

High-speed Laser Diagnostics in Hypersonic Flows

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Gordon Research Conference
Laser Diagnostics in Energy and Combustion Science
July 9–14, 2023

Challenges in Hypersonics

Hypersonics: Mach > 5

Shock wave–boundary layer interactions are a major source of flow unsteadiness and responsible for creating “hot spots” that can lead to catastrophic fin/wing/flap failure.

Flow-structure interaction can weaken aero-structures both internally and externally—difficult to model and requires simultaneous measurements.

High-temperature and ablating materials enable efficient thermal protection systems, but induce fluid and thermochemical effects which are challenging to model and measure.

Boundary layer transition measurement and prediction is critical for control surface authority and heating load predictions.

Aero-optical effects and associated beam-steering errors are important for target recognition, ISR applications, and high-speed diagnostics.

High-temperature sensors, both surface and optical, are a critical enabling technology for useful hypersonic flight and wind-tunnel tests.

Ideally Required Instrumentation Capabilities for Hypersonics

(To understand physics, to aid modeling and simulation, to develop sensors and control methodologies)

Parameters of interest	Requirements
Velocity (V)	100 kHz–1 MHz sensor capable of providing velocity along a line, a plane, or in a volume (Possible solutions: ns, ps, and fs burst-mode laser; plasma anemometer)
Temperature (T)	Pointwise and—if possible, along a line—rotational and vibrational temperatures at rates of 100–500 kHz (Possible solutions: dual-pump dual-broadband CARS N ₂ or NO)
Pressure (P)	Non-intrusive surface as well as off-body pressure distribution on a real-time basis (Possible solution: unsteady PSP, from flow velocities)
Flow structure	100 kHz–1 MHz rate 2D or 3D imaging (Possible solutions: Schlieren and burst-mode OPO-based Kr-PLIF, NO-PLIF, NO ₂ -PLIF)
Species concentration	100 kHz–500 kHz rate imaging of O, N, and other key chemical species for reacting hypersonic flows such as OH and CH ₂ O (Possible solutions: ns burst-mode laser for OH, CH ₂ O and other species for reacting hypersonic flows; fs burst-mode laser for O and N)
Heat flux	V and T measurements at a rate of 100 kHz–500 kHz will provide real-time heat-flux measurements
Characterization of ablating species	Real-time detection of species during ablation when material is exposed to relevant environments (Possible solutions: high-speed, hyperspectral 2D emission sensor)
Density	100 kHz–500 kHz rate 2D/3D Rayleigh Scattering (Possible solution: ns burst-mode laser) Background-oriented Schlieren (Possible solution: 100 kHz–500 kHz rate wide-angle plenoptic imaging)

Note: Most hypersonic facilities have short duration run times (1 ms– 2 s); hence they require the above-mentioned instrument data rates for capturing essential flow physics and for reducing tunnel operational costs.

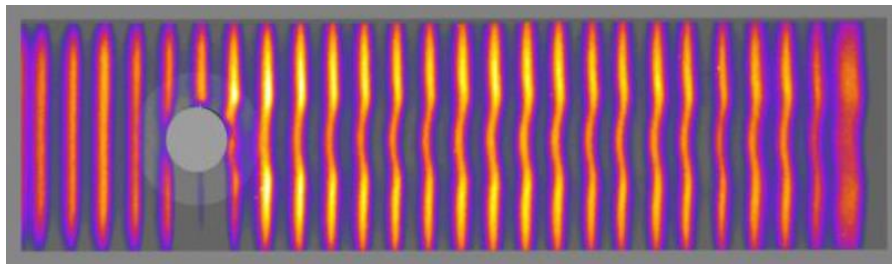
Facility Challenges

- Large test section, 1–2 m test section diameter
- Long focal length, small collection solid angle, and extremely low pressure
- Short test time, usually in ms level
- Harsh environment, long beam path, no/limited AC
- Limited optical windows
- Complicated system

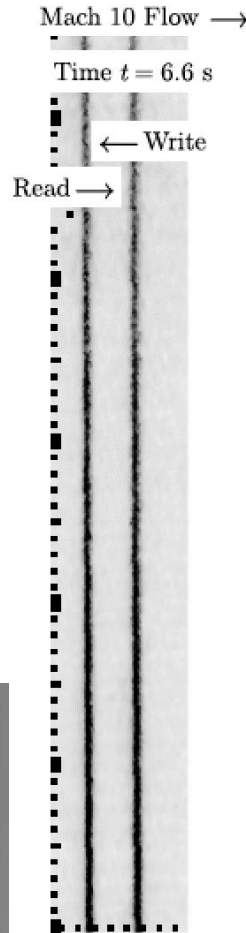


Hypersonic Flow Diagnostics

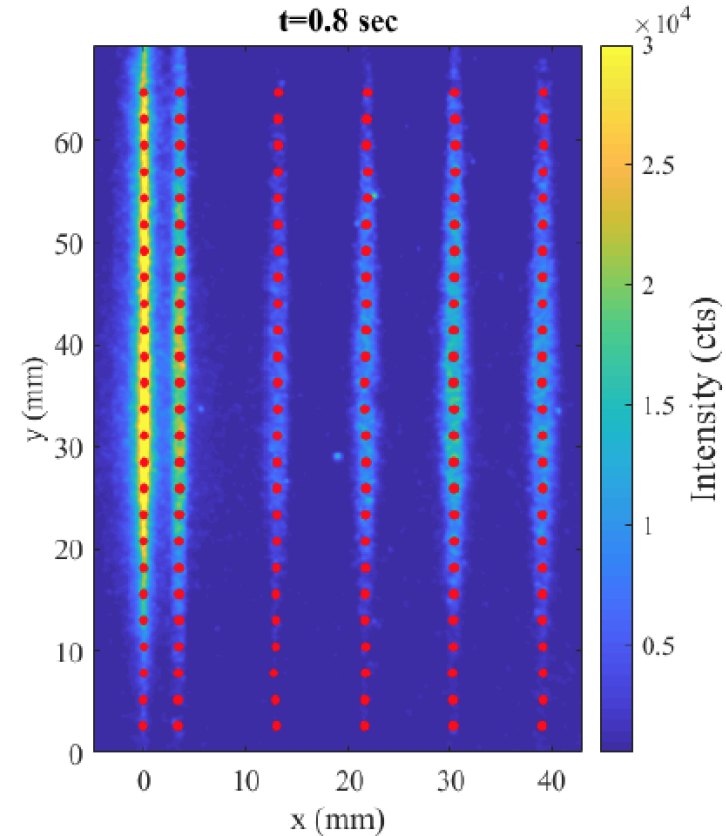
- Physical sensors
- Schlieren/shadowgraph
- 10-Hz: PLIF, MTV, Mie Scattering, CARS, Rayleigh/Raman
- 1-kHz: FLEET, fs-CARS
- Higher speed: Schlieren, FLDI, PLIF, MTV, Mie/Rayleigh scattering



NO MTV in Mach 10 Tunnel at
NASA Langley



10-Hz KTV in Tunnel 9



1-kHz FLEET in Tunnel 9

BF Bathel, PM Danehy, et al, AIAA J. 2011. N. Parziale, et al. AIAA Scitech 2015. A. Dogariu, et al. AIAA Scitech 2021.

Previous Work

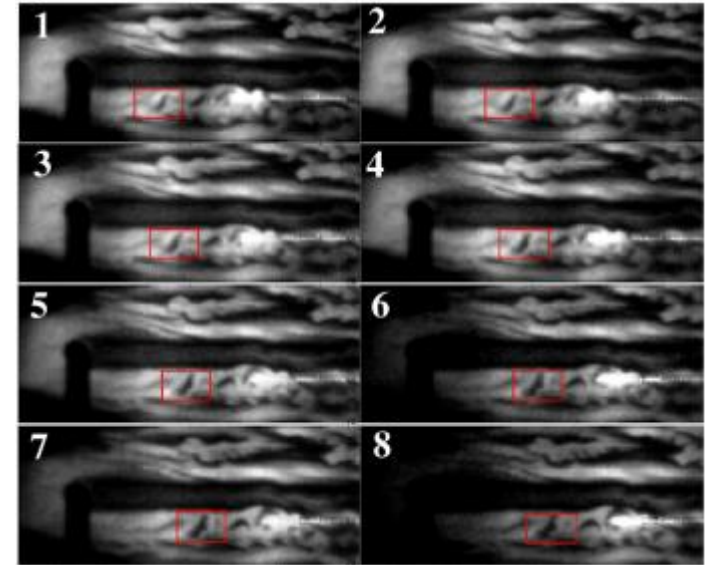
Heating up Discovery's heat shield

Discovery will plunge back through Earth's atmosphere with a built-in "speed bump" on one of its thermal tiles. The quarter-inch protuberance will increase temperatures to simulate conditions NASA's next-generation Orion space capsules will encounter during atmospheric re-entries.

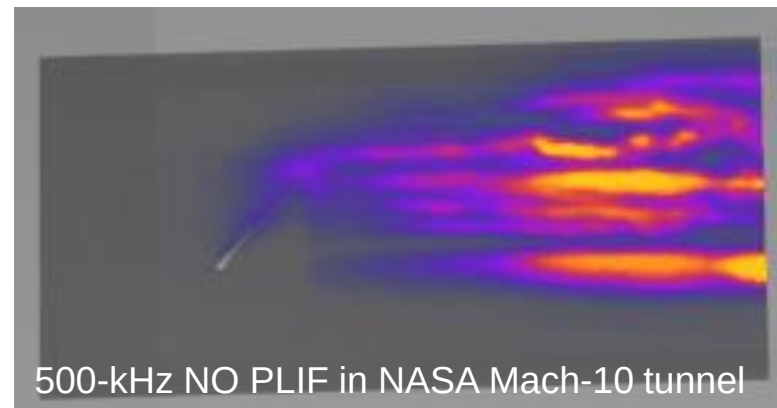


Sources: NASA, The Boeing Co., researched by James Dean, FLORIDA TODAY

Dennis Lowe, FLORIDA TODAY



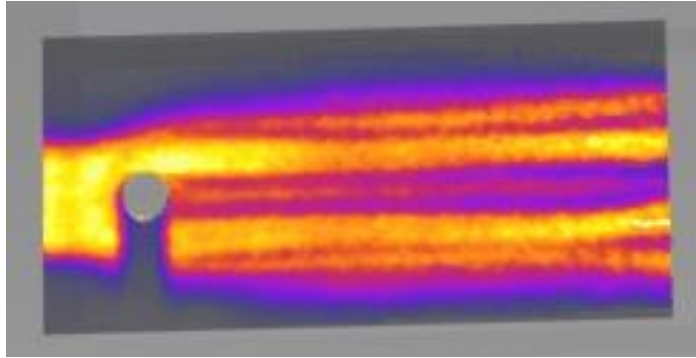
1MHz NO PLIF in NASA Mach 10 Tunnel



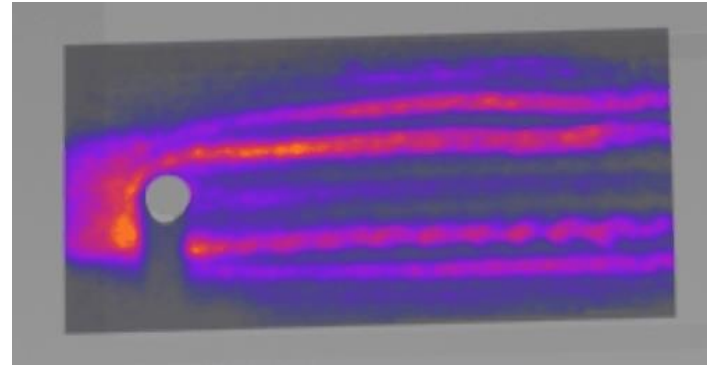
500-kHz NO PLIF in NASA Mach-10 tunnel

NO PLIF Imaging-NASA Langley

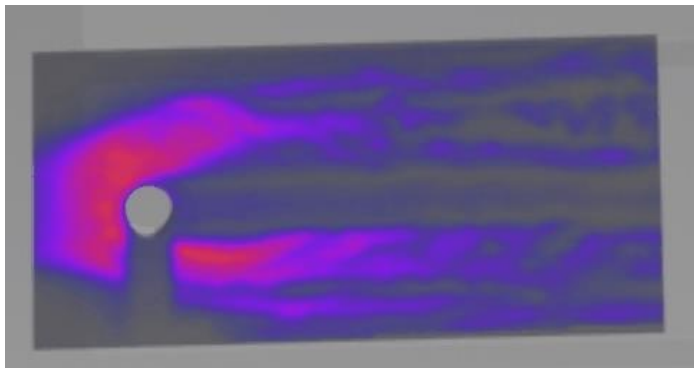
2.4 MPa, $Re = 1.5$ million/m 500 kHz



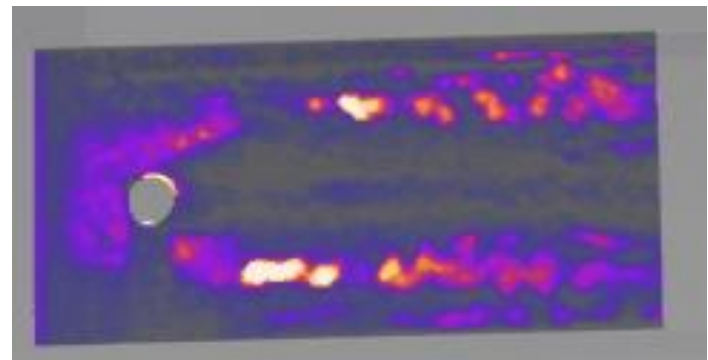
3.4 MPa, $Re = 2.1$ million/m 500 kHz



4.9 MPa, $Re = 3$ million/m 1 MHz

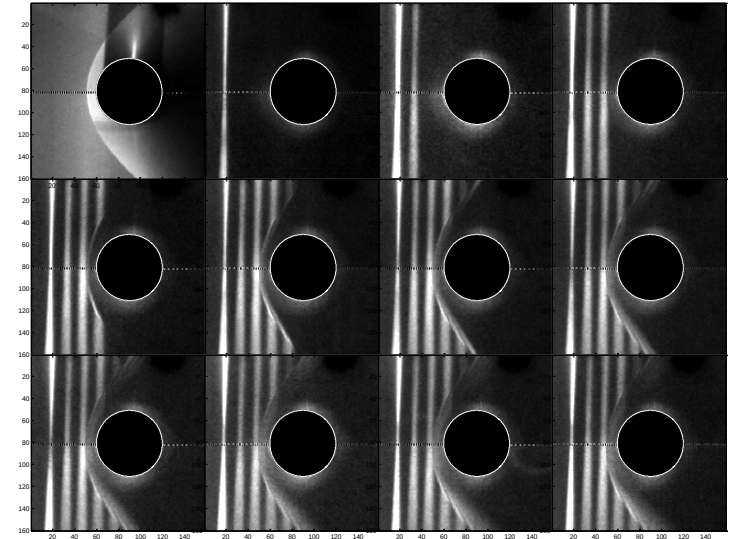
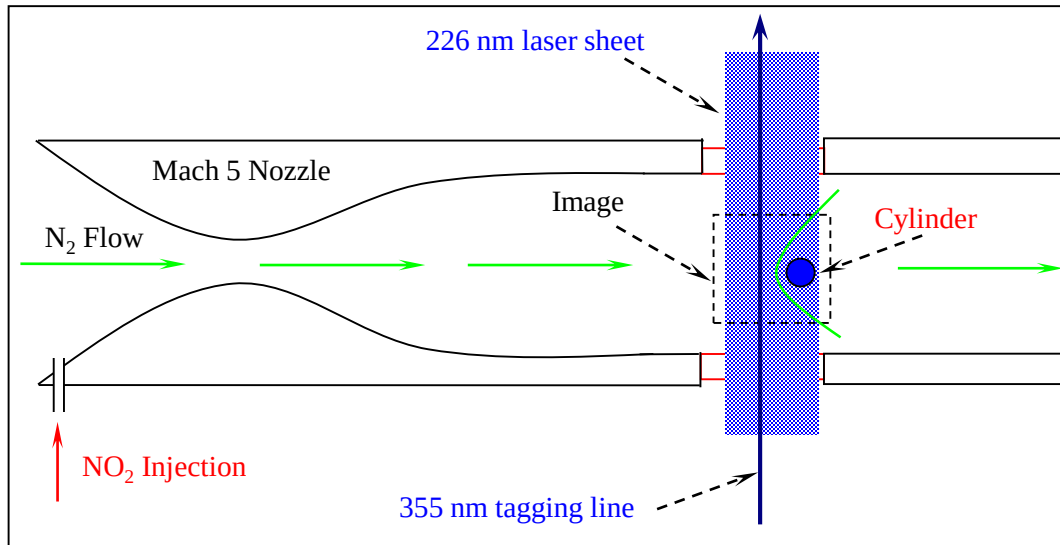


9.2 MPa, $Re = 5.6$ million/m 500 kHz

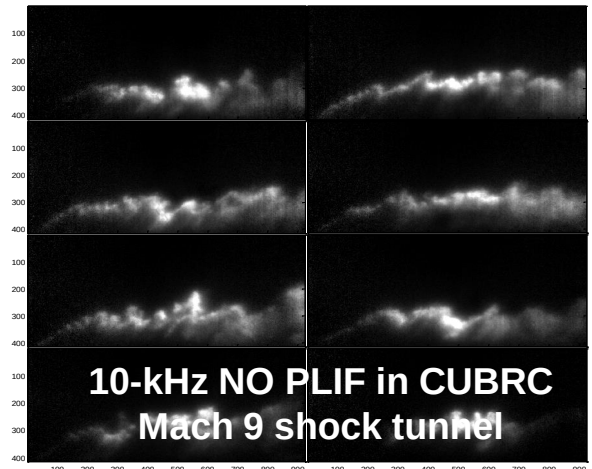
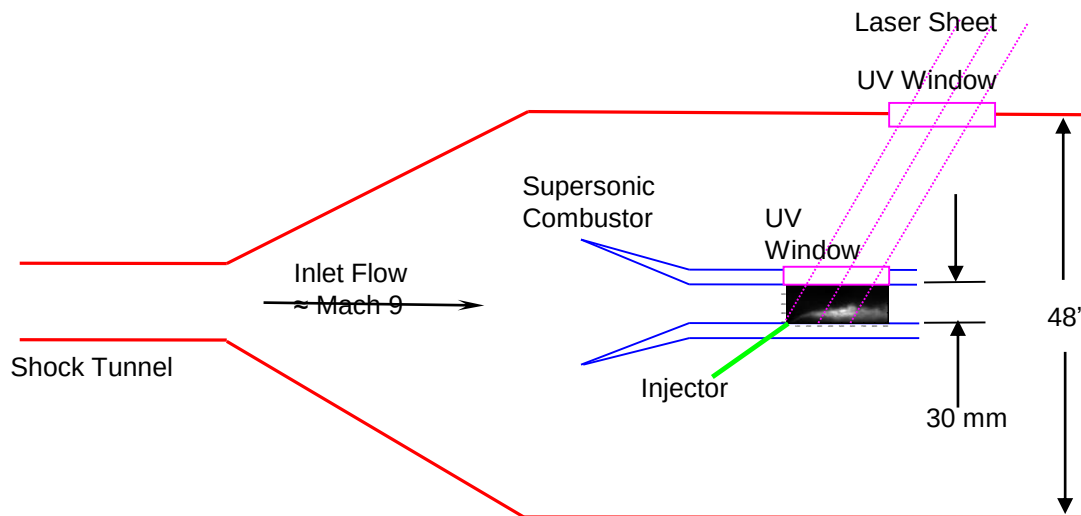


2 mm tall x 4 mm wide cyl trip - Reynolds Number Comparison
~ 1 mm above surface

Previous Work



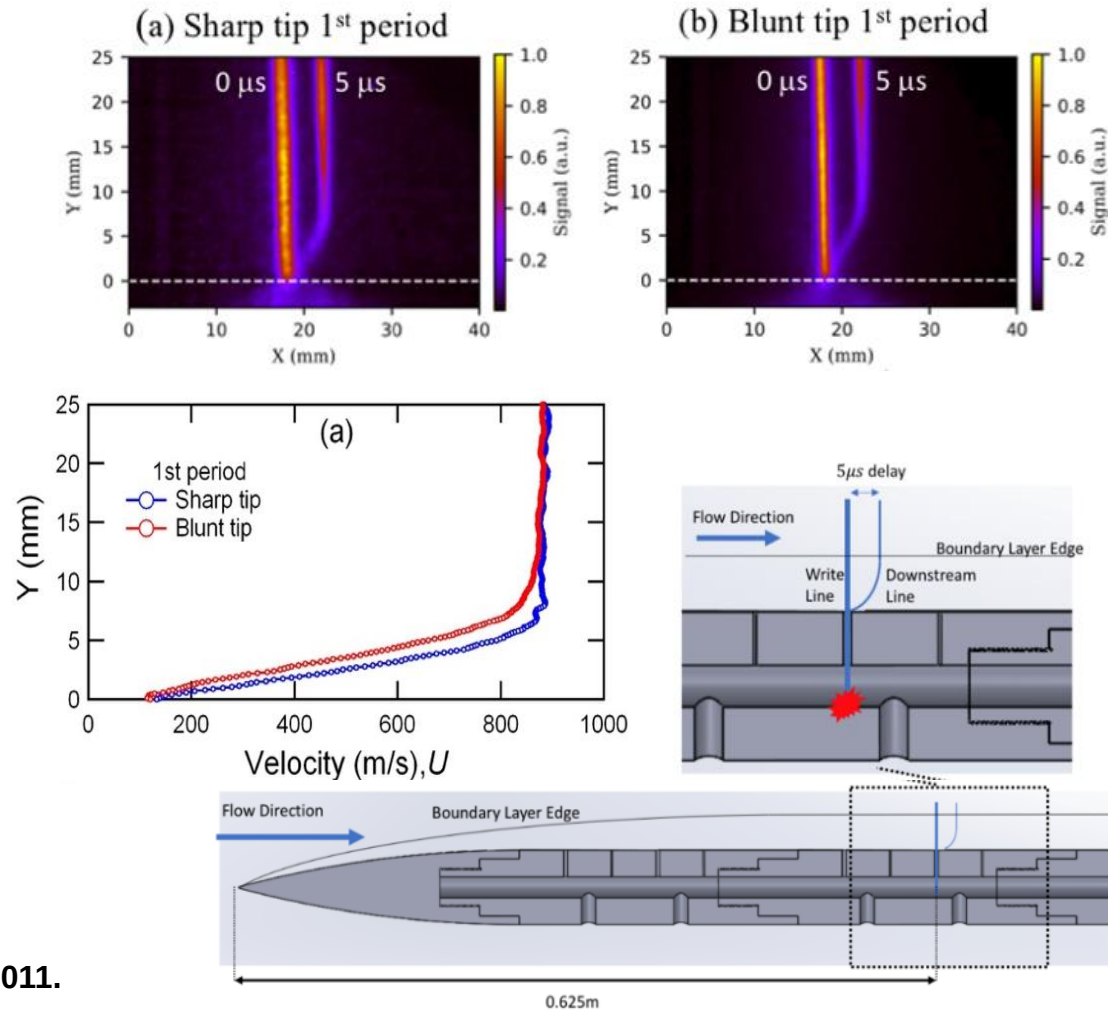
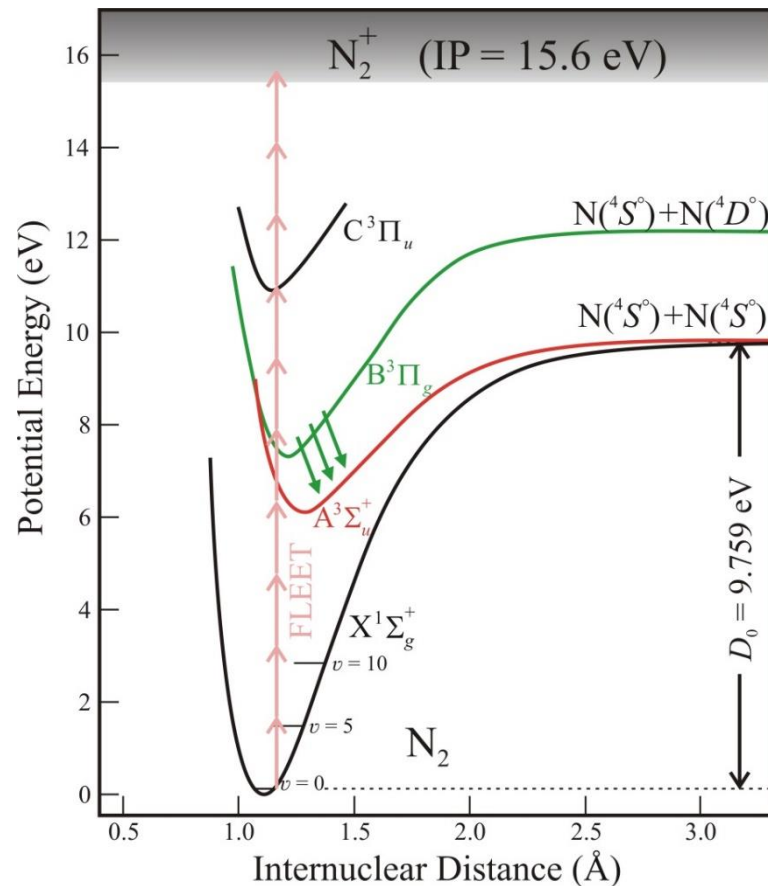
500 kHz NO_2 MTV in a Mach 5 Tunnel



10-kHz NO PLIF in CUBRC
Mach 9 shock tunnel

Velocimetry: FLEET for BL Profile

BL Velocity Profile Measured by 1-kHz FLEET in AFRL Mach 6 Ludwig Tube



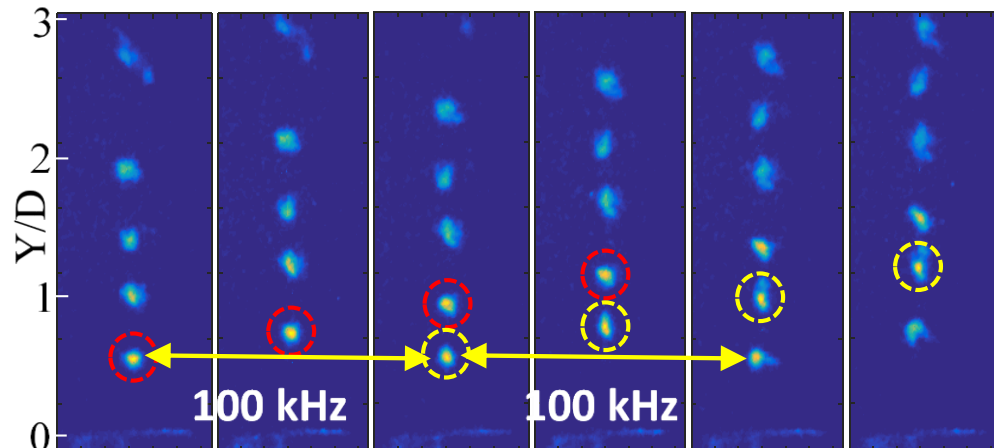
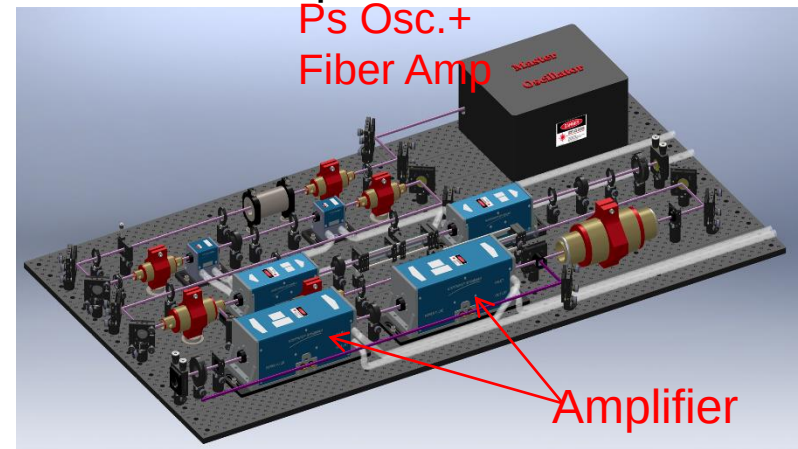
J. Michael, R. Miles et al, Appl. Opt. 50, 5158, 2011.

Ps-Burst-mode Laser-based 100 kHz PLEET Velocimetry

Picosecond laser electronic excitation tagging (PLEET)

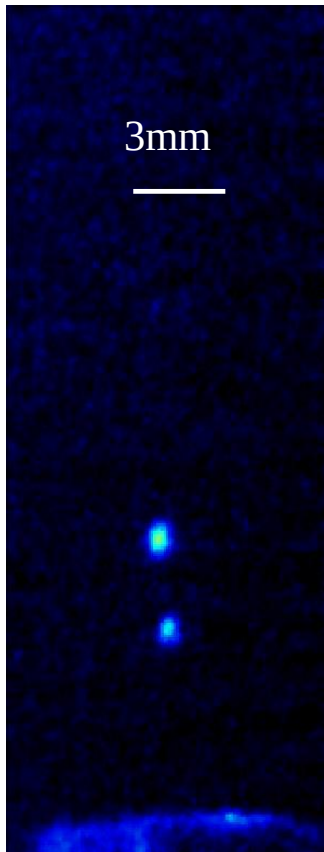
- Up to 500 kHz for both BML and camera
- Three component velocity (depends on imaging system)
- High accuracy (error<2%)
- Sufficient laser energy/power for PLEET at very high repetition rate (200 mJ/pulse at 100 kHz)
- Typical ps laser: 100-200 mJ/pulse @ 10 Hz
- Advantage of ps peak power for driving NL process

kHz-MHz ps-Burst-mode laser

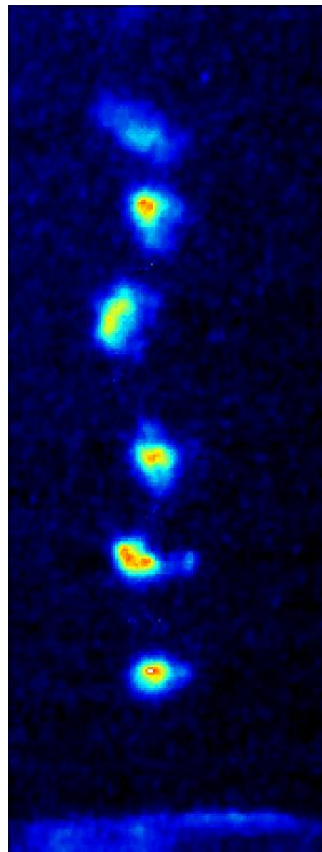


Laser at 100 kHz, camera at 200 kHz)

100-kHz PLEET Application

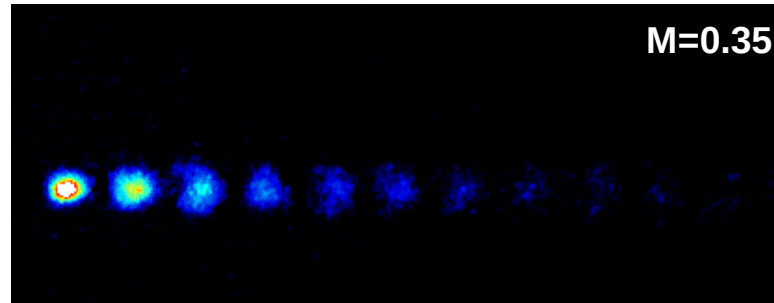


PLEET with
4.5mJ/pulse

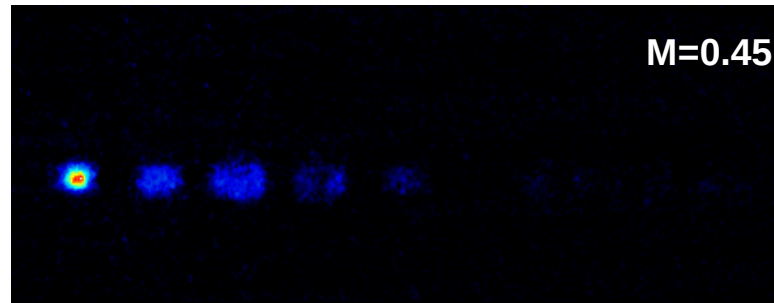


PLEET with
12mJ/pulse

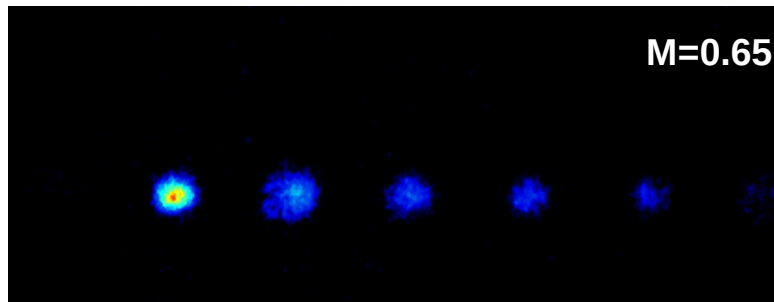
Nitrogen jet flow: ~275 m/s



M=0.35



M=0.45



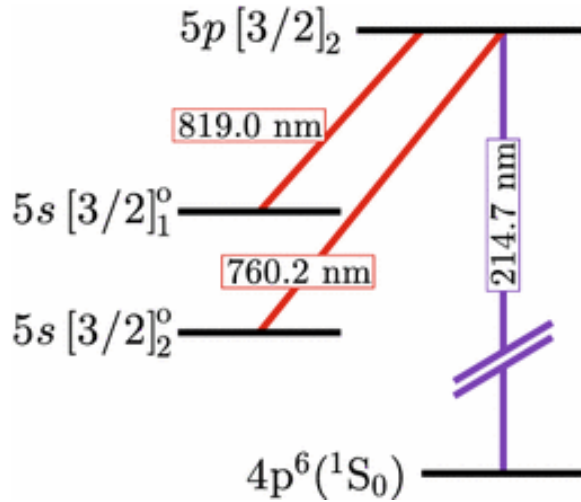
M=0.65

NASA Langley: Wind tunnel core flow measurements

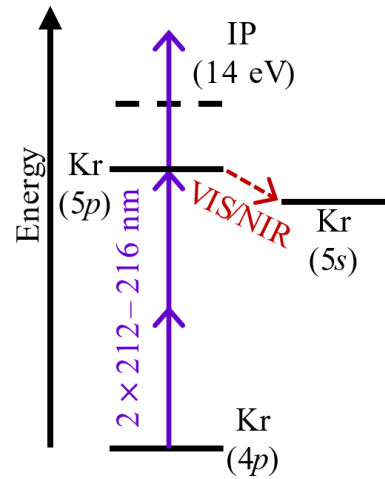
- **Measurement error 0.6–1.2 %**
- **High static pressure (300– 3000 torr)**

Burns et al., Measurement Science and Technology 29, 115203 (2018)

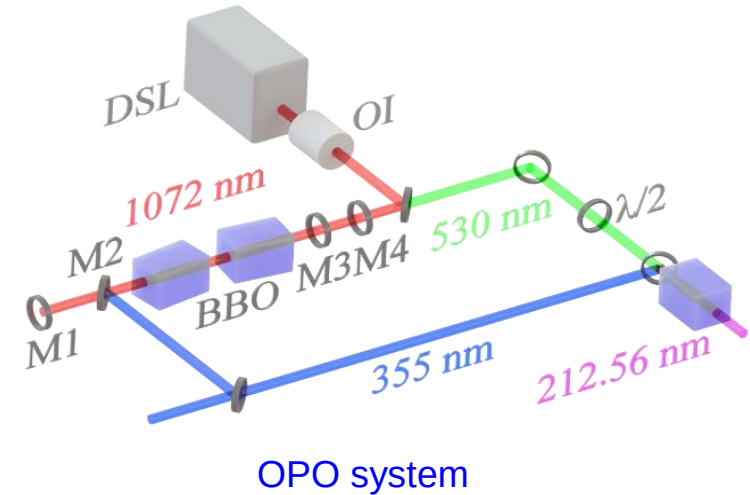
100-kHz KTV



Two-line KTV



Single-line KTV

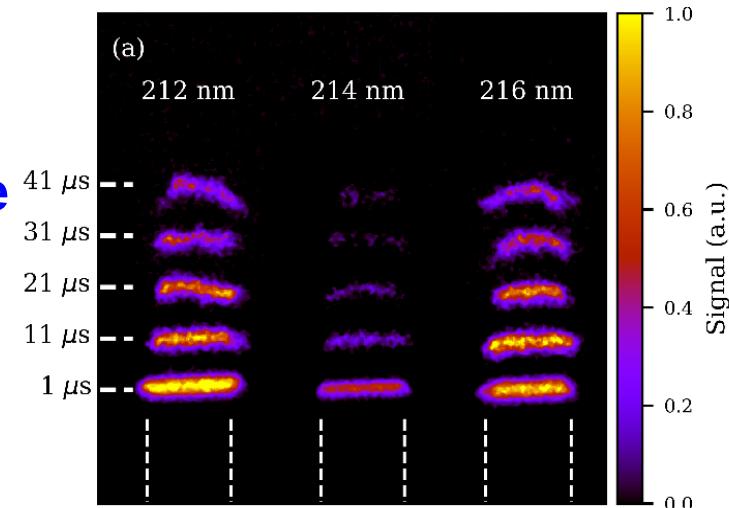


OPO system

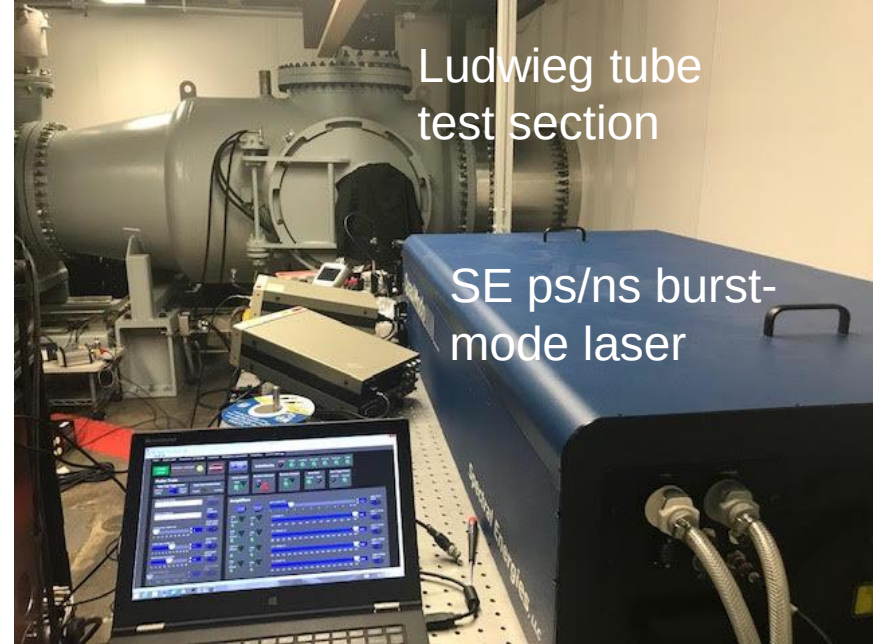
- Burst-mode laser and OPO system
- Single-line KTV is simplified from two-line KTV system with REMPI process
- Demonstrated in Mach-6 Ludwig tube

Jack Mills, Charles Sukenik, and Robert Balla, AIAA-2011-3459, 2011.

N. J. Parziale, et al, Appl. Opt. 54, 5094, 2015.

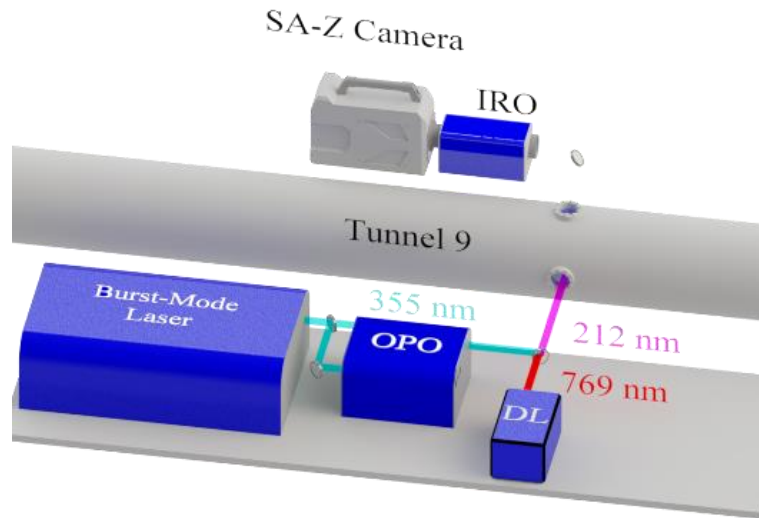


AFRL Mach 6 Ludwig Tube



- Mach 6 air flow at various stagnation pressures of 379 kPa – 4.14 MPa
- Unit freestream Reynolds numbers of $6.56 \times 10^5/\text{m}$ – $3.28 \times 10^7/\text{m}$
 - ~900 m/s with a large-format test section (~1 m from window to center)
 - Good optical access available for optical diagnostics
 - Environmentally controlled test cell
 - Located in Wright-Patterson AFB, convenient for experiments

AEDC Tunnel 9



Mach 18

Reynolds number of $\sim 1.5 \times 10^6/\text{ft}$

Nitrogen gas

Stagnation Pressure: 130 MPa

Stagnation temperature: 1844 K

Test time: ~ 5 seconds

Flow speed: $\sim 1.9\text{--}2.1$ km/s

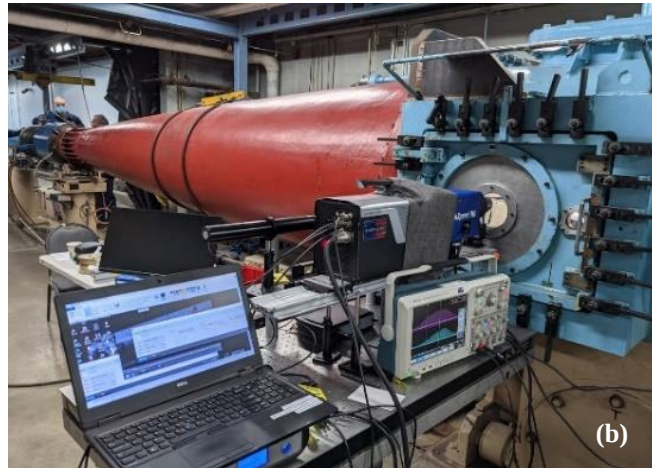
Static temperature: $\sim 35\text{K}$

Static Pressure: ~ 0.4 torr

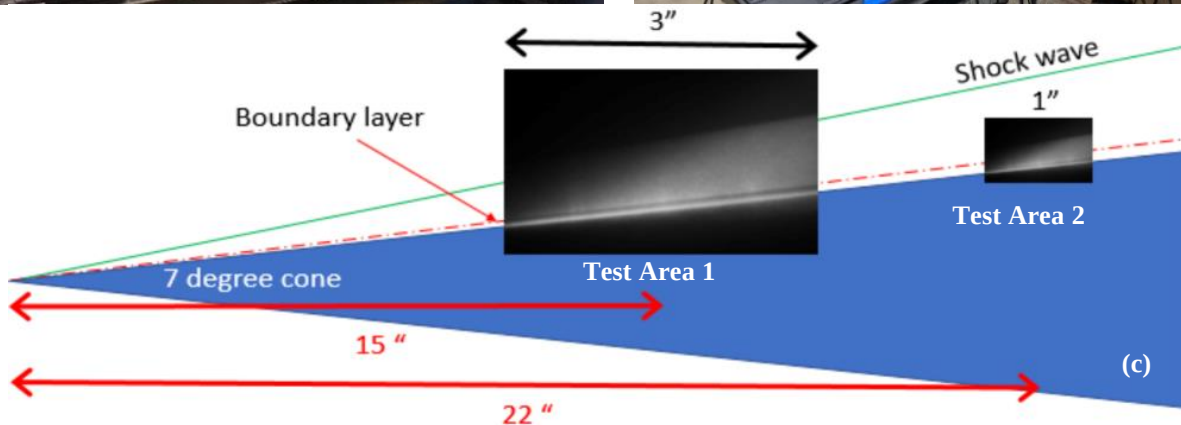
Gas seeding: 1% Kr (in mass) in N_2



CUBRC Mach 10 Shock Tunnel



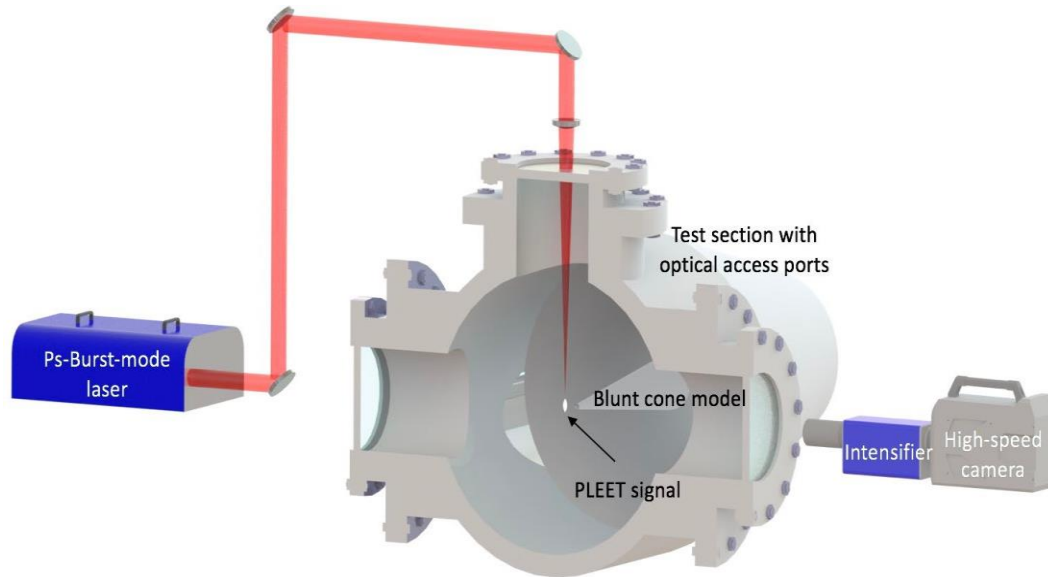
Burst-mode laser & OPO
Shimadzu & intensifier
Laser energy ~ 0.6 mJ/pulse
Sheet size $\sim 5''$



MHz NO PLIF in CUBRC shock tunnel



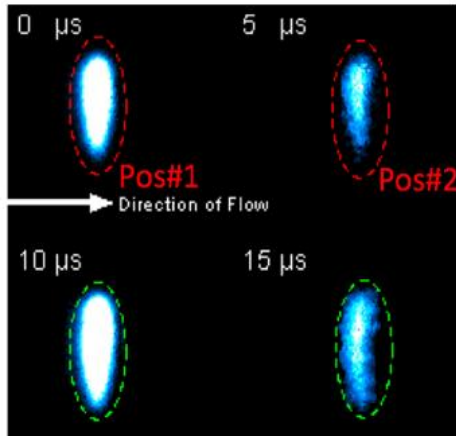
100-kHz PLEET in Ludwieg Tube



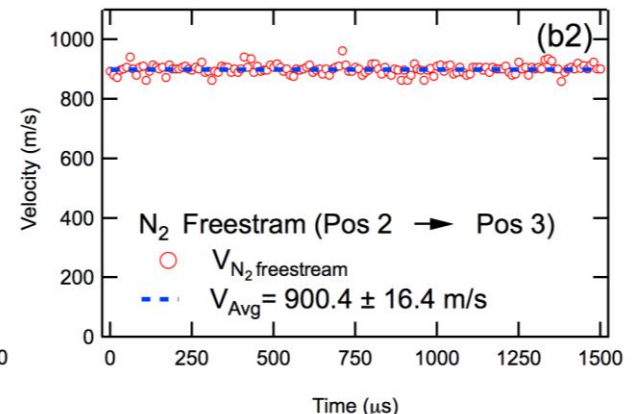
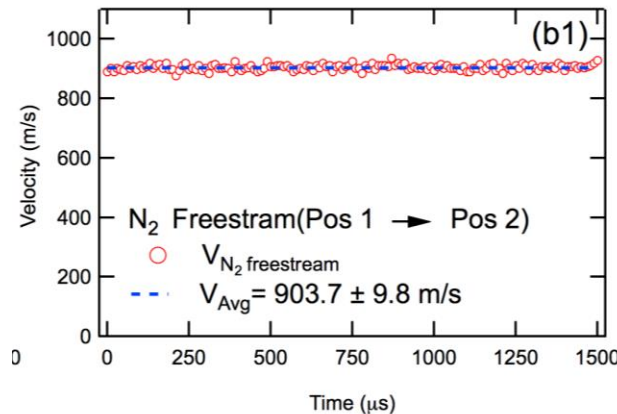
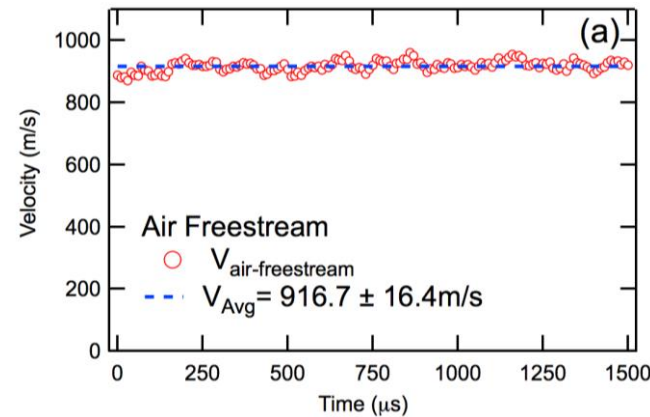
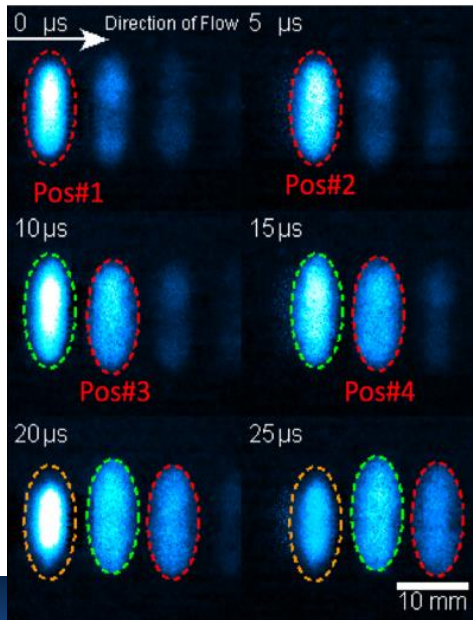
- 100-kHz rate PLEET using a ps burst-mode laser system
- Mach 6 Ludwieg tube, with flow speed of ~ 900 m/s,
- **Static pressure $\sim 5 - 20$ torr, static temperature ~ 60 K**
- **Laser energy is ~ 200 mJ/pulse at 100-kHz rate**
- High-speed Photron SA-Z and LaVision IRO intensifier
- From the side window to the center of test section is ~ 0.85 m.
- **Test conditions: Free stream and with a 14° cone model**

100-kHz PLEET Velocimetry

(a) Air Flow Freestream

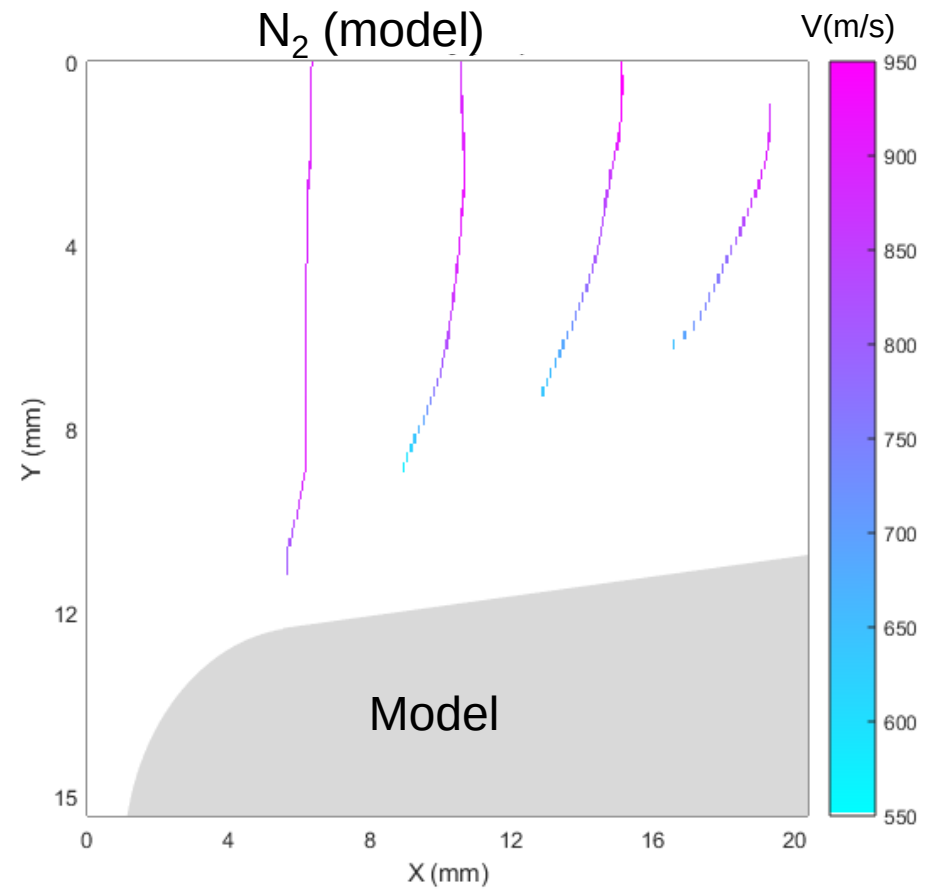
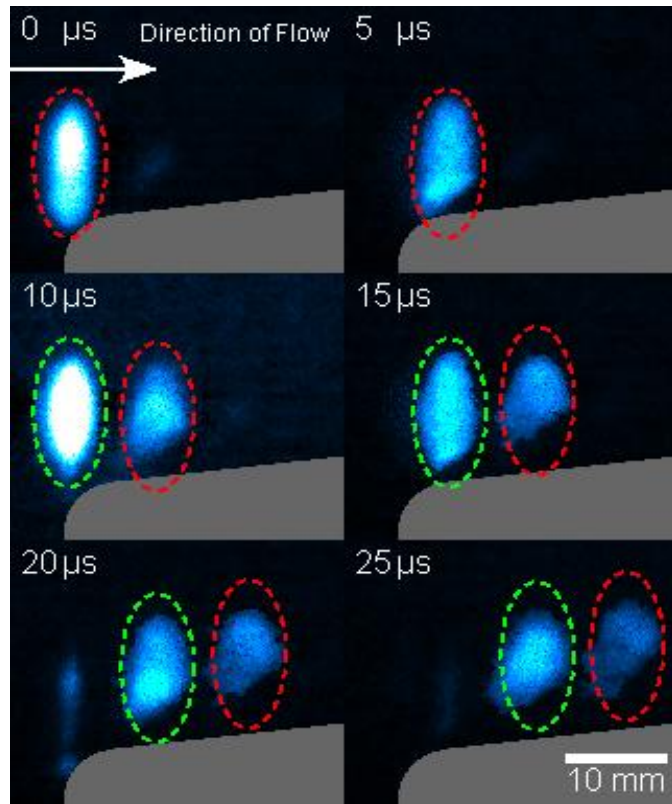


(b) Nitrogen Flow Freestream



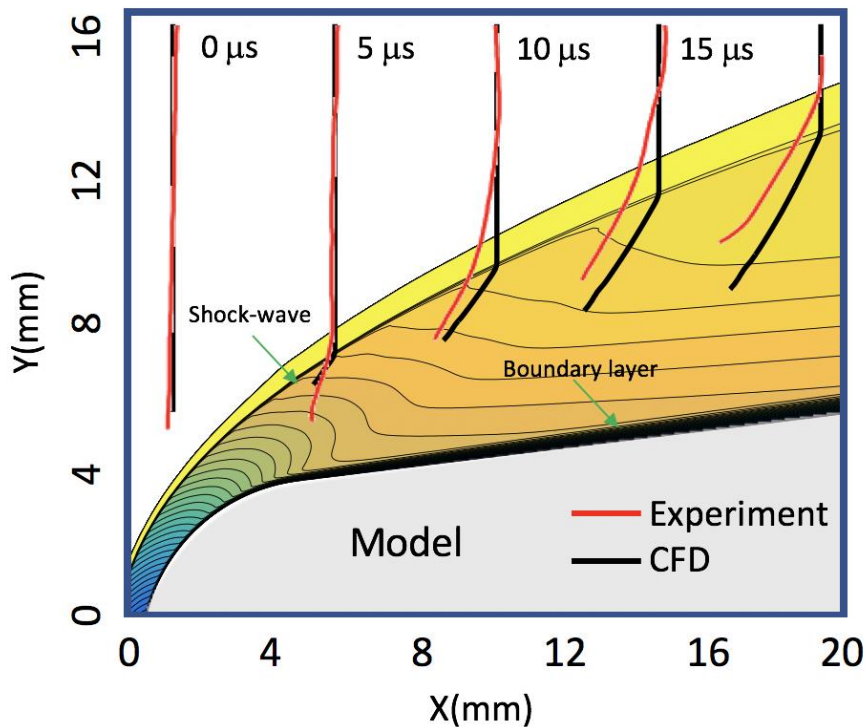
- With pure N_2 flow, PLEET signal lifetime exceeds 30 microseconds (in contrast, lifetime in air ~ 7 microseconds).
- The discrepancy between calculated air velocity (air 904 m/s) and measured velocity is $< 1\%$.
- Lowest static pressure for PLEET is 5 torr (limited by facility operation)
- Validated estimated stagnation temperature 460 K.

Time-resolved N_2 Flow Velocity Profile (model case)

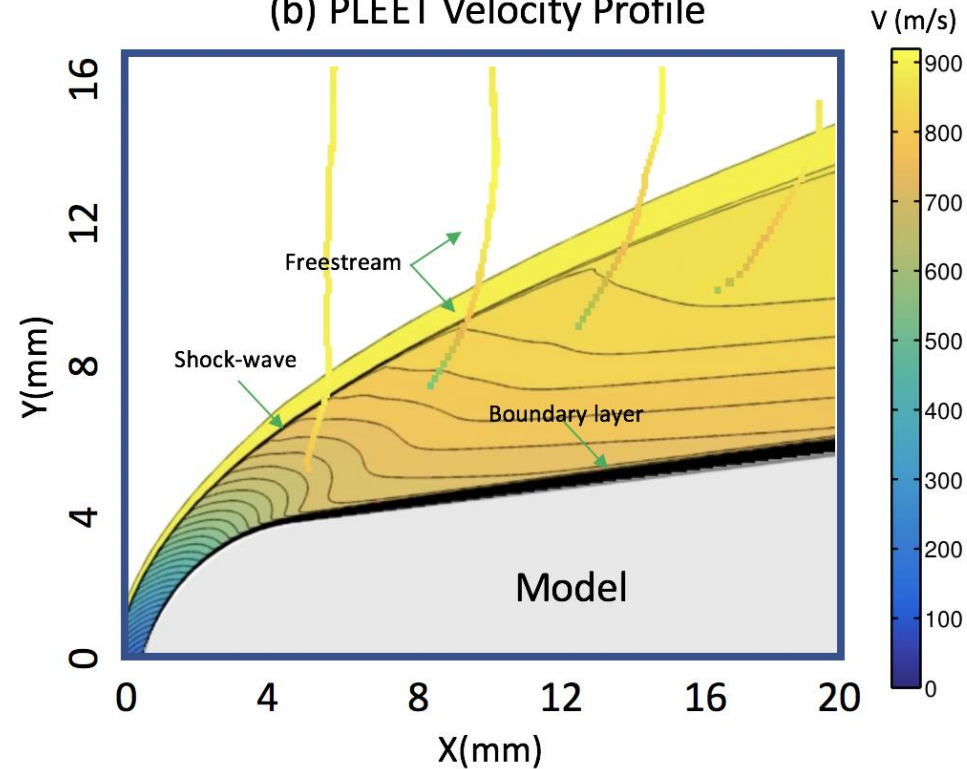


CFD vs. PLEET

(a) PLEET Signal Line Profile

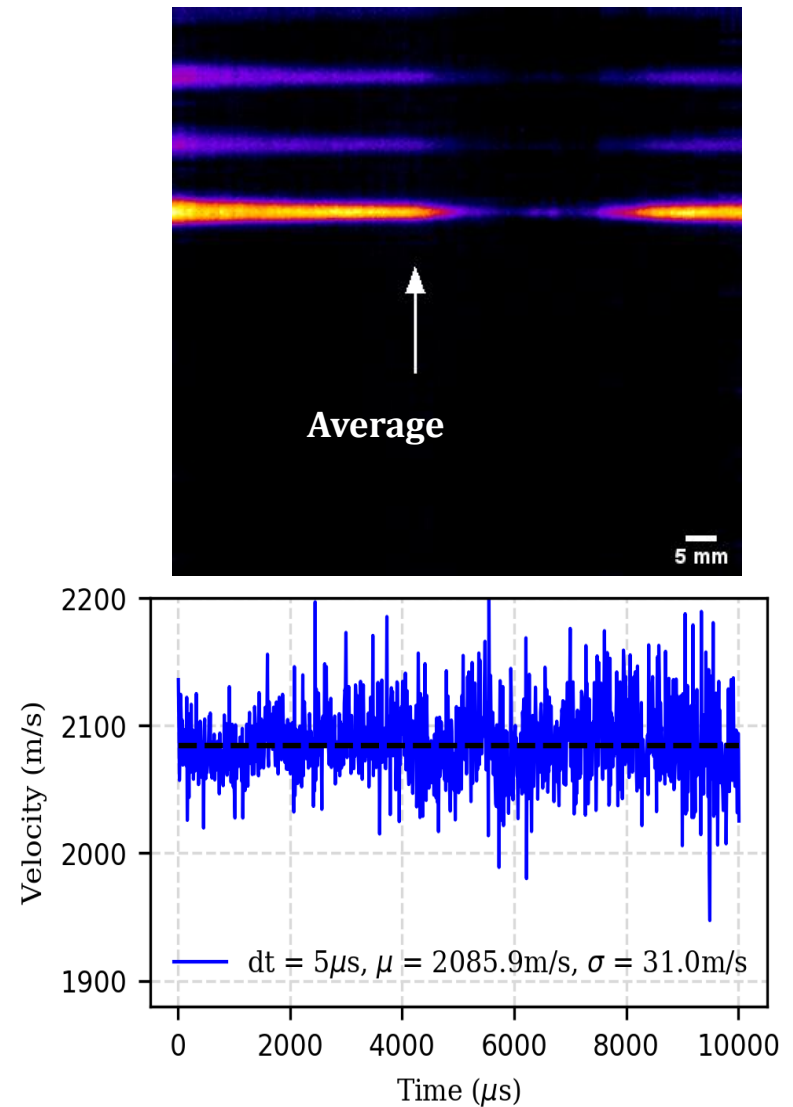
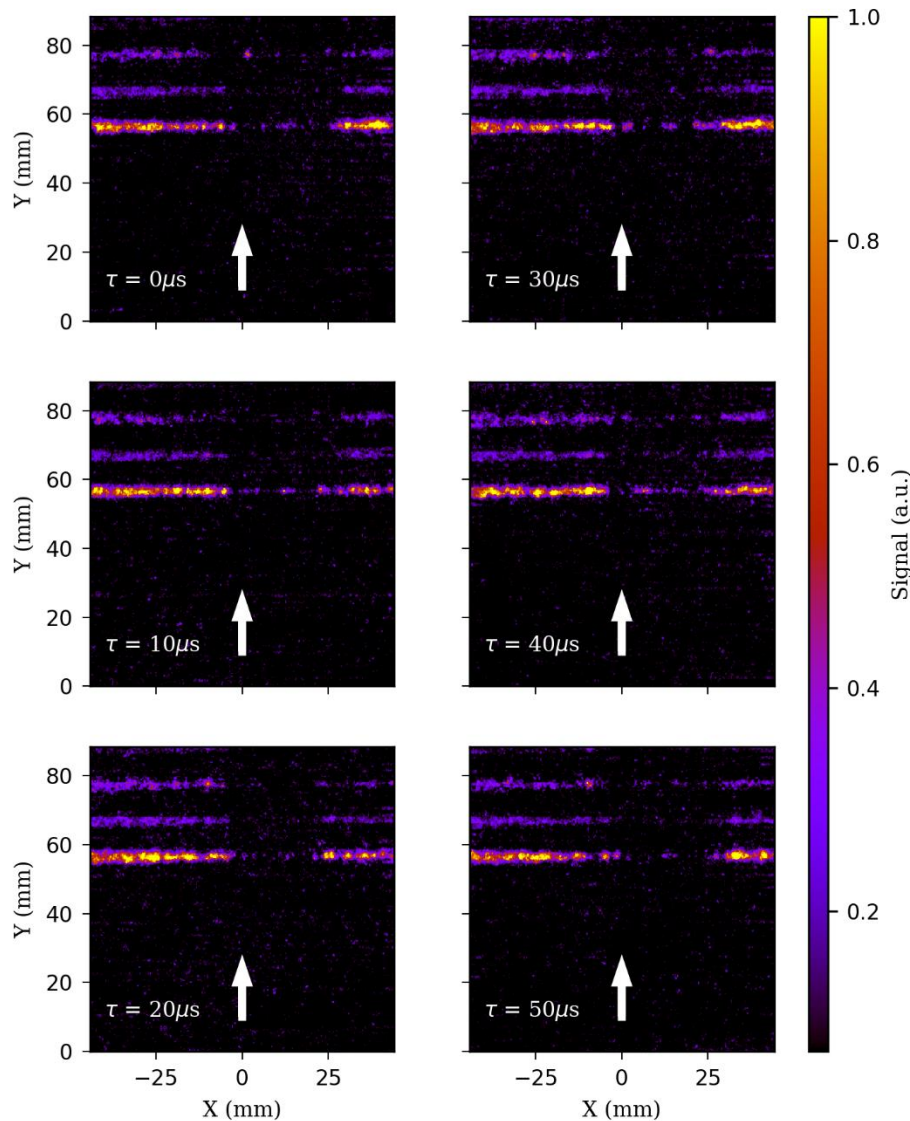


(b) PLEET Velocity Profile

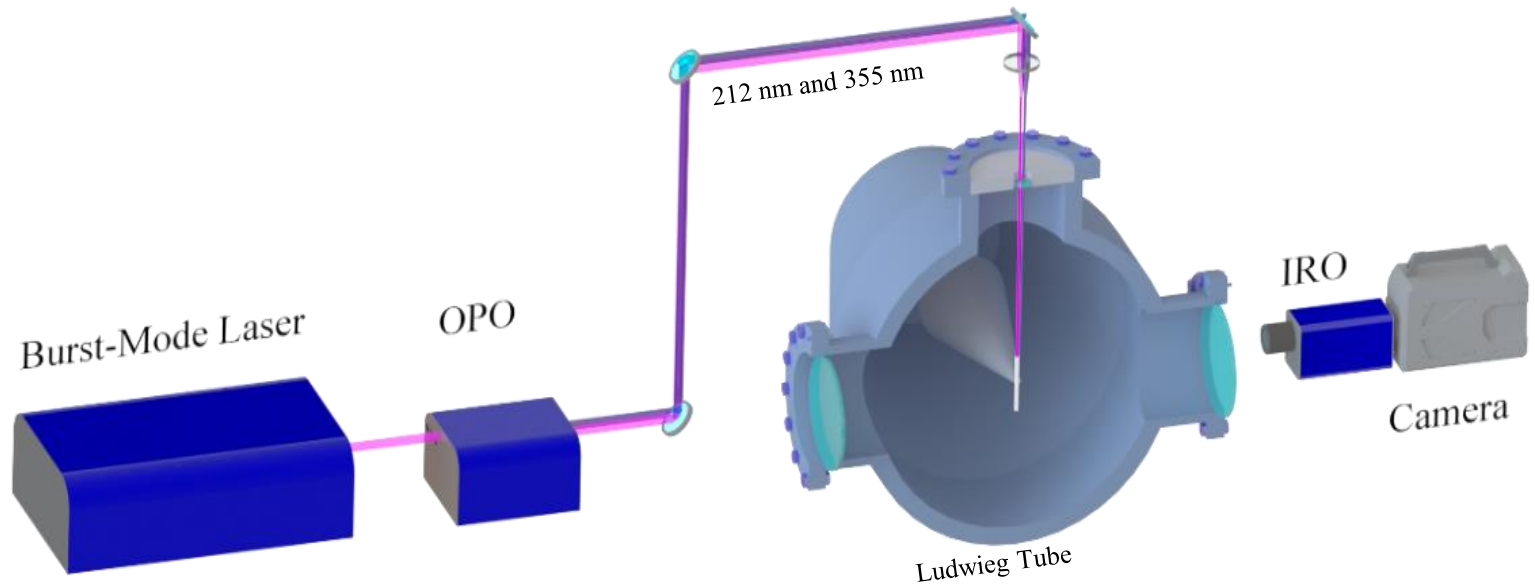


- The cone angle of attack may have a slight shift (nose up orientation)
- Low SNR behind the shock wave (difficult to determine line position)

100-kHz PLEET in Tunnel 9



100-kHz KTV in Ludwig Tube



Problem: 212 nm laser beam intensity applied to the wind tunnel is insufficient to ionize Kr and generate long-lived Kr fluorescent signal

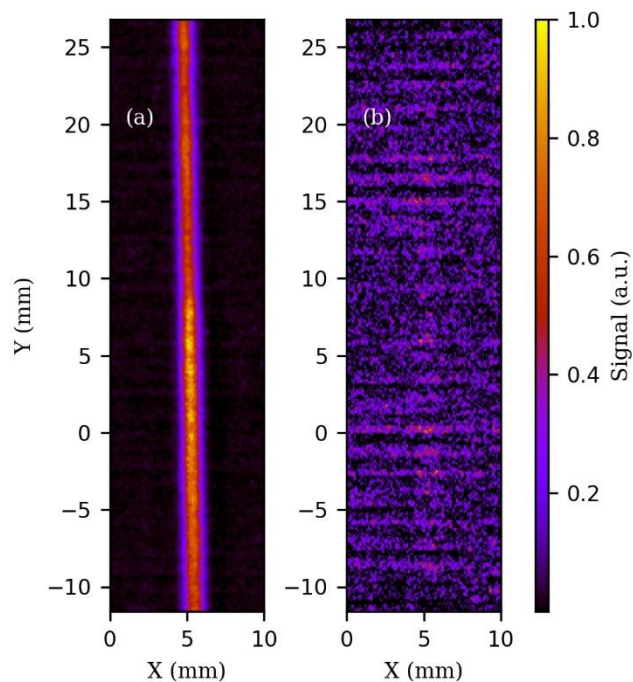
Kr Ionization energy (IP) $14 \text{ eV} = \sim 112914 \text{ cm}^{-1}$

(Two-photon) $212.56 \text{ nm} \times 2 = 94092 \text{ cm}^{-1}$

Requires one photon with 18670 cm^{-1} of energy ($\sim 531 \text{ nm}$)

By applying another 355 nm laser beam, Kr can be ionized.

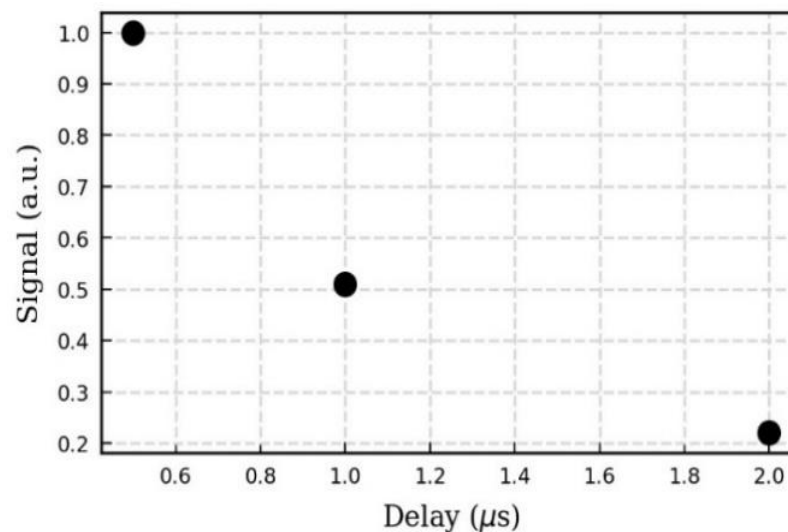
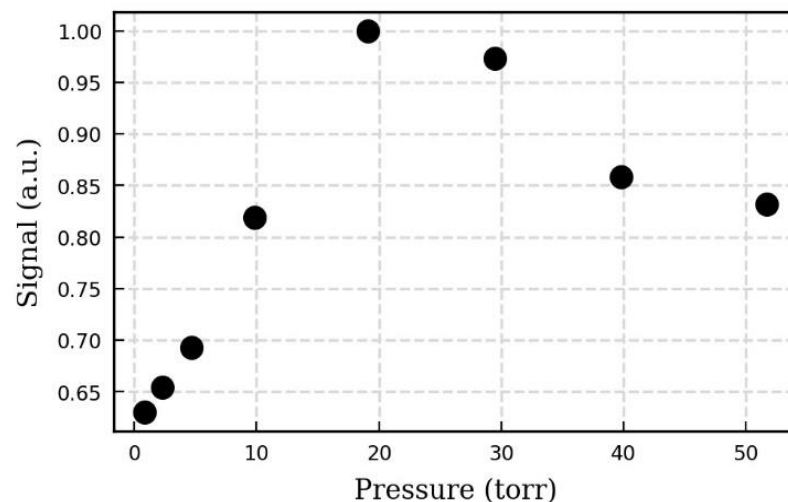
100-kHz KTV in Ludwieg Tube



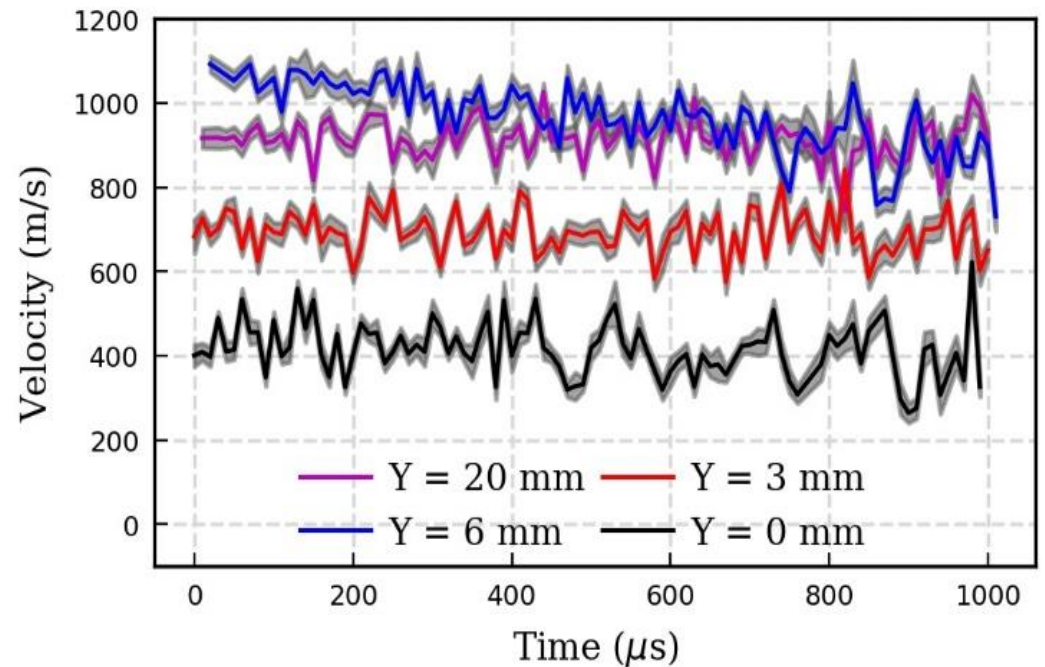
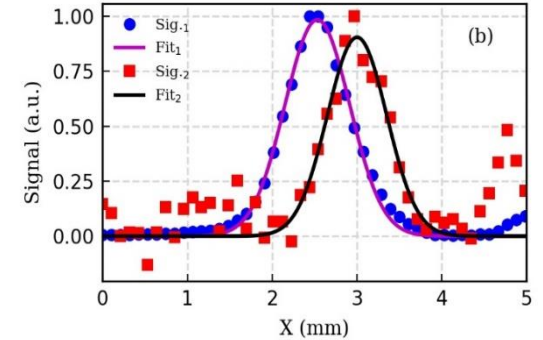
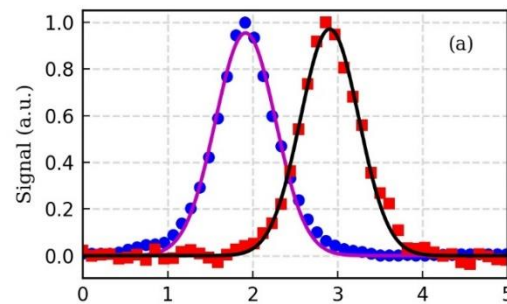
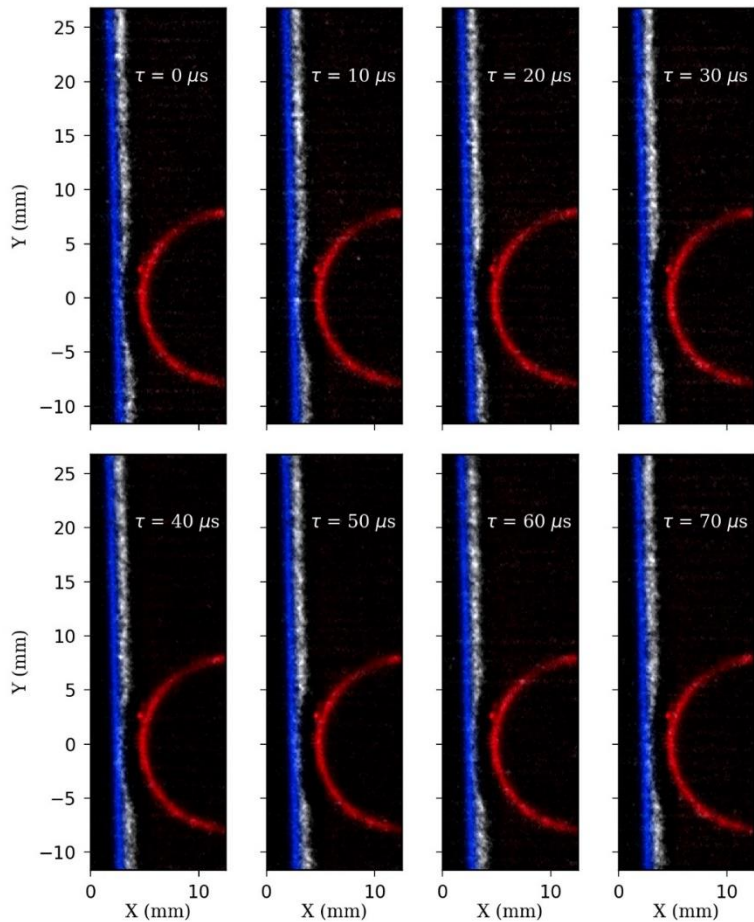
50ns Delay

200ns Delay

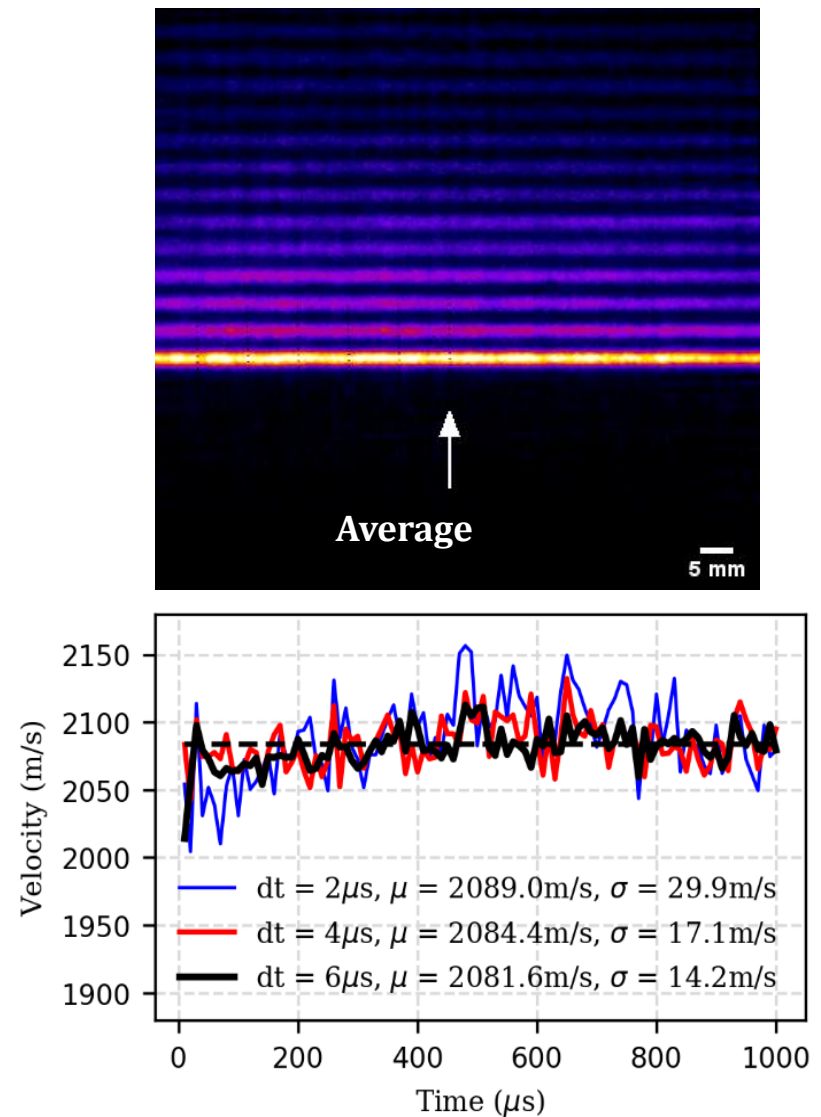
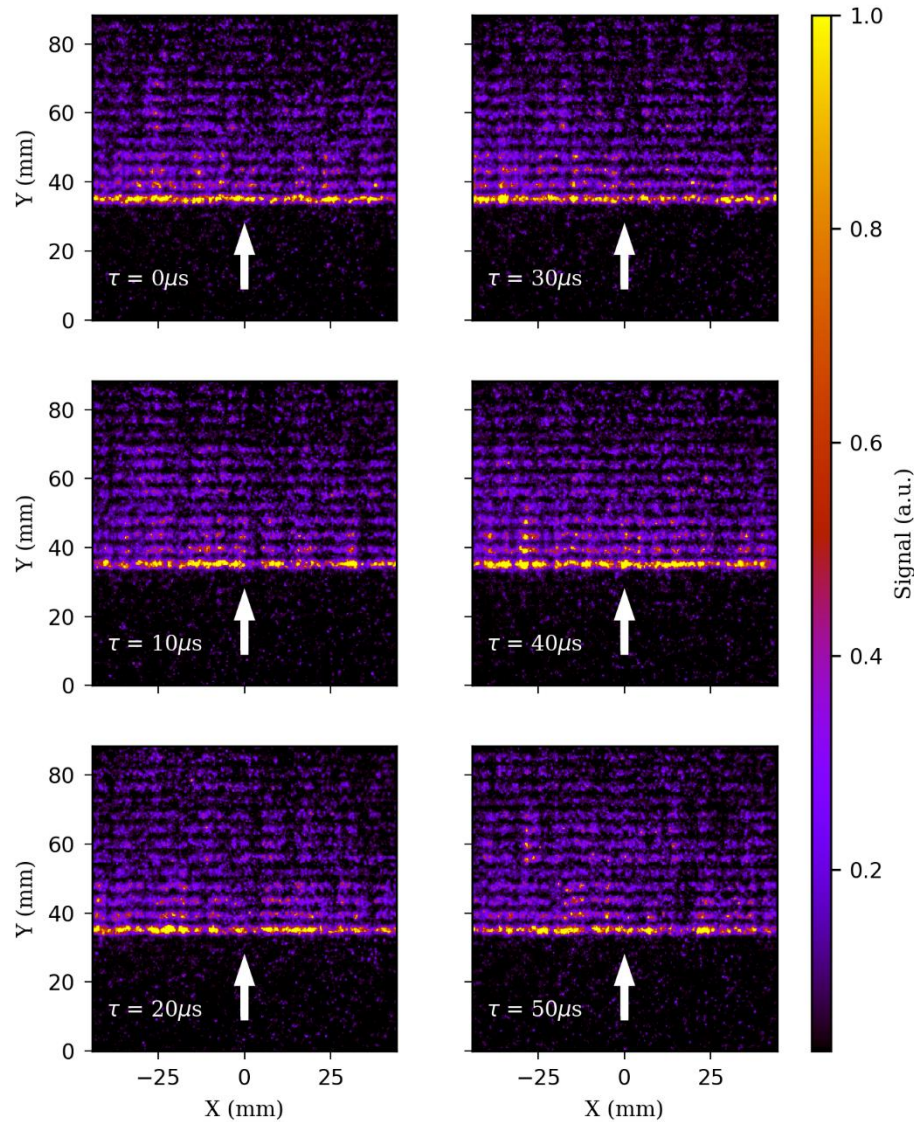
Short-lived Kr fluorescent signal at 2.5 torr static pressure and 55 K static temperature with 5% Kr seeding.



100-kHz KTV in Ludwig Tube



100-kHz KTV in Tunnel 9



MHz NO PLIF for Second Mode Instability Measurement

- The second mode instability is a primary feature in laminar-to-turbulent boundary layer transition at hypersonic conditions

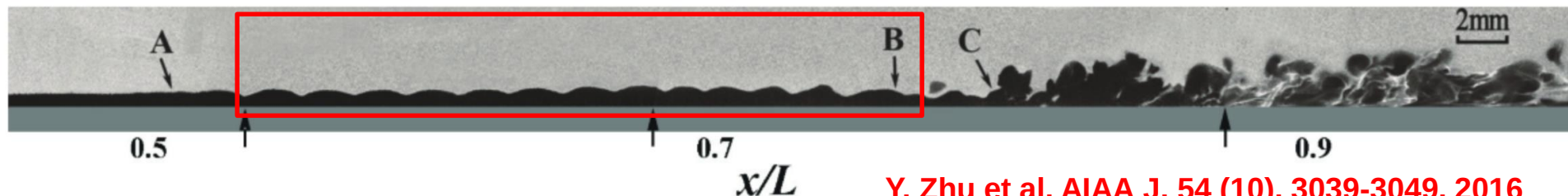
$$f_0 \sim U_e / 2\delta$$

- Most measurements are done with pressure sensors
- Some examples of Schlieren, 10-Hz laser diagnostics
- Most recently, FLDI has been applied
- Time-resolved 2D imaging is needed

U_e : boundary edge velocity

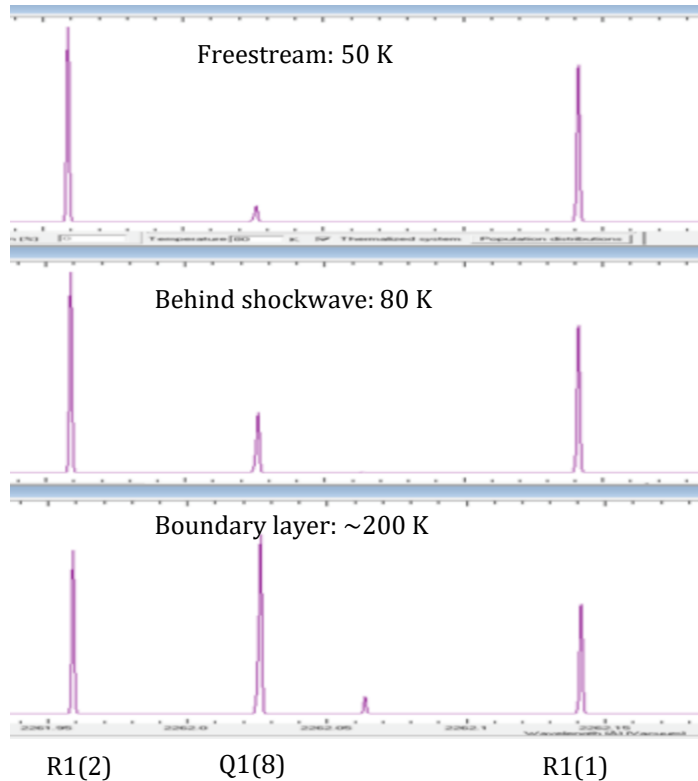
δ : boundary layer thickness

f : ~ a few 100 kHz



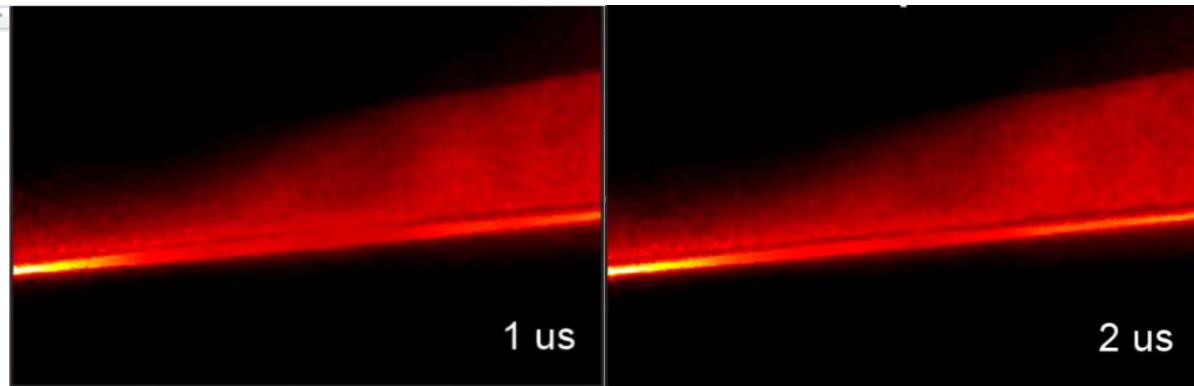
Y. Zhu et al. AIAA J. 54 (10), 3039-3049, 2016

NO Line Selection

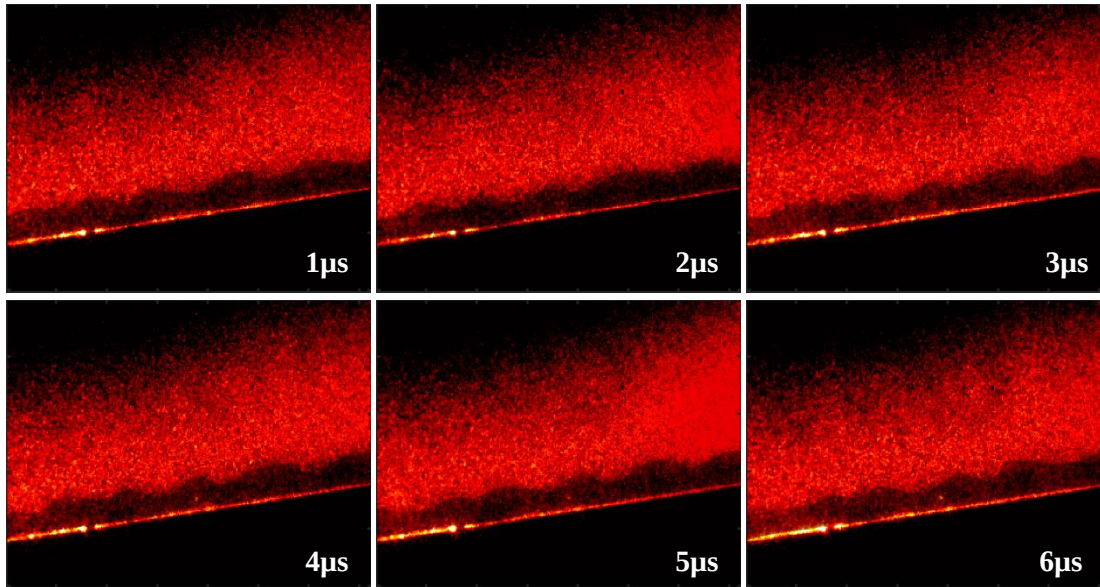


- NO seeding: whole tunnel flow
- Seeding concentration: ~0.25%
- Laser beam path: ~1 m inside the tunnel
- Boundary layer thickness: <10 mm
- Freestream condition: ~56K, ~1.2 torr
- Velocity: ~1500 m/s

MHz NO PLIF in test area 1: 15" to model tip

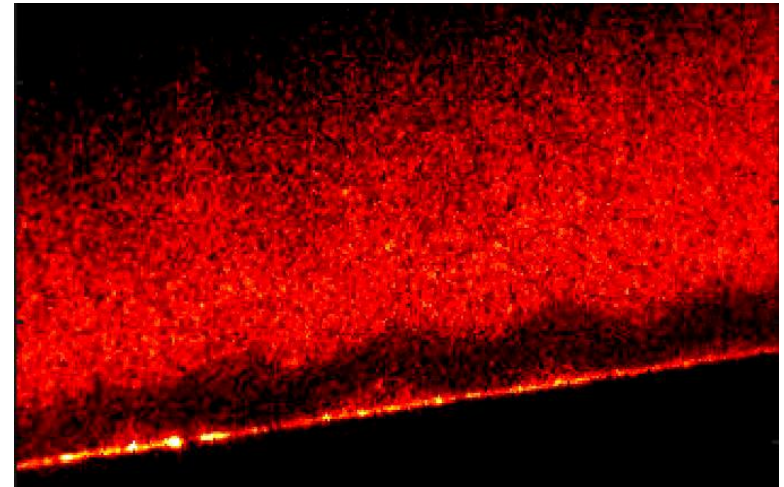


1MHz NO PLIF Images



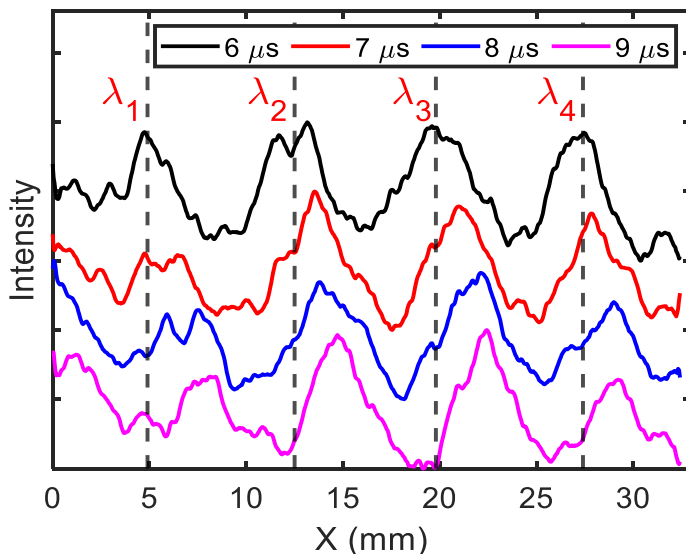
- No NO seeding in BL
- BL edge is clearly observed

- By tracking the peak position of the wave packets, the average speed is ~ 1250 m/s for the wave peaks
- By analyzing the MHz rate 2nd mode instability wave packet movement, the instability wavelength λ is growing from ~ 7 mm to ~ 8 mm in $10 \mu\text{s}$.



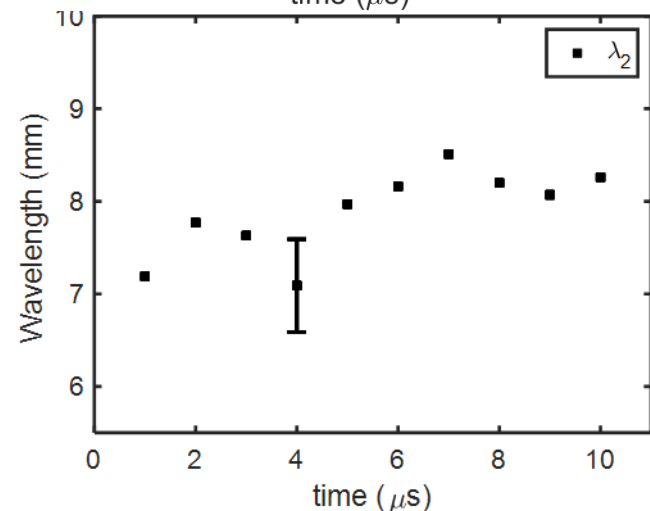
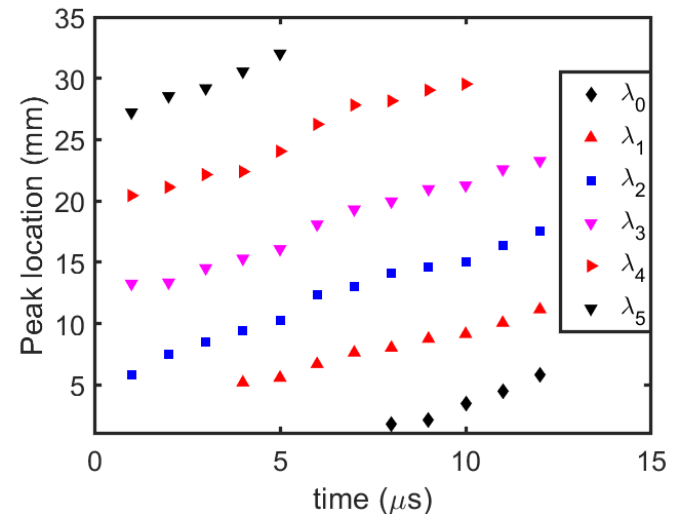
2nd Mode Instability Analysis

Instability wave packet along the model surface at various imaging time



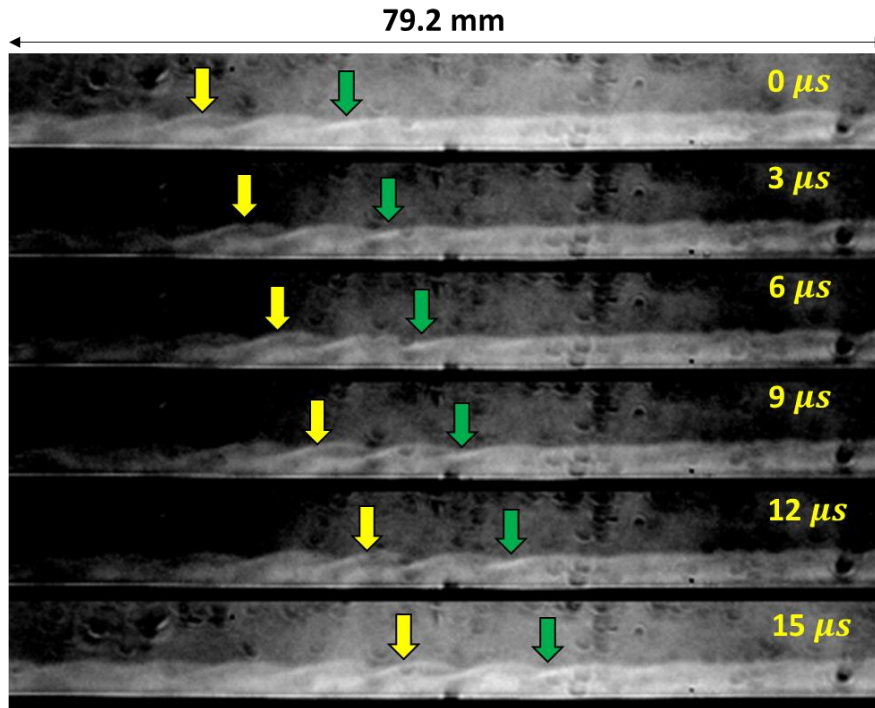
- Instability wave packet λ is growing from ~ 7 mm to ~ 8 mm in 10 μ s, recorded and tracked at 1 MHz rate
- With an average wavelength of 7.5 mm, the 2nd mode instability frequency is $\sim 166 \pm 15$ kHz.

Wave packet movement at MHz rate

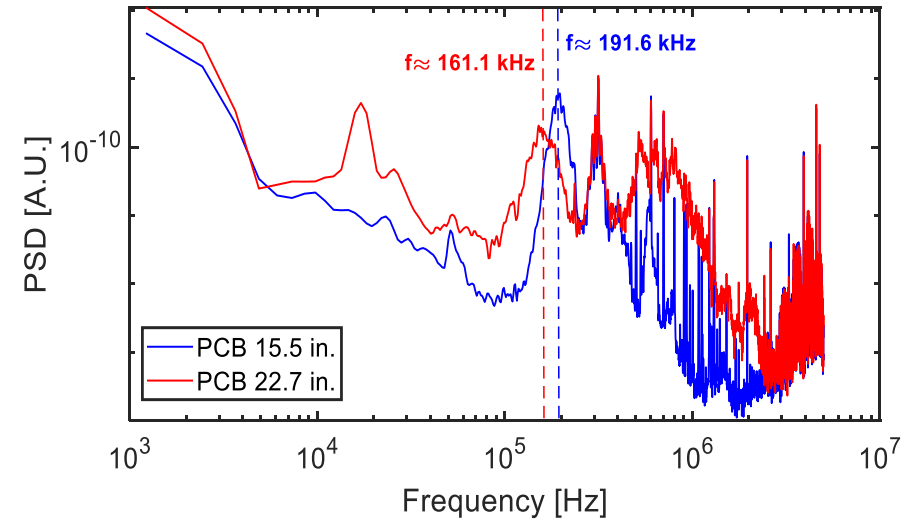


Evolution of Instability wavelength

Schlieren and pressure sensor



22" to the model tip
Velocity: 1086 ± 216 m/s
Frequency: 150 ± 38 kHz



In comparison:

NO PLIF at 22": 166 ± 15 kHz

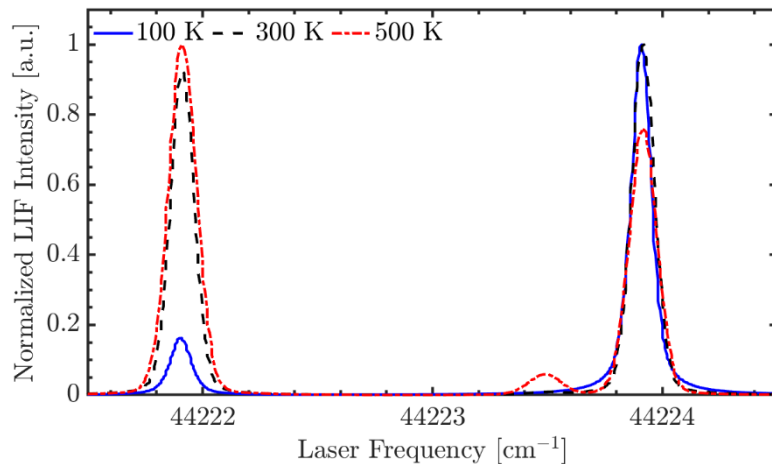
2D Pressure measurement with NO PLIF

Pressure Shift (cm⁻¹): $\delta\nu_C = -0.18 \frac{P [\text{kPa}]}{101.32 [\text{kPa}]} \left(\frac{300 [\text{K}]}{T [\text{K}]} \right)^{0.56}$

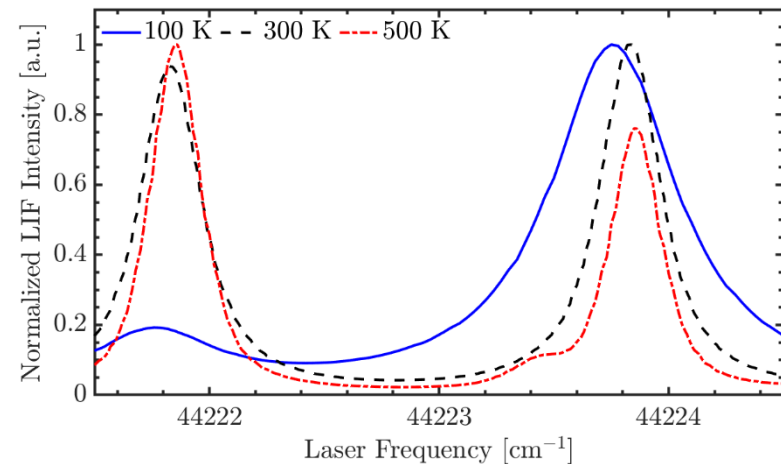
300K, 1bar, Shift=0.18 cm⁻¹, ~5.4GHz

NO Lines :

- Q₁(11.5) + R₂₁(11.5) near 22221.9 cm⁻¹
- R₁(5.5) + Q₂₁(5.5) near 22223.9 cm⁻¹

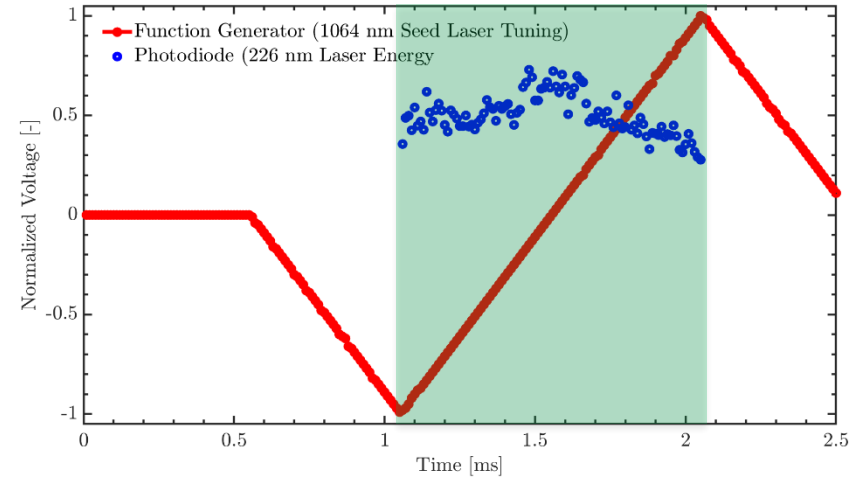
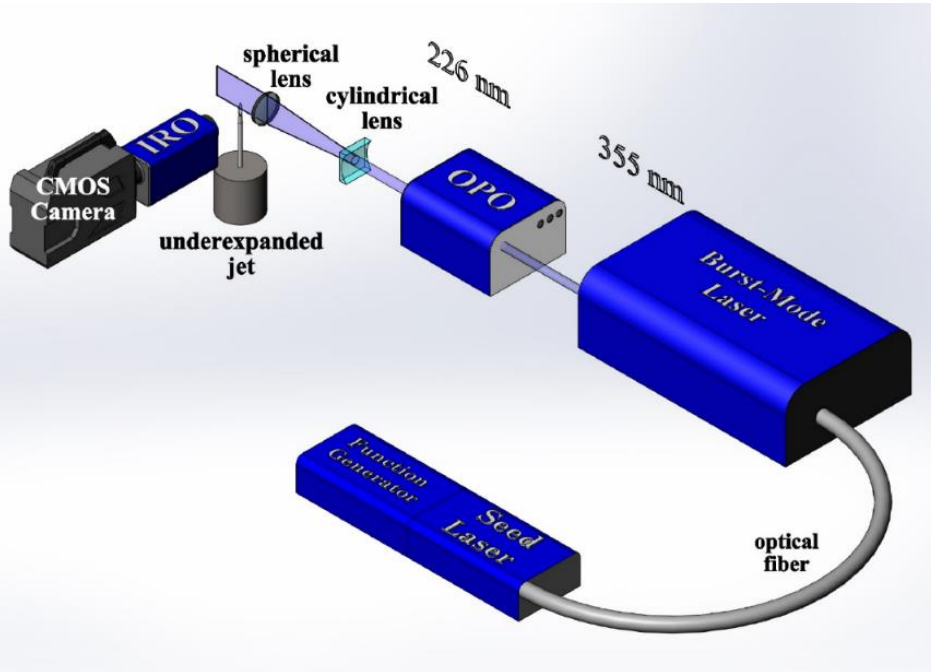


P = 5 kPa



P = 50 kPa

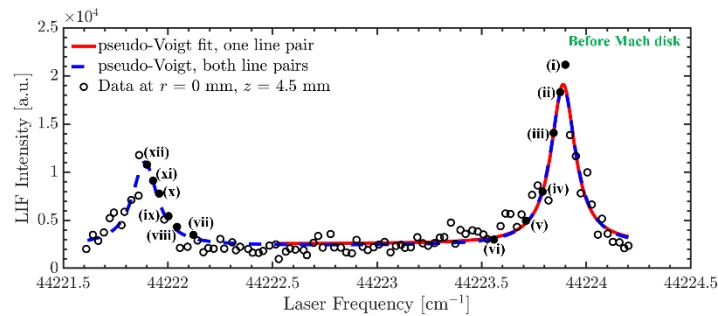
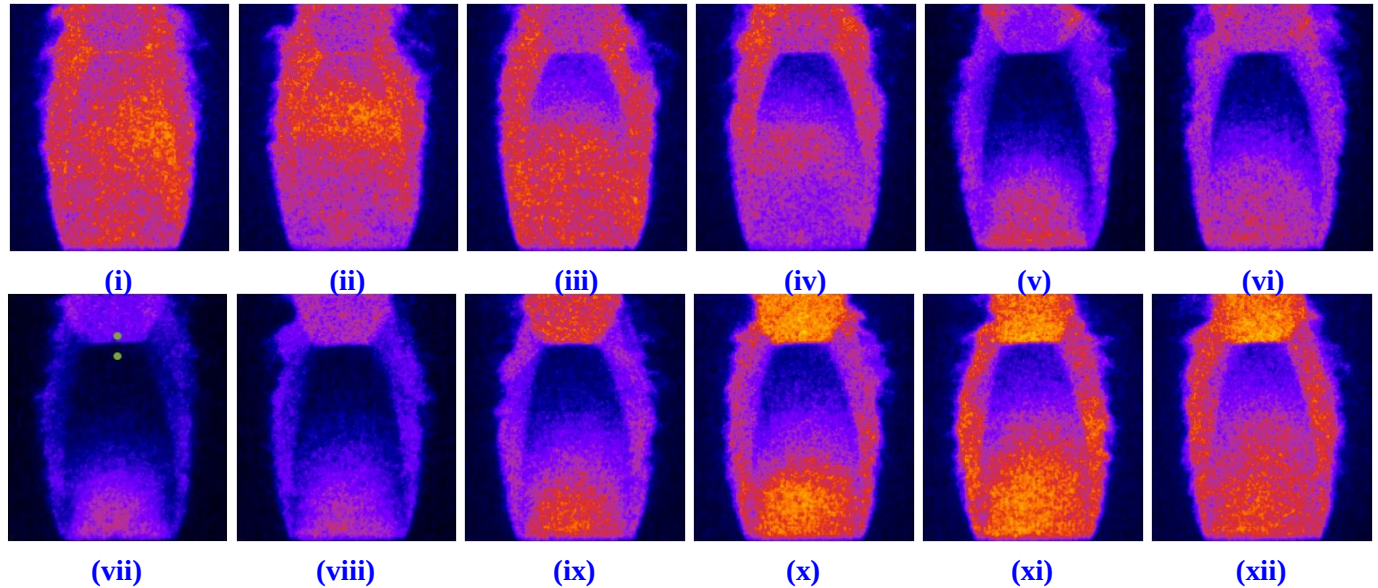
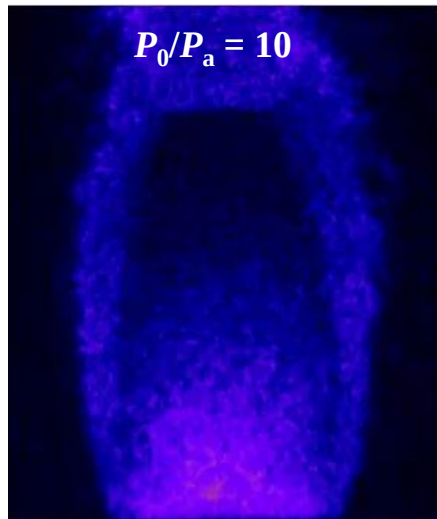
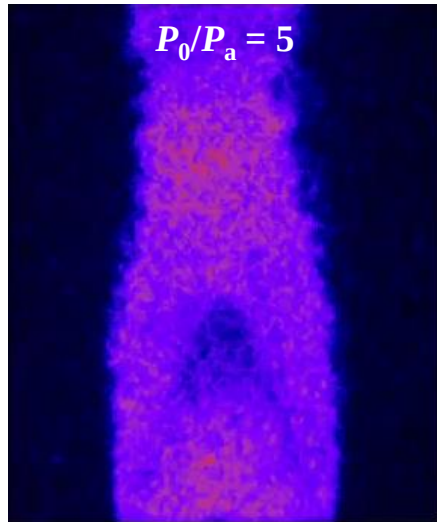
Experiments



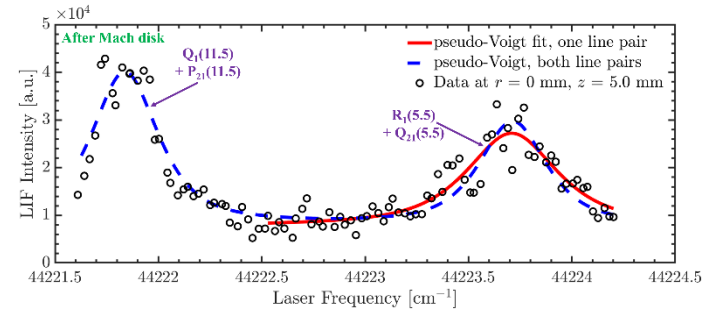
Data during relatively constant laser energy portion of burst used for analysis

- Operating at 100 kHz repetition rate with 2.5 ms burst duration
- Function generator used to scan the 1064 nm laser at 500 Hz
- 100 pulses for two-line scans

100-kHz NO PLIF Imaging

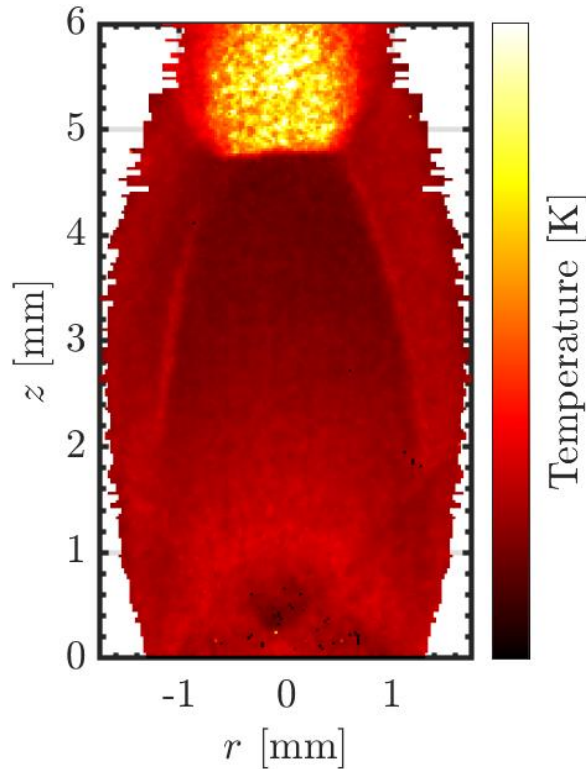


Upstream of Mach Disk

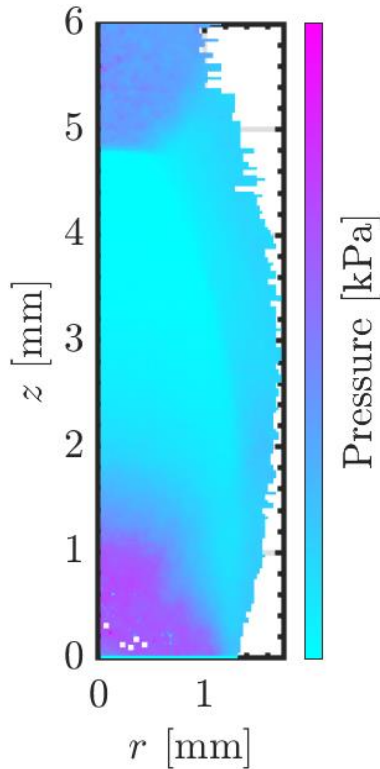


Downstream of Mach Disk

2D Pressure and Temperature Measurement



Temperature



Pressure

- Laser energy fluctuation
- High temperature uncertainty with two-line technique
- Wavelength scan fast monitoring
- Other applications

Summary

- 100-kHz PLEET and KTV in AFRL Mach 6 Ludwig Tube
- 100-kHz PLEET and KTV in AEDC Tunnel 9 with Mach 18 flow
- MHz-rate NO PLIF imaging in hypersonic boundary layer at CUBRC 48" Mach 10 shock tunnel.
- 2D pressure imaging with 100-kHz NO PLIF