Recent high-speed laser diagnostics in hypersonic ground test facilities

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Purdue:	**Terrence R. Meyer, Daniel K. Lauriola, Austin M. Webb**
AFRL:	**Stephen A. Schumaker, Matthew Borg, Mike S. Smith, Addison J. Spicer**
UTSI:	**Mark Gragston**
Stevens Institute:	**Nick. J. Parziale, David Shekhtman**
Iowa State	**Hui Hu, Jincheng Wang**
CUBRC:	**Ron Parker, Timothy P. Wadhams, Phillip Portoni, Conor McDermott, Kevin Seitz**

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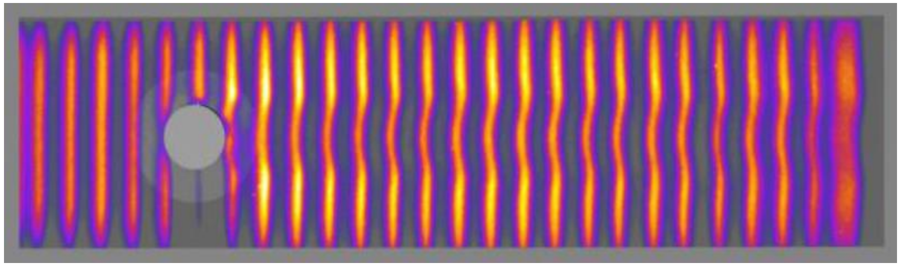
Measurement Challenges

- **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**

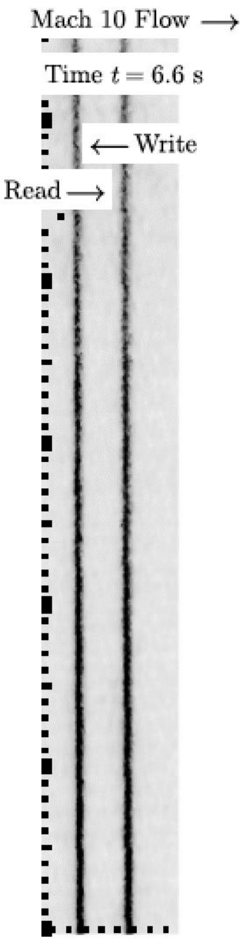
Hypersonic Flow Diagnostics

- **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**



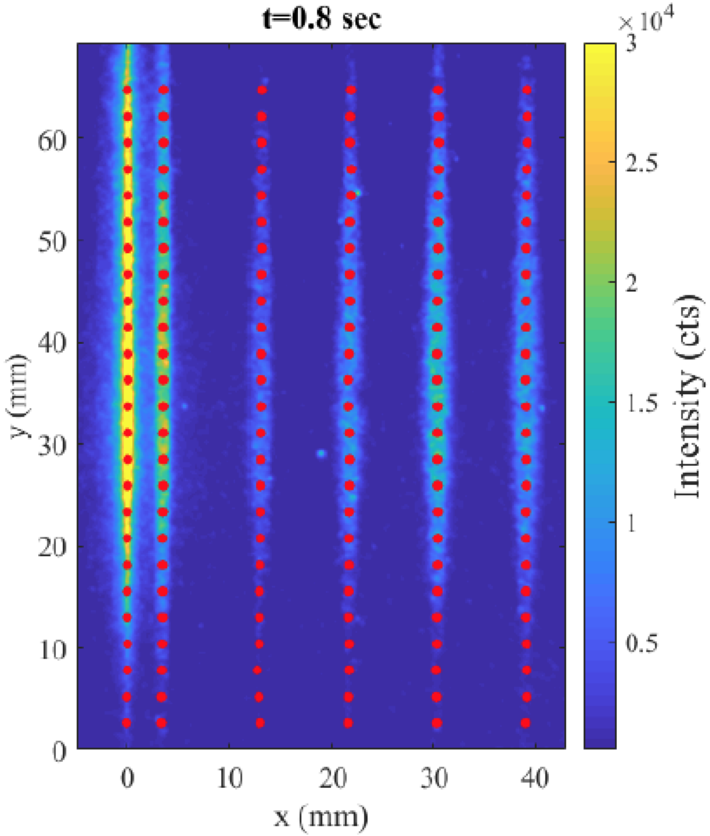
NO MTV in Mach 10 Tunnel at NASA Langley

BF Bathel, PM Danehy, et al, AIAA J. 2011.



10-Hz KTV in Tunnel 9

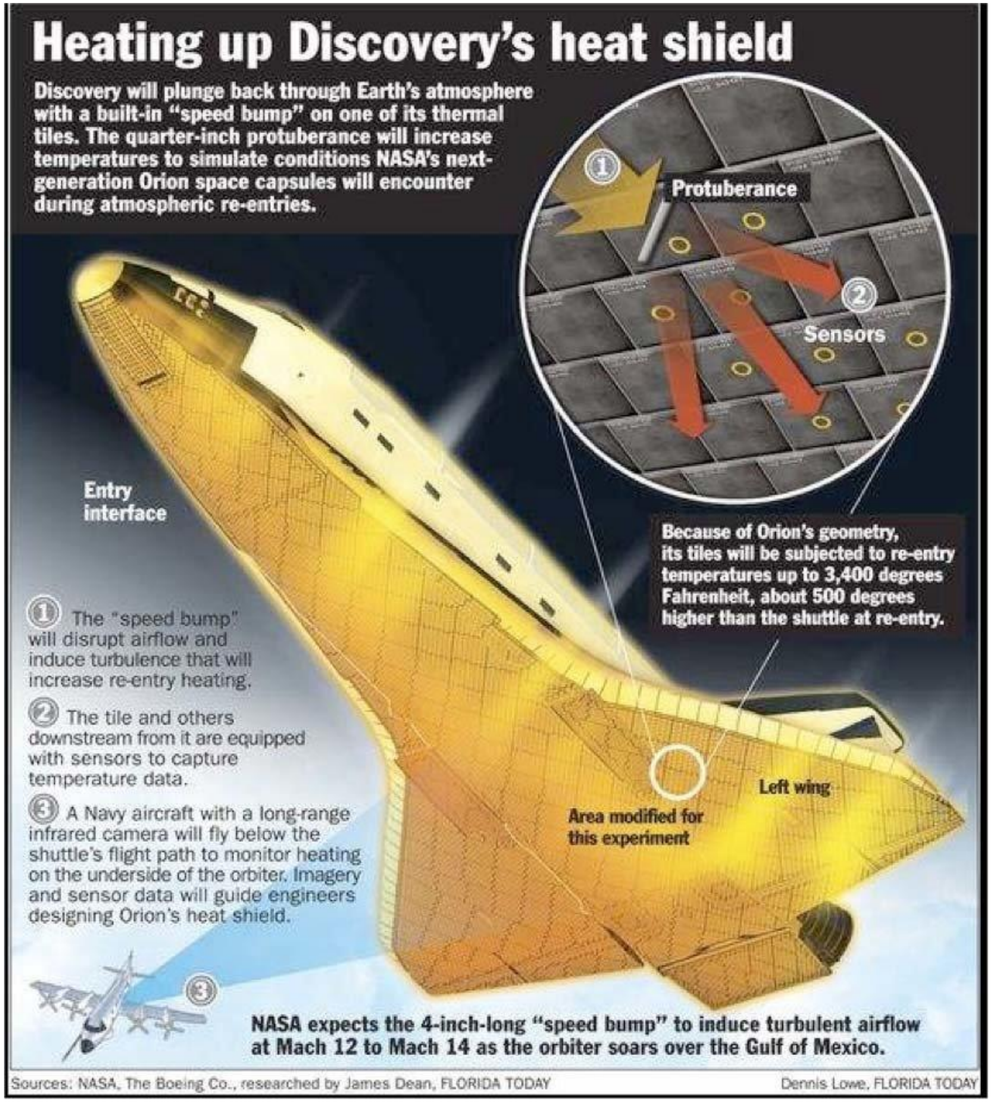
N. Parziale, et al. AIAA Scitech 2015.

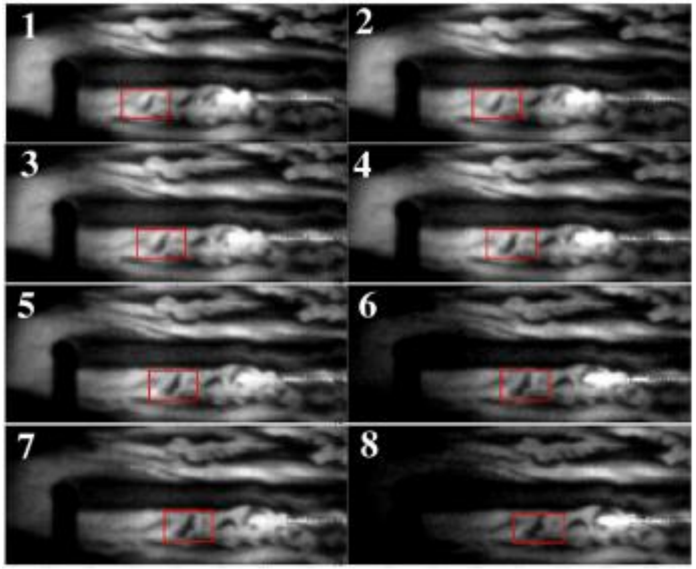


1-kHz FLEET in Tunnel 9

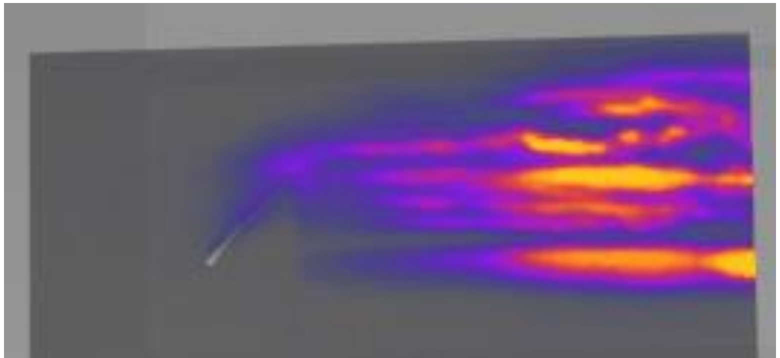
A. Dogariu, et al. AIAA Scitech 2021.

Previous Work: NO PLIF





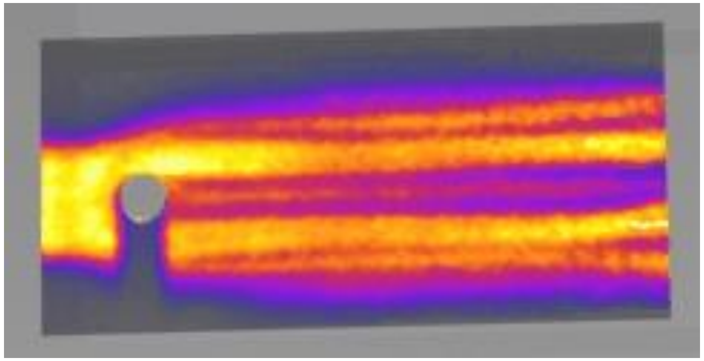
1MHz NO PLIF in NASA Mach 10 Tunnel



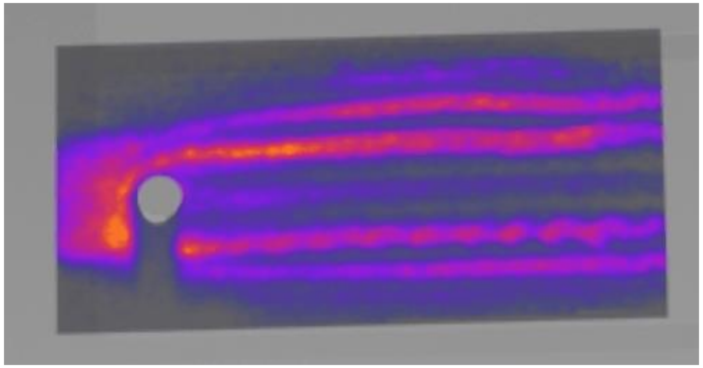
500-kHz NO PLIF in NASA Mach-10 tunnel

NO PLIF Imaging-NASA Langley

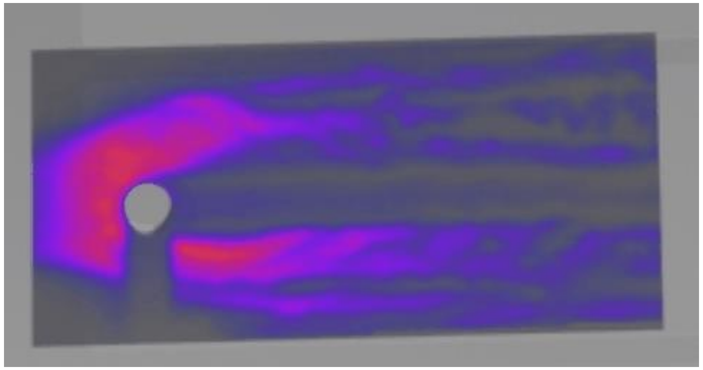
2.4 MPa, Re = 1.5 million/m 500 kHz



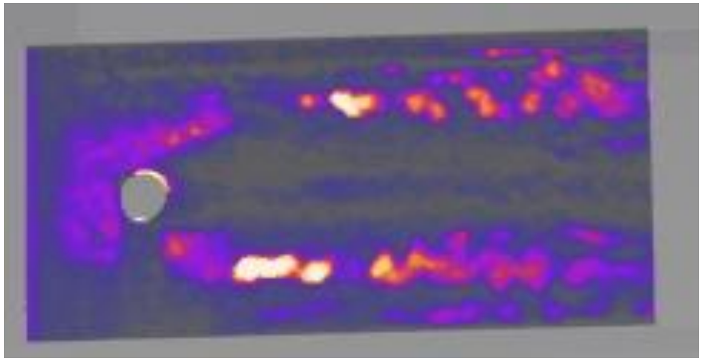
3.4 MPa, Re =2.1 million/m 500 kHz



4.9 MPa, Re = 3 million/m 1 MHz



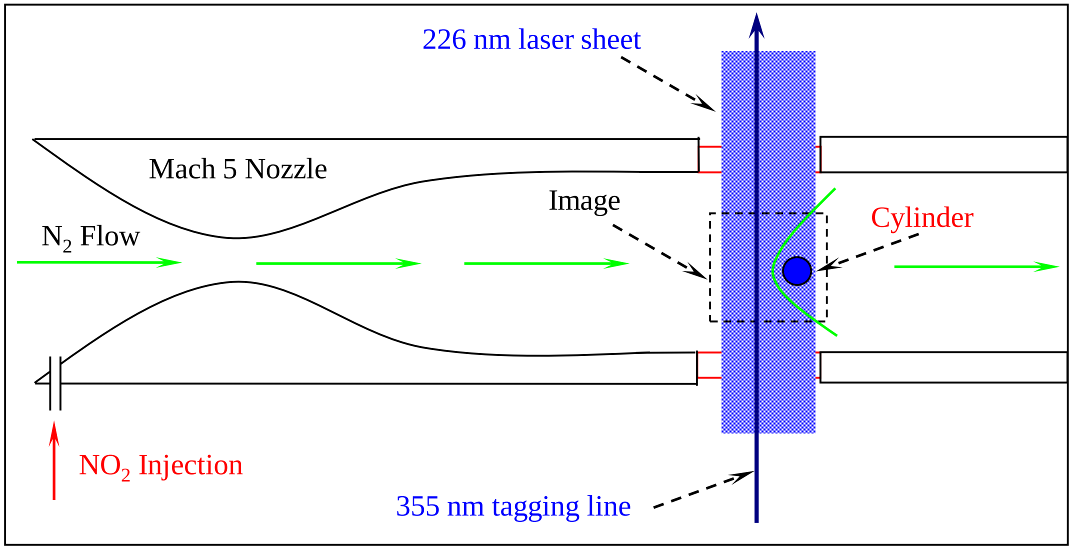
9.2 MPa, Re = 5.6 million/m 500 kHz

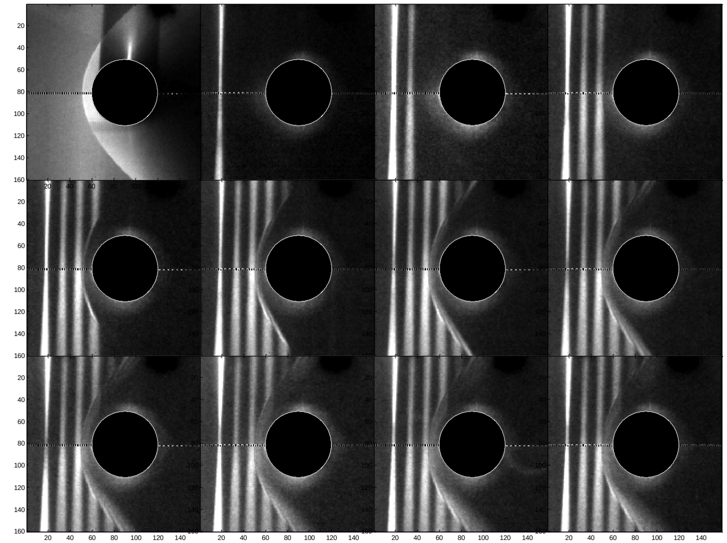


2 mm tall x 4 mm wide cyl trip - Reynolds Number Comparison

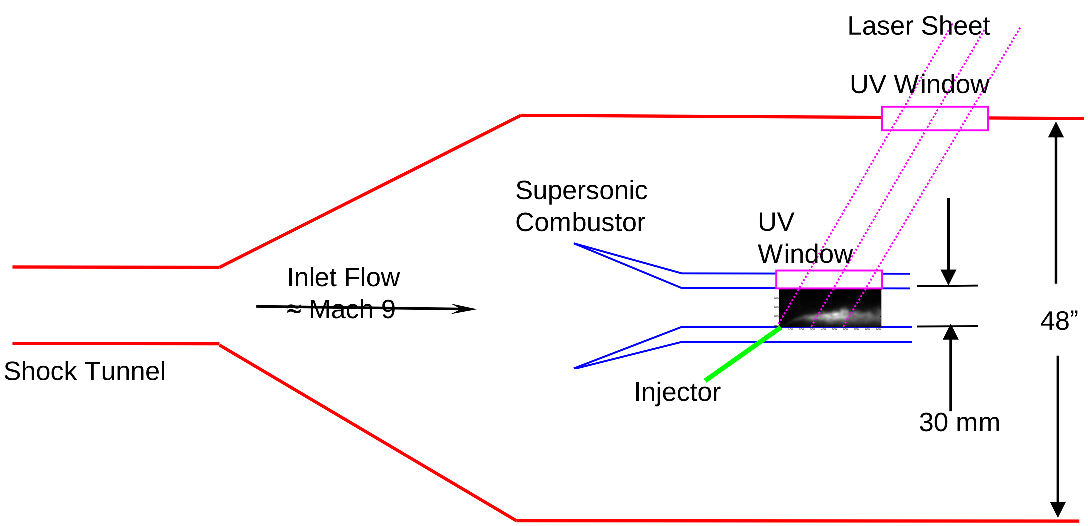
~ 1 mm above surface

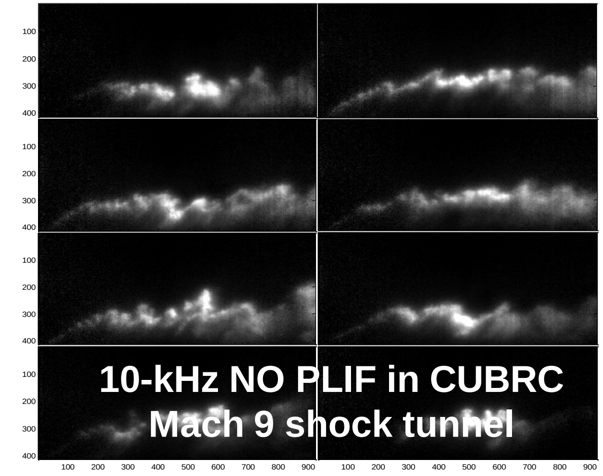
Previous Work





500 kHz NO2 MTV in a Mach 5 Tunnel

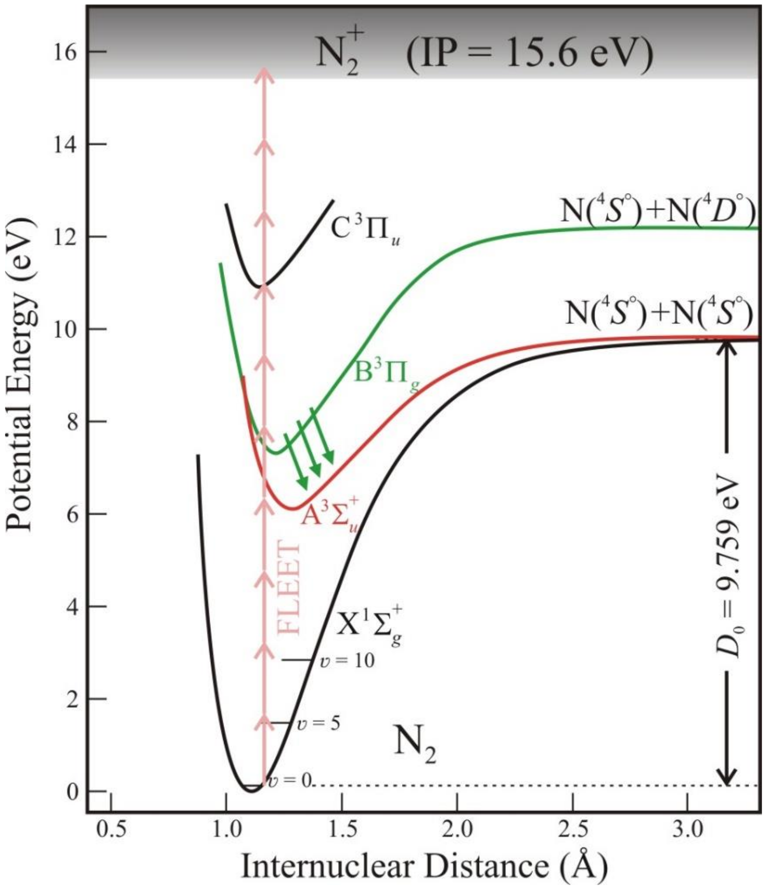


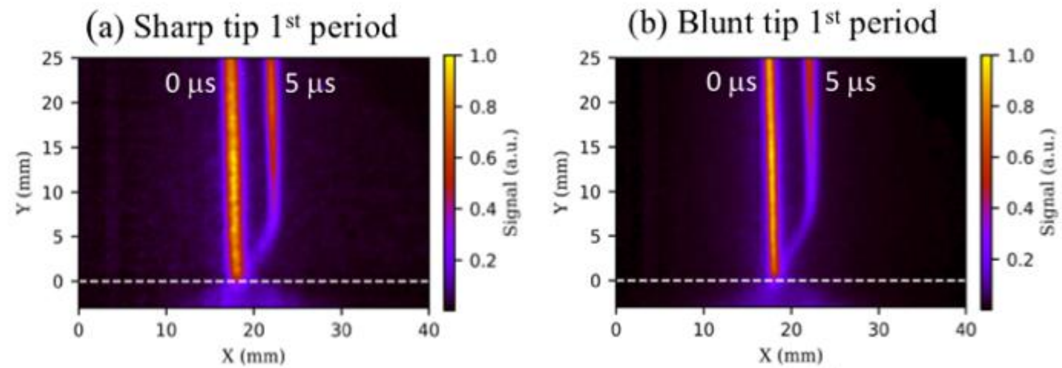


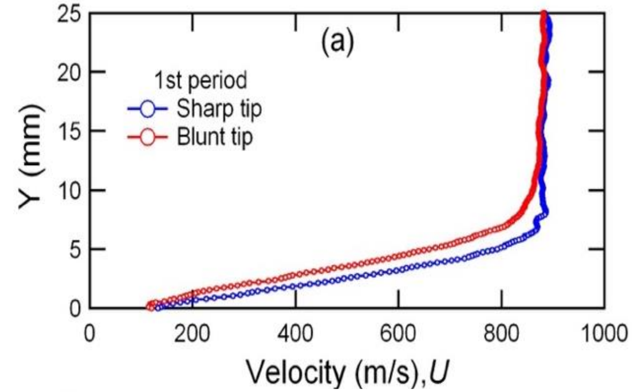
10-kHz NO PLIF in CUBRC Mach 9 shock tunnel

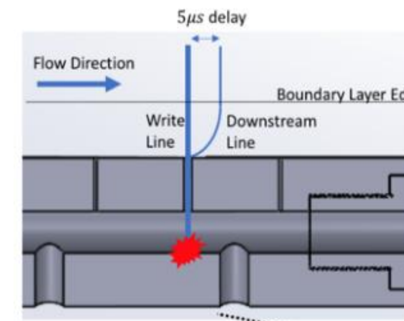
Technique: FLEET Velocimetry

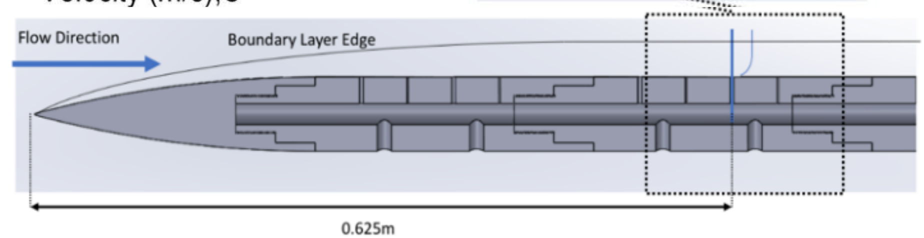
BL Velocity Profile Measured by 1-kHz FLEET in AFRL Mach 6 Ludwieg Tube





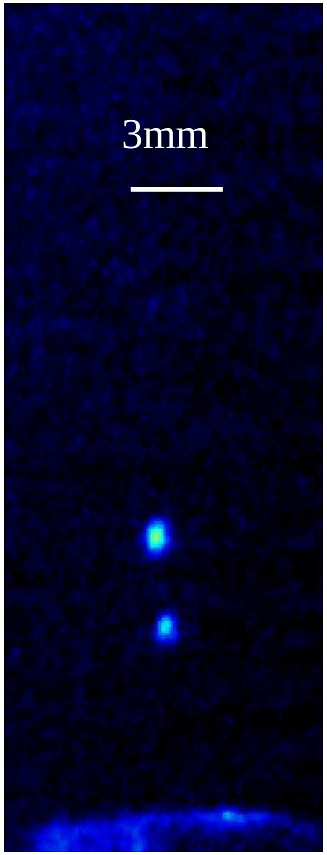




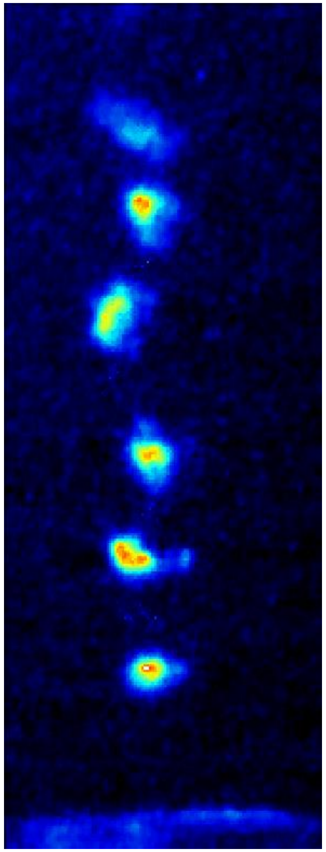


J. Michael, R. Miles et al, Appl. Opt. 50, 5158, 2011.

Technique: 100-kHz PLEET



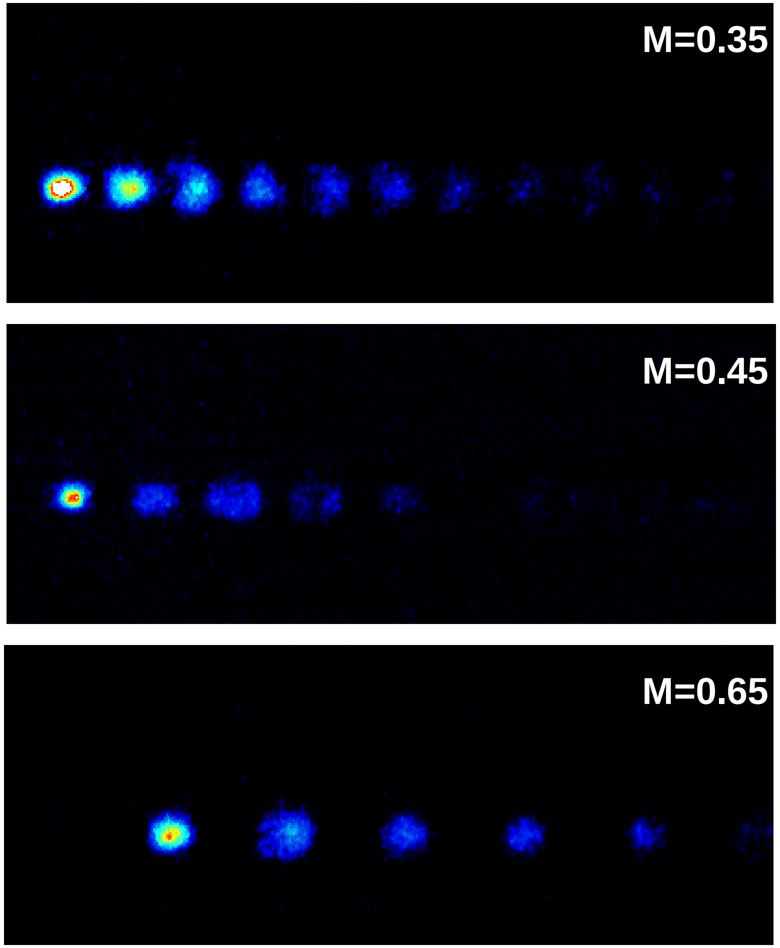
PLEET with
4.5mJ/pulse



PLEET with
12mJ/pulse

Nitrogen jet flow: ~275 m/s

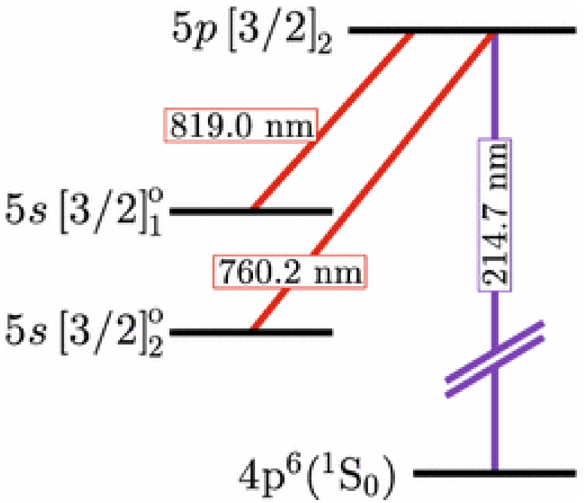
- **Measurement error 0.6–1.2 %**
- **High static pressure (300– 3000 torr)**



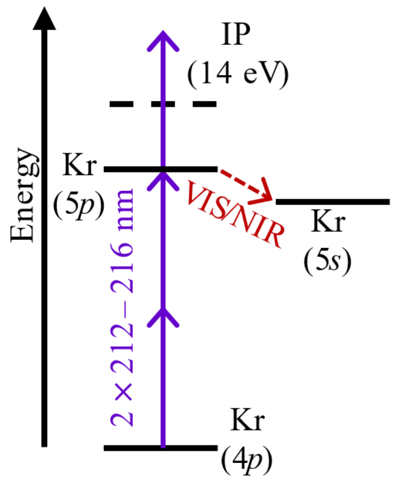
NASA Langley: Wind tunnel core flow measurements

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

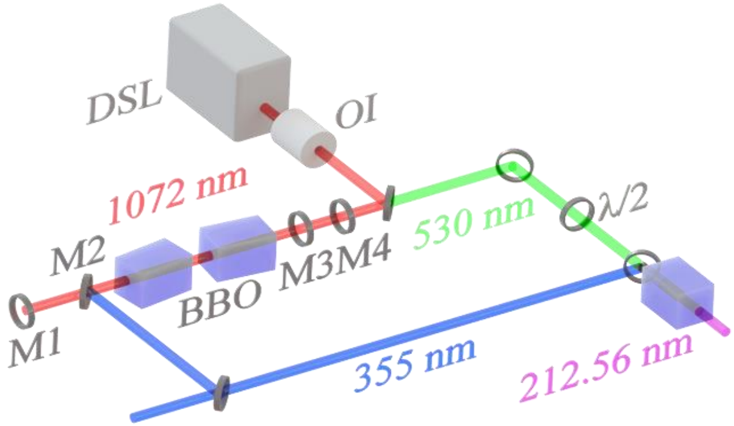
Technique: 100-kHz KTV



Two-line KTV

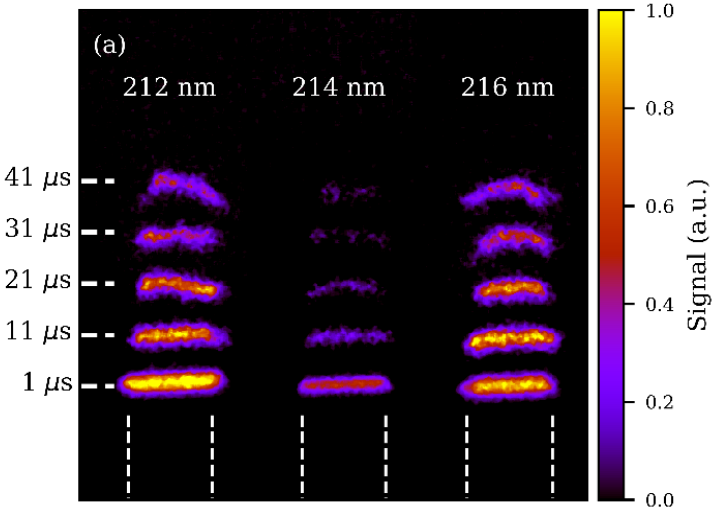


Single-line KTV



OPO system

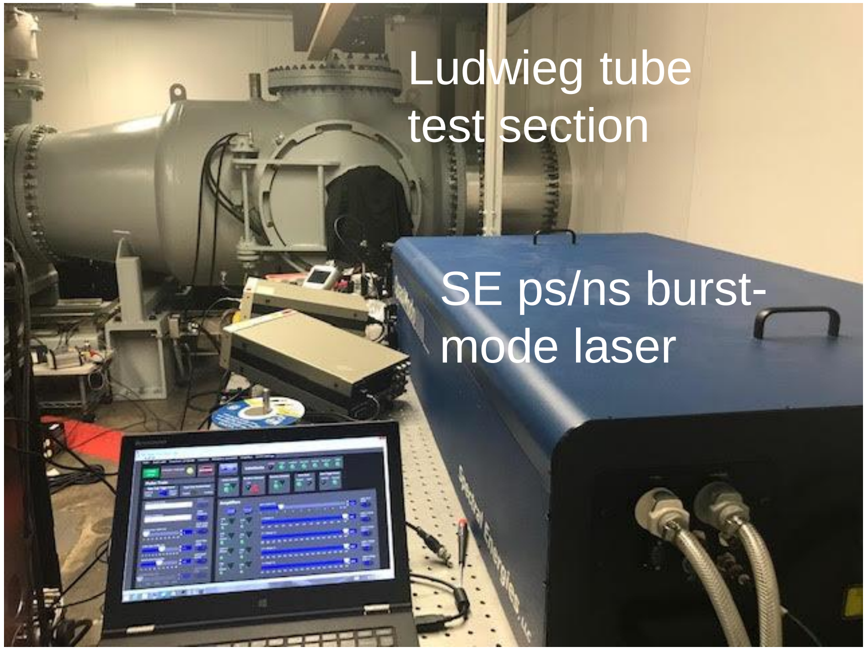
- **Burst-mode laser and OPO system**
- **Single-line KTV is simplified from two-line KTV system with REMPI process**
- **Demonstrated in Mach-6 Ludwieg tube**



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

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

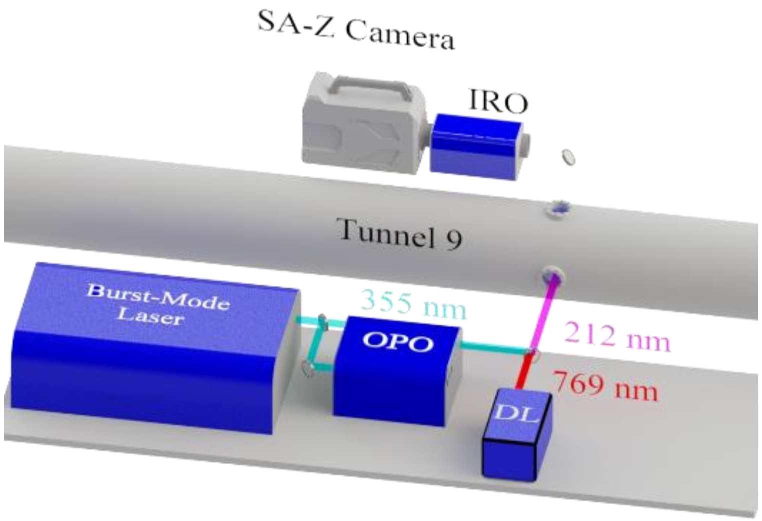
Facility: AFRL Mach 6 Ludwieg Tube



Mach 6 air flow at various stagnation pressures of 379 kPa – 4.14 MPa

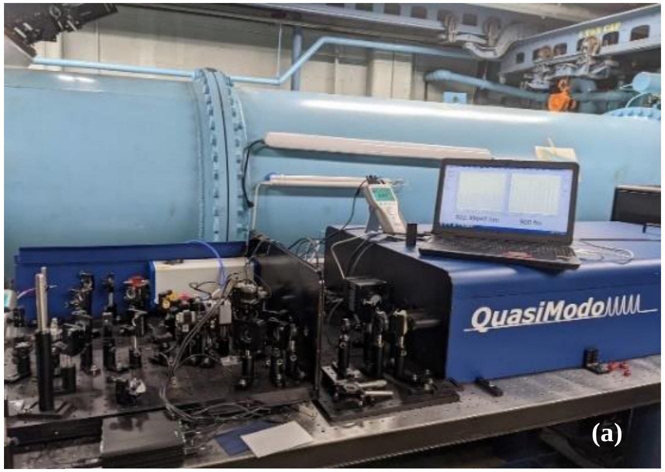
- Unit freestream Reynolds numbers of 6.56×10^5/m – 3.28×10^7/m
- ~900 m/s with a large-format test section (~1 m from window to center)
- Good optical access available for optical diagnostics
- Environmentally controlled test cell
- Located in Wright-Patterson AFB, convenient for experiments

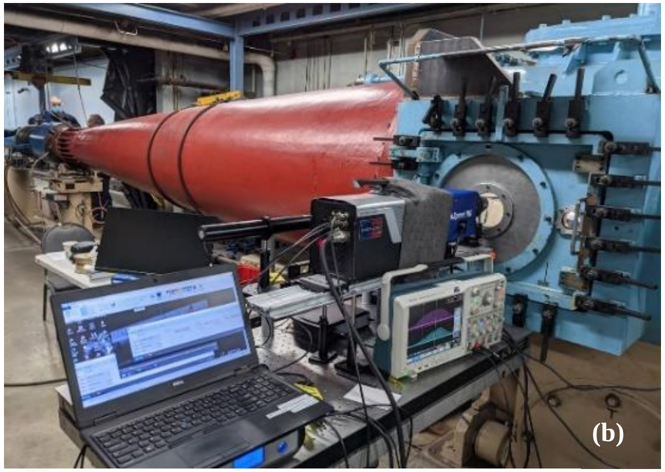
Facility: AEDC Tunnel 9



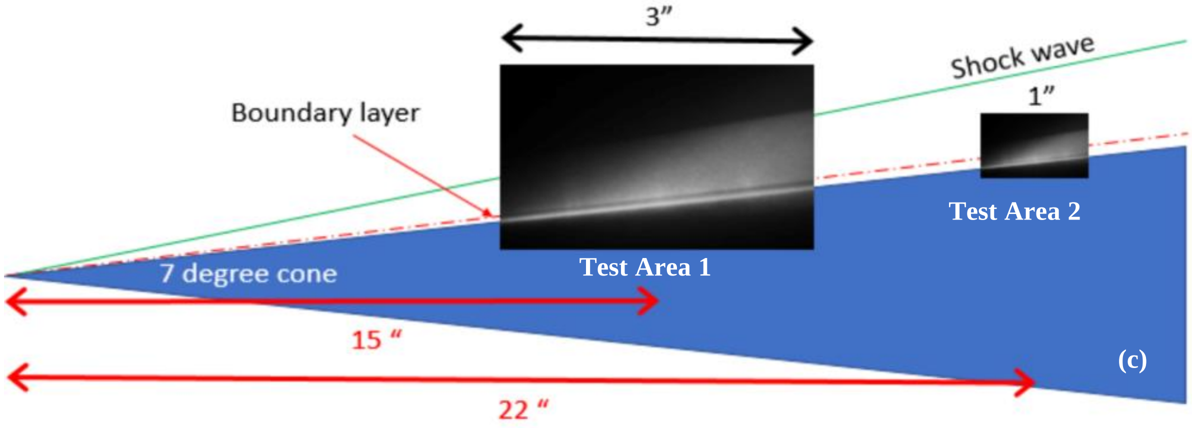
Mach 18
Reynolds number of ~1.5×10^6/ft
Nitrogen gas
Stagnation Pressure: 130 MPa
Stagnation temperature: 1844 K
Test time: ~5 seconds
Flow speed: ~1.9–2.1 km/s
Static temperature: ~35K
Static Pressure: ~0.4 torr
Gas seeding: 1% Kr (in mass) in N_2

Facility: CUBRC Mach 10 Shock Tunnel





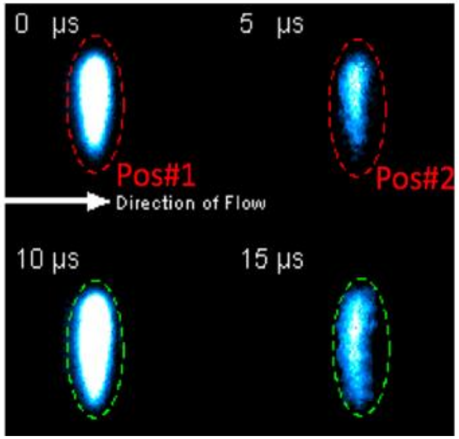
- Burst-mode laser & OPO
- Shimadzu & intensifier
- Laser energy ~0.6 mJ/pulse
- Sheet size ~5"



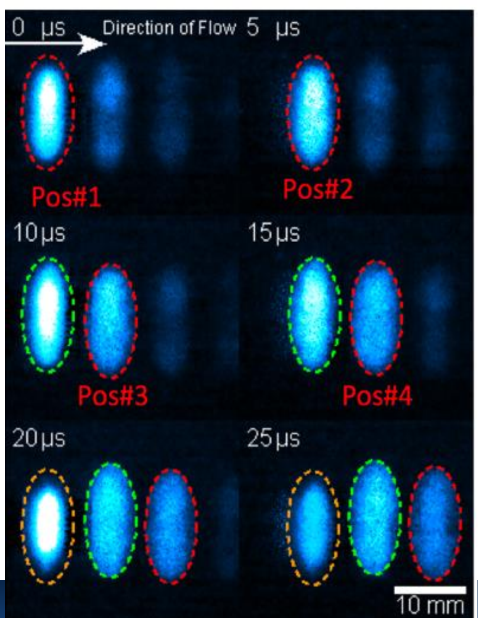
MHz NO PLIF in CUBRC shock tunnel

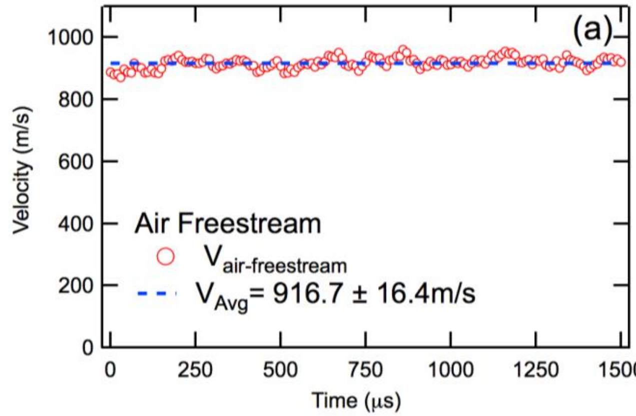
100-kHz PLEET Velocimetry

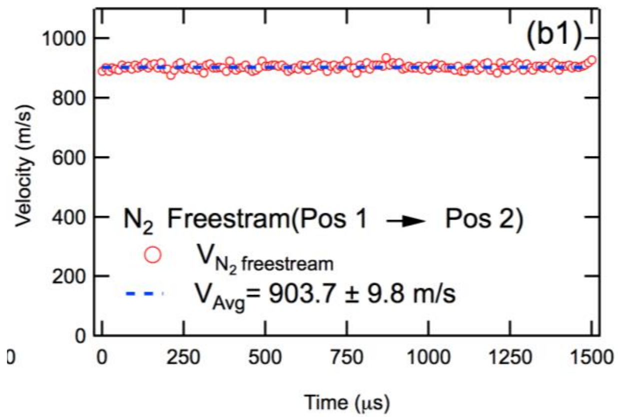
(a) Air Flow Freestream

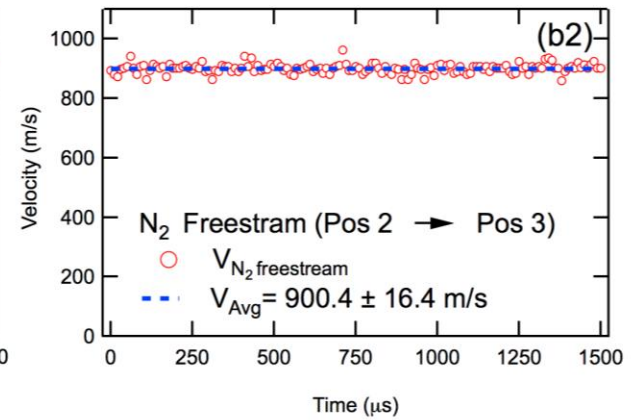


(b) Nitrogen Flow Freestream



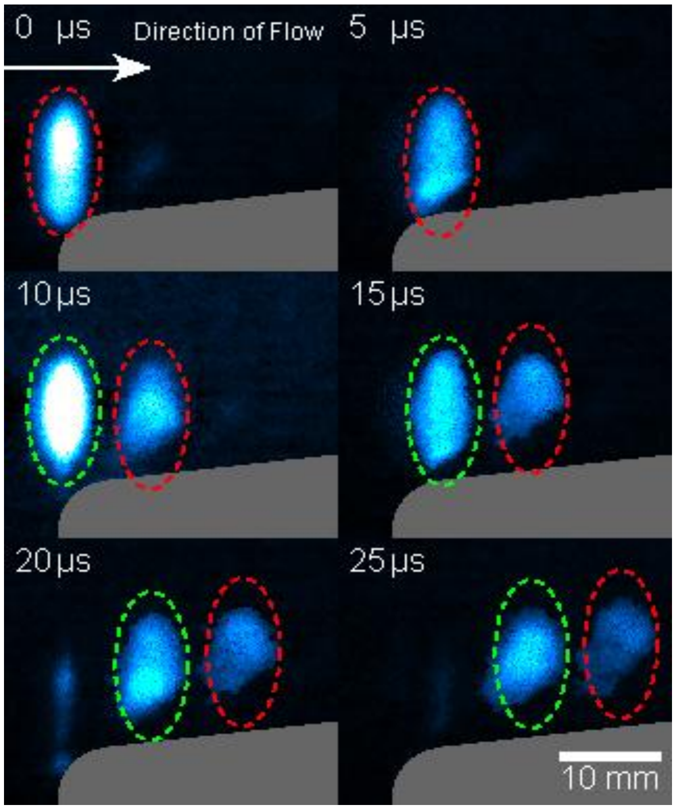


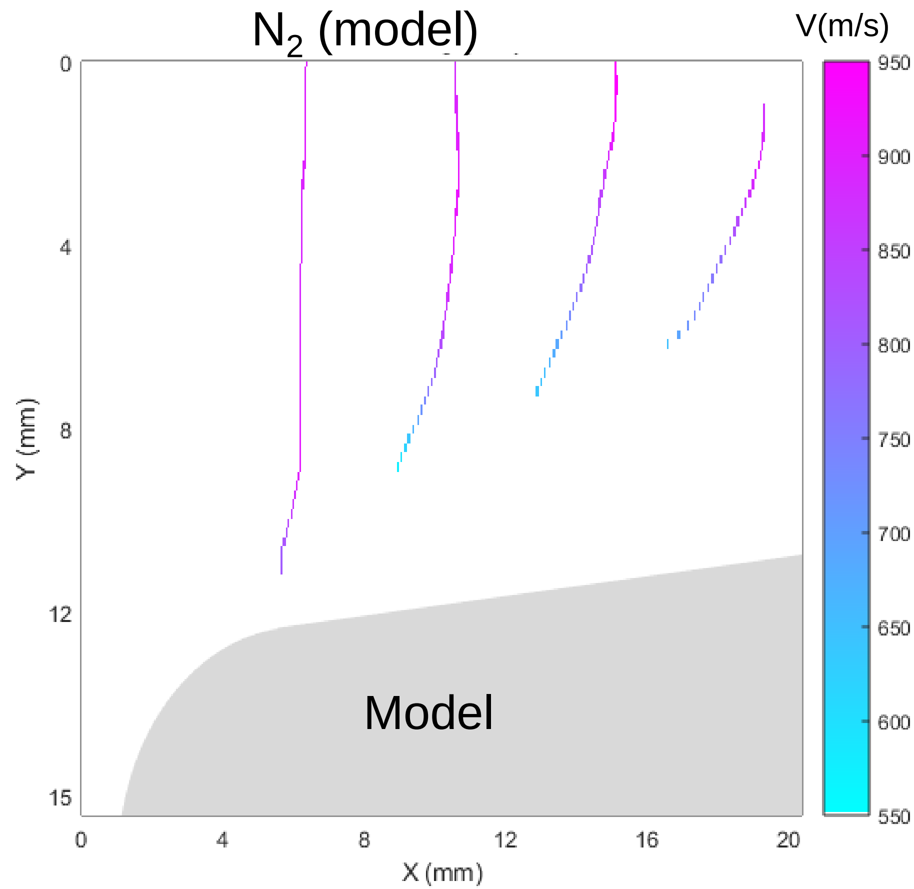




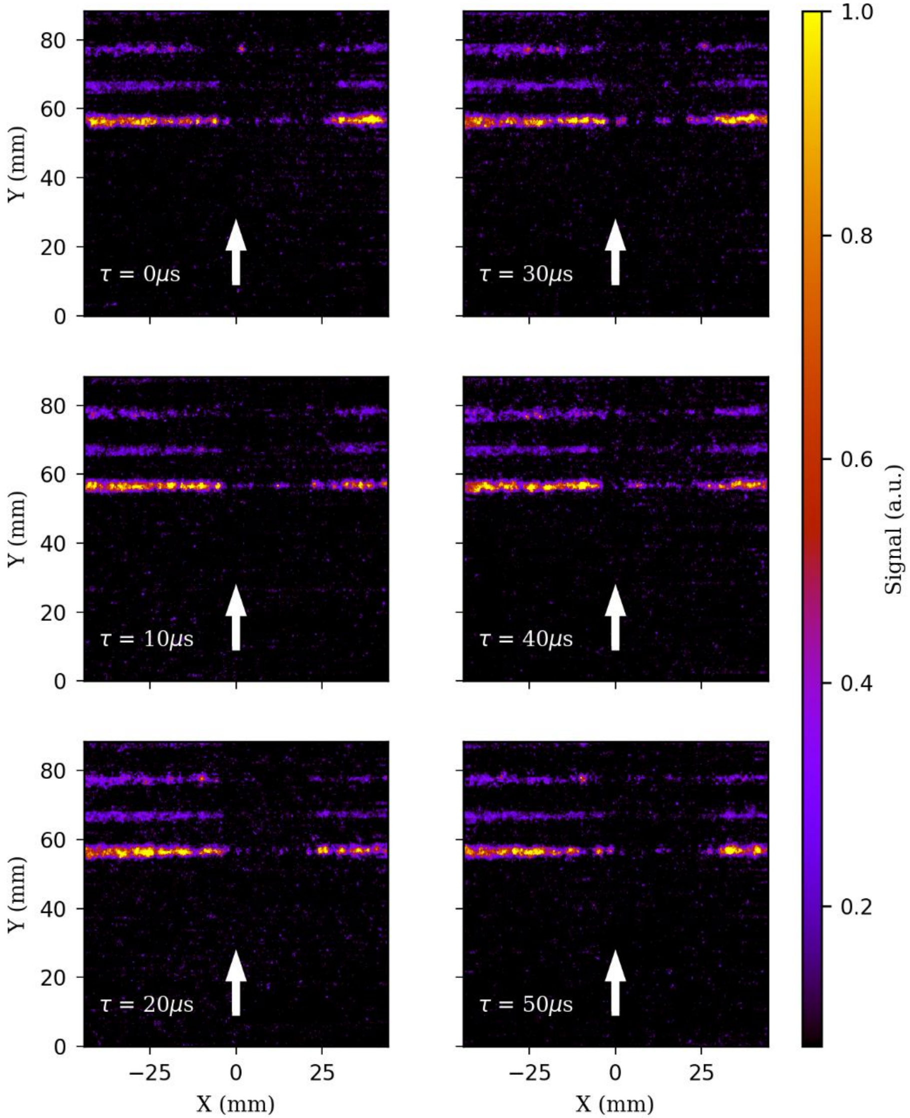
- With pure N_2 flow, PLEET signal lifetime exceeds 30 microseconds (in contrast, lifetime in air ~ 7 microseconds).
- The discrepancy between calculated air velocity (air 904 m/s) and measured velocity is <1%.
- Lowest static pressure for PLEET is 5 torr (limited by facility operation)
- Validated estimated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

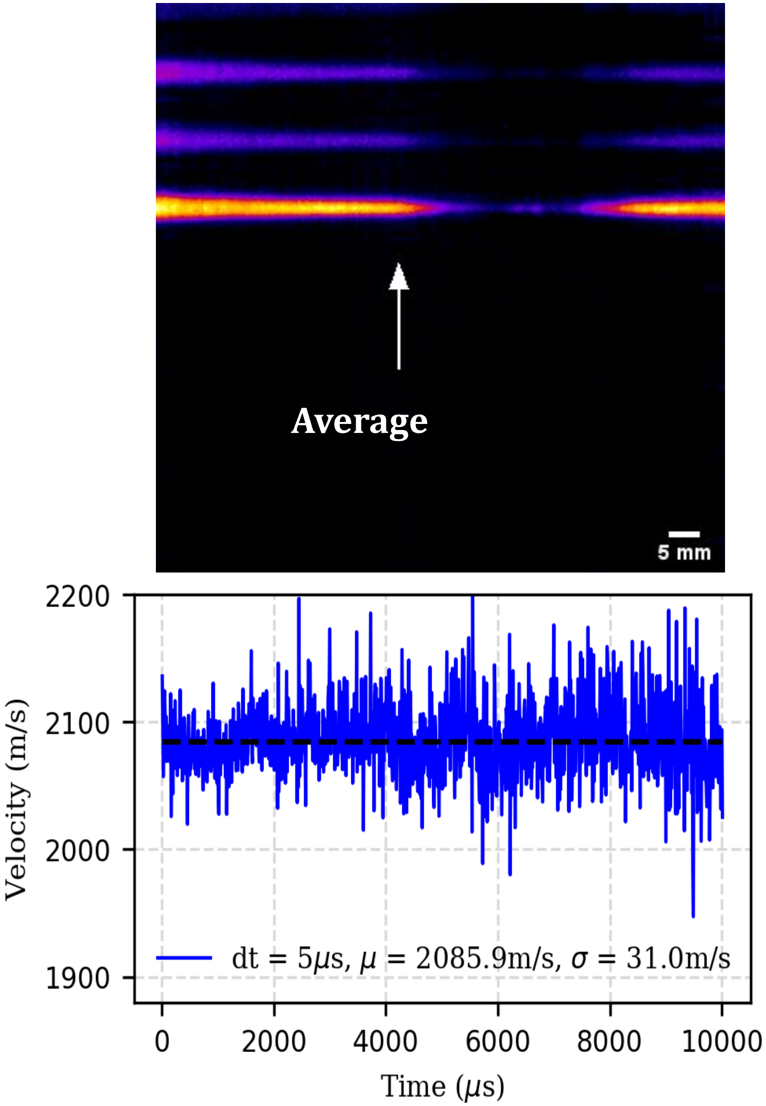
Time-resolved N_2 Flow Velocity Profile (model case)



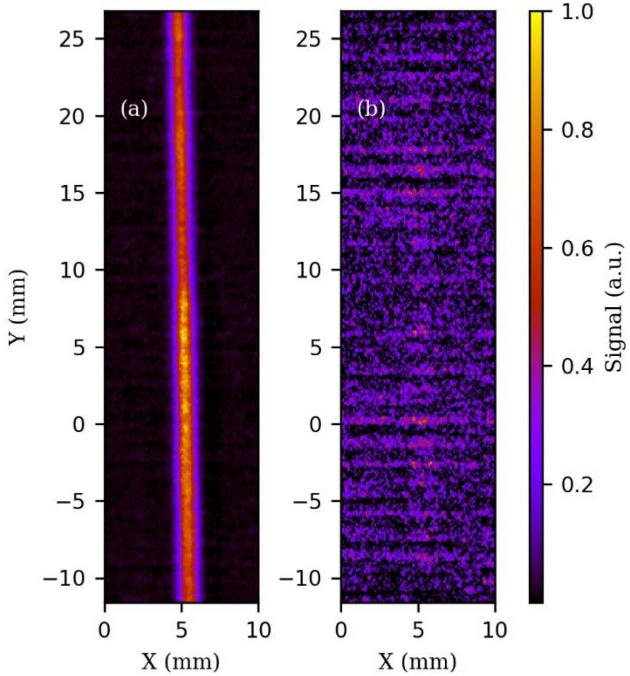


100-kHz PLEET in Tunnel 9

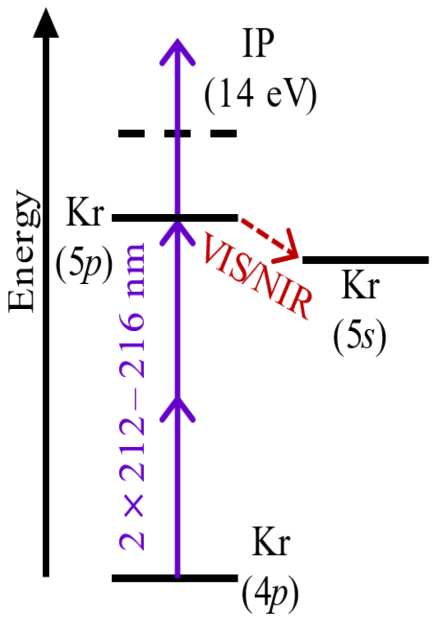




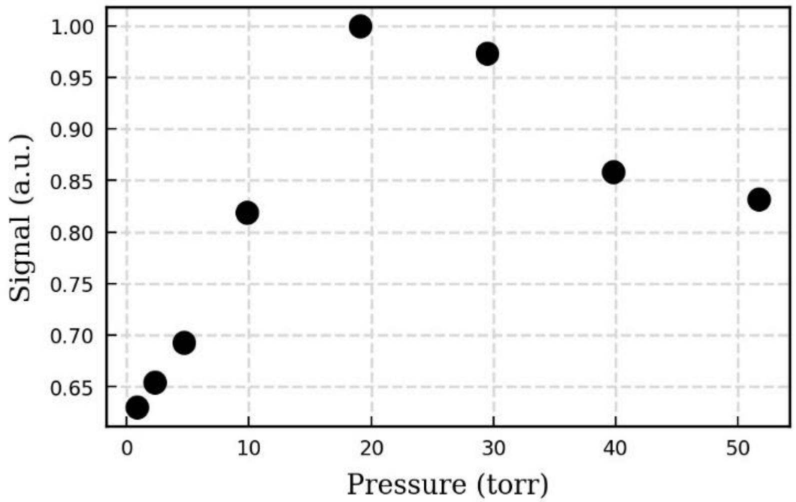
100-kHz KTV in Ludwieg Tube

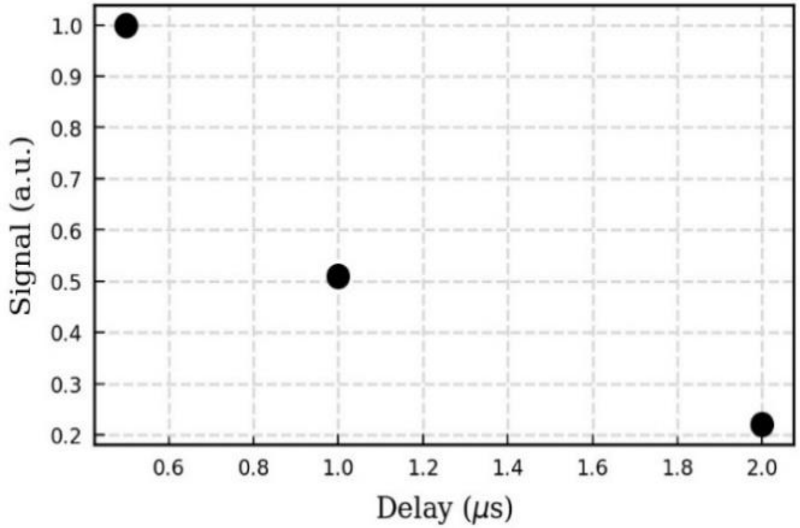


50ns Delay   200ns Delay

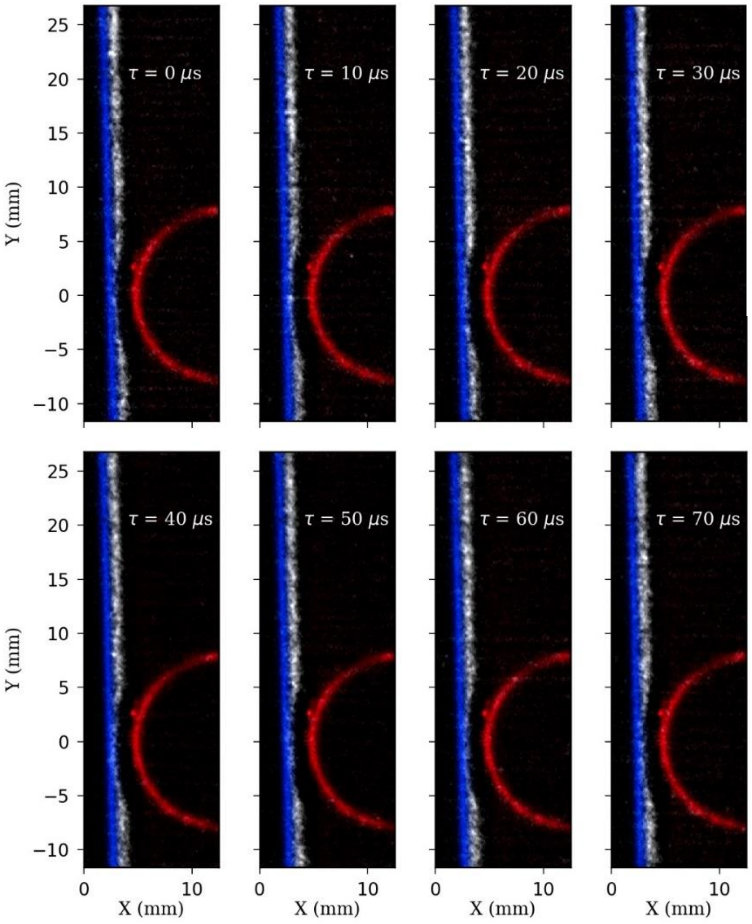


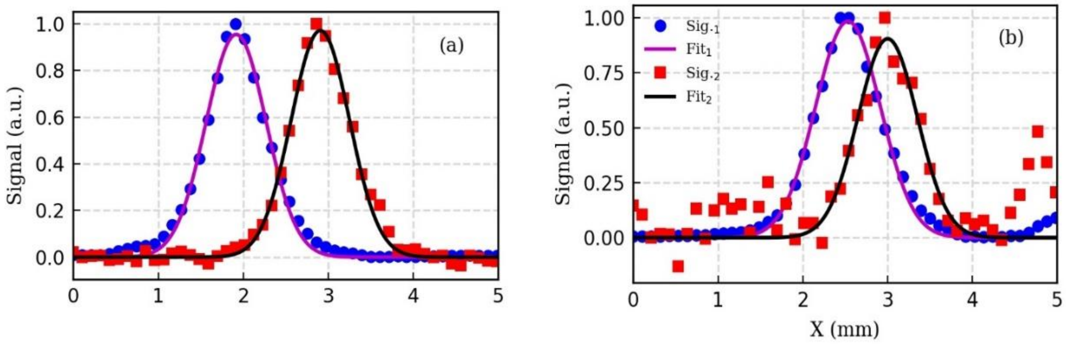
Short-lived Kr fluorescent signal at 2.5 torr static pressure and 55 K static temperature with 5% Kr seeding.

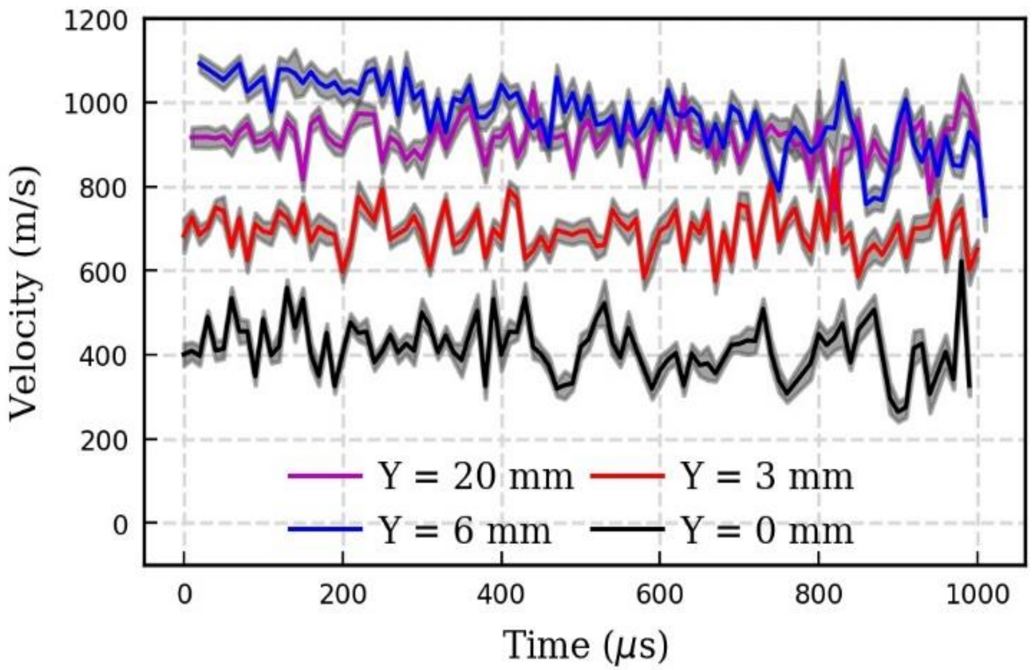




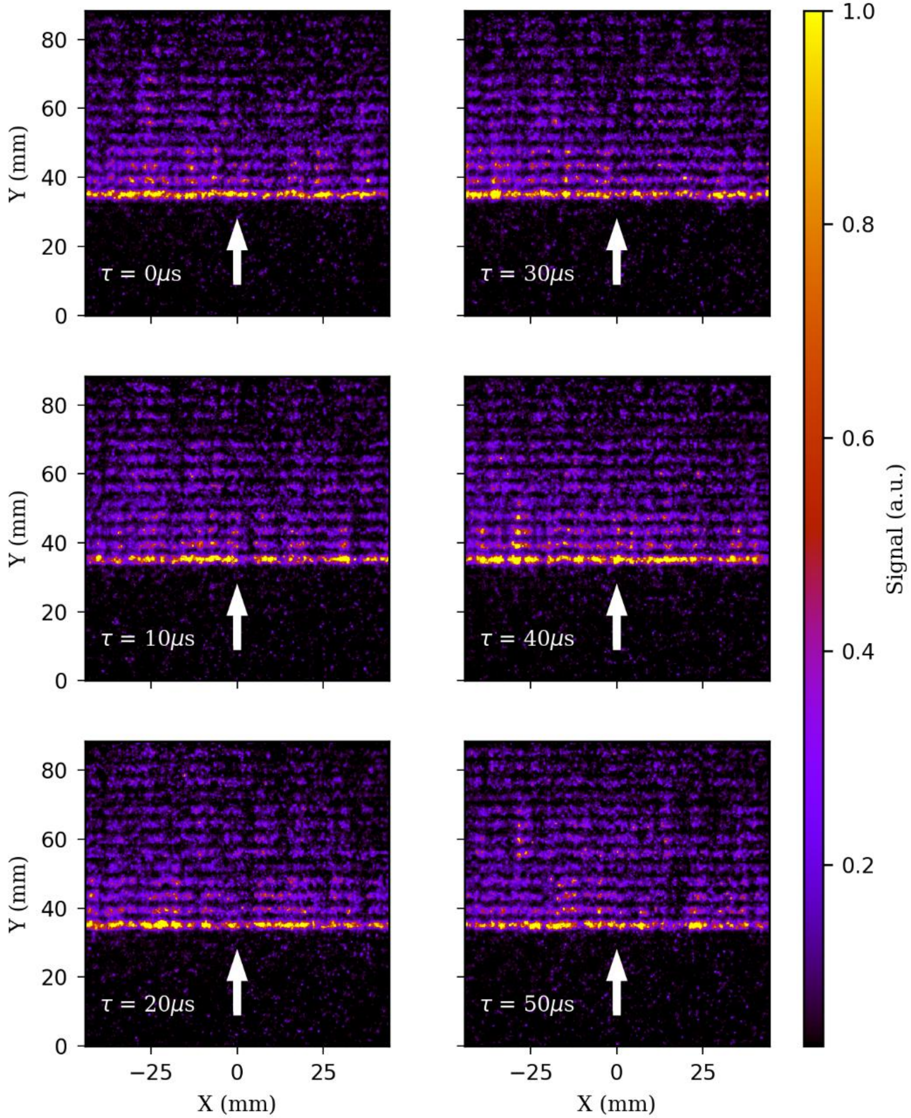
100-kHz KTV in Ludwieg Tube

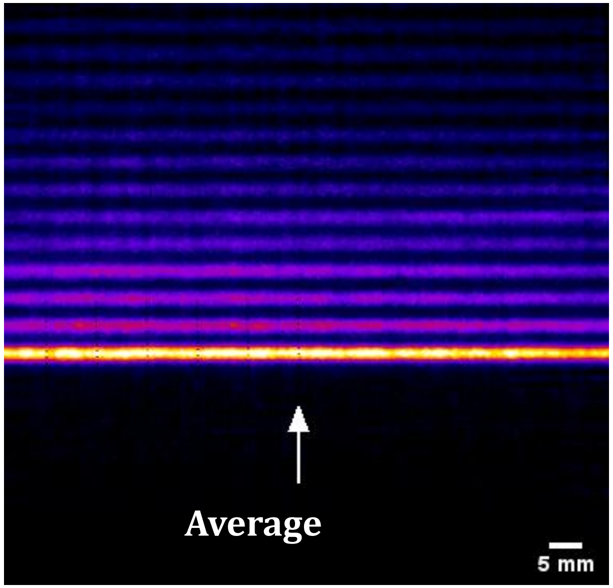


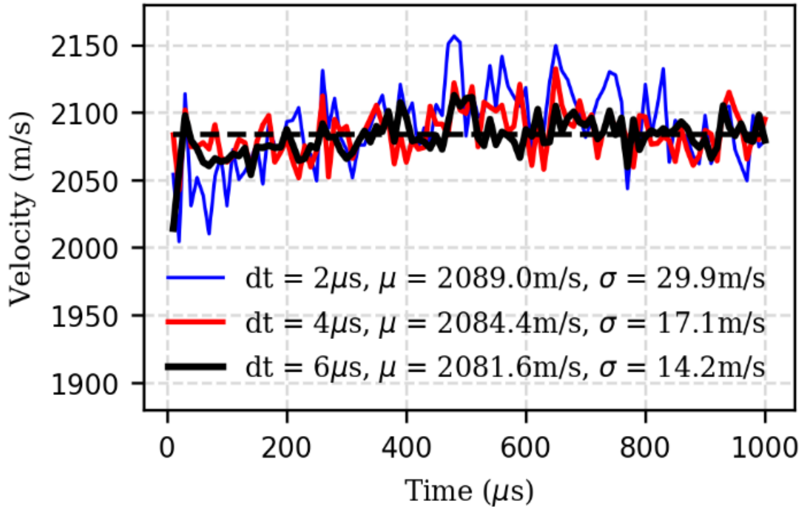




100-kHz KTV in Tunnel 9







MHz NO PLIF for Second Mode Instability Measurement

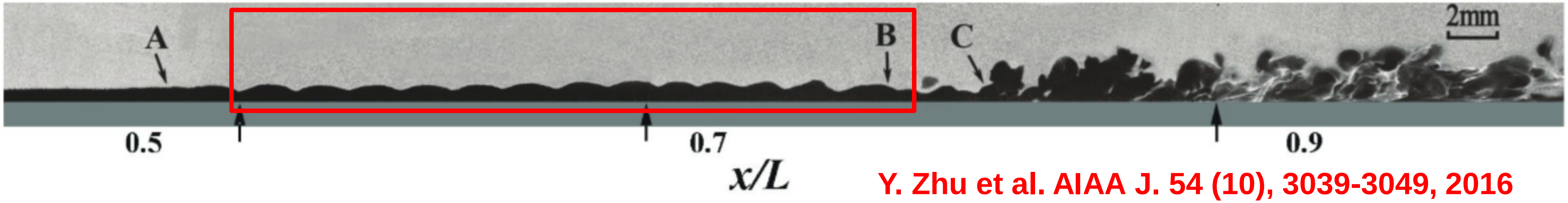
- **The second mode instability is a primary feature in laminar-to-turbulent boundary layer transition at hypersonic conditions**
- **Most measurements are done with pressure sensors**
- **Some examples of Schlieren, 10-Hz laser diagnostics**
- **Most recently, FLDI has been applied**
- **Time-resolved 2D imaging is needed**

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

U_e : boundary edge velocity

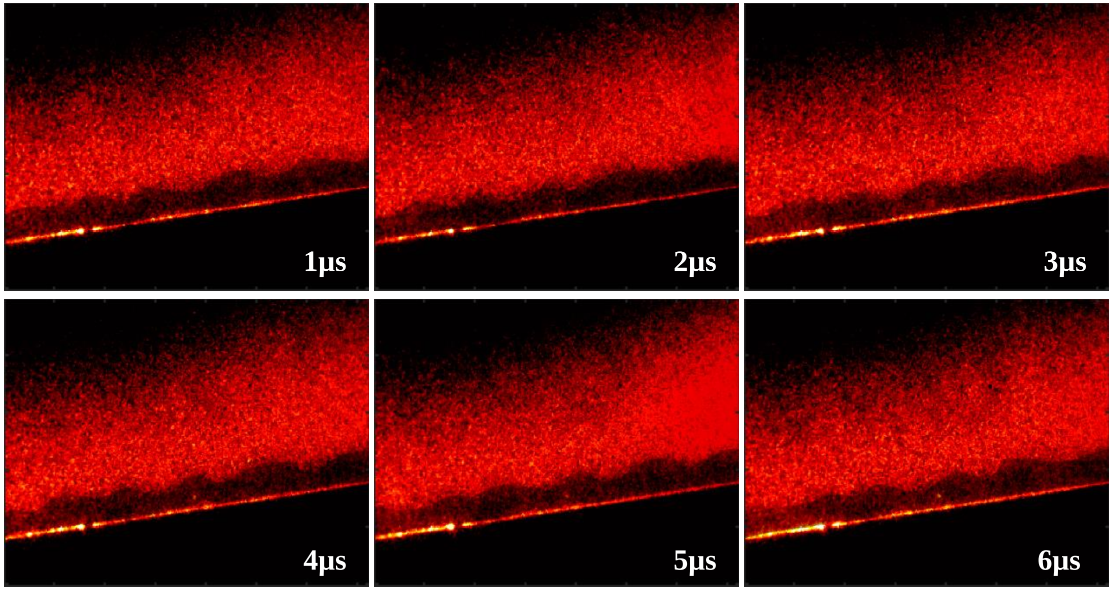
δ : boundary layer thickness

f : ~ a few 100 kHz



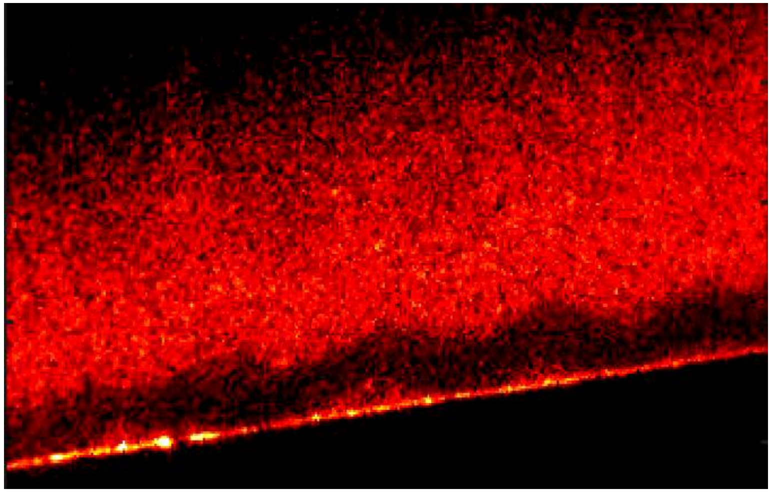
Y. Zhu et al. AIAA J. 54 (10), 3039-3049, 2016

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 μs.**



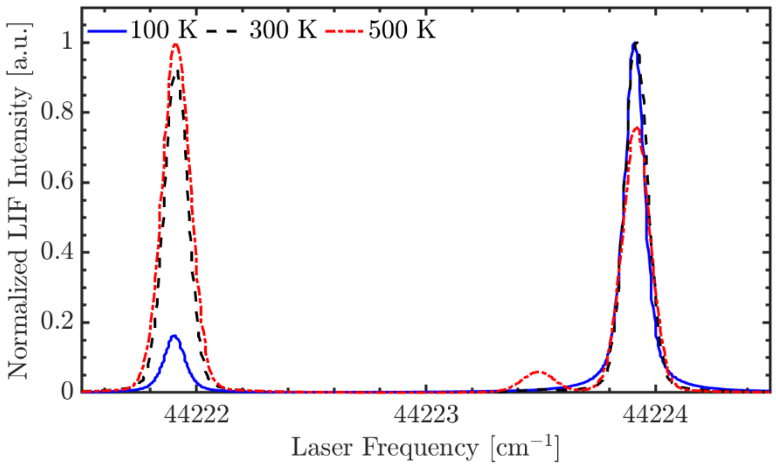
New Technique: 2D Pressure measurement with NO PLIF

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

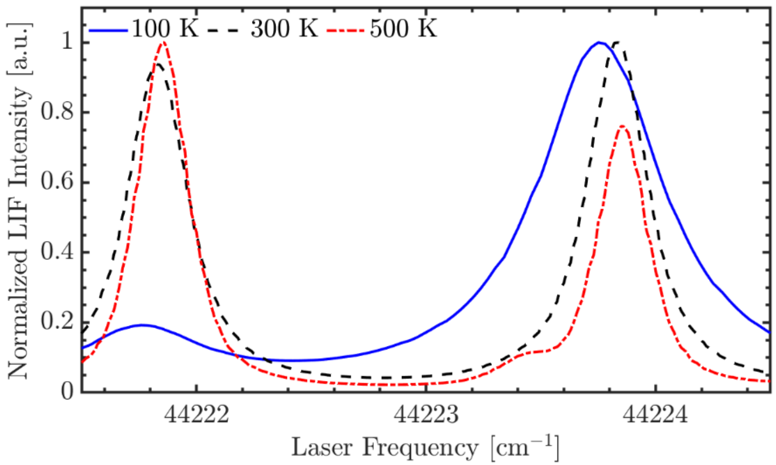
300K, 1bar, Shift=0.18 cm^{-1}, ~5.4GHz

NO Lines :

- $Q_1(11.5) + R_{21}(11.5)$ near 22221.9 cm^{-1}
- $R_1(5.5) + Q_{21}(5.5)$ near 22223.9 cm^{-1}

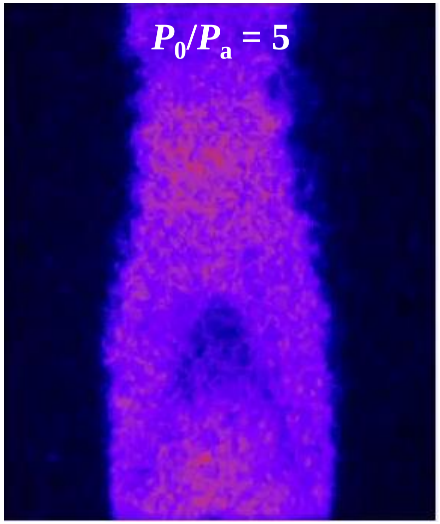


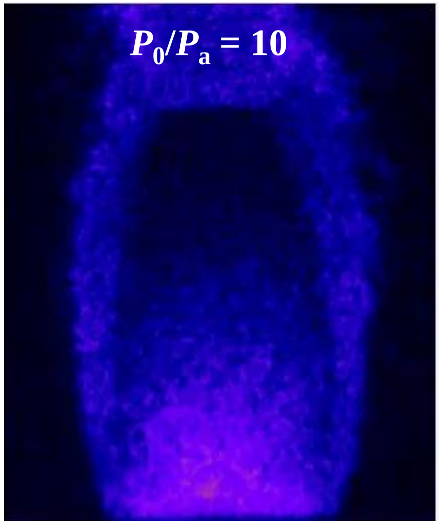
P = 5 kPa

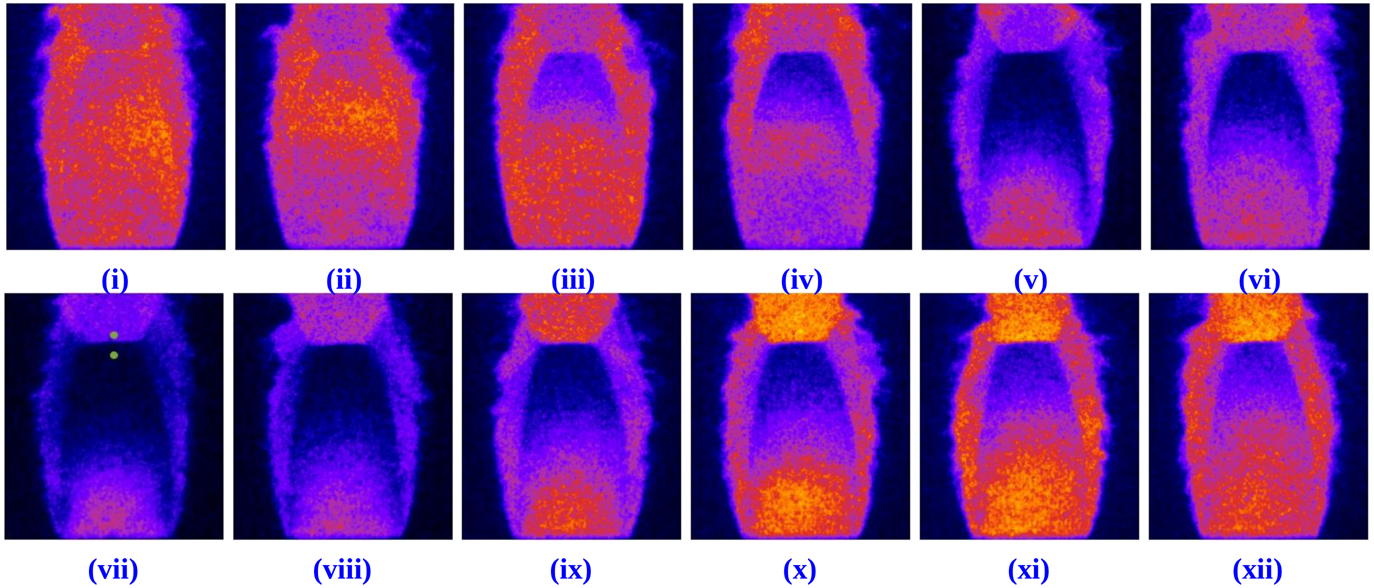


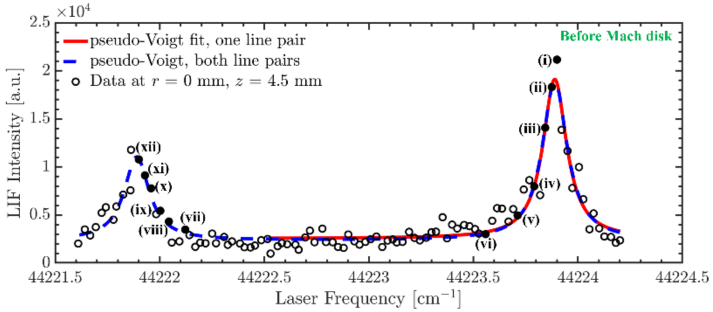
P = 50 kPa

100-kHz NO PLIF Imaging

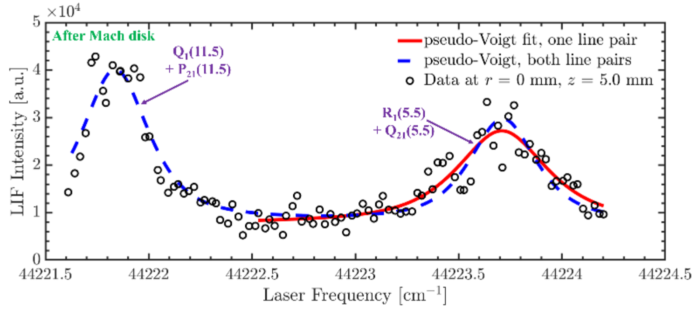






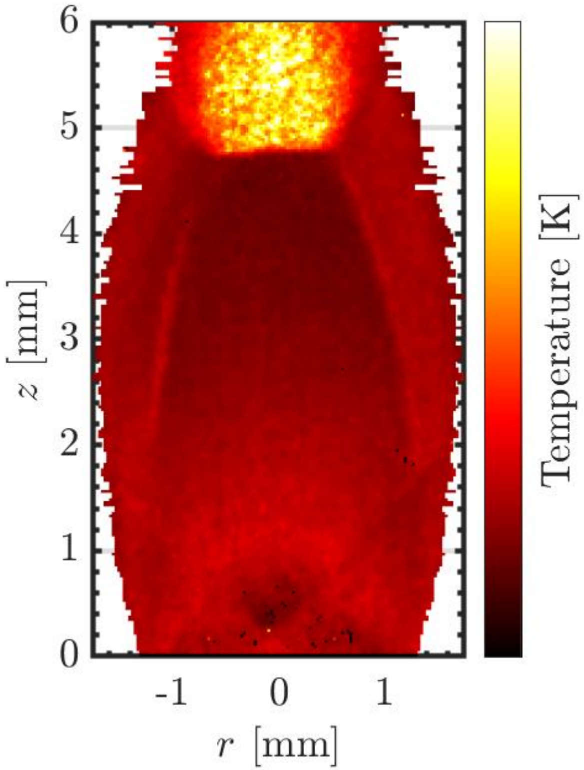


Upstream of Mach Disk

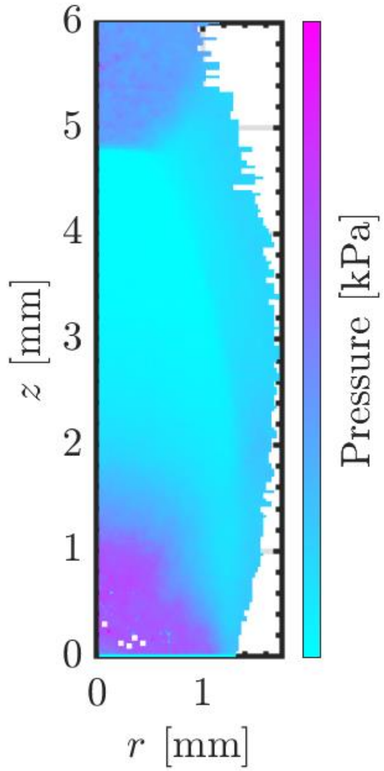


Downstream of Mach Disk

2D Pressure and Temperature Measurement



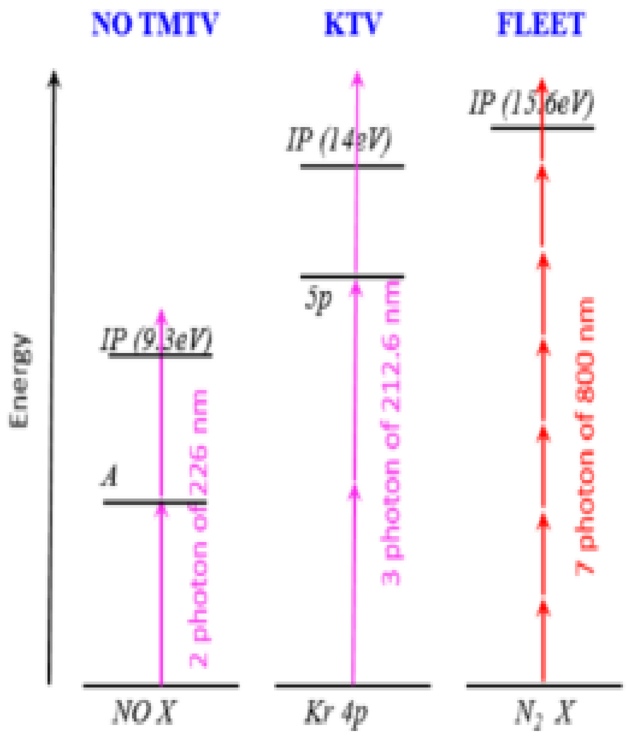
Temperature

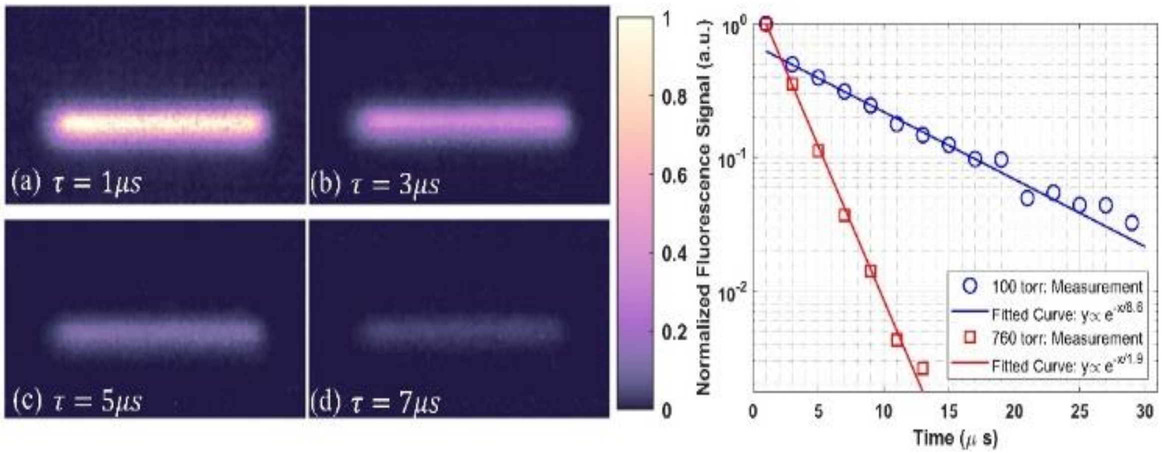


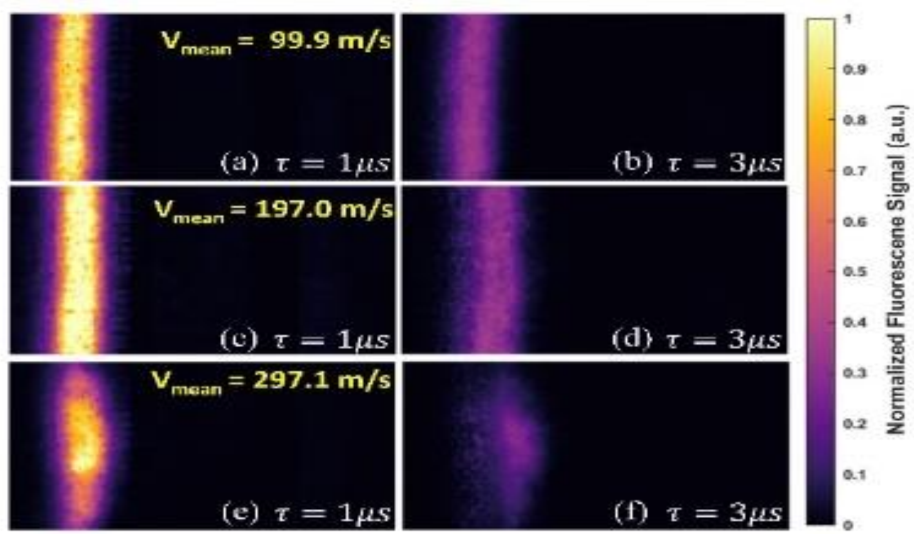
Pressure

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

New Technique: Two-Photon NO MTV







Summary

- 100-kHz PLEET and KTV in AFRL Mach 6 Ludwieg 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 NO PLIF and Two-photon NO MTV