Wall-jet evolution during plume-surface interaction using PLIF imaging

Neil S. Rodrigues[1], Ross A. Burns[2], Olivia K. Tyrrell[1], and Paul M. Danehy[1]

[1]NASA Langley Research Center, [2]ViGYAN, Inc.

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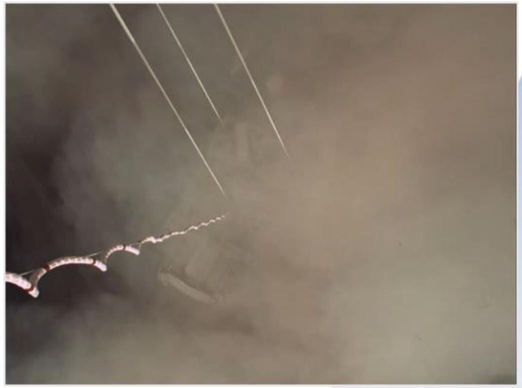
  - J. Sebastian Rubio (Johns Hopkins University)
  - W. Holt Ripley and Dr. Timothy W. Fahringer, Jr. (NASA Langley)

Introduction

- **Rocket Plume-Surface Interaction (PSI):**
  - Induced environment due to impingement of hot rocket exhaust on landing surface
  - Complex flowfield: multi-scale and often multi-phase (unimproved Lunar or Martian surface)
  - Realistic environments: plumes within reduced ambient pressures (continuum to rarefied scales)
- **Driven by risks associated with spacecraft landings on extraterrestrial environments**
- **Scarcity of experimental data to validate high-fidelity models**

Lunar Landings: Apollo program → Artemis missions



Martian: rover landings → human landings

NASA STMD PSI Ground Tests

- **NASA Space Technology Mission Directorate (STMD) funded 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

- **Measurements led by Prof. Rui Ni's group at JHU**
  - Sebastian Rubio, Matt Gorman, Miguel Diaz-Lopez
  - Several conference papers/presentations
  - 2023 journal article: "Scaling laws of plume-induced granular cratering" by Gorman *et al.*

On the Interaction Between a Flow Instability and Inertial Particles in Supersonic Jet Plume-Surface Interaction

J. Sebastian Rubio[*], Yinghe Qi[†], Miguel X. Diaz-Lopez[‡], Matthew T. Gorman[§], and Rui Ni[¶]
Johns Hopkins University, Baltimore, MD 21218, United States

Neil S. Rodrigues[‖]
NASA Langley, Research Center, Hampton, VA 23681, United States

Extraterrestrial landings often require spacecraft to deploy supersonic jets directed at dusty planetary surfaces to ensure controlled descents. This interaction, termed plume-surface interaction (PSI), critically influences crater formation and the dynamics of ejected particles, which can obscure vision, damage onboard sensors, and impact nearby infrastructure with significant particle velocities. The physics of PSI remain poorly understood due to the complexities in simulating the involved multiphysics and experimentally replicating reduced atmospheric pressure conditions. This article discusses a collaborative effort to investigate PSI in reduced atmospheric pressure environments using a Mach 5.3 jet impinging on a granular bed. The results highlight observations of an azimuthal pattern in the ejecta distribution, characterized by alternating ejecta streaks of varying particle concentrations. This phenomenon suggests the presence of a low Reynolds number instability, a notable discovery given the supersonic nature of the jet.

FD62: Plume-Surface Interaction II
1:00 – 1:20 pm

NASA STMD PSI Ground Tests

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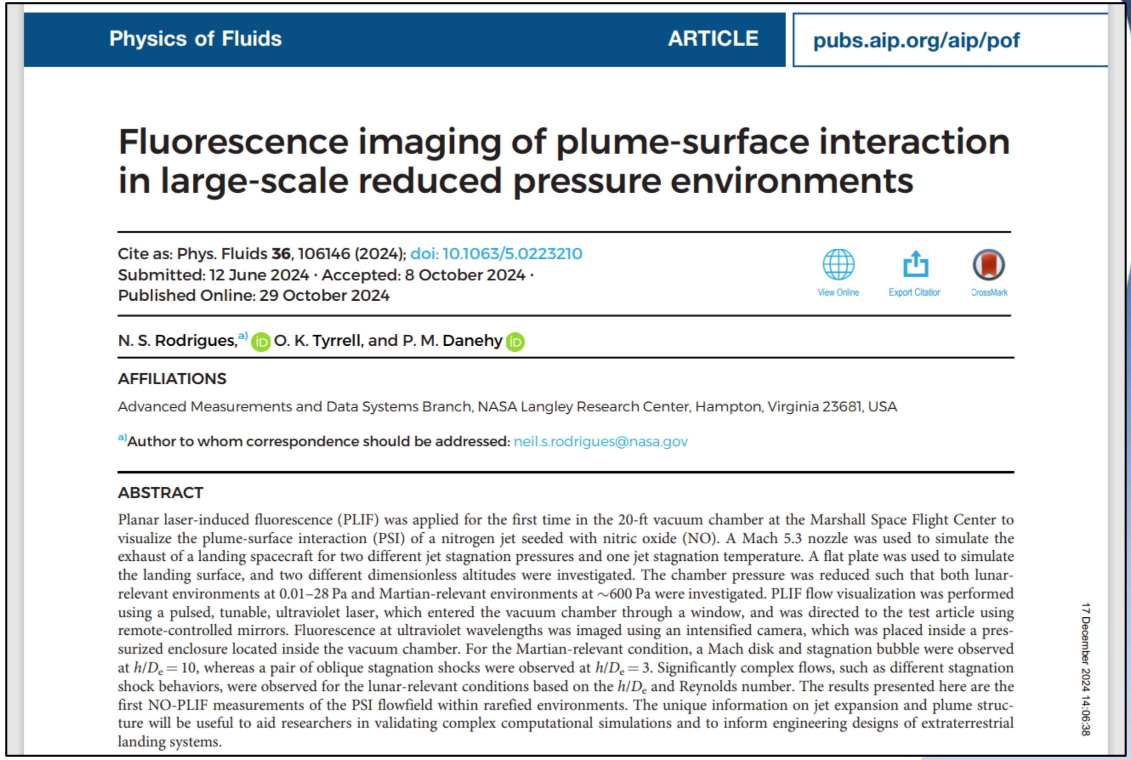
  - 20-ft Vacuum Chamber (2022)



Physics of Fluids ARTICLE pubs.aip.org/aip/pof

Fluorescence imaging of plume-surface interaction in large-scale reduced pressure environments

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N. S. Rodrigues,[a] O. K. Tyrrell, and P. M. Danehy

AFFILIATIONS

Advanced Measurements and Data Systems Branch, NASA Langley Research Center, Hampton, Virginia 23681, USA

[a] Author to whom correspondence should be addressed: neil.s.rodrigues@nasa.gov

ABSTRACT

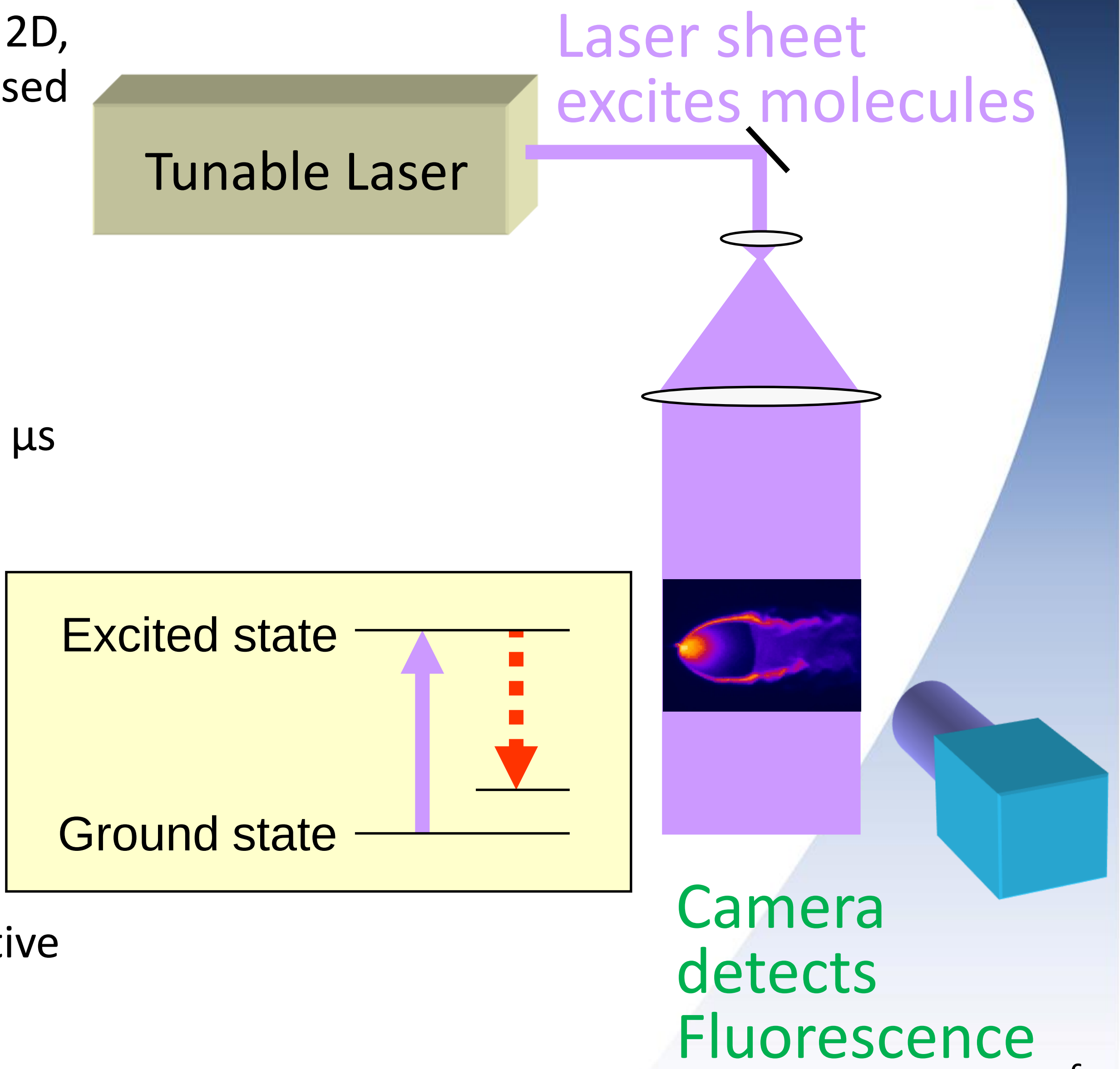
Planar laser-induced fluorescence (PLIF) was applied for the first time in the 20-ft vacuum chamber at the Marshall Space Flight Center to visualize the plume-surface interaction (PSI) of a nitrogen jet seeded with nitric oxide (NO). A Mach 5.3 nozzle was used to simulate the exhaust of a landing spacecraft for two different jet stagnation pressures and one jet stagnation temperature. A flat plate was used to simulate the landing surface, and two different dimensionless altitudes were investigated. The chamber pressure was reduced such that both lunar-relevant environments at 0.01–28 Pa and Martian-relevant environments at ~600 Pa were investigated. PLIF flow visualization was performed using a pulsed, tunable, ultraviolet laser, which entered the vacuum chamber through a window, and was directed to the test article using remote-controlled mirrors. Fluorescence at ultraviolet wavelengths was imaged using an intensified camera, which was placed inside a pressurized enclosure located inside the vacuum chamber. For the Martian-relevant condition, a Mach disk and stagnation bubble were observed at $h/D_e = 10$, whereas a pair of oblique stagnation shocks were observed at $h/D_e = 3$. Significantly complex flows, such as different stagnation shock behaviors, were observed for the lunar-relevant conditions based on the h/D_e and Reynolds number. The results presented here are the first NO-PLIF measurements of the PSI flowfield within rarefied environments. The unique information on jet expansion and plume structure will be useful to aid researchers in validating complex computational simulations and to inform engineering designs of extraterrestrial landing systems.

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

- **Measurements led by NASA Langley researchers**
  - Neil Rodrigues, Olivia Tyrrell, Paul Danehy
  - Several conference papers/presentations
  - 2024 journal article

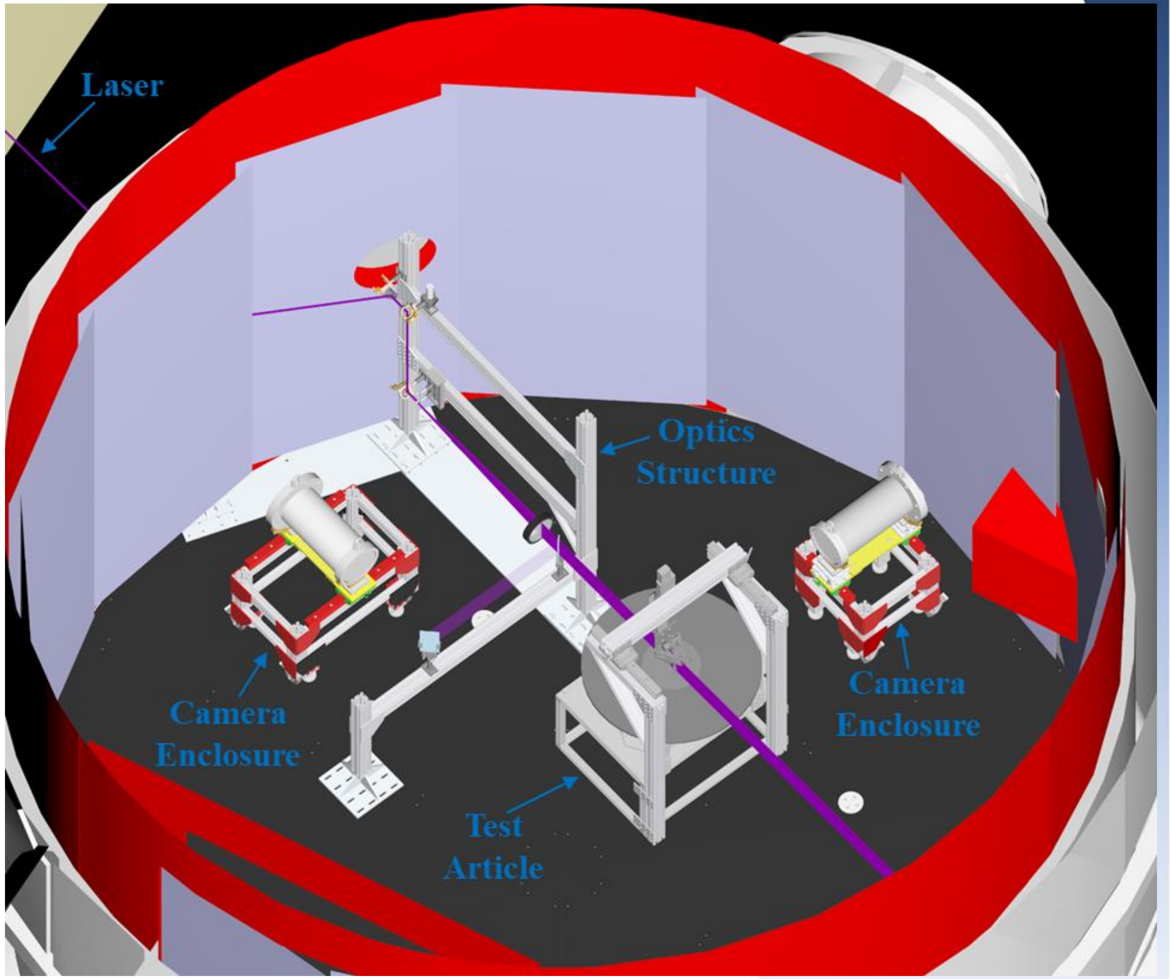
Planar Laser-induced Fluorescence

- 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 µs
- PLIF for PSI test used seeded nitric oxide gas (< 1%)
  - Well-suited for low-pressure environments
- PLIF signal roughly scales with gas density
  - Signal intensity is qualitative
  - Location of flow structures (e.g., shocks) is quantitative



20-ft Vacuum Chamber Overview

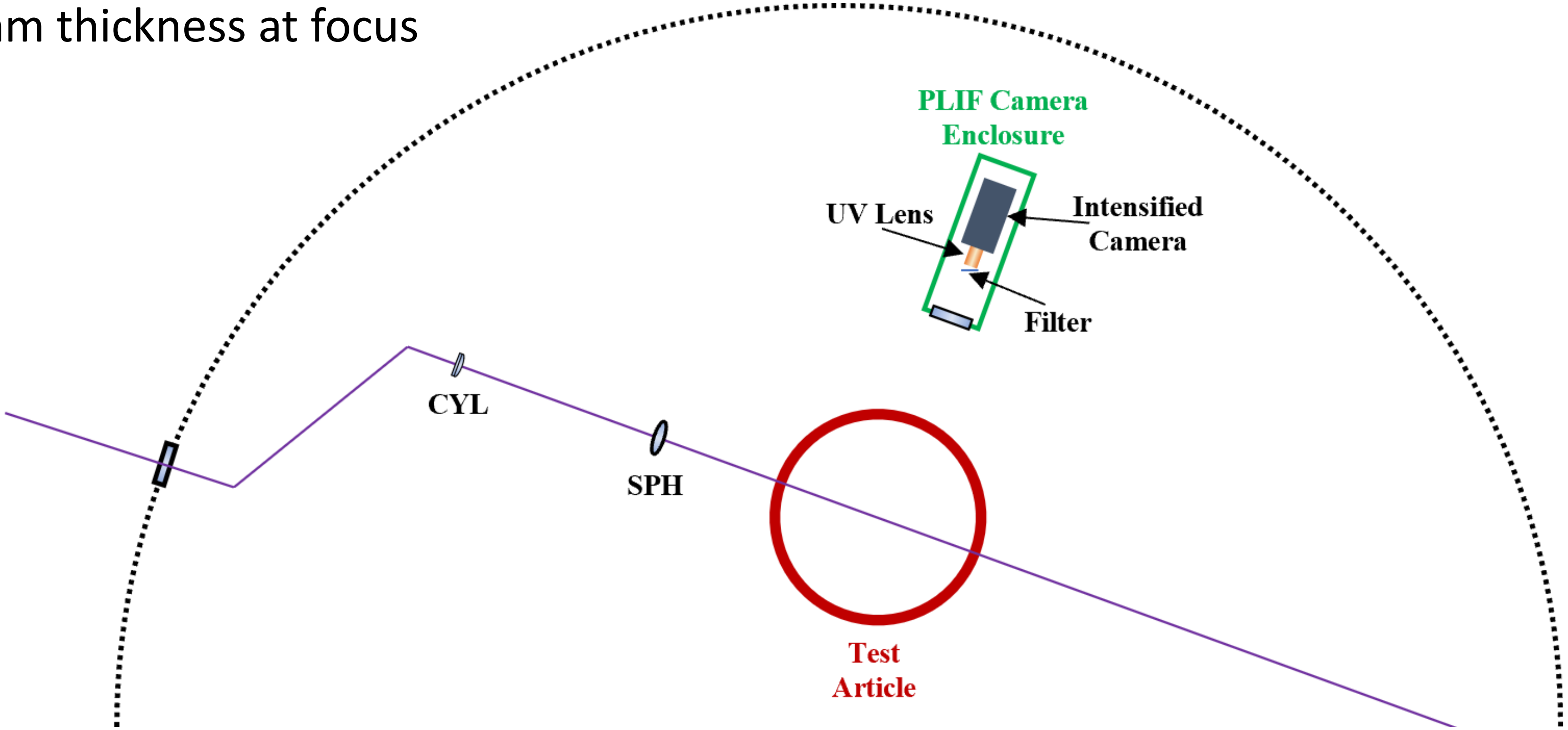
- Jet nozzle assembly and impingement plate test article
  - Mach 5.3 supersonic nozzle
  - Located near middle of chamber
- Heated inert gas (nitrogen) plume
  - Premixed with nitric oxide (<1%) for PLIF visualization
- UV laser (near 226 nm) brought into vacuum chamber through viewport window
  - Optics for PLIF laser sheet placed on custom structure
- PLIF cameras located within custom camera enclosures
  - Intensified sCMOS camera used for UV imaging



Additional details regarding experimental systems found in Rodrigues et al. (2024)

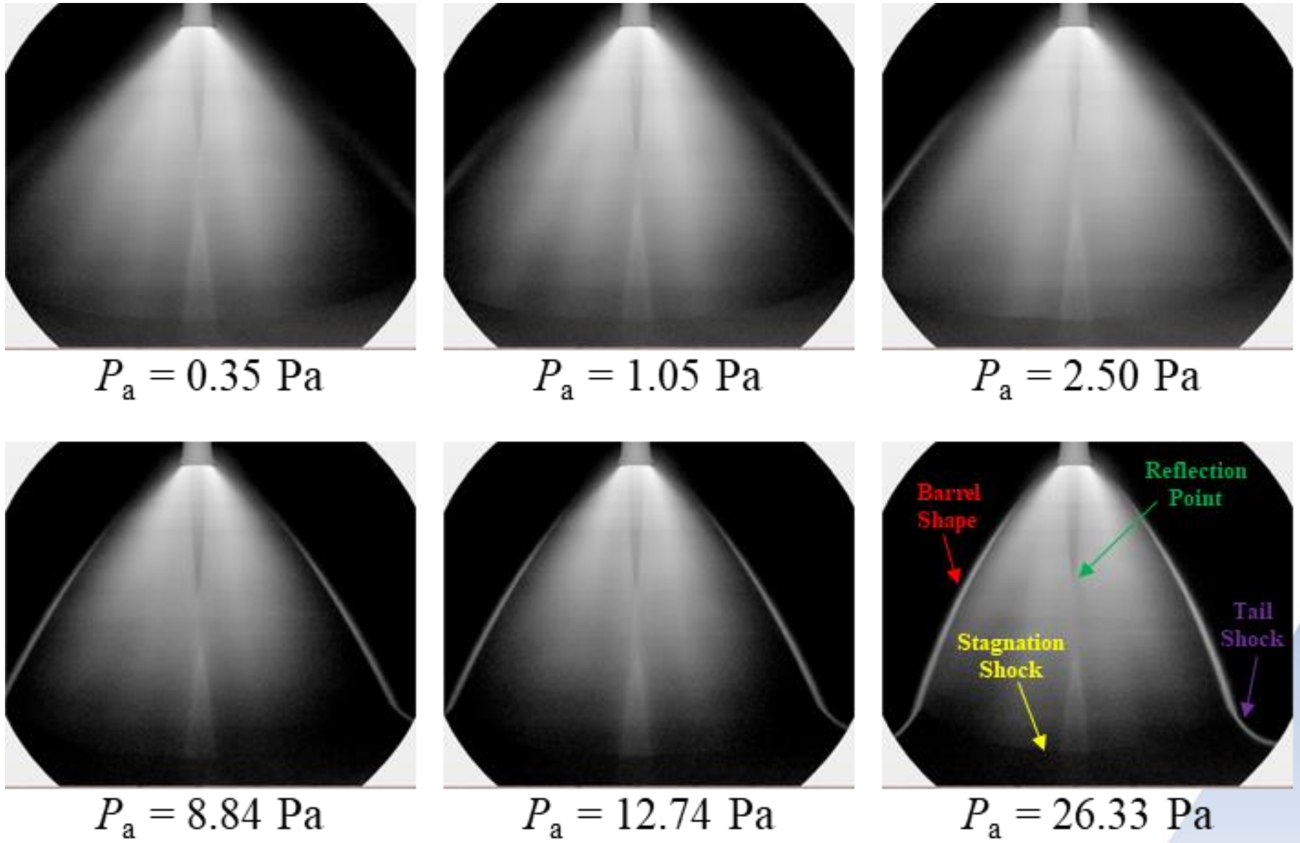
Experimental Schematic

- Laser sheet formed using cylindrical (+25 mm) and spherical (+1000 mm) lenses
  - 150 mm height
  - <1 mm thickness at focus



Plume Impingement at h/D_e = 10

- High flow (P_0 = 965 kPa) at lunar-relevant conditions (P_a = 0.35 Pa → P_a = 26 Pa)
- PLIF used to measure:
  - Nozzle Reflection Point
  - Radial Extent of Jet
  - Stagnation Shock Height

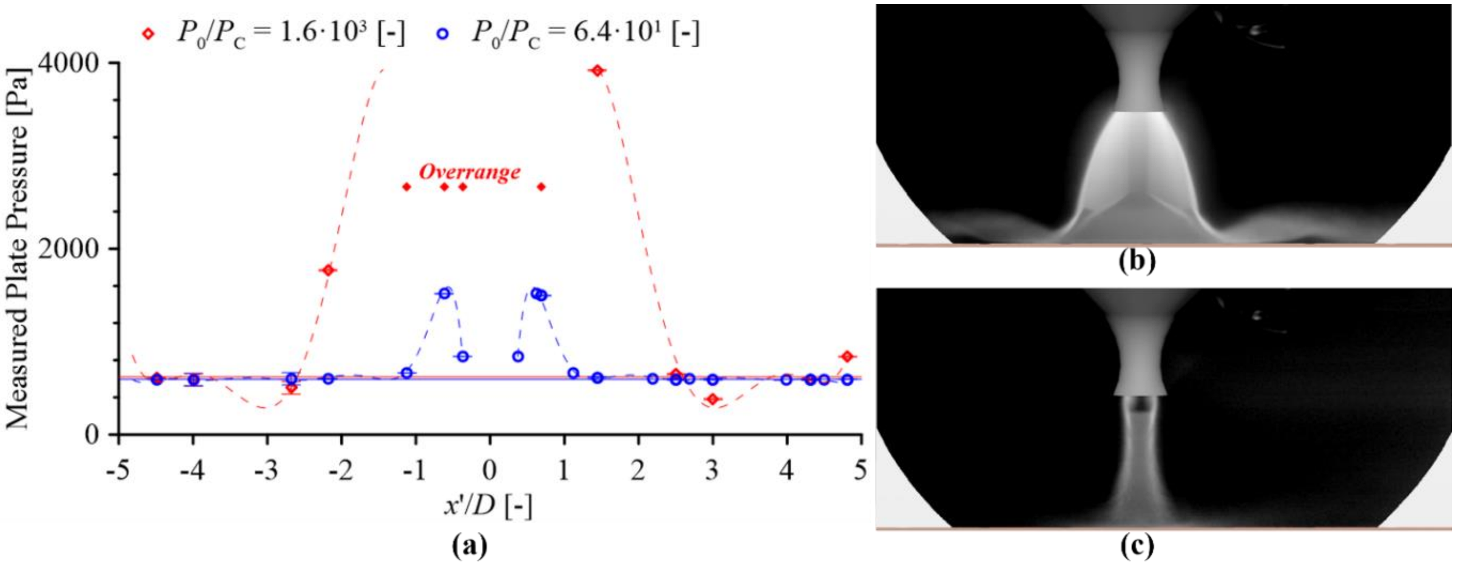


h/D_e: dimensionless height
P_a: ambient pressure
P_0: jet stagnation pressure (nozzle plenum)

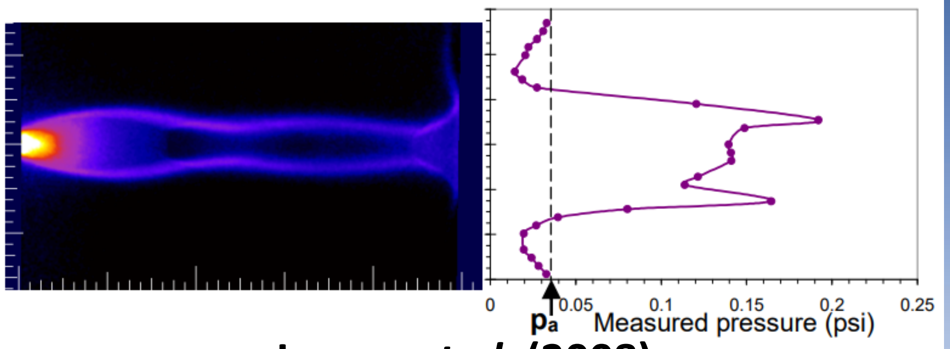
From 2024 *Physics of Fluids* paper by Rodrigues *et al.*

Test Campaign Overview

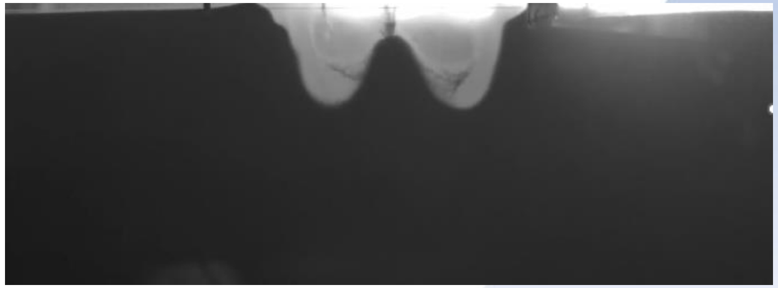
- **Overview of test campaign provided by December 2023 JANNAF paper**
- Impingement pressure with time-averaged flow visualization
  - Impingement structure apparent from pressure data (but not fully resolved)
    - Double peaks and low-pressure suction region
    - Similar to Inman *et al.* pressure measurements
    - May explain annular crater behavior



Martian-relevant test data: (a) impingement pressure, (b) highest P_0, and (c) lowest P_0.



Inman *et al.* (2008)

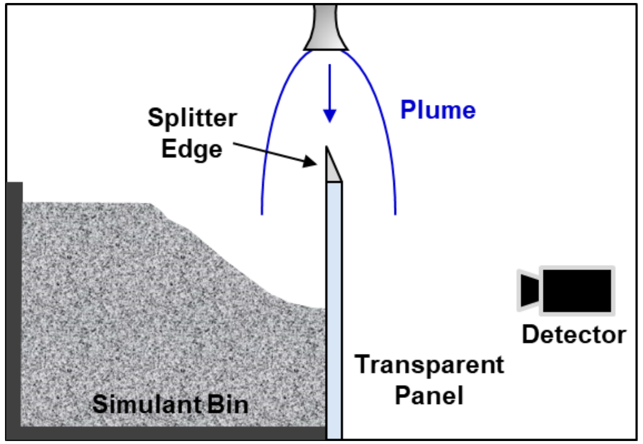


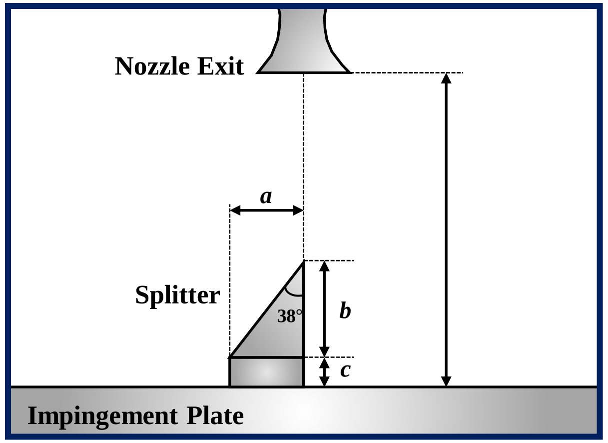
Rubio *et al.* (2023)

From December 2023 JANNAF paper by Rodrigues *et al.*

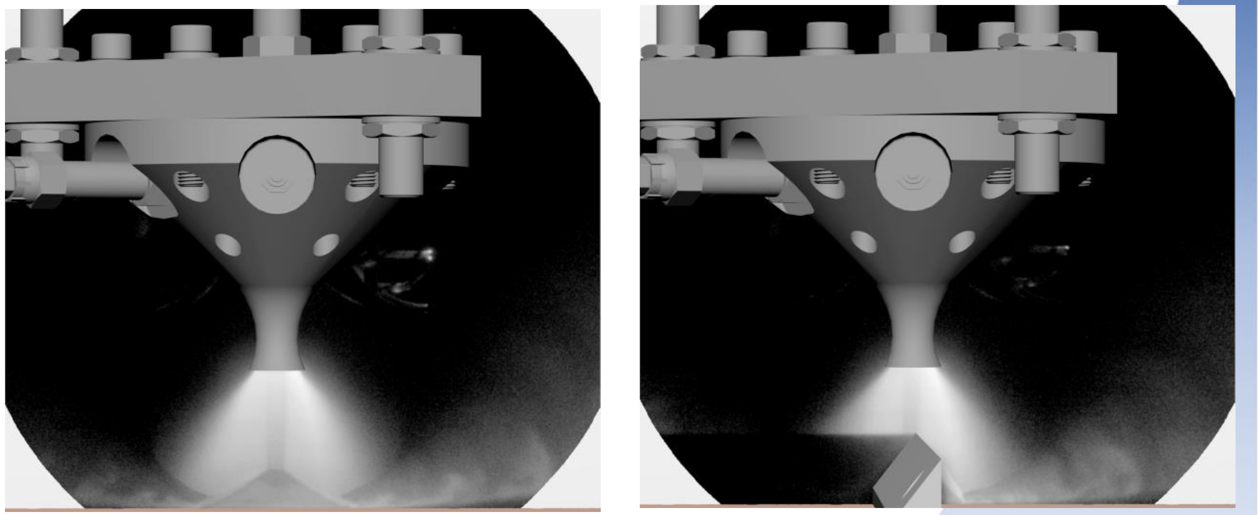
Effect of Test Design on PSI

- **Effect of geometric configuration evaluated in 2024 AIAA SciTech paper**
- Past experimental PSI work frequently utilized a “half-space” design
  - Flow bisected with splitter edge (enables erosion measurements with single camera)
  - How does this affect plume impingement?





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

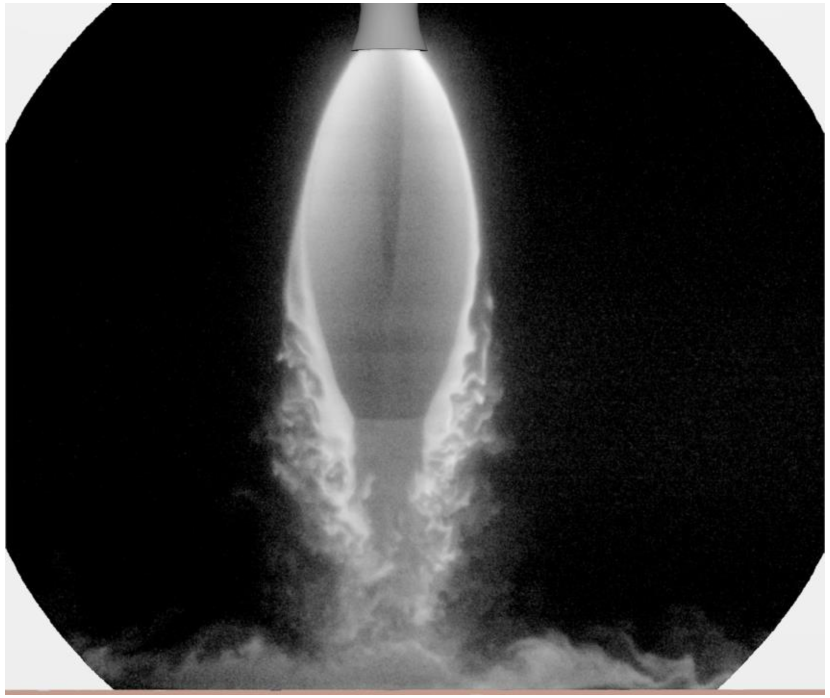


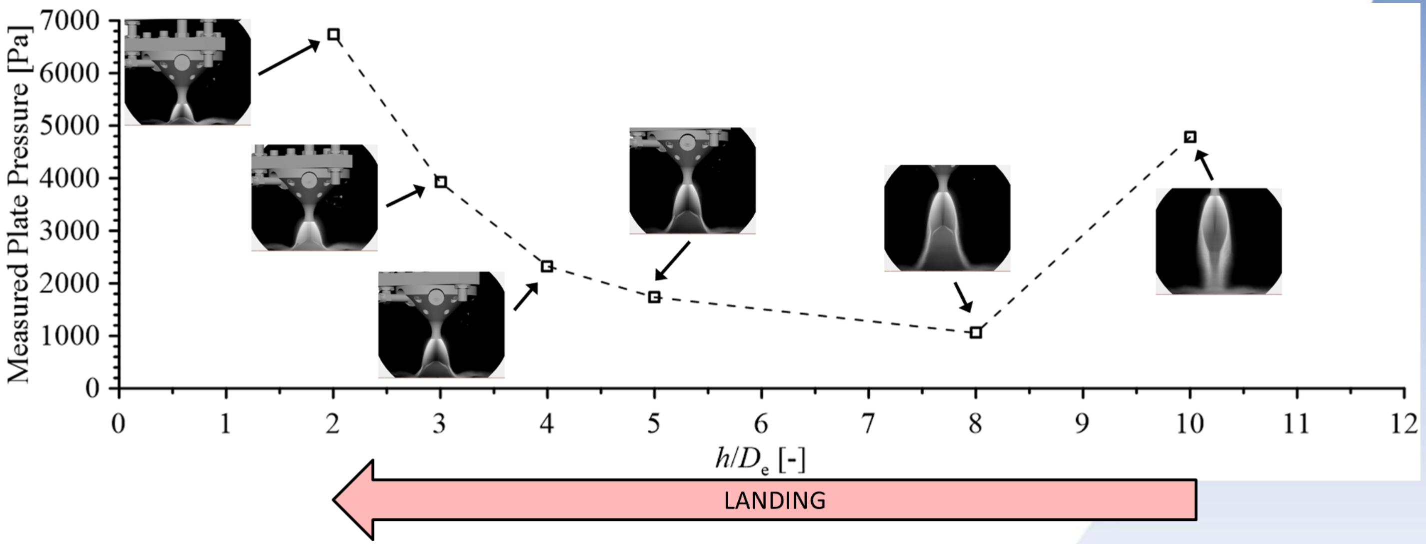
Lunar-relevant test data: full-space design (left) and half-space design (right)

From 2024 AIAA SciTech Paper by Tyrrell *et al.*

Effect of h/D_e at Martian Conditions

- **Effect of h/D_e on stagnation shock behavior**
- Transition of stagnation shock from concave to triangular
  - 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

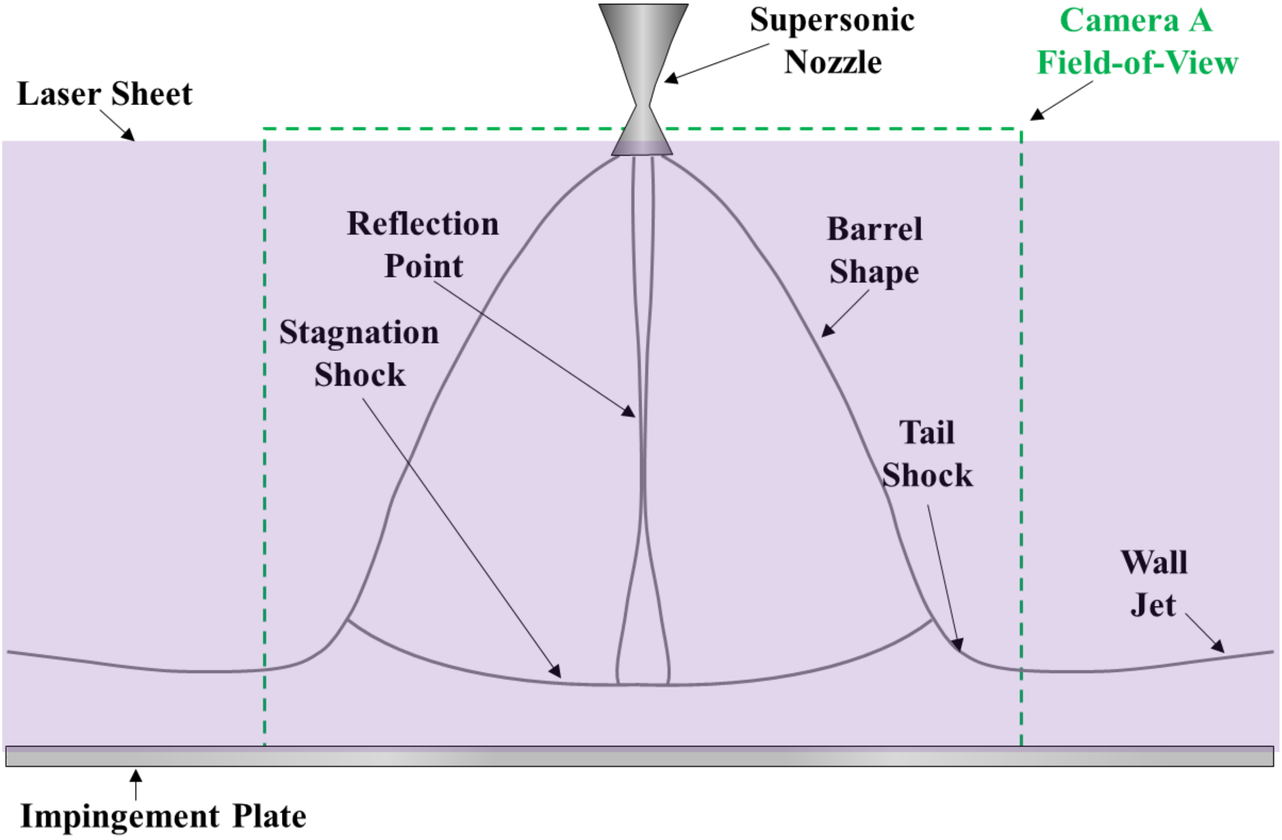




From 2024 AIAA Ascend Paper by Rodrigues *et al.*

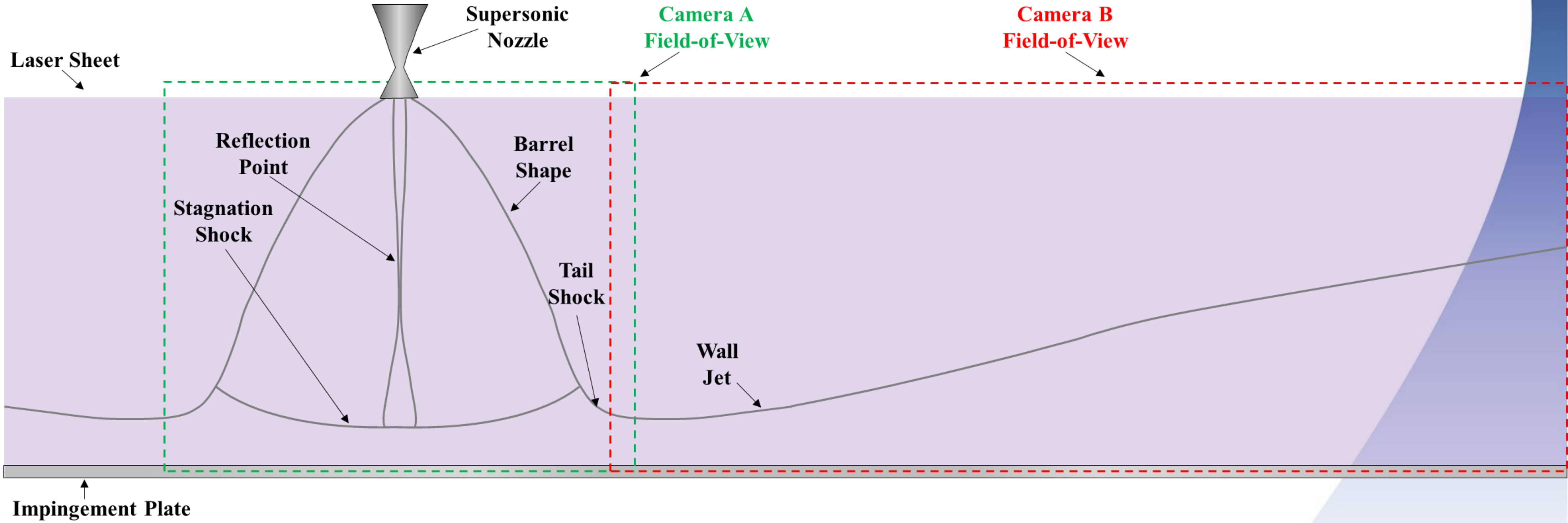
PSI Schematic

- Primary PLIF camera captures key flow structures



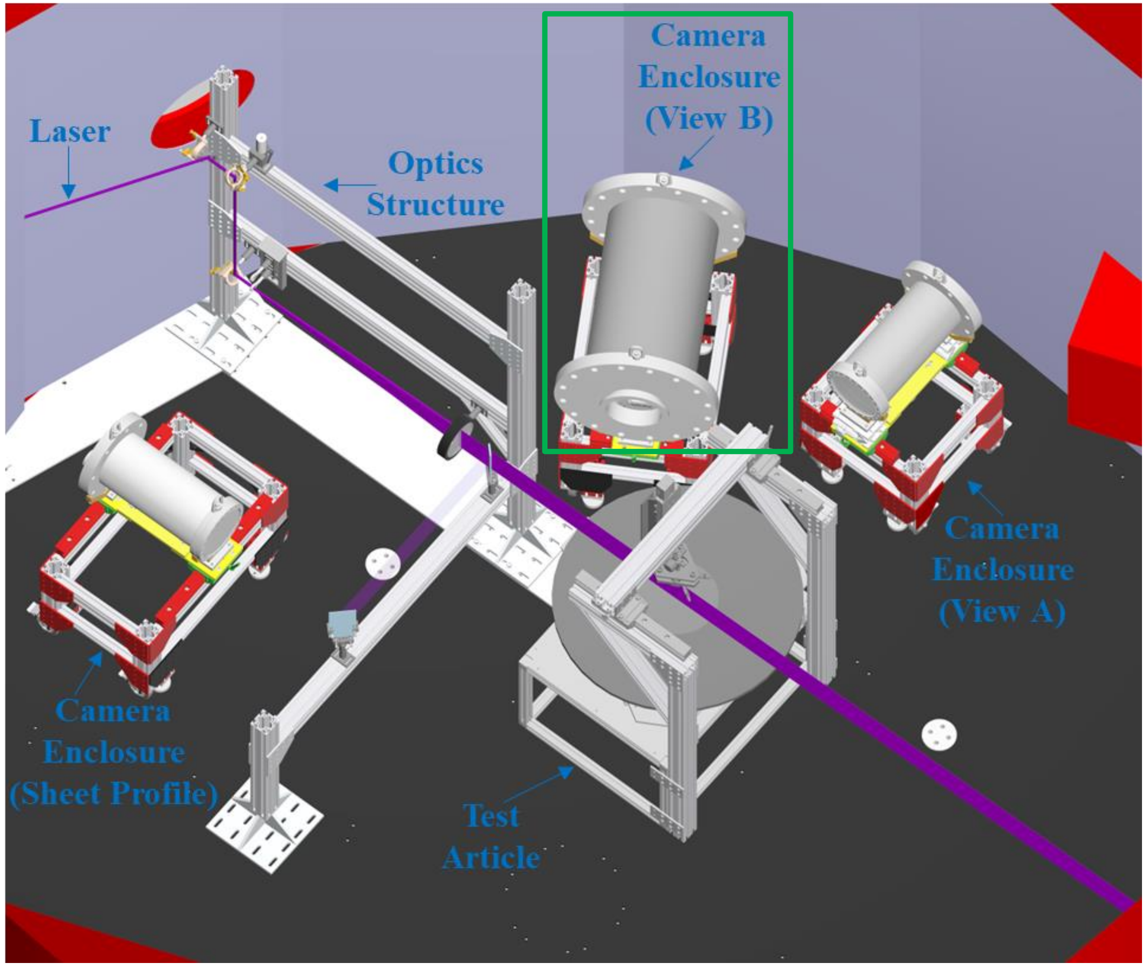
PSI Schematic

- Primary PLIF camera captures key flow structures
  - Secondary PLIF camera desired to visualize spatial evolution of wall-jet



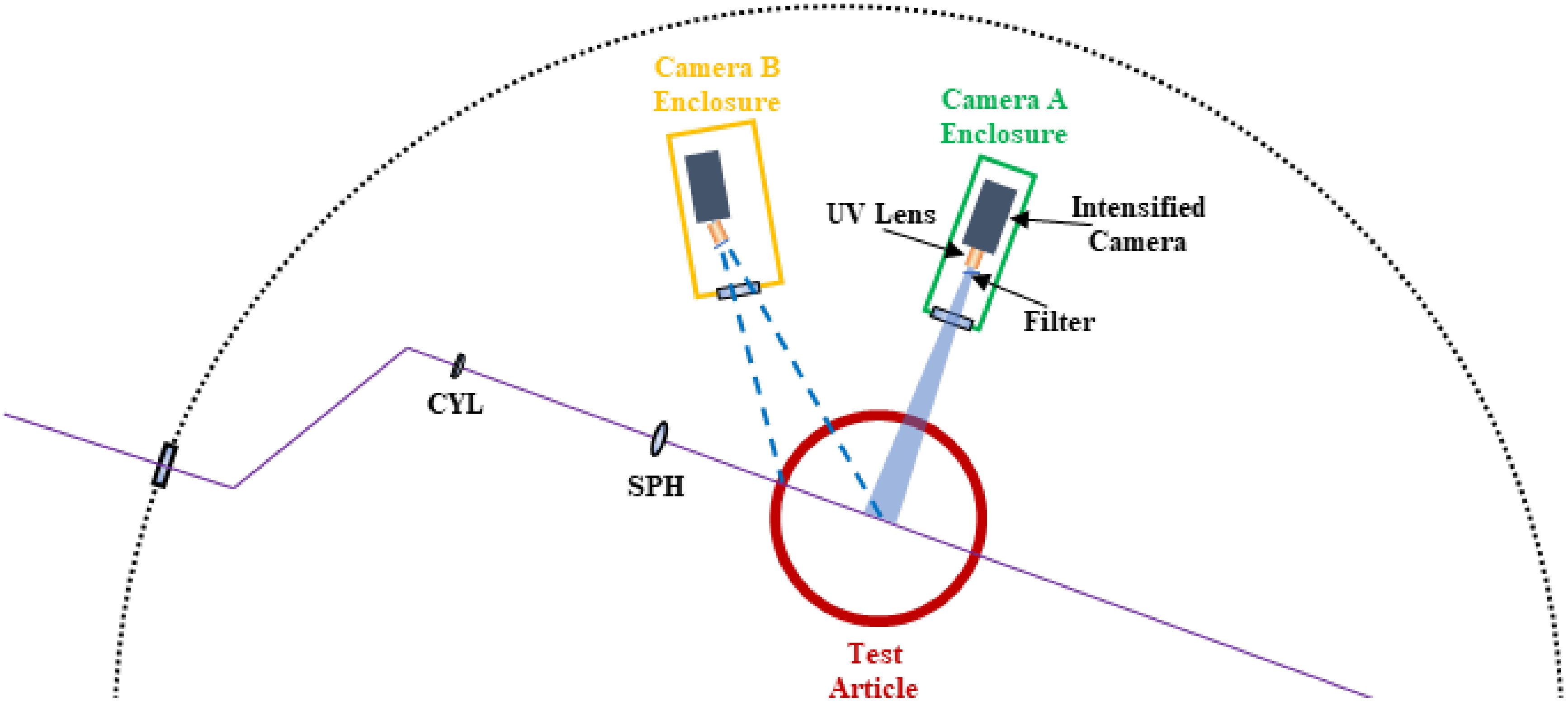
Addition of Second Camera

- 2nd intensified sCMOS camera inside camera enclosure used for limited test conditions



Experimental Schematic w/ 2nd Camera

- 2nd intensified sCMOS camera incorporated in Scheimpflug configuration



Test Conditions

		[-]	[Pa]	[kPa]
		h/D_e	P_a	P_0
Lunar-relevant	Case I	10	3.8	38.7
	Case II	3	1.8	38.3
Martian-relevant	Case III	3	584 → 618	743 → 962

h/D_e: dimensionless height
P_a: ambient pressure
P_0: jet stagnation pressure (nozzle plenum)

Test Conditions

- Average image (40 instantaneous images) after flatfield correction

		[-]	[Pa]	[kPa]
		h/D_e	P_a	P_0
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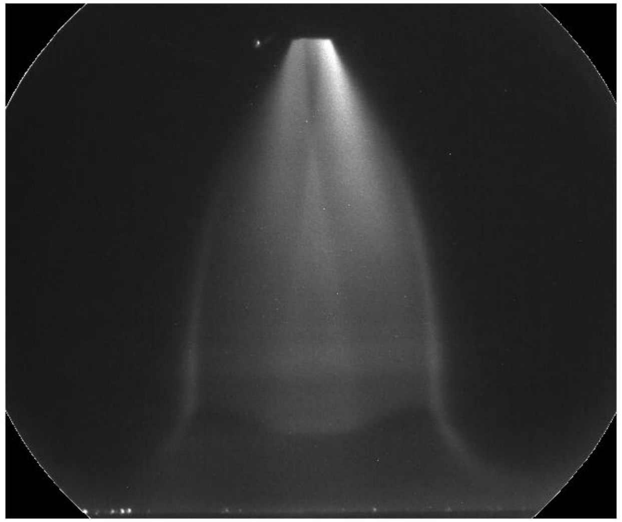
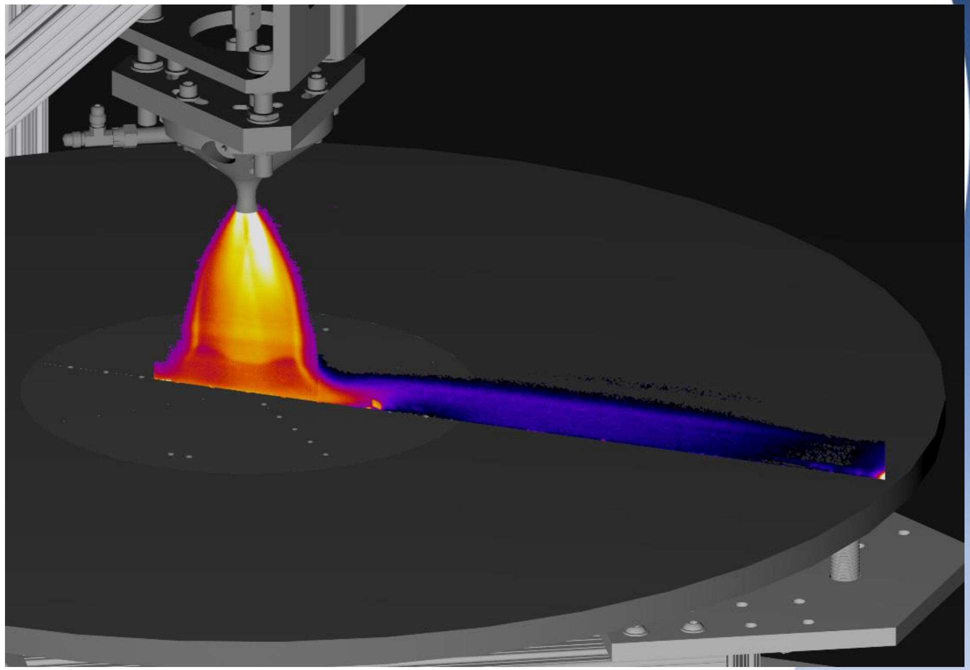


View A (linear scale)

View B (linear scale)



Processed images (log scale) with CAD

- Mapping spatial calibration of View B (image dewarping) most complicated part of image processing

Test Conditions

- Average image (40 instantaneous images) after flatfield correction

		[-]	[Pa]	[kPa]
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Lunar-relevant	Case I	10	3.8	38.7
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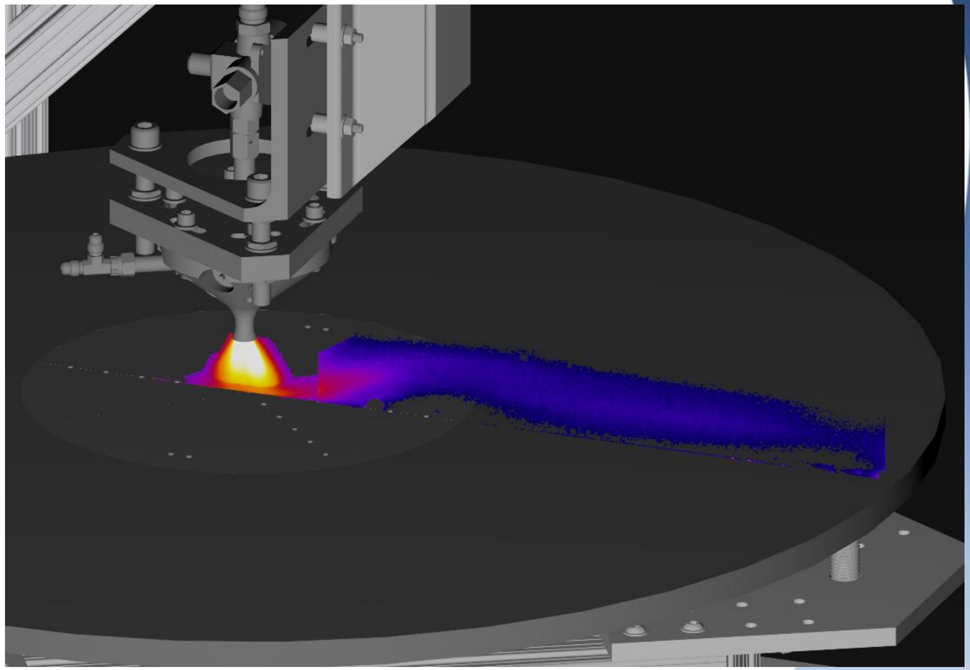
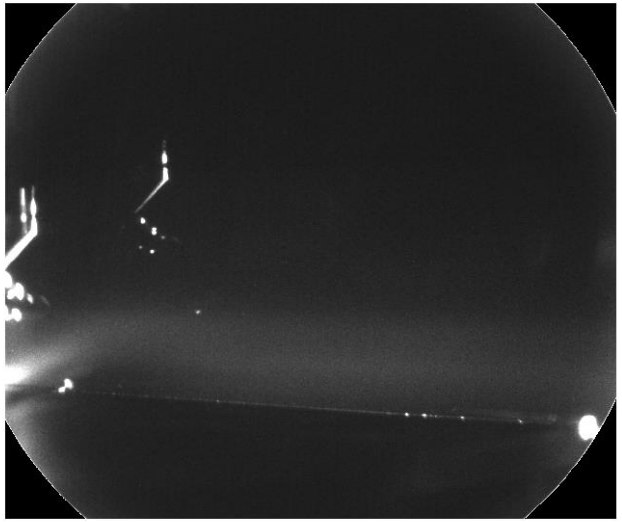


Processed images (log scale) with CAD

View A (linear scale)



View B (linear scale)

- Mapping spatial calibration of View B (image dewarping) most complicated part of image processing

Test Conditions

- Average image (40 instantaneous images) after flatfield correction

		[-]	[Pa]	[kPa]
		h/D_e	P_a	P_0
Lunar-relevant	Case I	10	3.8	38.7
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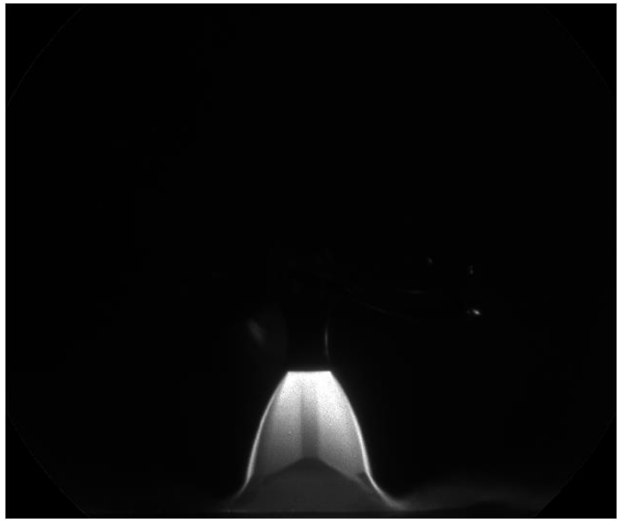
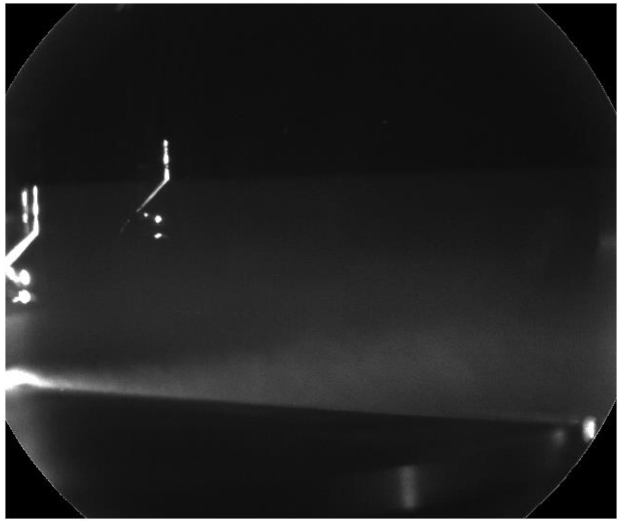
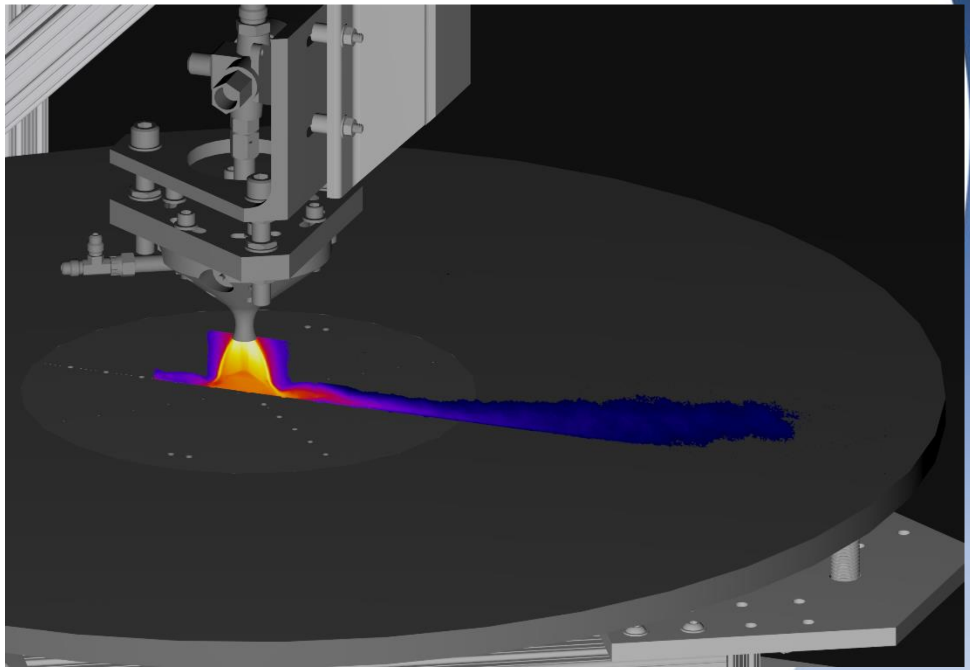


View A (linear scale)



View B (linear scale)



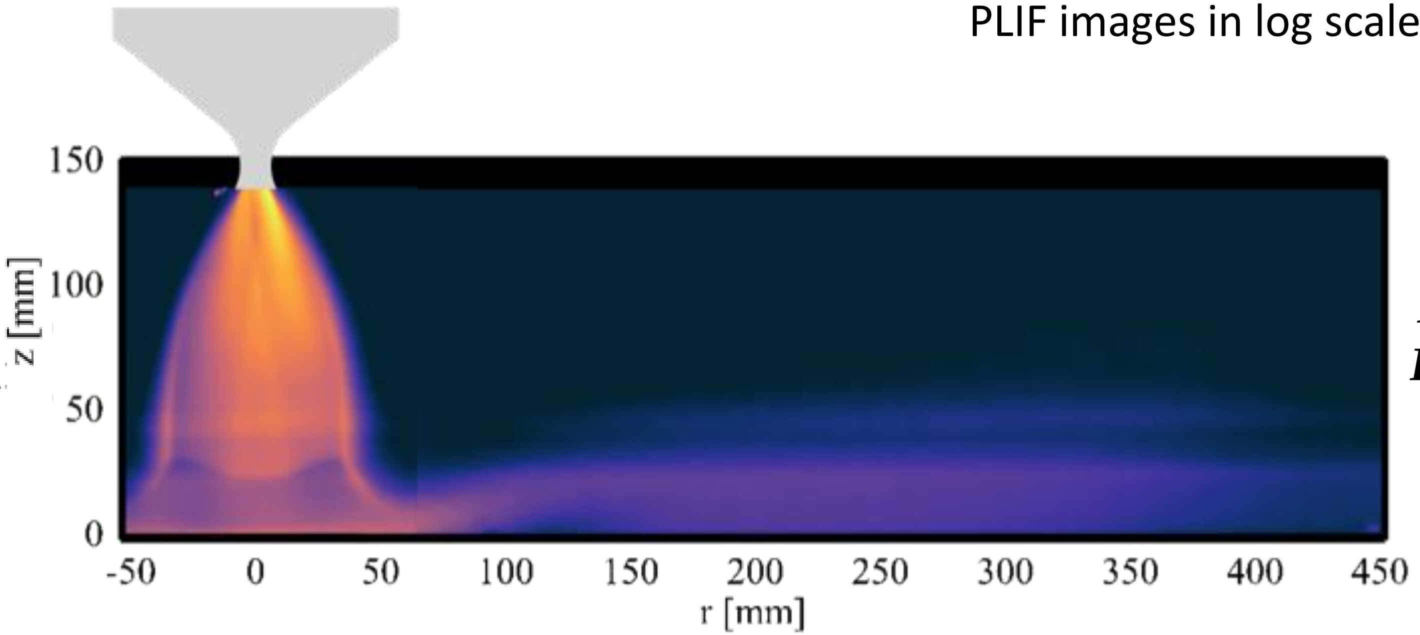
Processed images (log scale) with CAD

- Mapping spatial calibration of View B (image dewarping) most complicated part of image processing

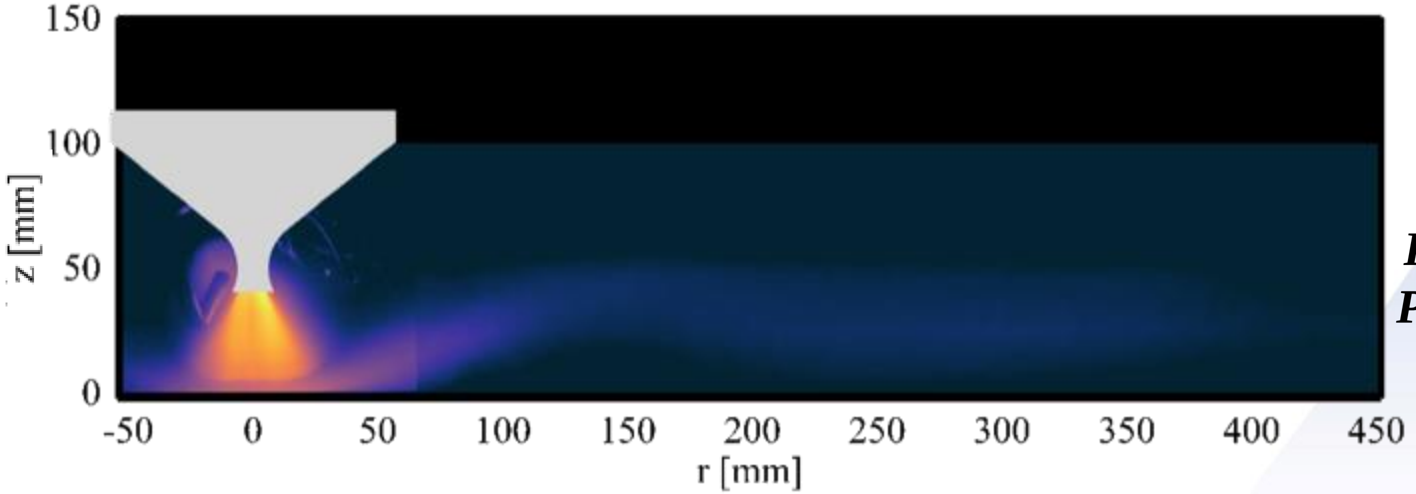
Lunar-relevant Average Images

- 40 instantaneous images used to generate average image
  - Laminar jets
- At h/D_e = 10, wall-jet lifts off plate near *r* = 80 mm and returns near *r* = 150 mm
  - Maximum height near *z* = 50 mm
- At h/D_e = 3, wall-jet lifts off plate near *r* = 60 mm and returns near *r* = 200 mm
  - Maximum height near *z* = 50 mm

PLIF images in log scale



$h/D_e = 10$
$P_a = 3.8$ Pa
$P_0 = 39$ kPa



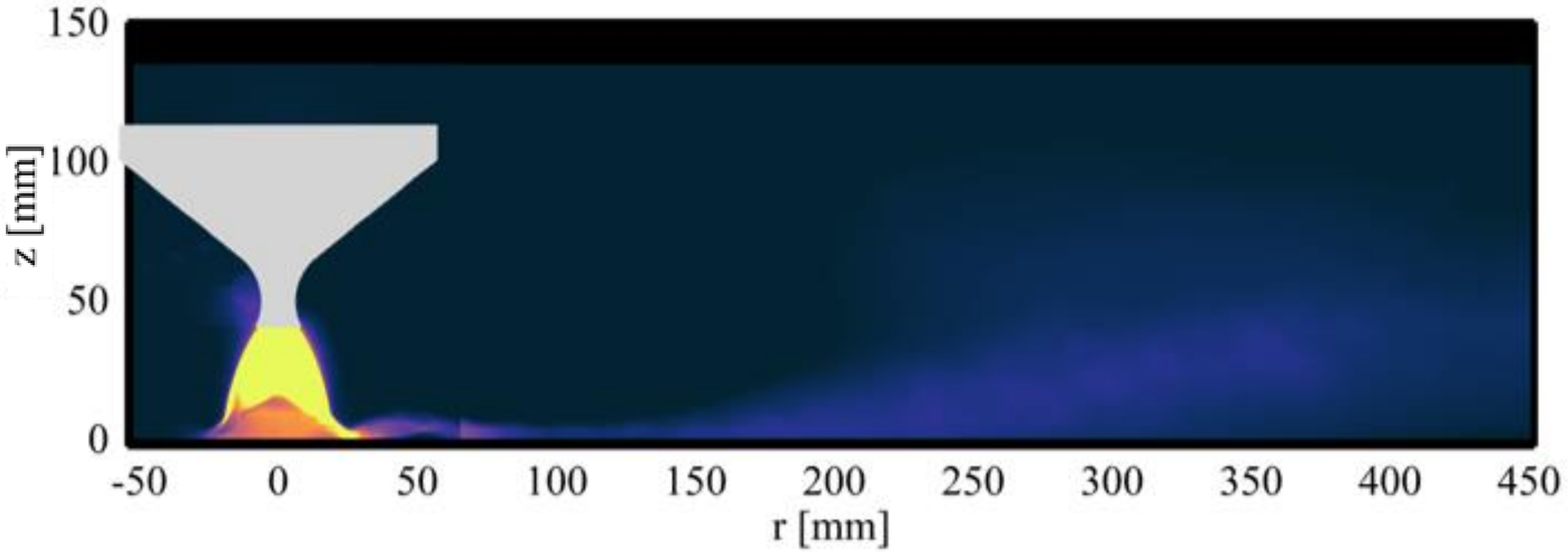
$h/D_e = 3$
$P_a = 1.8$ Pa
$P_0 = 38$ kPa

Martian-relevant Average Images

- 40 instantaneous images used to generate average image
  - Unsteady flow structures appear to be smeared by average image
- Wall-jet much closer to the surface
  - Rapid expansion of the wall-jet from *r* = 150 mm
    - Hypothesized to be due to a Kelvin–Helmholtz instability

PLIF images in linear scale

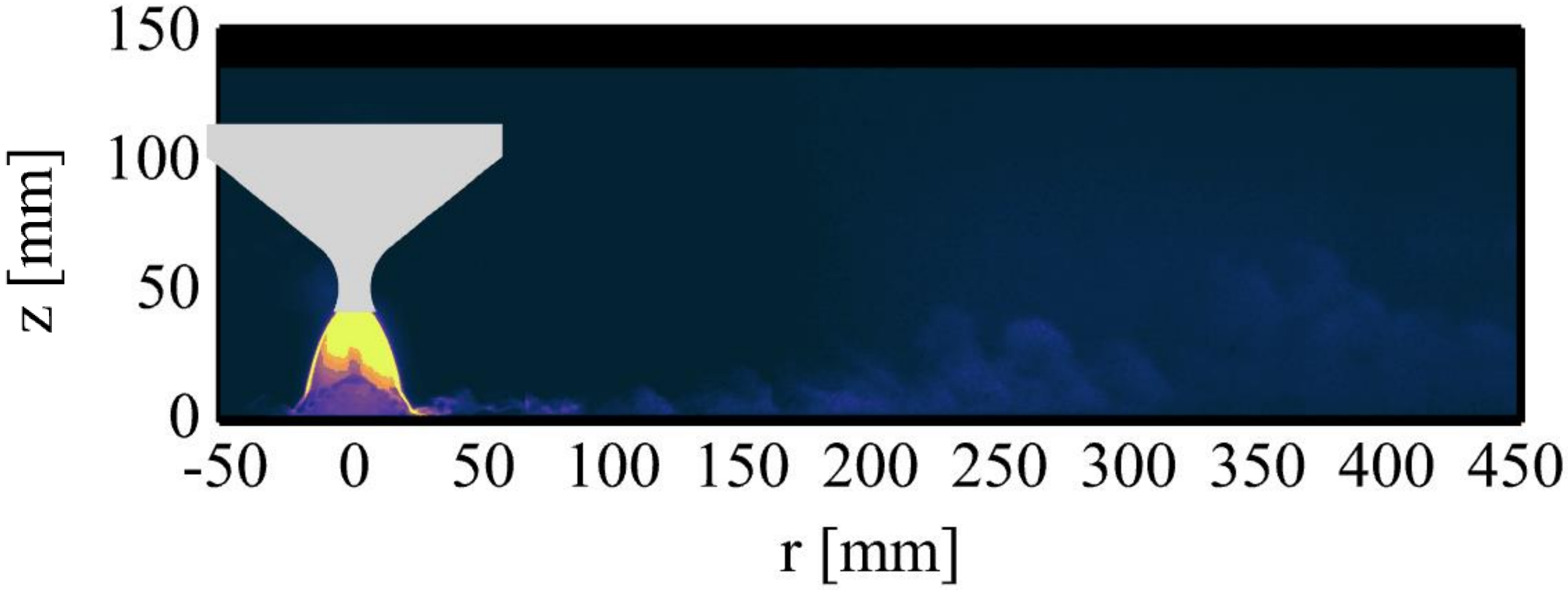
$h/D_e = 3$
$P_a = 1.8$ Pa
$P_0 = 38$ kPa



Martian-relevant Steady-State

- Instantaneous images reveal unsteady turbulent flow structures

PLIF images in linear scale

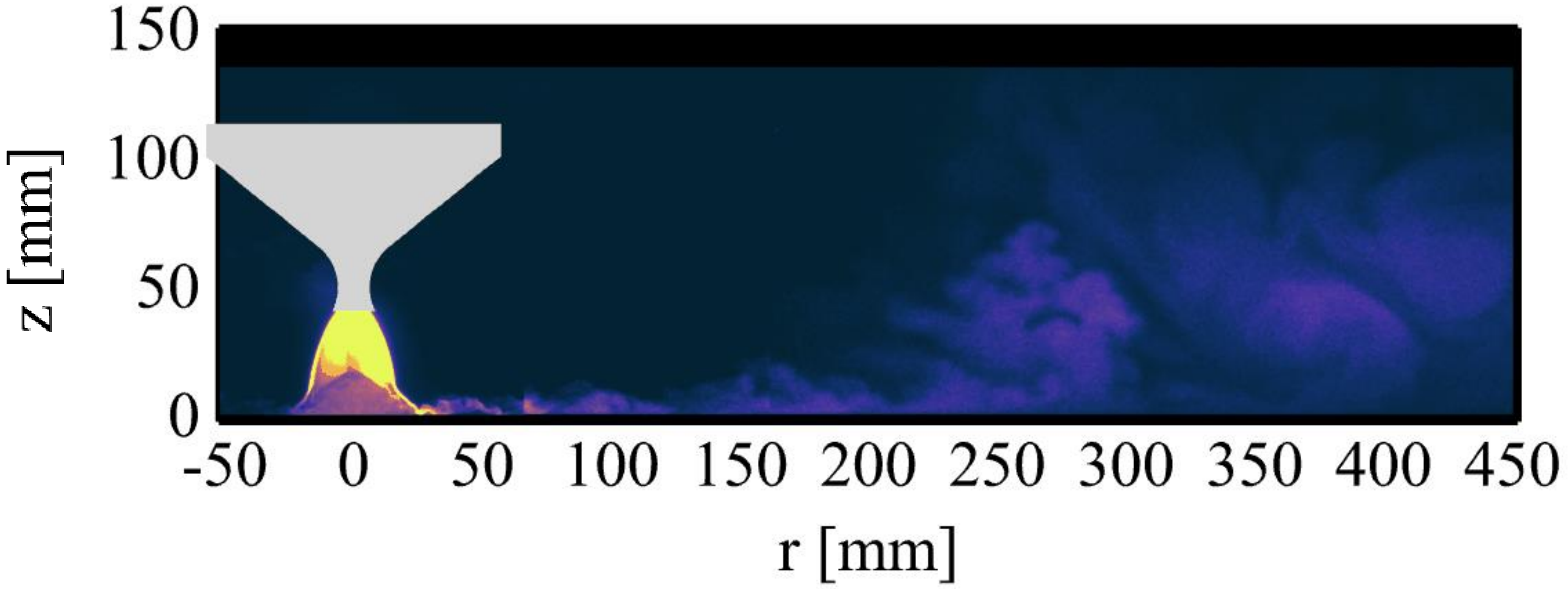


Sequence of 10 images acquired at 10 Hz, displayed at 5 fps

Martian-relevant Jet Start-Up

- Jet start-up and stabilization behavior captured by PLIF

PLIF images in linear scale

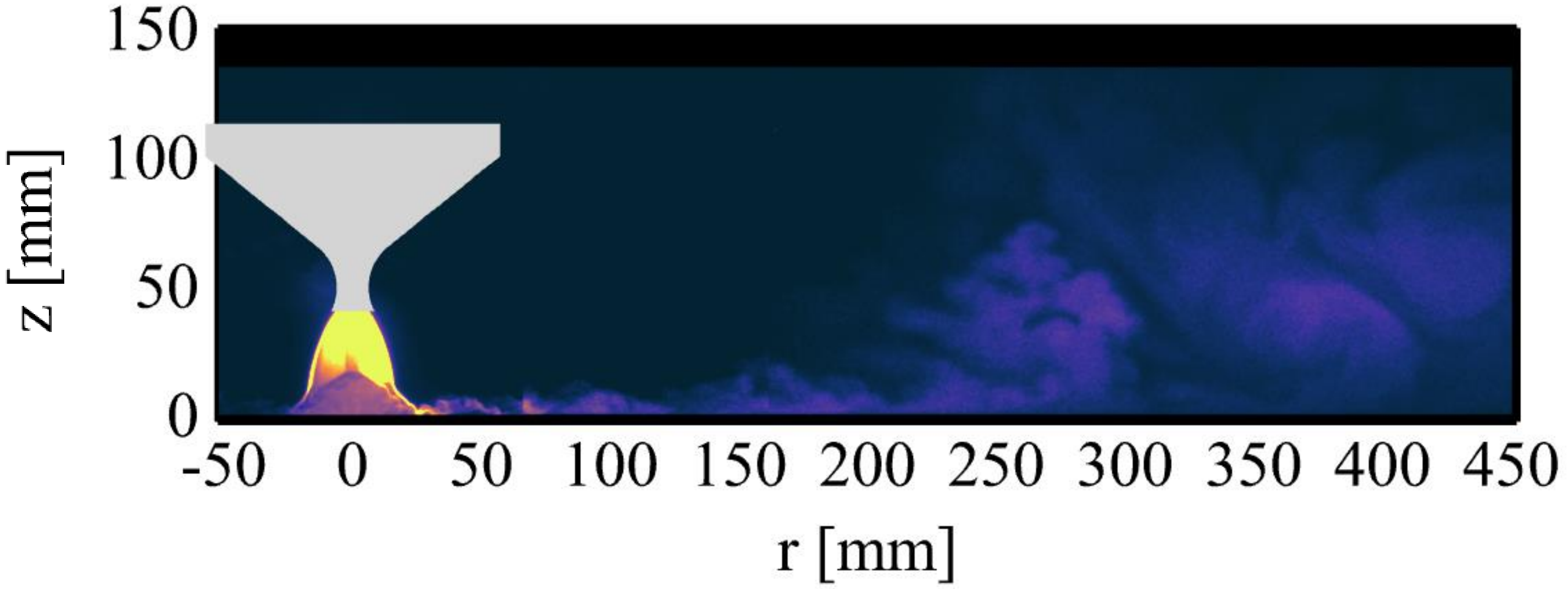


Sequence of 10 images acquired at 10 Hz, displayed at 2 fps

Martian-relevant Jet Start-Up

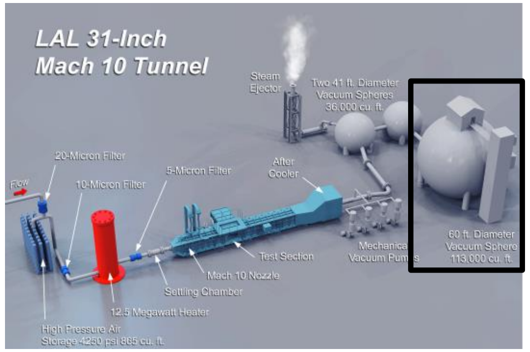
- Jet start-up and stabilization behavior captured by PLIF
  - Initial instability may be related to jet impingement pressure spike
    - Observed in other PSI experiments including by Al-Rashdan *et al.* (2021)

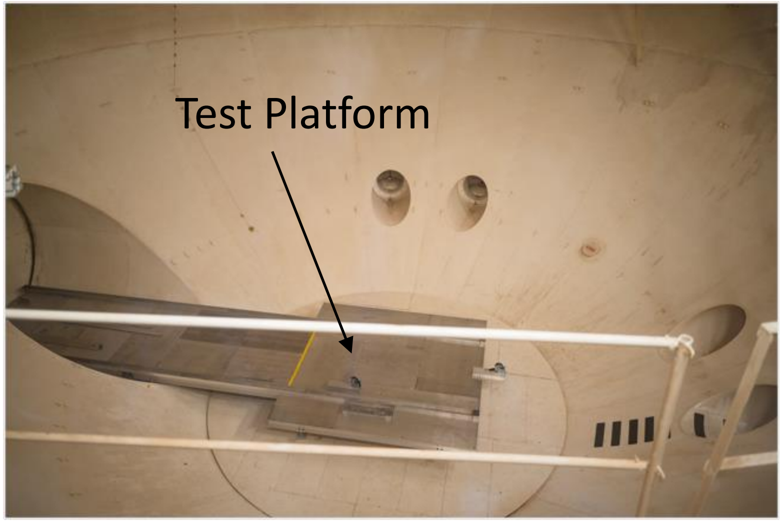
PLIF images in linear scale



Instantaneous image at approximately t = 0.02 s from valve opening

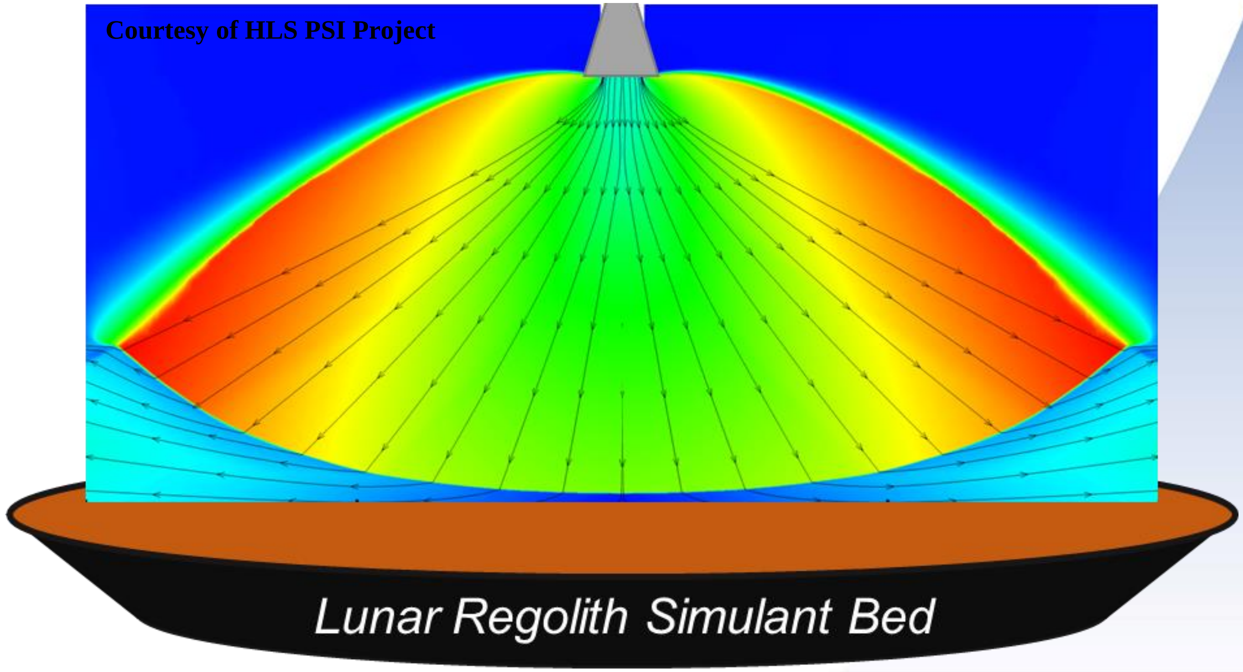
Upcoming Lunar HLS-focused Test at NASA Langley





- 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

Plume impingement visualization of flat plate and in the presence of regolith planned



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