Flow visualization for Plume-Surface Interaction testing with large-scale vacuum environments at conditions relevant to Lunar and Martian Landers

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JANNAF December 2023: 40th Exhaust Plume and Signatures (EPSS) Meeting
Plume / Wake / Hypersonic Flowfield Measurements

Acknowledgements

- Ground test conducted under support of *Plume Surface Interaction* project, previously funded by the NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD)

- High-speed PLIF development primarily under support of NASA Phase II SBIR Award to Spectral Energies, LLC

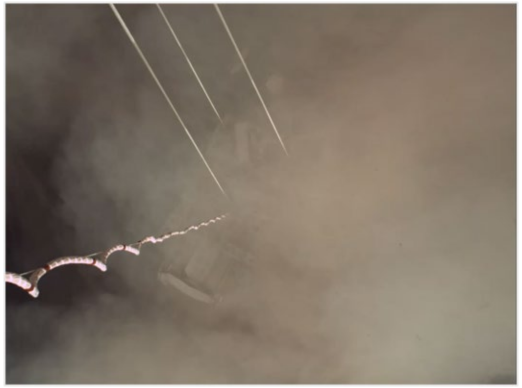
- NASA Marshall: S. Harris, Dr. M. Mehta, Dr. J. West, Dr. A. Weaver, T. Shurtz, Dr. J. Sisco, K. Miasek, K. Thompson, and the entire staff of ET-10 involved with this work

- NASA Langley: H. Ripley and Dr. T. Fahringer

Introduction

- **Rocket Plume-Surface Interaction (PSI):**
  - Induced environment due to impingement of hot rocket exhaust on landing surface
    - Complex: multi-scale and often multi-phase (unimproved Lunar or Martian surface)

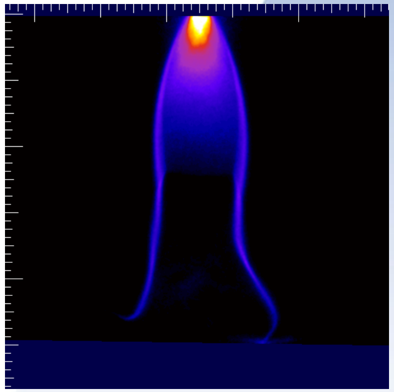
Lunar: Apollo 16 landing → Artemis missions



Martian: rover landings → human landings

- **Scarcity of experimental data to validate high-fidelity models:**
  - Realistic environments: plumes within reduced ambient pressures (continuum to rarefied scales)

- **Martian-relevant environments can leverage data from Space Shuttle *Return to Flight* efforts**
  - 46th AIAA Aerospace Sciences Meeting (Inman, Danehy, Nowak, Alderfer; 2008)

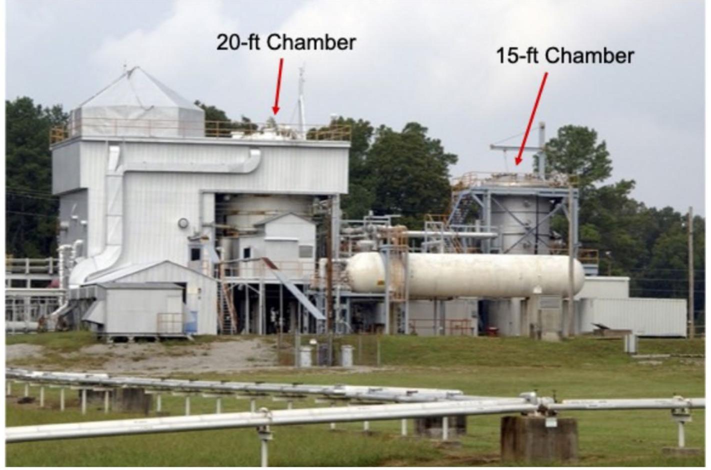


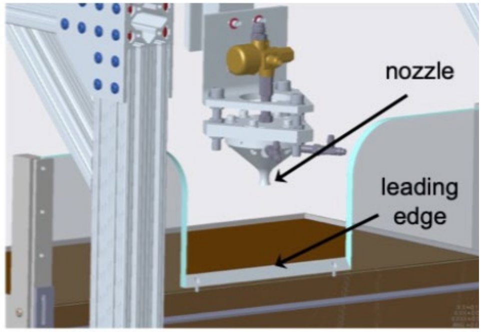
Inman *et al.* (2008)

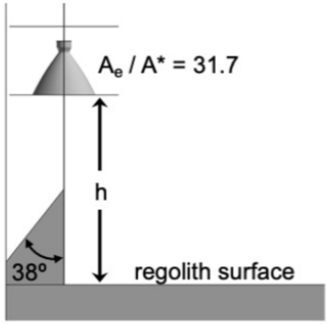
- **Plume-surface flow visualization for near-lunar ambient pressures not available in literature**

Background

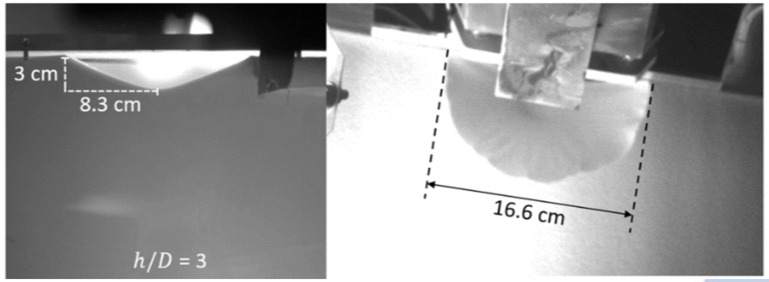
- **NASA Space Technology Mission Directorate (STMD) funded two ground tests within large-scale vacuum chambers at NASA Marshall Space Flight Center**
  - 15-ft Vacuum Chamber (2021-2022)
  - 20-ft Vacuum Chamber (2022)







- **15-ft Vacuum Chamber:**
  - Half-plane regolith bin geometry:
    - Imaging of plume-induced crater
    - Ejecta imaging and tracking
  - Half-plane flat impingement plate:
    - Impingement pressure



- **20-ft Vacuum Chamber:**
  - Full-plane and half-plane flat impingement plate:
    - PLIF flow visualization
    - Impingement pressure

References
- Korzun *et al*., Design of a Subscale, Inert Gas Test for Plume-Surface Interactions in a Reduced Pressure Environment, in AIAA SciTech Forum, San Diego, CA (Jan. 2022).
- Eberhart *et al*., Overview of Plume-Surface Interaction Data from Subscale Inert Gas Testing at NASA MSFC Test Stand 300 Vacuum Facilities, in AIAA SciTech Forum, San Diego, CA (Jan. 2022).
- Rubio *et al*., Plume-Surface Interaction Physics Focused Ground Test 1: Setup and Preliminary Results, in AIAA SciTech Forum, San Diego, CA (Jan. 2022).
- Diaz-Lopez *et al*., Plume-surface Interaction Physics Focused Ground Test 1: Diagnostics and Preliminary Results, in AIAA SciTech Forum, AIAA 2022-1810, AIAA, San Diego, CA (Jan. 2022).

Planar Laser-induced Fluorescence

- Planar laser-induced fluorescence (PLIF) is a 2D, temporarily and spatially-resolved laser-based measurement technique
    - Spatial resolution < 1 mm

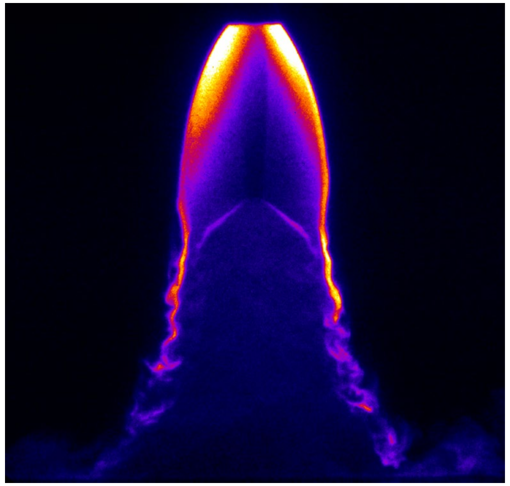
- Tunable, pulsed, laser used to excite the NO molecules
    - Repetition-rate of 10 Hz but temporal resolution < 1 µs

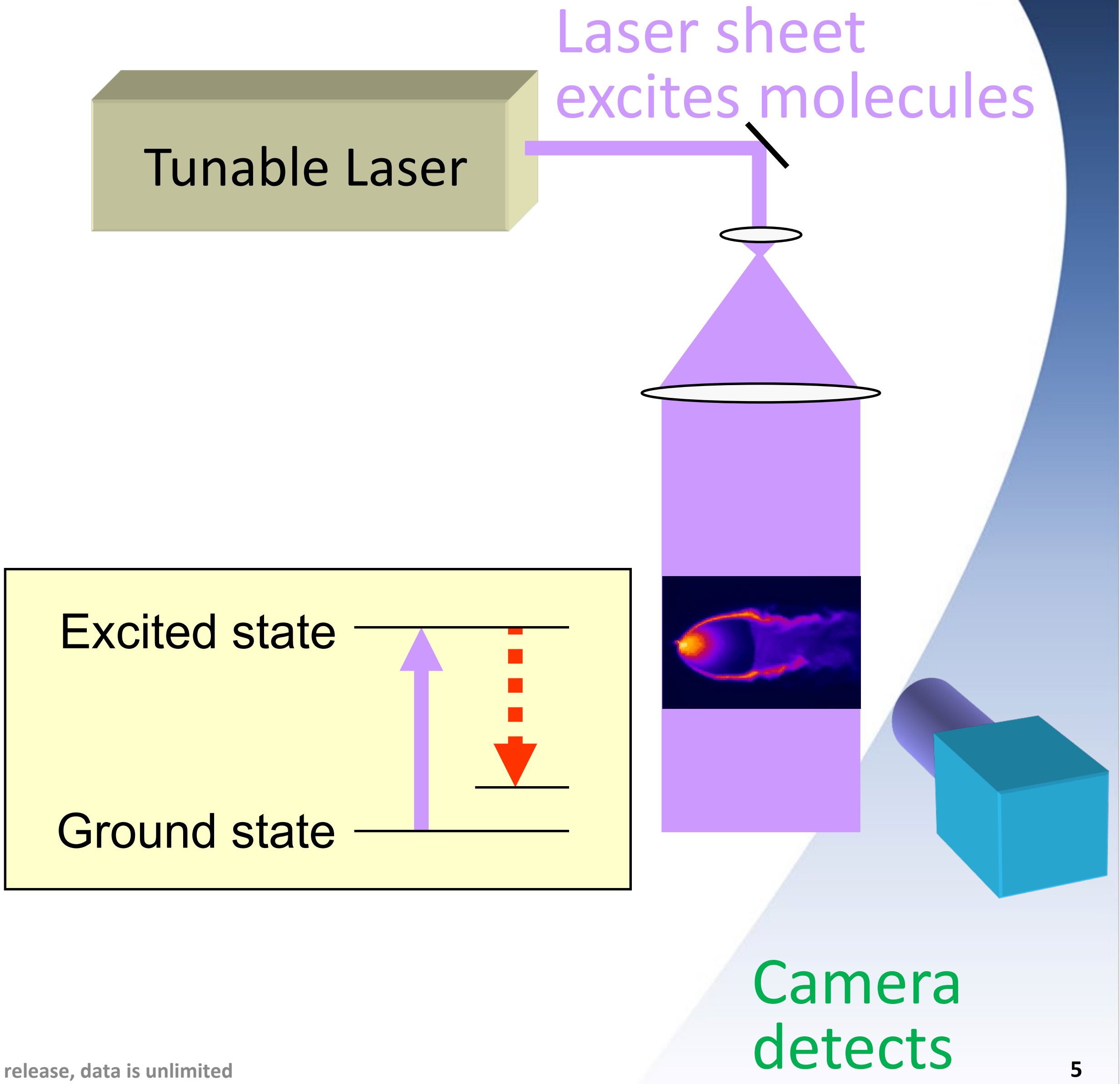
- PLIF for PSI test used seeded nitric oxide gas (< 1%)
    - Well suited for low-pressure environments
        - More so than schlieren and shadowgraph

- On the first order, PLIF signal scales with gas density

- Signal intensity is qualitative

- Location of flow structures (e.g., shocks) is quantitative





Laser sheet excites molecules

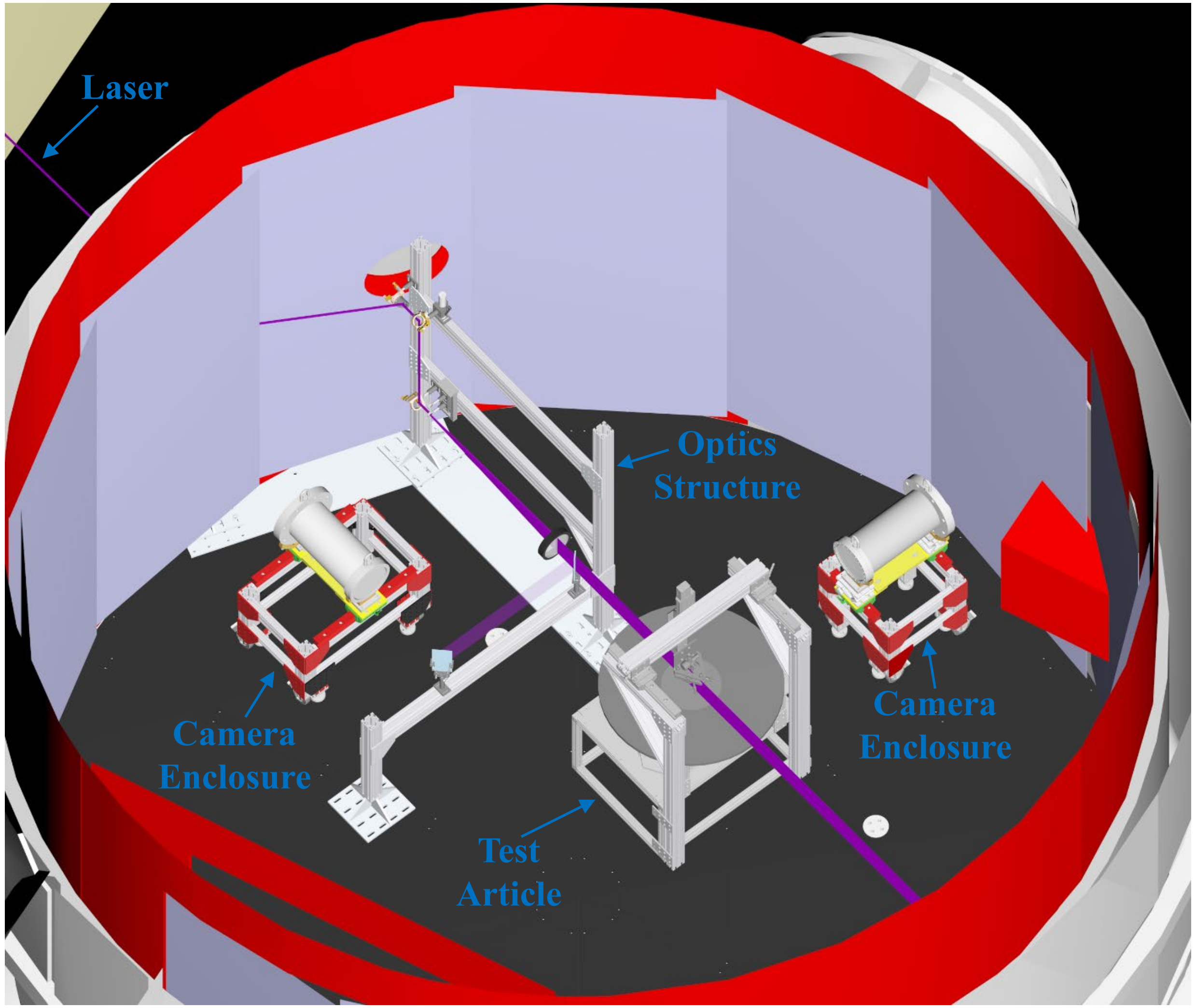
Tunable Laser

Excited state

Ground state

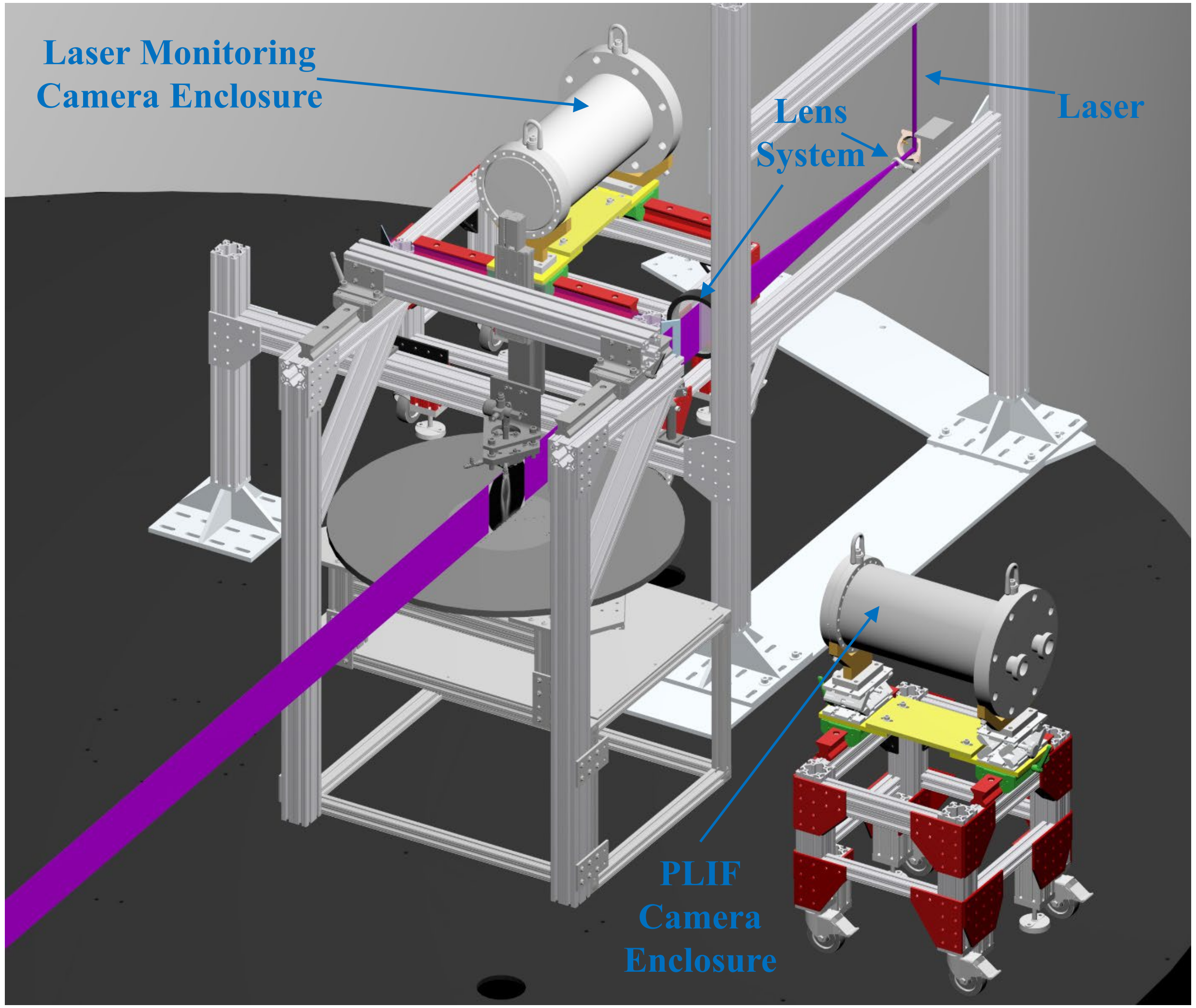
Camera detects

20-ft Vacuum Chamber Overview



- Jet nozzle assembly and impingement plate test article
  - Located near middle of chamber
- Heated inert gas (nitrogen) plume
  - Premixed with nitric oxide for PLIF visualization
- UV laser (near 226 nm) brought into vacuum chamber through viewport window
- Optics for PLIF laser sheet placed on custom structure
- PLIF cameras located within custom camera enclosures

10 Hz PLIF Systems



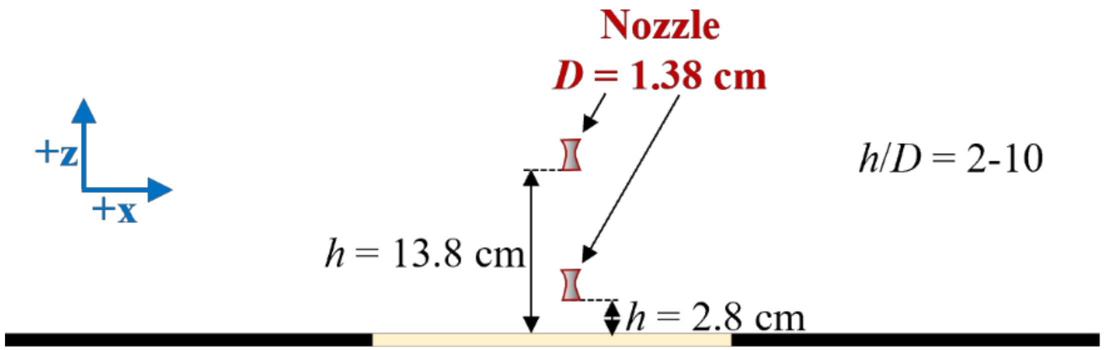
- 226-nm laser: Sirah® Cobra-Stretch Dye laser with sum-frequency-mixing wavelength extension, pumped by Spectra-Physics® Pro-230
  - Laser beam alignment adjusted using remote-controlled mirrors

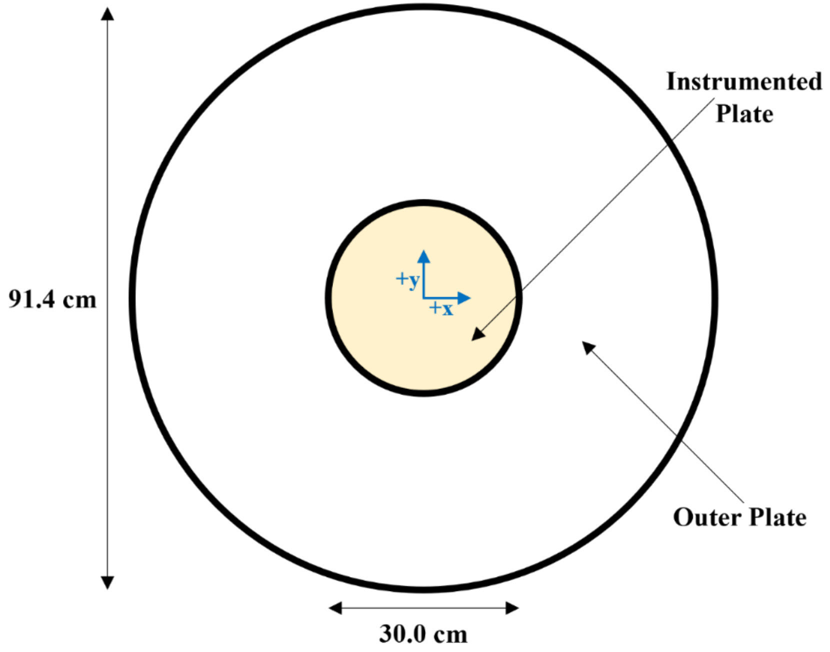
- PLIF laser sheet expanded to ~140 mm using negative cylindrical lens
  - Height collimated using positive spherical lens
  - Laser sheet thickness <1 mm near nozzle

- PLIF Camera: Andor® iStar sCMOS camera
  - 100 mm UV lens *f*/2.8
  - Long-wavelength-pass filter near 230 nm

- ~1% of laser energy reflected off glass window and directed towards diffuser plate
  - Laser sheet monitoring
  - Imaged by Cooke® Sensicam

Test Article Overview



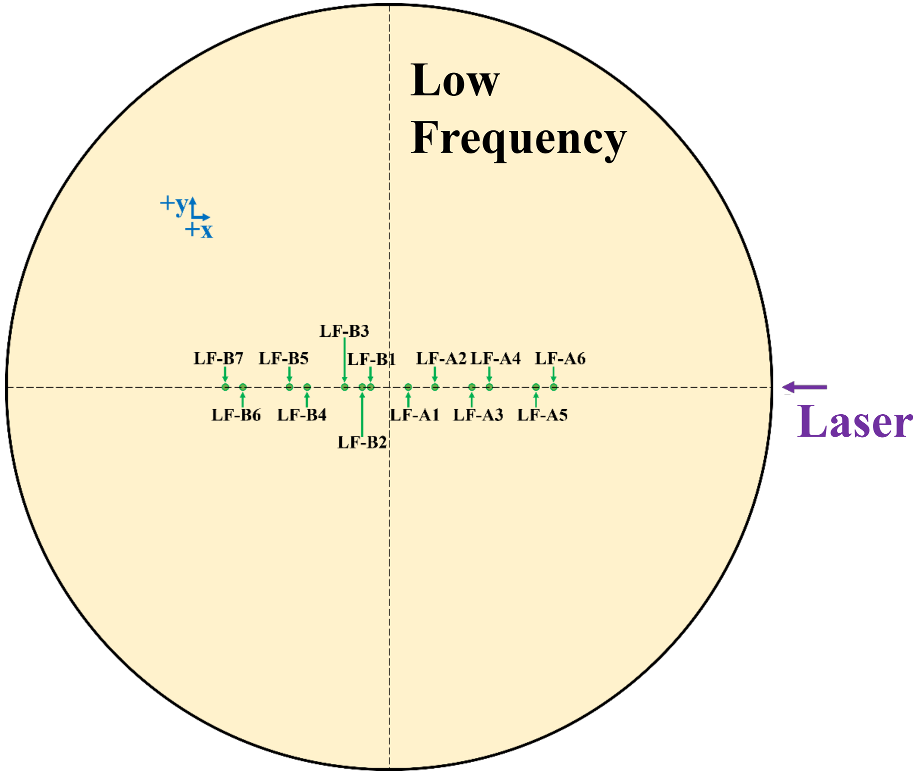


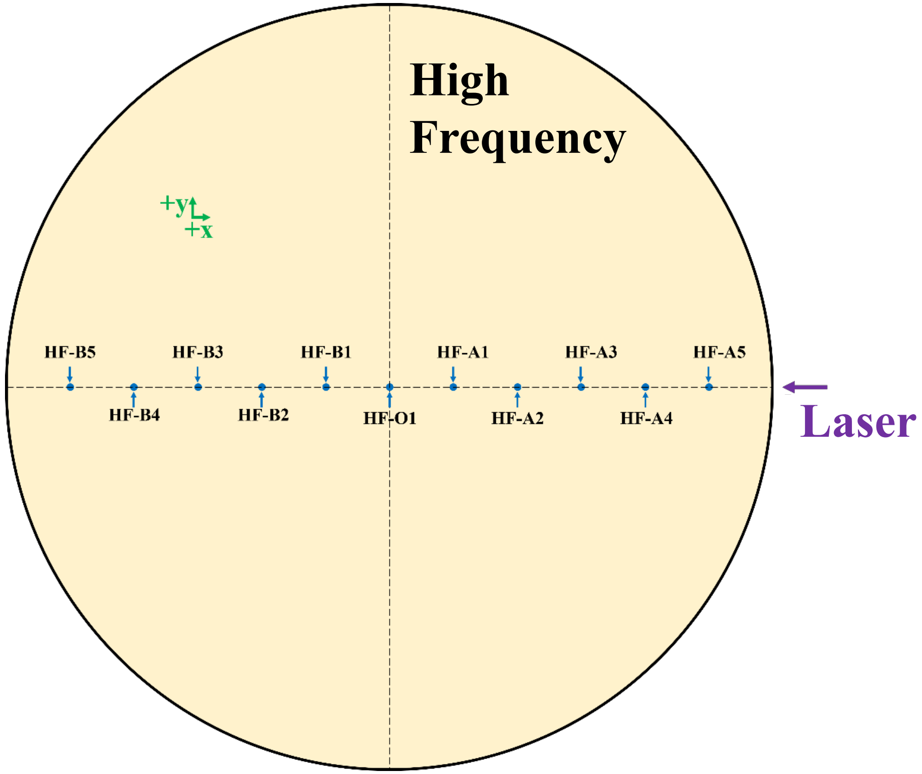
- Mach 5.3 supersonic nozzle:
  - Exit diameter *D*
- Nozzle vertically translated with respect to plate:
  - h/D = 10 to 2
- Jet and facility instrumentation:
  - Pressure
  - Temperature
- Impingement plate:
  - Instrumented plate
  - Outer plate

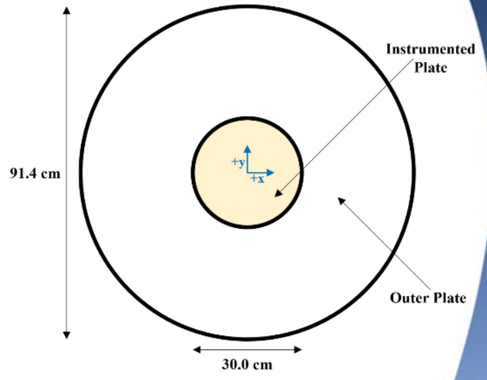
Measurement	Instrument	Range	Uncertainty
Initial Vacuum Pressure, $P_{C,i}$	Wall-located cold cathode	$1.0 \cdot 10^{-6} – 1.0 \cdot 10^{0}$ Pa	30% reading
	Ex-situ transducer (10 Torr)	$< 1.3 \cdot 10^{3}$ Pa	$6.7 \cdot 10^{-1}$ [Pa]
Vacuum Pressure, P_C	Wall-located transducer (1 Torr)	$1.3 \cdot 10^{-3} – 1.3 \cdot 10^{2}$ Pa	0.08% reading
	Wall-located transducer (1000 Torr)	$4.0 \cdot 10^{1} – 1.3 \cdot 10^{5}$ Pa	0.5% reading
Jet Stagnation Pressure, P_0	Nozzle plenum transducer I (250 psia) Nozzle plenum transducer II (250 psia)	$< 1.7 \cdot 10^{6}$ Pa	$8.6 \cdot 10^{3}$ [Pa]
Jet Stagnation Temperature, T_0	Nozzle plenum thermocouple (K-type)	273 – 373 K	2.2 [K]
		> 373 K	0.75% reading

Plate Pressure Instrumentation

- Inner plate equipped with low-frequency (LF) and high-frequency (HF) pressure instrumentation







- Low-frequency (100 Hz) pressure instrumentation (InstruTech CDM900 vacuum gauge) located outside vacuum chamber
  - Connected to impingement plate using plastic *sense tubes* (order of seconds time response)

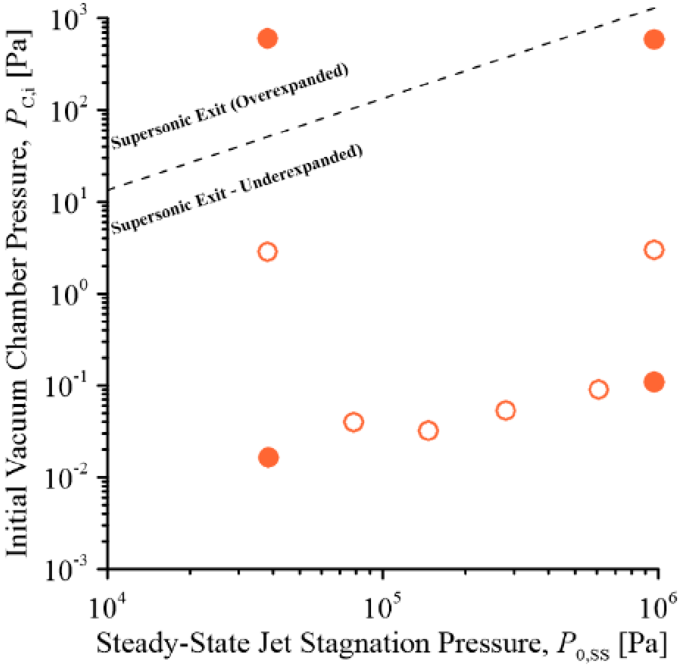
- High-frequency (200 kHz) pressure instrumentation (Kulites) flush-mounted on impingement plate
  - 100 Hz moving mean filter applied for static pressure measurements reported here

Test Matrix Overview

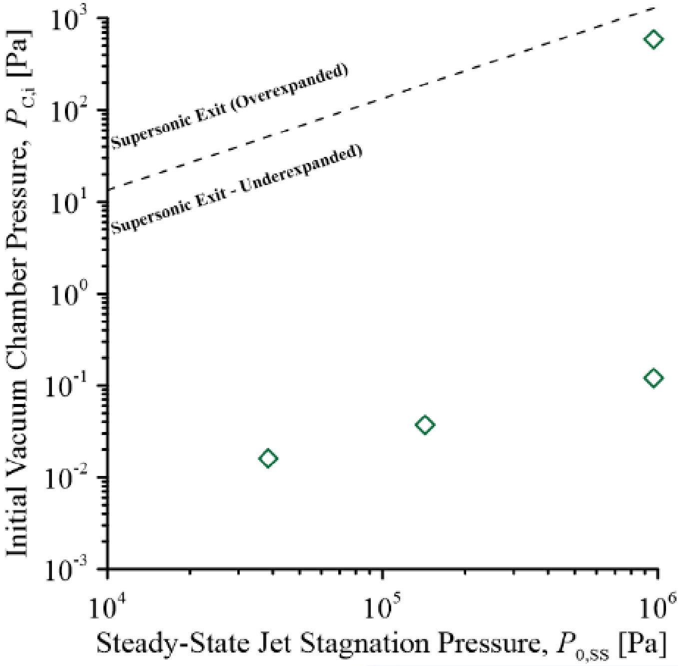
		[Pa]		
$\dot{m}_{SS}$ [g/s]	**$P_{0,SS}$ [Pa]**	**$10^{-3} < P_{C,i} < 10^{-1}$**	**$2 < P_{C,i} < 3$**	**$590 < P_{C,i} < 610$**
0.32	$3.8 \cdot 10^4$	*h*/*D* = 10, 8, 5, 4, **3**, 2	*h*/*D* = 10, 3	*h*/*D* = 10, **3**
0.65	$7.9 \cdot 10^4$	*h*/*D* = 3, 10		
1.2	$1.5 \cdot 10^5$	*h*/*D* = 10, 8, 5, 4, 3, 2		
2.4	$2.8 \cdot 10^5$	*h*/*D* = 3, 10		
5.1	$6.1 \cdot 10^5$	*h*/*D* = 3, 10		
8.1	$9.7 \cdot 10^5$	*h*/*D* = 10, 8, 5, 4, **3**, 2	*h*/*D* = 10, 3	*h*/*D* = 10, 8, 5, 4, **3**,2

$\dot{m}_{SS}$: steady-state mass flow rate
$P_{0,SS}$: steady-state stagnation pressure
$P_{C,i}$: initial vacuum chamber pressure
h/D: dimensionless nozzle height

- Parametric test matrix designed to study the effects of *h*/*D*, $P_{0,SS}$ and $P_{C,i}$
- Three different vacuum chamber pressure groups:
  - Near-lunar: $10^{-3} < P_{C,i} < 10^{-1}$ Pa
  - Lunar-relevant: $2 < P_{C,i} < 3$ Pa
  - Martian-relevant: $590 < P_{C,i} < 610$ Pa
- This presentation focuses on *h*/*D* = 3
  - Near-lunar: high & low flow
  - Martian-relevant high & low flow



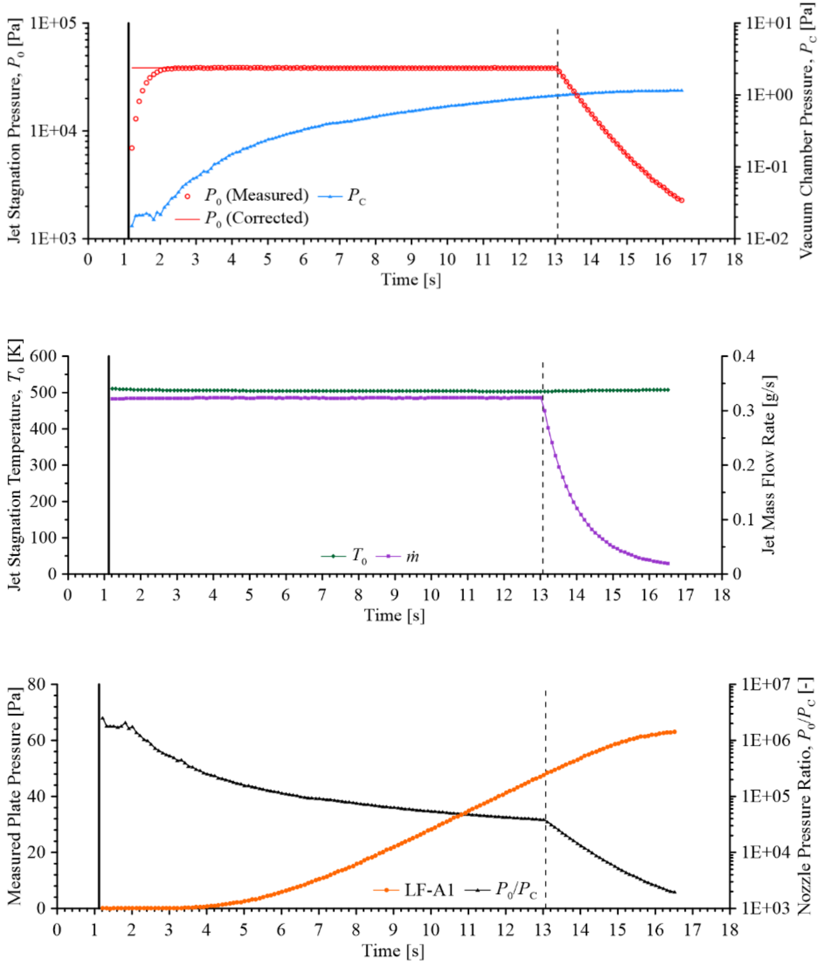
***h*/*D* = 10, 3**



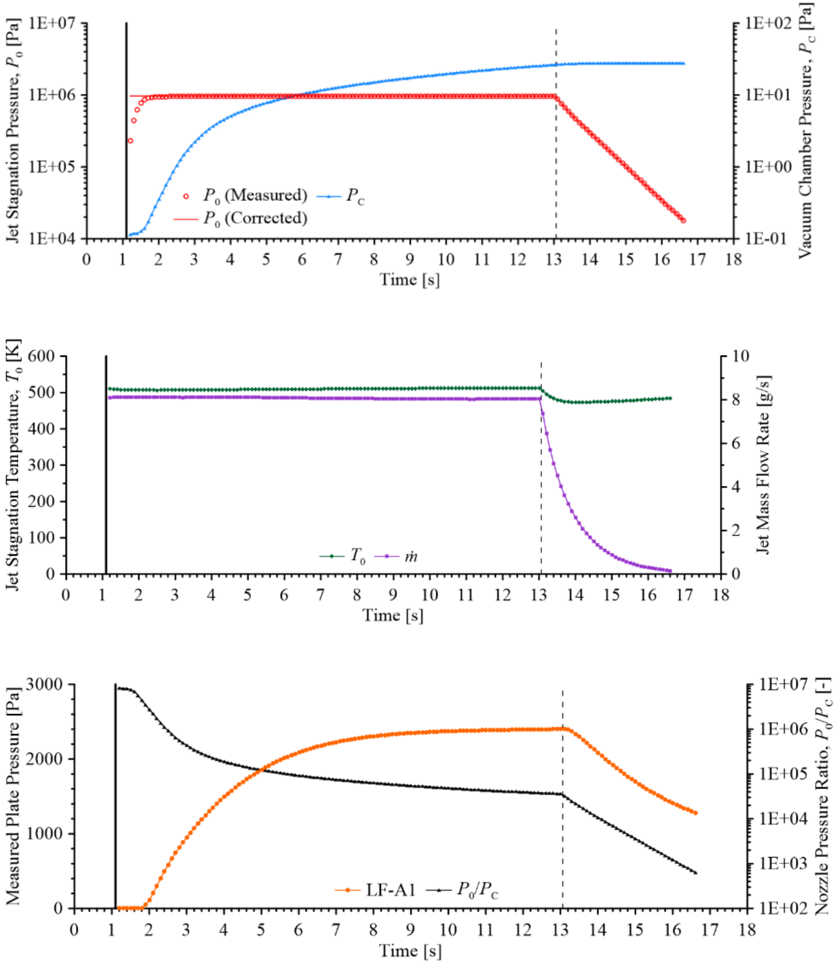
***h*/*D* = 8, 5, 4, 2**

Near-lunar Vacuum Conditions

Low Flow: $P_{0,SS} = 3.8 \cdot 10^4$ Pa ($\dot{m}_{SS} = 0.32$ g/s)



High Flow: $P_{0,SS} = 9.7 \cdot 10^5$ Pa ($\dot{m}_{SS} = 8.1$ g/s)

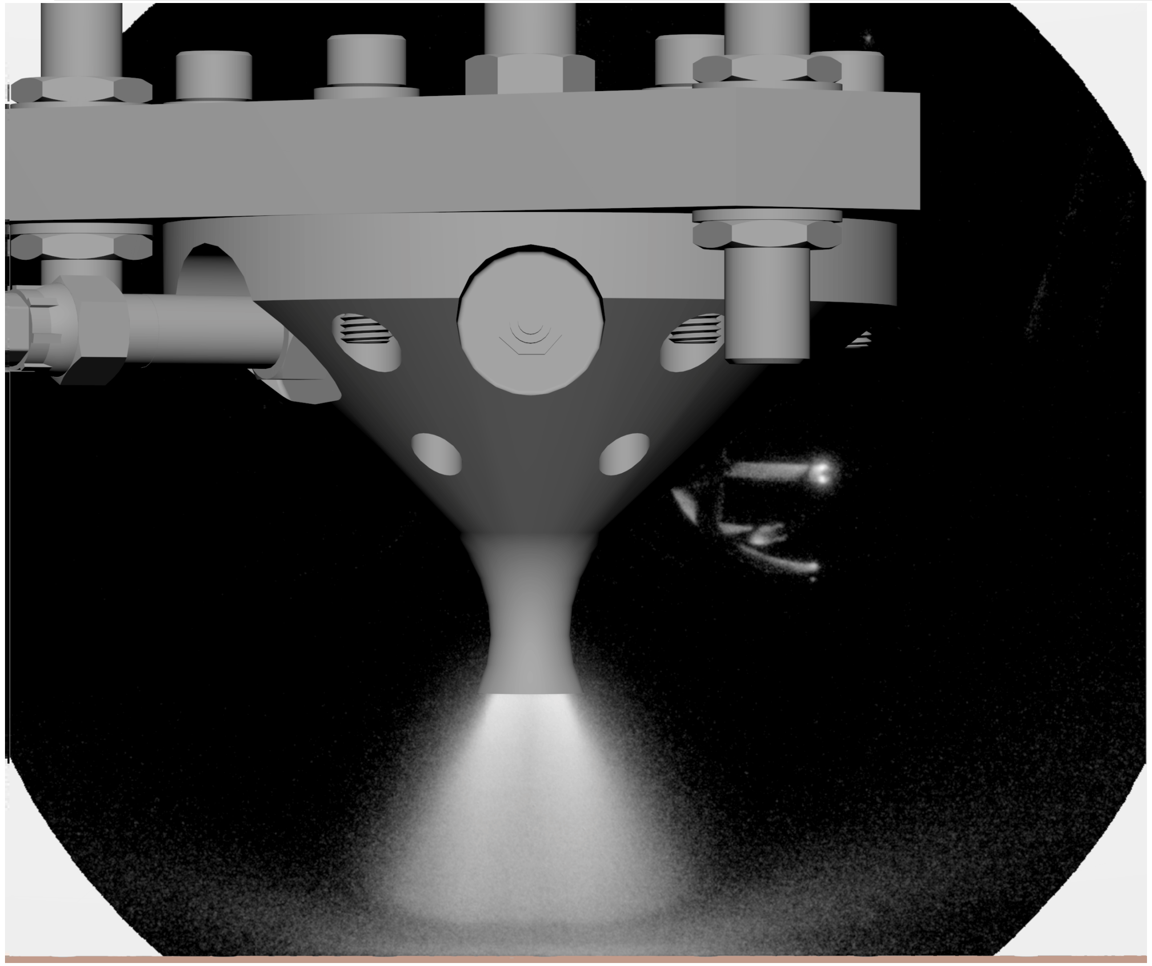


- P_C increases throughout run
- P_0 corrected to account for ρU^2 after valve opening

- T_0 relatively constant
- $\dot{m}$ relatively constant 100-200 ms after valve opening
  - Scales with P_0

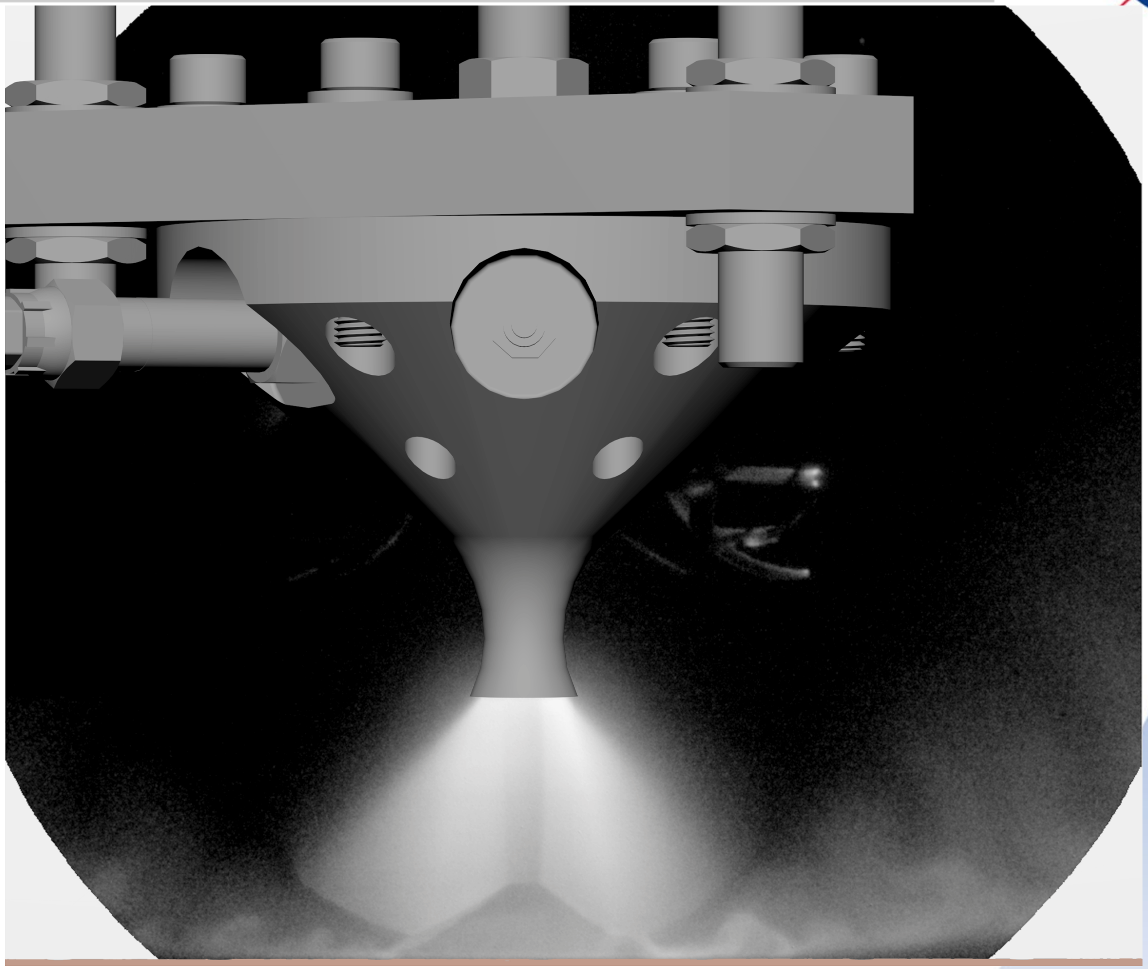
- P_0/P_C varies throughout run
- Low-frequency impingement pressure LF-A1 cannot be attributed to a single P_0/P_C

Near-lunar Flow Visualization (log-scale)



Low Flow: $P_{0,SS} = 3.8 \cdot 10^4$ Pa ($\dot{m}_{SS} = 0.32$ g/s)
$P_{C,i} \sim 0.02 \rightarrow 1$ Pa

Very low gas density → diffuse flow structures



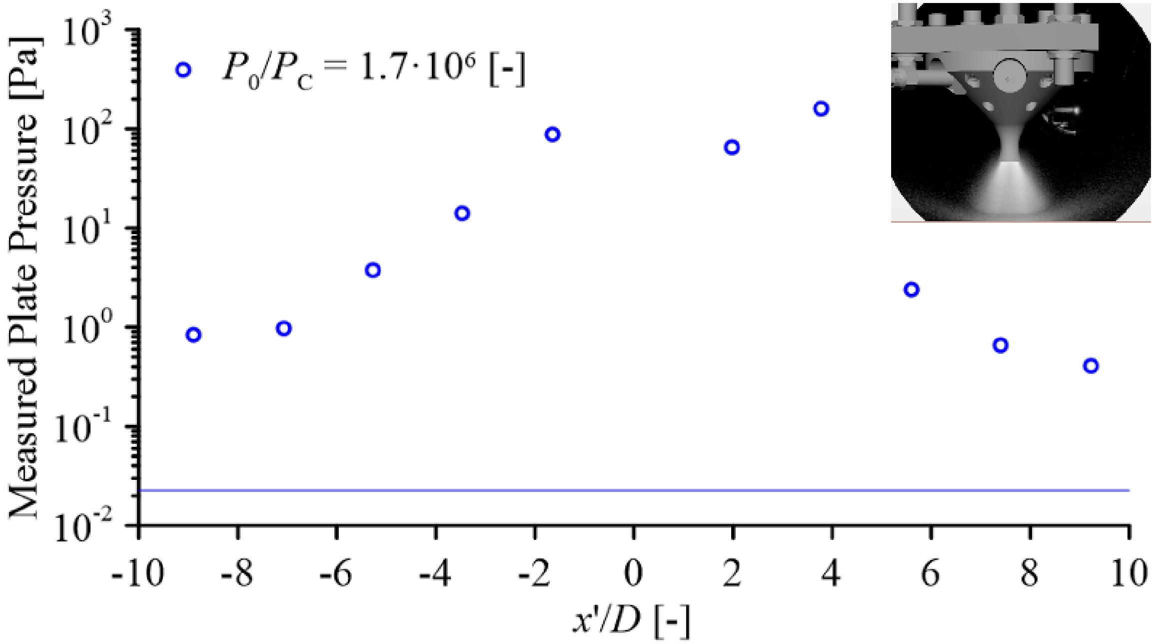
High Flow: $P_{0,SS} = 9.7 \cdot 10^5$ Pa ($\dot{m}_{SS} = 8.1$ g/s)
$P_{C,i} \sim 0.1 \rightarrow 3$ Pa

Salient features: stagnation shock, wall jet, unsteady flow

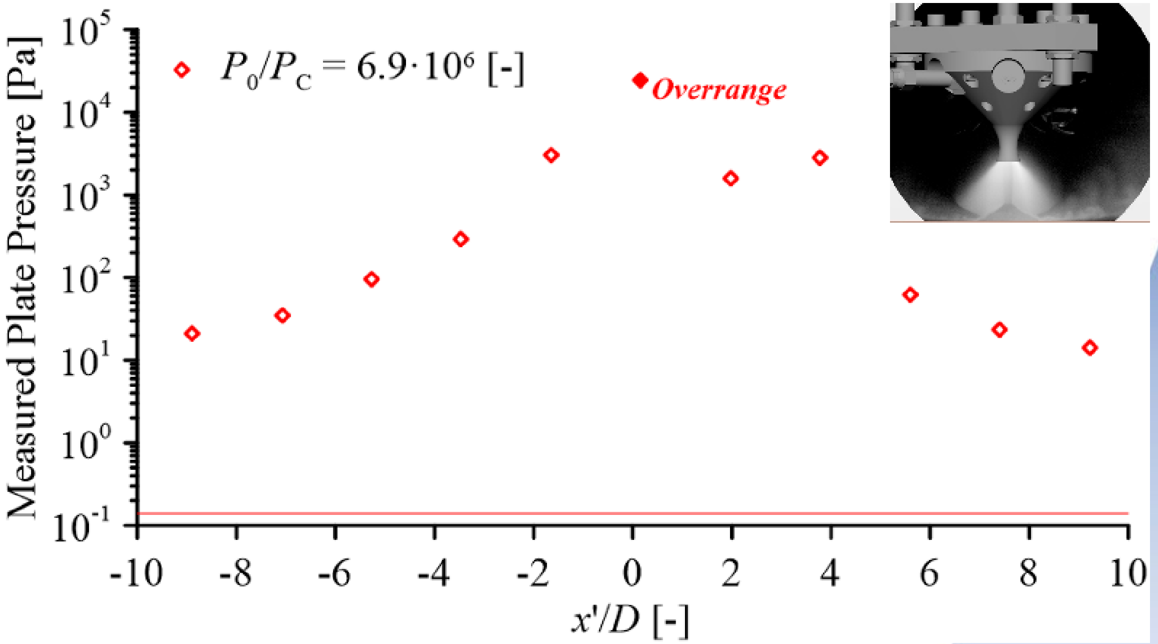
- Fluctuations with NO mass flow rate

Near-lunar Impingement Pressure

- Transient vacuum condition inhibits attributing low-frequency pressure measurement to a single P_0/P_C
- High-frequency pressure measurements recorded on 200 kHz DAQ (synchronized with camera exposure signal)
  - Impingement pressure can be paired to P_0/P_C and corresponding PLIF image



Low Flow: $P_{0,SS} = 3.8\cdot10^4$ Pa ($\dot{m}_{SS} = 0.32$ g/s)

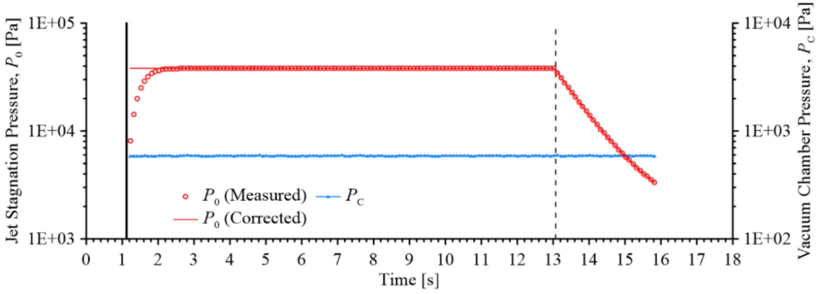


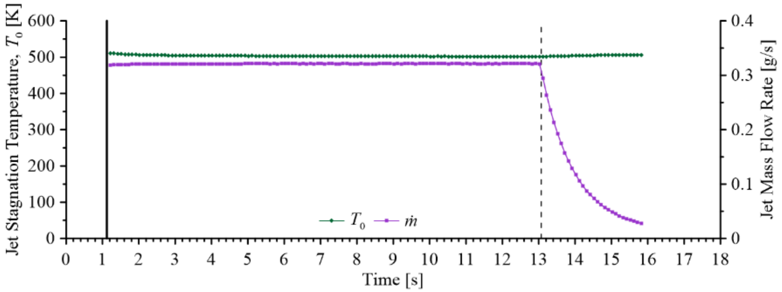
High Flow: $P_{0,SS} = 9.7\cdot10^5$ Pa ($\dot{m}_{SS} = 8.1$ g/s)

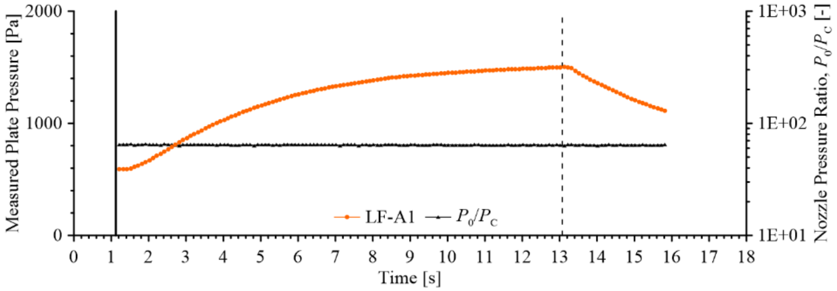
- Impingement plate pressure mapped for several jet diameters in radial direction
  - Very different plume structures for qualitatively similar pressure profiles and P_0/P_C

Martian-relevant Vacuum Conditions

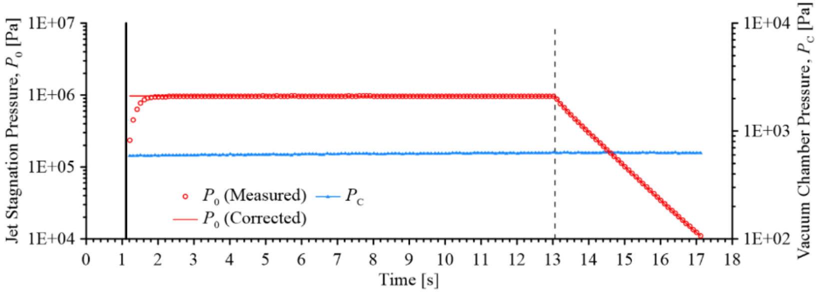
Low Flow: $P_{0,SS} = 3.8\cdot10^4$ Pa ($\dot{m}_{SS} = 0.32$ g/s)

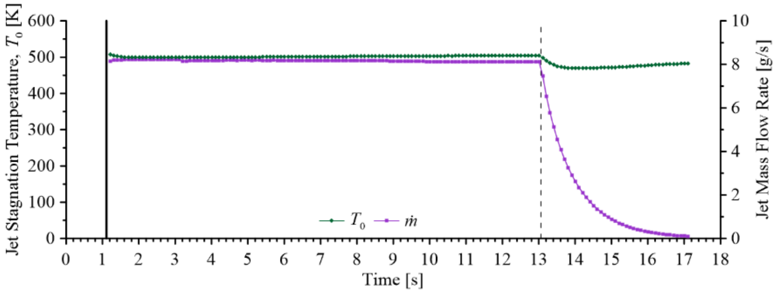


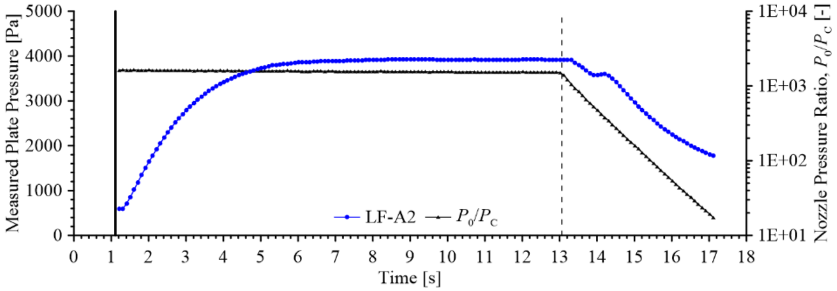




High Flow: $P_{0,SS} = 9.7\cdot10^5$ Pa ($\dot{m}_{SS} = 8.2$ g/s)





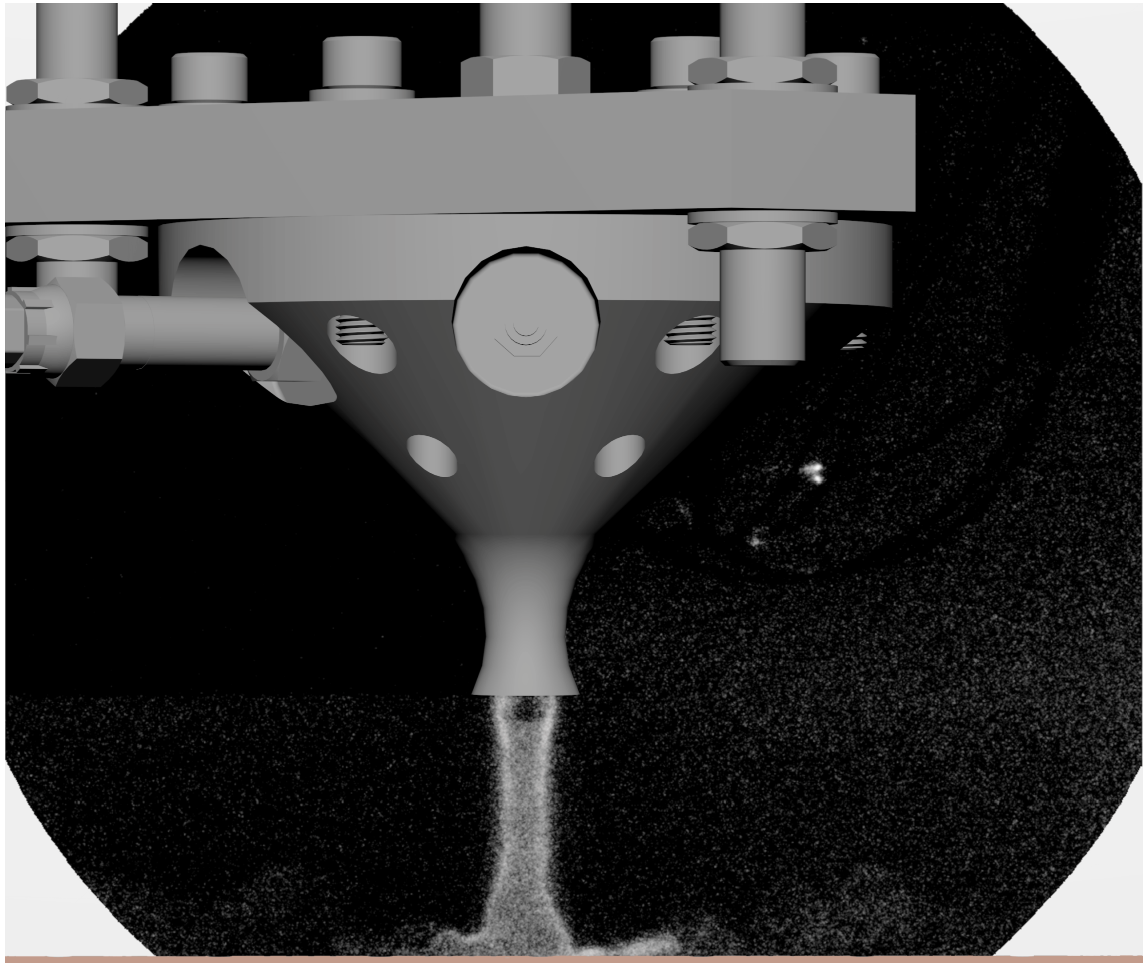


- P_C relatively constant throughout run
- Same P_0 correction applied

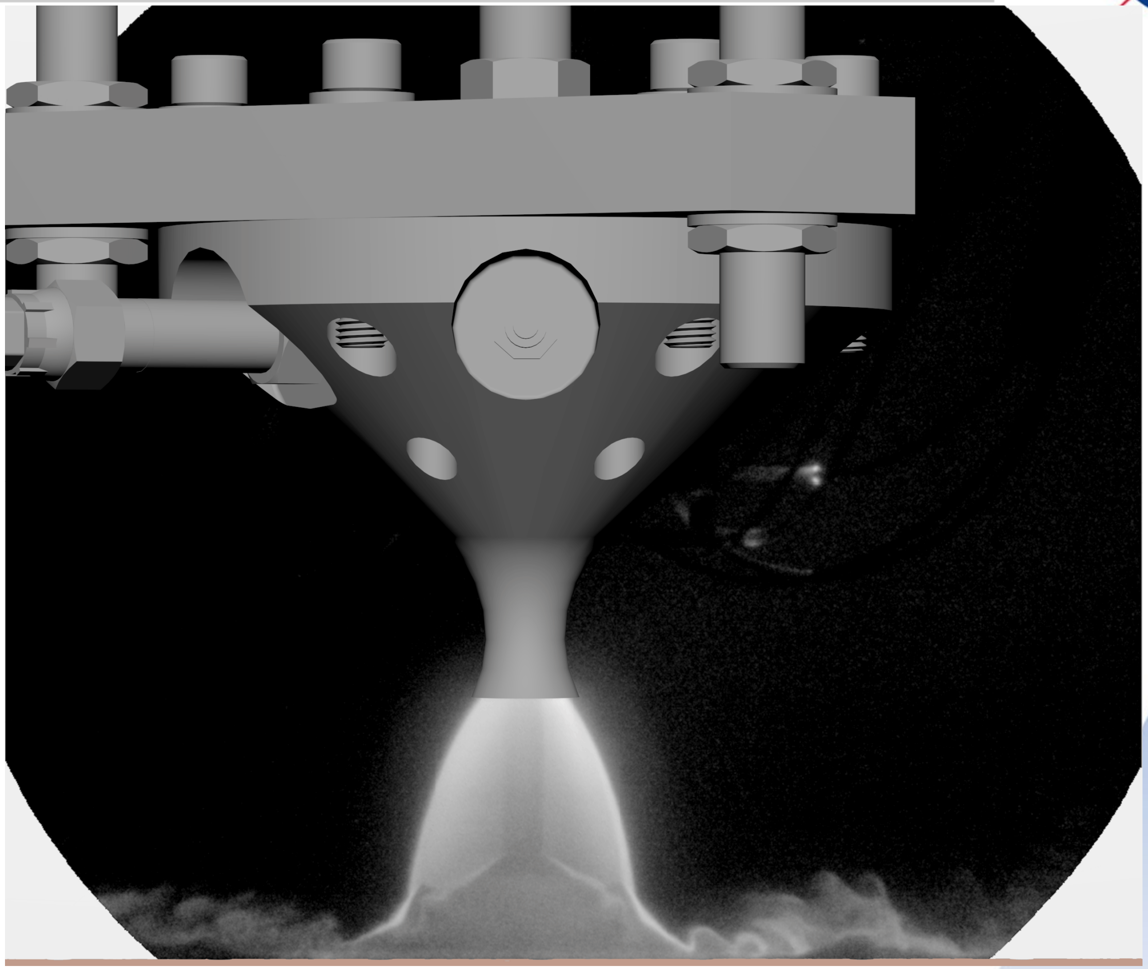
- T_0 relatively constant
- $\dot{m}$ relatively constant (using P_0 correction)

- P_0/P_C relatively constant throughout run
- Low-frequency impingement pressure at steady-state used
- LF-A1 saturated at high flow condition; LF-A2 used

Martian-relevant Flow Visualization (log-scale)



Low Flow: $P_{0,\mathrm{SS}} = 3.8\cdot10^4$ Pa ($\dot{m}_{\mathrm{SS}} = 0.32$ g/s)



High Flow: $P_{0,\mathrm{SS}} = 9.7\cdot10^5$ Pa ($\dot{m}_{\mathrm{SS}} = 8.2$ g/s)

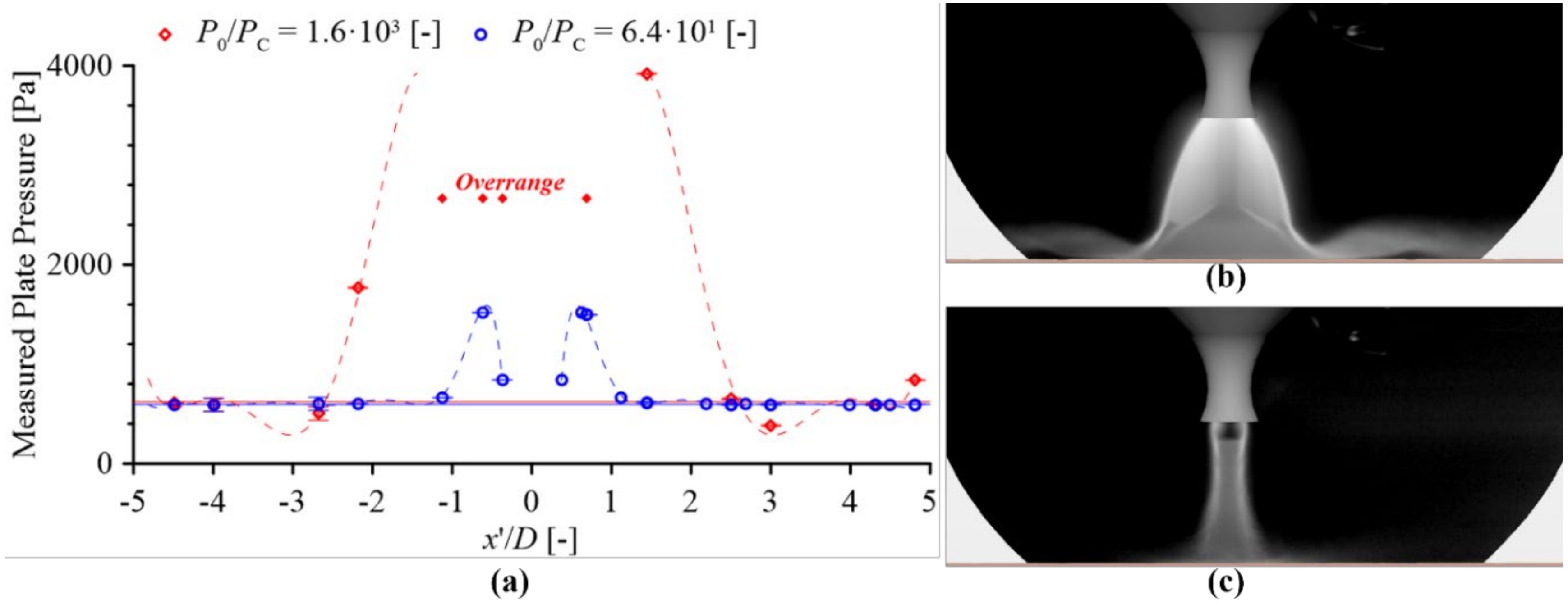
Overexpanded nozzle condition, flow separation

- Lower S/N, laser burn mark on viewport window

Salient features: stagnation shock, wall jet, unsteady flow

Martian-relevant Impingement Pressure

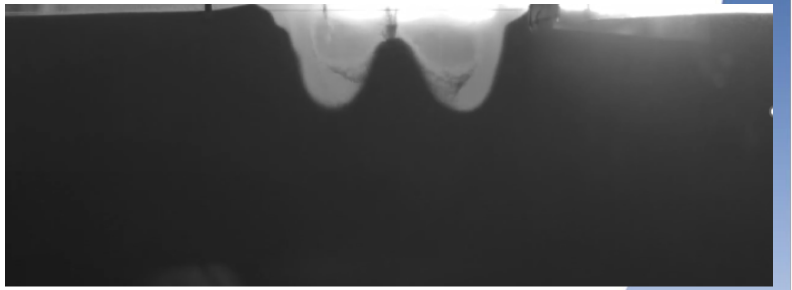
- Steady-state vacuum conditions allow low-frequency pressure measurement to be attributed to a single P_0/P_C



(a)

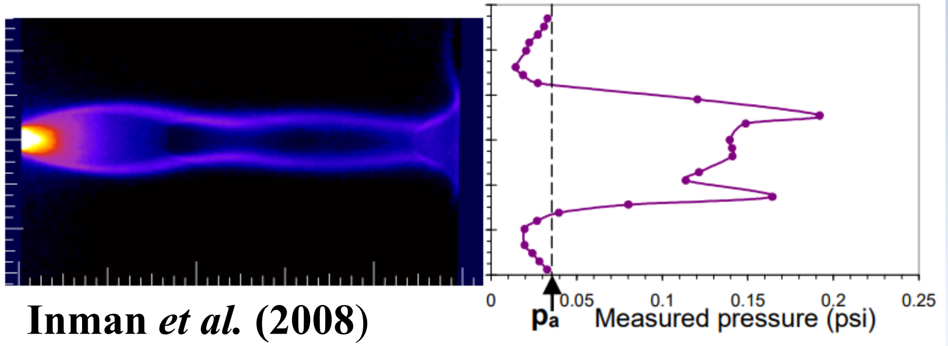
(b)

(c)



PSI crater view from Rubio *et al.* (2023)

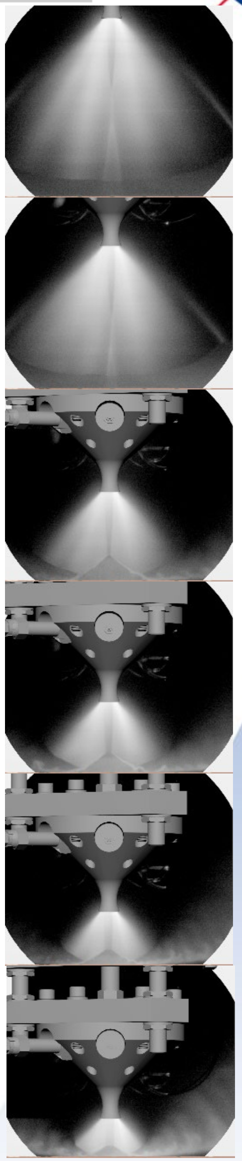
- Impingement pressure structure apparent (but not fully resolved)
  - Double peaks and low-pressure suction region
    - Similar to Inman *et al.* pressure measurements
  - May explain annular crater behavior



Inman *et al.* (2008)

Test Summary and Data Analysis Plans

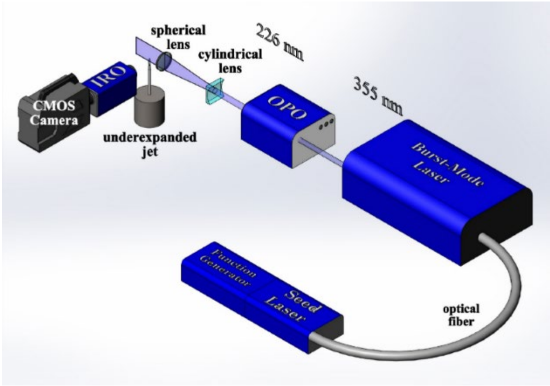
- Planar laser-induced fluorescence applied for first time at NASA Marshall historic East Test Area
    - Plume-surface interaction studied within a 20-ft vacuum chamber
- Very difficult to perform flow visualization at near-lunar vacuum chamber conditions (10^{-3} to 10^{-1} Pa)
    - NO-PLIF measurement technique performed quite well
- PLIF flow visualization can provide corroborative evidence to trends observed for tests with regolith performed in 15-ft vacuum chamber and impingement pressure measurements
- Distinct flow regimes observed over the test matrix (beyond scope of current presentation)
    - Detailed data analysis continues with focus on reporting plume physics within such environments
- Stay tuned for upcoming conference and journal articles
    - SciTech 2024:
        - *"Flow visualization comparisons between intrusive and non-intrusive experimental configurations for plume-surface interactions at lunar- and Martian-relevant conditions"*
            - *O.K. Tyrrell, N.S. Rodrigues, A.M. Korzun, P.M. Danehy*

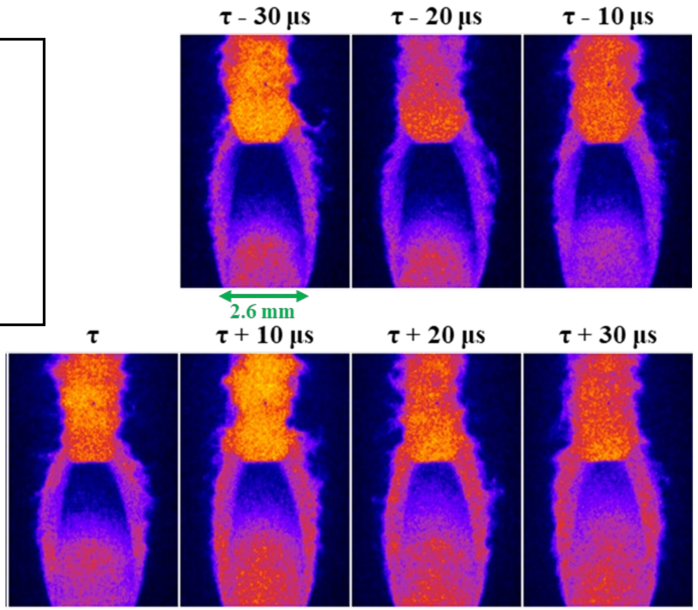


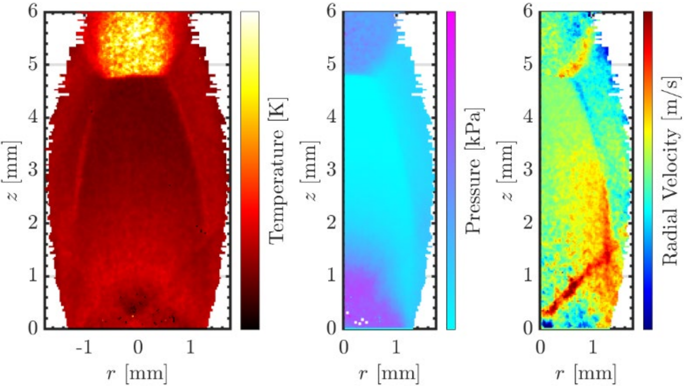
Near-lunar, High-Flow

High-Speed PLIF Capability

- **High-speed PLIF measurements of lab-scale underexpanded jet**
  - Flow visualization: 10 kHz – 1 MHz
  - Simultaneous multi-parameter: 1C/2C PLIF velocity and temperature averaged over 1 ms
  - 1C/2C PLIF velocimetry: 10 kHz – 1 MHz

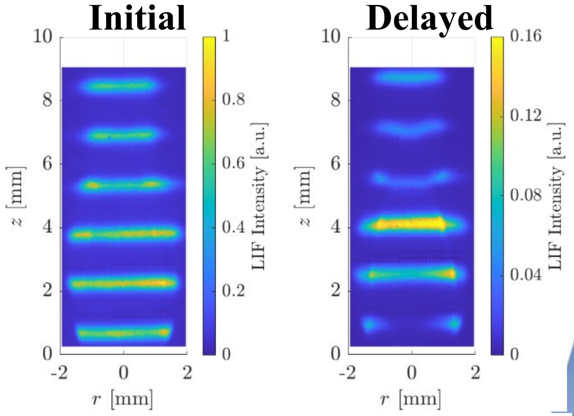


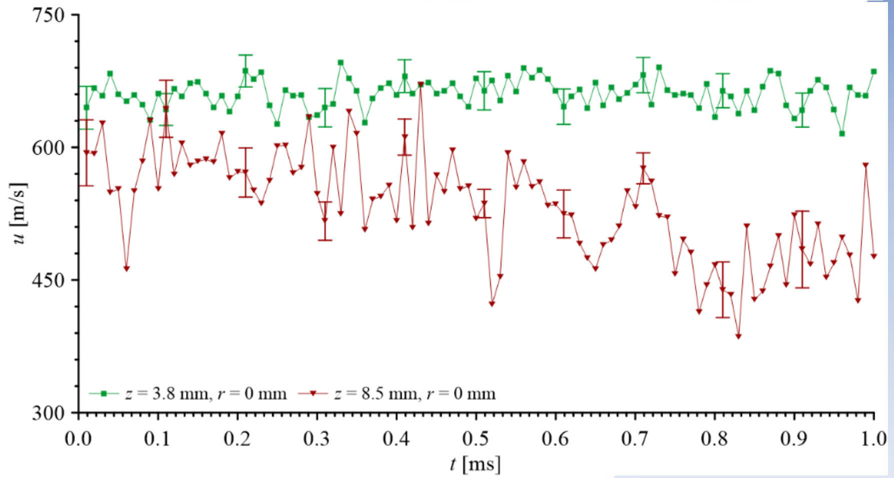




Top: NO-PLIF flow visualization at 100 kHz repetition-rate
Left: Simultaneous multiparameter maps of T, P, and v

From SciTech 2023
(Rodrigues, Danehy, Jiang, Hsu, Leicht, Roy)

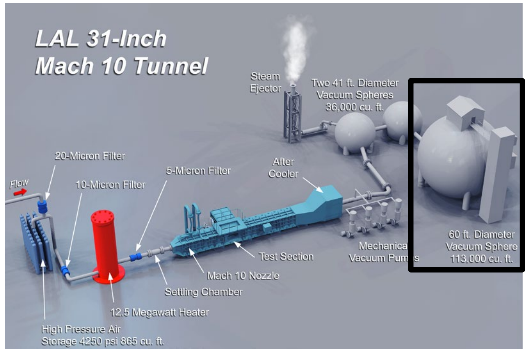


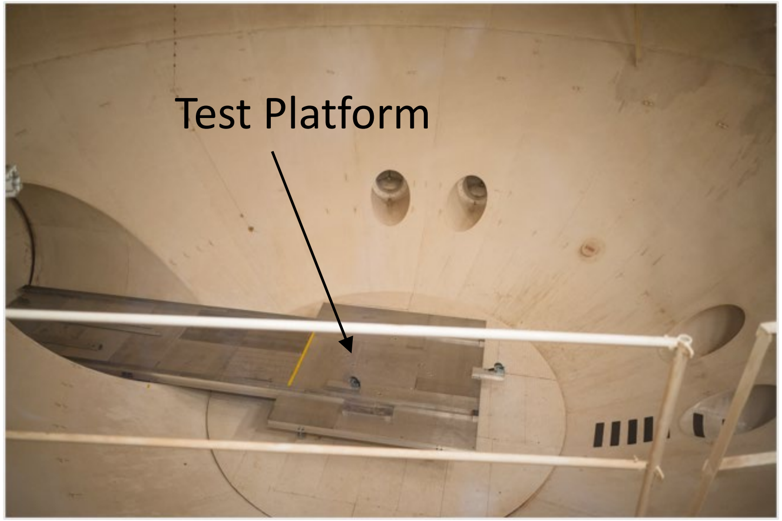


Top: Visualization of multi-line PLIF molecular tagging velocimetry
Bottom: time series of velocity at 100 kHz at jet centerline

From Journal article submission to *Applied Optics* in October 2023
(Rodrigues, Jiang, Hsu, Roy, Danehy)

Upcoming PSI Flow Visualization at NASA Langley

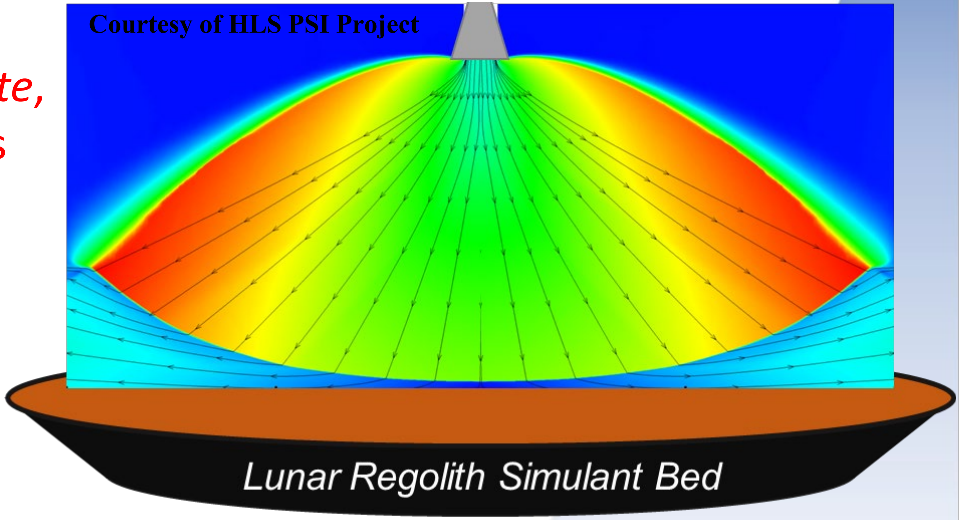




- NASA Langley 60-ft Vacuum Sphere:
  - 100 Pa (0.75 Torr)
- Multiphase flow:
  - Regolith simulants
- Inert Gas Test:
  - Non-reacting ethane
- Hot-fire Test:
  - Hybrid (solid-fuel, gaseous oxidizer) rocket motor

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

- Ethane Plume:
  - Laser Rayleigh Scattering
- Hybrid Rocket Plume:
  - OH Planar Laser-induced Fluorescence

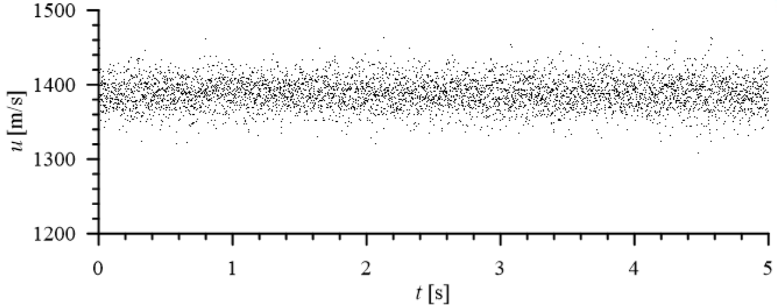

Courtesy of HLS PSI Project

- Future (currently unplanned) PSI flow visualization efforts may focus on plume impingement on flat or curved surfaces
  - Applying high-speed, multi-parameter measurements such as PLIF with pulse-burst laser desirable

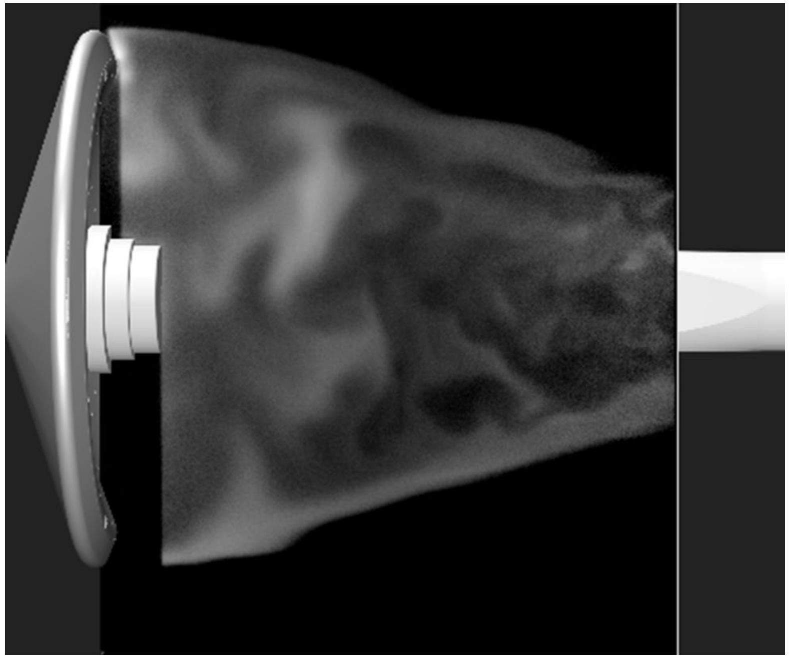
Upcoming at SciTech 2024

- Hypersonic Wakeflow Measurements at Mach 10:
  - “FLEET and PLIF velocimetry within a Mach 10 hypersonic air flow”
    - N.S. Rodrigues, O.K. Tyrrell, B.R. Hollis, P.M. Danehy

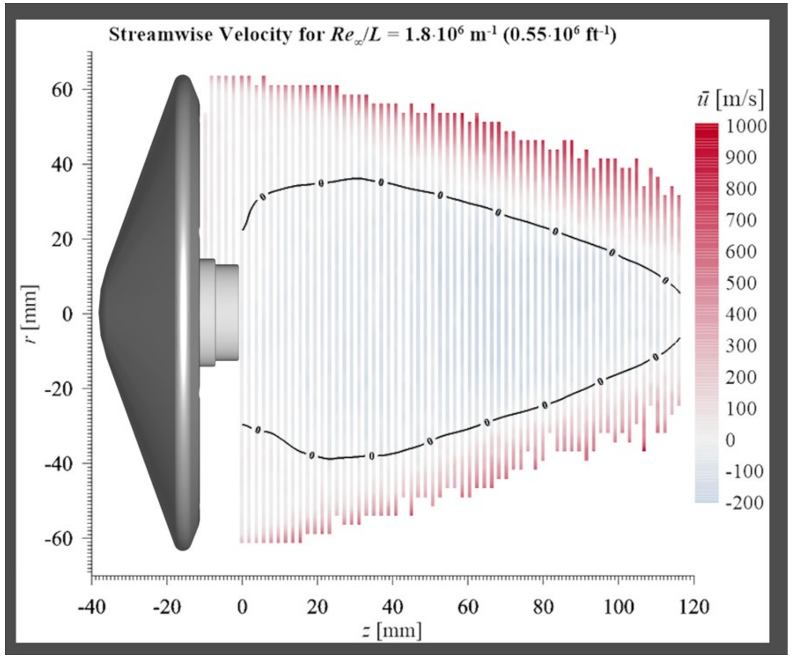
- Measurements made in wake of blunt body HIAD wind tunnel model
  - Same tools could also be applied to wakes of slender models



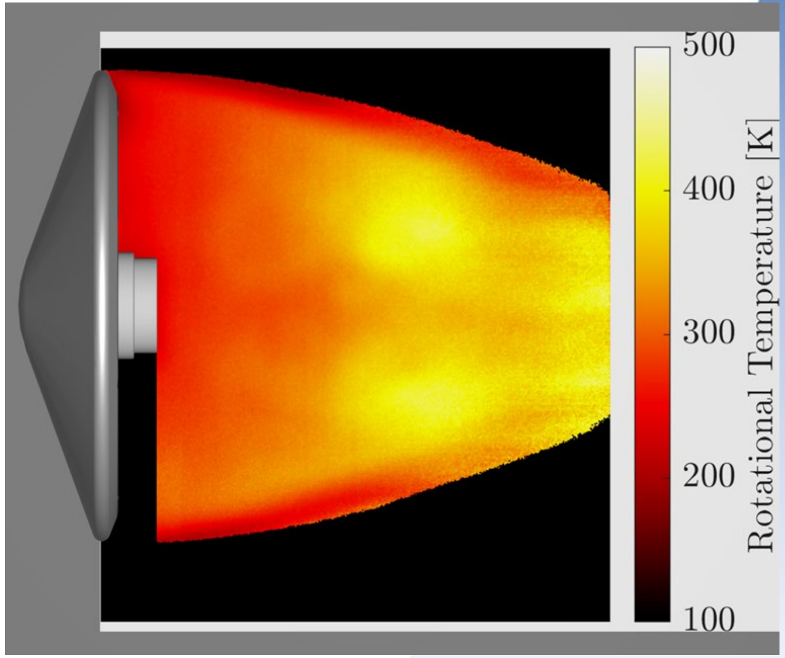
1 kHz Freestream Velocity using FLEET



Instantaneous Flow Visualization



Average Streamwise Velocity



Average Rotational Temperature