



Flow visualization for Plume-Surface Interaction at Martian-relevant Lander Environments

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Acknowledgements



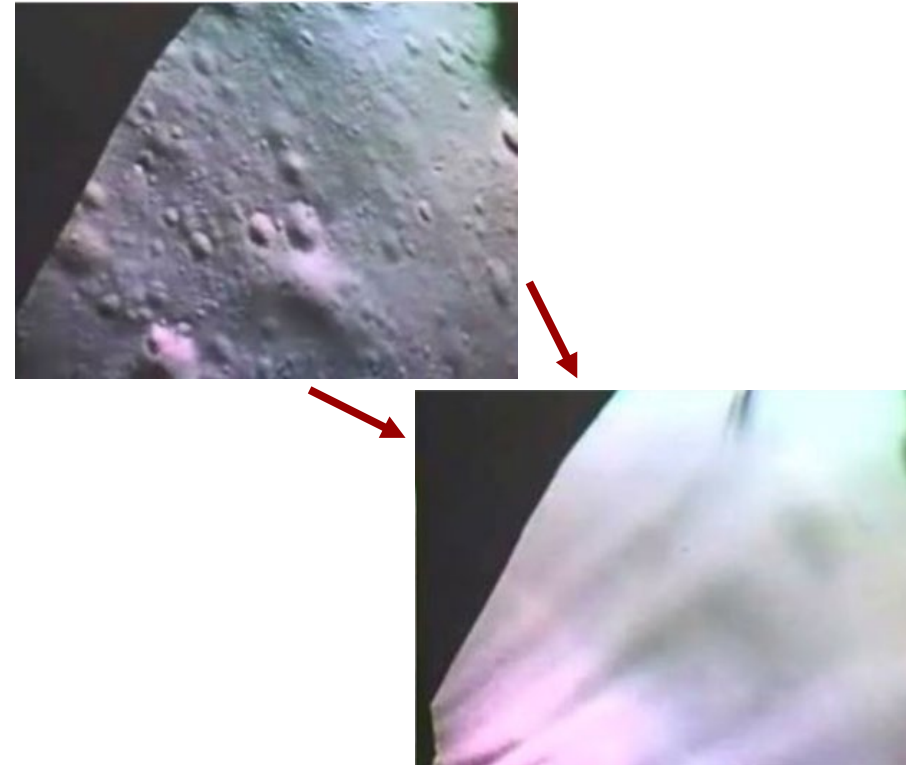
- **Ground test conducted under support of *Plume Surface Interaction* project, previously funded by the NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program**
- **Conference Travel support from FY24 Langley Transformation Initiative (LTI) Knowledge Growth Initiative (KGO) is gratefully acknowledged**
- **NASA Marshall: S. Harris, Dr. M. Mehta, Dr. J. West, Dr. A. Weaver, T. Shurtz, T. Liu, T. Reynolds, Dr. J. Sisco, K. Miasek, K. Thompson, and the entire staff of ET-10 involved with this work**
- **NASA Langley: H. Ripley, Dr. T. Fahringer, Dr. S. Rubio (NSTGRO Fellow, Johns Hopkins University)**

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 planetary surface)



- **Scarcity of experimental data to validate high-fidelity models:**

- Realistic environments: plumes within reduced ambient pressures (continuum to rarefied scales)

- **Lunar: Apollo landings → Artemis Human Landing Systems (HLS)**

- Lunar-relevant data acquired during recent *Physics Focused Ground Tests* at NASA Marshall (2021-2022)

Background

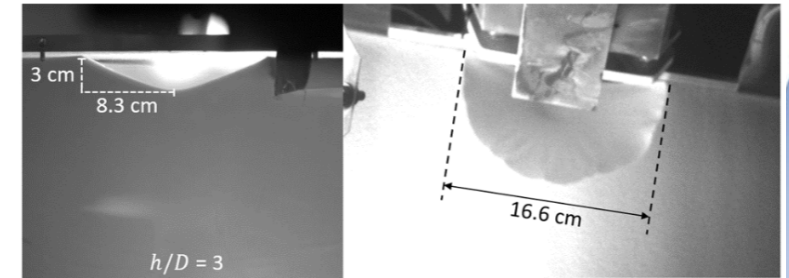
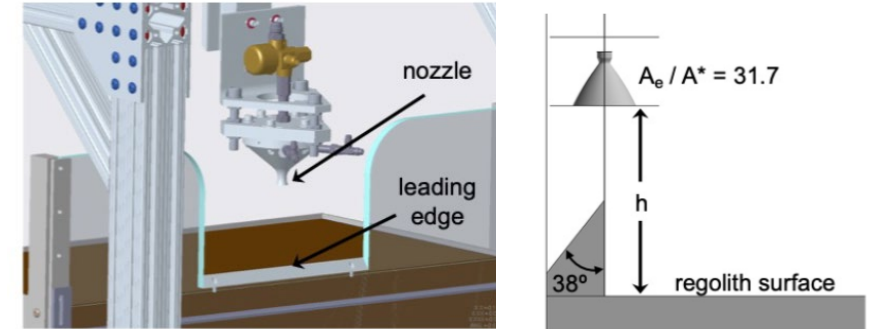
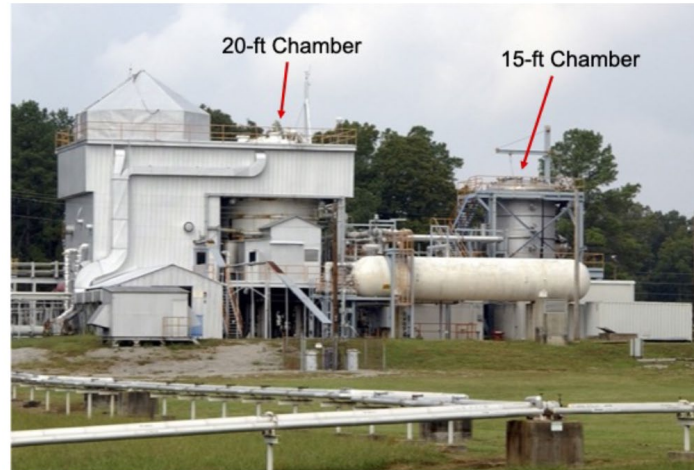


- NASA Space Technology Mission Directorate (STMD) funded two ground tests within large-scale vacuum chambers at NASA Marshall Space Flight Center

- 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



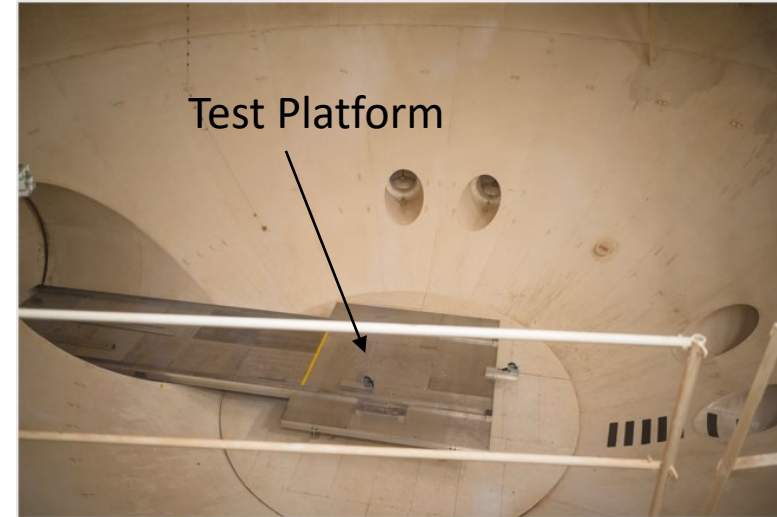
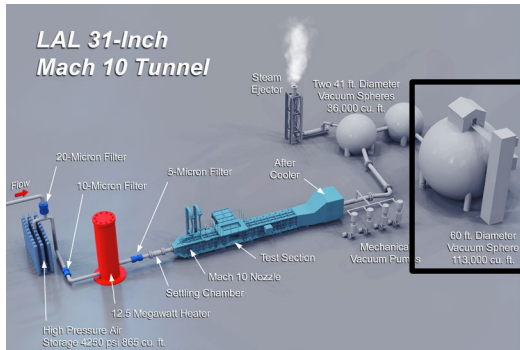
- **20-ft Vacuum Chamber:**

- Full-plane and half-plane flat impingement plate:
 - PLIF flow visualization
 - Impingement pressure

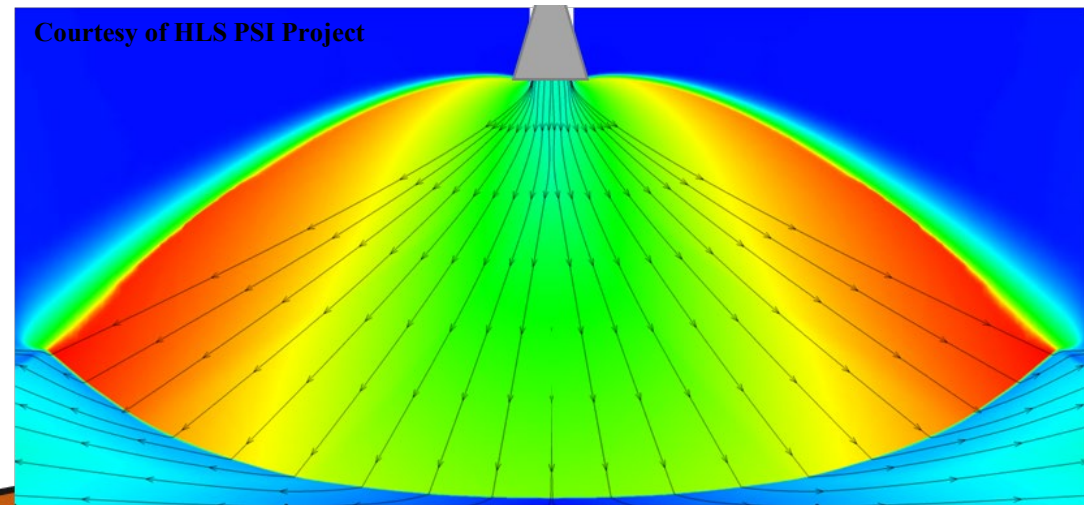
References

- Korzun *et al.*, Design of a subscale, inert gas test for plume-surface interactions in a reduced pressure environment, in 2022 AIAA SciTech Forum.
- Eberhart *et al.*, Overview of plume-surface interaction data from subscale inert gas testing at NASA MSFC Test Stand 300 vacuum facilities, in 2022 AIAA SciTech Forum.
- Rubio *et al.*, Plume-surface interaction Physics Focused Ground Test 1: setup and preliminary results, in 2022 AIAA SciTech Forum.
- Diaz-Lopez *et al.*, Plume-surface interaction Physics Focused Ground Test 1: diagnostics and preliminary results, in 2022 AIAA SciTech Forum.
- Rodrigues *et al.*, Flow visualization for plume-surface interaction testing within large-scale vacuum environments at conditions relevant to lunar and Martian landers, in 2023 JANNAF Conference.
- Tyrrell *et al.*, Flow visualization of intrusive and non-intrusive configurations for lunar-and Martian-relevant plume-surface interaction, in 2024 AIAA SciTech Forum.

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



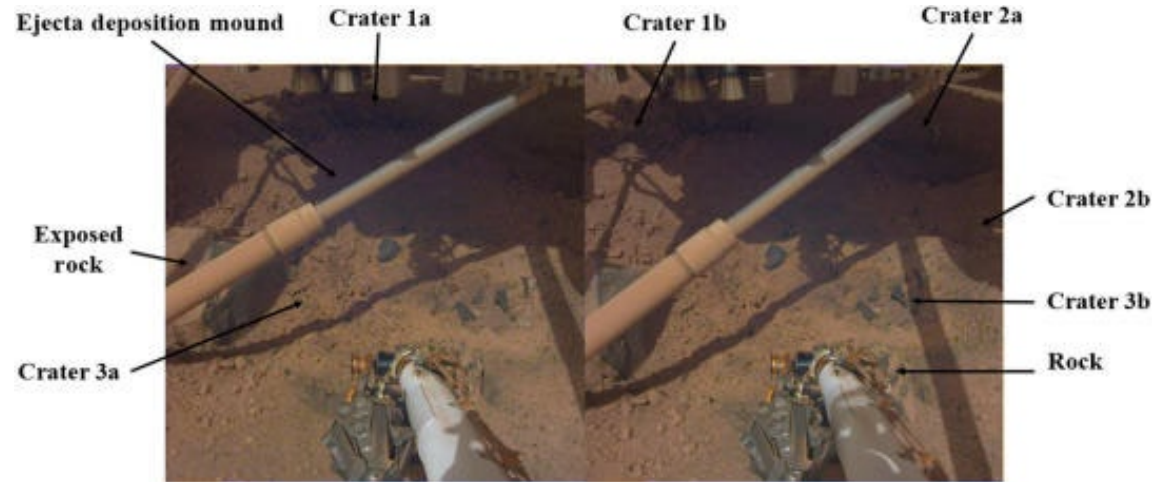
Upcoming ground tests, funded by NASA
Exploration Systems Development Mission Directorate,
designed to reduce PSI risks for HLS program landers

Lunar Regolith Simulant Bed

Martian Plume-Surface Interaction



- PSI behavior also important for Martian landings (even with a parachute)



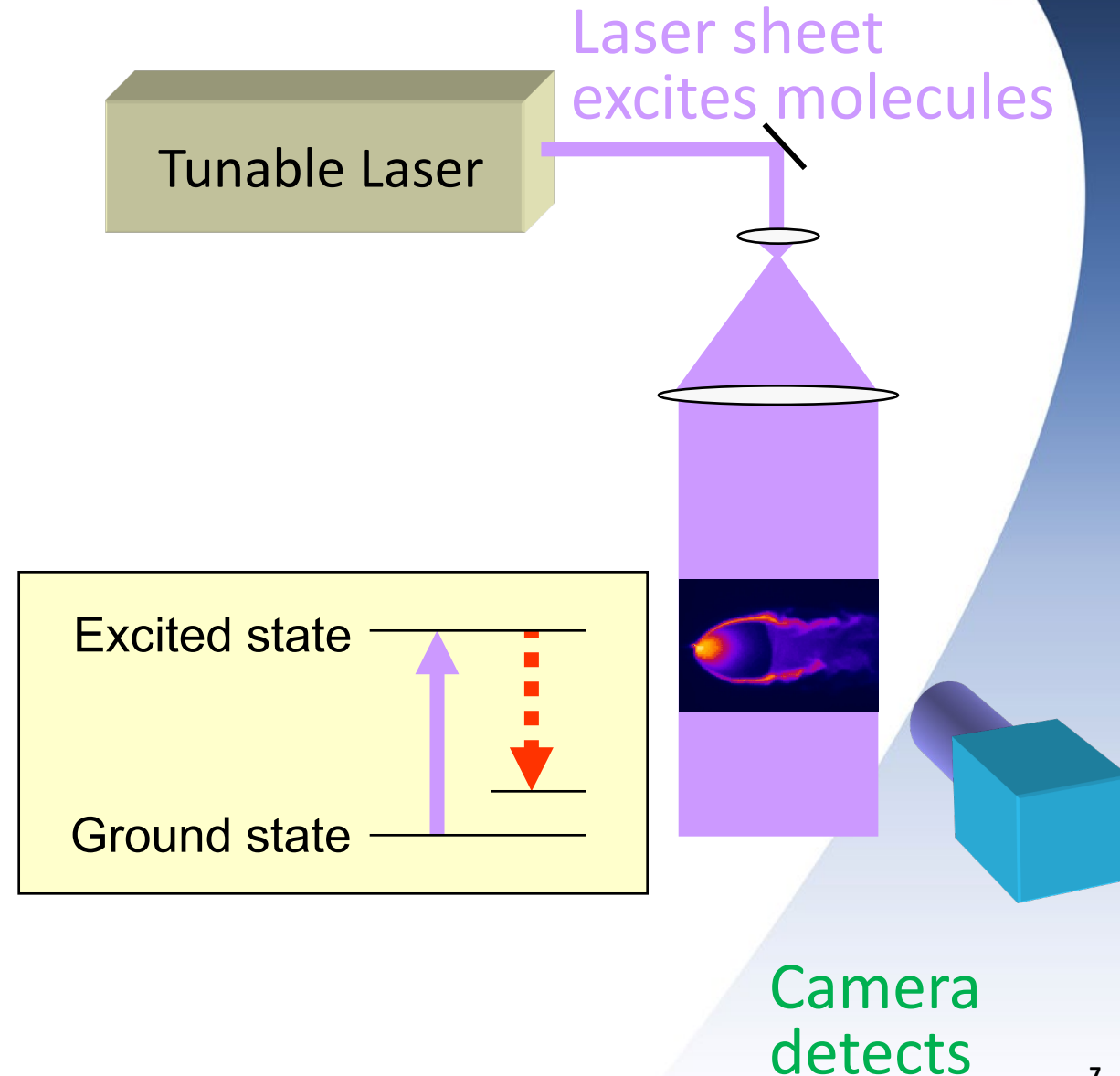
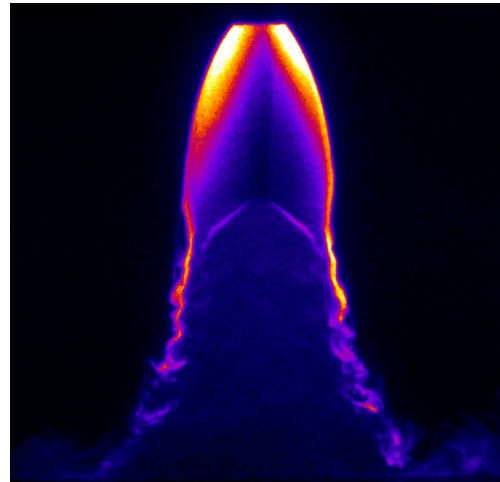
Manginelli *et al.* (2021)

- Scarcity of experimental data to validate high-fidelity models: multi-phase, multi-scale (turbulence modeling)
 - Realistic environments: plumes within reduced ambient pressures (continuum to rarefied scales)
- Martian-relevant environments can also leverage data from Space Shuttle *Return to Flight* efforts
 - 2022 AIAA SciTech Paper (Shurtz and West)
 - 46th AIAA Aerospace Sciences Meeting (Inman, Danehy, Nowak, Alderfer; 2008)
- STMD Physics Focused Ground Test had dedicated runs for Martian-relevant conditions

Planar Laser-induced Fluorescence



- Planar laser-induced fluorescence (PLIF) is a 2D, temporally 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 μ s
- PLIF for PSI test used seeded nitric oxide gas ($< 1\%$)
 - Well suited for low-pressure environments
 - More so than schlieren and shadowgraph
- To the first order, PLIF signal scales with gas density
- Signal intensity is qualitative
- Location of flow structures (e.g., shocks) is quantitative



2022 STMD PSI Test in 20-ft Vacuum Chamber

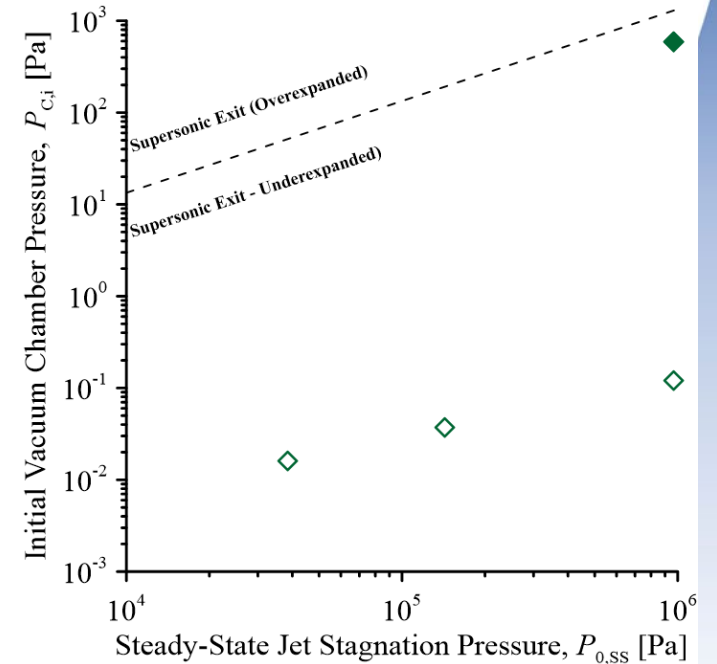
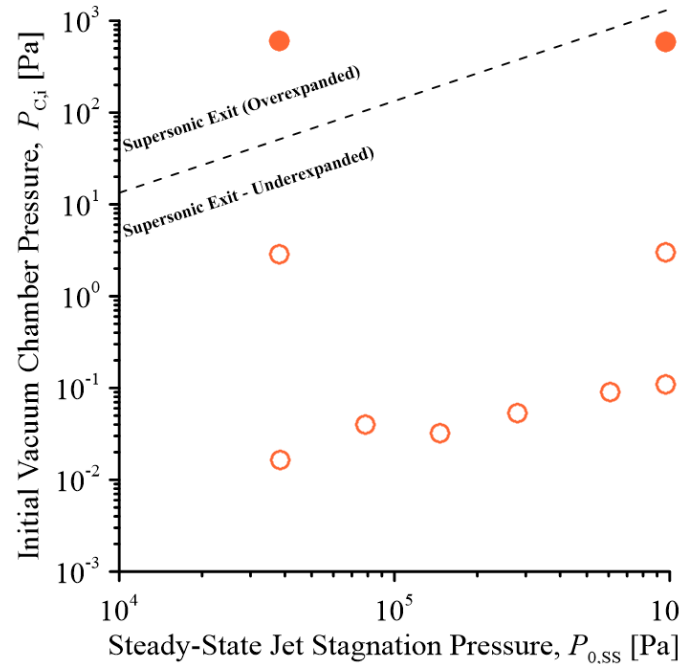


- Select test conditions focus on plume impingement at Martian-relevant conditions

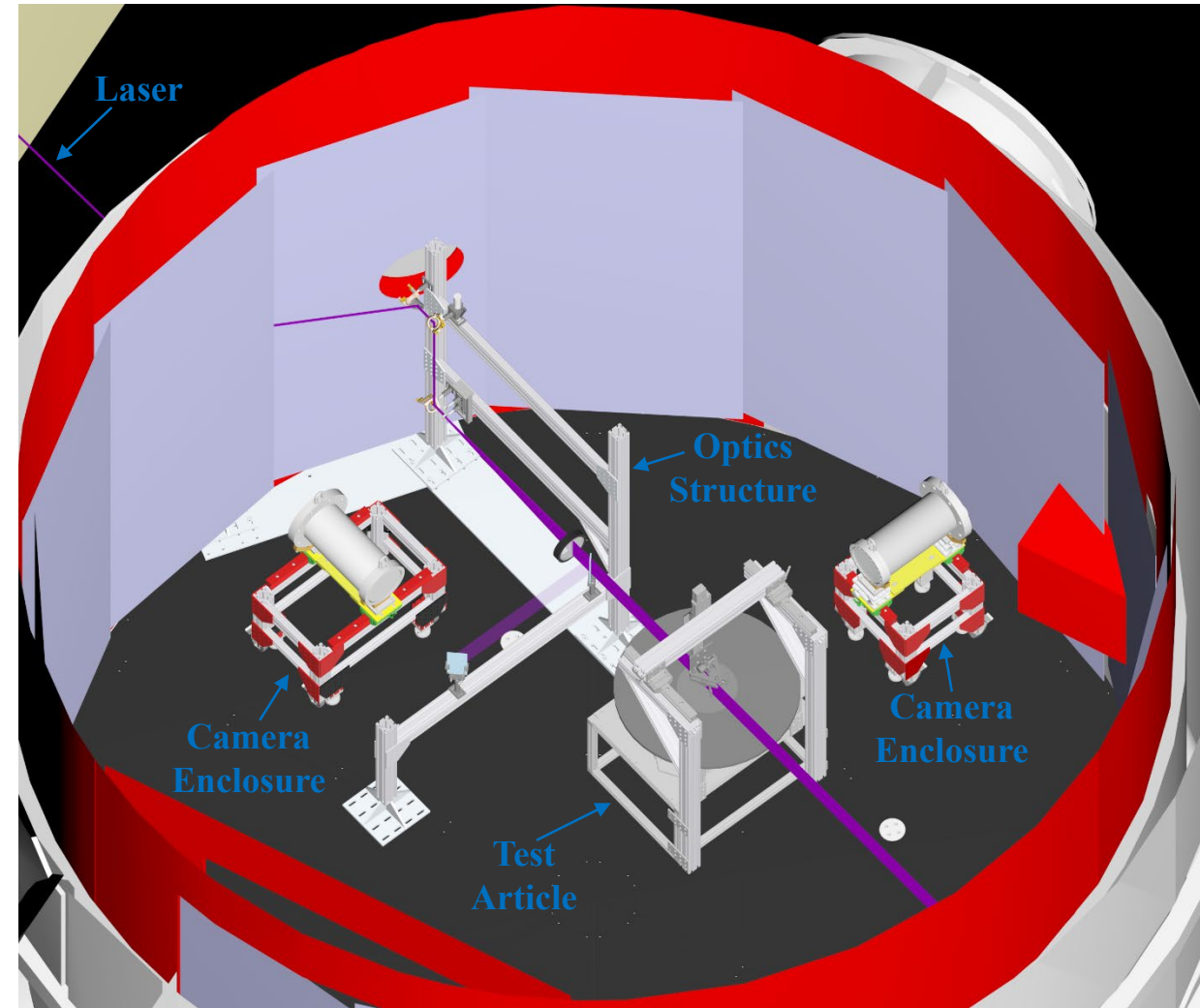
\dot{m}_{SS} [g/s]	$P_{0,SS}$ [Pa]	$P_{C,i}$	
		$10^{-3} - 10$ [Pa]	$590 - 610$ [Pa]
0.32	$3.8 \cdot 10^4$	$h/D_e = 10, 8, 5, 4, 3, 2$	$h/D_e = 10, 3$
0.65	$7.9 \cdot 10^4$	$h/D_e = 3, 10$	
1.2	$1.5 \cdot 10^5$	$h/D_e = 10, 8, 5, 4, 3, 2$	
2.4	$2.8 \cdot 10^5$	$h/D_e = 3, 10$	
5.1	$6.1 \cdot 10^5$	$h/D_e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

\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_e , $P_{0,SS}$ and $P_{C,i}$
- Two different vacuum chamber pressures:
 - Near-lunar: $10^{-3} < P_{C,i} < 10$ Pa
 - Martian-relevant: $590 < P_{C,i} < 610$ Pa
- This presentation focuses on *Martian-relevant* test conditions
 - Underexpanded: $h/D_e = 10, 8, 5, 4, 3, 2$
 - Overexpanded: $h/D_e = 10, 3$



20-ft Vacuum Chamber Overview

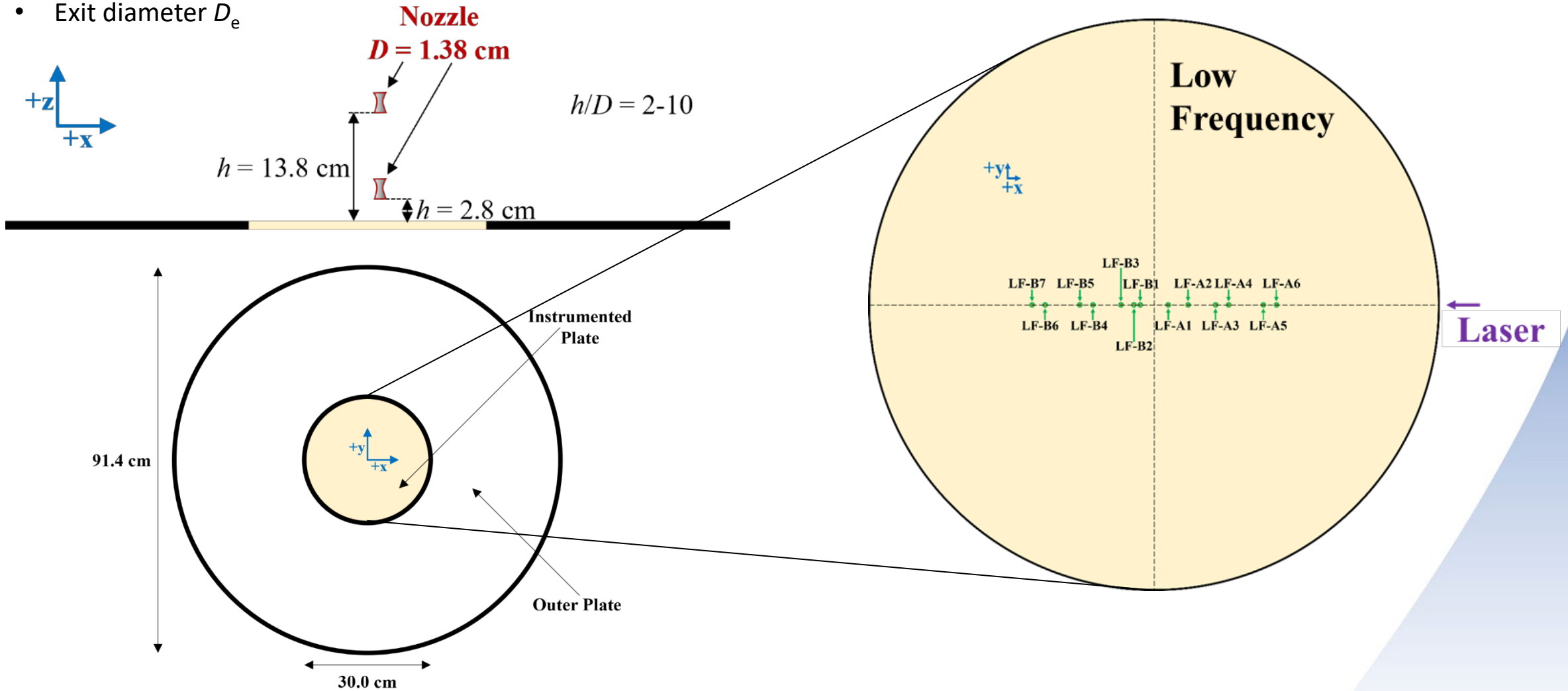


- Jet nozzle assembly and impingement plate test article
 - Located near middle of chamber
- Heated inert gas (nitrogen) plume
 - Premixed with nitric oxide for PLIF visualization
- UV laser (near 226 nm) brought into vacuum chamber through viewport window
- Optics for PLIF laser sheet placed on custom structure
- PLIF cameras located within custom camera enclosures
- Low-frequency (100 Hz) pressure instrumentation located outside vacuum chamber
 - Connected using plastic *sense tubes*
 - Order of seconds time response

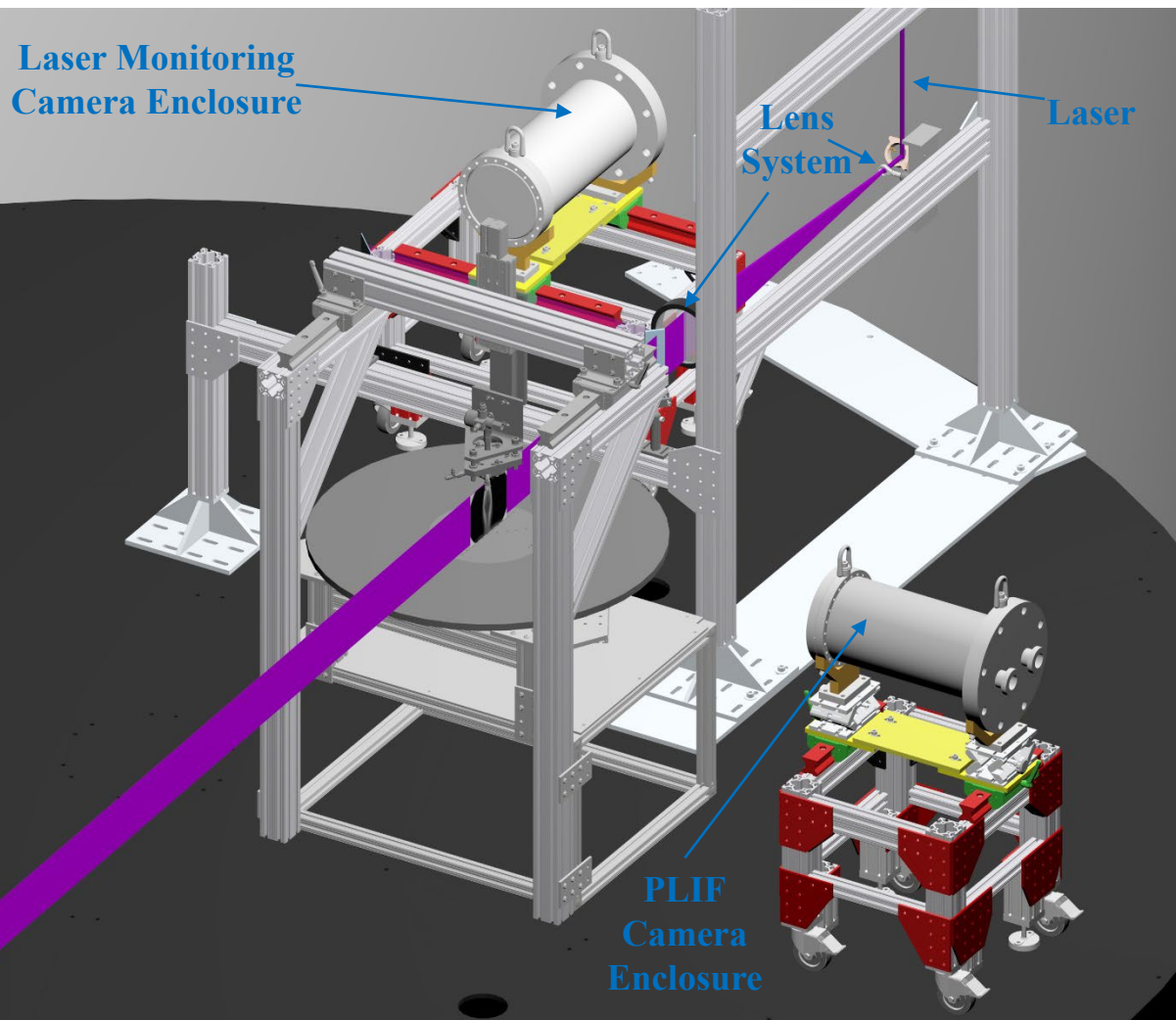
Test Article Overview

- **Mach 5.3 supersonic nozzle:**

- Exit diameter D_e



10 Hz PLIF Systems

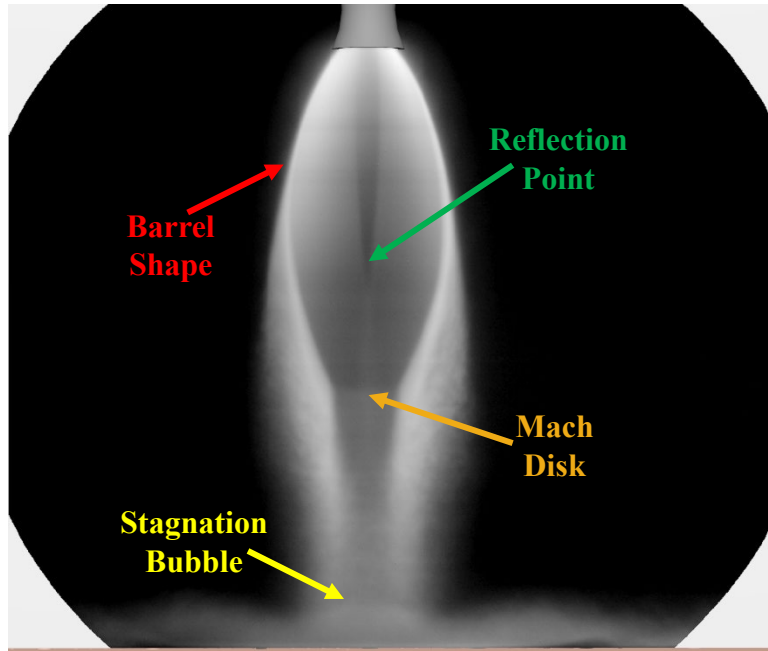


- 226-nm laser: Sirah[®] Cobra-Stretch Dye laser with sum-frequency-mixing wavelength extension, pumped by Spectra-Physics[®] Pro-230
 - Laser beam alignment adjusted using remote-controlled mirrors
- PLIF laser sheet expanded to ~140 mm using negative cylindrical lens
 - Height collimated using positive 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

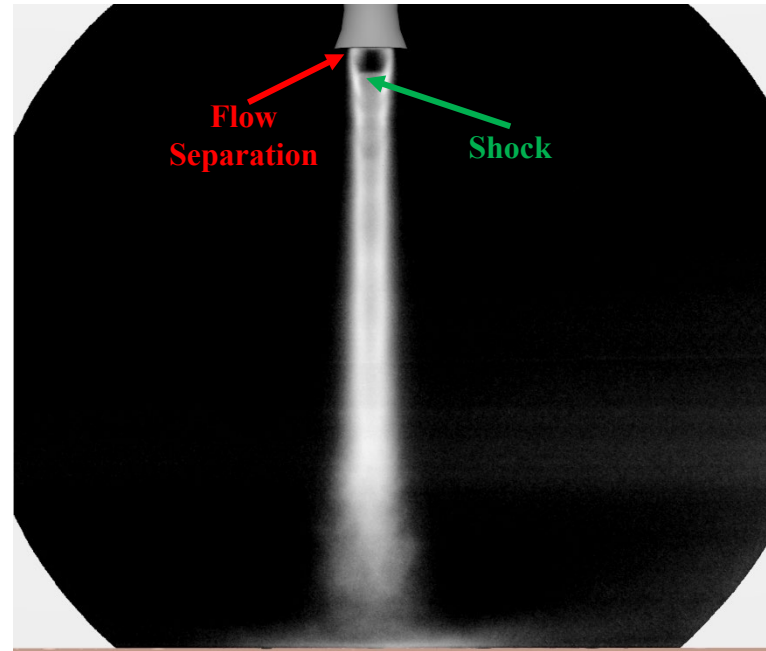
Jet Impingement at $h/D = 10$



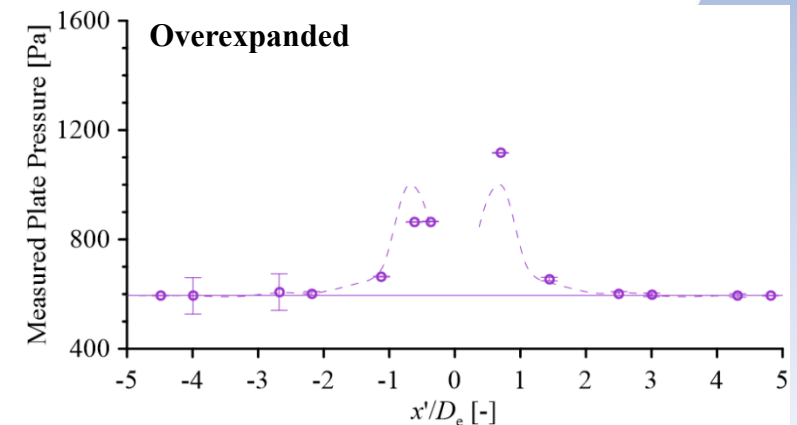
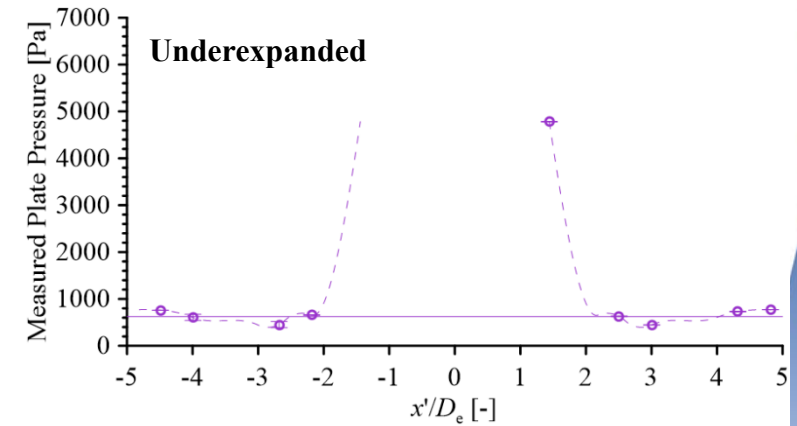
- Very different impingement behavior for underexpanded (higher P_0) and overexpanded (lower P_0) jets



Underexpanded Jet ($P_0 = 9.68 \cdot 10^5$ Pa)



Overexpanded Jet ($P_0 = 3.80 \cdot 10^4$ Pa)



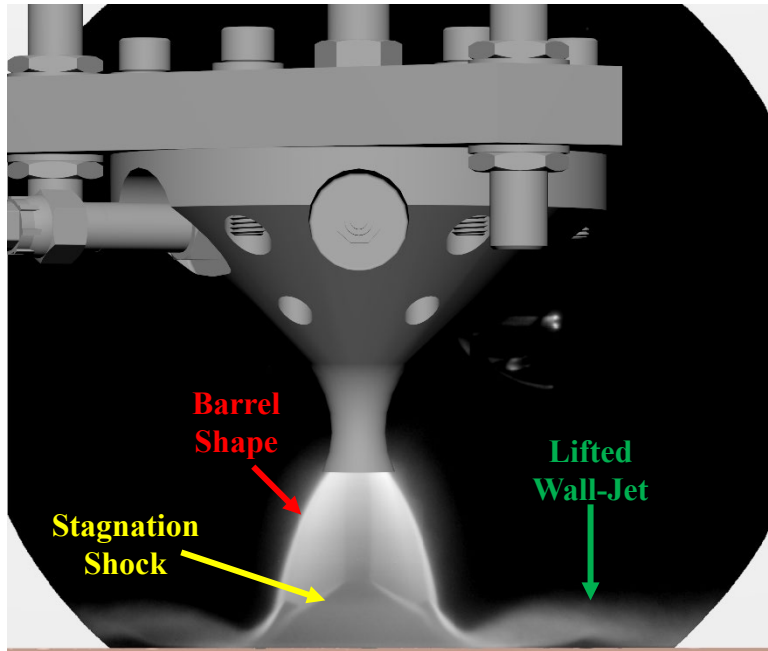
- Underexpanded jet has much larger impingement pressure footprint
 - Overexpanded jet highly collimated
 - Impingement pressure significantly higher for underexpanded jet

- Significantly different cratering behavior expected from 15-ft Chamber Test (outside scope of present work)

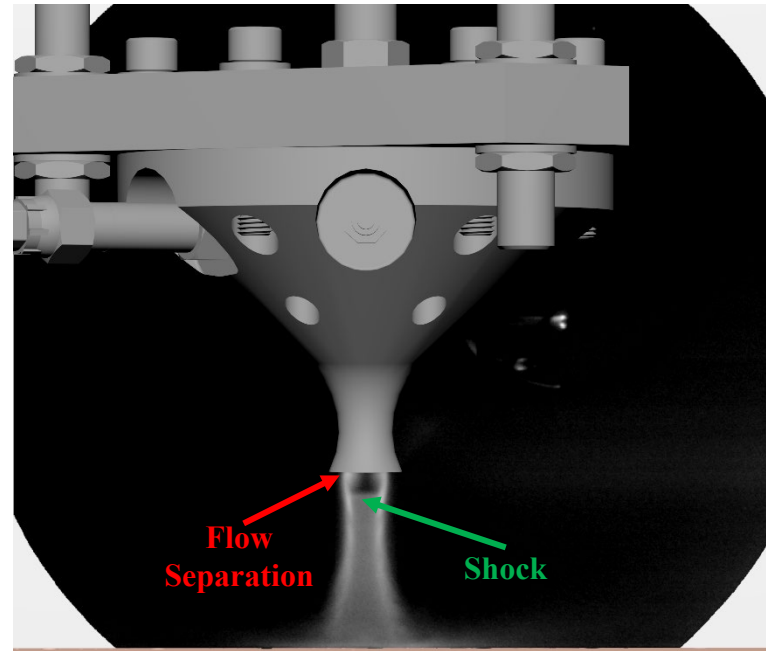
Jet Impingement at $h/D = 3$



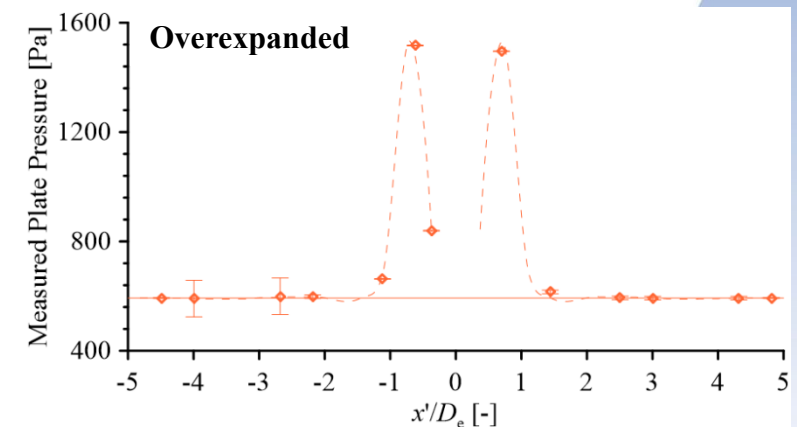
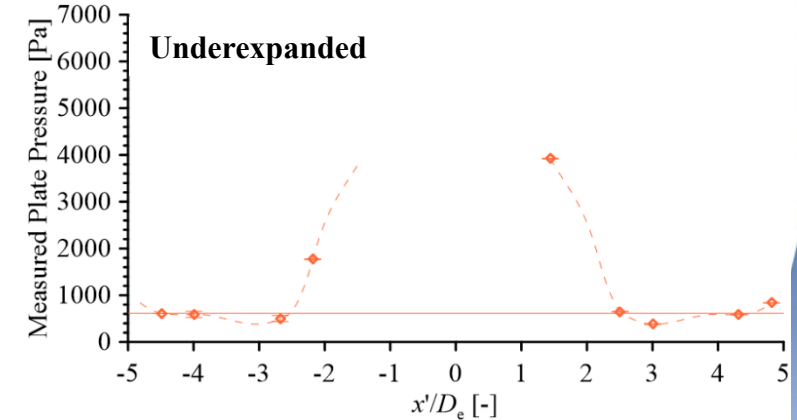
- Very different impingement behavior for underexpanded (higher P_0) and overexpanded (lower P_0) jets



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



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



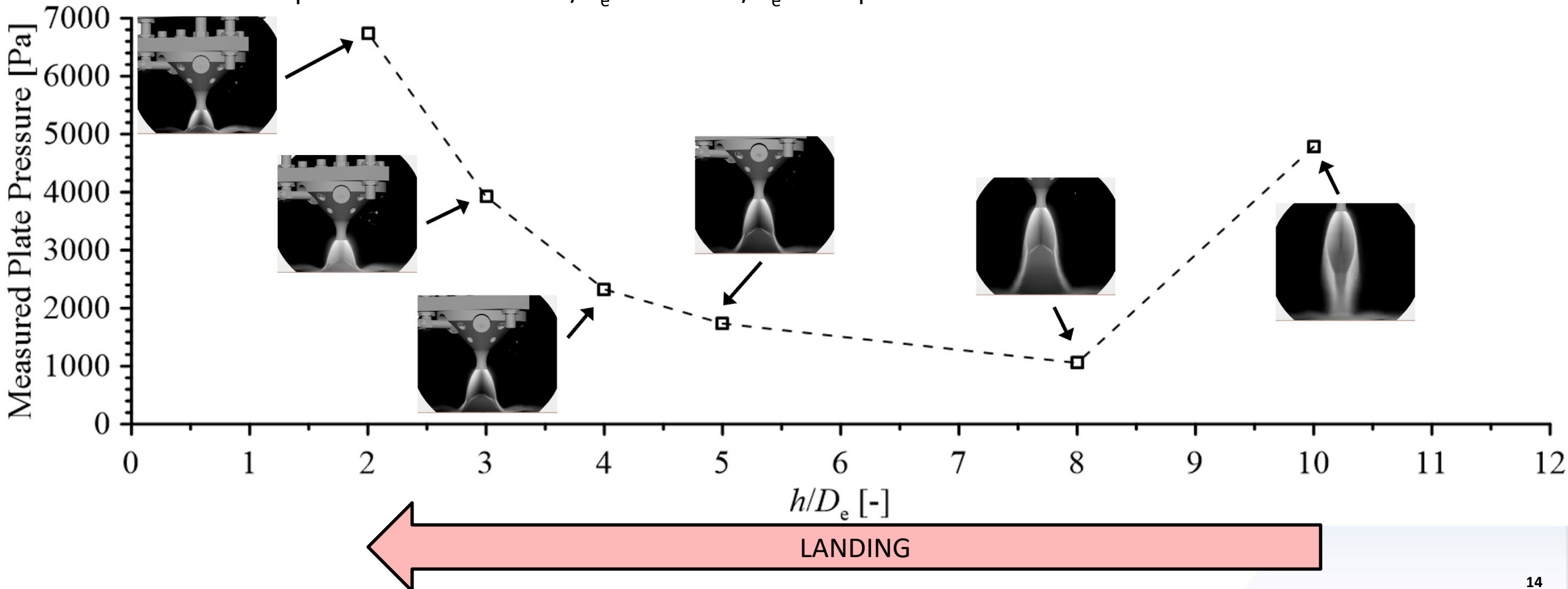
- Underexpanded jet has much larger pressure footprint and magnitude
 - Low-pressure *suction* region apparent for underexpanded jet
 - Double-peak structure resolved for overexpanded jet

- Significantly different cratering behavior expected from 15-ft Chamber Test (outside scope of present work)

Effect of h/D for Underexpanded Jet



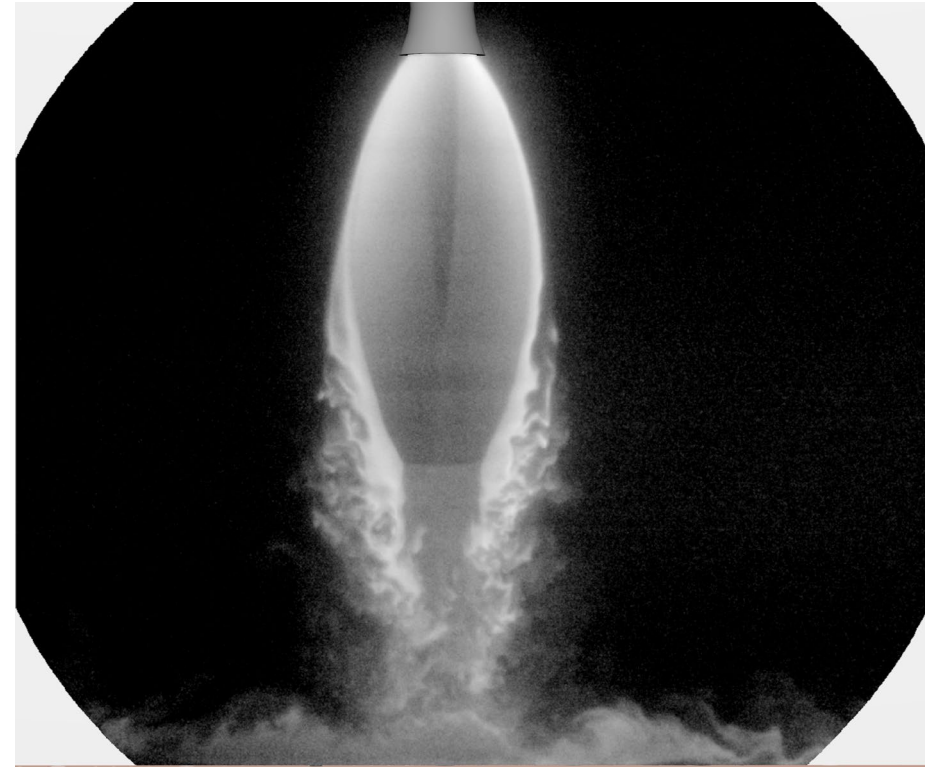
- Non-monotonic behavior observed between impingement pressure and h/D_e
 - Observation also noted in University of Illinois Urbana-Champaign
- PLIF flow visualization brings context to pressure data
 - Normal vs. oblique shock behavior at $h/D_e = 10$ and $h/D_e = 8$ explains observation



Summary and Conclusions



- Many challenges for both initial and sustained presence on Mars
 - Plume-surface Interaction one of these challenges
- Understanding plume is a key part of understanding Martian PSI
- PLIF (planar laser-induced fluorescence) applied for first time at NASA Marshall historic East Test Area 20-ft vacuum chamber
 - Make the invisible plume visible through PLIF
- PLIF flow visualization can provide corroborative evidence for:
 - Erosion and crater behavior (outside current scope)
 - Impingement pressure behavior
- Distinct plume impingement behavior with h/D_e

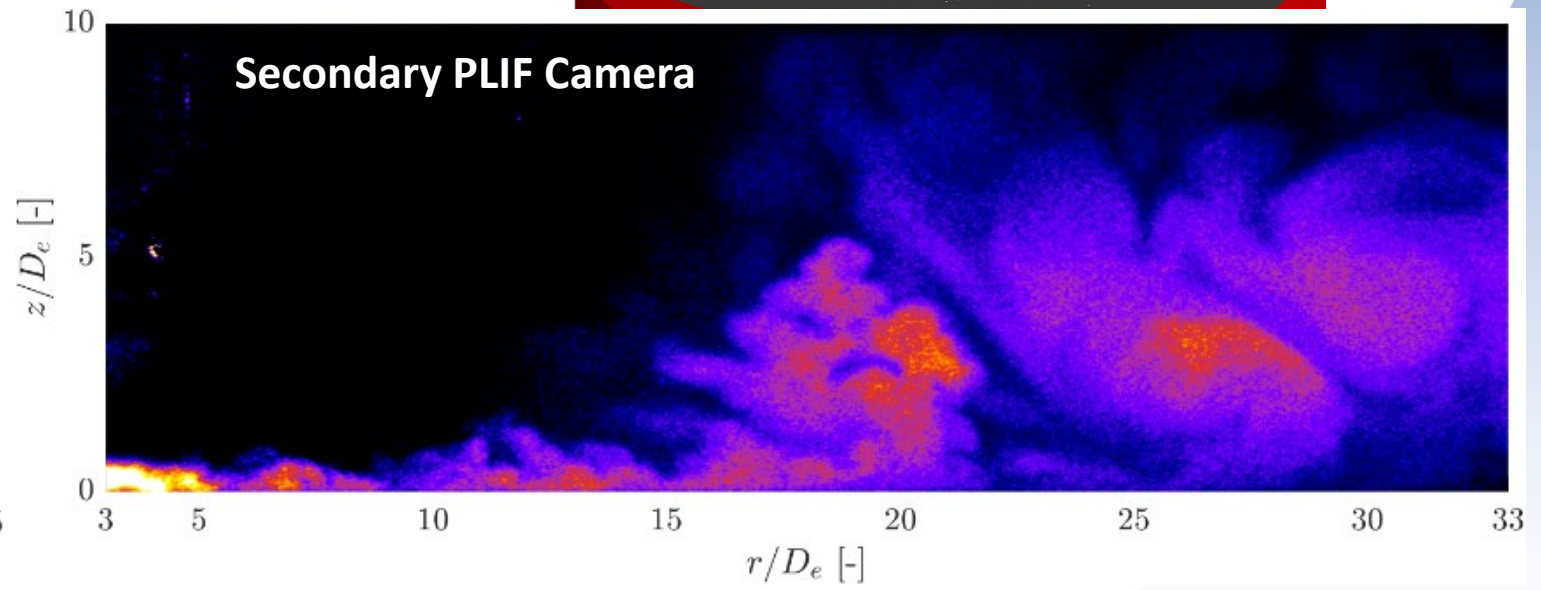
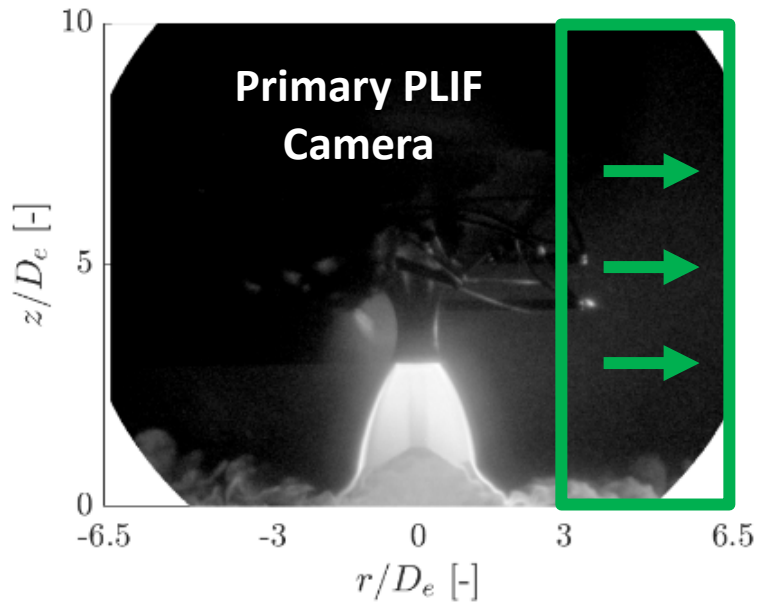
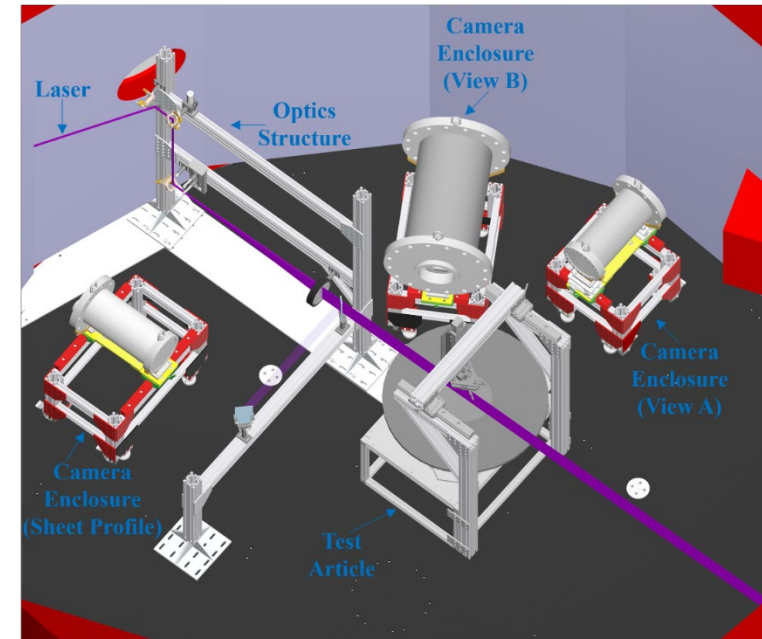


Upcoming at AIAA SciTech 2025



- “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



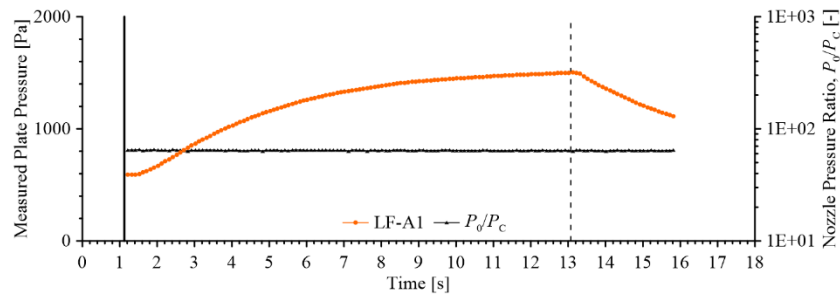
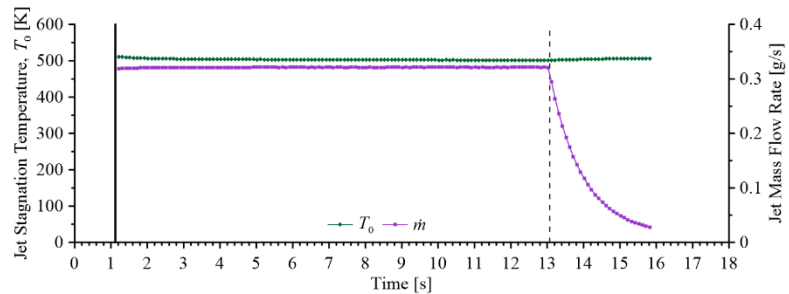
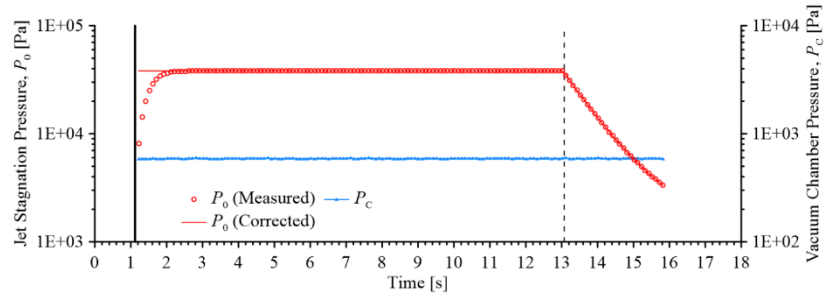
Appendix



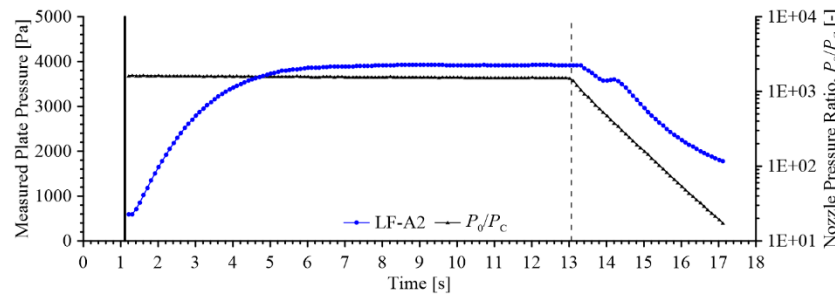
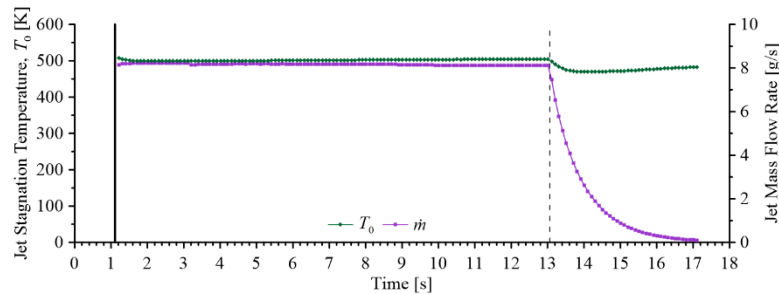
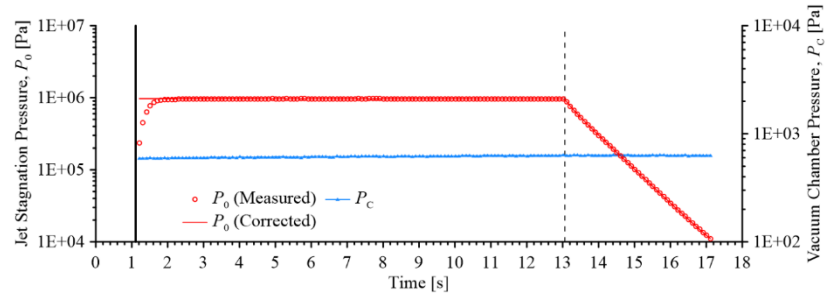
Martian-relevant Vacuum Conditions



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

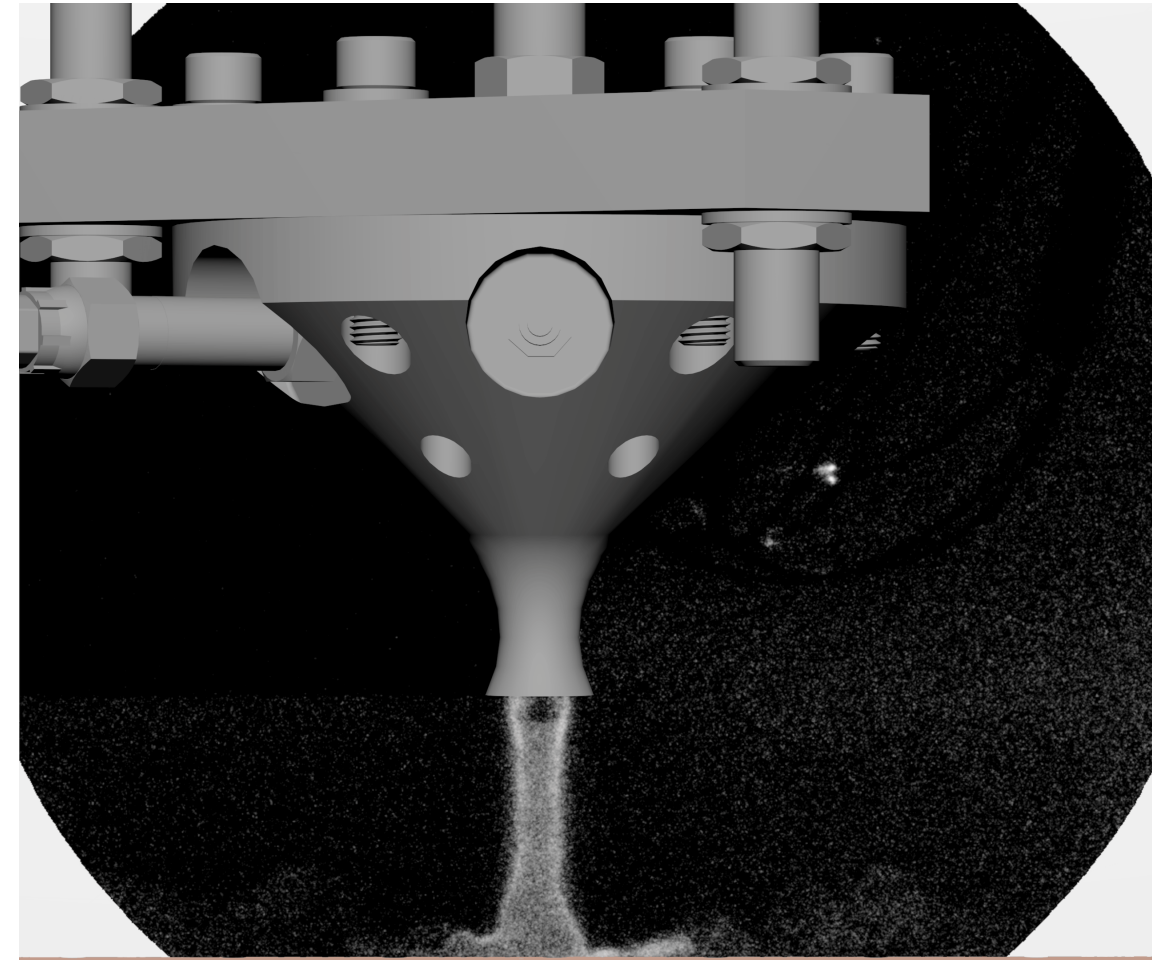


High Flow: $P_{0,SS} = 9.7 \cdot 10^5 \text{ Pa}$ ($\dot{m}_{SS} = 8.2 \text{ g/s}$)

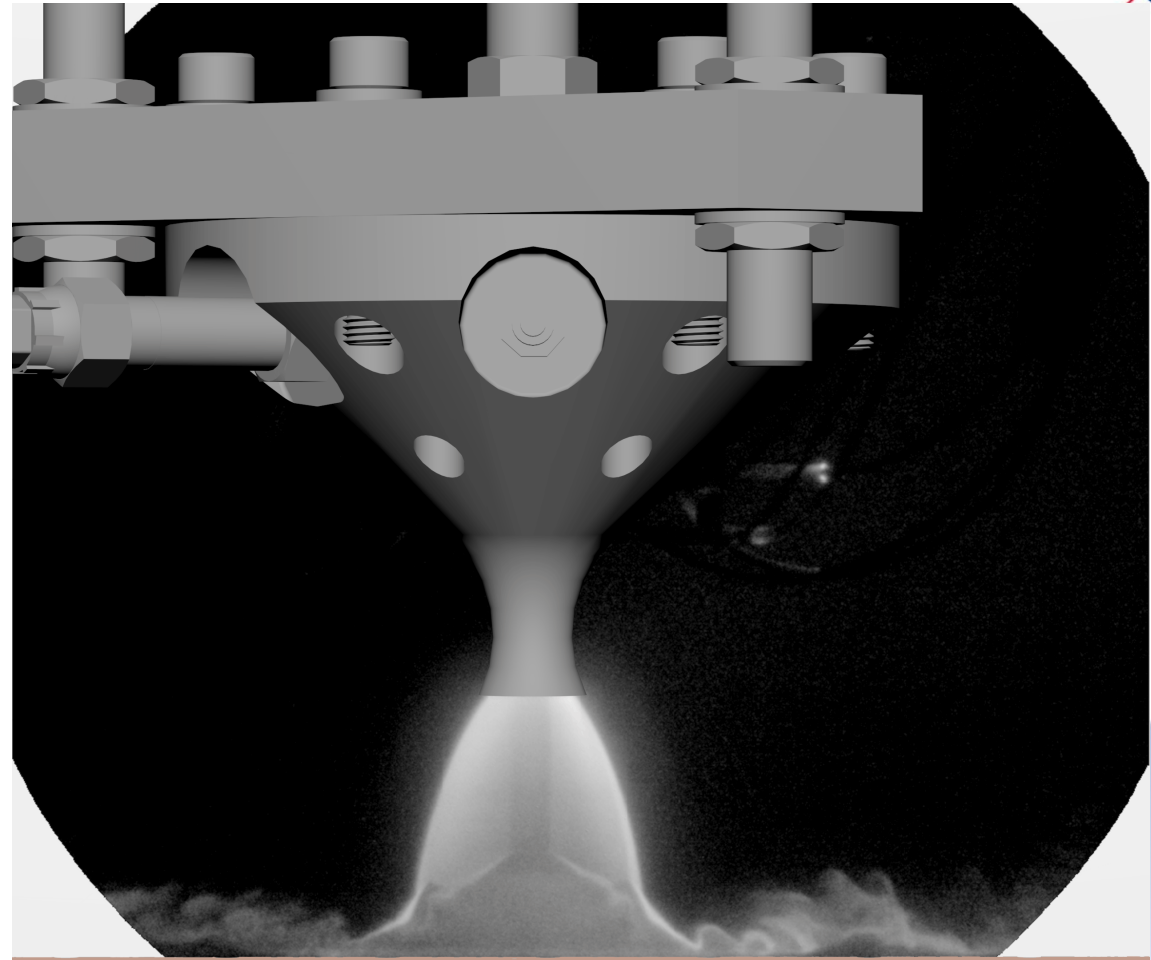


- P_c relatively constant throughout run
- Same P_0 correction applied
- T_0 relatively constant
- \dot{m} relatively constant (using P_0 correction)
- P_0/P_c relatively constant throughout run
- Low-frequency impingement pressure at steady-state used
- LF-A1 saturated at high flow condition; LF-A2 used

Martian-relevant Flow Visualization (log-scale)



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



High Flow: $P_{0,SS} = 9.7 \cdot 10^5$ Pa ($\dot{m}_{SS} = 8.2$ g/s)

Overexpanded nozzle condition, flow separation

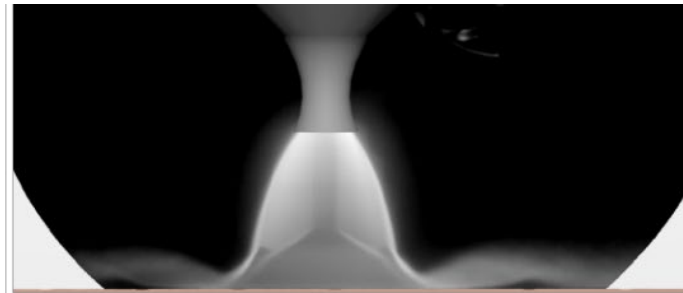
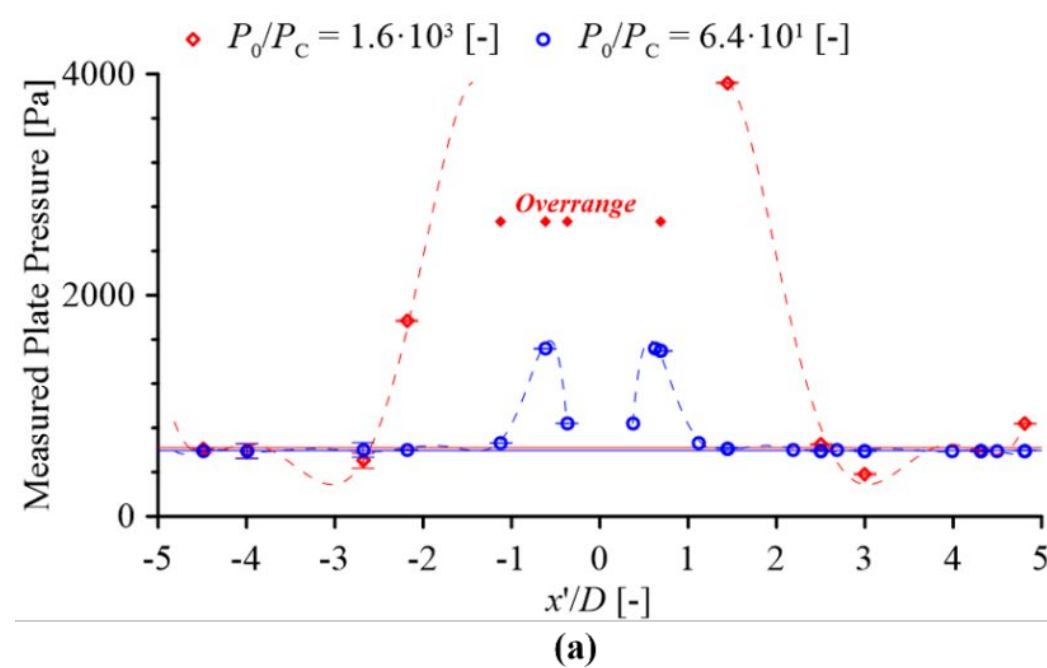
- Lower S/N, laser burn mark on viewport window

Salient features: stagnation shock, wall jet, unsteady flow

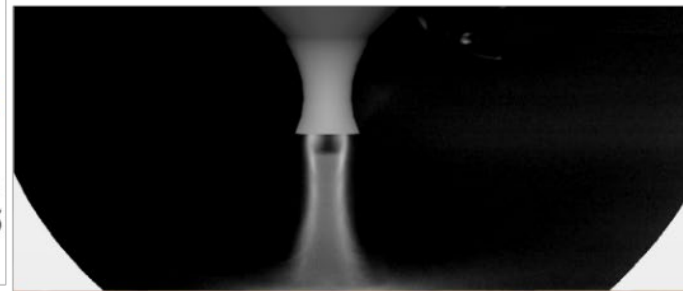
Martian-relevant Impingement Pressure



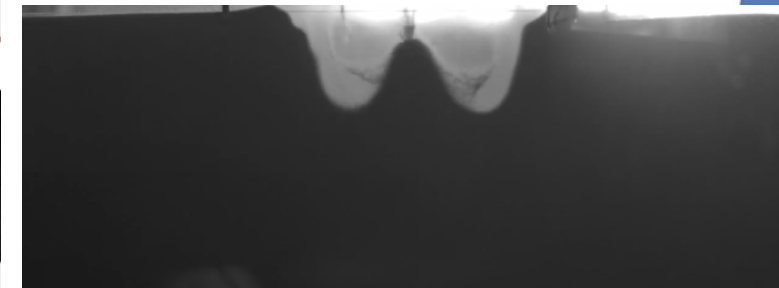
- Steady-state vacuum conditions allow low-frequency pressure measurement to be attributed to a single P_0/P_C



(b)

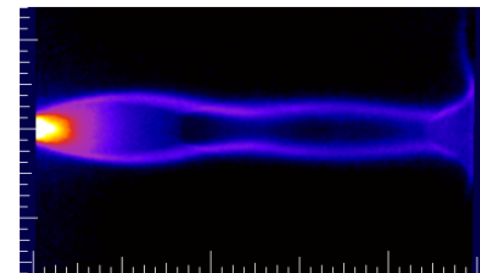


(c)



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)

