Towards the Measurement of Ablation Products in Hypersonic Boundary Layers

Current & Upcoming Ground Testing Efforts in Sandia's Diagnostic Sciences Department

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Sandia National Laboratories

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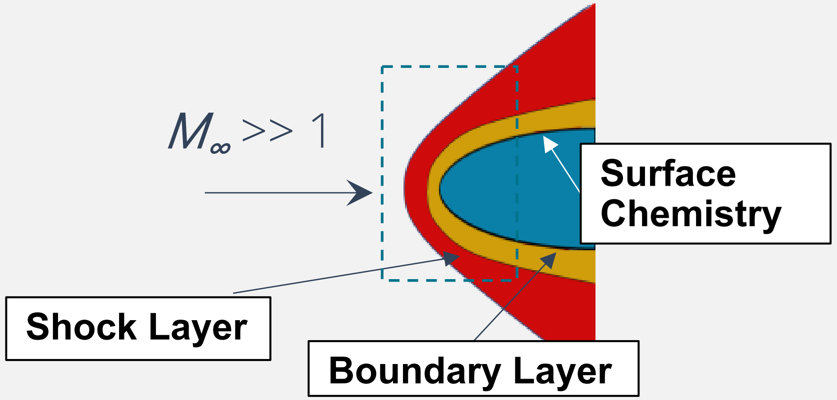
Motivation: Ablation & Gas-Surface Interactions



Shock Layer (Gas Chemistry)

- Species dependent thermodynamic nonequilibrium
  - Vibrational temp ≠ rotational temp ($T_V \neq T_R$)
- Dissociation produces atomic N and O and formation of nitric oxide (NO)

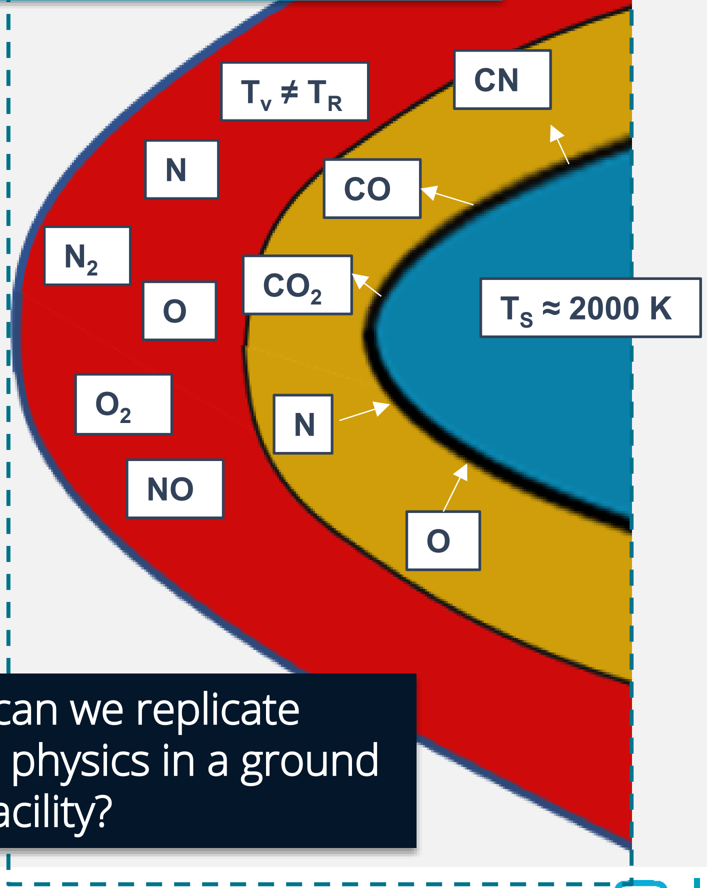
Surface Chemistry

- N and O interact (adsorb) with surface.
- Oxidation and nitridation
- CN, CO, CO_2 production.

Boundary Layer

- Diffusion of oxidization products
- Air chemistry
- Vibrationally excited species (N_2 , O_2)

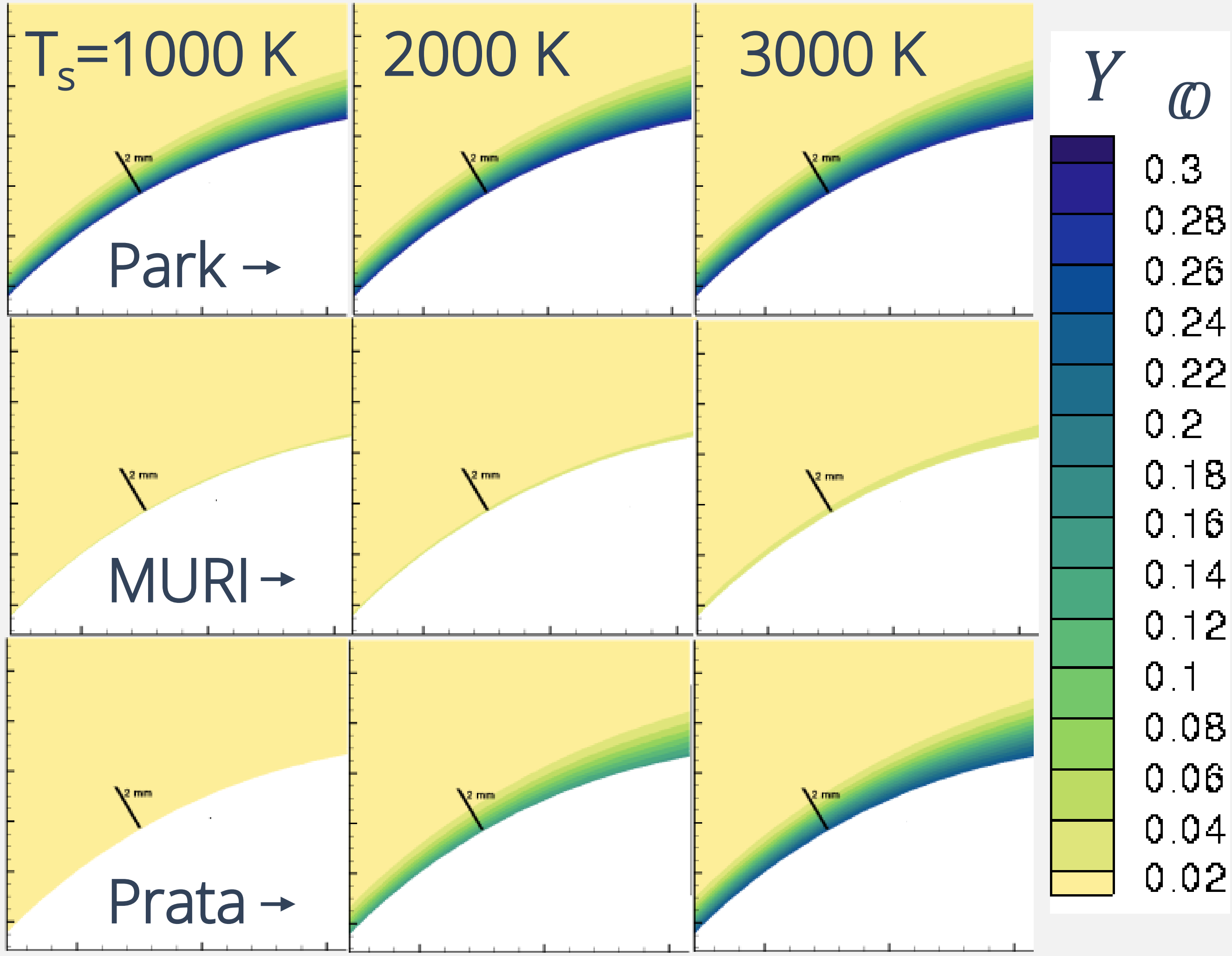
Hypersonic flow, high gas temperature, and elevated surface temperatures are critical to enacting the proper physical/chemical mechanisms



How can we replicate these physics in a ground test facility?

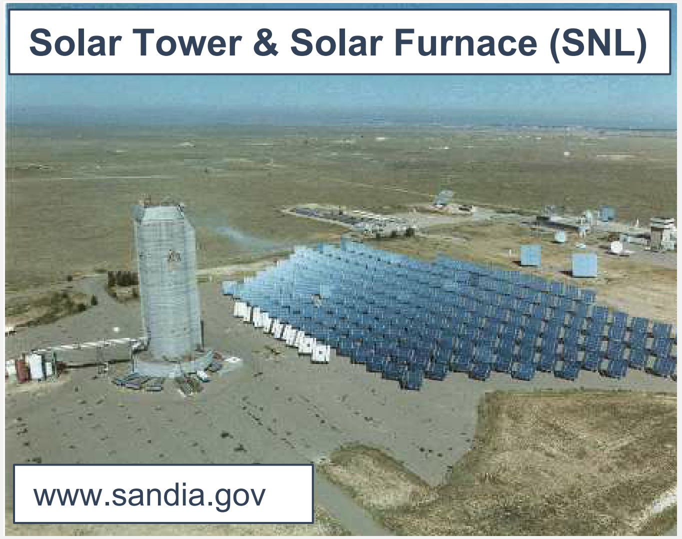
Air-Carbon Ablation Model Considerations

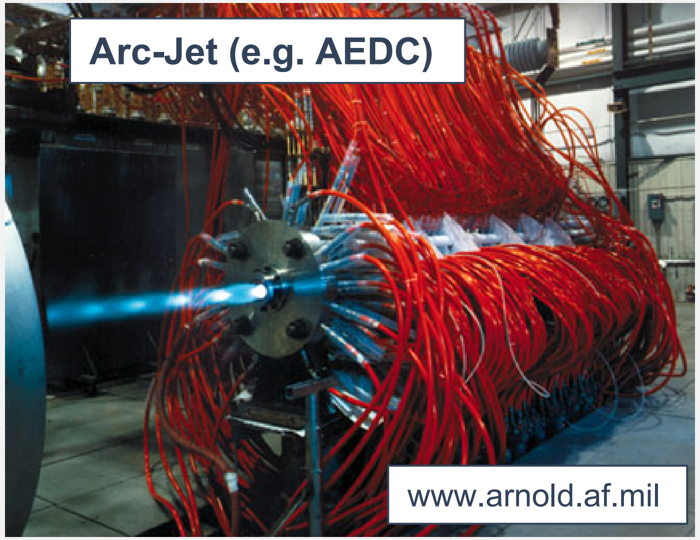
- Various literature models available
  - Park, et al. (1976)
  - MURI (2015)
  - Prata (2022)
- Differences in model formulation
  - Number of reactions
  - Active surface site treatment
  - Model formulation data
- Model Comparisons (US3D)
  - Which is correct?
- Need speciation data for validation

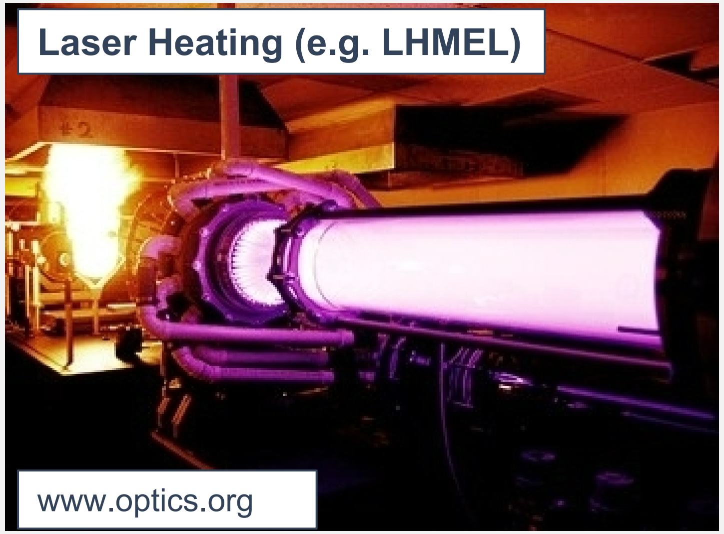


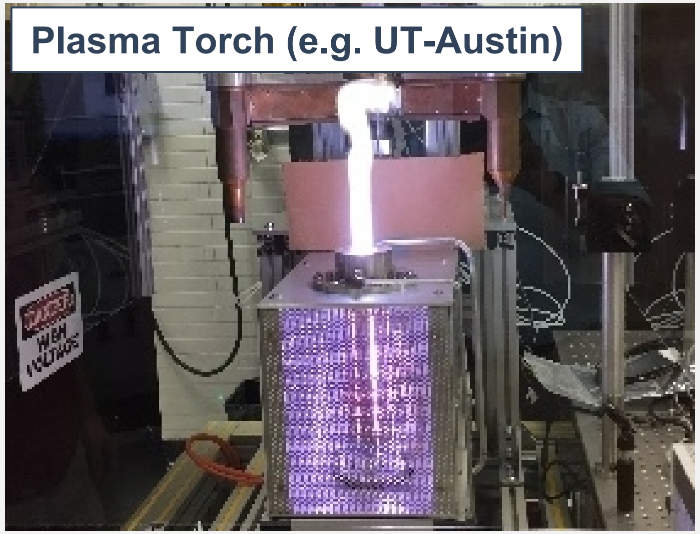
Thanks to Erin Mussoni (SNL) for performing these simulations

Established Methods for TPS Characterization







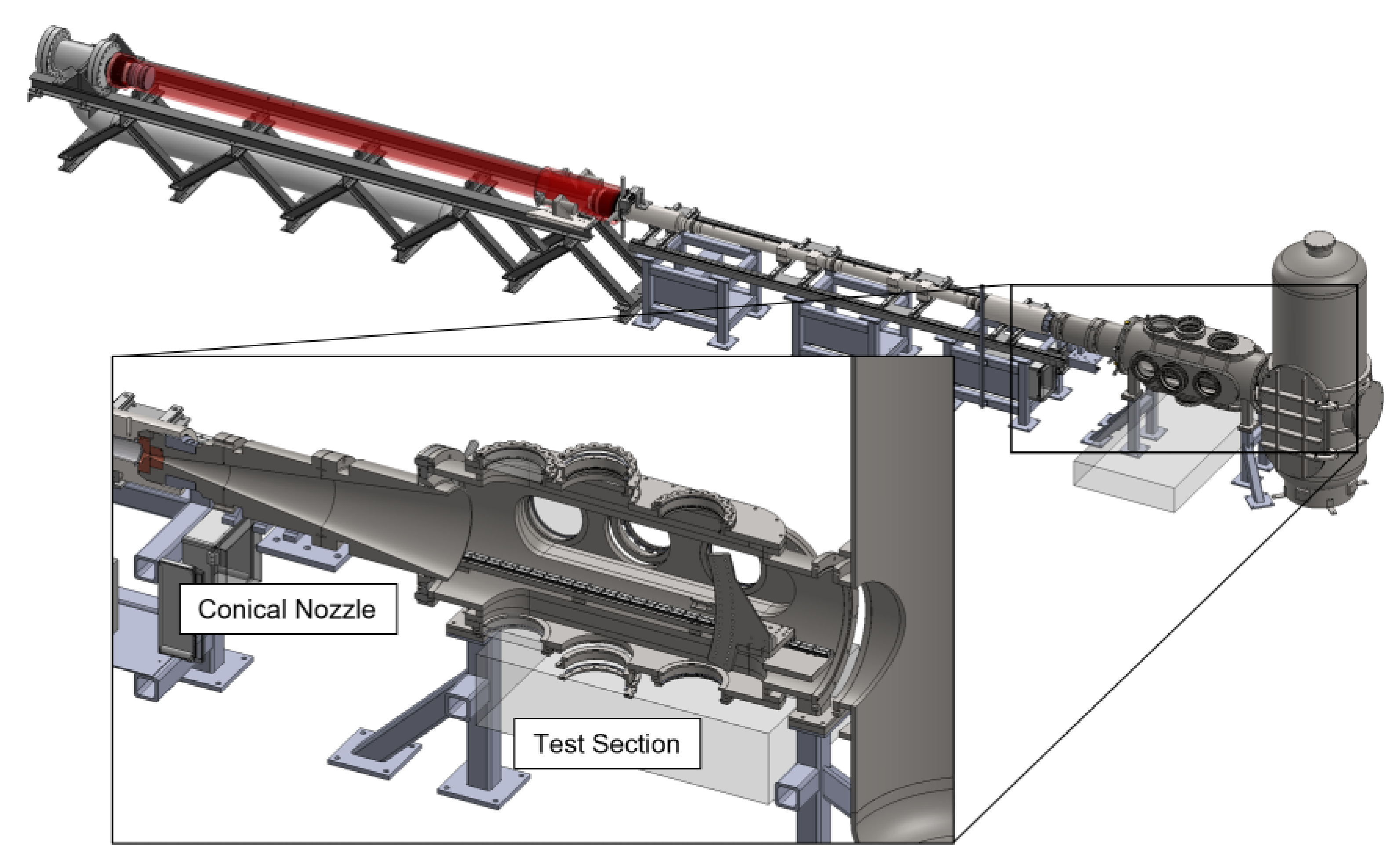


Summary

- Each method produces the realistic heating over run times of several minutes.
- These facilities cannot reproduce flight velocity, aerodynamic heating and the correct air chemistry concurrently.

We desire to conduct experiments and observe ablation products in a coupled aero-thermal environment

A Compliment to Traditional Material Characterization Facilities: Sandia Hypersonic Shock Tunnel (HST)



Tunnel Specifications

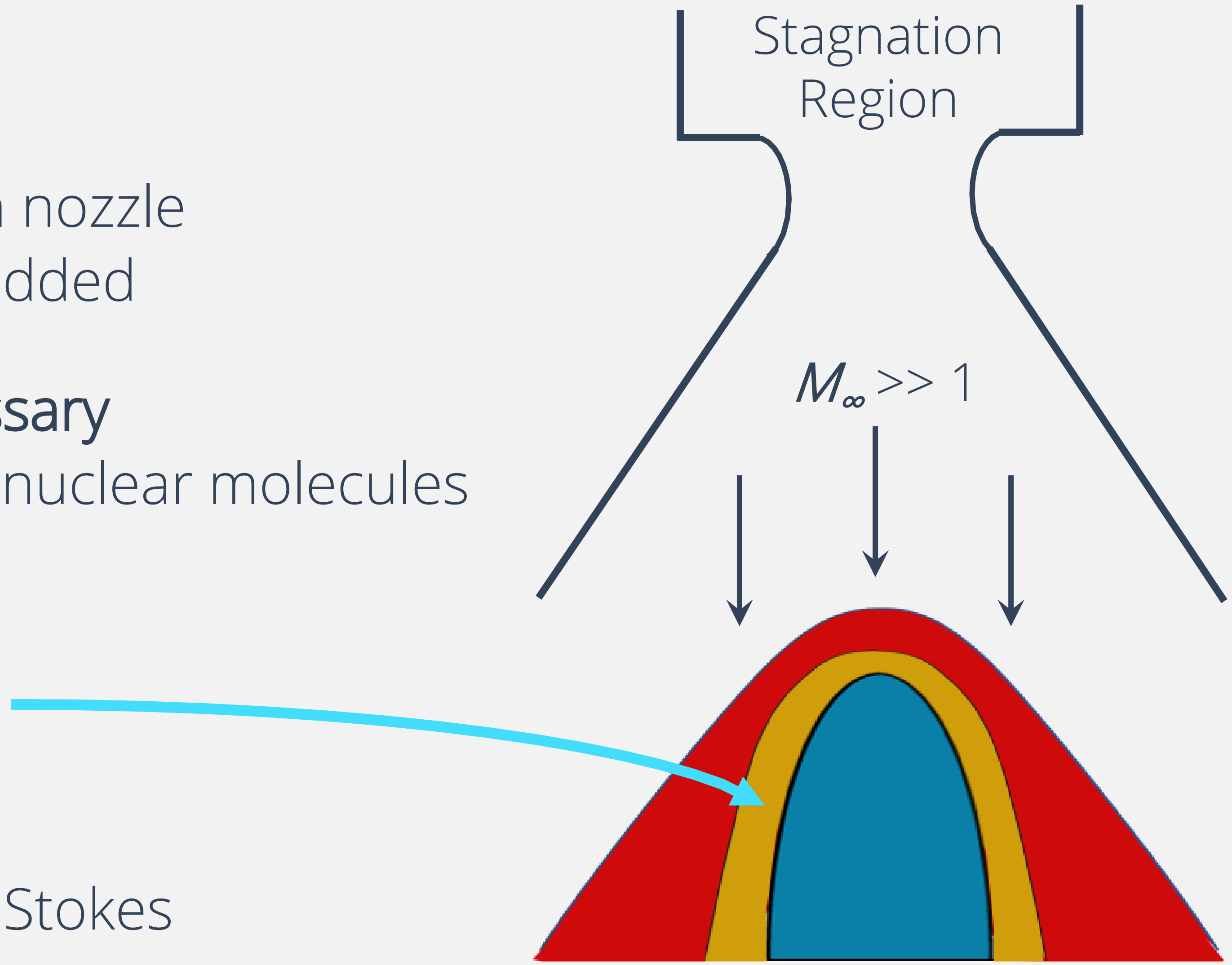
- Nozzle Exit Dia. = 0.36 m
- Test section diameter 0.5 m
- Run times of 1-2 milliseconds

U_∞ (m/s)	H_0 (MJ/kg)	T_0 (K)	P_0 (MPa)
2850	4.6	3400	12
4060	9	6000	17

Target applications include high-temperature surface chemistry and hypersonic thermochemistry.

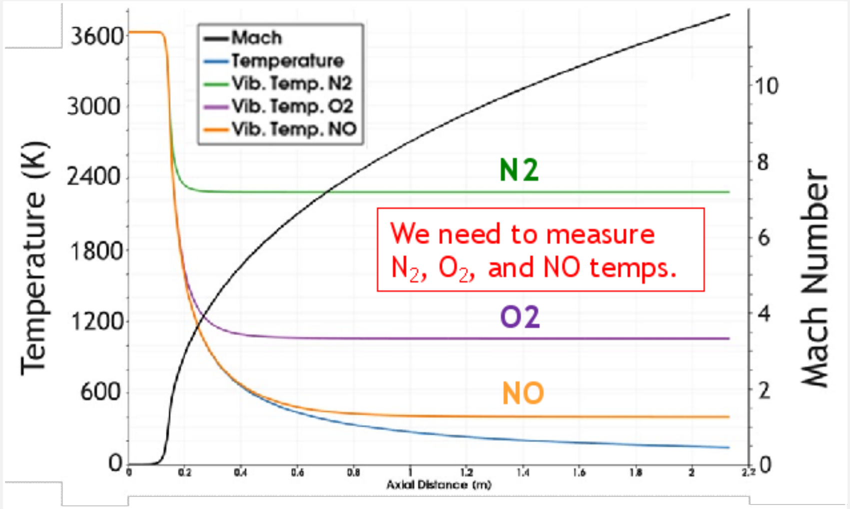
Survey of Upcoming Experiments in HST

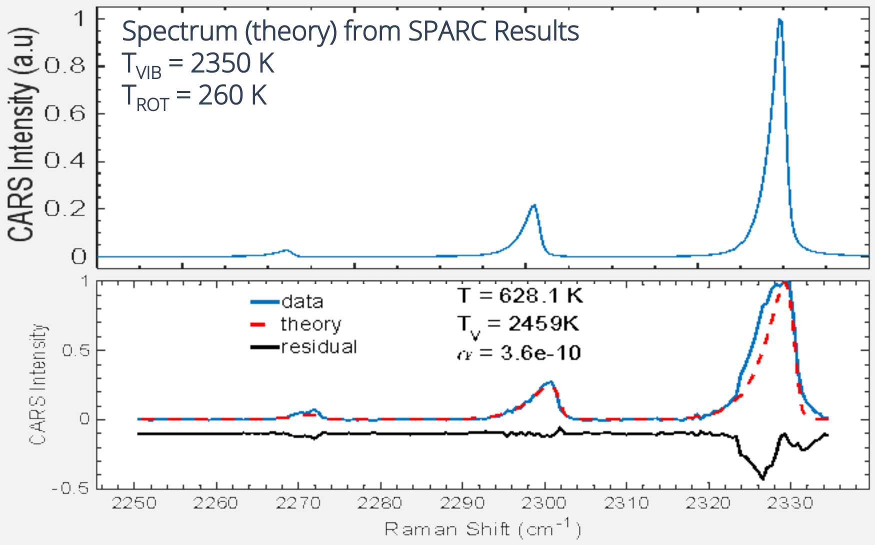
- HST introduces flow complexities
  - Stagnation region gases react
  - Gas rapidly expanded through nozzle
  - Result: thermal non-eq., N-O added
- Free-stream characterization necessary
  - Temperature: CARS for heteronuclear molecules
  - Velocity: NO LIF
- Examine boundary layer products
  - Speciation/temperature of CO
    - Laser absorption
    - CARS (Coherent Anti-Raman Stokes



Free-Stream Characterization: Temperature

- Free-stream conditions
  - Major source of uncertainty in shock tunnels
  - Temperature non-eq. in nozzle is expected
- Simulation of nozzle temperatures
  - Significant T_v differences between species
  - N_2 has highest degree of non-eq
- Characterizing temperature non-eq. in HST
  - Use CARS to measure T_{vib}, T_{rot} for N_2
  - Further improvement needed for T_{rot}
  - Next: O_2 CARS temp. measurements

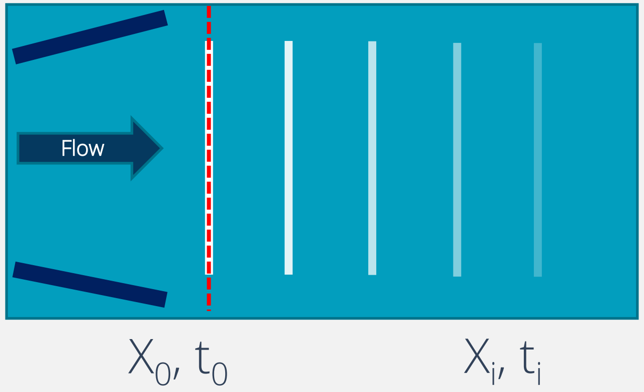


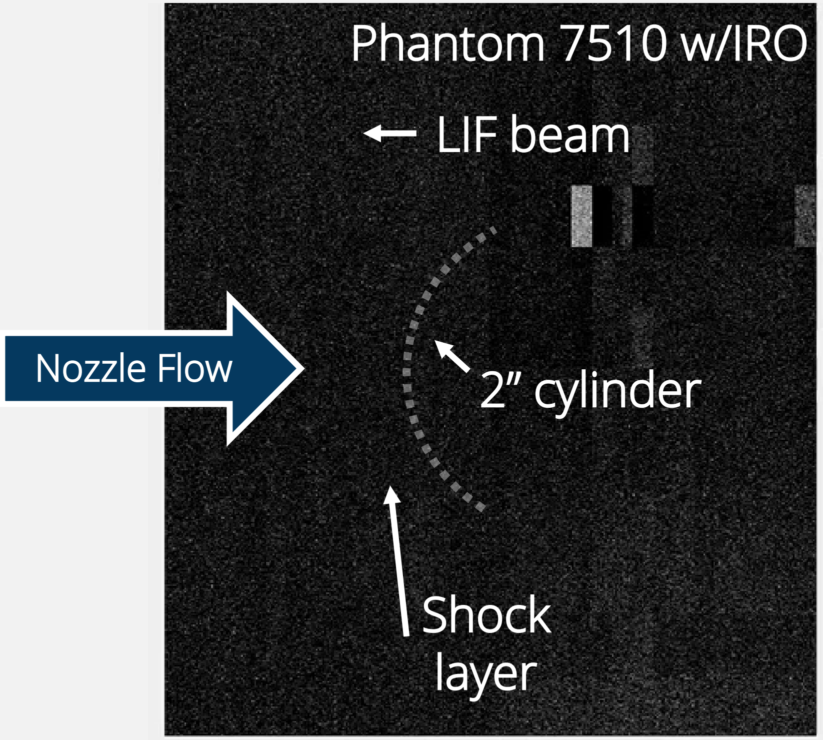


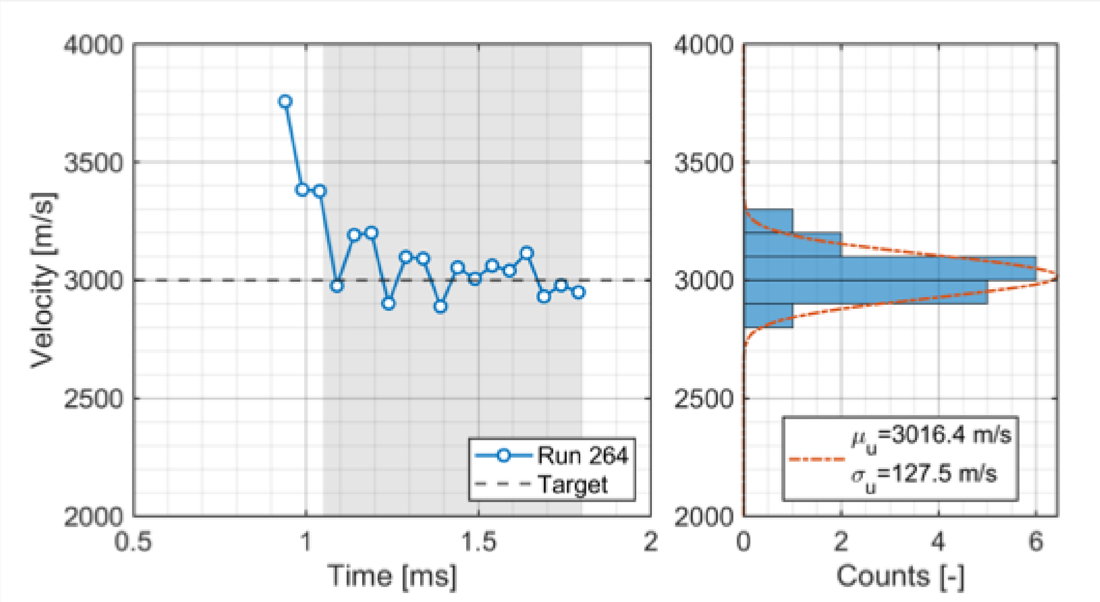
Free-Stream Characterization: Velocity

- NO is present in shock tunnel flow (X_{NO}~4-5%)
- Tracer for flow visualization
- Nitric Oxide Tagging Velocimetry
- Long fluorescence lifetime, >100 ns
  - U_{∞}=3 km/s = 3 μm/ns, Δt~100 ns → Δx~300 μm
  - Track NO fluorescence at high image magnification

LIF beam tracks flow

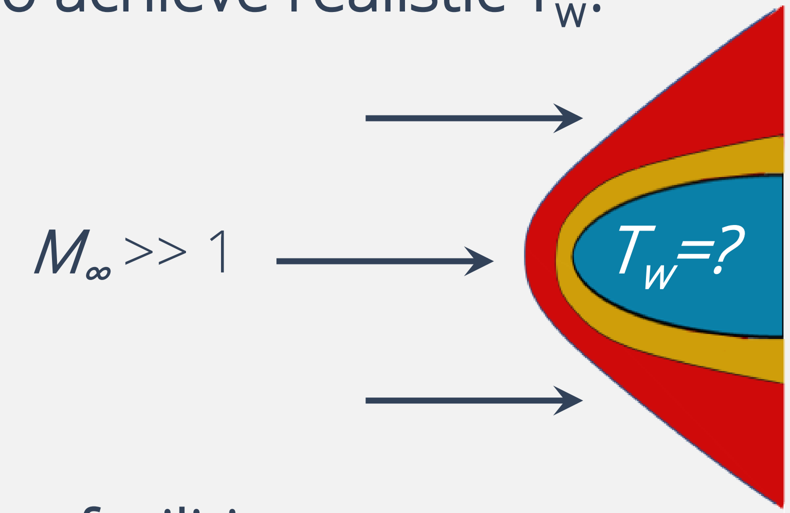






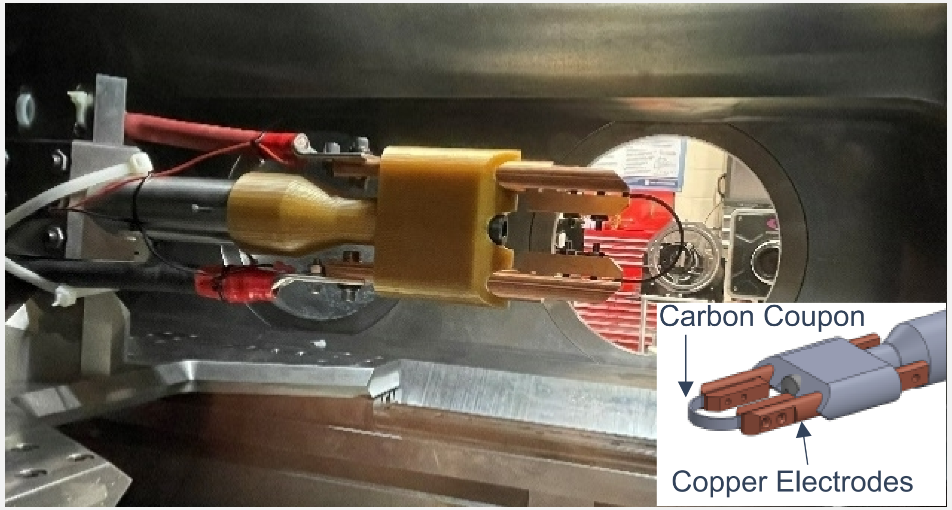
Impulse Facility Material Testing Considerations

- Generate free-stream condition in HST
- How to achieve realistic T_w?



- Impulse facilities
  - Short test time
  - Unable to achieve realistic Tw
  - Must preheat model

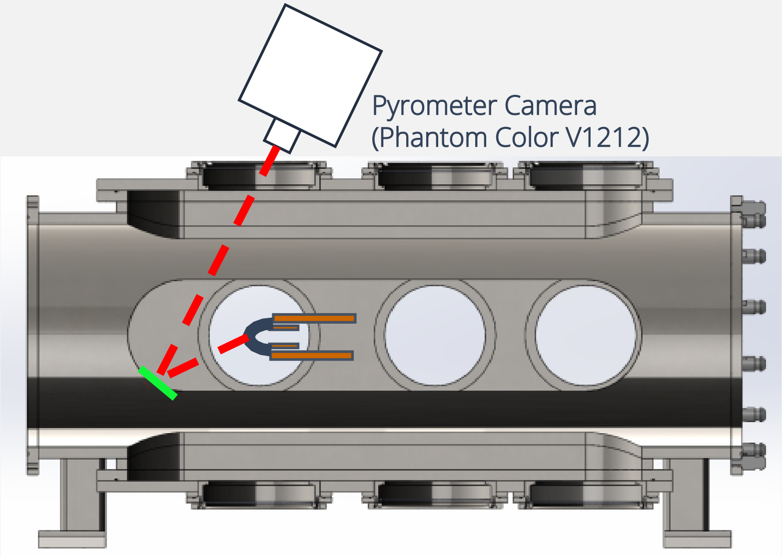
- Resistively heat models
  - Joule heating: $T \propto I_{supply}^2 R_{Mat'l}$
  - *Hot Wall Re-entry Testing in Hypersonic Facilities*, Zander et al. 2013 (others)
- Graphite Coupons
  - Good surrogate for wall mat'l.
  - Easily scalable

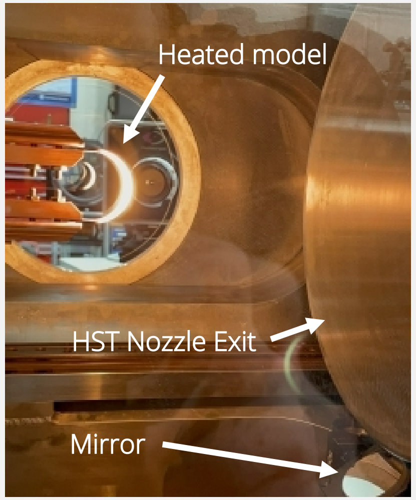


Tunnel Experiments: Mounting and Pyrometer

- Model Mounting Within HST
  - High-temperature 3D printed plastic
    - Electrical isolation of electrodes

  - Mirror mounted within test section to provide better viewing angle of model front surface



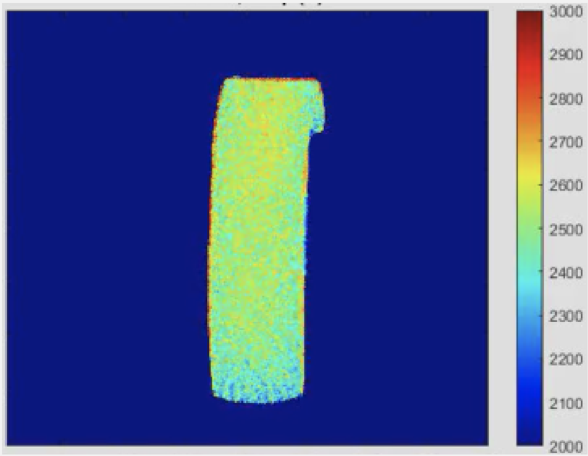


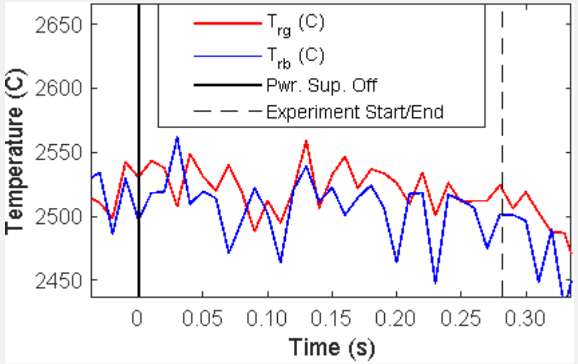
Heating process prior to an experiment

- Pyrometer (Prior to Experiment)

Lower Temp ~800-1000 K, no filters

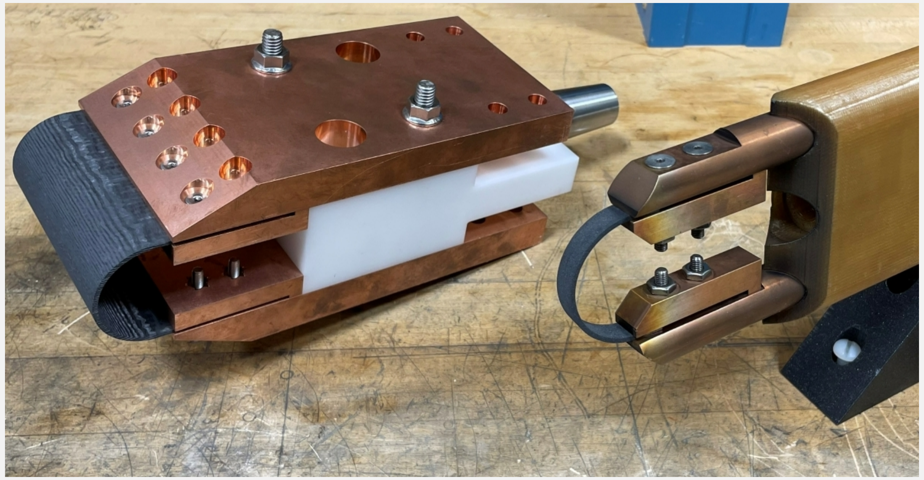
Higher temp w/filters: ~2550 C ≈ 2825 K

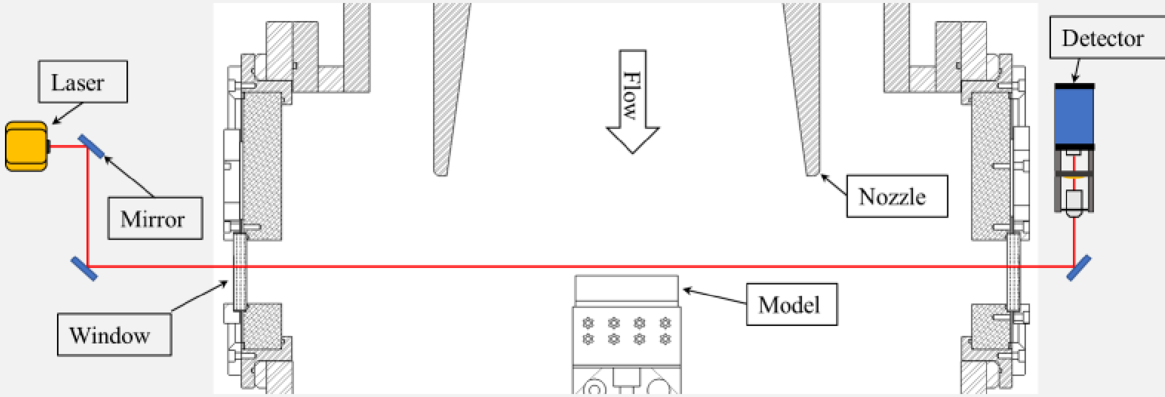




Extension to Larger Test Model Geometry

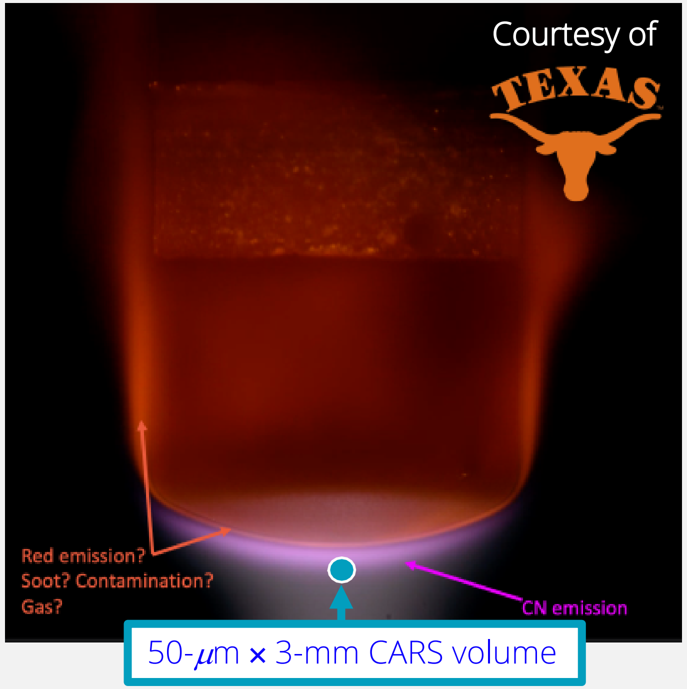
- Original TPS Geometry Was Proof-of-Concept
  - Subject to 3D flow effects
  - Insufficient probe volume for diagnostics
- Modify TPS Geometry to Simulate 2D Flow
  - Utilize same cylindrical cross-section
  - Elongate span from 10 mm to 100 mm
- Measure boundary layer products (CO, etc)
  - Laser absorption spectroscopy
  - CARS (for temperature, concentrations)

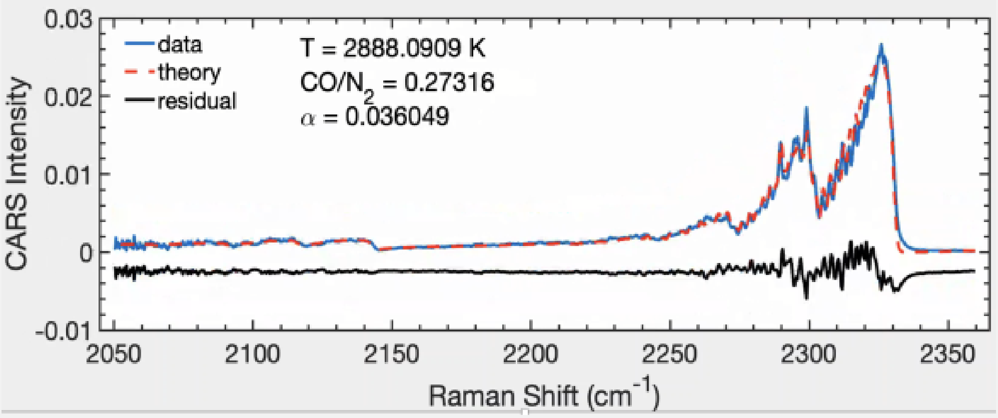


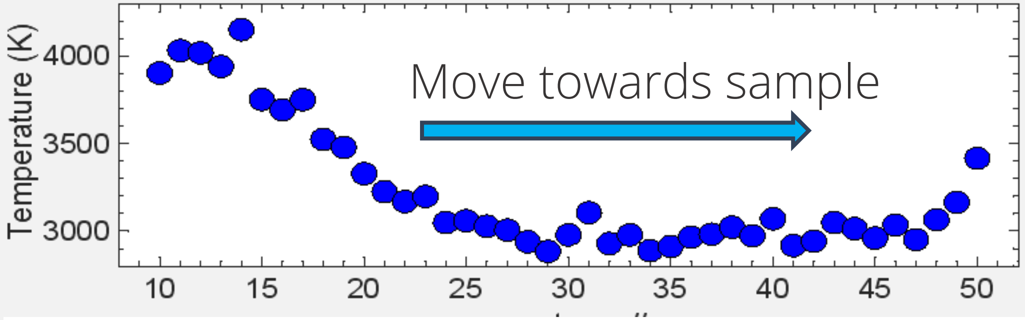


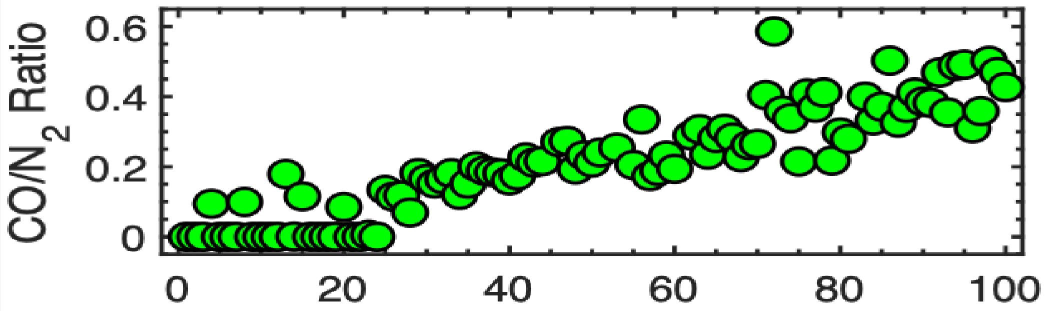
Complimentary Measurements in UT ICP

- Collaboration with UT
  - Used CARS to measure
    - N_2 temperatures
    - CO/N_2 mass ratios
  - Utility
    - High resolution
    - Near-surface detection
  - Challenges:
    - High luminosity/temp

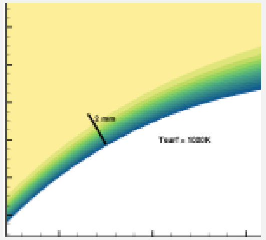








- Next: Measurements in SNL HST
  - Pulseburst CARS in TPS boundary layer



- Compare HST/ICP CARS data w/models

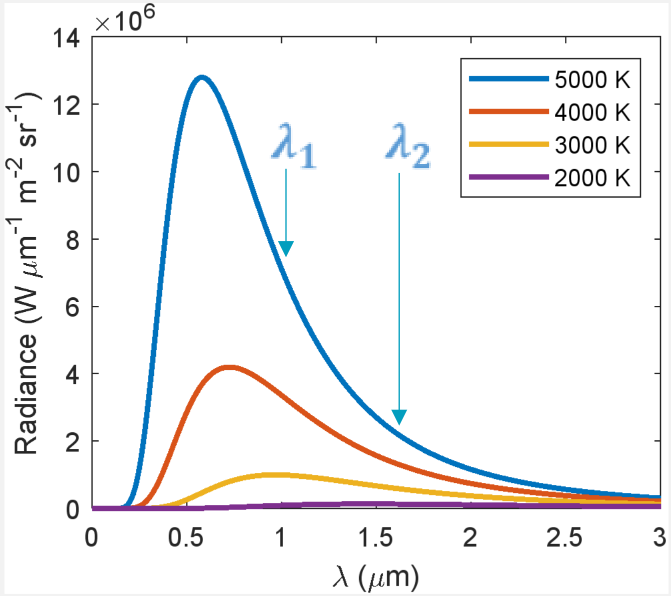
Conclusions

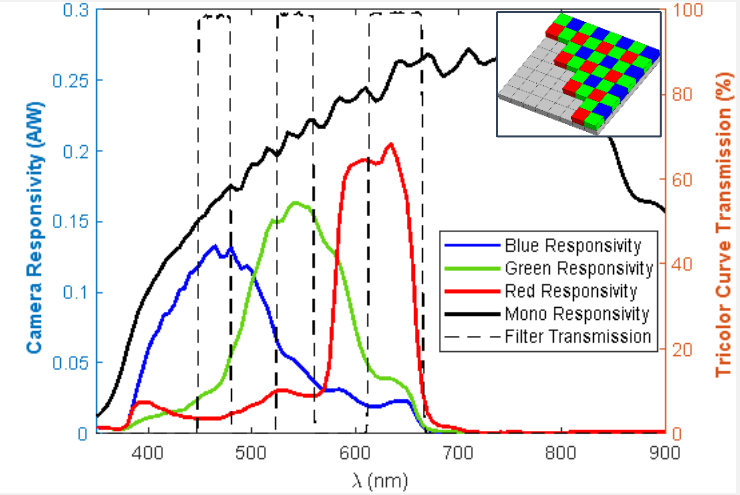
- Ablation modeling
  - Predictions vary between models
  - Validation needed
  - Sparse literature data
- Utilize HST in TPS characterization
  - Replicate hypersonic flow
  - Thermo-chemical
  - Velocity
- Free-stream characterization needed
  - N_2 CARS, $T_{rot, vib}$
  - NO PLIF, U_∞
- Impulse facility test times
  - Model preheating required
  - Use pyrometer to measure T_w
- Stay Tuned: Boundary Layer Data
  - Laser Absorption measurements (CO)
  - CARS measurements of temp., relative concentrations
  - More UT Plasma torch measurements

Questions?

Surface Temperature Characterization: Pyrometry

- How to Measure T_w? : Thermal Radiation
  - Some real surfaces (like graphite) are similar to a blackbody
  - Ratio of signal from discrete wavelengths: $\frac{S_{\lambda_1}}{S_{\lambda_2}} = f(T_{object})$
    - Unique to a particular BB temperature
    - Also true if emitter is a gray body (constant emissivity)
  - Measuring 2 discrete wavelengths is challenging
  - Measure wavelength bands instead (more signal, better for cameras)
  - Use color camera (Phantom V1212)
  - Increase temp. sensitivity with tri-color filter



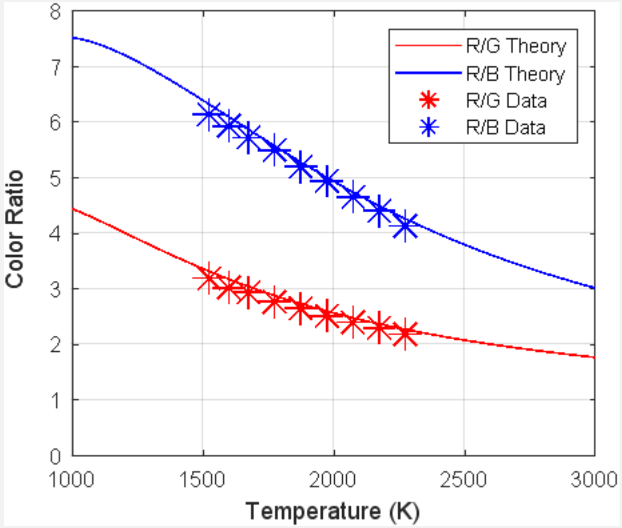


Pyrometry Calibration

- Calibration Source:
  - Use blackbody source for calibration
  - Temperature range 1200 C – 2700 C
    - Same as that of model T_w

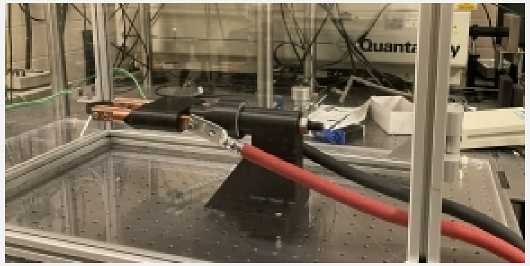
$$I_{ratio} = \frac{\int_0^\infty E(\lambda, T_{obj})\, \tau_{filt}\, \tau_{lenses}\, S_{\lambda_1,cam}\, d\lambda}{\int_0^\infty E(\lambda, T_{obj})\tau_{filt}\, \tau_{lenses}\, S_{\lambda_2,cam} d\lambda}$$

- Ratio Calibration:
  - Data (*) of R/G and R/B ratios compare well to theoretical values (line) for calibration range
    - 1250 C – 2000 C shown at right
  - Additional calibration data up to 2700 C recorded



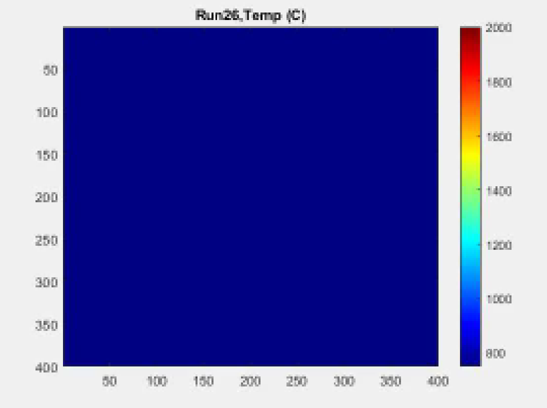
Benchtop Testing & Pyrometer Validation

- Testing and Validation:



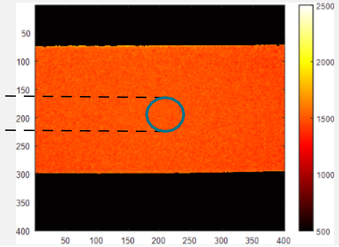

Benchtop heating using Color Pyrometer:

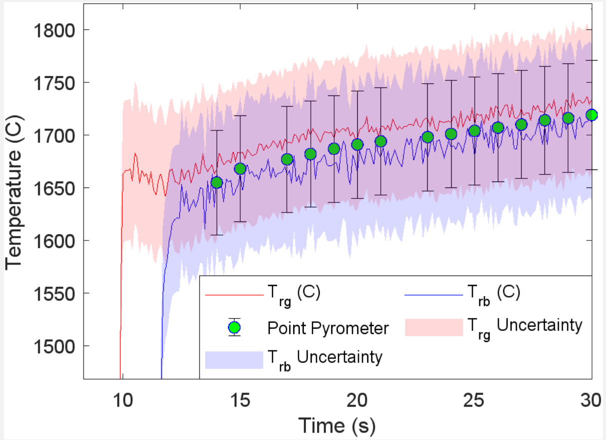
$$t_{0,video} = t_{0,current}$$



- Video: pyrometer cannot capture entire heat-up duration
  - Not enough visible signal at lower temps and near-saturation at higher temps
  - Pixels with intensity < 5% of saturation or >86% of saturation are removed from analysis
- Average 100 pixels at center of color pyrometer frame vs time
  - T_{rg} : temp from the R/G ratio T_{rb} : temp from the R/B ratio
  - 2D pyrometer compared to IR point pyrometer

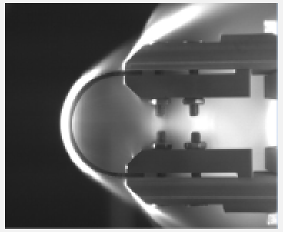
Handheld pyrometer focuses on a point at center of strip

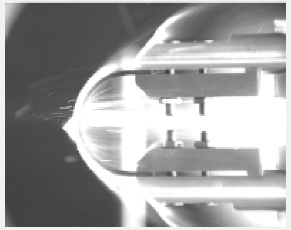




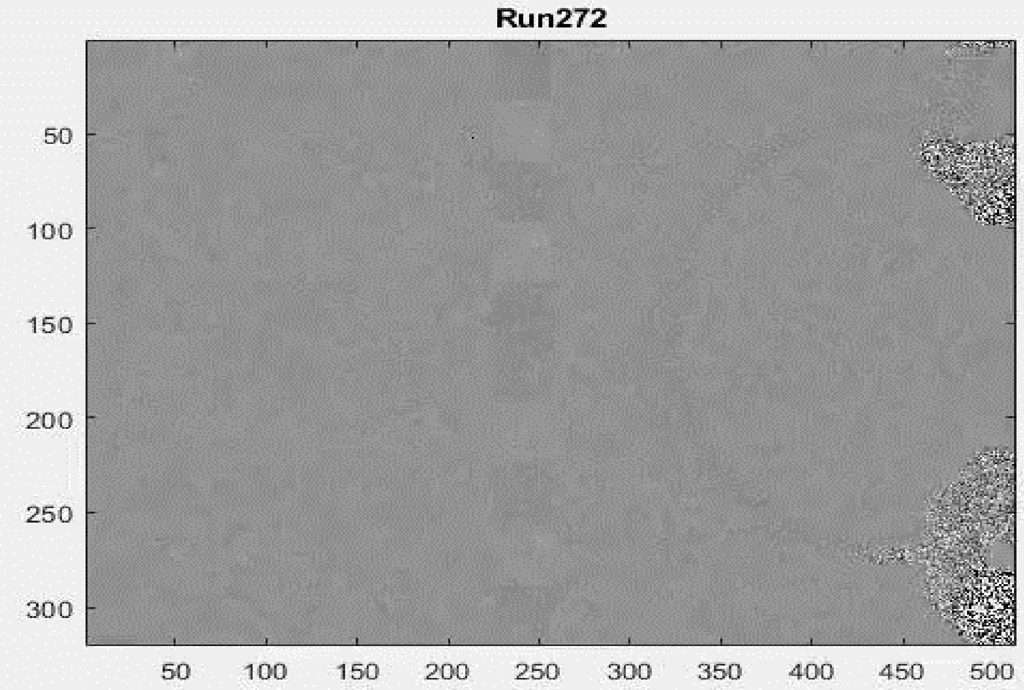
Tunnel Experiments: High Speed Video & Schlieren

- High Speed Video (Run HST-277)
  - Model has no preheating for better viewing of shock layer



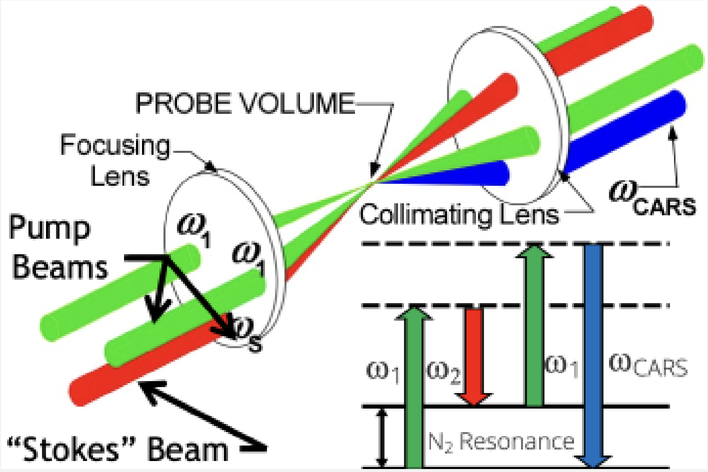


- Schlieren (Run HST-272)
  - Prior to backlighting, model is visible in the frame due to high temperature
  - Shock standoff ~2.8mm (with / without heating

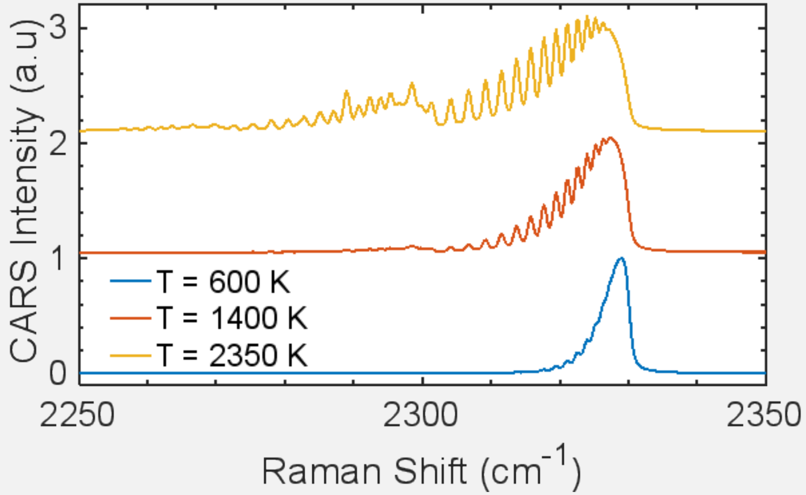


Free-Stream Characterization: N_2 CARS Temperature

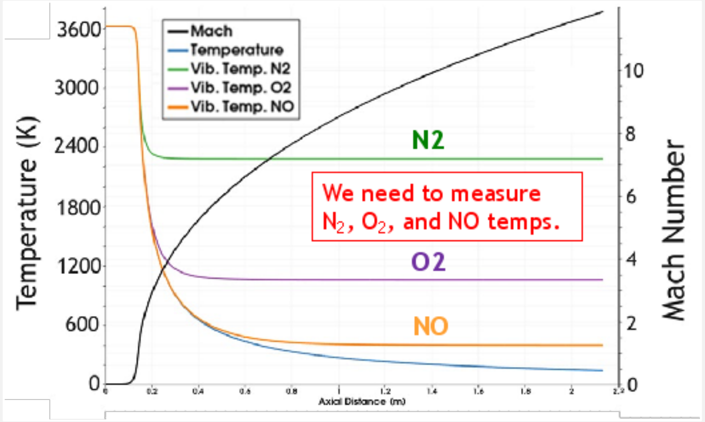
Free-Stream Boundary Conditions : A Major Source of Uncertainty in Shock-Tunnel Measurements



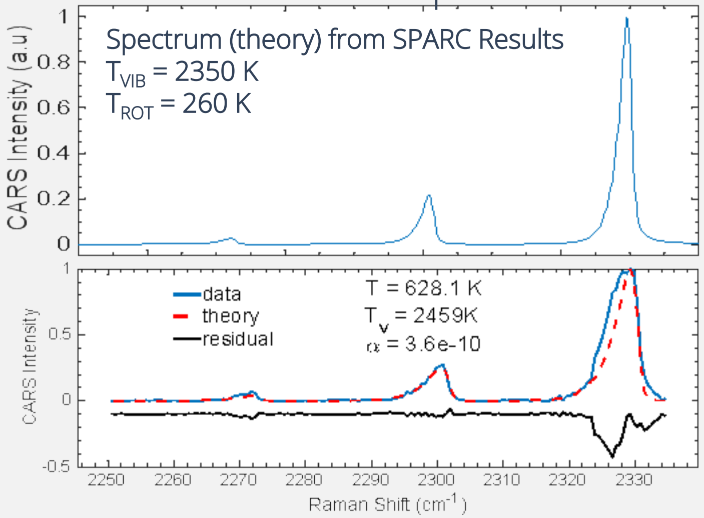
Equilibrium Temp. Dependence in N2

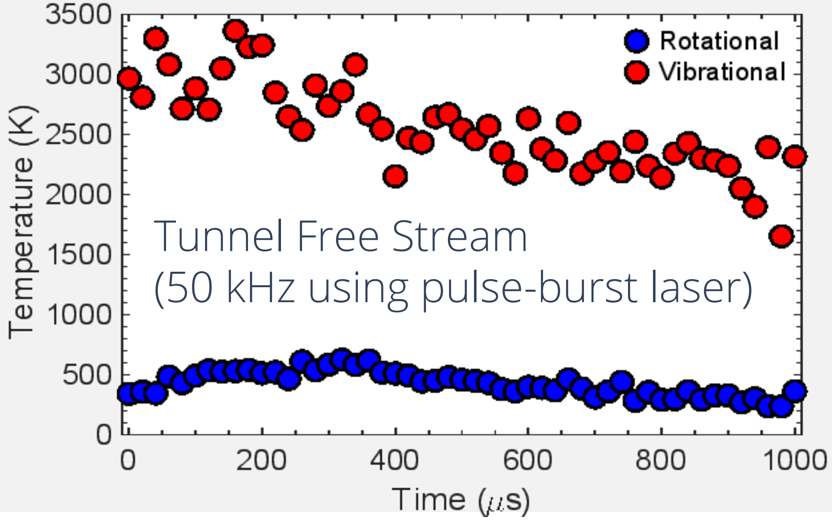


SPARC Sim. of Nozzle Non-Eq.



Thermal Nonequilibrium



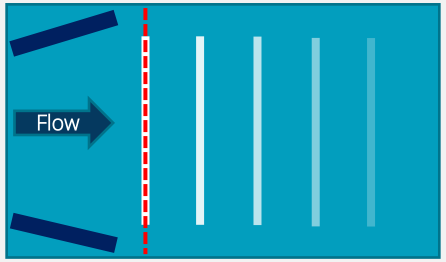


- Next Steps
  - Improve sensitivity to T_{rot}
  - Repeat N_2 measurements
  - Measure O_2 temperatures

Free-Stream Characterization: Velocity

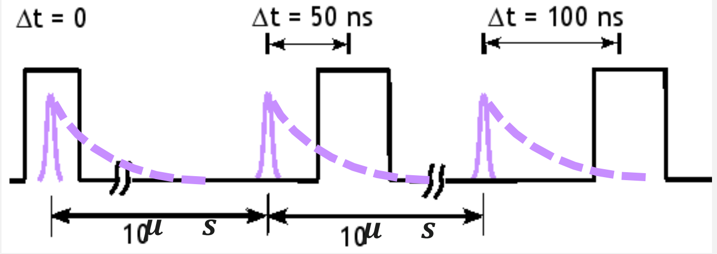
- NO is present in shock tunnel flow (X_{NO}~4-5%)
- Tracer for flow visualization
- Nitric Oxide Tagging Velocimetry
- Long fluorescence lifetime, >100 ns
  - U_∞=3 km/s = 3 μm/ns, Δt~100 ns → Δx~300 μm
  - Track NO fluorescence at high image magnification

Δt_i short for camera!



X_0, t_0 X_i, t_i

Pulse-burst Laser and HS Camera



Phantom 7510 with IRO