



High-speed imaging of atomic oxygen emission in the HyMETs arcjet tunnel

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Background and Motivation

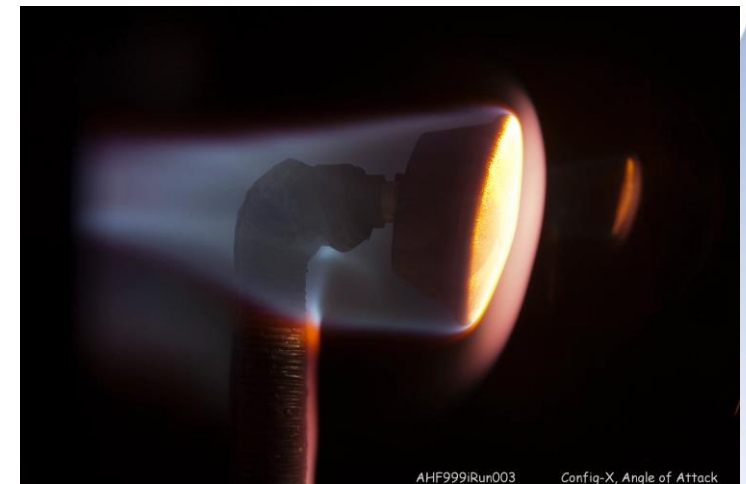


- Development of complex **thermal protection systems (TPS)** is an ongoing challenge for hypersonic and reentry flight.
- Evaluation of TPS performance continues to rely on extensive testing in **arcjet wind tunnels**.
- The **flow conditions** in arcjet facilities are generally unsteady and difficult to predict.
 - e.g., thermochemical nonequilibrium, nonuniform flow profiles, flow contamination, temporal fluctuations.
- Developing advanced **flow diagnostics** for arcjets is critical for reducing uncertainty.



Space Shuttle Discovery TPS Tiles

Credit: NASA (https://spinoff.nasa.gov/Launch_Return_Repeat)



TPS Test in the 60-MW IHF at NASA Ames

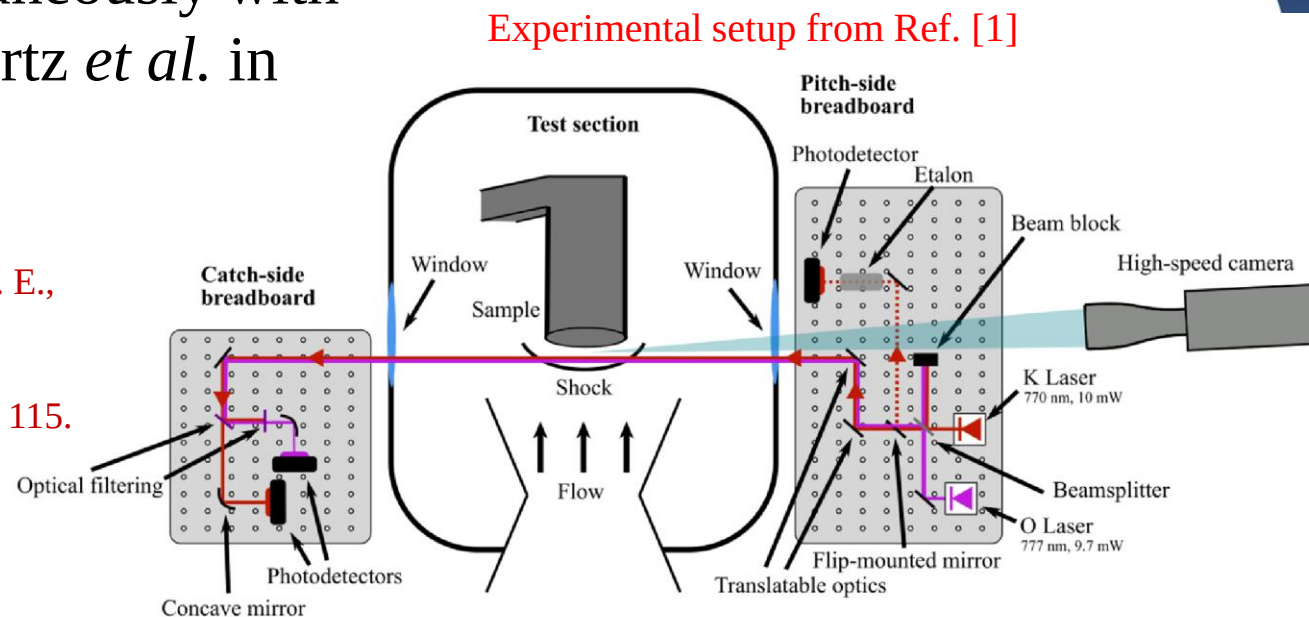
Credit: NASA (<https://www.nasa.gov/thermophysics-facilities-branch-arc-jet-complex/>)

Introduction



- This investigation was conducted simultaneously with a TDLAS experiment reported by Schwartz *et al.* in August 2024.

Schwartz, T., Splinter, S. C., Rodrigues, N. S., Danehy, P. M., Samuels, K. E., Kostyk, C. B., and Hanson, R. K., “Spatially-Resolved Atomic Oxygen Absorption and Emission Measurements in the Hypersonic Materials Environmental Test System,” *Applied Physics B*, Vol. 131, No. 6, 2025, p. 115.



Goals of this work:

- 1) Deliver a spatially-resolved qualitative representation of the thermochemical state of the flow with a relatively simple experimental setup.
- 2) Investigate the spatial and temporal variations of the excited-state atomic oxygen and its downstream effects.

Hypersonic Materials Environmental Test System



- Located at NASA Langley Research Center
- 400 kW Mach 5 continuous arcjet wind tunnel

- Feed gas composition: N_2 , O_2 , Ar, and CO_2
- Bulk enthalpies: 4.5 – 28 MJ/kg
- Mass flow rates: 2 – 13 g/s
- Nozzle exit diameter: 63.5 mm (2.5")

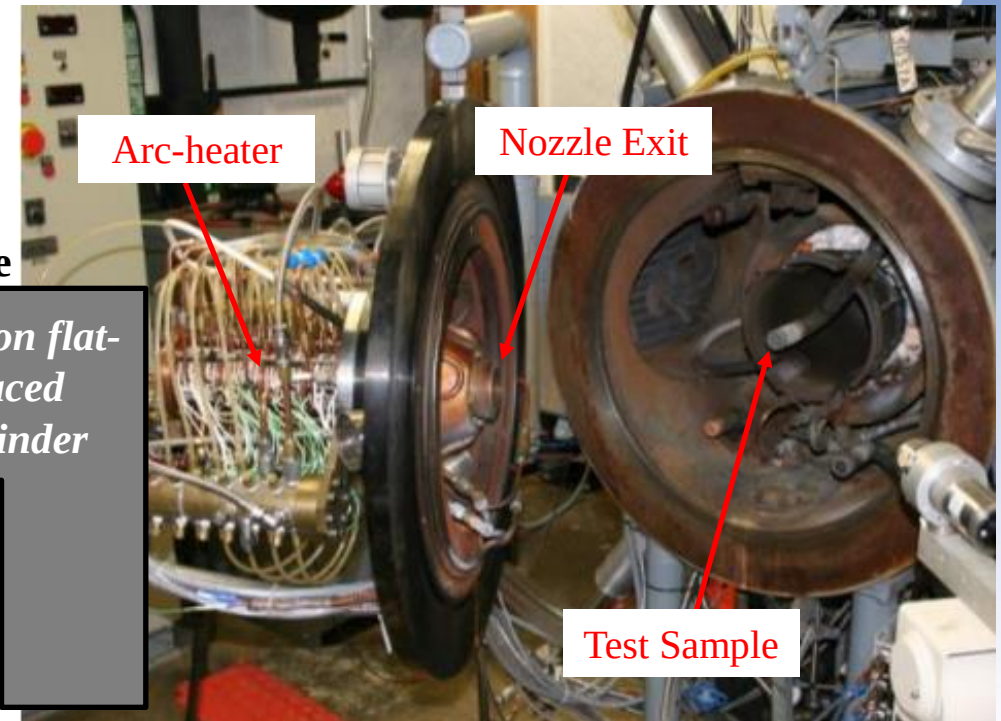
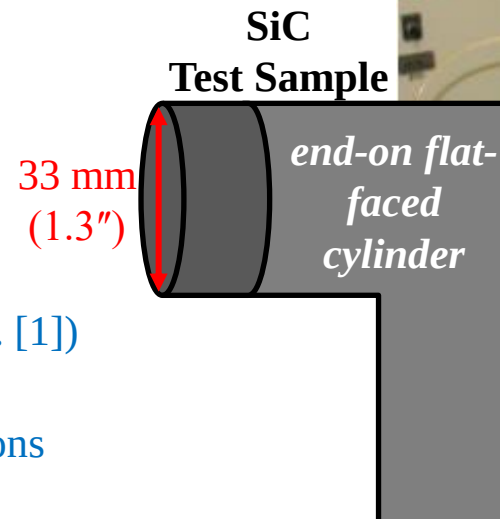
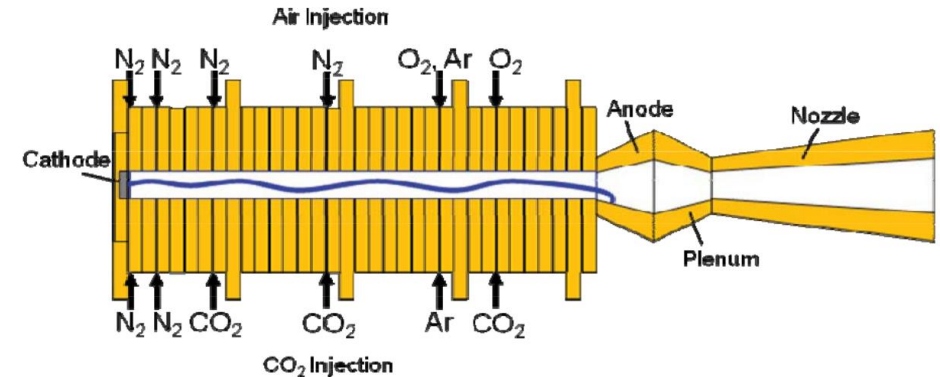
Selected Operating Conditions:

- Gas composition: 95% Ar / 5% O_2
- Arc-currents: 150, 175, and 200 A

Estimated Freestream Conditions:

- $T_\infty = 450 - 1200$ K (measurements from Ref. [1])
 - $M_\infty = 7.1 \pm 0.5$
 - $U_\infty = 2800 - 4600$ m/s
- } Isentropic relations

HyMETs arc-heater illustration from Ref. [2]



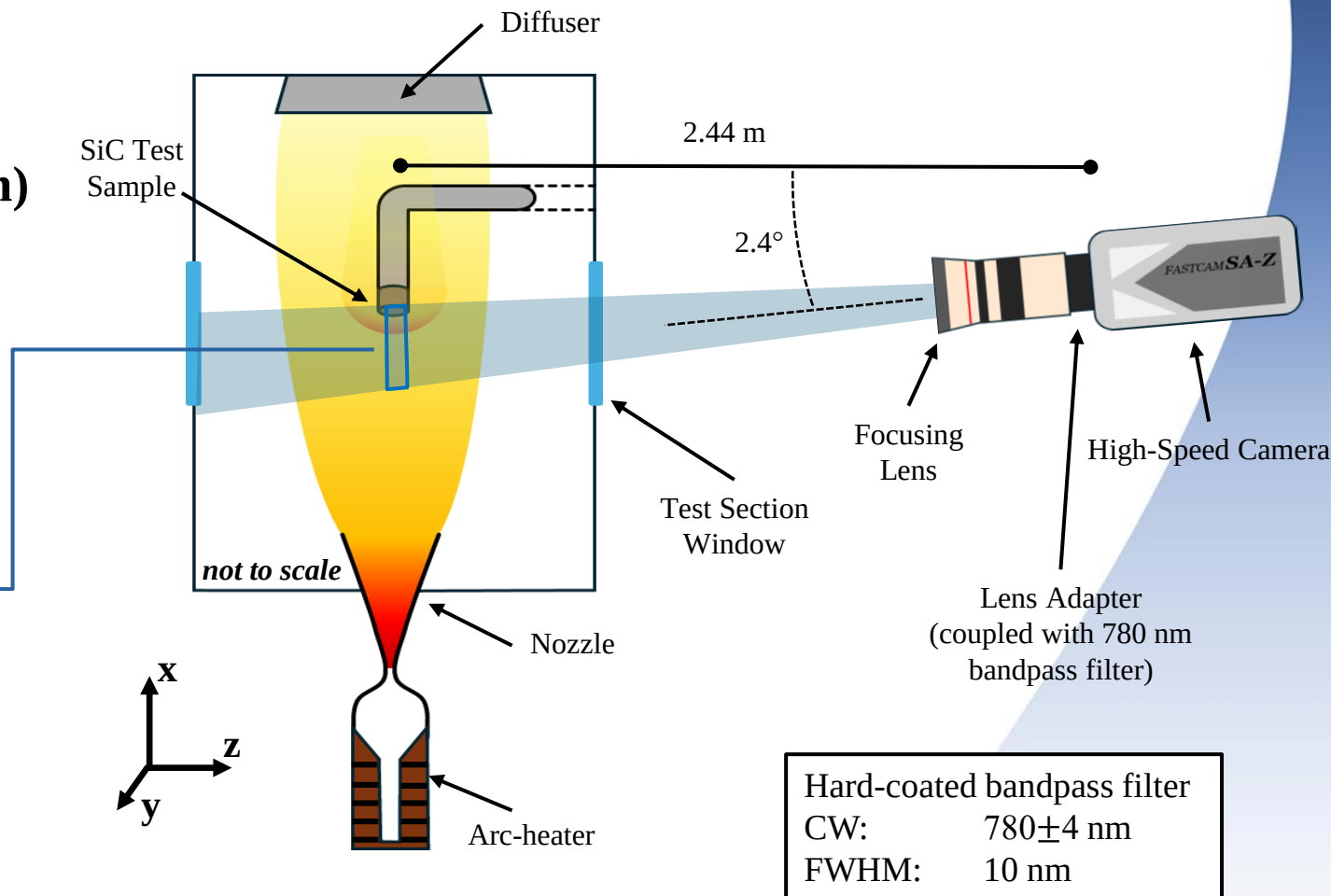
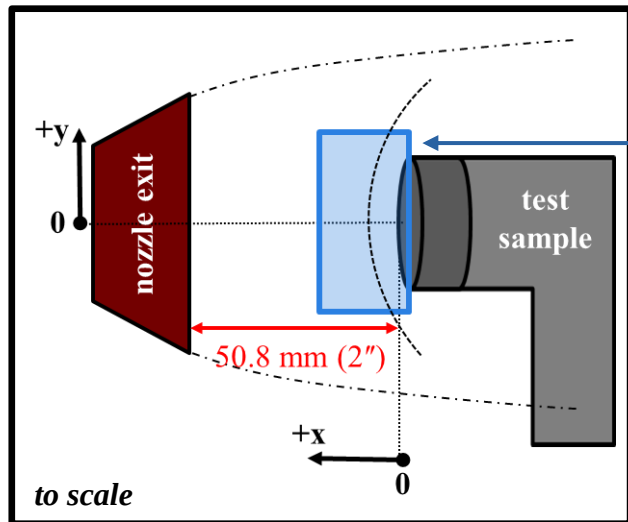
Experimental Setup



Oxygen emission images are acquired with the test sample **retracted** from and **inserted** into the freestream flow for each test case.

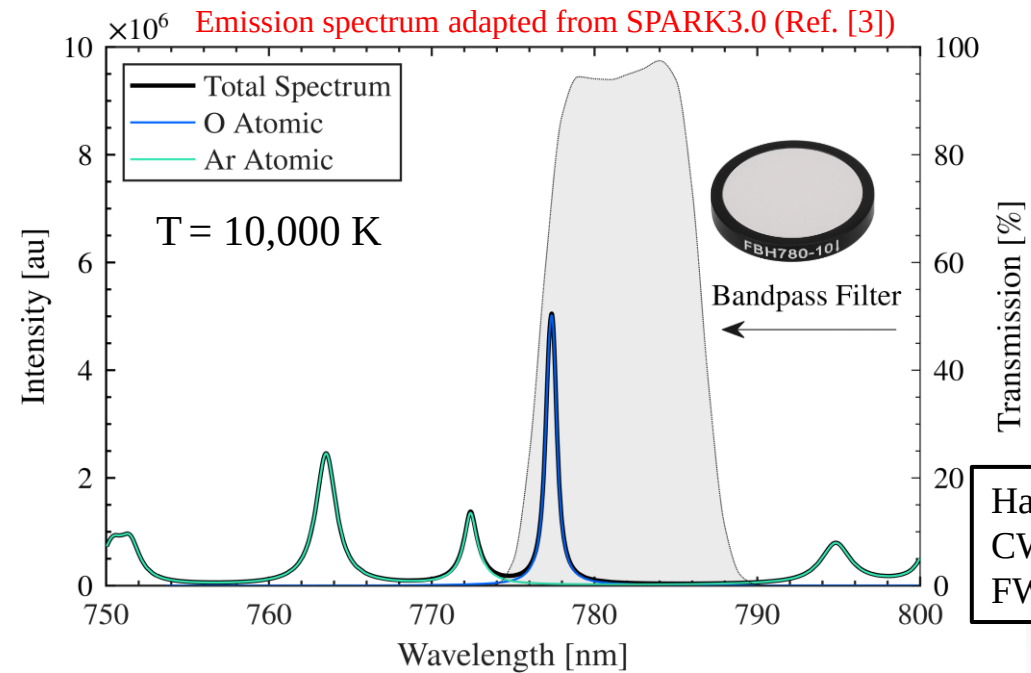
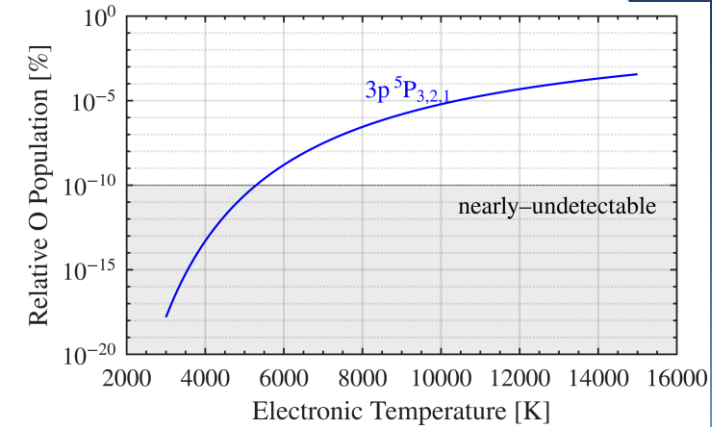
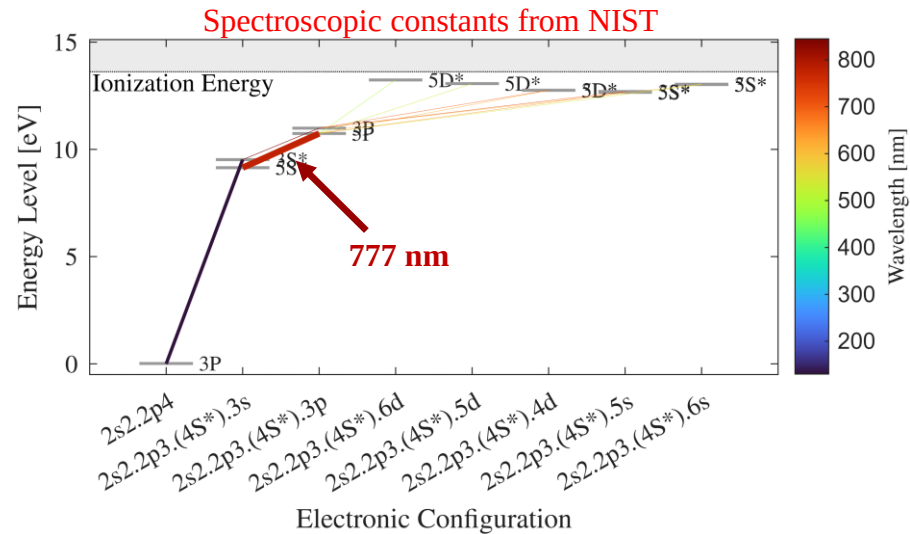
Acquisition Settings

- Frame rate = 300 kHz
- Pixel resolution = 256×128 (44×22 mm)
- Exposure times = $1.37 \mu\text{s}$ (freestream)
 $0.35 \mu\text{s}$ (shock-layer)
- Total frames = 10,000 each (33.33 ms)



- $$E_{ion} = 13.62 \text{ eV}$$

- O₂ dissociation: > 3000 K
- Relevant electronic excitation: > 5000 K



Hard-coated bandpass filter	
CW:	780±4 nm
FWHM:	10 nm

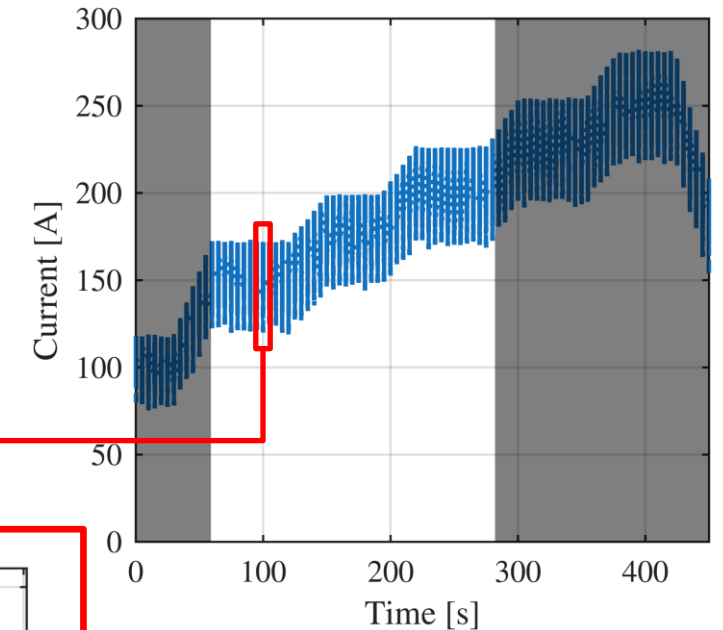
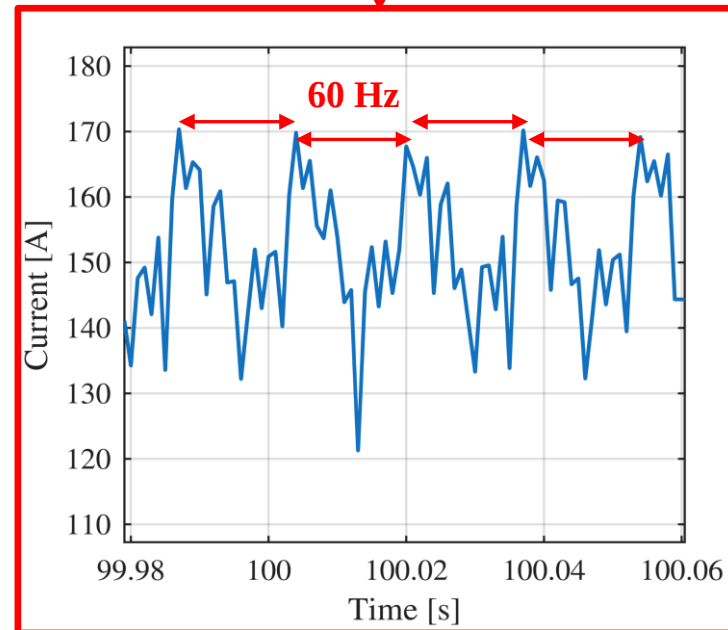
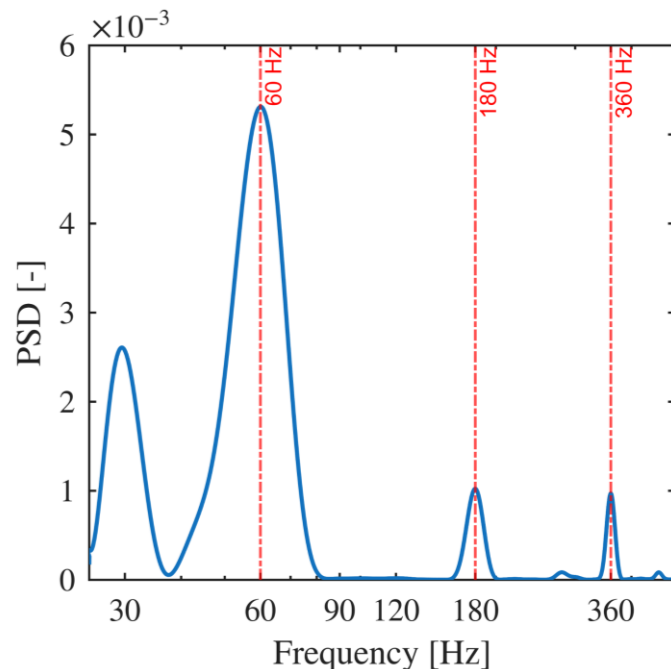


Results

Tunnel Operational Measurements



- Arc-current measured at a 1000 Hz acquisition rate.
- Low-frequency fluctuations are visible at each operating condition.
 - 60 Hz fundamental frequency with 3rd and 6th harmonics, and sub-harmonic.
- Possibly due to residual AC component that is unfiltered in AC/DC converter.

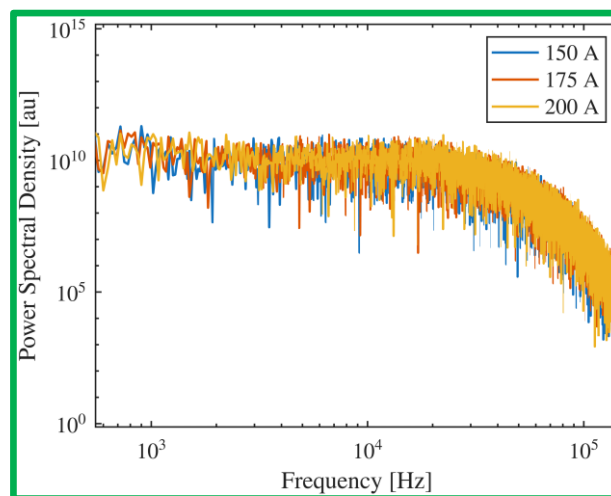
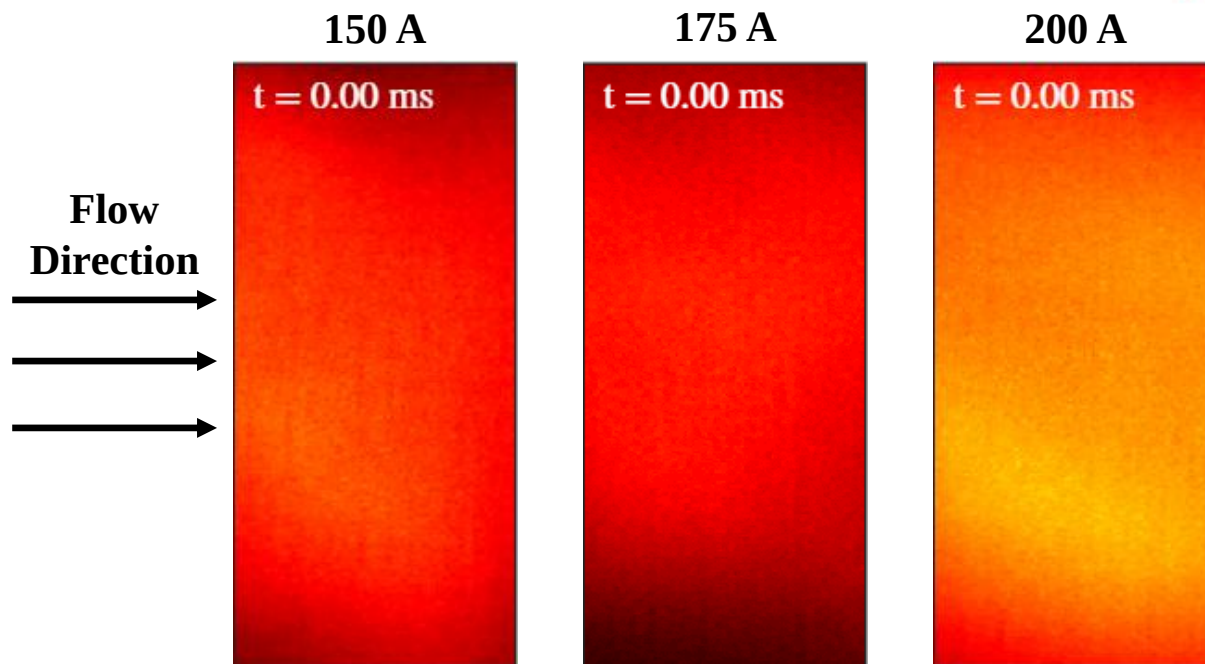
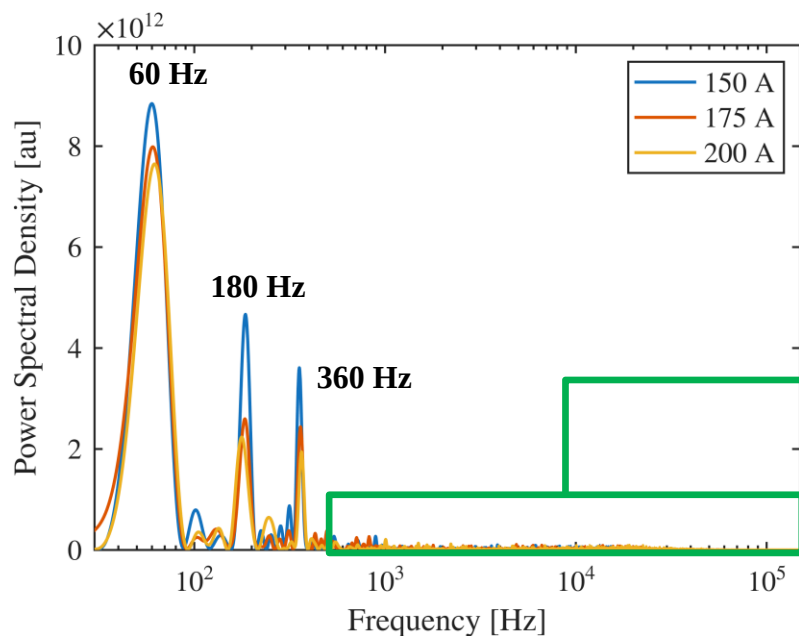


Freestream Oxygen Emission



➤ Consistent temporal fluctuations at each test condition.

- Notable low- and high-frequency variation.
- FFT dominated by 3 low-frequency oscillations.
 - $f = 60, 180, \text{ and } 360 \text{ Hz}$



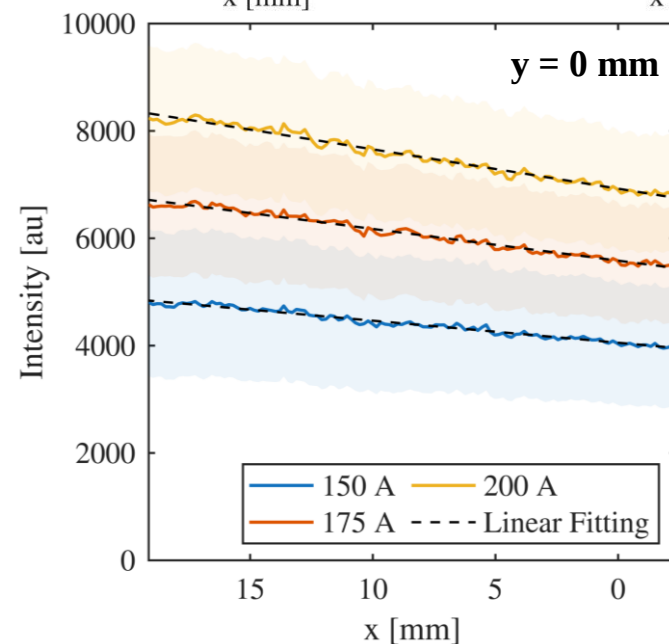
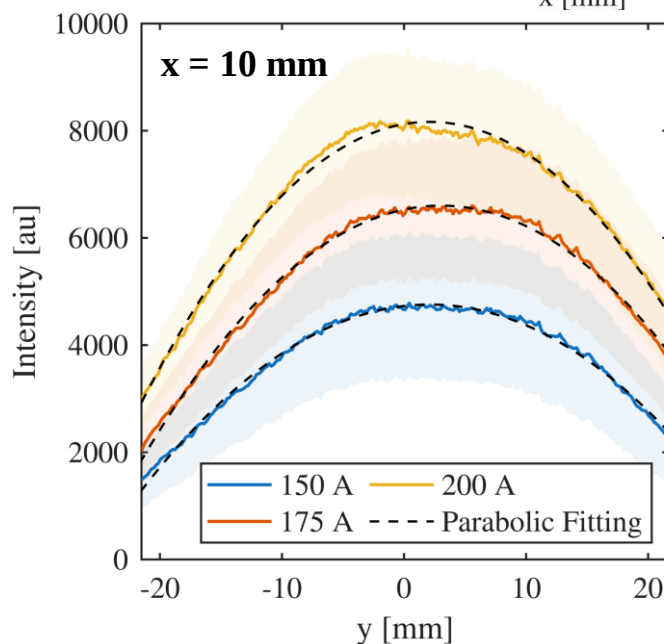
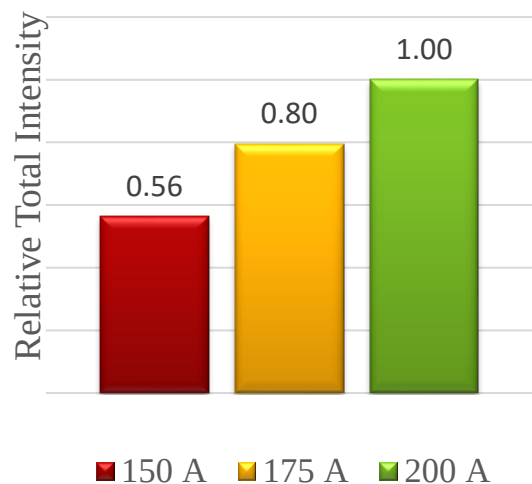
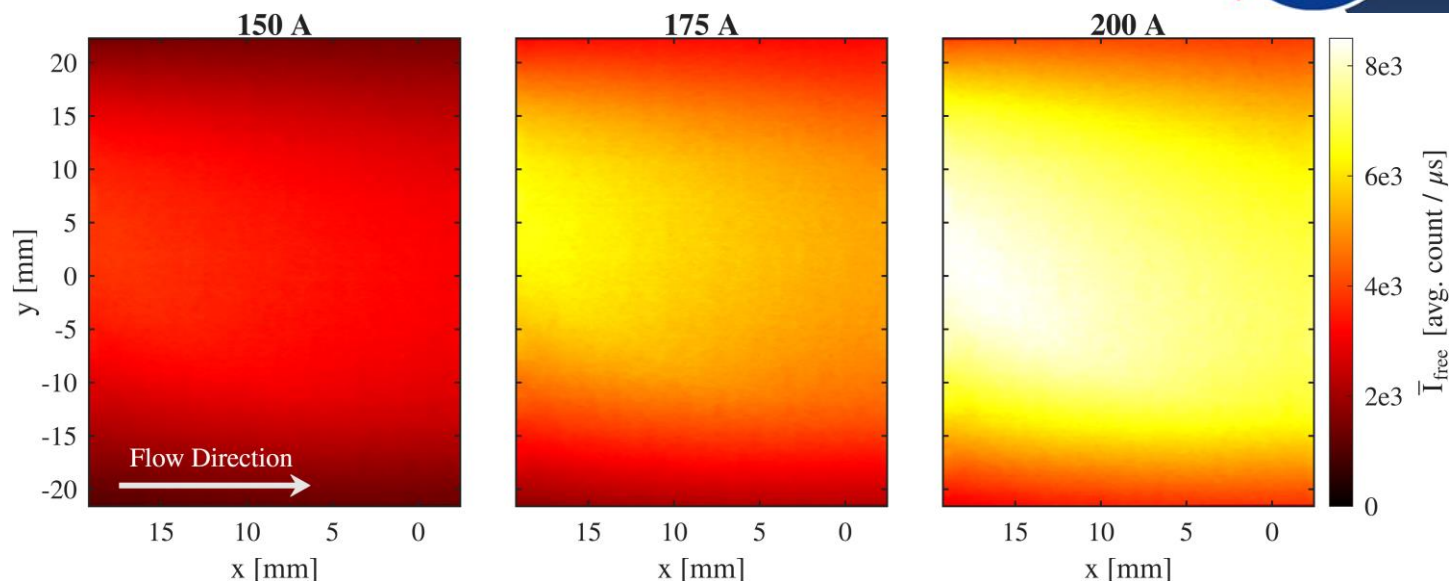
❖ All frequency spectra are measured between 30 and 150,000 Hz with a resolution of 30 Hz.

Freestream Oxygen Emission



- Time-averaged emission reveals a linear ramping in total intensity with increasing arc-current.

$$I_{tot} = \iint_{\Omega} I(x, y) dA$$

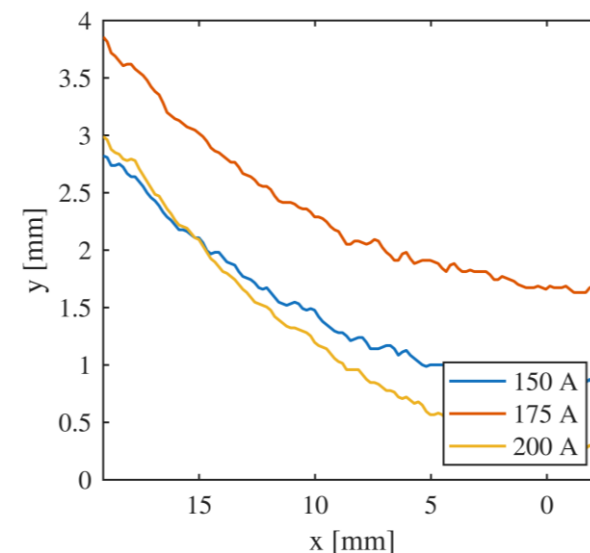
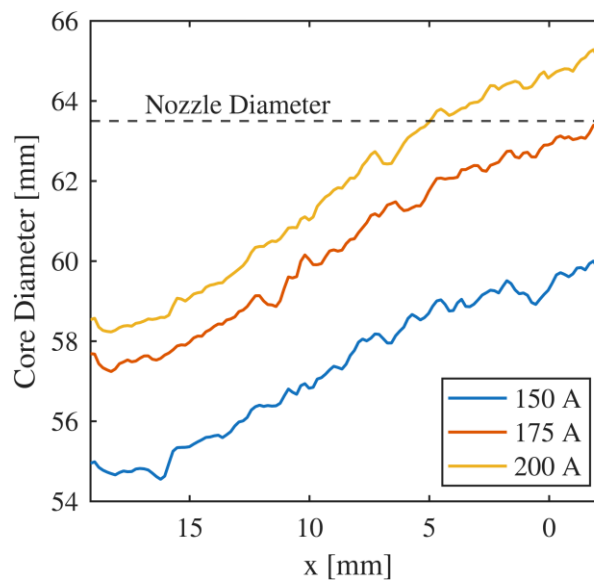
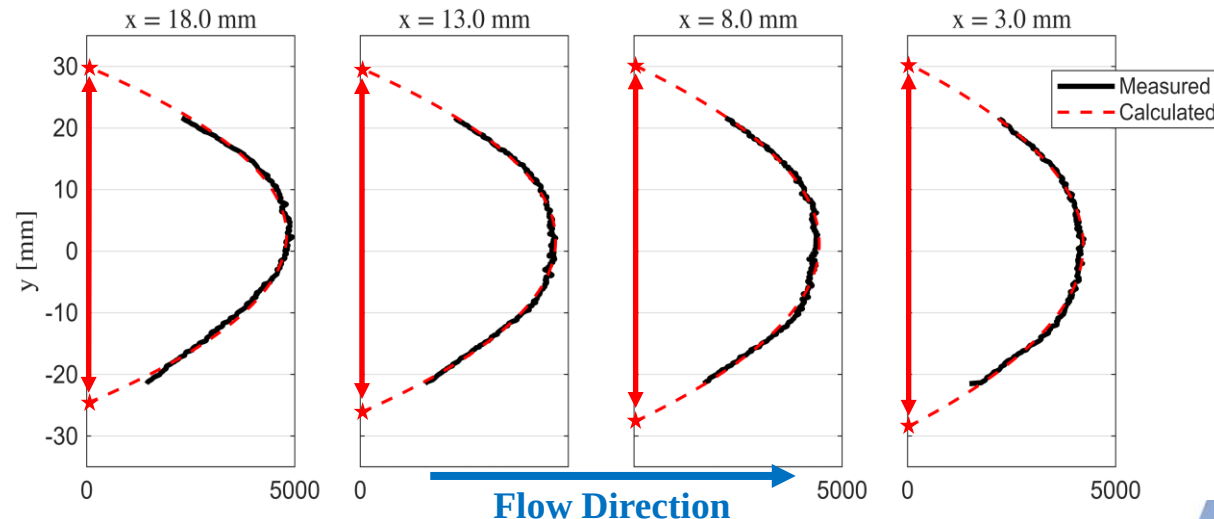
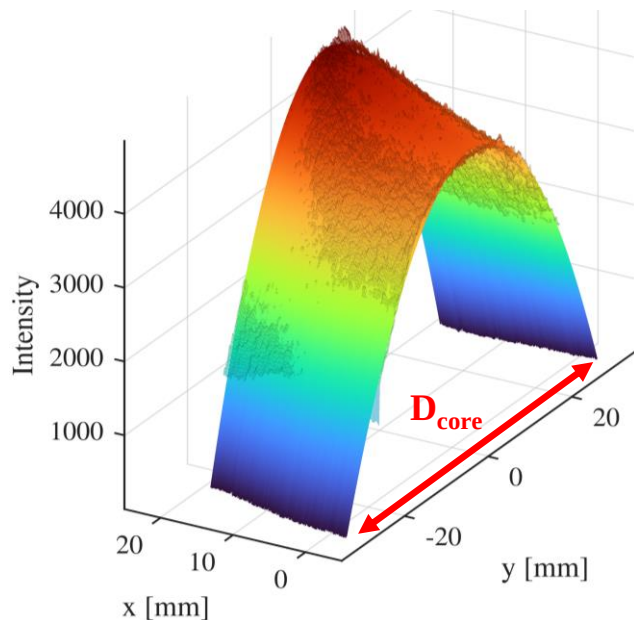


Freestream Oxygen Emission



➤ Expanding the 2nd order polynomial profile to estimate the hot core diameter (D_{core}).

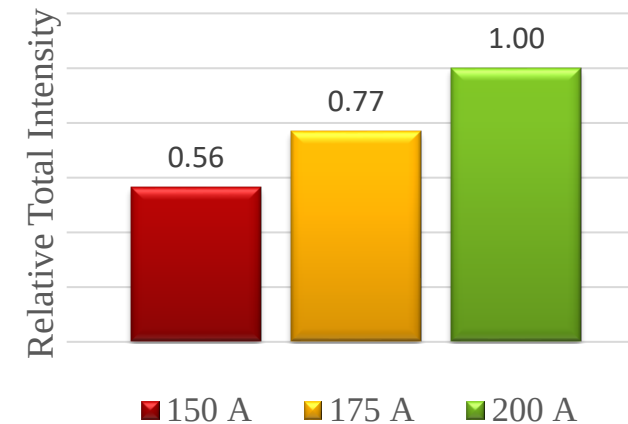
- D_{core} expands in the streamwise direction and increases with arc-current.
- Peak emission propagates with a slight downwards tilt.



Oxygen Emission in Shock-Layer

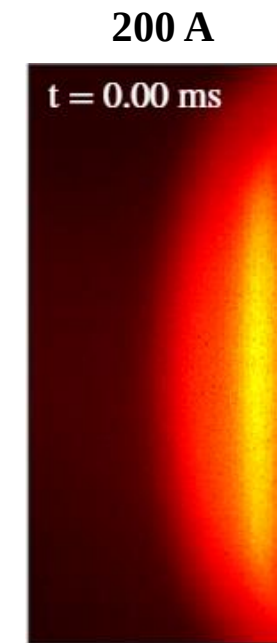
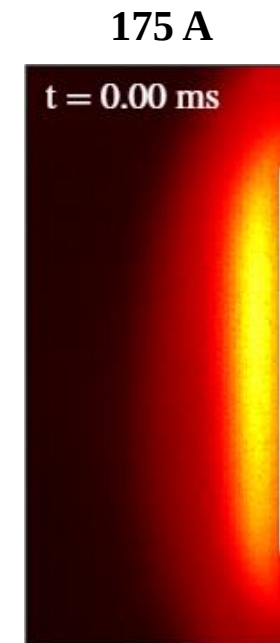
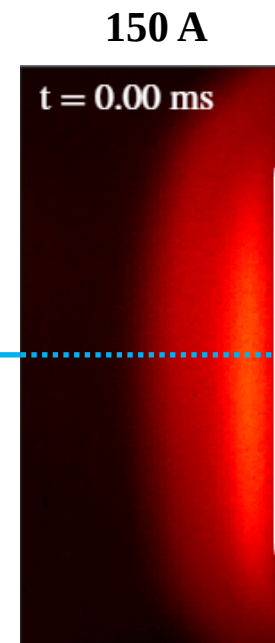
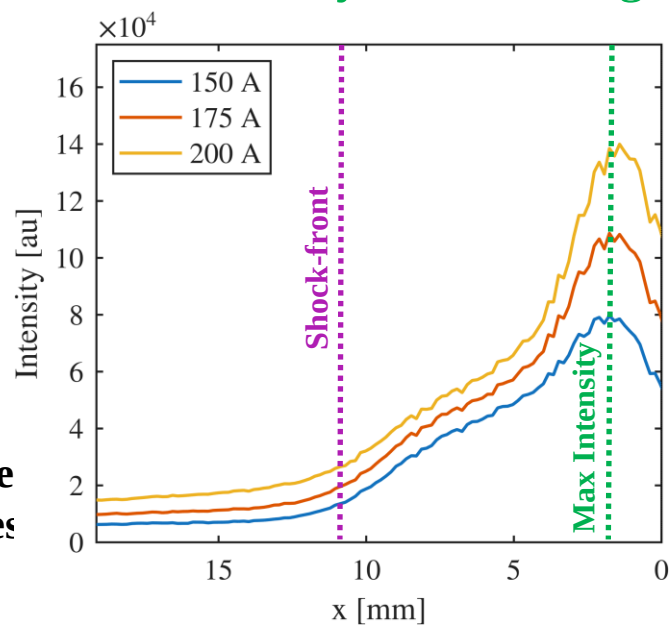


- Upstream fluctuations have notable impact on the shock-layer emission.
- Total intensity increases with arc-current.
 - Relative intensity changes are nearly the same as freestream.



Main Regions of Interest:

1. Emission near the shock-front.
2. Maximum intensity near the stagnation region.



SiC Test Sample

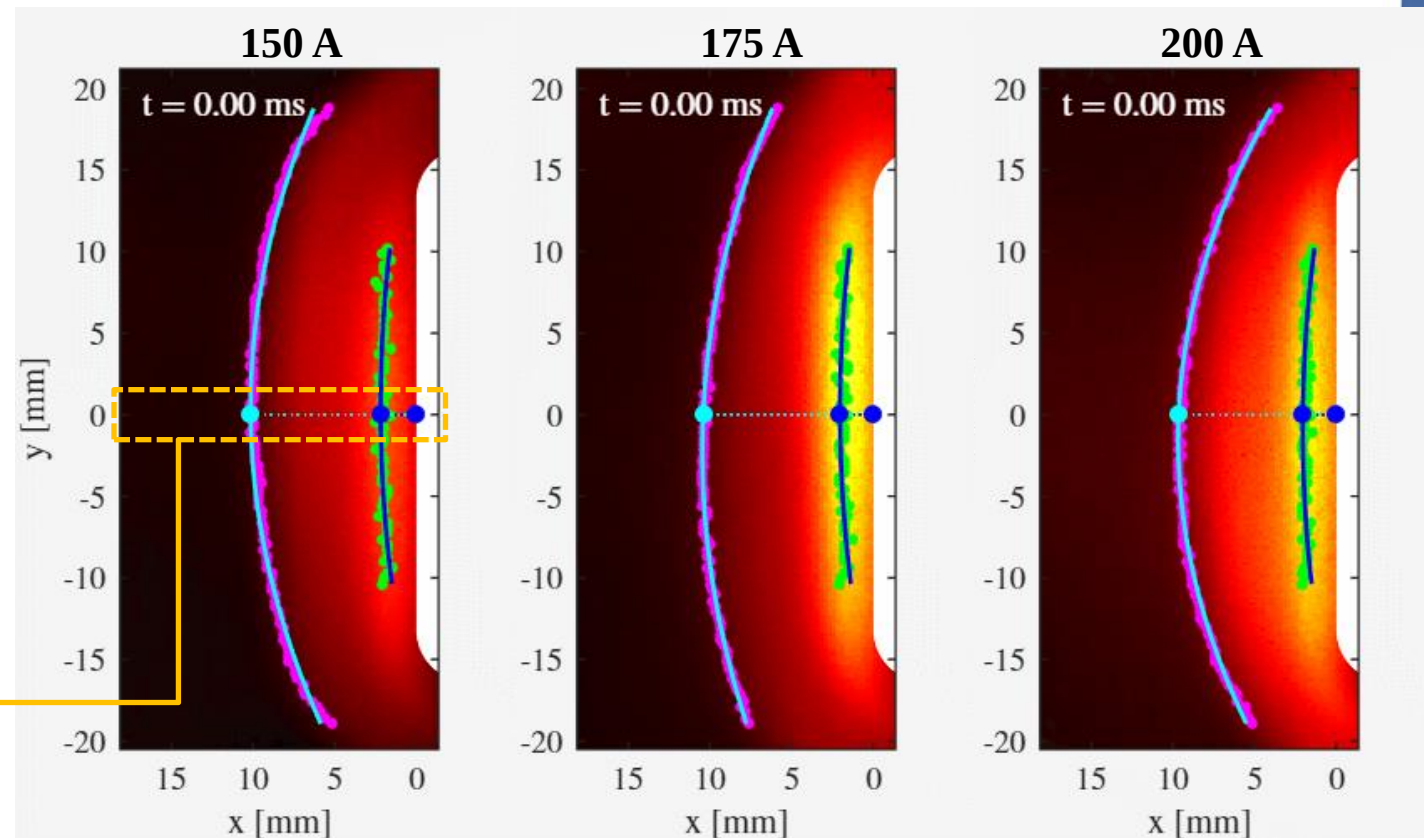
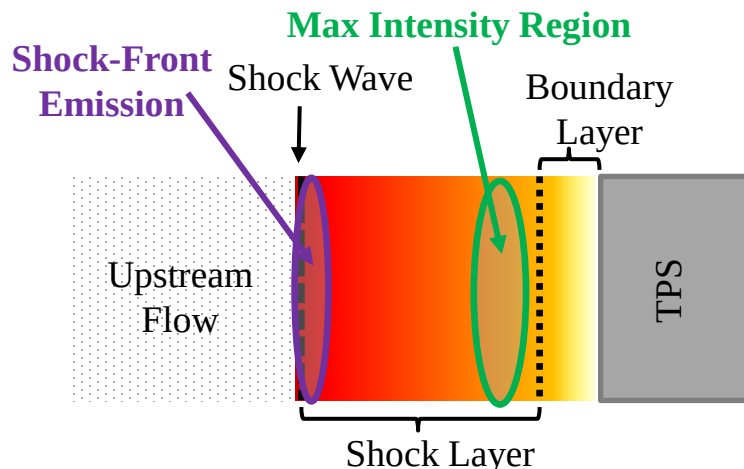
Oxygen Emission in Shock-Layer



Line tracking is used to evaluate the location of the initial intensity increase behind the shock front and the maximum intensity near the stagnation region.

Tracking Method:

- Flagged locations are defined by the 1st x-position to reach the intensity threshold.
 - $I_{SF} = 2 * \bar{I}_{\infty}$ $I_{max} = \max(I)$
- Adaptive 2nd order fitting to reject outlier and reduce noise.

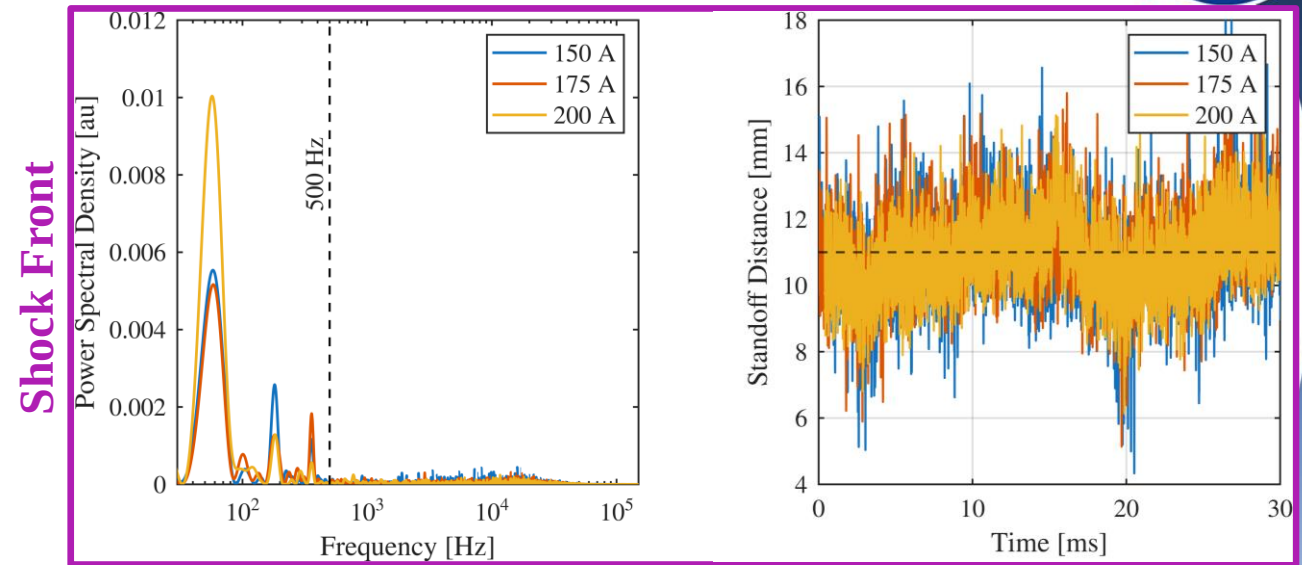


Oxygen Emission in Shock-Layer



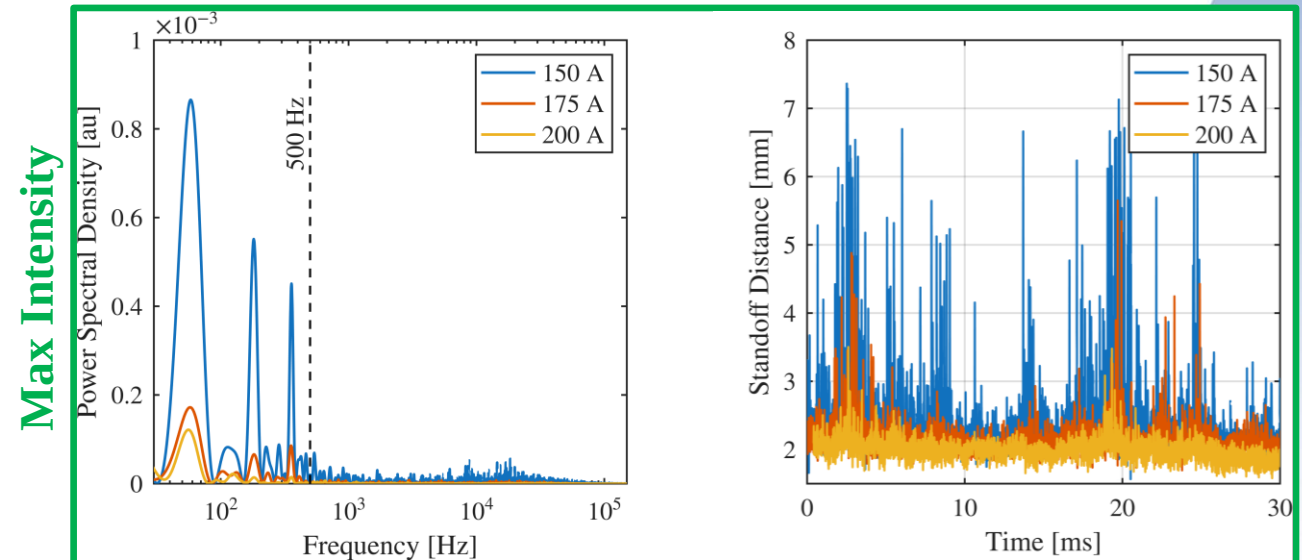
Shock-Front at $y = 0$

- FFT dominated by 60, 180, and 360 Hz oscillations.
 - Magnitudes are independent of arc-current.
- Standoff distance is 11 ± 5 mm over the 33 ms duration for each case.



Max Intensity at $y = 0$

- Higher arc-current leads to lower magnitude of the same frequencies.
- Mean standoff distances are **2.4**, **2.2**, and **2.0 mm** at 150, 175, and 200 A, respectively.



Standoff distances with marker * have zero-phase low pass filtering at 500 Hz.

Conclusion



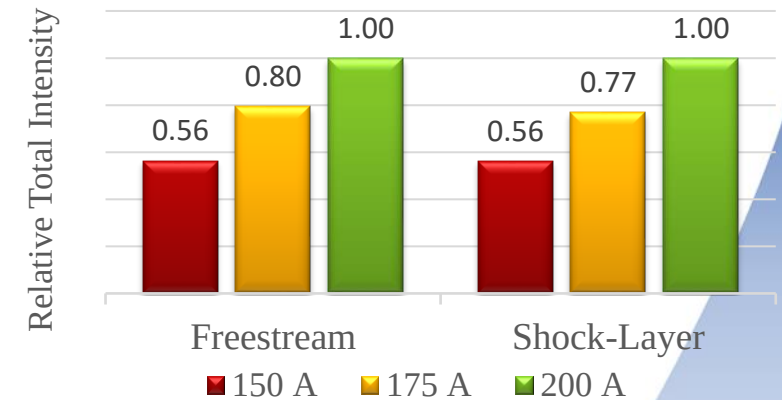
➤ Freestream Emission

- Qualitative imaging revealed positive correlation between arc current and emission intensity.
 - i.e., increase in $3p^5P_{3,2,1}$ atomic oxygen number density (along line of sight).
- Hot-core diameter increased with current and in streamwise direction.
 - Resembling slightly under expanded jet.
- Large temporal fluctuations (60, 180, and 360 Hz)

➤ Shock-Layer Emission

- Upstream fluctuations have large effects on shock-front standoff distance and the max intensity location.

➤ The propagation of arc-current fluctuations to the freestream and shock-layer motivates the need for improved AC/DC conversion.



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References



1. Schwartz, T., Splinter, S. C., Rodrigues, N. S., Danehy, P. M., Samuels, K. E., Kostyk, C. B., and Hanson, R. K., “Spatially-Resolved Atomic Oxygen Absorption and Emission Measurements in the Hypersonic Materials Environmental Test System,” *Applied Physics B*, Vol. 131, No. 6, 2025, p. 115.
2. Splinter, S., Bey, K., Gragg, J., and Brewer, A., “Comparative Measurements of Earth and Martian Entry Environments in the NASA Langley HYMETs Facility,” *49th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, American Institute of Aeronautics and Astronautics, Orlando, Florida, 2011.
3. Lopez, B., and Lino Da Silva, M., “SPARK: A Software Package for Aerodynamics, Radiation and Kinetics,” *46th AIAA Thermophysics Conference*, American Institute of Aeronautics and Astronautics, Washington, D.C., 2016.



Thank You for Your Attention.

Any Question?