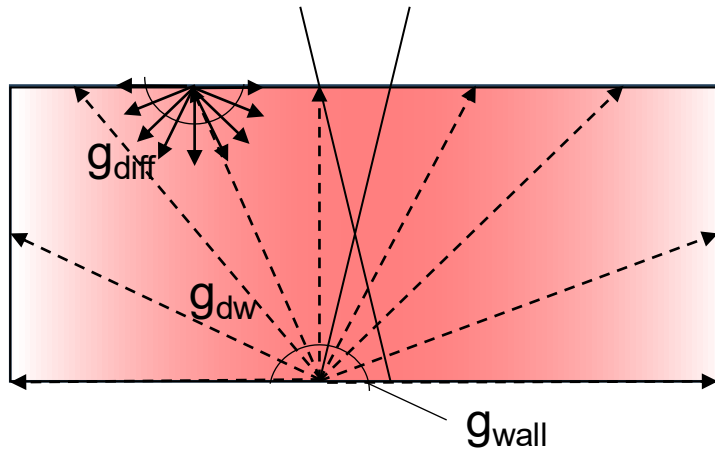
$$g_d(\Delta x) = \frac{1}{2\pi R} \int_{\tan^{-1} \left| \frac{\Delta x}{2R} \right|}^{\frac{\pi}{2}} \int_0^{\varphi_{max}(\theta, \Delta x)} \frac{\cos \theta}{\cos \varphi} d\varphi d\theta$$

Convolve:

$$SRF_1(\Delta x) = g_w(\Delta x) \otimes g_d(\Delta x)$$

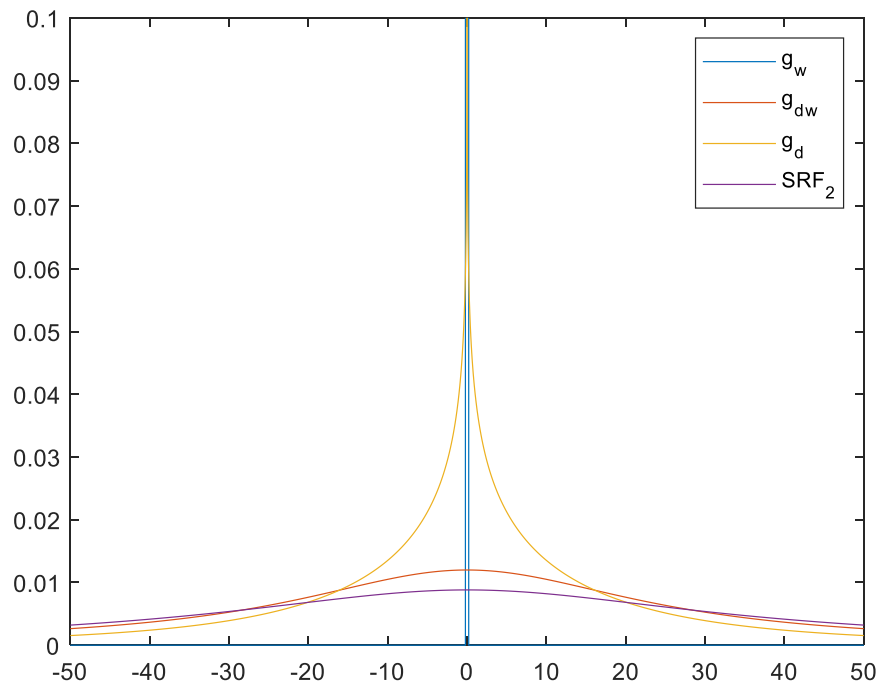


# Diffuse Reflectance



- For diffusely reflecting wall:  $SRF(\Delta x) = \sum \mathcal{R}^n SRF_n(\Delta x)$
- 0 reflections: bi-conic  $SRF_0$  as given previously
- 1 reflection: Conical wall transfer function, convolved with diffuse collection through the medium

$$SRF_1(\Delta x) = g_w(\Delta x) \otimes g_d(\Delta x)$$



- 2 reflections: Conical wall transfer function:  $g_w(\Delta x)$

Diffuse wall transfer function:

$$g_{dw}(\Delta x) = \frac{1}{\pi R} \left[ \left( \frac{\Delta x}{R} \right)^2 + 1 \right]^{-1}$$

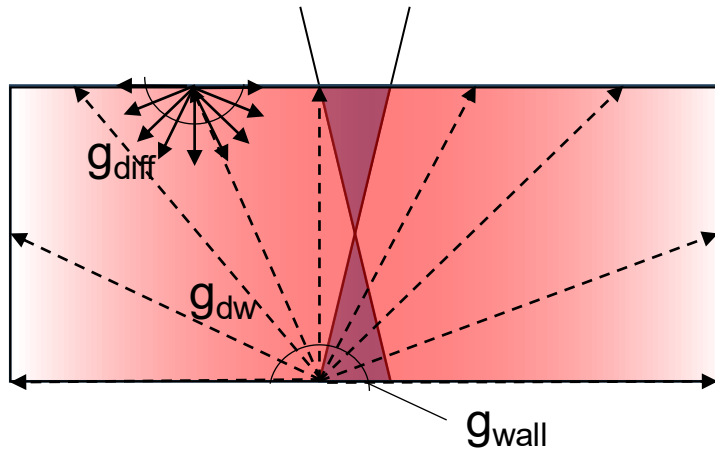
Collection through the medium:

$$g_d(\Delta x)$$

Convolve:

$$SRF_2(\Delta x) = g_w(\Delta x) \otimes g_{dw}(\Delta x) \otimes g_d(\Delta x) = SRF_1(\Delta x) \otimes g_{dw}(\Delta x)$$

# Diffuse Reflectance



- For diffusely reflecting wall:  $SRF(\Delta x) = \sum \mathcal{R}^n SRF_n(\Delta x)$
- 0 reflections: bi-conic  $SRF_0$  as given previously
- 1 reflection:  $SRF_1(\Delta x) = g_w(\Delta x) \otimes g_d(\Delta x)$
- 2 reflection:  $SRF_2(\Delta x) = SRF_1(\Delta x) \otimes g_{dw}(\Delta x)$
- N reflections:

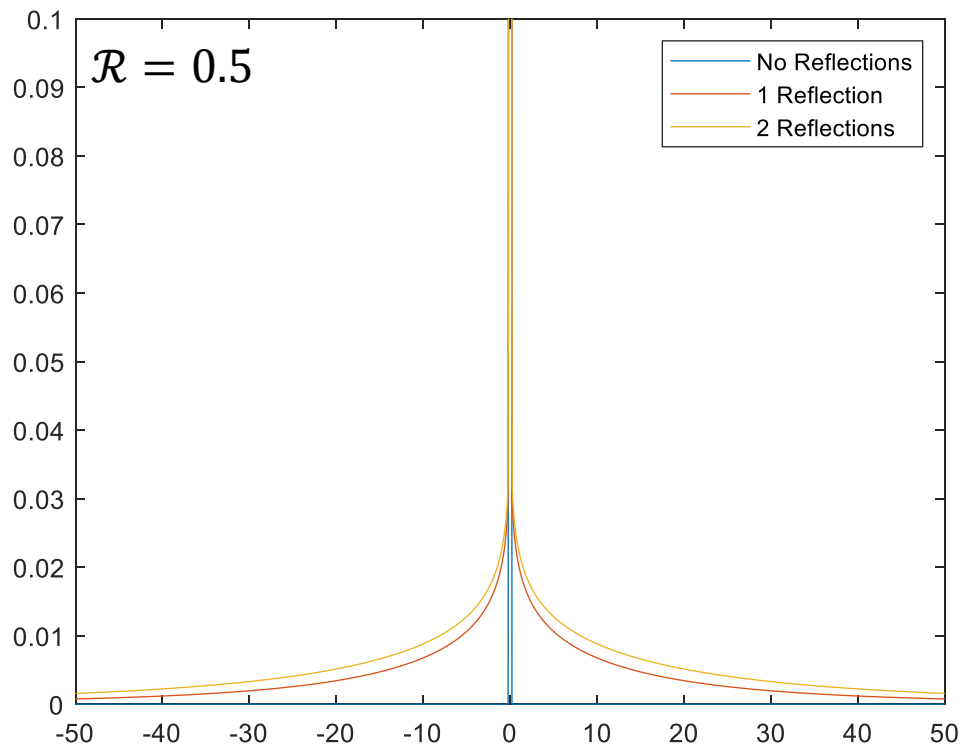
Conical wall transfer function

N diffuse wall transfer functions

Collection through the medium

$$SRF_N(\Delta x) = g_w(\Delta x) \otimes g_{dw}(\Delta x) \cdots \otimes g_{dw}(\Delta x) \otimes g_d(\Delta x)$$

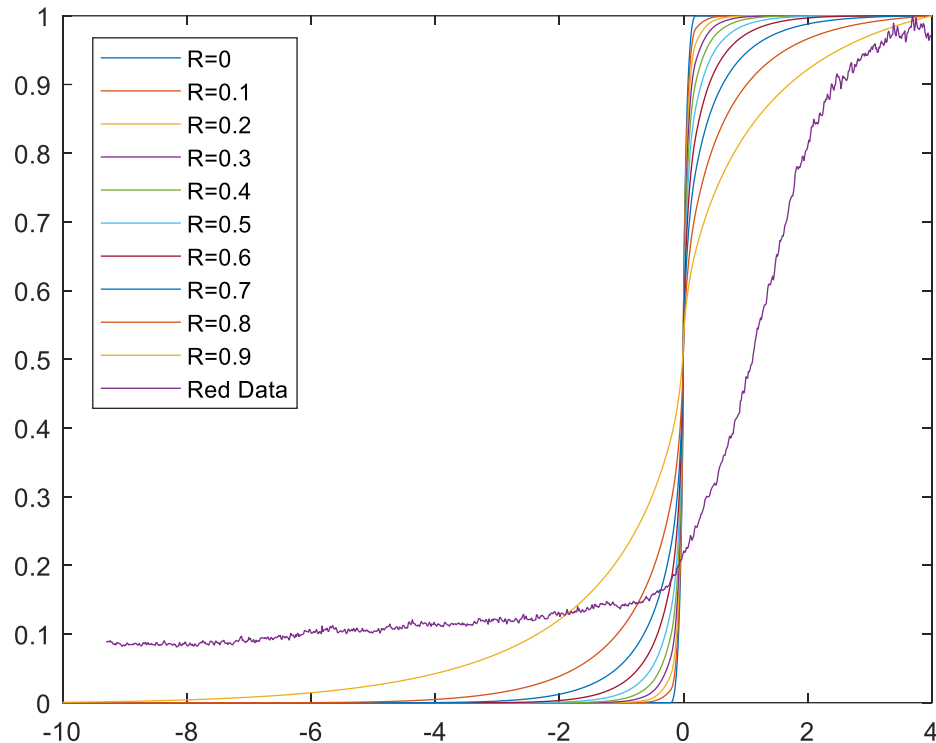
$$= SRF_{N-1}(\Delta x) \otimes g_{dw}(\Delta x)$$



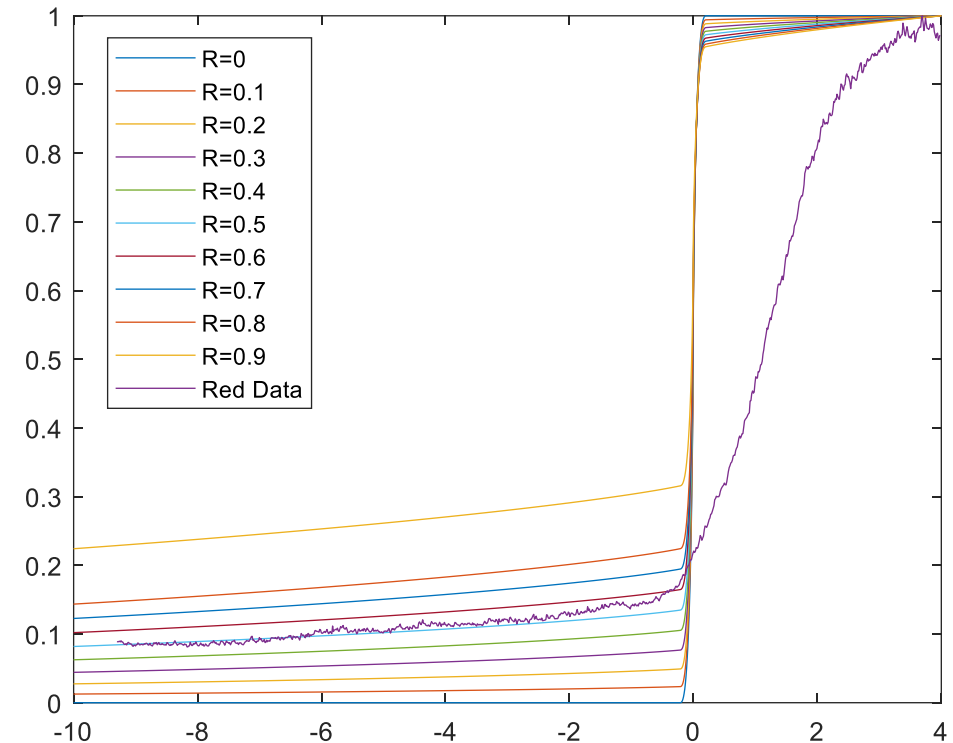
# Compare SRFs on Step (Heaviside) Function



Specular

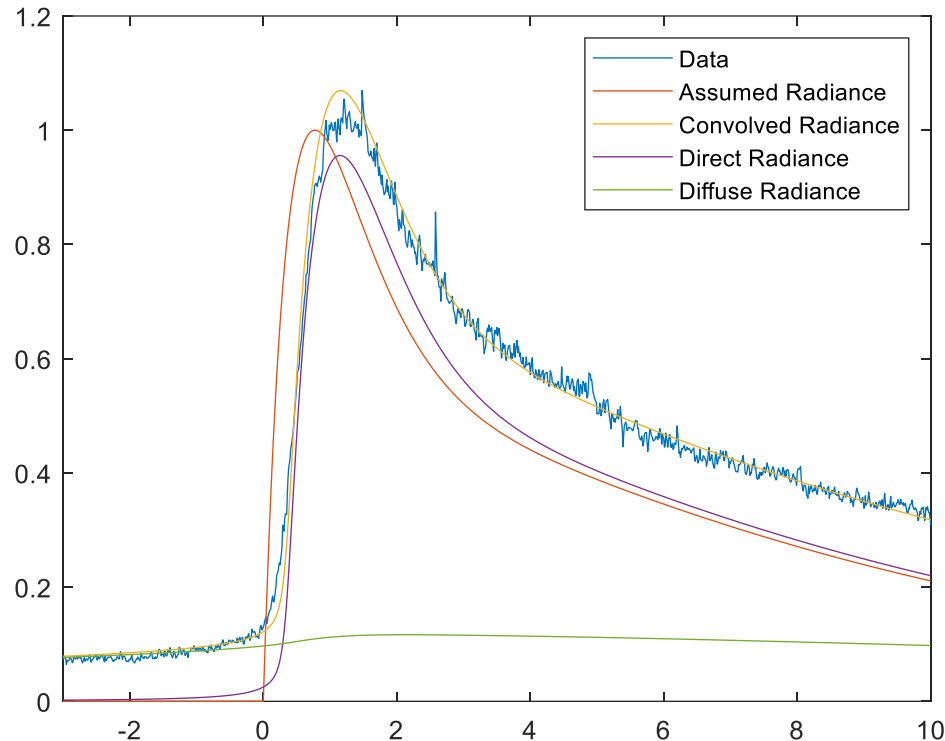


Diffuse

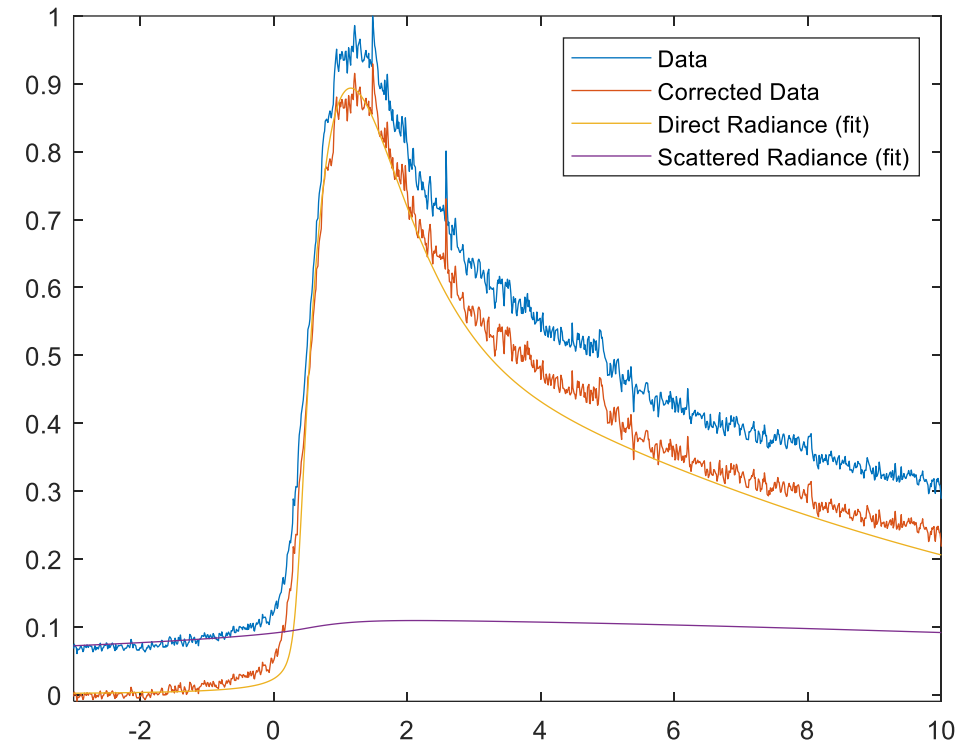


- Examine impact of SRFs on shock as a step function, compare to Shot 9
- Specular reflections do not capture the shape of the data
- Diffuse reflections with reflectivity near 0.5 in reasonable agreement with shape
- Diffuse reflections span multiple tube diameters (100s of cm)

# Reflectance Correction

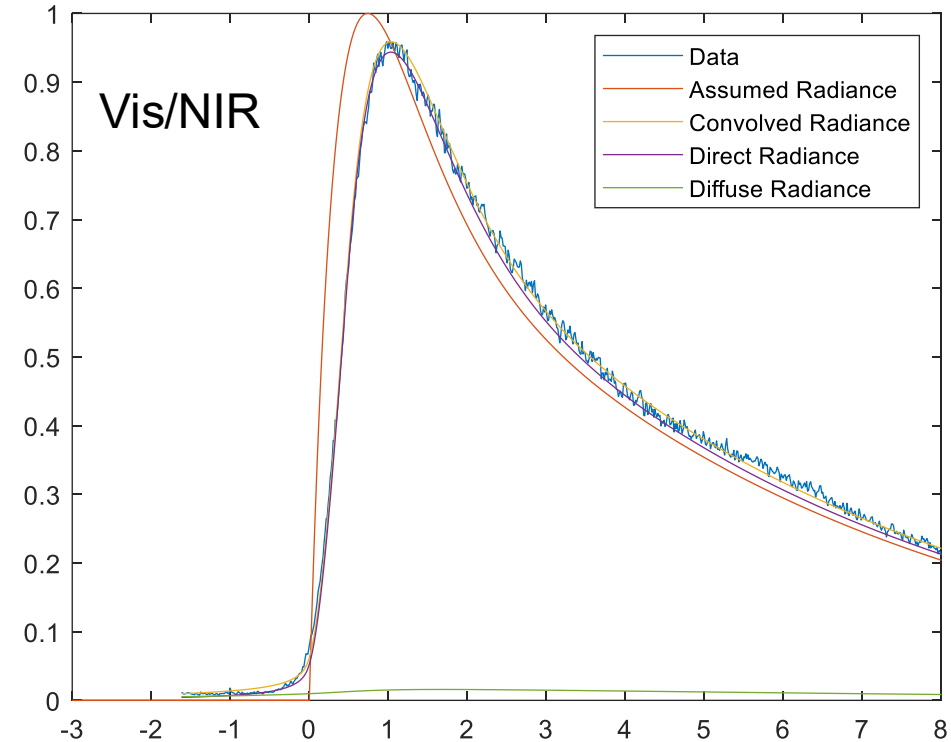
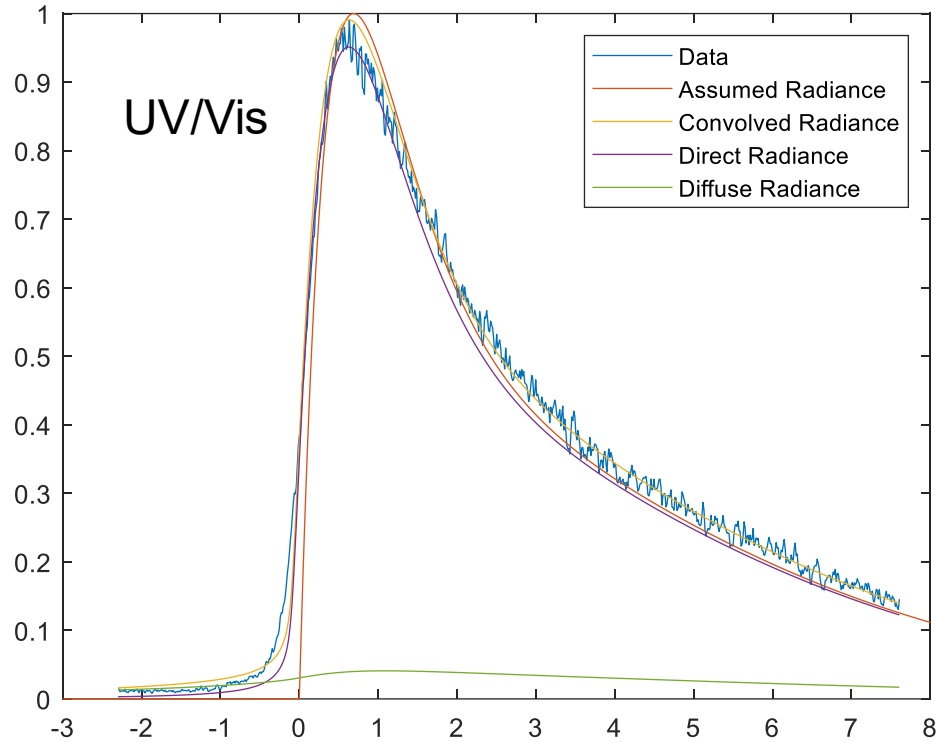


Subtract  
→  
Pre-shock



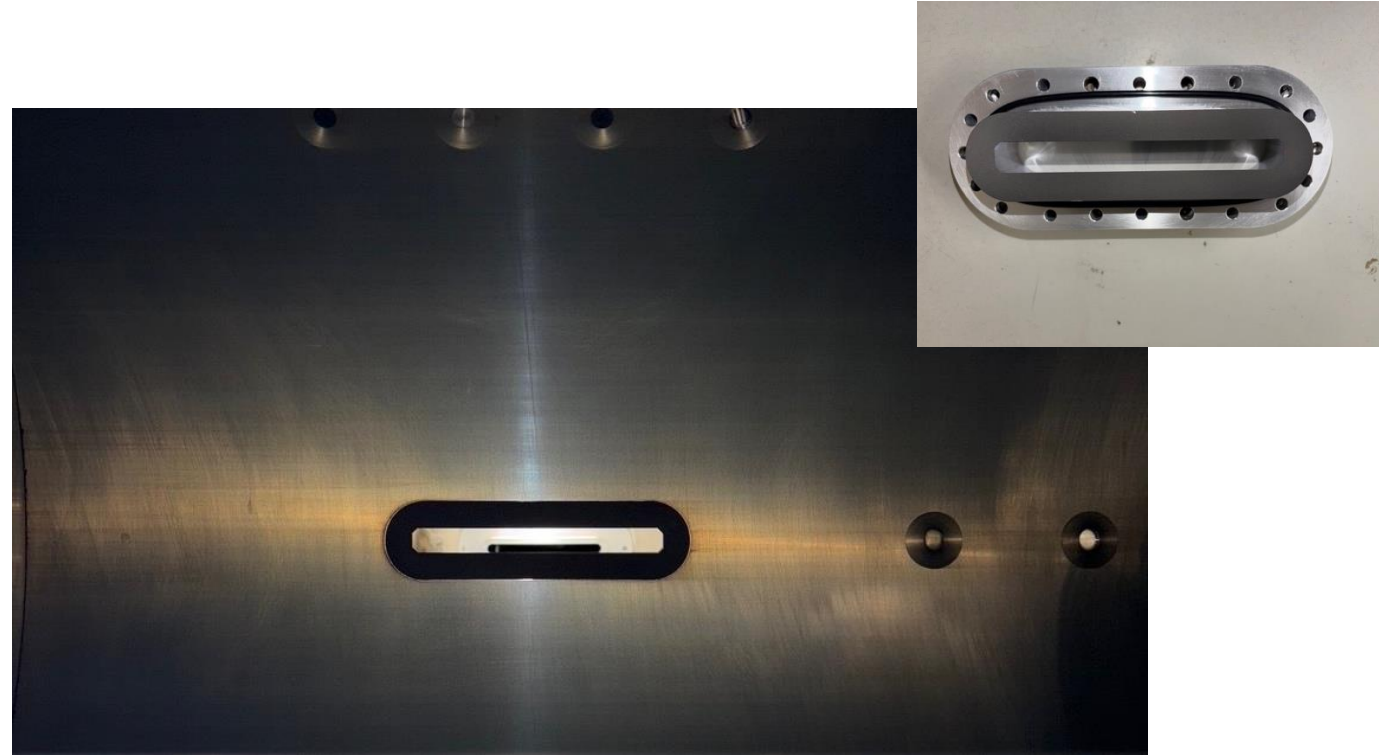
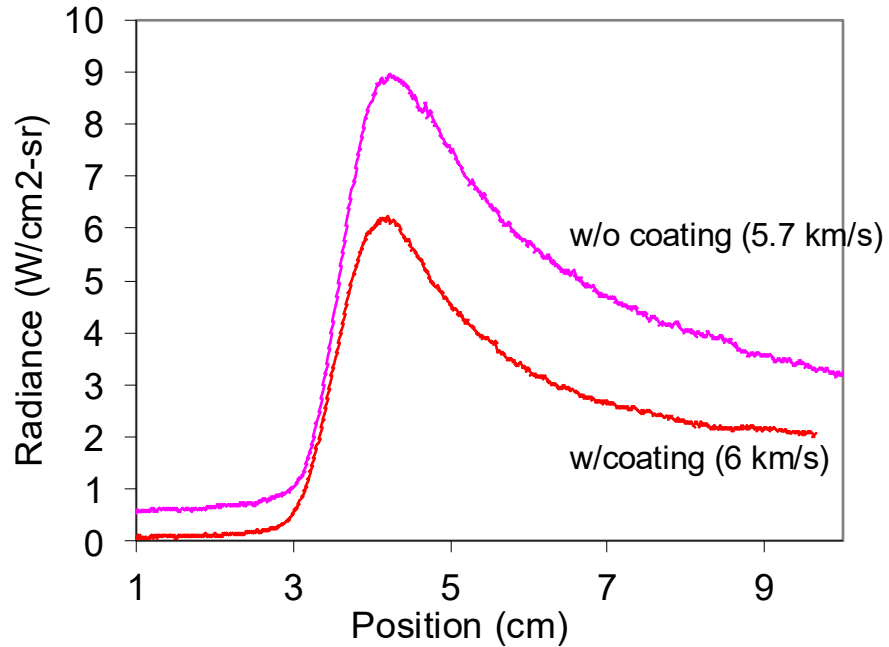
- Assume radiance rises and falls exponentially and convolve with camera and diffuse SRF
- Multi-parameter fit to data returns reflectance and functional parameters
- Correcting data by subtracting the pre-shock reduces scattered contribution from 11% to 4%
- Error in the peak signal ~4%, error at edge of domain ~10%

# Comparison to HVST (10 cm tube)



- Reflection contribution much smaller in HVST
- More attenuation at smaller radius
- Lower Reflectance from HVST walls

# Non-reflective Coating



- Adding non-reflective strip to opposite wall reduces pre-shock signal substantially
- A non-outgassing black coating was applied to inserts on the opposite wall
- Will be deployed in next test series

# Conclusion



- Low Density Shock Tube (LDST) in EAST is operational
- Initial series performed for Dragonfly (Titan) entry conditions
- LDST shows much longer test times, lower deceleration
- Initial data shows quantitative agreement to data collected in High Velocity Shock Tube (HVST)
  - Spatial axis must be converted to Lagrangian (Time of Flight) basis
- Issues identified and being addressed
  - Pre-shock signal caused by diffuse reflections mitigated by non-reflective coating
  - Non-planarity with Helium/Argon mixtures addressed through driver loading panel
- Presently starting repeat of air testing studied in HVST
- Low density Mars/Venus testing next year

# Contributors



## **EAST Facility Staff**

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## **LDST Design**

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## **Research Staff**

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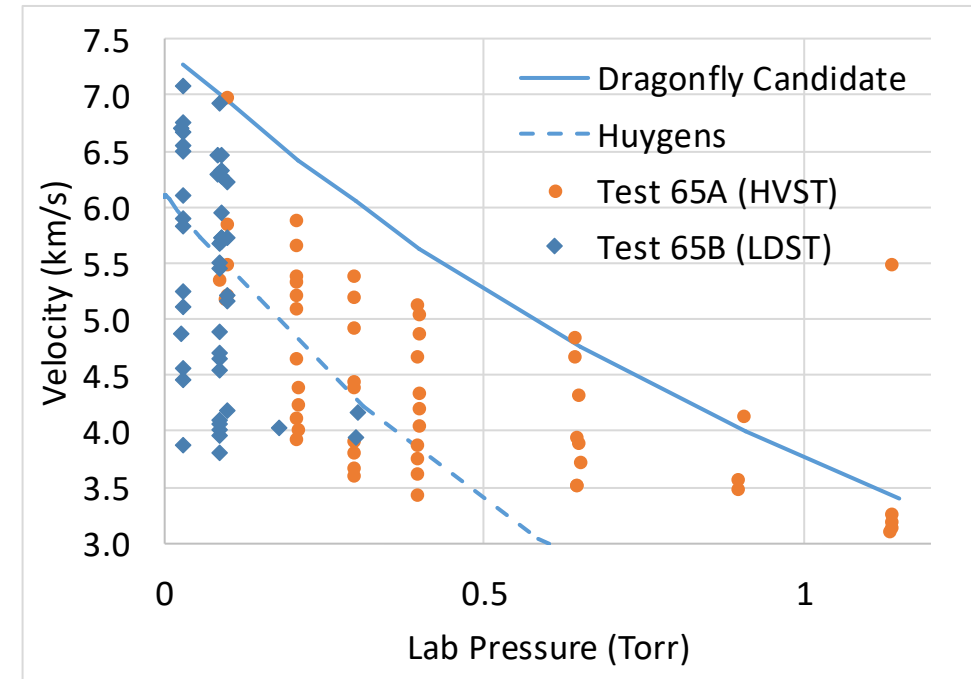
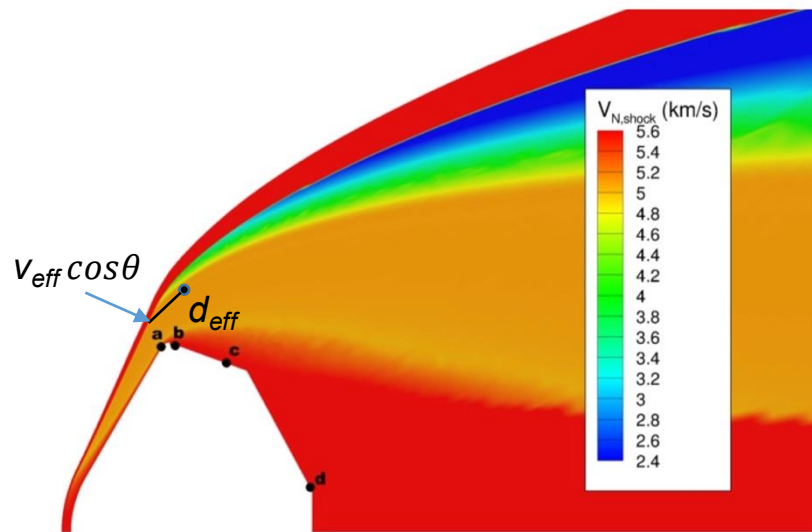
# Backup



# First Test Series in LDST (Test 65B, Dragonfly/Titan)



- Shocks from 3-8 km/s in Titan simulant (2.2% CH<sub>4</sub> in N<sub>2</sub>) are performed for Dragonfly Mission
- The “Shock Tube Informed Bias” Approach is used to compare to radiative heating on vehicle backshell<sup>1</sup>
  - These will be compared to radiometers installed on the vehicle backshell (Dragonfly Entry Aerothermal Measurement – DrEAM)
- Test 65A was conducted in HVST in 2021 at (mostly) 0.2 Torr and Above<sup>2</sup>
- Test 65B includes 0.09 and 0.03 Torr conditions for early trajectory points<sup>3</sup>
  - Includes overlap to Test 65A



<sup>1</sup>Johnston, C.O. “Evaluating Shock-Tube Informed Biases for Shock-Layer Radiative Heating Simulations,” *JTHT* 2021.

<sup>2</sup>Tibère-Inglesse, A. C., Johnston, C. O., Brandis, A. M., and Cruden, B. A. “Backshell radiation measurements in the EAST facility for Titan entry,” *AIAA AVIATION 2023 Forum*, 2023.

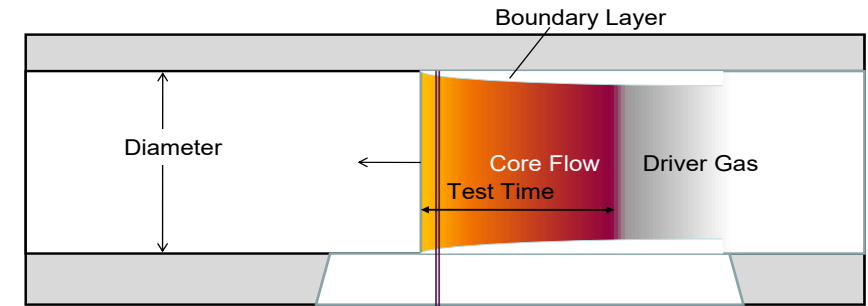
<sup>3</sup>Fagnani, A., Brandis, A. M., and Cruden, B. A. “Characterization of Titan Entry Radiative Heating in the Low Density Electric Arc Shock Tube,” *AIAA SCITECH* 2025.

<sup>4</sup>Fagnani, A., et al. “Assessment of CN non-Boltzmann kinetics against Low Density Shock Tube data,” *AIAA SCITECH* 2026.

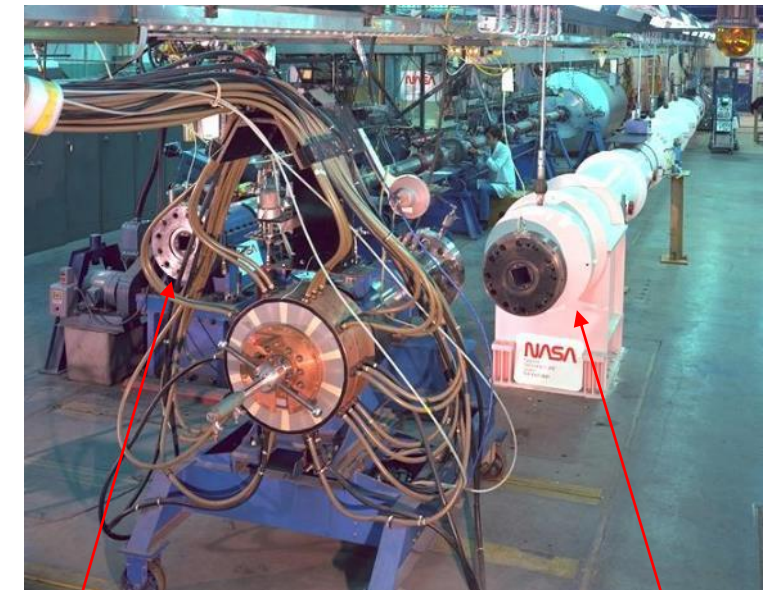
# Testing at low density



- Around 2011, HEDL project expressed interest in low density testing for high mass mars landers, e.g. HIAD, ADEPT
- Difficulty achieving sufficient test time, signal in HVST at these conditions
- The LDST should achieve longer test times based on Mirels (Roshko) Theory (1963)
  - $\tau \sim PD^2$ 
    - At 6x diameter, possible 36x increase in test time
    - Actual gain is less than this due to length scaling
- A series of tests were performed in the 24" Low Density Shock Tube (LDST) from 2012-15
  - Quality of shots was generally poor
  - Attributed to quality of fabrication of tube
  - It was decided to construct a replacement for LDST
- Fabrication of new LDST started ~2020
- New LDST became operational in late 2024



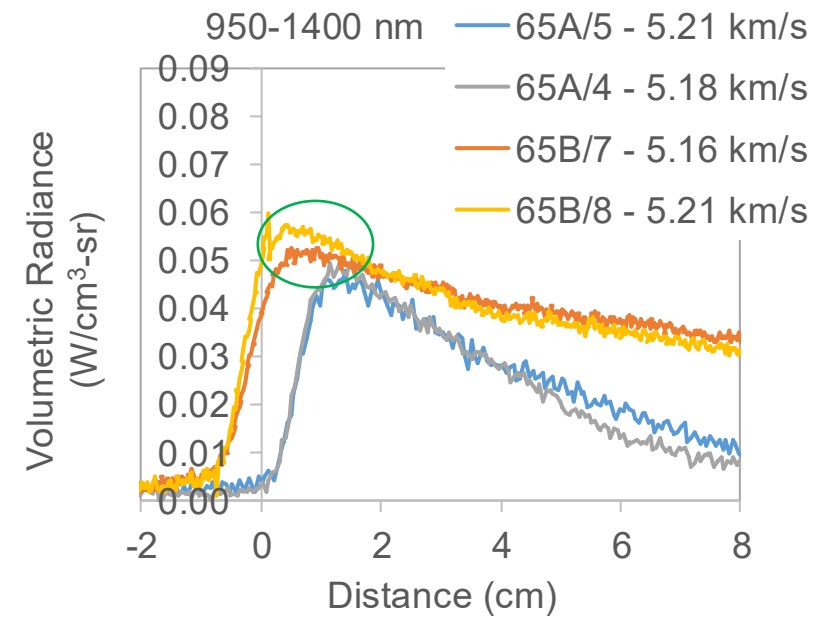
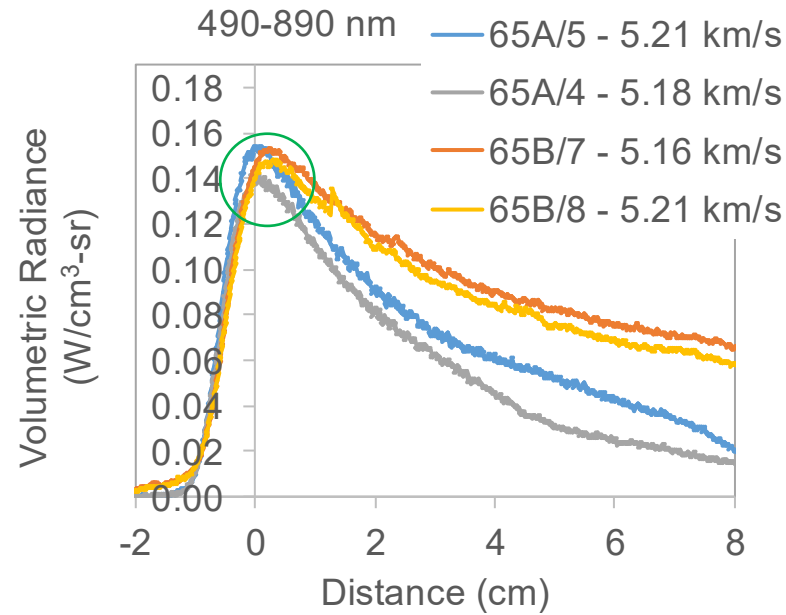
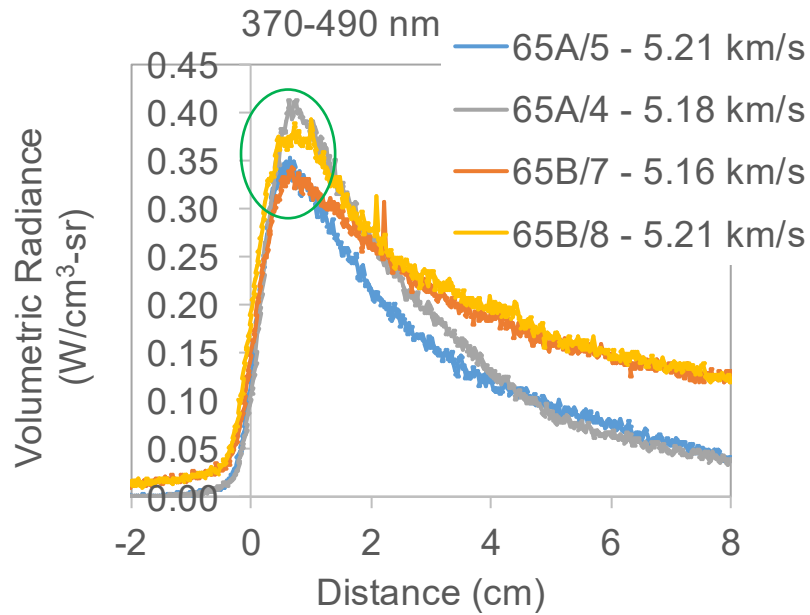
Radiation Observed  
Integrated over tube diameter  
And through the boundary layer



4" HVST

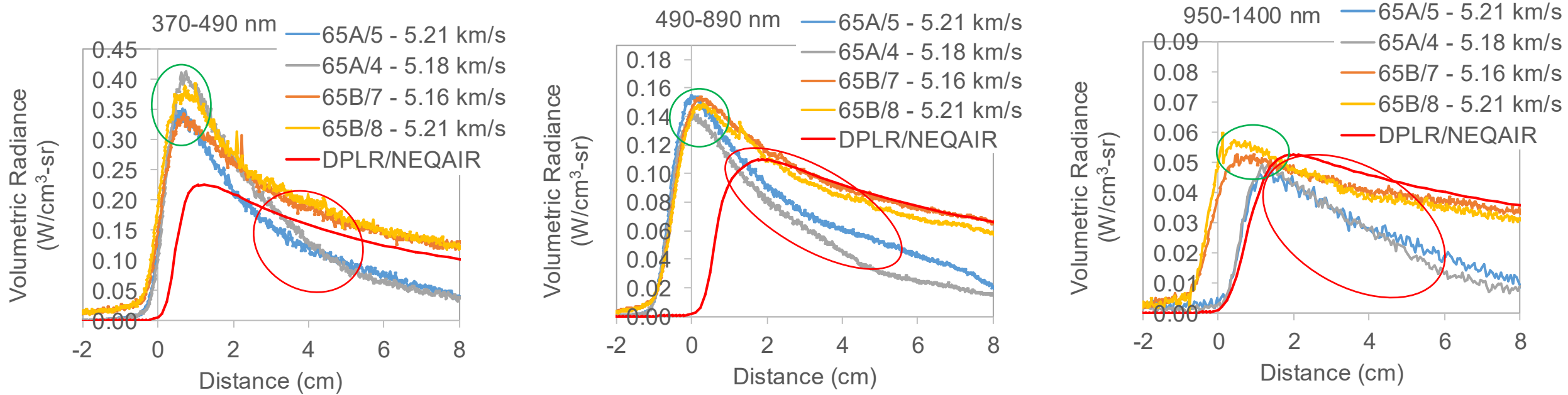
Old 24" LDST

# Spatial Comparison – LDST to HVST



- Radiance vs distance from shock front
- Comparing 2 Shots from each tube
- Nominally 5.2 km/s and 0.1 Torr
- Normalized by Tube Diameter
  - 65A – HVST (10.16 cm)
  - 65B – LDST (54.31 cm)
- Intensity at peak generally agrees between tubes

# Spatial Comparison – LDST to HVST

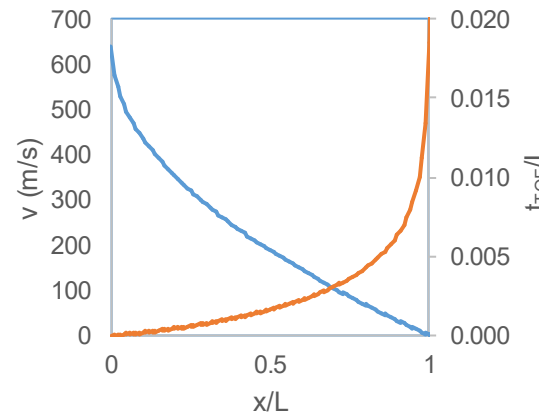
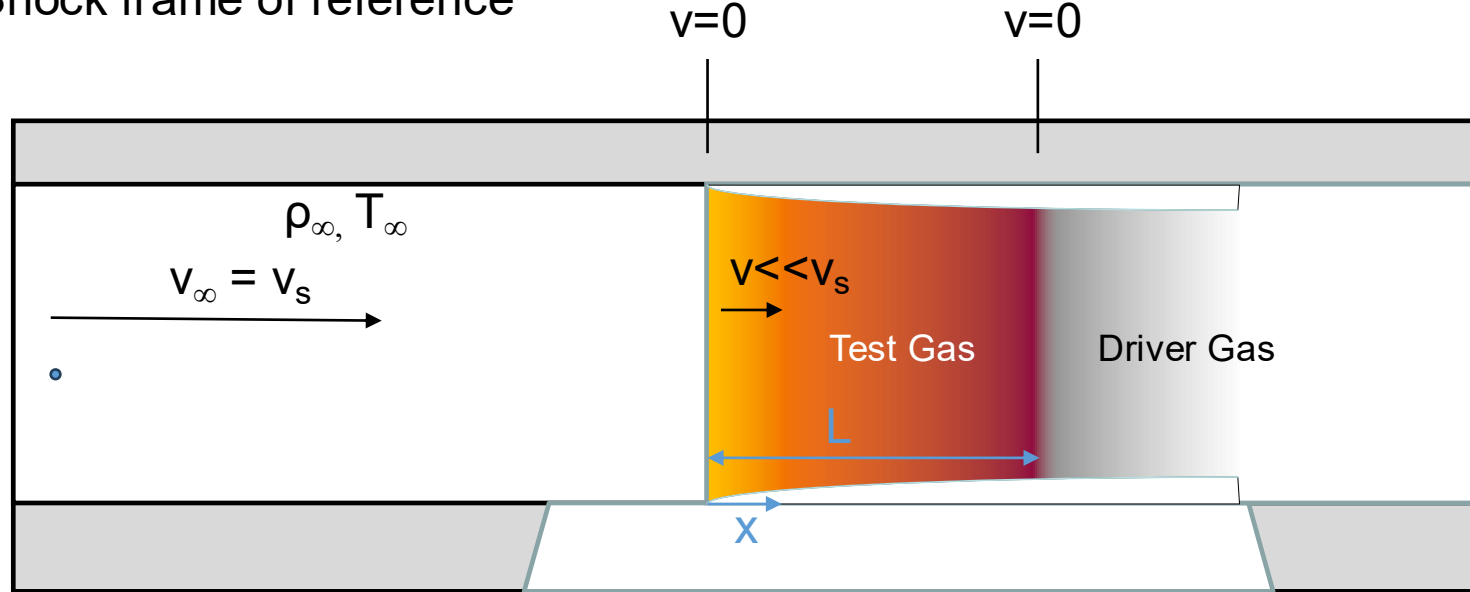


- Comparing radiance vs distance from shock
- Results diverge ~4 cm from shock
- DPLR/NEQAIR
  - Peak is generally delayed relative to camera alignment
  - CN Violet peak is lower, trends between LDST and HVST
  - CN Red peak is later, trends with LDST data

# Spatial Comparison –Time of Flight



Shock frame of reference



- Clarke, et al. (2023), recognized spatial transform required
- This is due to the deceleration of gas from the shock front to the contact front

$$v = \frac{\rho_s}{\rho} v_s \left( 1 - \sqrt{\frac{x}{L}} \right)$$

- Time spent in the flow is the integral of velocity:

$$t_{TOF} = \int \frac{dx}{v}$$

- Data can be compared on a Lagrangian, or time-of-flight, basis:

$$t_{TOF} \approx -\frac{2\rho L}{\rho_s v_s} \left[ \ln \left( 1 - \sqrt{\frac{x}{L}} \right) + \sqrt{\frac{x}{L}} \right]$$

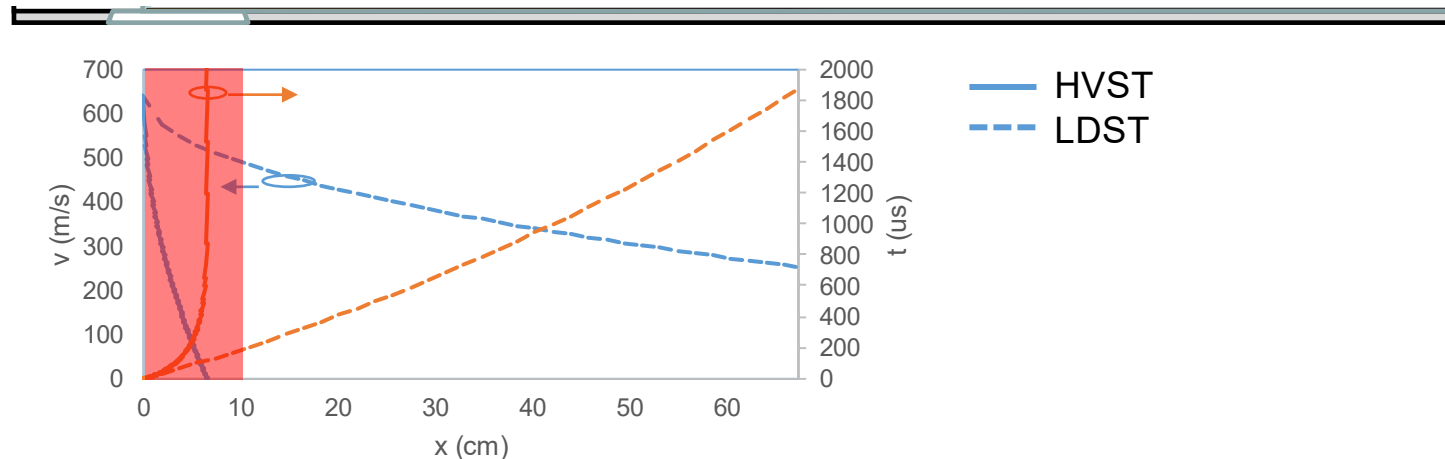
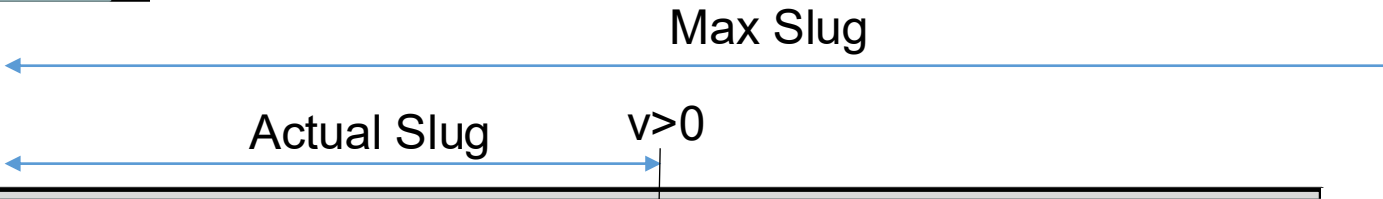
# Time of Flight HVST vs LDST



HVST



LDST



- LDST has 5.4x diameter
- Maximum slug length is 28x larger than in HVST
- Actual slug length (at test section) is 10x larger
- $v > 0$  at end of slug
  - Contact front continues moving backward with particle
- For measurement at a particular time/location
  - TOF calculation should use maximum slug length
  - Data not obtained beyond the actual slug length
- The time of flight on HVST is longer than on LDST

# Combined Diffuse + Reflective



- Consider n total reflections, with m specular

$$SRF(\Delta x) = \sum_{n=0}^{\infty} \sum_{m=0}^n \mathcal{R}_s^m \mathcal{R}_d^{n-m} SRF_m^n(\Delta x)$$

- Relationships get complicated, embedded sums:

$$SRF_m^n(\Delta x) = \sum_{i=0}^m \sum_{k=0}^{m-i} \sum_{j_1=0}^{m-i-k} \dots \sum_{j_{n-m-2}=0}^{m-i-k-\sum j} g_{w,i}(\Delta x) \otimes g_{dw,j_1} \otimes \dots g_{dw,j_{n-m-2}}(\Delta x) \otimes g_{dw,j_{m-i-k-\sum j}}(\Delta x) \otimes g_{d,k}(\Delta x)$$

$$g_{w,N}(\Delta x) = (R^2 + \Delta x^2) \ln \left( \frac{1 + \sin \varphi_{e,N}}{1 - \sin \varphi_{e,N}} \right)$$

$$g_{dw,n}(\Delta x) = \frac{1}{\pi R} \left[ \left( \frac{\Delta x}{nR} \right)^2 + 1 \right]^{-1}$$

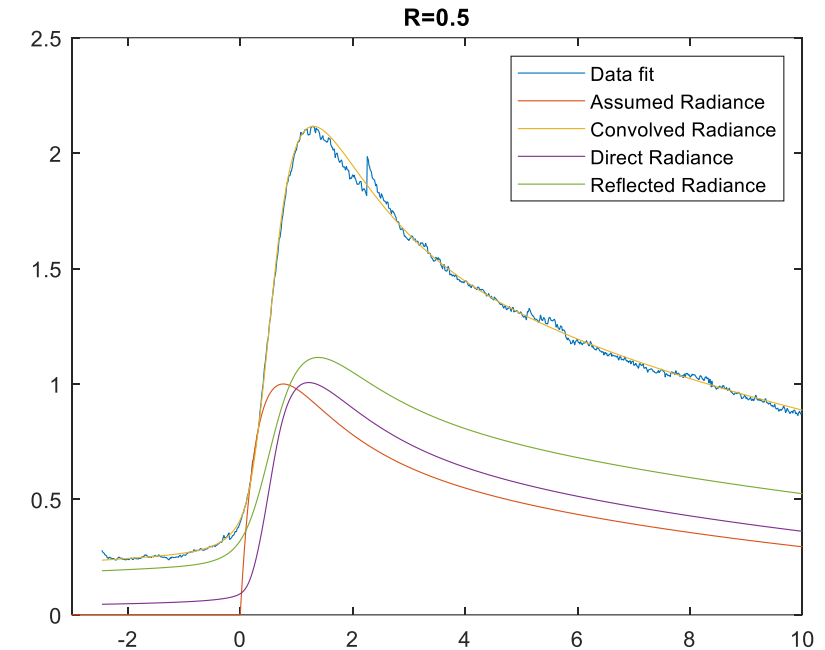
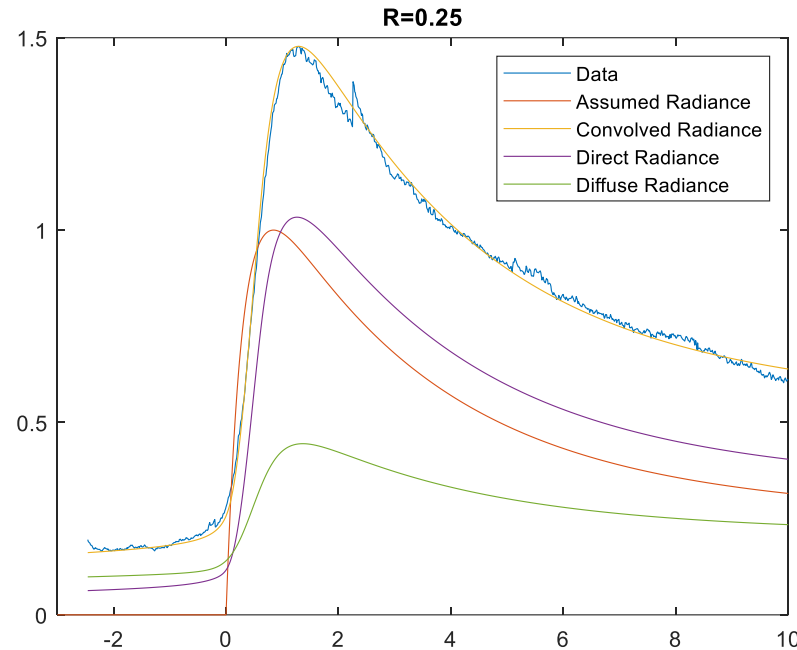
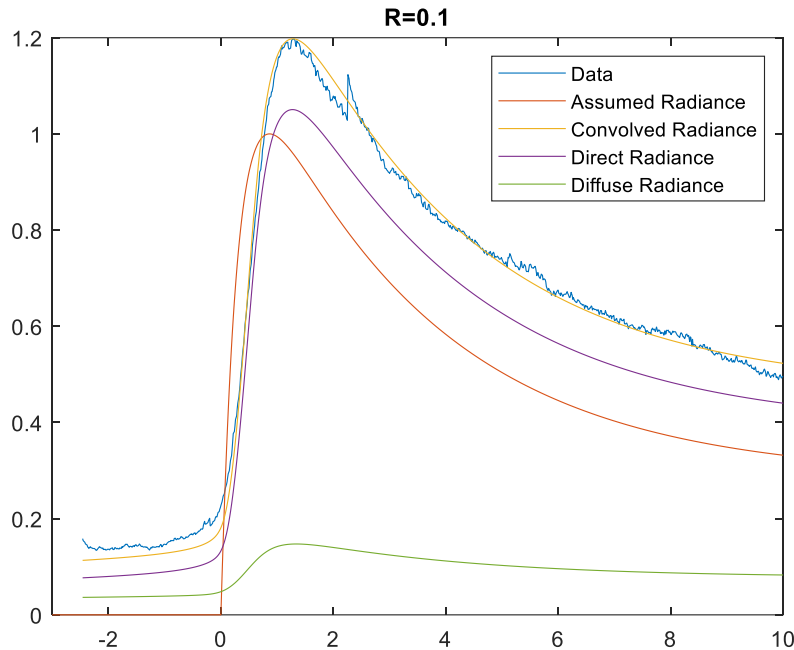
$$g_{d,n}(\Delta x) = \frac{1}{2\pi R} \int_{\tan^{-1} \left| \frac{\Delta x}{2nR} \right|}^{\frac{\pi}{2}} \int_0^{\varphi_{\max}(\theta, \Delta x)} \frac{\cos \theta}{\cos \varphi} d\varphi d\theta$$

- A recursive algorithm is written to compute the combinatorics

# Combined Specular+Diffuse vs Data



- Fix diffusive reflectance at 0.5, vary specular reflectance

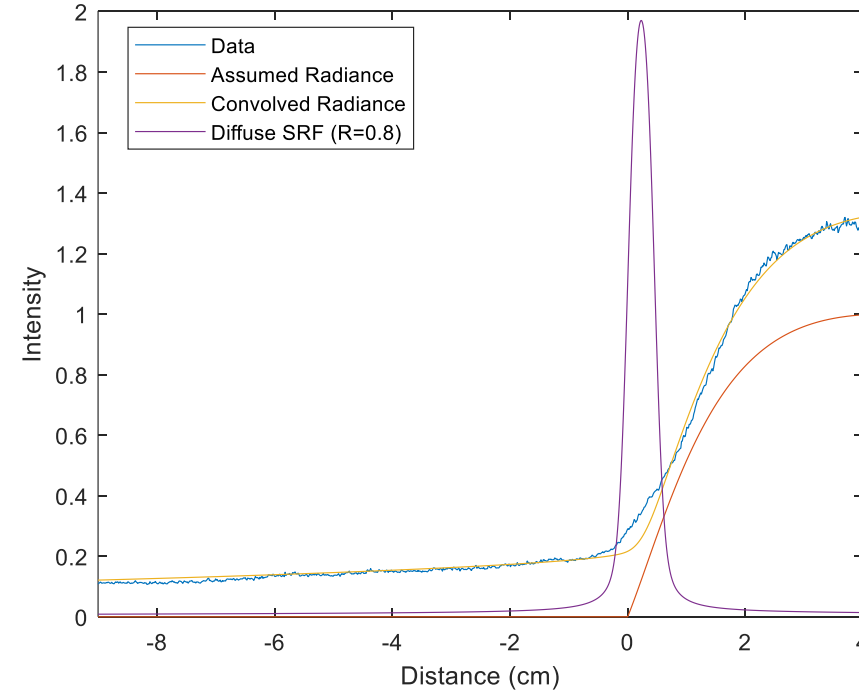
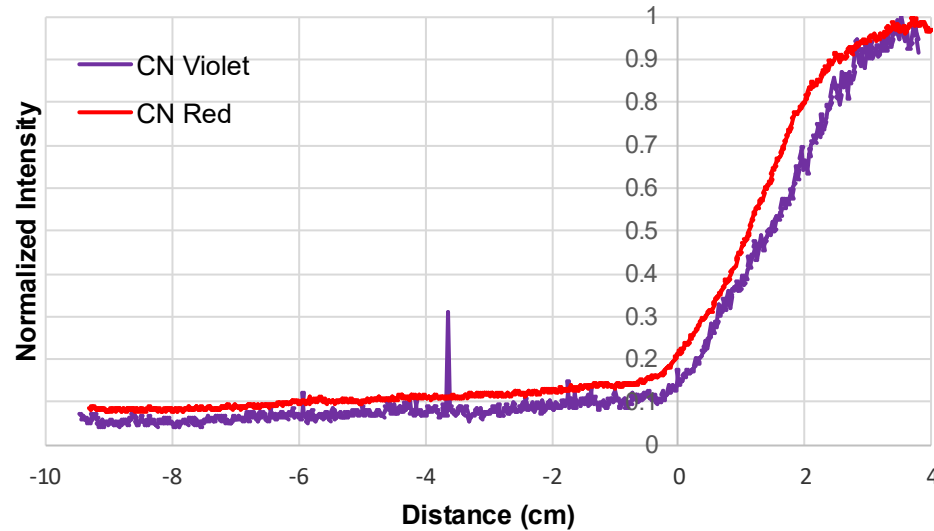


- Fit is not unique, but  $R > 0.1$  seems necessary
- Specular reflectance leads to potentially significant overestimates of radiance

# Pre-shock signal – Scattered Light

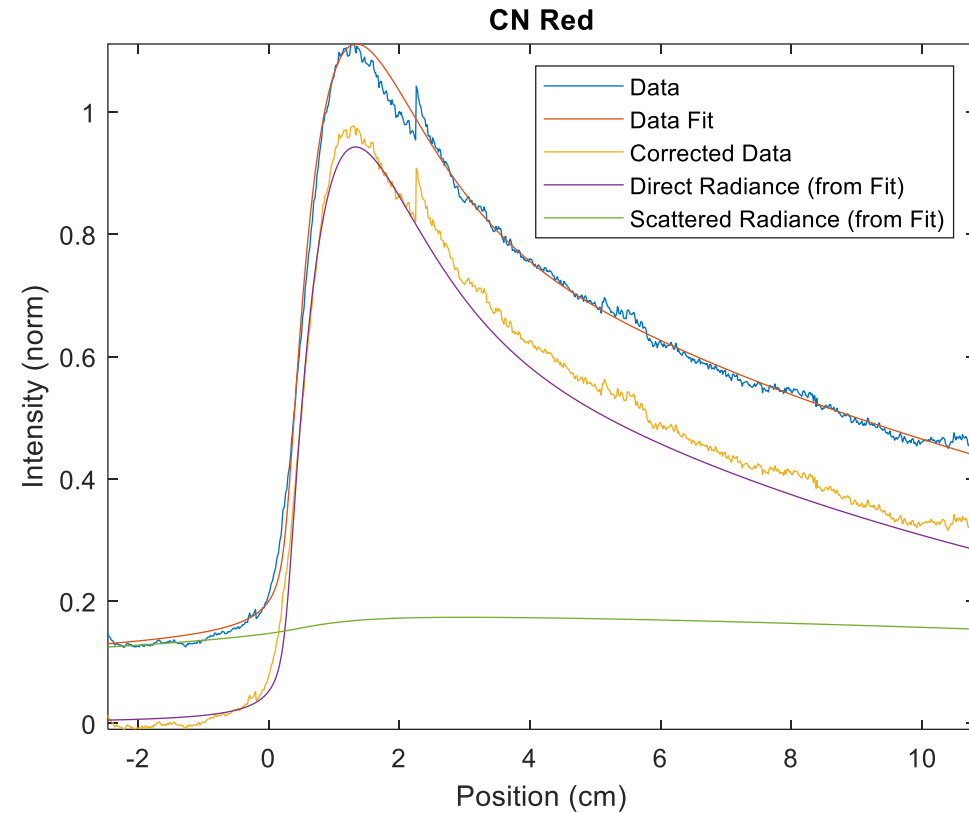
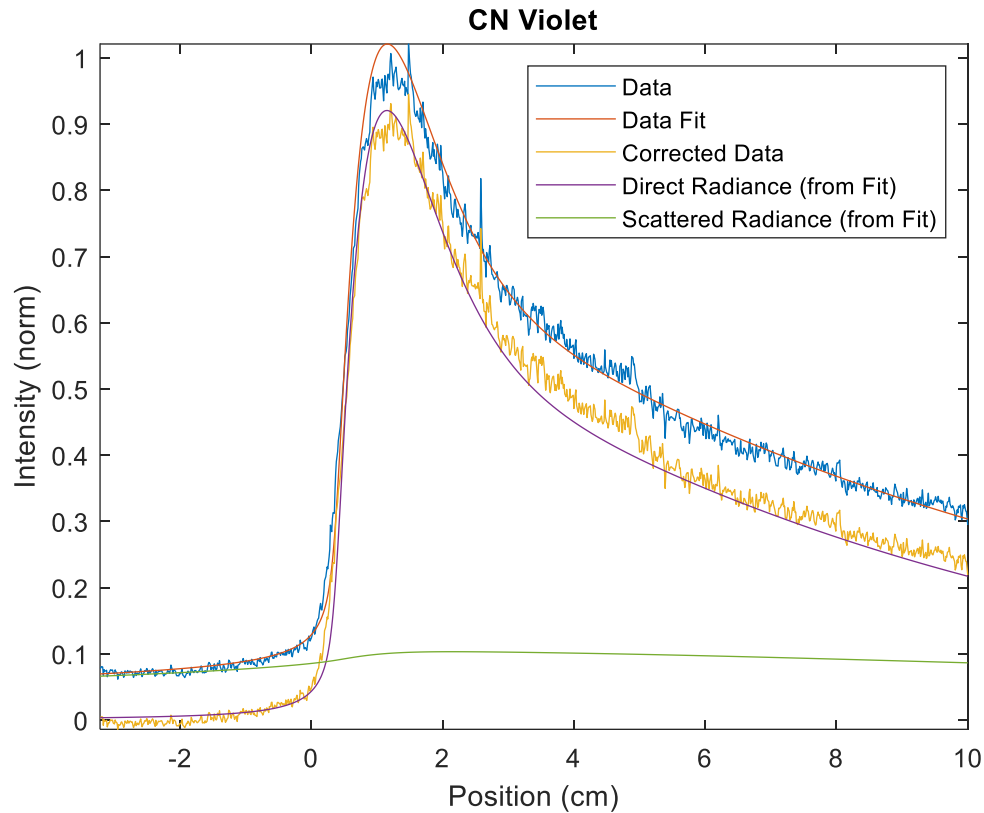


4.53 km/s, 0.09 Torr



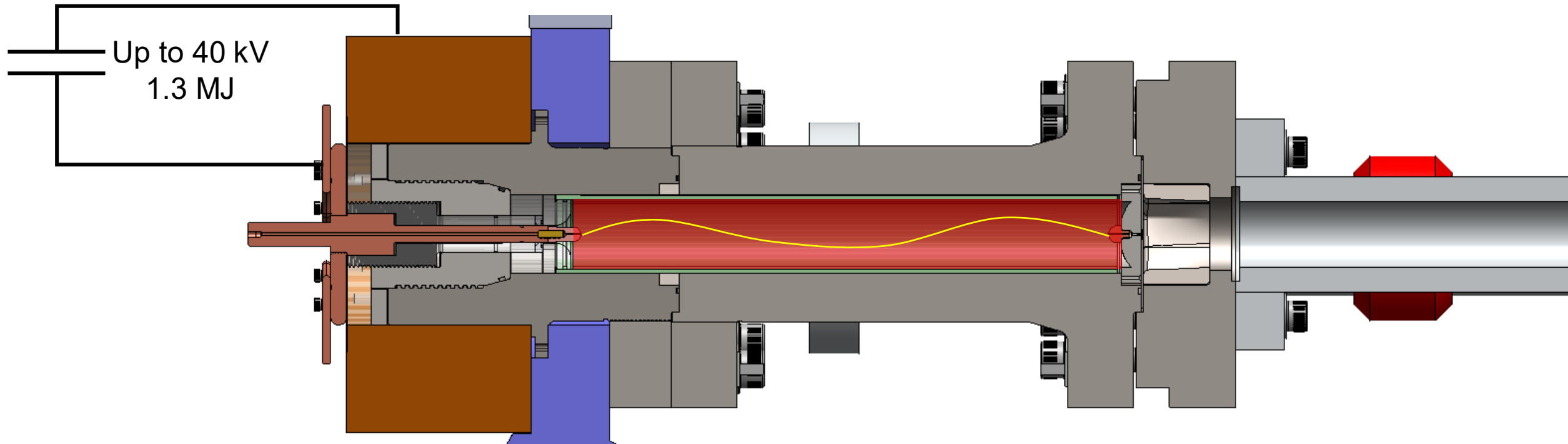
- Pre-shock signal persists for several cm in front of shock arrival
- A scattering function is analytically derived which acts as a convolution on the unscattered signal
- Influence of scattered radiation spans multiple tube diameters (100's cm), depends on signal measured outside of spectrometer image

# Scattered Light Correction



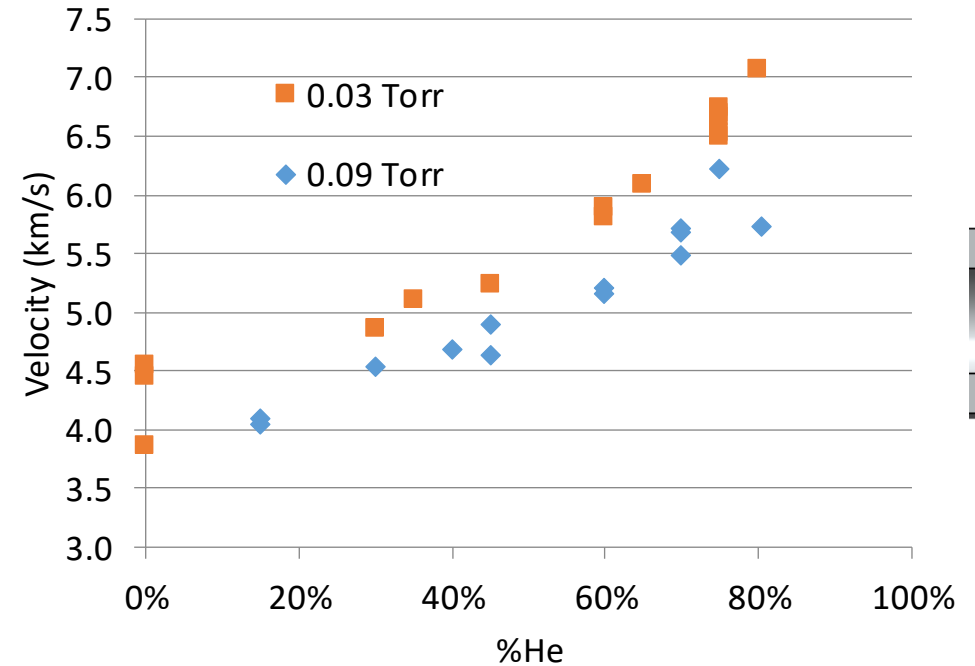
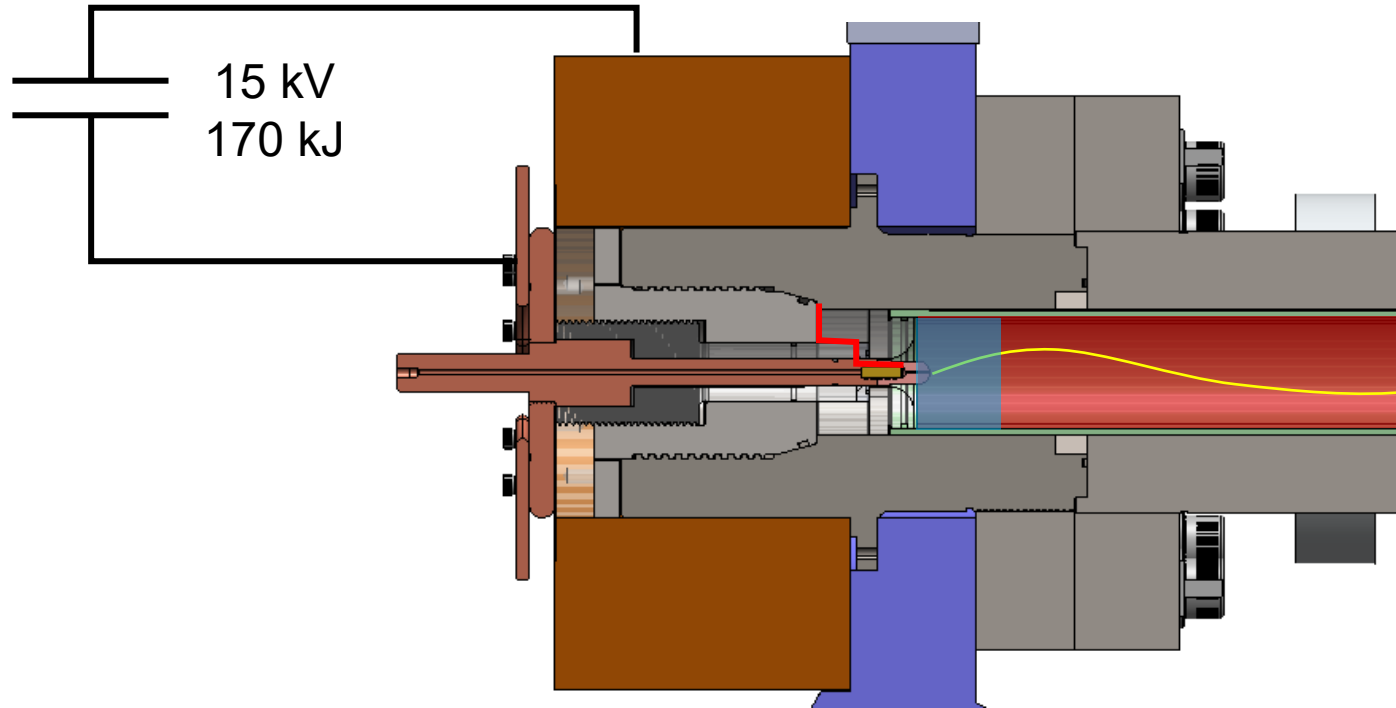
- Scattered signal is about 10% of the peak signal, but ~30% of signal at camera edge
- Scattering model shows scattered signal before shock is smaller than post-shock signal
- Subtracting the pre-shock signal leaves <6% error in post-shock signal

# The Arc Driver



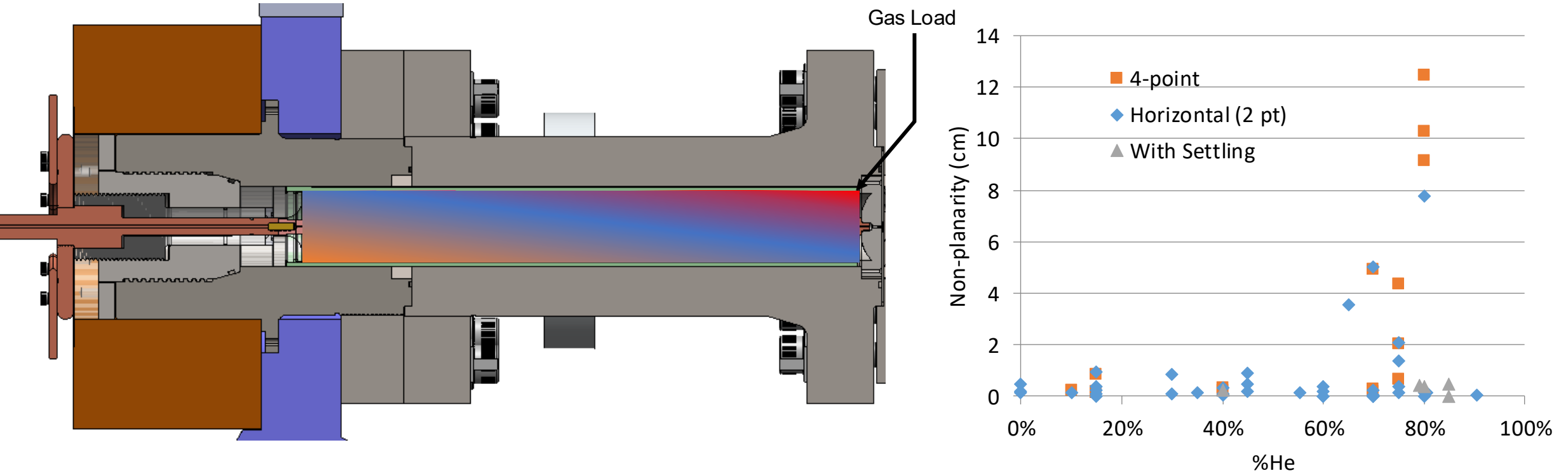
- In EAST, shocks are propelled by Arc Driver
- The “30 inch” driver is the preferred driver for LDST but has not been used much in last 20 yrs.
- Arc Driver gives high  $T_4$  –  $O(10,000K)$ , increases shock speed by  $>5x$  over cold driver
- Energy Pressure  $P_E = \frac{\gamma-1}{2} \frac{CV^2}{Vol} \sim O(50 \text{ MPa})$  far exceeds the fill pressure –  $O(1 \text{ MPa})$
- Diaphragm rupture pressure typ.  $1/2P_E$

# Driver Optimization



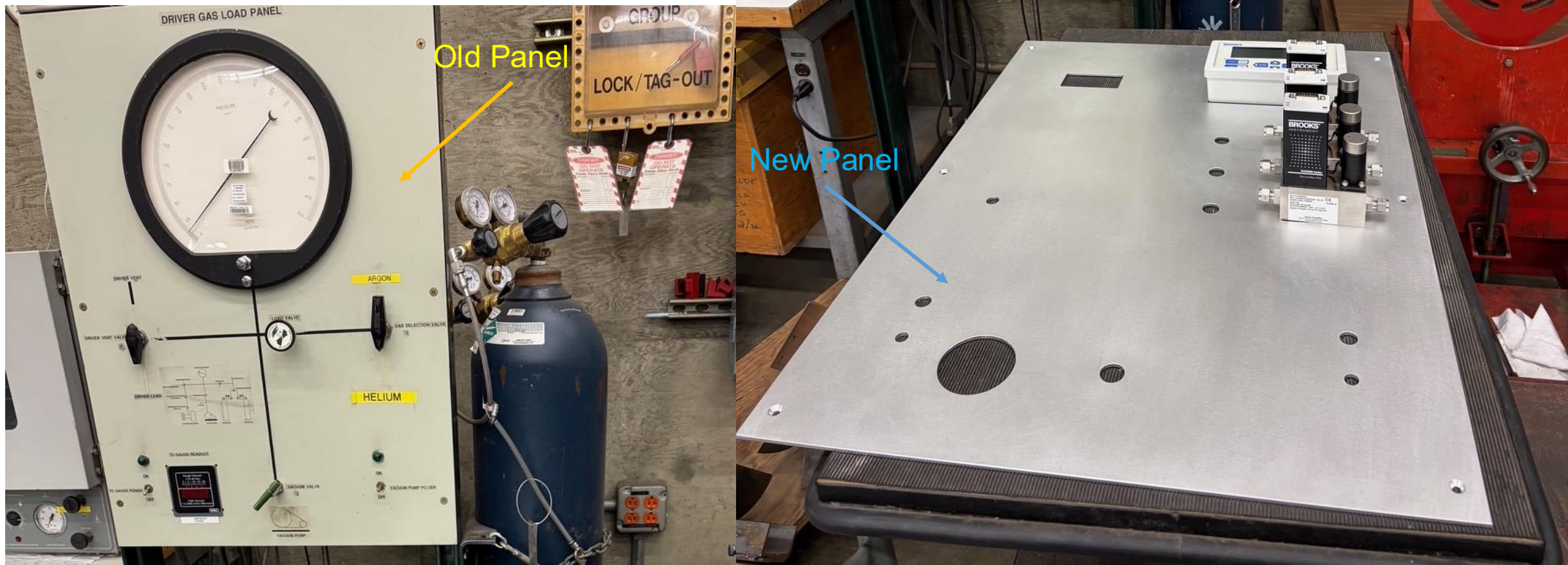
- Poorly chosen driver conditions may not fully discharge the capacitor bank
- Reflected shock return causes secondary discharge which damages the driver
- Necessary to reduce pressure, add Argon and/or increase Voltage to reduce “Arc-out”
- Increasing voltage raises shock speed – Add Argon to tune the velocity

# Driver Mixing/Planarity



- Observed a loss of planarity when Helium % exceeds ~60% ( $v > 6$  km/s)
- For 0.7 MPa initial pressure, the Ar-He diffusion length is ~5 cm in 5 min
- Increasing settling time to ~40 minutes improved planarity
- Future plan to load gases simultaneously to improve mixing

# Mixed Gas Loading



- A gas loading panel for the driver was designed
- Gas loading panel delivers Ar and He in controlled ratio simultaneously, eliminating Ar/He stratification