Recent Applications of Molecular-Based Laser Diagnostics Relevant to Space Technology and Exploration

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  - Test Facility Staff: Langley Aerothermodynamics Laboratory, Marshall Test Stand 300

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  - Game Changing Development (GCD) program *Entry Systems Modeling* project [STMD]
  - Game Changing Development (GCD) program *Plume Surface Interaction* project [STMD]
  - Technology Demonstration Missions (TMD) program *LOFTID* project [STMD]
  - Aerosciences Evaluation and Test Capabilities (AETC) program *Test Technology* (TT) project
  - Human Landing Systems (HLS) program *Plume Surface Interaction Ground Test*
  - Small Business Innovative Research (SBIR) Program

Outline

- Introduction
- Mach 10 Tunnel Freestream Characterization
- Hypersonic Wakes for Planetary Entry
- Supersonic Plume Impingement for Spacecraft Landings
- Lab-scale Diagnostics Development
- Summary & Conclusions

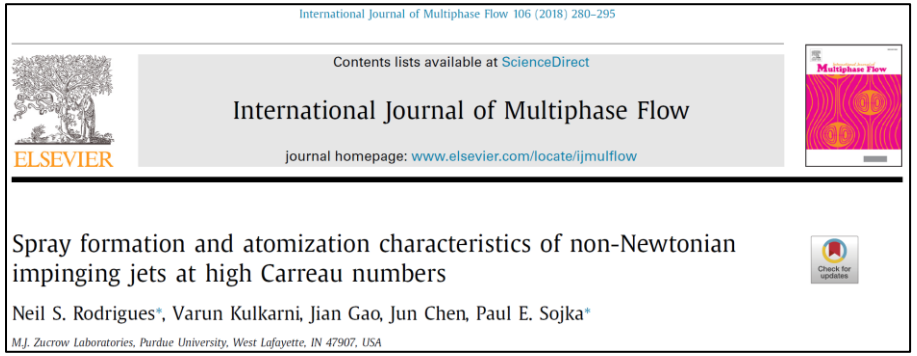
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About Me

Educational and Work Background

- 2008-2012: Fairfield University, CT (B.S.)
- 2010-2011: Undergraduate internships at Hologic Corporation (Marlborough, MA)
- 2012-2014: Purdue University, IN (M.S.)
  - Thesis: Impinging jet spray formation using non-Newtonian Liquids (Advisor: Prof. Paul Sojka)
- 2014-2016: Engineer at Xerox Corporation (Rochester, NY)
- 2016-2020: Purdue University, IN (Ph.D.)
  - Dissertation: Reacting jets in compressible vitiated crossflow with negligible swirl (Advisor: Prof. Robert Lucht)
- 2020-2022: NASA Postdoctoral Program (Hampton, VA)
  - Proposal: High-speed planar laser-induced fluorescence (Advisor: Dr. Paul Danehy)
- 2022+: Staff Scientist at NASA Langley Research Center


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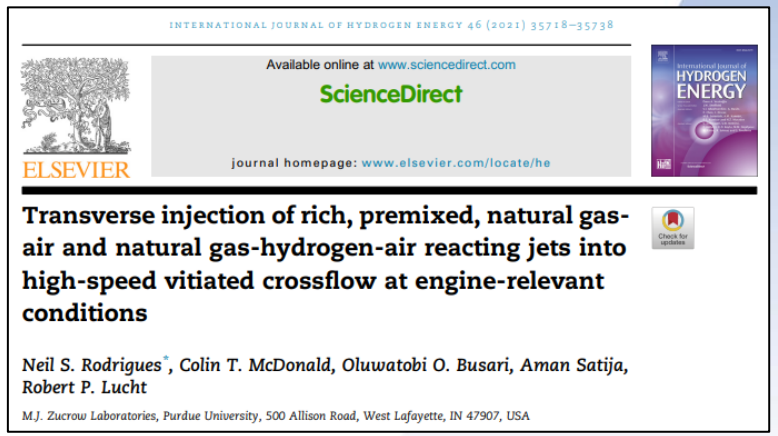
journal homepage: www.elsevier.com/locate/ijmulflow

ELSEVIER

Spray formation and atomization characteristics of non-Newtonian impinging jets at high Carreau numbers

Neil S. Rodrigues*, Varun Kulkarni, Jian Gao, Jun Chen, Paul E. Sojka*

M.J. Zucrow Laboratories, Purdue University, West Lafayette, IN 47907, USA


INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 46 (2021) 35718–35738

Available online at www.sciencedirect.com

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ELSEVIER

Transverse injection of rich, premixed, natural gas-air and natural gas-hydrogen-air reacting jets into high-speed vitiated crossflow at engine-relevant conditions

Neil S. Rodrigues*, Colin T. McDonald, Oluwatobi O. Busari, Aman Satija, Robert P. Lucht

M.J. Zucrow Laboratories, Purdue University, 500 Allison Road, West Lafayette, IN 47907, USA

Motivation for Molecular-Based Measurements

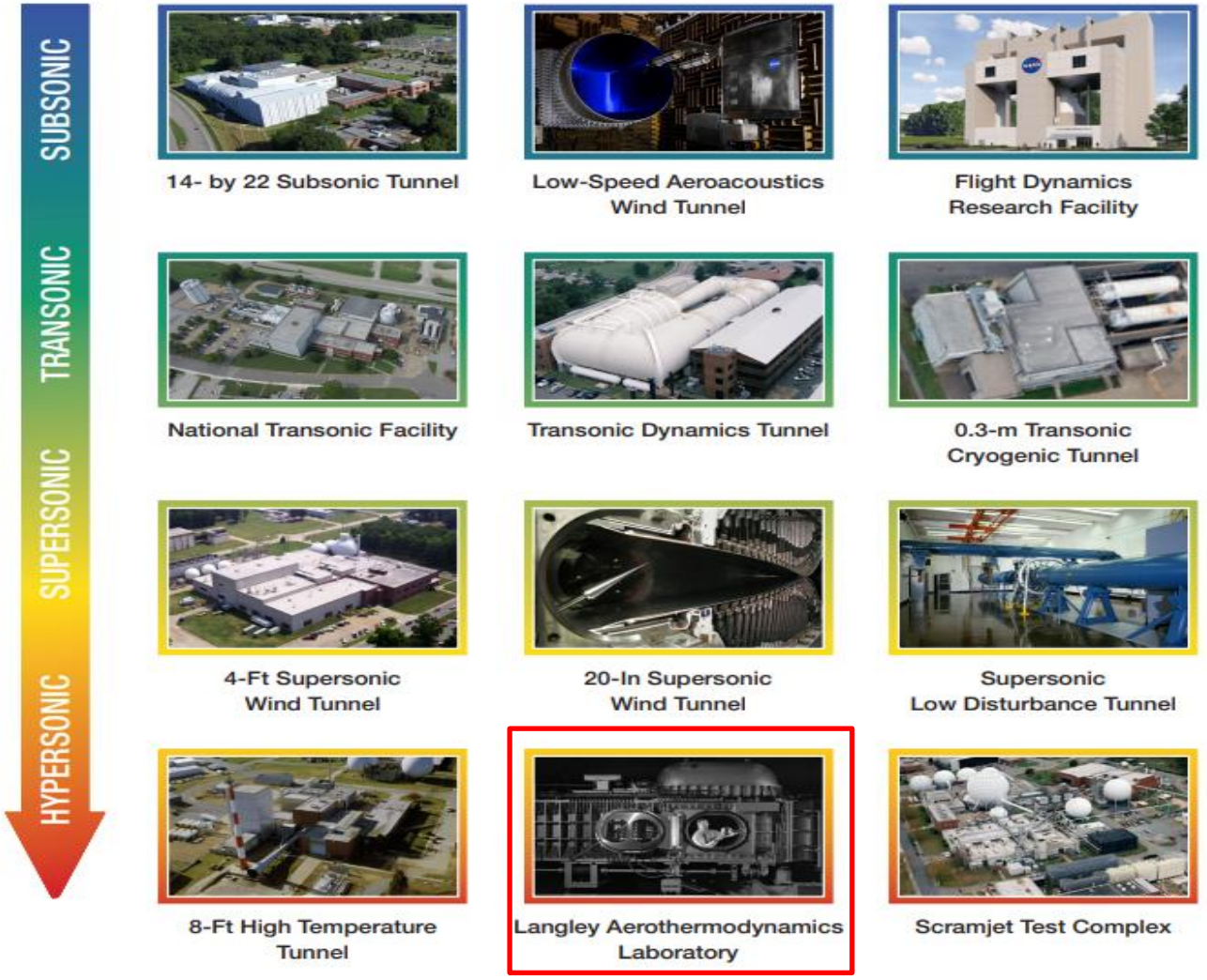
- **Enable study of a scientific problem and ultimately engineer better flight vehicles**
  - Deeper understanding of flow physics
    - Flow separation, laminar/turbulent transition, aeroheating
  - Data for validation of CFD codes

- **Ground test (often wind tunnel) data:**
  - Used to predict response of vehicle design through a specified flight trajectory
  - Validate increasingly complex computational models

- **Among various types of molecular-based diagnostics at NASA Langley, flow visualization using seeded Nitric Oxide (NO-PLIF) most common for Space Technology and Exploration applications**
  - Often low-density flows; NO-PLIF works very well at low gas densities
  - PLIF molecular tagging velocimetry most common quantitative PLIF variant
  - Multi-parameter spectroscopic measurements an active area of research
  - 10 Hz repetition-rate typical; high-speed PLIF also an active area of research

- **Confidence in test data:**
  - Directly related to confidence that data was acquired at known test conditions

NASA Langley Aerosciences Facilities



Recent Applications

NO-PLIF and FLEET within 31-in Mach 10 Tunnel at NASA Langley Research Center (LaRC)



- Characterize freestream velocity
- Investigate hypersonic wakes of blunt bodies for terrestrial and Martian planetary entry

NO-PLIF within 20-ft Vacuum Chamber at NASA Marshall Space Flight Center (MSFC)



- Investigate plume impingement flow behavior for lunar and Martian landings

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Hypersonic Freestream Characterization

- **On the use of test data for CFD validation:**
  - "Variability and uncertainty of inputs to fluid dynamic problems are largely unquantified"
    - CFD Vision 2030 Study (Slotnick *et al.*, 2014)
  - Computational methods "could be correct but didn't simulate the same experiment"
    - NATO Manuscript on hypersonic wind tunnel characterization (Danehy *et al.*, 2018)

- **Non-intrusive measurements are challenging in such environments:**
  - Physical probes and particle-based measurements not suited
  - Density-gradient-based (shadowgraph, schlieren) measurements limited by low static densities
  - Laser-induced fluorescence limited by need to seed gas with tracers (krypton, nitric oxide, etc.)

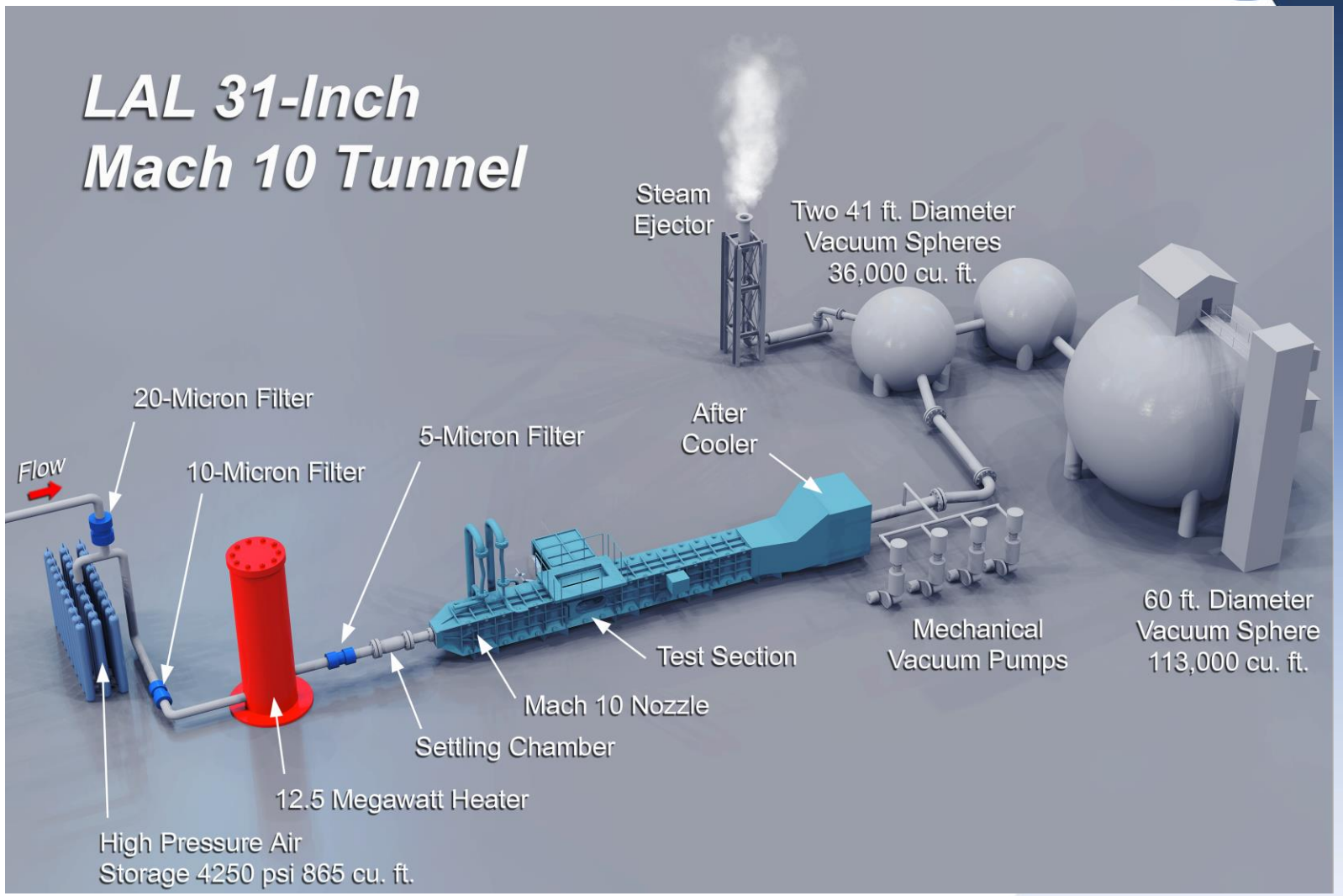
- **Objective: freestream velocity measurements in NASA Langley 31-inch Mach 10 Tunnel**

NASA Langley 31-inch Mach 10 Air Tunnel

- **Blowdown wind tunnel**
  - 10 – 100 second runs
- **Optical access on 3 sides**
  - 4th side model injection
- **3 typical unit Reynolds numbers**

M_∞ [-]	9.688	9.821	9.944
Re_∞/L [m^{-1}]	$1.78 \cdot 10^6$	$3.58 \cdot 10^6$	$6.27 \cdot 10^6$
T_0 [K]	968	964	966
T_∞ [K]	51.0	49.6	48.8
P_0 [MPa]	2.42	4.98	8.99
P_∞ [Pa]	68.4	130.2	219.9
ρ_∞ [kg/m^3]	$4.67 \cdot 10^{-3}$	$9.16 \cdot 10^{-3}$	$1.58 \cdot 10^{-2}$
u_∞ [m/s]	1385	1386	1385

- **Low freestream densities:**
  - 0.4 -1.3% of standard temperature and pressure



Freestream velocity never directly measured at this hypersonic tunnel

Hypersonic Blowdown Facility Diagnostics

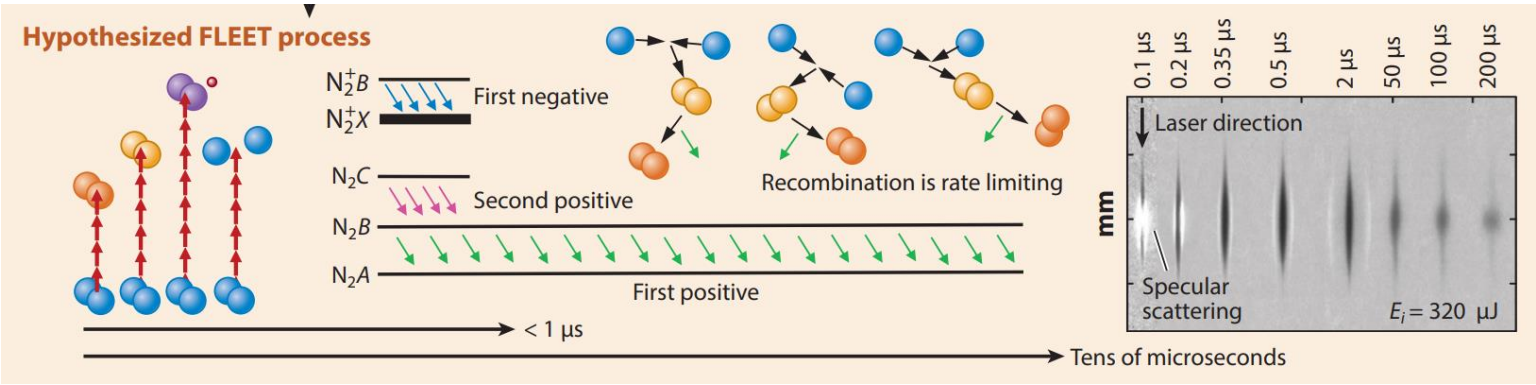
- **NASA Langley 31-inch Mach 10 Air tunnel is a *hypersonic blowdown* facility similar to:**
  - Sandia Hypersonic Wind Tunnel and AEDC Hypervelocity Wind Tunnel 9
  - One difference: air as test gas for NASA Langley 31-inch Mach 10 (N_2 as test gas for Sandia/AEDC)

- **Femtosecond Laser Electronic Excitation Tagging (FLEET) promising for blowdown N_2/Air tunnels:**
  - Used at several N_2 blowdown tunnels:
    - Sandia Hypersonic Wind Tunnel (Carter and Beresh, 2024; Zhang *et al.*, 2019)
    - AEDC Tunnel 9 (Dogariu *et al.* 2019 and 2021)
    - Boeing/AFOSR Mach 6 quiet tunnel at Purdue (Fisher *et al.*, 2021)
  - Recently pushed towards hypersonic air facilities (Grib *et al.*, 2022; Pehrson *et al.*, 2023)

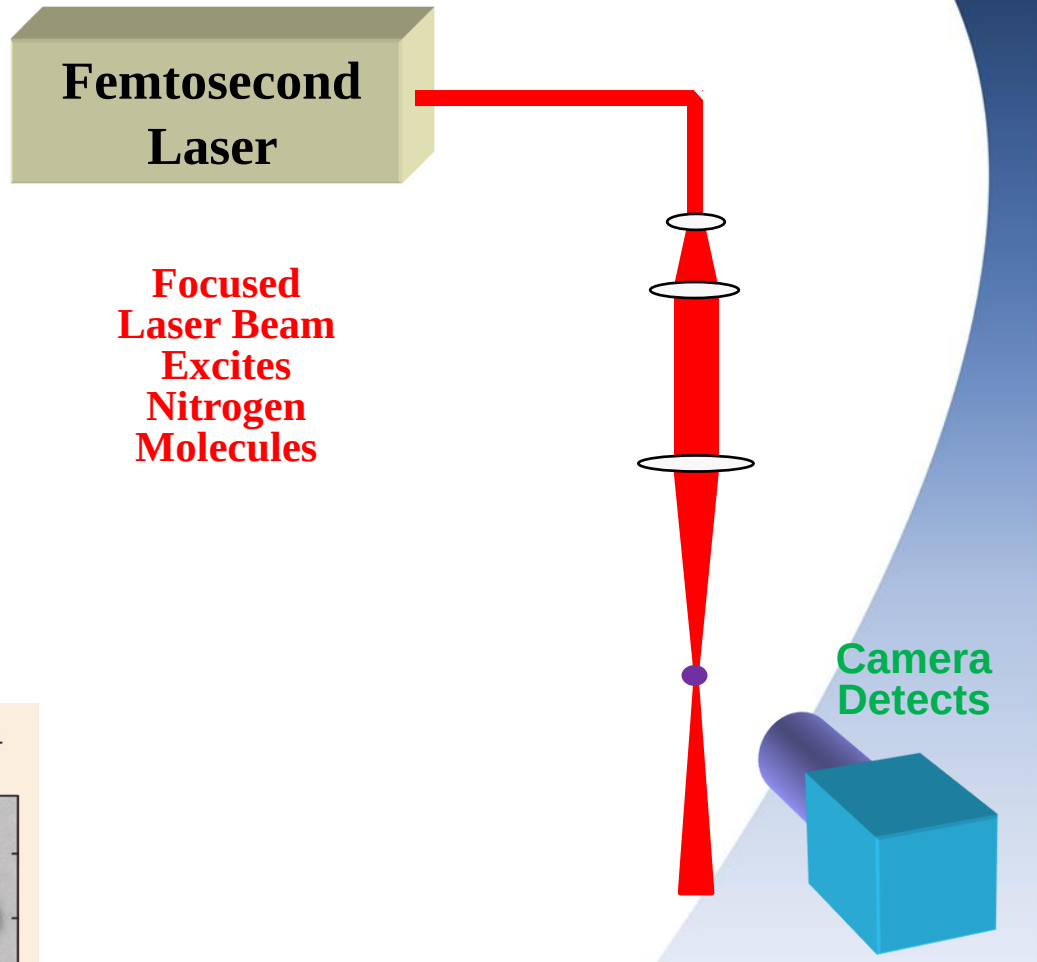
- **FLEET likely promising but challenging at NASA Langley 31-inch Mach 10 Air tunnel**
  - Very low gas densities
  - Air instead of nitrogen
  - Large-scale facility

Femtosecond Laser Electronic Excitation Tagging

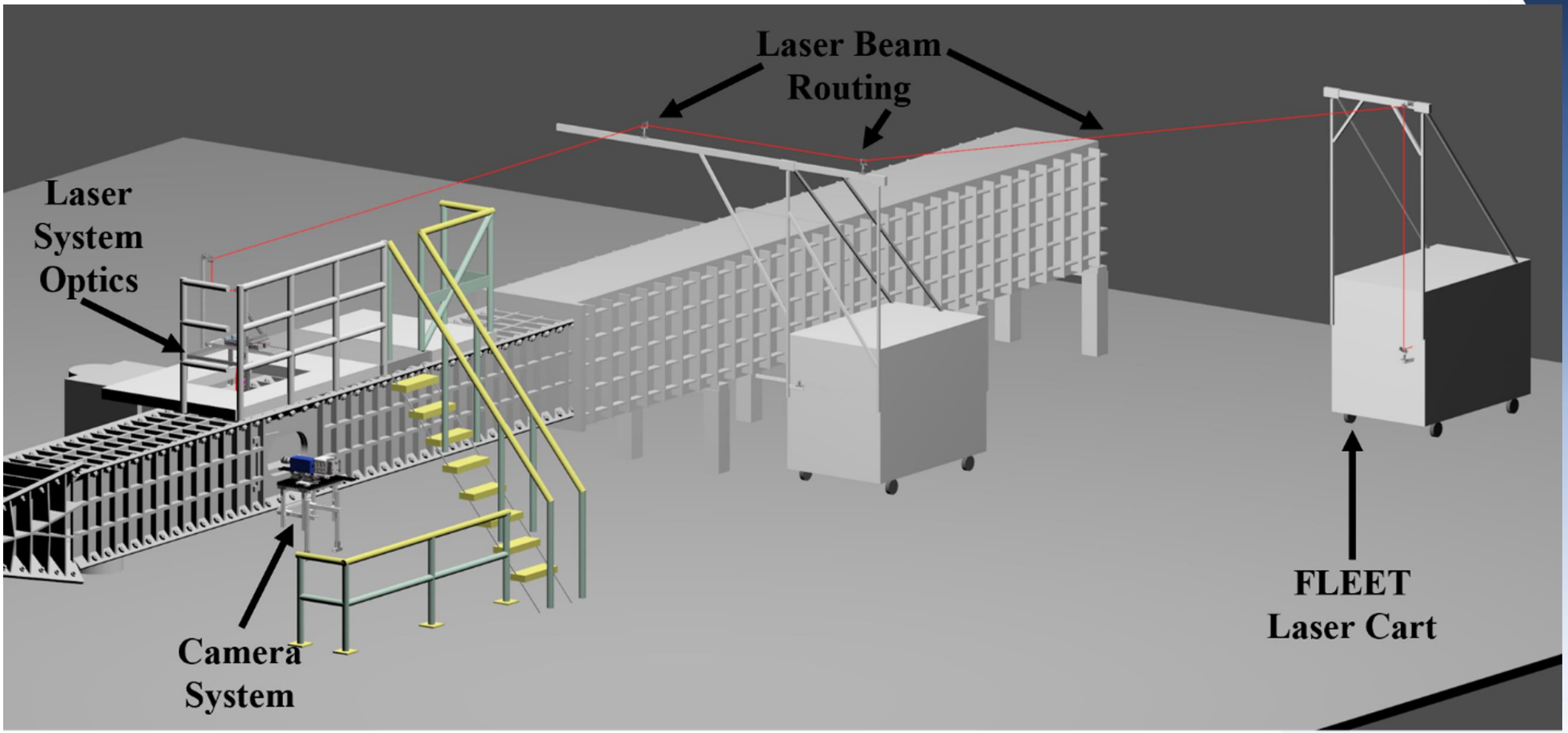
- **FLEET probes nitrogen molecule in air**
  - Does not require any seed gas
- **Near-IR excitation wavelength accessible with commercially available femtosecond lasers**
- **Visible fluorescence detectable with commercial high-speed (kHz-MHz) intensified cameras**
- **Spectroscopic mechanism of FLEET not fully understood**
  - Very little in literature for low pressure air



From FLEET review paper by Danehy *et al.* (2022)

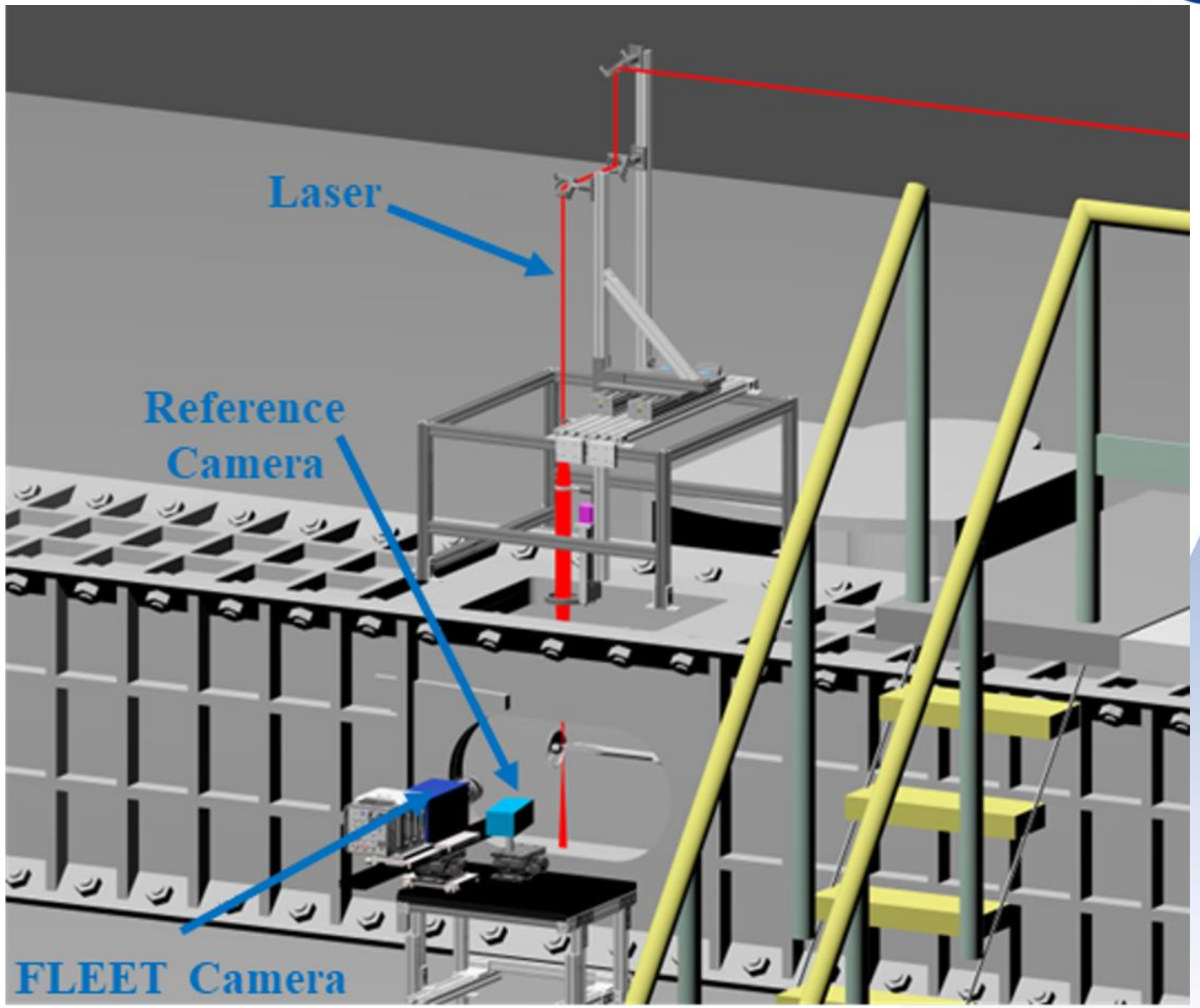


FLEET Setup at Wind Tunnel



FLEET Setup at Test Section

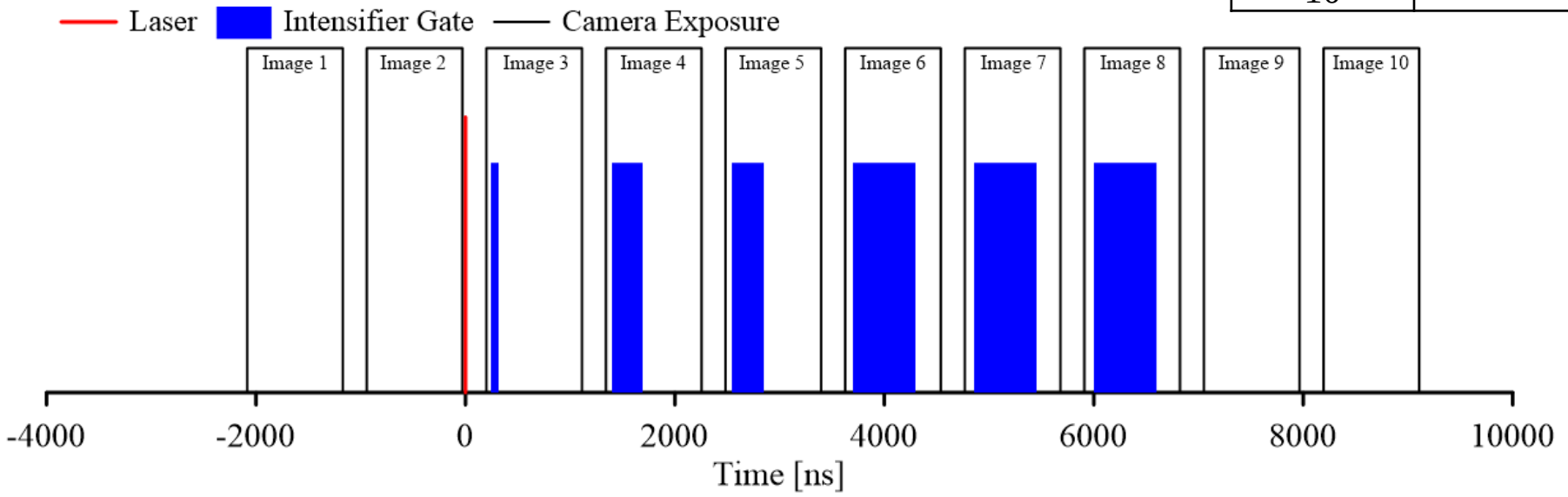
- **3.5 W Spectra-Physics Solstice©**
  - 2.5 W in test section
  - +500 mm focusing lens
- **Phantom© TMX-7510 w/ LaVision© High-Speed VIS-NIR intensifier**
  - 135 mm *f*/2 Canon© lens
  - ISSI© Lens Controller
  - Camera configured for initial image and 5 delayed images per laser pulse
- **Remotely controlled translation stage to vary FLEET probe location**



FLEET Timing Scheme

- **Camera operated in burst-mode with 10 images per laser pulse (similar scheme as Burns and Danehy, 2017)**
  - Image intensifier used for initial (Δt = 0) image and up to 5 delayed images at discrete Δt
  - First intensifier gate delayed from laser pulse by 250 ns
  - 4th and 5th delayed images acquired for alternating laser pulses due to limitations of delay generator

		[ns]	[ns]
Image Sequence	**FLEET Image**	**Gate Center**	**Gate Duration**
1	-	-	-
2	Background	-	-
3	Initial	0	70
4	1st Delayed	1265	300
5	2nd Delayed	2415	300
6	3rd Delayed	3715	600
7	4th Delayed	4865	600
8	5th Delayed	6015	600
9	-	-	-
10	-	-	-

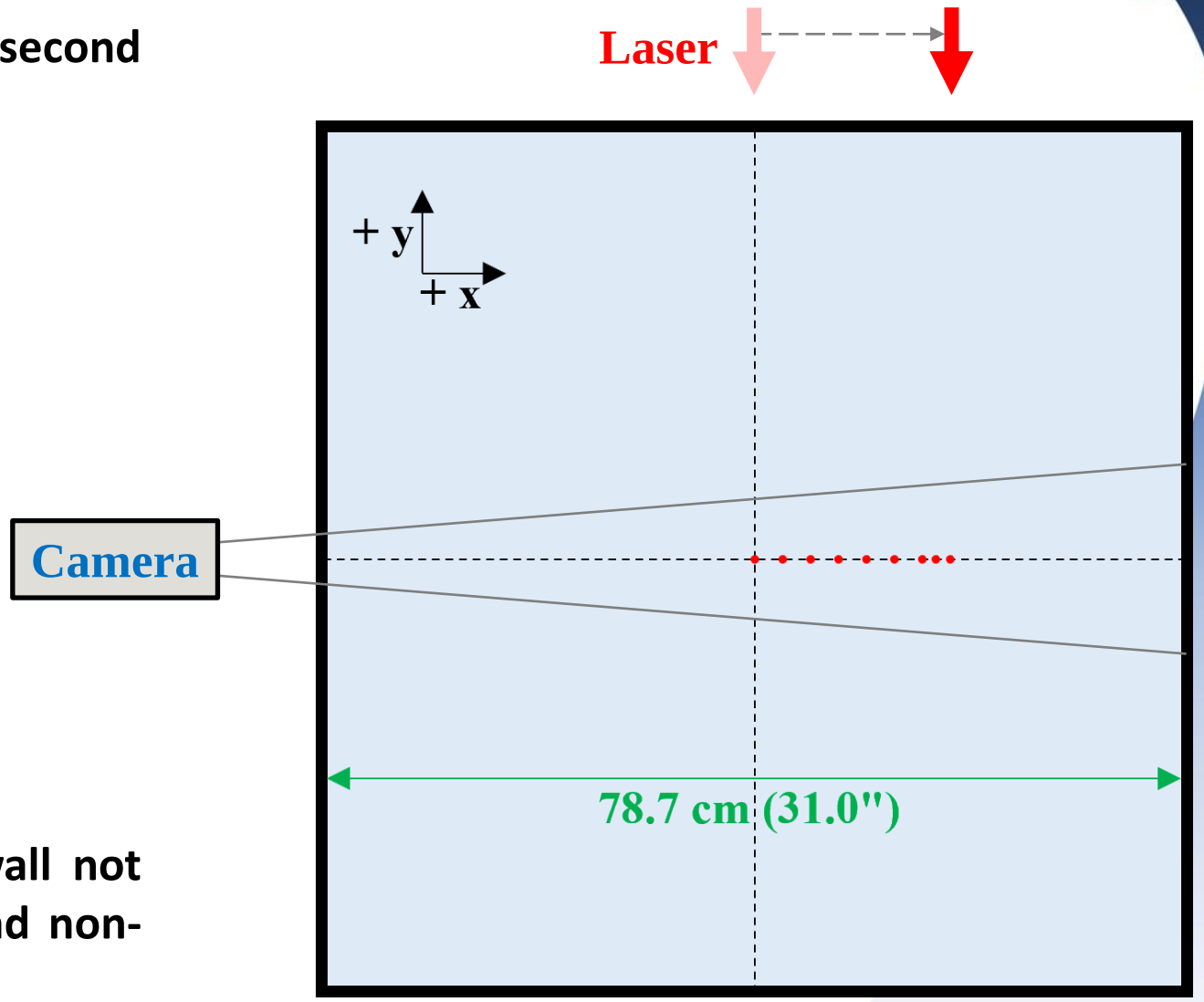


FLEET Measurement Locations

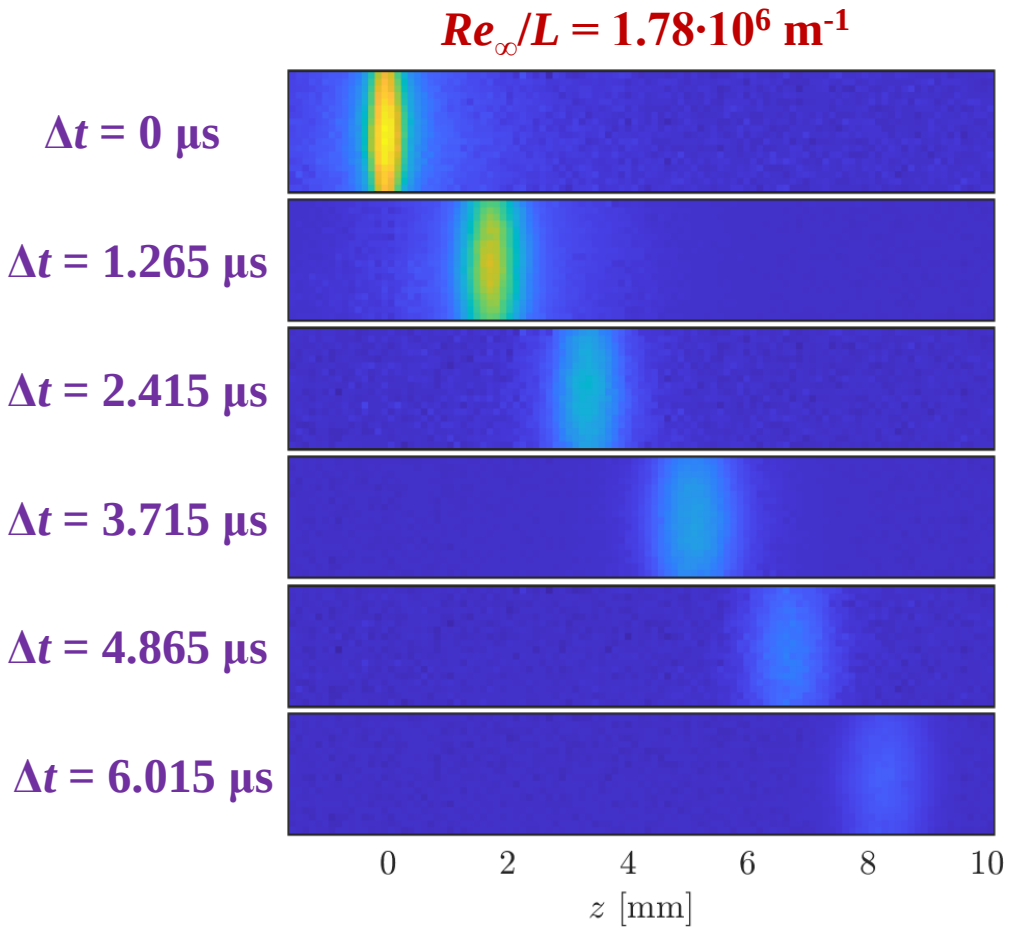
- **9 different spatial points measured over 100 second wind tunnel run for each Reynolds number**
  - 5 seconds at each measurement location
    - 5000 samples per measurement location

[cm]	[cm]
X-location	**Y-location**
0	0
2.54	0
5.08	0
7.62	0
10.2	0
12.7	0
15.2	0
16.5	0
17.8	0

- **Measurements closer to the wind tunnel wall not possible due to optic mount interference and non-optically accessible portion of wind tunnel**

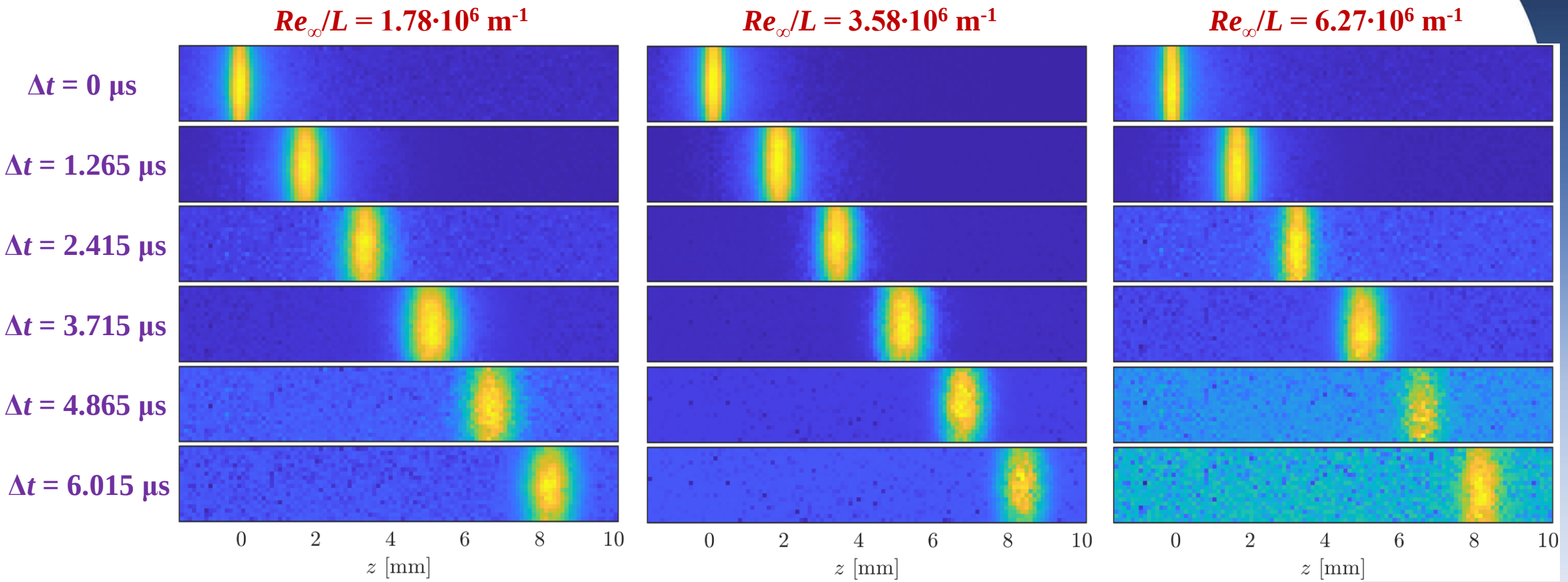


Time-Averaged FLEET Images



- Images cropped to region of interest

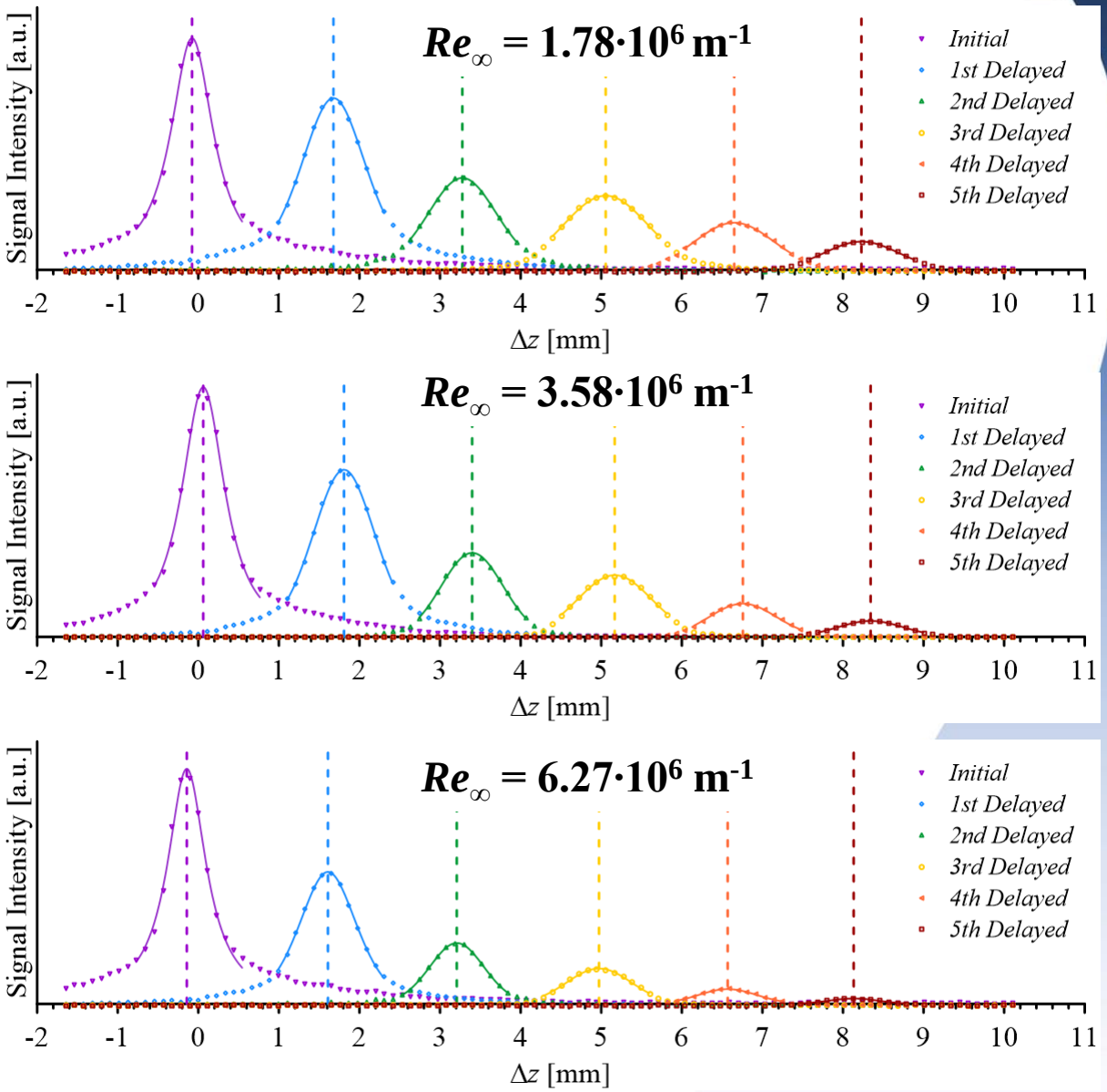
Time-Averaged FLEET Images



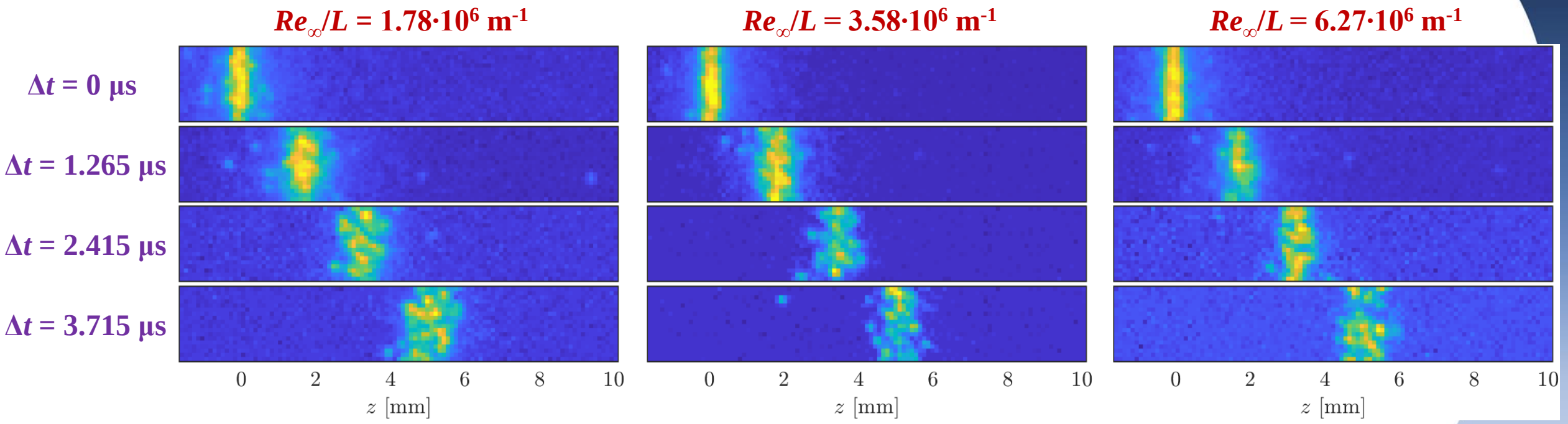
- Images cropped to region of interest and scaled to maximum signal intensity
- **Lower signal-to-noise at greater Reynolds numbers (increased quenching due to higher gas densities)**

Time-Averaged Centerline Data

- **Data processing steps include:**
  - Images averaged in vertical direction
  - Custom algorithm utilizing Pseudo-Voigt fit applied to determine centroid
  - Only initial image and 1st delayed image used for velocity in this work
- Additional information in 2024 AIAA SciTech Paper (Rodrigues *et al.*) and 2024 Lisbon Laser Symposium Paper (Rodrigues *et al.*).



Instantaneous FLEET Images



- **Diffusion of FLEET signal apparent:**
  - Despite Δt = 1.265 µs and Δt = 2.415 µs possessing identical intensifier gates (300 ns)
- Each image cropped and scaled to maximum signal intensity (identical to average images)
- Identical velocity data processing method used for instantaneous images as average images

Instantaneous Centerline Velocity

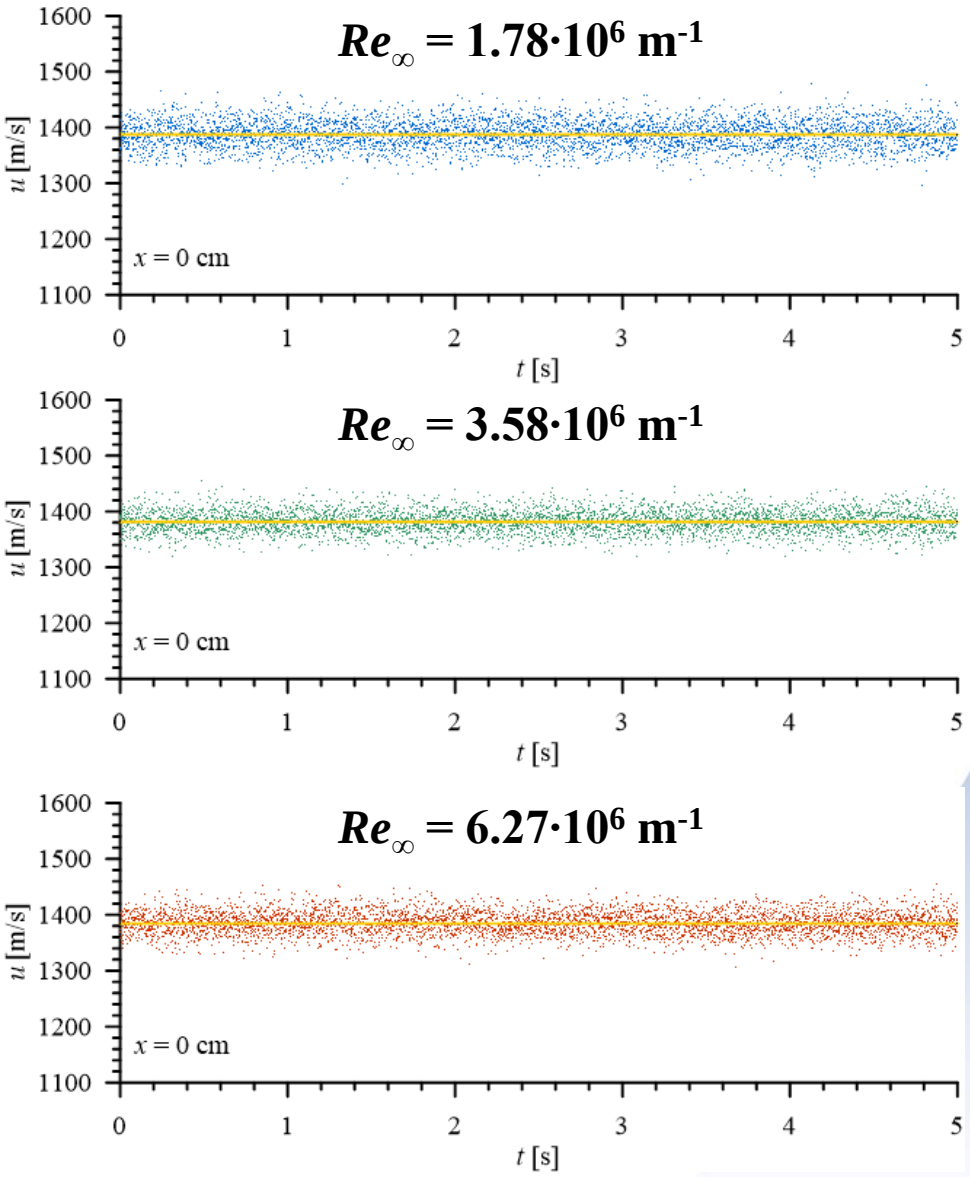
- **Instantaneous velocity data over 5 seconds**
  - 1 kHz data acquisition; 5000 data points
  - ~0.8 MHz bandwidth (Δt = 1.265 µs)

- **Mean of instantaneous velocity agrees within 0.4%!**

[-]	[m/s]	[m/s]	[m/s]	[%]
Re_∞/L	u_μ	$u_\mu - u_\infty$	u_σ	$(u_\mu - u_\infty)/u_\infty$
$1.78 \cdot 10^6$	1387	1	24	0.1%
$3.58 \cdot 10^6$	1382	-3	20	-0.2%
$6.27 \cdot 10^6$	1384	-5	20	-0.4%

- **Mean of calculated uncertainty ~25 m/s or <2%**
  - 2σ/√N standard error in the mean ~0.6 m/s

- **No dominant frequencies observed (< 500 Hz)**

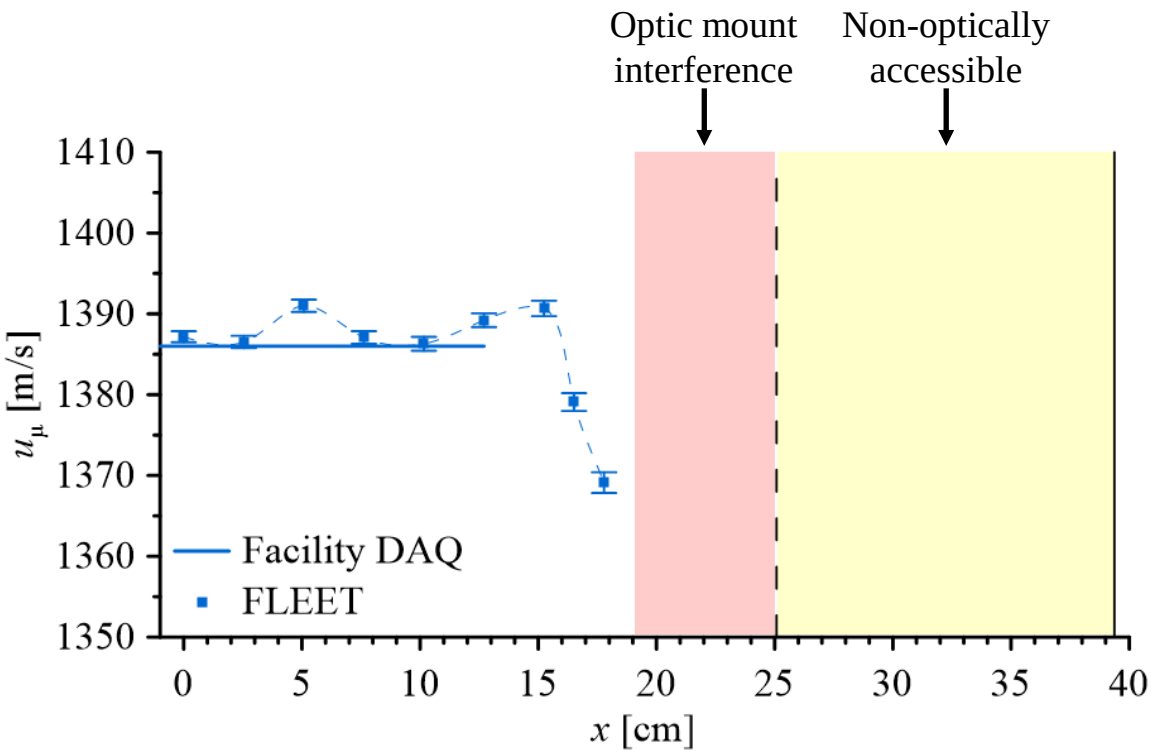


u_μ: Mean of measured instantaneous velocity
u_σ: Standard deviation of measured instantaneous velocity
u_∞: Calculated velocity using DAQ

Velocity Spatial Distribution at $Re_\infty = 1.78 \cdot 10^6$

- **Edge of core flow apparent in the 15-20 cm region**

- **Accurately characterizing uncertainty important: 16 m/s difference at x = 17.8 cm vs. x = 0 cm**
  - Standard error in the mean used for vertical bars
    - Additional factors to characterize uncertainty in-progress



Highlights

- **First direct measurement of freestream velocity at this hypersonic wind tunnel facility**
- **First use of FLEET diagnostics at this hypersonic wind tunnel facility**

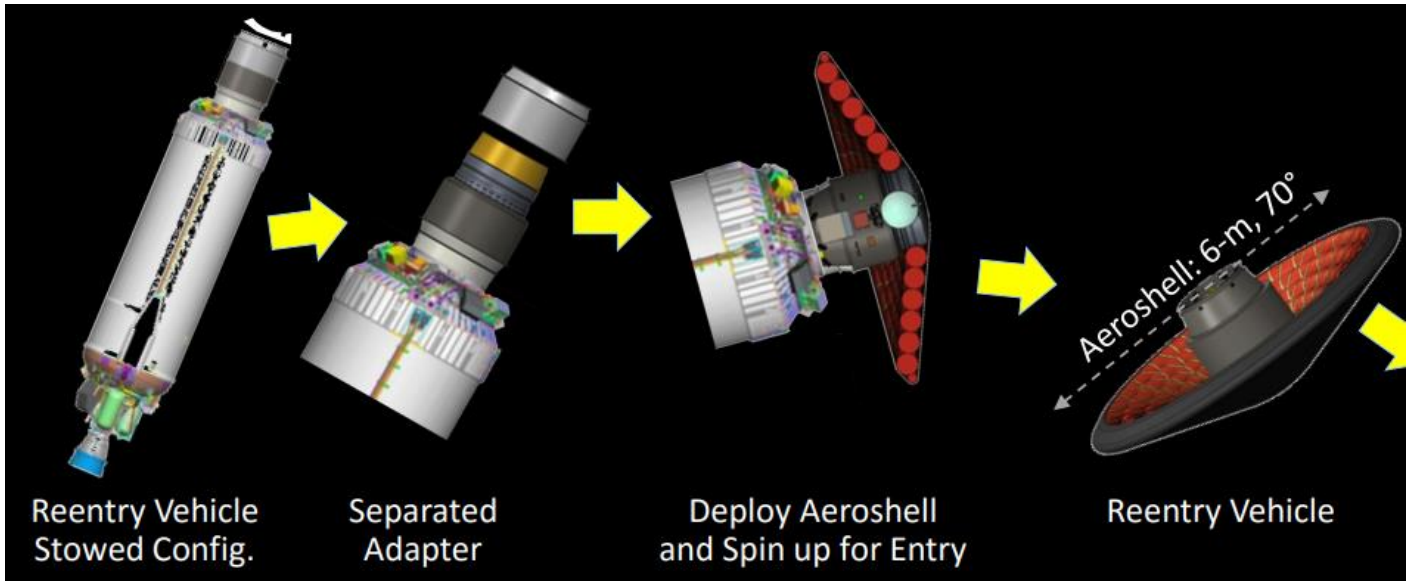
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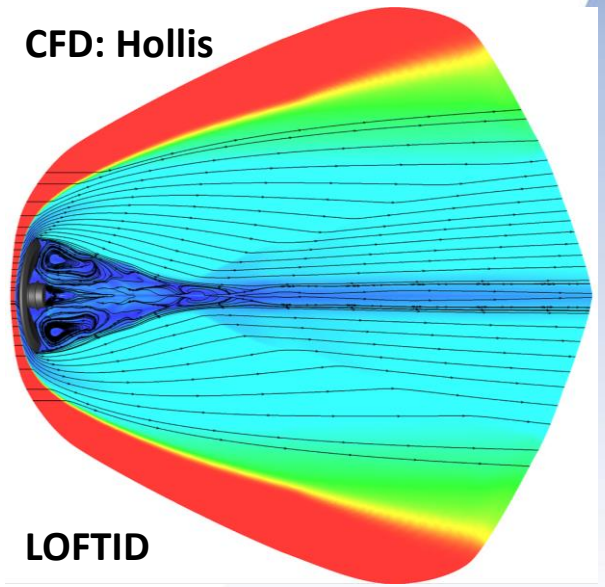
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Hypersonic Wakeflow

- **Driven by emerging Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology:**
  - Effective, mass-saving alternative to conventional aerodynamic decelerators
    - Terrestrial (Earth) and Mars applications: recovery/reuse of launch vehicles, large mass payloads
  - IRVE-3 (suborbital): Inflatable Re-entry Vehicle Experiment (2012)
  - LOFTID: Low-Earth Orbit Flight Test of an Inflatable Decelerator (2022)

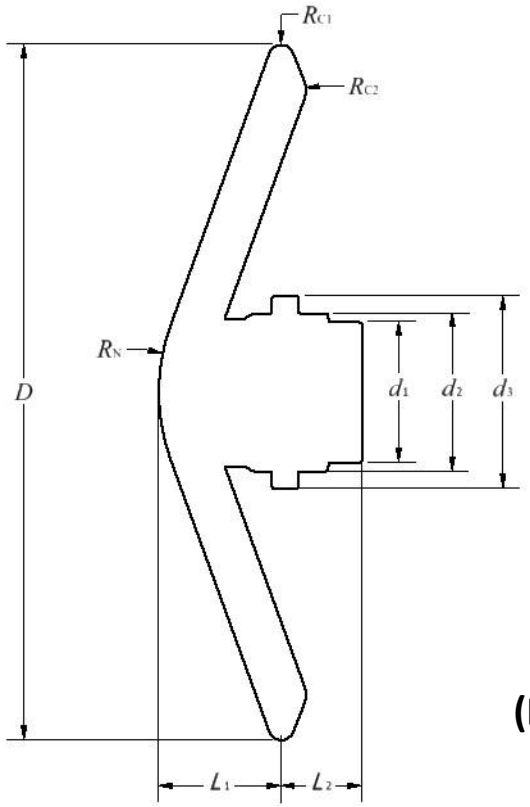
- **Large regions of separated hypersonic wakes are computationally challenging for simulations**
  - Unsteady flows require 3D, time-accurate calculations
  - Lower gas densities (approaching rarefied) in wake compared to forebody

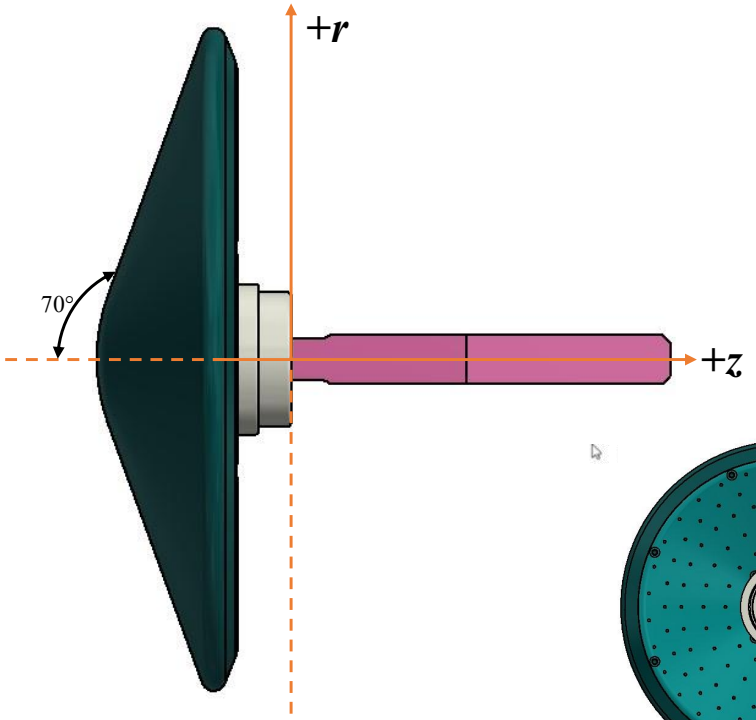


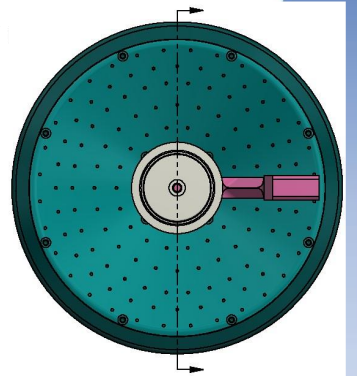


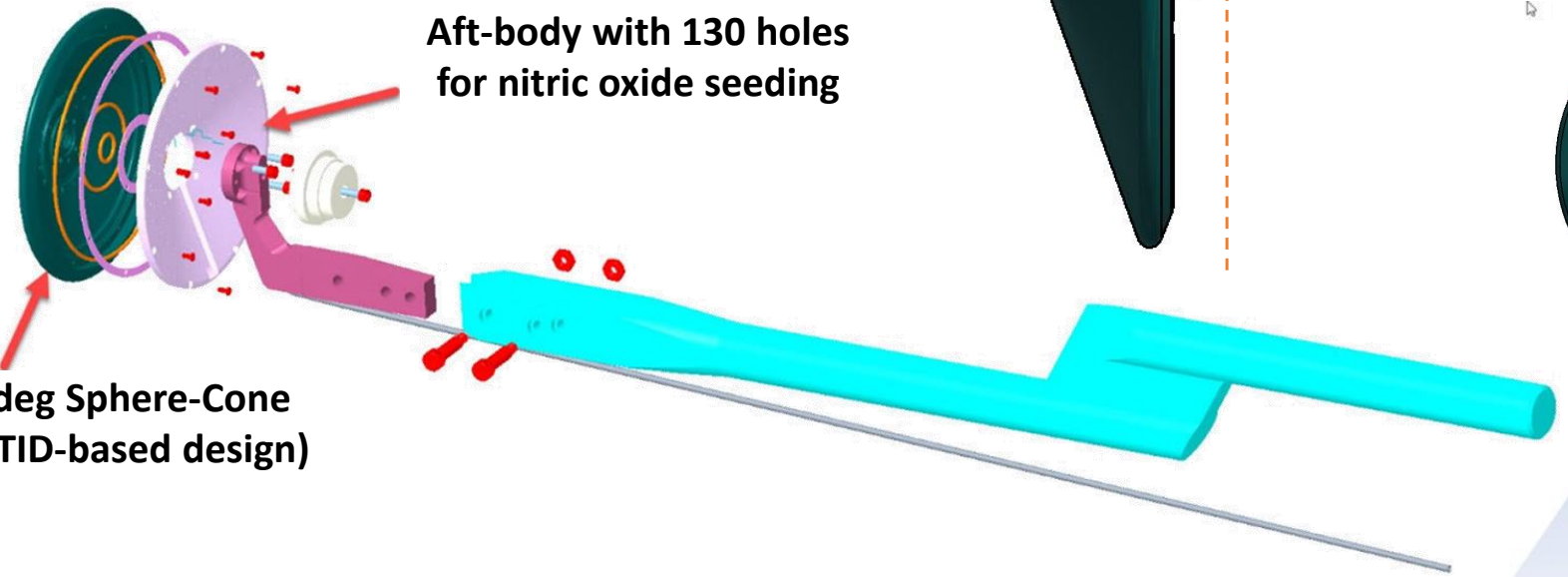
Wind Tunnel Model for 31-inch Mach 10 Tunnel

- **70-deg sphere-cone forebody, smooth aft-body, blade-style sting**









Aft-body with 130 holes for nitric oxide seeding

70-deg Sphere-Cone (LOFTID-based design)

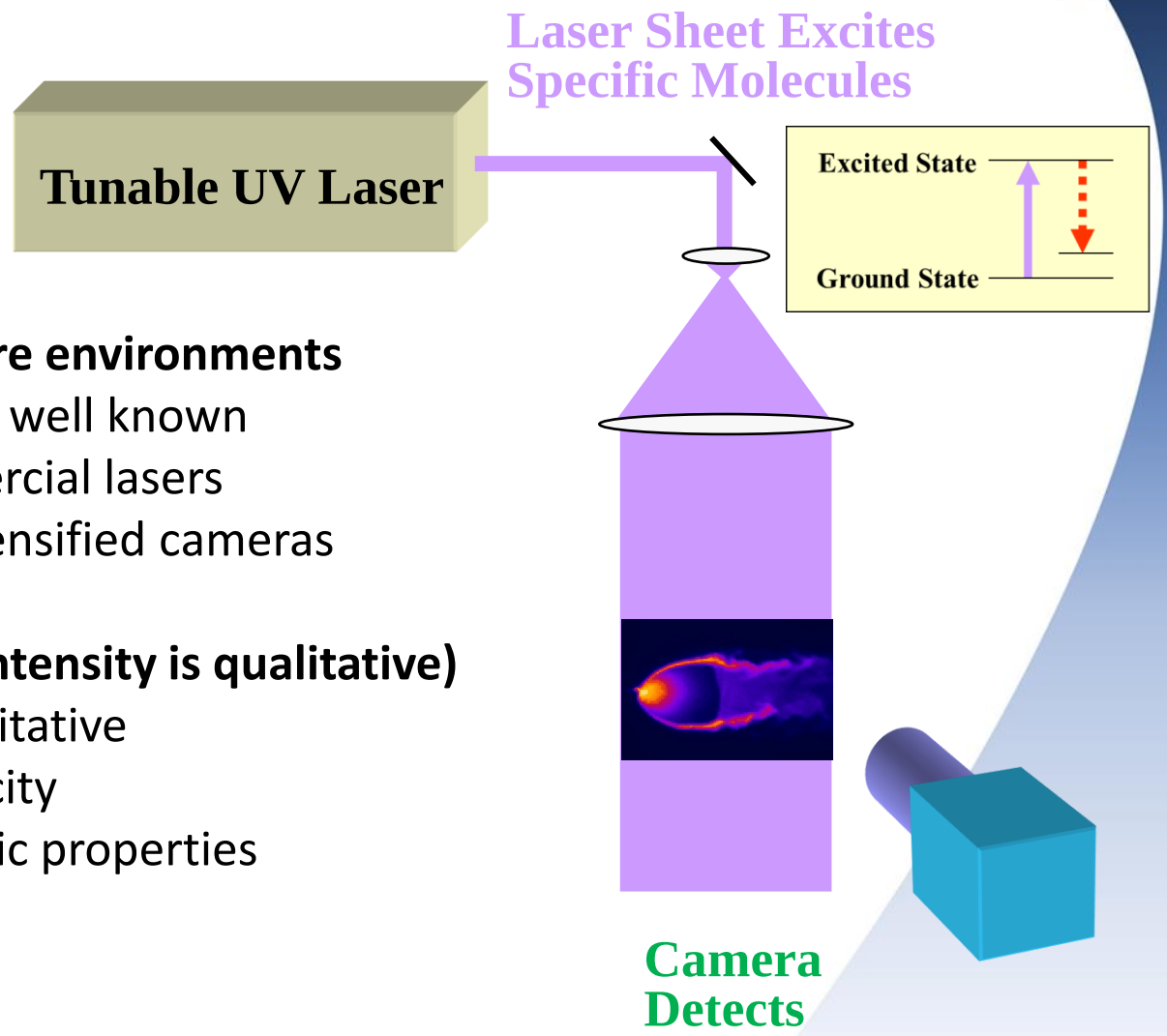
D	d_1	d_2	d_3	L_1	L_2	R_N	R_{C1}	R_{C2}
127 mm	25.7 mm	29.0 mm	35.1 mm	22.4 mm	14.8 mm	36.1 mm	2.3 mm	4.4 mm

Planar Laser-induced Fluorescence

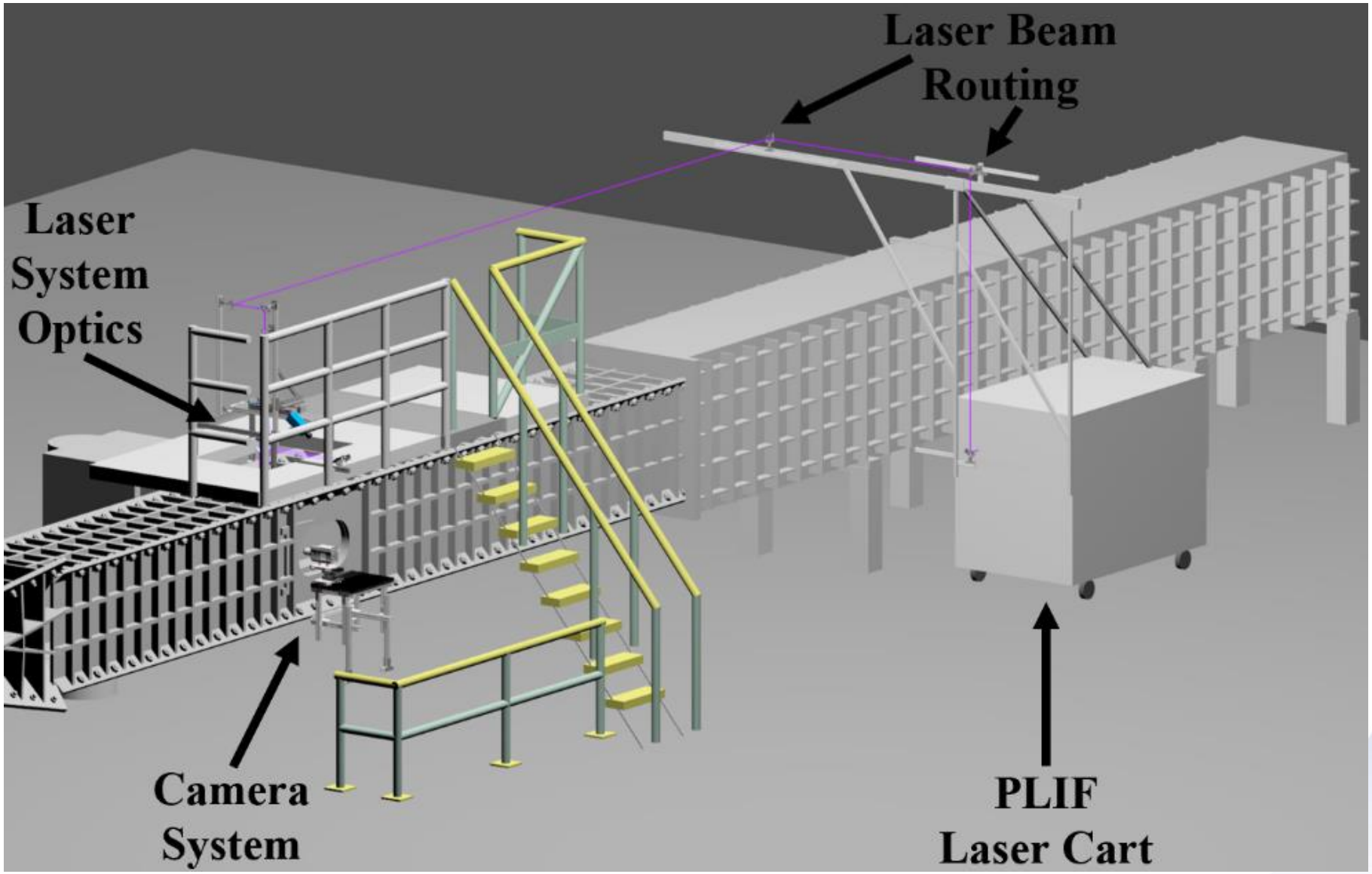
- **2D, temporally and spatially-resolved technique**
  - Spatial resolution < 1 mm
  - Temporal resolution < 1 µs
    - Repetition-rate of 10 Hz typical

- **PLIF of seeded nitric oxide (NO) ideal for low-pressure environments**
  - Spectroscopic and chemical properties of NO are well known
  - UV excitation wavelength accessible with commercial lasers
  - UV fluorescence detectable with commercial intensified cameras

- **PLIF signal generally scales with gas density (signal intensity is qualitative)**
  - Location of flow structures (e.g., shocks) is quantitative
  - Molecular tagging methods can be used for velocity
  - Spectroscopy can be exploited for thermodynamic properties

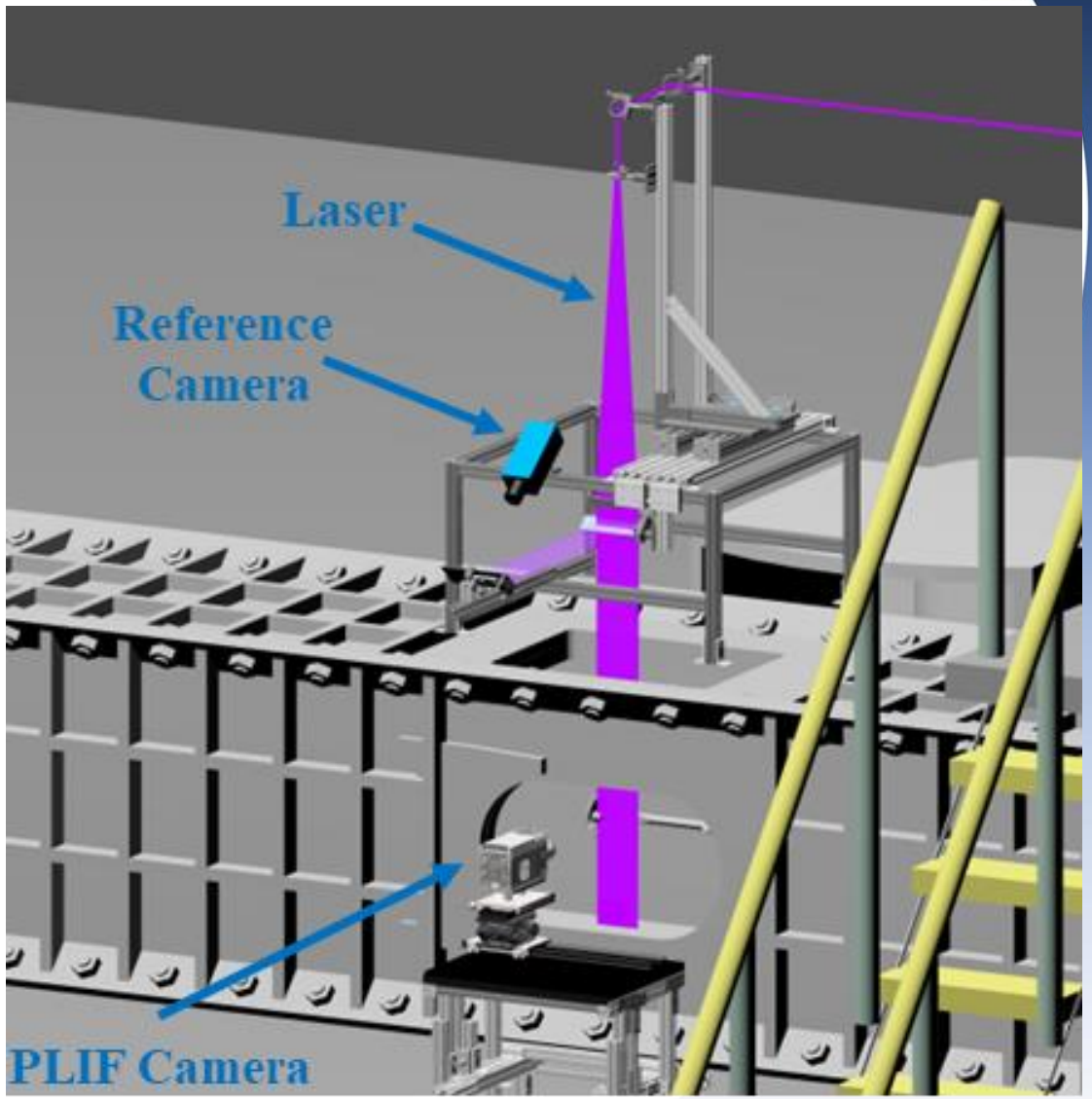


PLIF Setup at Wind Tunnel



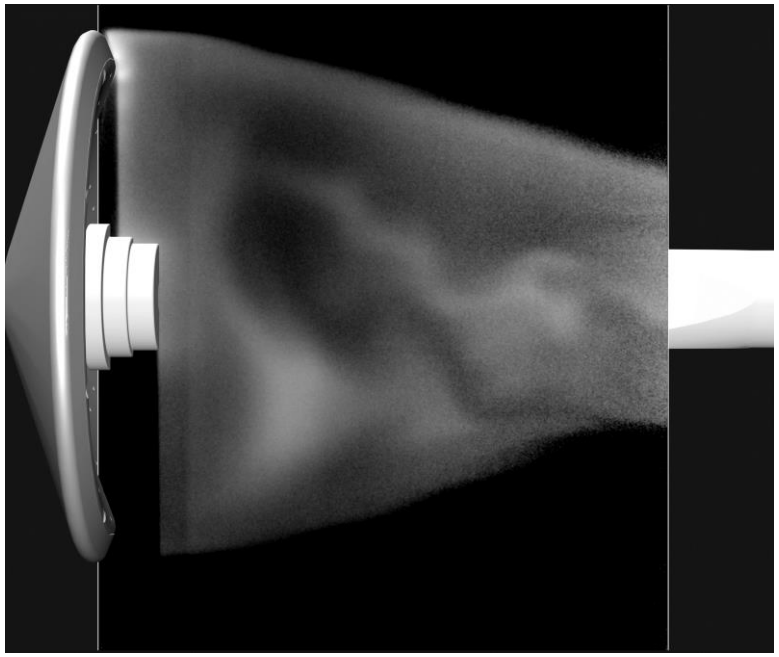
PLIF Setup at Test Section

- **226-nm laser enters wind tunnel through top window**
  - Cylindrical and spherical lenses used to create 2D laser sheet from laser beam
  - ~150 mm wide and <1 mm thick at model centerline
- **Intensified sCMOS camera images from side window (230 – 300 nm fluorescence wavelengths)**
  - 0.5 µs exposure for each image
- **Reference CCD camera mounted on top of tunnel used to monitor laser sheet energy distributions**
  - Blue fluorescence from glass diffuser plate

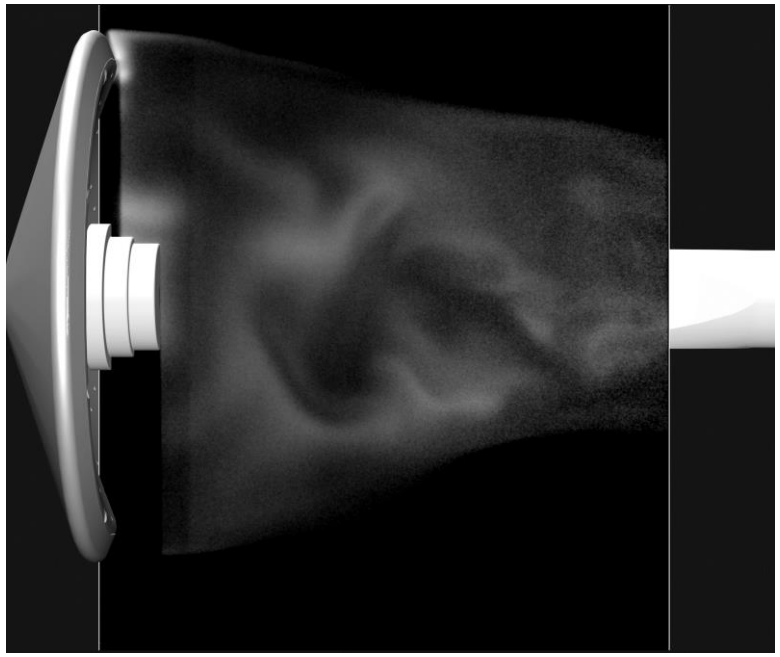


PLIF Flow Visualization: Re_∞/L effect

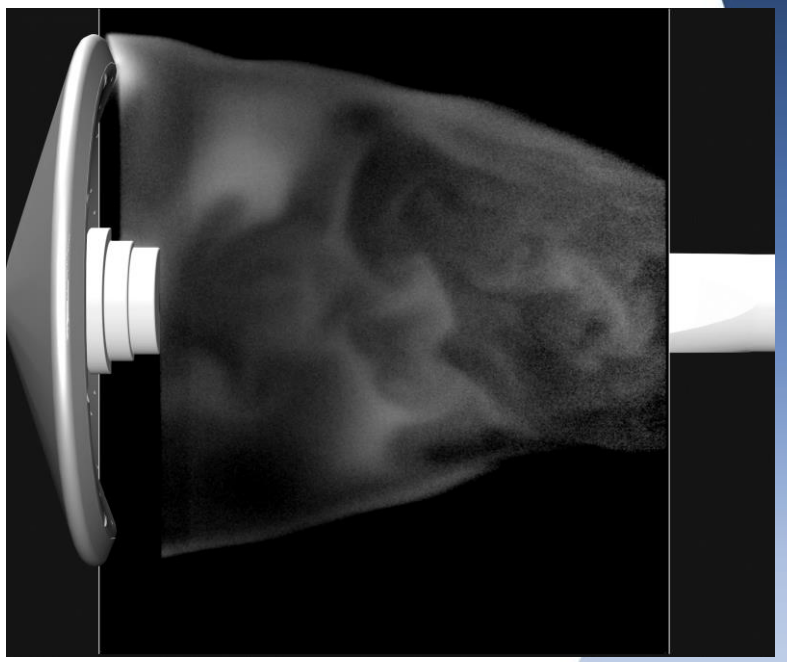
$Re_\infty/L = 1.8 \cdot 10^6\ m^{-1}$



$Re_\infty/L = 3.6 \cdot 10^6\ m^{-1}$



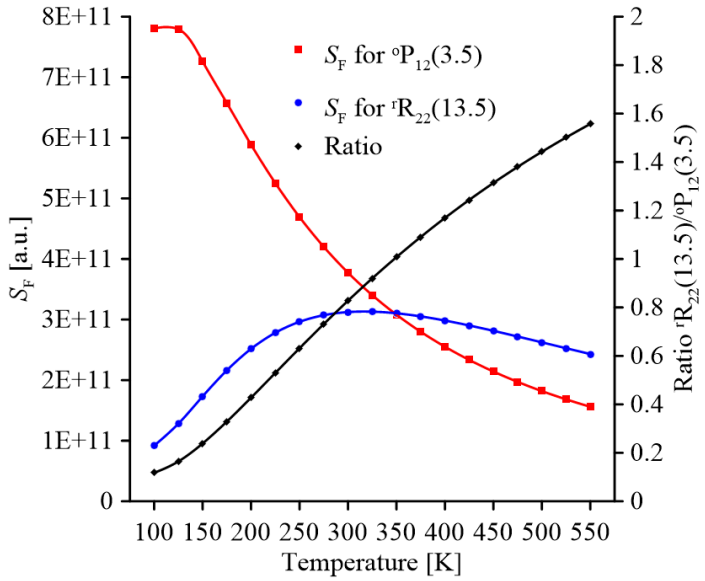
$Re_\infty/L = 6.3 \cdot 10^6\ m^{-1}$

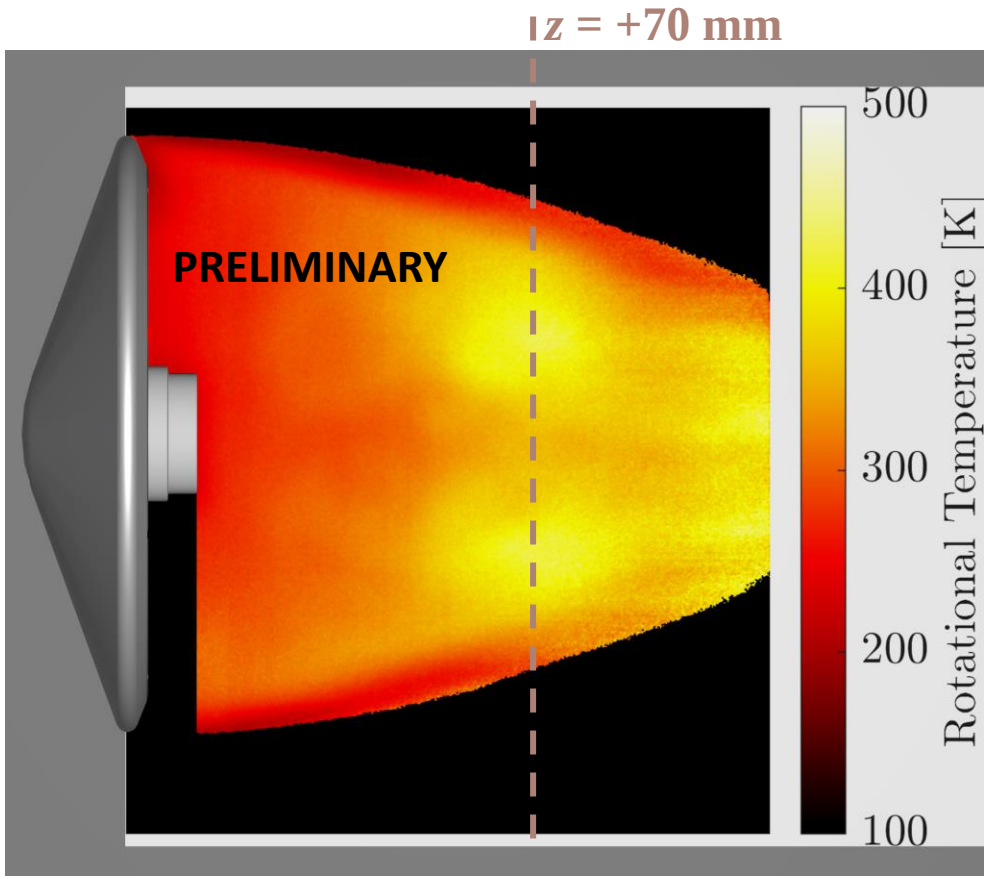


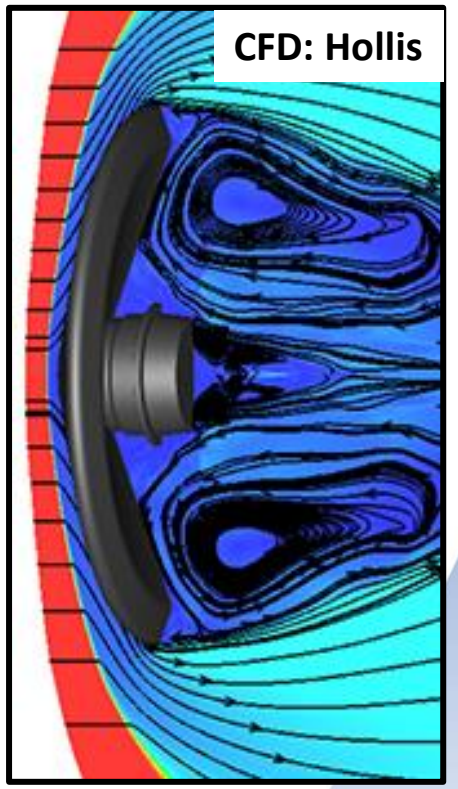
- **Flow is unsteady for all three Reynolds number conditions (~3.5x factor in Re_∞/L)**
  - Large-scale structures present throughout (arguably smaller structures for higher Re_∞/L)
- PLIF signal intensity visualized in logarithmic grayscale to preserve flow structures while minimizing large signal variation near the model due to varying NO gas concentrations

Time-averaged, Planar Temperature

Laser Wavelength [nm]	Transition
226.9356	$P_{12}(3.5)$
226.1391	$R_2(13.5)$







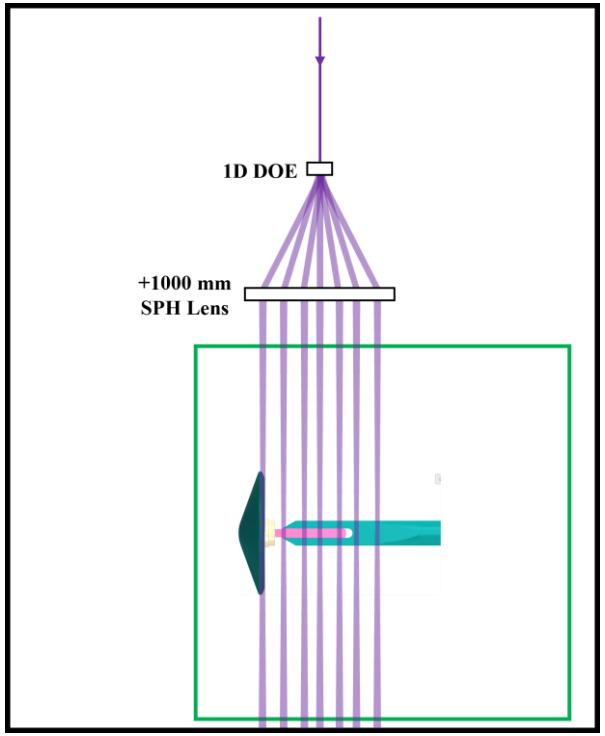
- **Time-averaged 2D temperature estimated using two different laser wavelengths over 2 tunnel runs**
  - Fluorescence from two different laser wavelengths have different temperature sensitivity
- **Upcoming effort: extend to instantaneous temperature measurements using two-laser PLIF system**

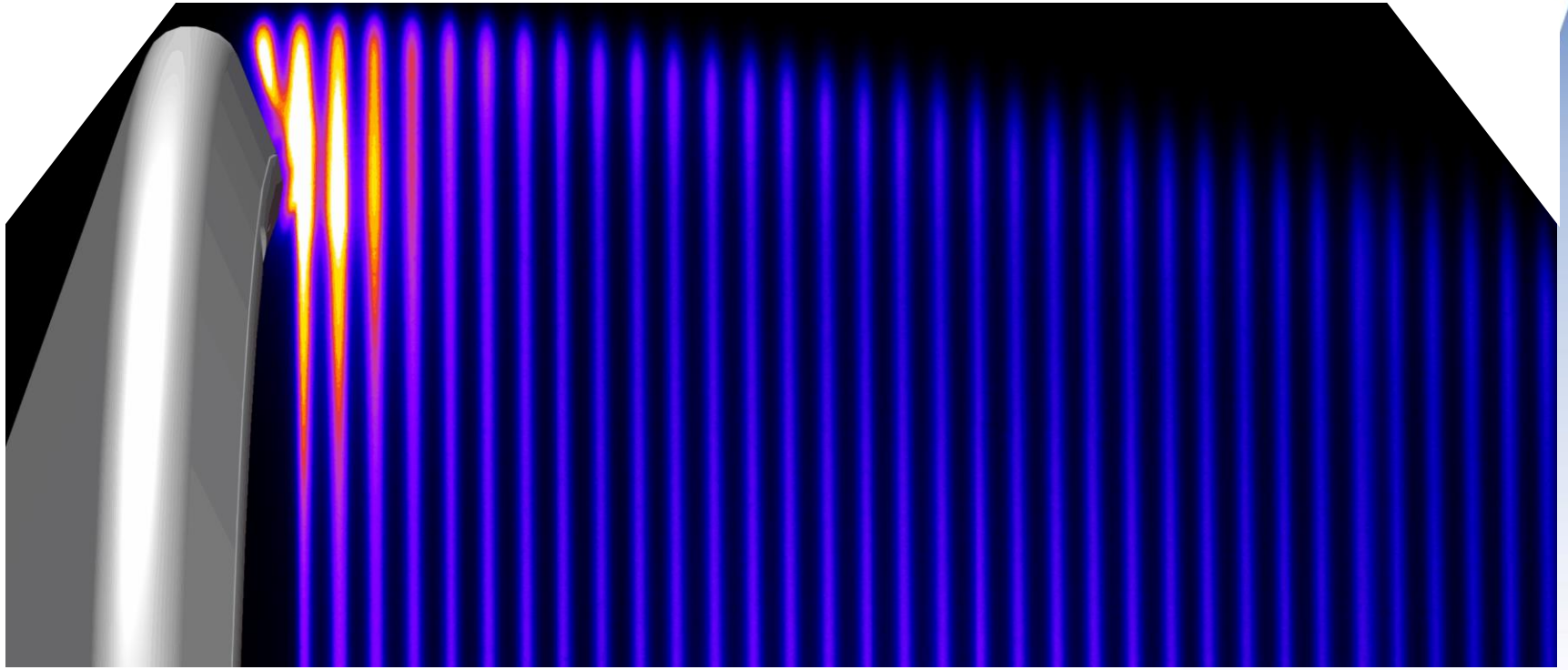
NO-PLIF Molecular Tagging Velocimetry

- **1D DOE (Diffractive Optical Element) used to create 75 laser beamlets from a single laser beam**
  - 3x improvement in spatial extent compared to previous work such as Bathel *et al.* (2011)

- **Velocity determined based on measurement displacement of PLIF signal and known Δ*t***
  - 2 images acquired ~500 ns apart: $u = \Delta x/\Delta t$

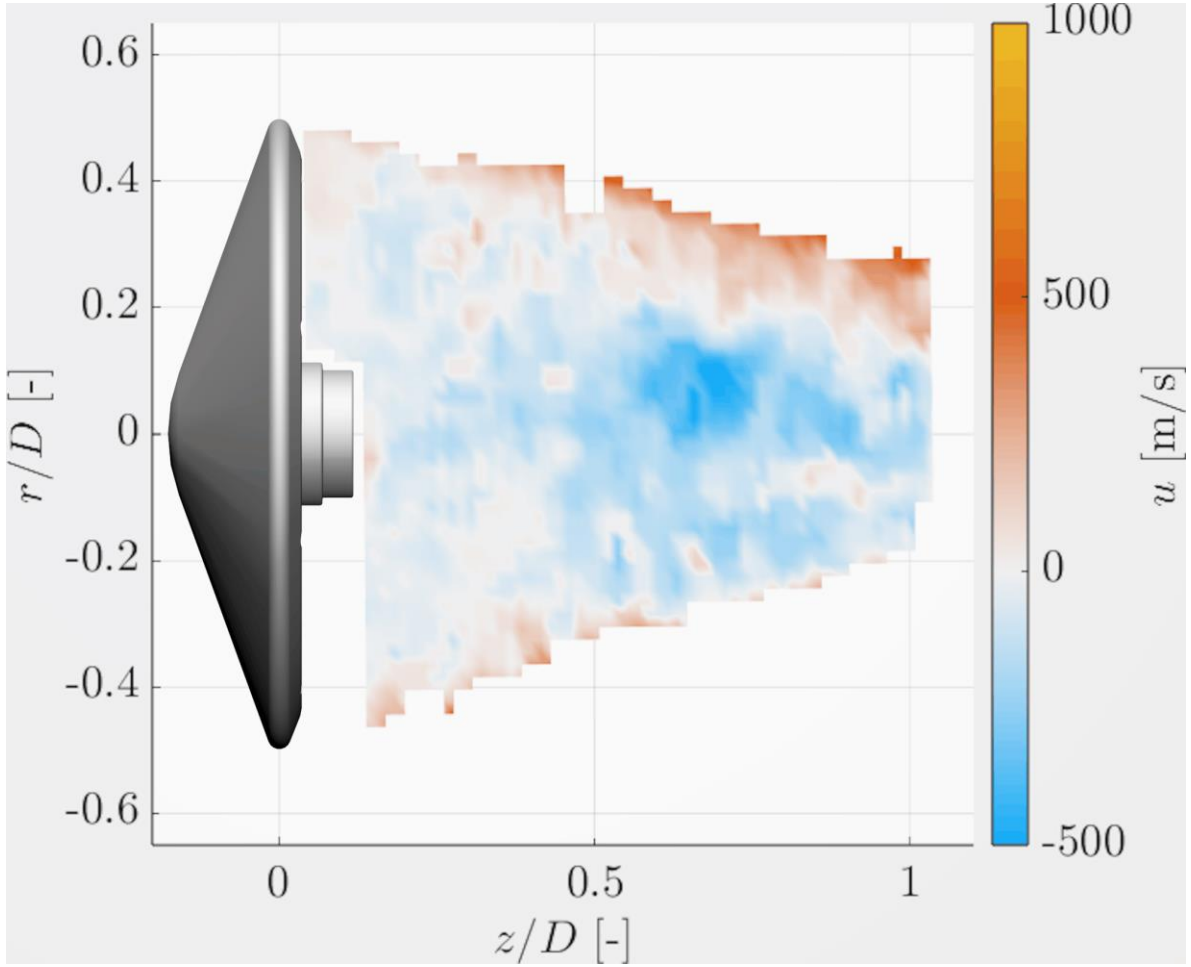
- **Additional experimental details in 2024 AIAA SciTech Paper (Rodrigues *et al.*)**

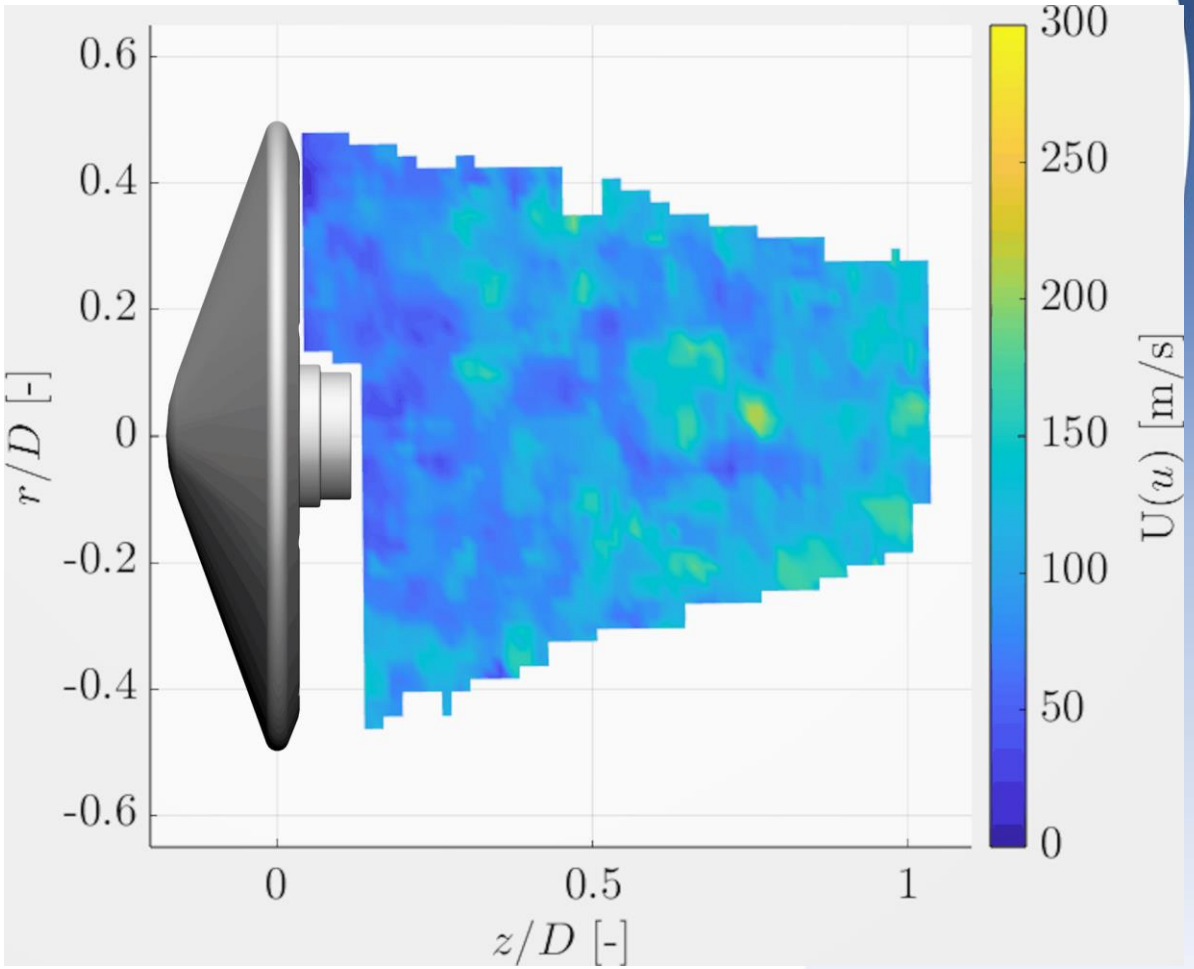




Instantaneous Velocity

- **Two-Dimensional (2D), One-Component (1C) velocity and estimated velocity uncertainty**

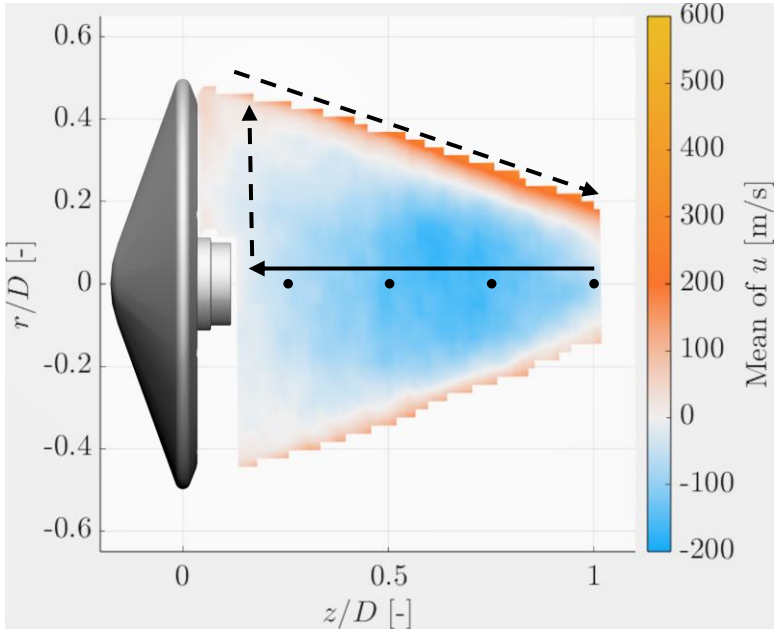




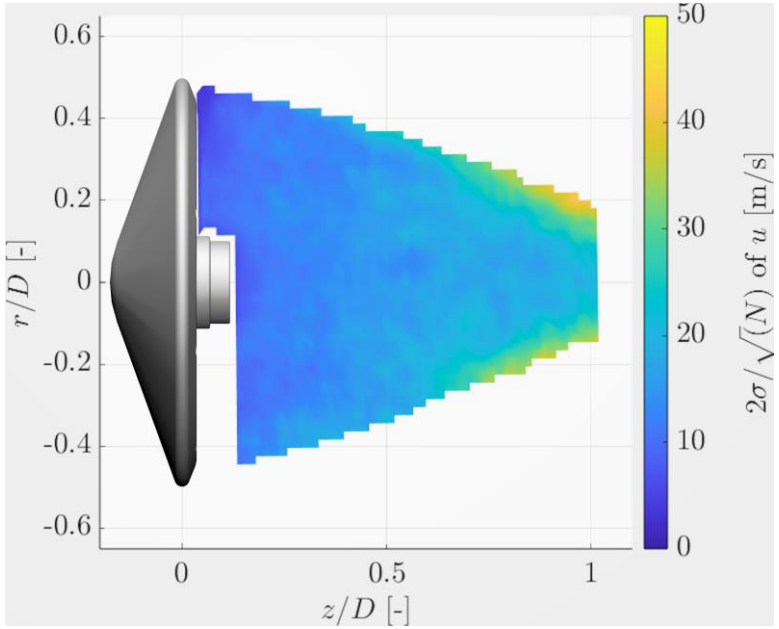
- **In-preparation for journal submission (Rodrigues, Tyrrell, Hollis, Danehy)**

Velocity Statistics

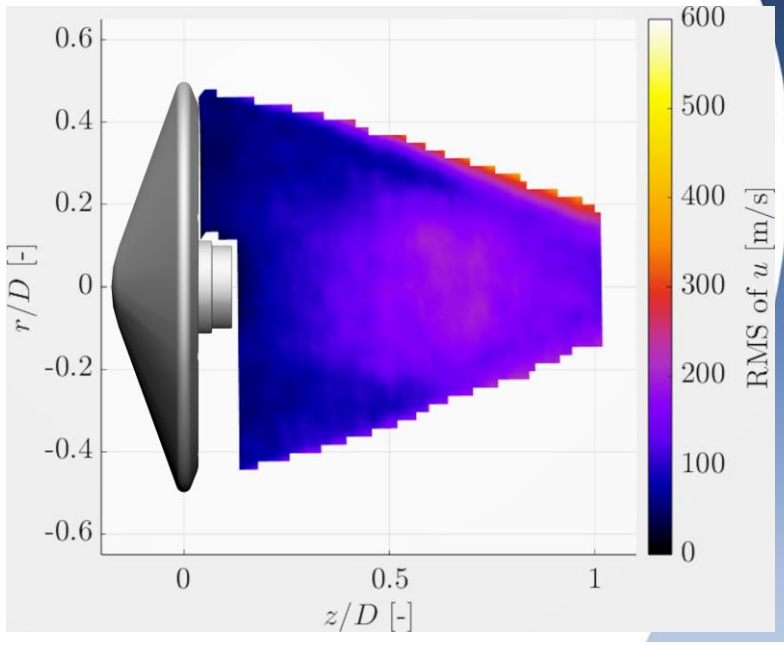
Mean of *u*

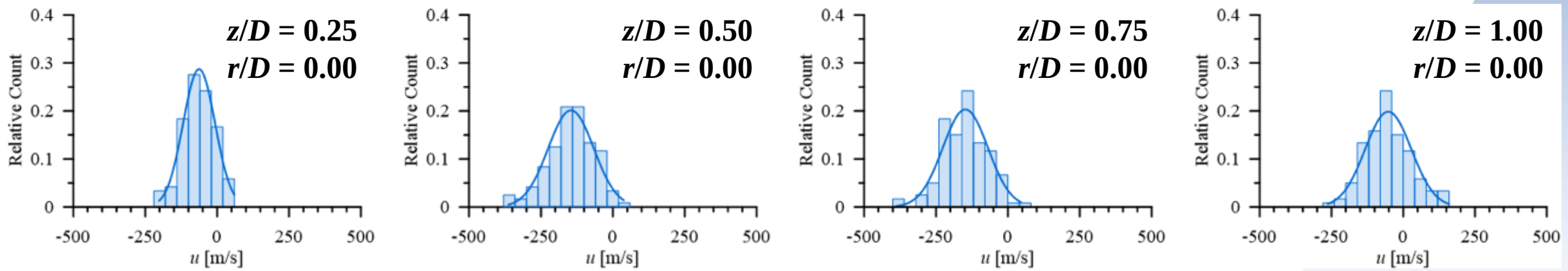


Std. Error in Mean of *u*



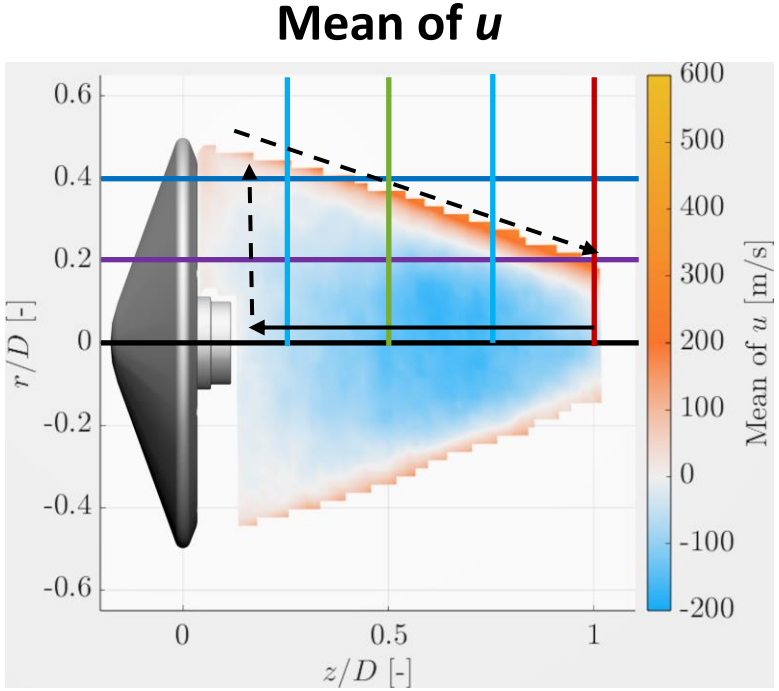
RMS of *u*



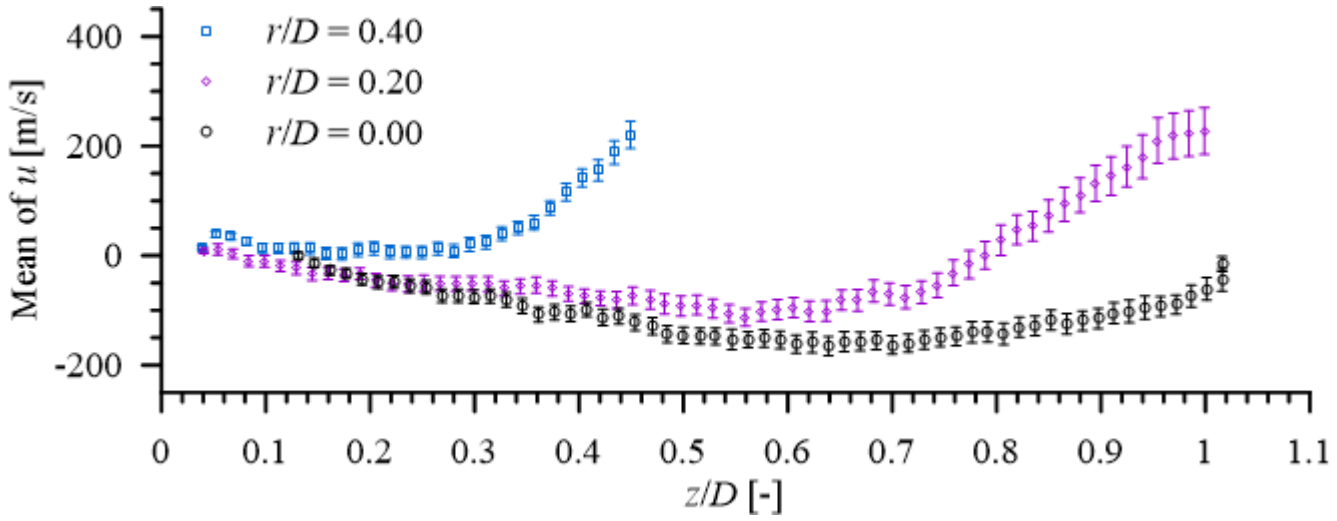


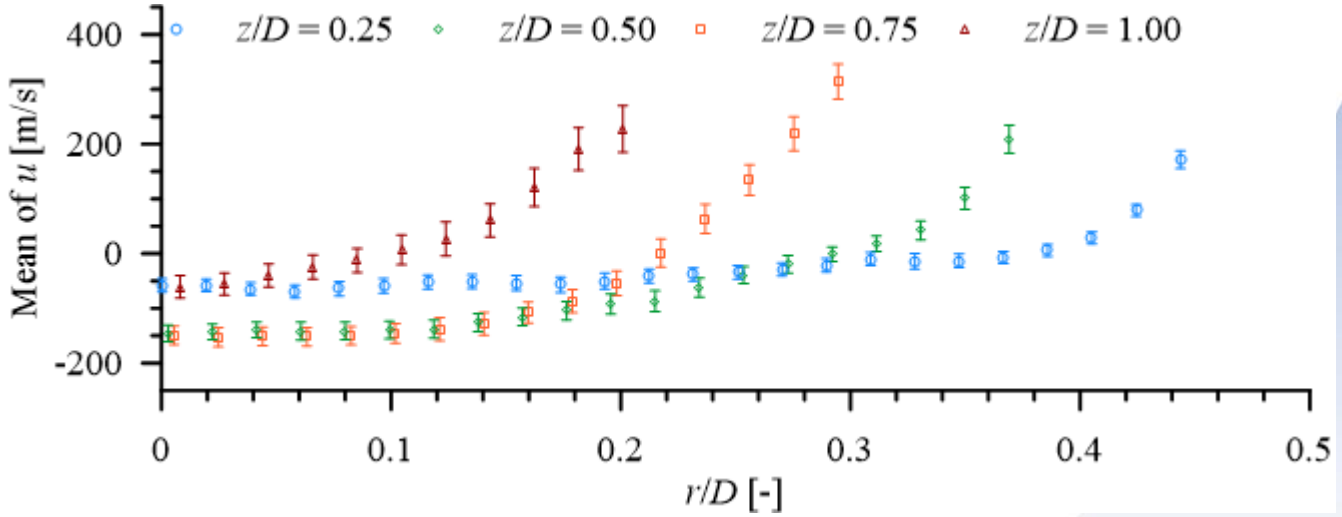
- In-preparation for journal submission (Rodrigues, Tyrrell, Hollis, Danehy)

Wake Structure



- Reverse flow
- Stagnation regions
- High-velocity shear layer





- Upcoming effort: extend to 2C velocimetry by forming a tagged grid

Outline

- Introduction
- Mach 10 Tunnel Freestream Characterization
- Hypersonic Wakes for Planetary Entry
- Supersonic Plume Impingement for Spacecraft Landings
- Lab-scale Diagnostics Development
- Summary & Conclusions

Plume-Surface Interaction

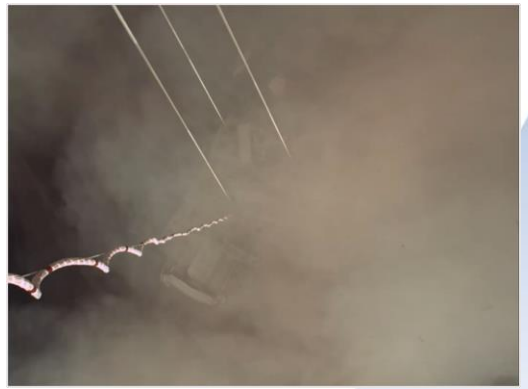
- **Rocket Plume-Surface Interaction (PSI):**
  - Induced environment due to impingement of hot rocket exhaust on landing surface

- **Driven by risks associated with spacecraft landings on extraterrestrial environments**
  - Complex: multi-scale and often multi-phase (unimproved Lunar or Martian surface)
  - Realistic environments: plumes within reduced ambient pressures (continuum to rarefied scales)

- **2022 Ground Test of Supersonic Plume Impingement at NASA Marshall 20-ft Vacuum Chamber**



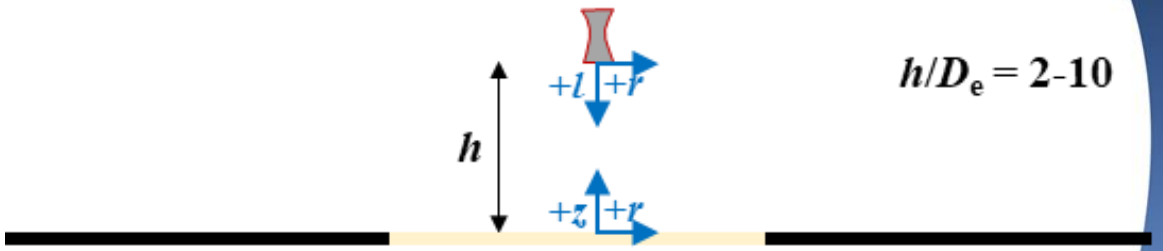
Lunar Landings: Apollo program → Artemis missions

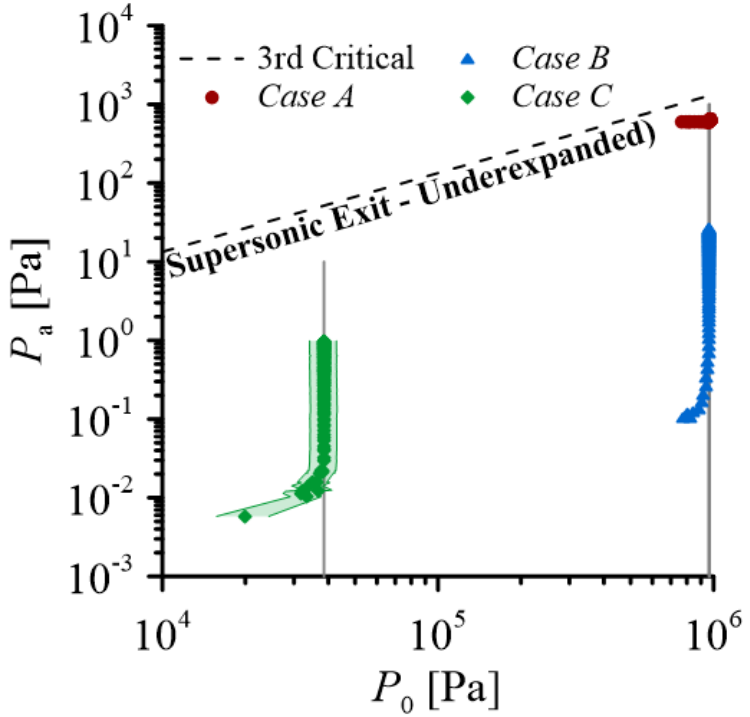


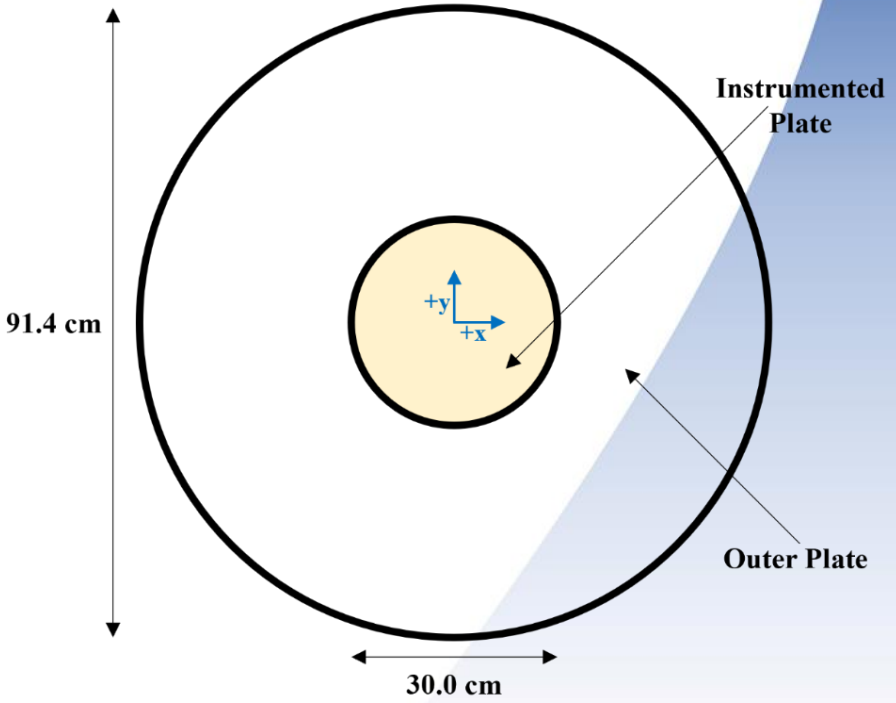
Martian: rover landings → human landings

Plume Impingement Test Article

- **Mach 5.3 supersonic nozzle:**
  - Heated N_2 seeded with NO
  - Exit Diameter D_e = 1.38 cm
- **Nozzle oriented downward and translated vertically:**
  - h/D_e = 10 to 2
- **3 of 10 Plume Conditions:**
  - Case A: Highest P_0, Martian P_a
  - Case B: Highest P_0, Lunar P_a
  - Case C: Lowest P_0, Lunar P_a

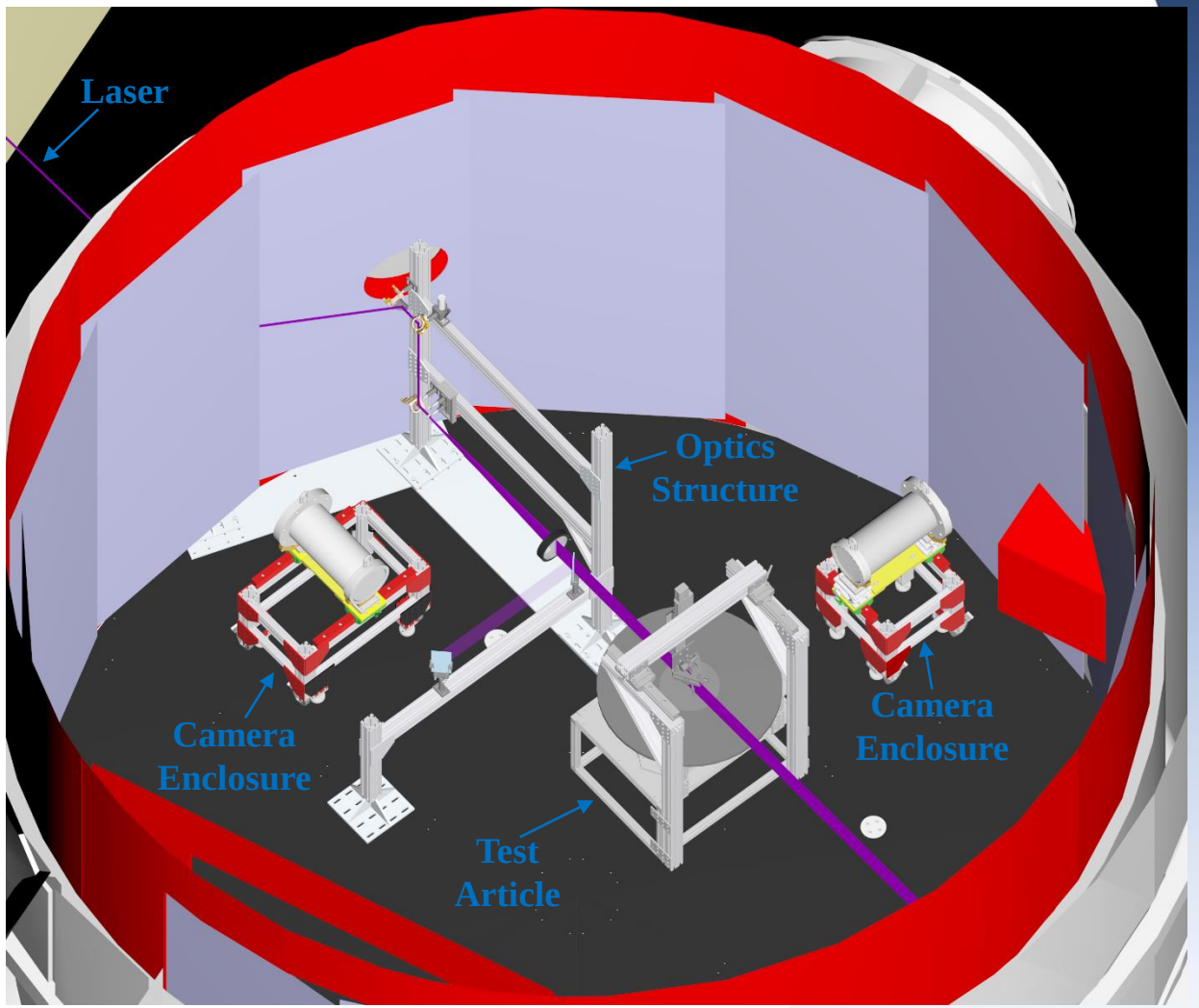






20-ft Vacuum Chamber Overview

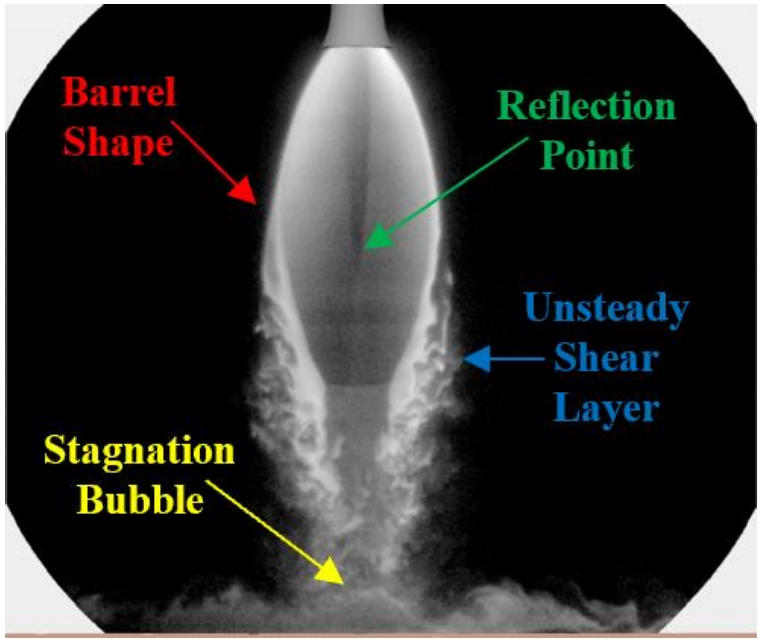
- **Plume impingement test article located near middle of chamber**
- **UV laser (near 226 nm) brought into vacuum chamber through viewport window**
- **Optics for PLIF laser sheet placed on custom structure inside chamber**
  - Laser beam alignment adjusted using remote-controlled mirrors
  - Laser sheet expanded to ~140 mm; <1 mm thickness near nozzle
- **PLIF cameras located within custom camera enclosures inside chamber**
  - Intensified sCMOS (PLIF)
  - CCD (Laser sheet monitoring)



PLIF Flow Visualization

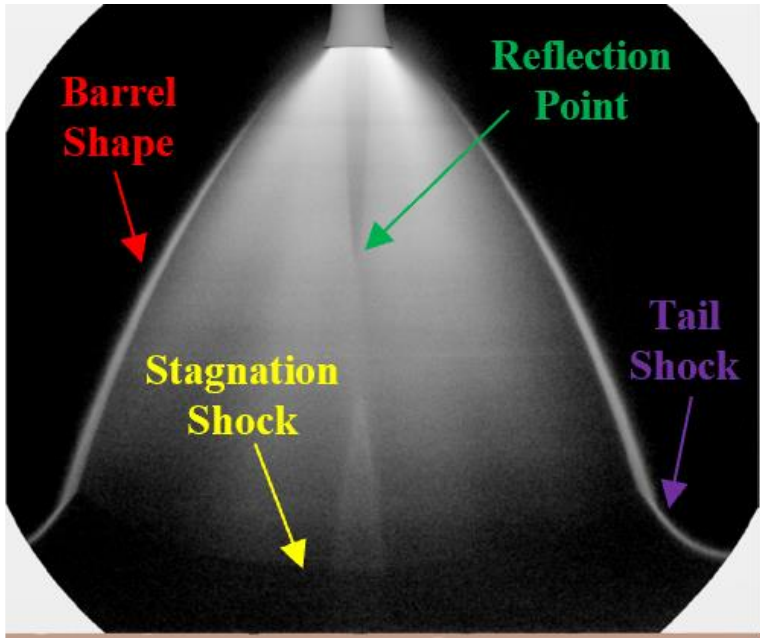
- **Results in recently accepted *Physics of Fluids* journal publication (Rodrigues, Tyrrell, Danehy)**

Case A: Highest P_0, Martian P_a



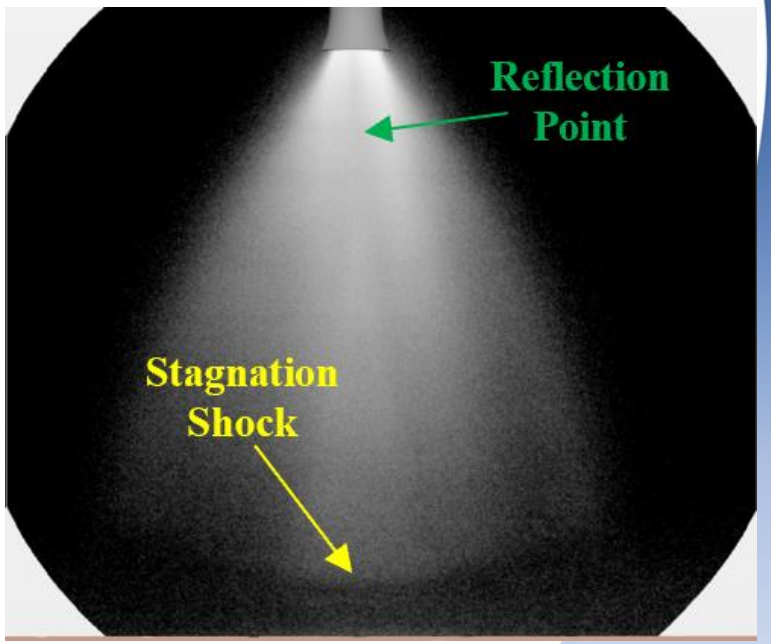
- **Measure location of:**
  - Nozzle Reflection Point
  - Mach Disk Position
  - Stagnation Bubble Height

Case B: Highest P_0, Lunar P_a



- **Measure location of:**
  - Nozzle Reflection Point
  - Radial Extent of Jet
  - Stagnation Shock Height

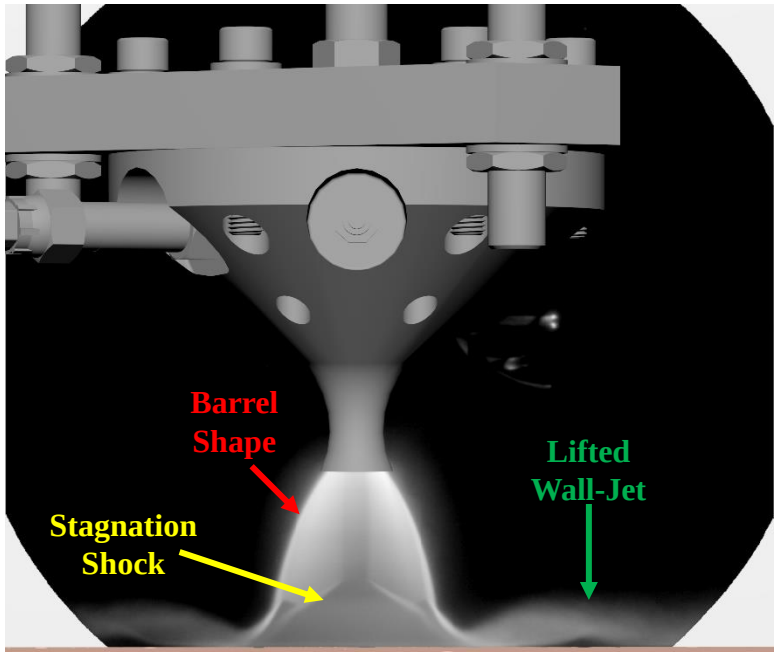
Case C: Lowest P_0, Lunar P_a



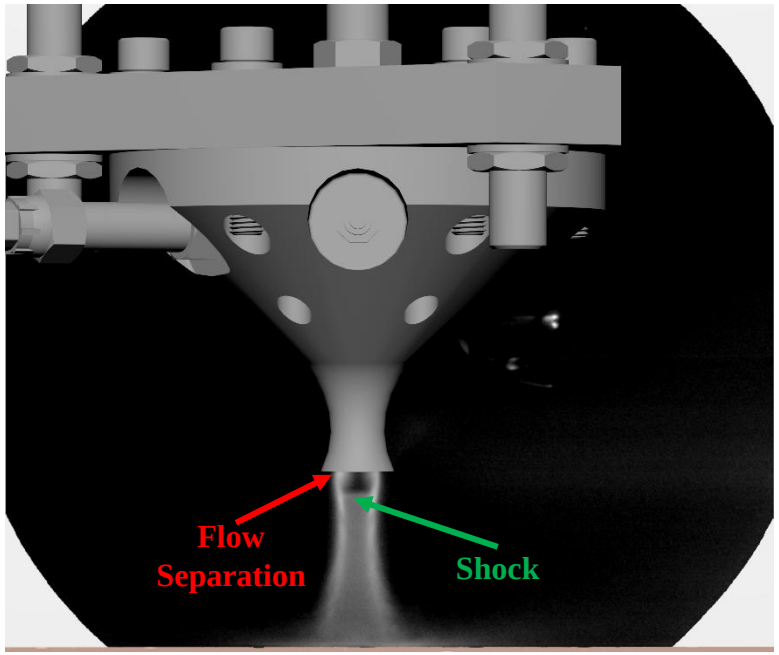
- **Measure location of:**
  - Nozzle Reflection Point
  - Radial Extent of Jet
  - Stagnation Shock Height

Effect of P_0 at Martian-relevant Conditions

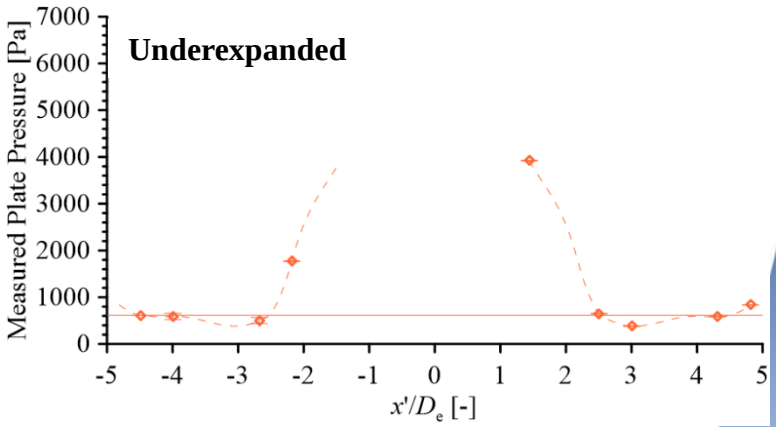
- Very different impingement behavior for underexpanded (higher P_0) and overexpanded (lower P_0) jets
  - 2024 AIAA Ascend Paper (Rodrigues *et al.*)

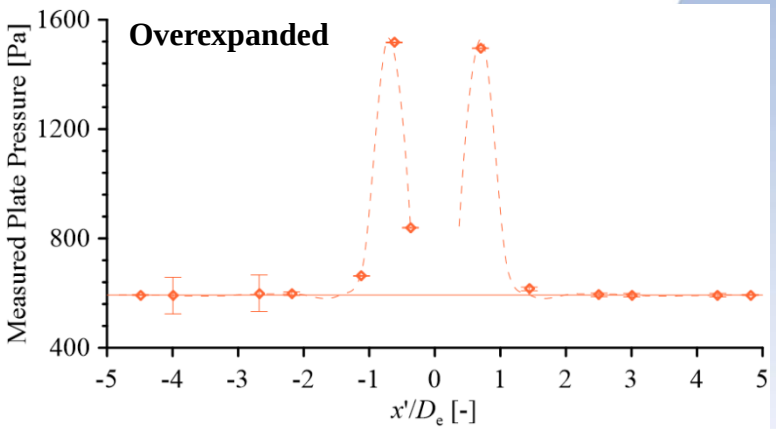


Underexpanded Jet
($P_0 = 9.67 \cdot 10^5$ Pa)



Overexpanded Jet
($P_0 = 3.83 \cdot 10^4$ Pa)





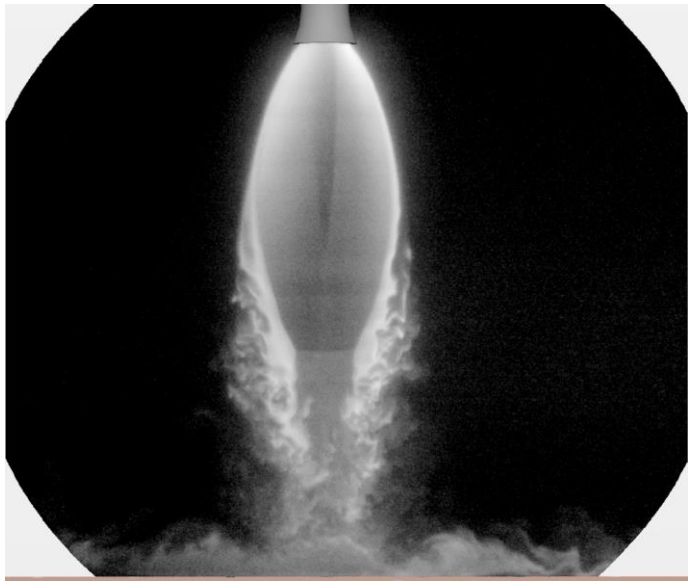
- Underexpanded jet has much larger pressure footprint and magnitude
  - Low-pressure *suction* region apparent for underexpanded jet
  - Double-peak structure resolved for overexpanded jet

Effect of Dimensionless Altitude h/D_e

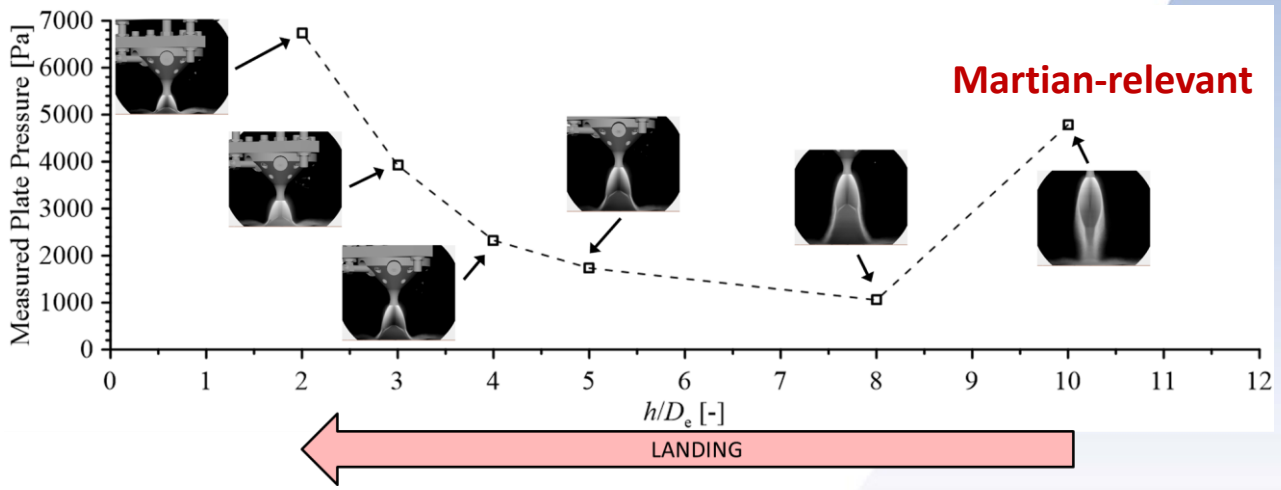
Lunar-relevant



Martian-relevant



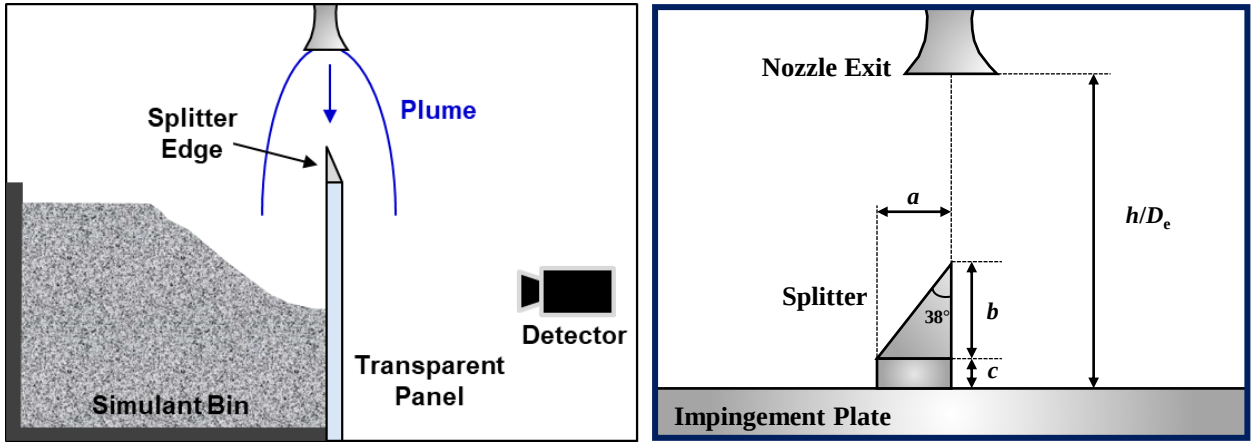
- Transition of stagnation shock from concave to triangular
- Martian: non-monotonic behavior observed between impingement pressure and h/D_e
- PLIF flow visualization adds context to pressure data
  - Different shock behavior at h/D_e = 10 and 8



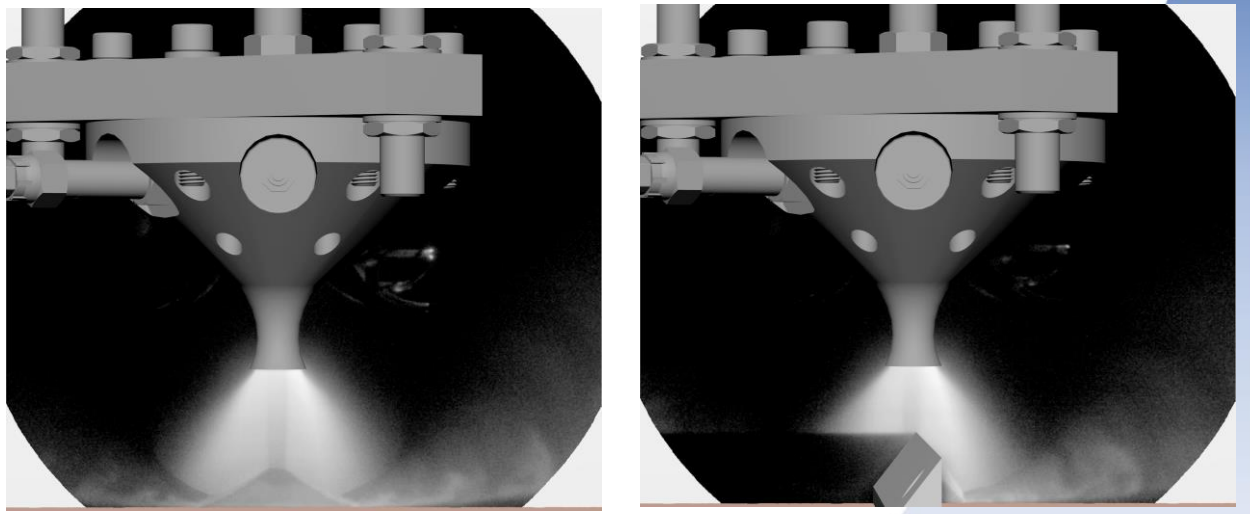
Effect of Geometric Configuration

- Past experimental PSI work frequently utilized a “half-space” design
  - Optical access enables erosion measurements with single camera
  - Flow bisected with splitter edge

- How does this affect plume impingement?
  - Results in 2024 SciTech Paper (Tyrrell *et al.*)

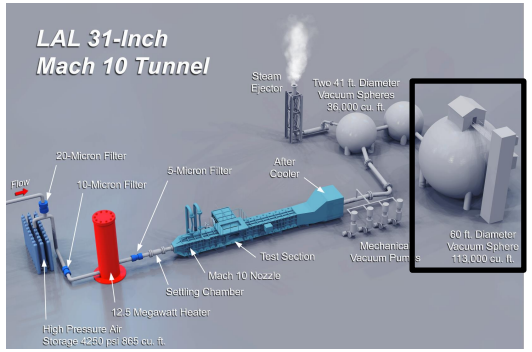


Common “half-space” PSI test design (left) and plume impingement geometric configuration (right)

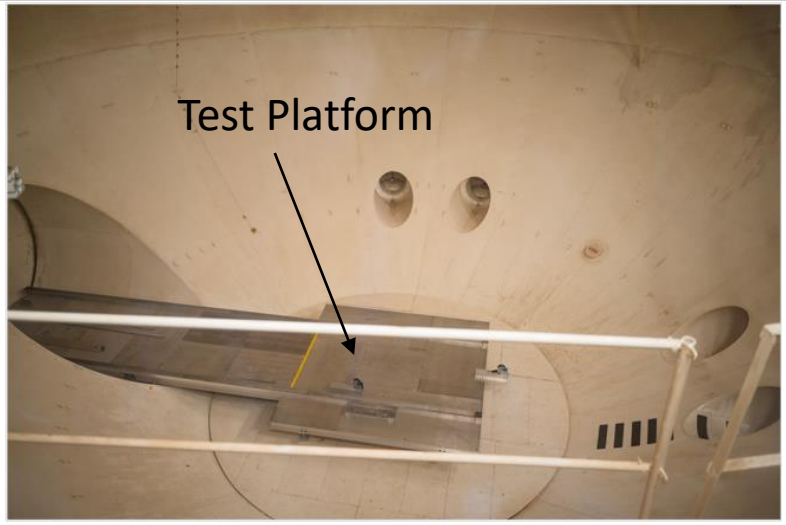


Lunar-relevant test data: full-space design (left) and half-space design (right)

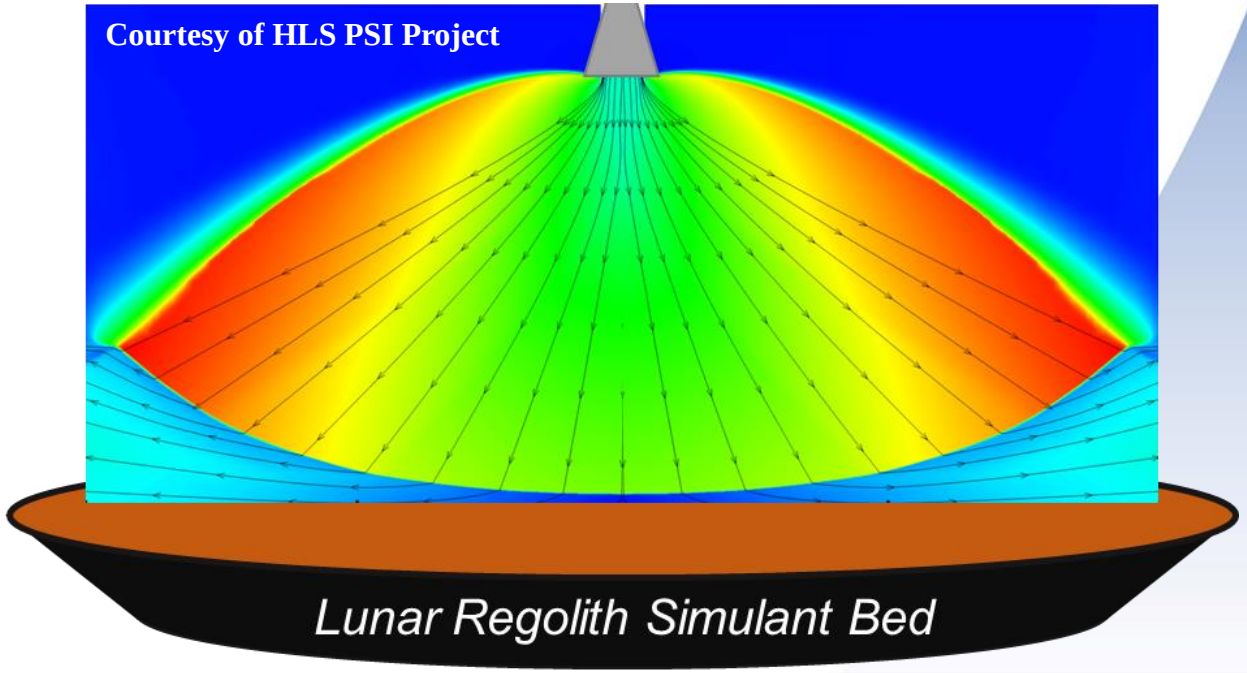
Upcoming Lunar HLS-focused Test at NASA Langley







- NASA Langley 60-ft Vacuum Sphere:
  - 100 Pa (0.75 Torr)
- Multiphase flow:
  - Regolith simulants
- Inert Gas Test:
  - Non-reacting ethane
- Hot-fire Test:
  - Hybrid (solid-fuel, gaseous oxidizer) rocket motor



Upcoming ground tests, funded by NASA *Exploration Systems Development Mission Directorate*, designed to reduce PSI risks for HLS program landers

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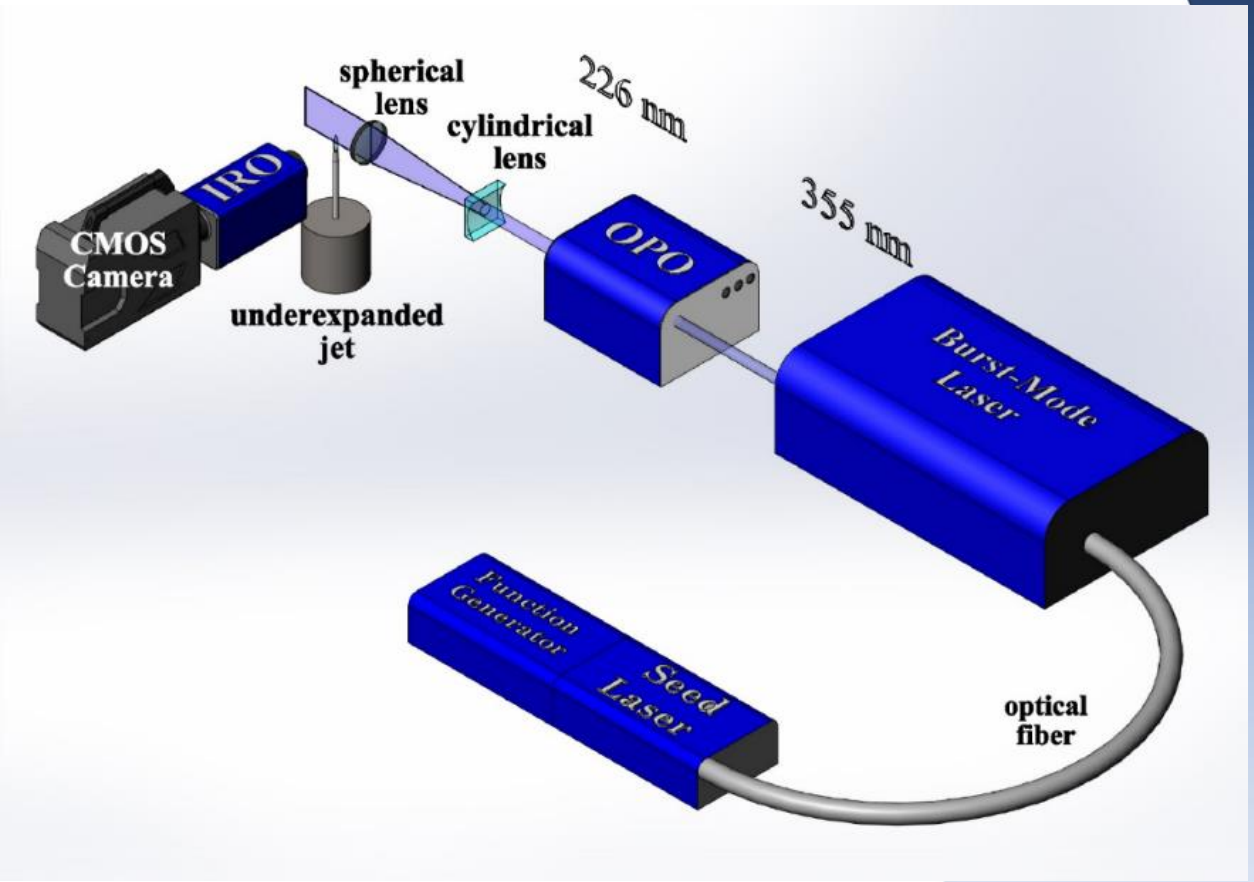
Lab-scale experiments using high-speed PLIF

- **Underexpanded jet system:**
  - **Sonic nozzle with ambient temperature nitrogen seeded with 300 ppm NO**

- **Spectral Energies Burst-Mode Laser:**
  - CW 1064 nm oscillator with pulse generator and 7 amplifier stages (custom design)
  - Operated at 100 kHz repetition rate with 2.5 ms burst duration

- **Spectral Energies Burst-Mode Optical Parametric Oscillator (OPO)**
  - Injection-seeded OPO with sum-frequency mixing

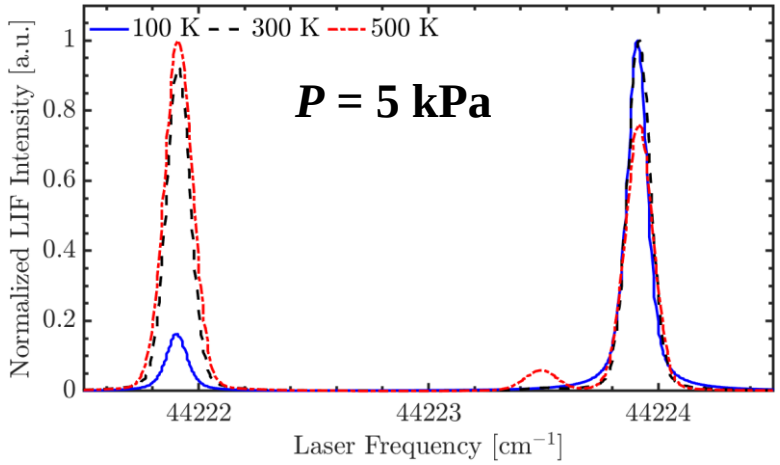
- **Function generator used to scan the 1064 nm laser wavelength at 500 Hz**

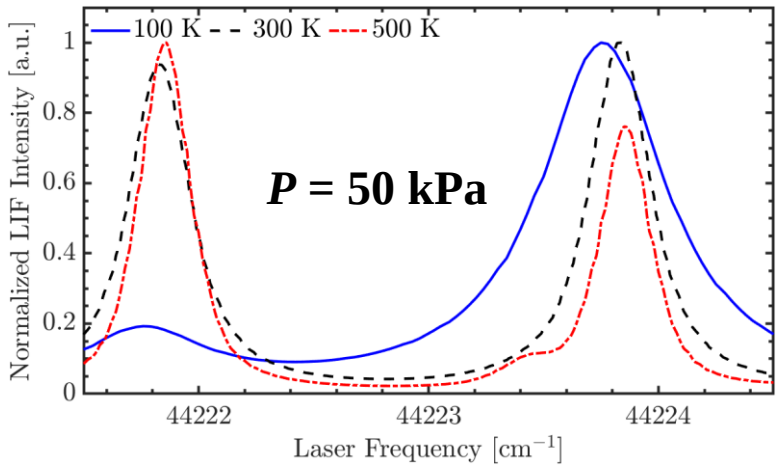


Frequency Scans at 100 kHz Laser Repetition Rate

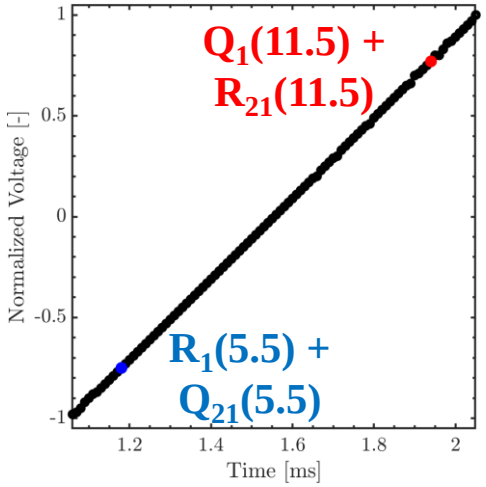
- **226 nm laser wavelength scanned over two LIF transitions**

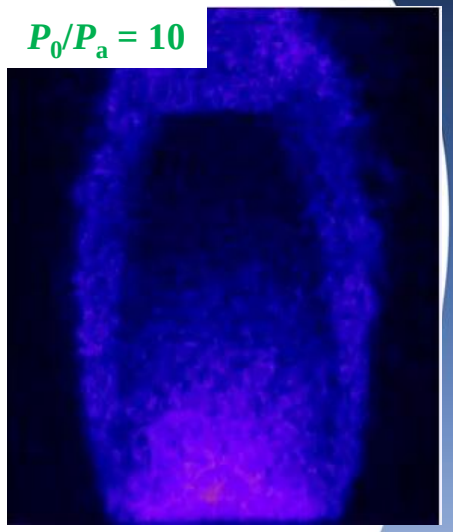
$Q_1(11.5) + R_{21}(11.5)$ $R_1(5.5) + Q_{21}(5.5)$

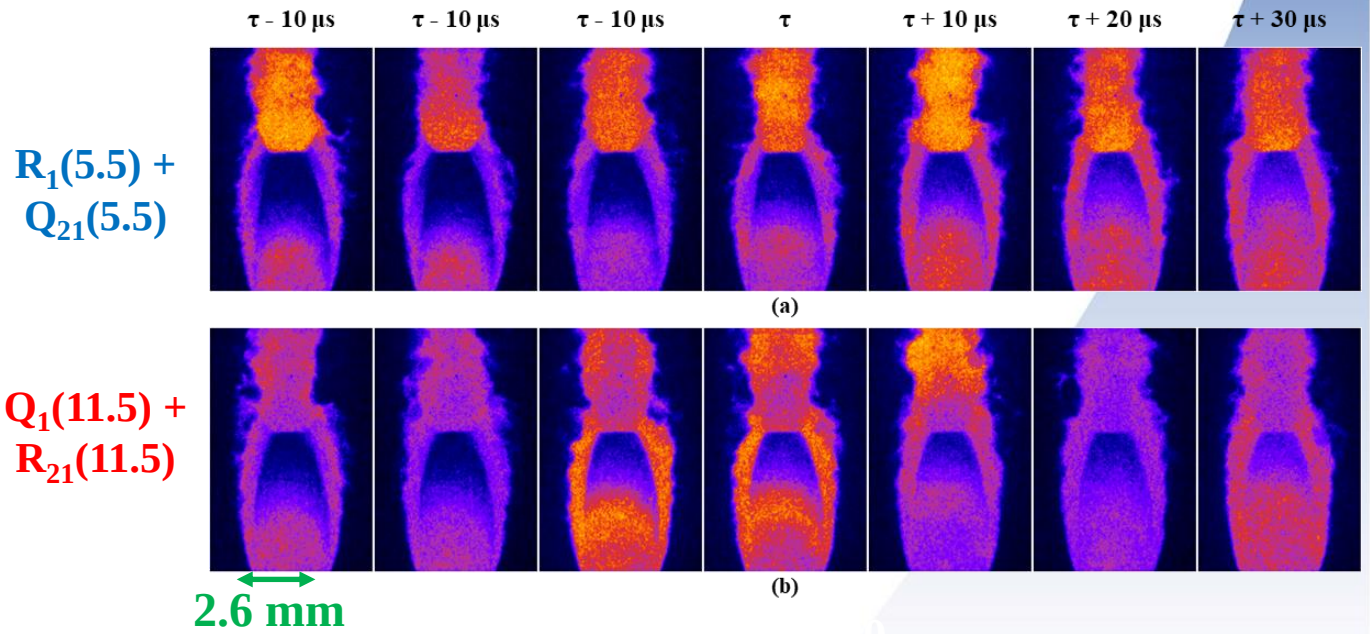




Calculated using LIFBASE





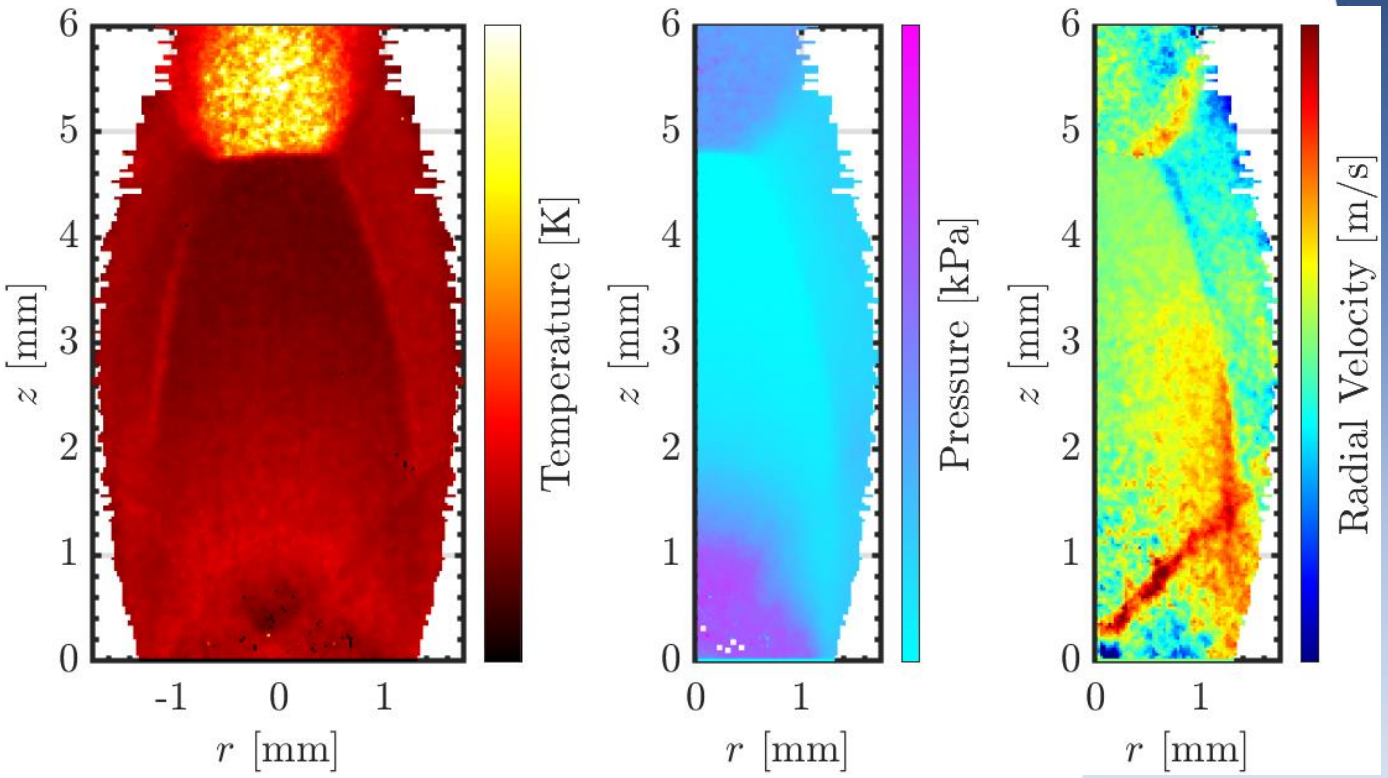


Towards Quantitative *T*, *P*, and *V*

- **2D Temperature**
  - Rotational thermometry
- **2D Pressure: Collisional Shift**
  - Collisional broadening another option
- **2D-1C Velocity: Doppler Shift**

- **Progress summarized in 2023 AIAA SciTech paper (Rodrigues *et al.*)**
  - Shown qualitatively due to issues with wavelength scan uniformity

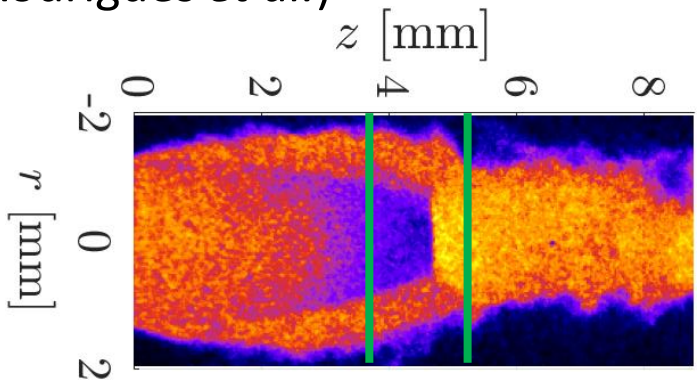
- **Current efforts including using high-speed wavemeter for wavelength monitoring**
  - Successfully used for Filtered Rayleigh Scattering measurements in 2024 AIAA SciTech Paper (Braun *et al.*)
  - PLIF improvements expected in upcoming 2025 AIAA SciTech Paper (Braun *et al.*)

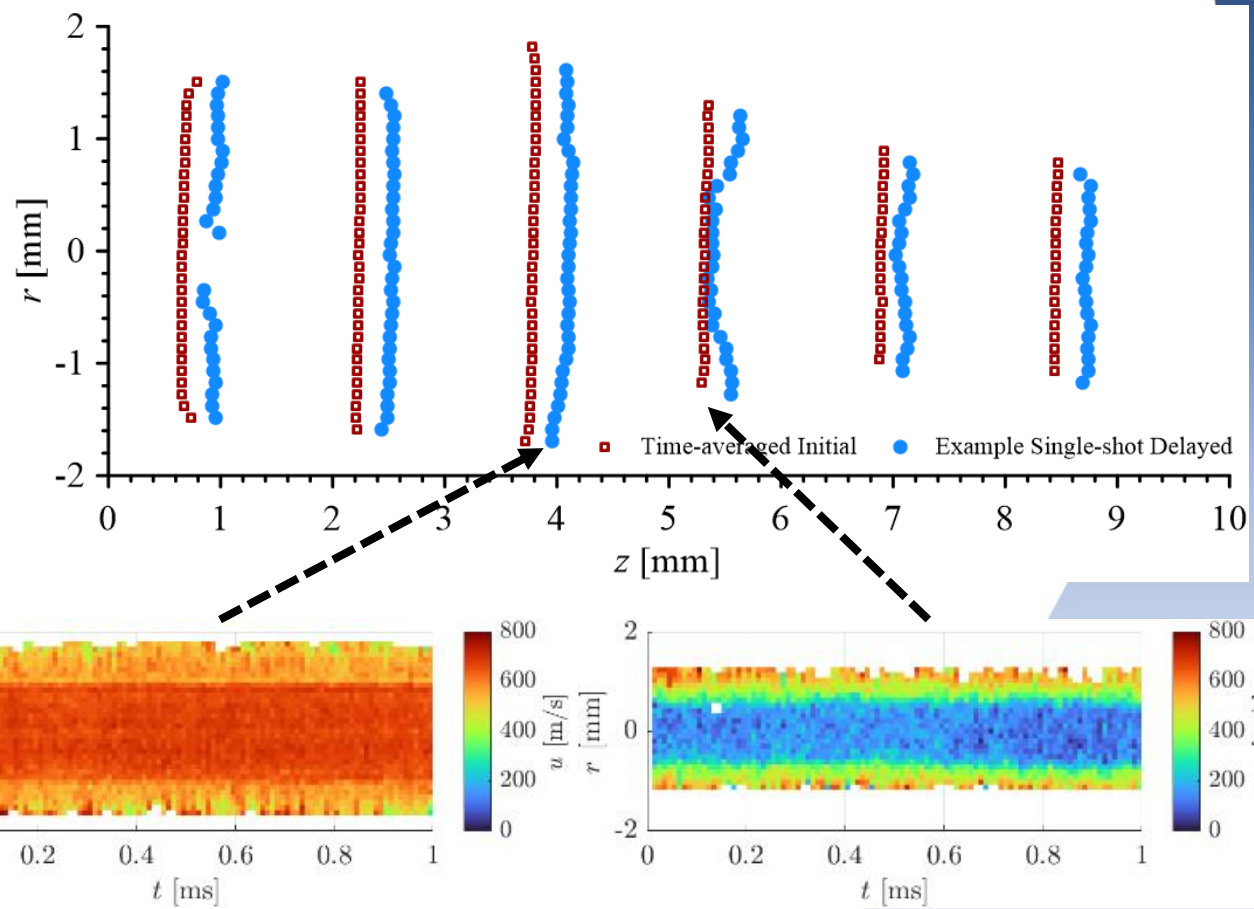


Temperature **Pressure** **Radial Velocity**

Molecular Tagging Velocimetry at 100 kHz

- **6 laser lines simultaneously used to tag and track underexpanded jet at 100 kHz repetition-rate**
  - More details in 2024 *Applied Optics* Paper (Rodrigues *et al.*)





- **New NO MTV technique using resonance-enhanced multiphoton ionization with same laser system detailed in 2024 *Optics Letters* paper (Jiang *et al.*)**
  - Similar technique also recently reported by Texas A&M group

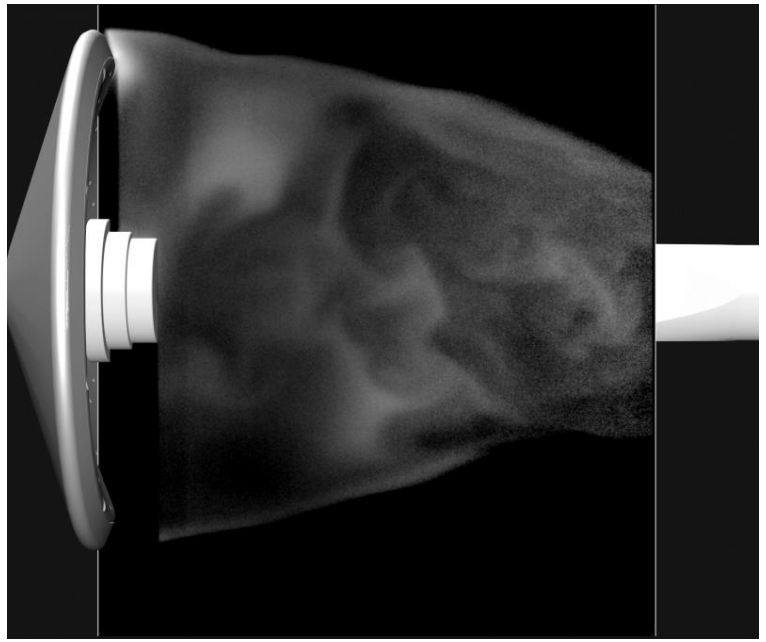
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Summary

- **Molecular-based Laser Diagnostics used at NASA Langley to support Space Technology and Exploration**
  - Provides understanding of flow physics, validation of CFD codes, help engineer better flight vehicles

- **Three recent applications in large-scale environments summarized:**
  - Freestream Characterization
  - Hypersonic Wakes
  - Supersonic Plume Impingement





Outlook:

- **Interest in space technology and exploration higher than recent decades**
- **Advanced measurements needed for physical insights and to validate computational models**

Opportunities at NASA

- **Undergraduate and Graduate Student Internships:**
  - NASA's Office of STEM Engagement (OSTEM) paid internships
    - https://stemgateway.nasa.gov/public/s/explore-opportunities
  - NASA Pathways Program:
    - https://www.nasa.gov/careers/pathways/
- **Graduate Student Fellowships (including Seniors applying to Graduate School):**
  - NASA Space Technology Graduate Research Opportunities (NSTGRO)
    - www.nasa.gov/nasa-space-technology-graduate-research-opportunities-nstgro/
- **Post-Doctoral Fellowships:**
  - NASA Postdoctoral Program (https://npp.orau.org)
- **Full-Time Opportunities after Graduation:**
  - USA Jobs (https://nasa.usajobs.gov)

Appendix

Upcoming at AIAA SciTech 2025

- “Wake velocimetry of a sphere-cone model in a Mach 10 air freestream using FLEET”
  - N.S. Rodrigues, O.K. Tyrrell, B.R. Hollis, P.M. Danehy

Upcoming at AIAA SciTech 2025

- "Wall-jet evolution during plume-surface interaction using PLIF imaging"
  - N.S. Rodrigues, R.A. Burns, O.K. Tyrrell, P.M. Danehy

		[-]	[Pa]	[kPa]
		h/D_e	P_a	P_0
Lunar-relevant	Case I	10	3.6 → 4.6	38.7 ± 0.2
	Case II	3	1.6 → 2.6	38.3 ± 0.1
Martian-relevant	Case III	3	585 → 622	743 → 961

