High-Repetition-Rate Flow Visualization and Velocimetry for Large-Scale Ground Test Facilities

Paul Hsu, Naibo Jiang, Christopher Fugger, Mikhail Slipchenko, Sukesh Roy

Spectral Energies, LLC

Jan. 6, 2022

Extensive Teaming and Collaboration

Daniel Lauriola, Austin Webb, Dr. Terrence Meyer (Purdue University)

Ms. Sara Schmidheiser, Dr. Benjamin Emerson, Dr. Timothy C. Lieuwen (Georgia Tech)

Dr. Mark Gragston (UTSI)

Dr. Ron Parker, Dr. Timothy P. Wadhams (CUBRC)

Dr. Andrew Cutler(George Washington University)

Dr. Ross A. Burns, Dr. Timothy W. Fahringer, Jr , Dr. Paul Danehy (NASA Langley)

Outline

- Measurement need for high-speed flow and combustion ground test facilities
- Challenges of high-repetition-rate PLIF, Mie scattering, and DSPIV flow visualization in large-scale ground test facilities (Hypersonic wind tunnel & combustion facility)
- Potential Solutions
- Summary

Measurement for High-speed Flow Diagnostics

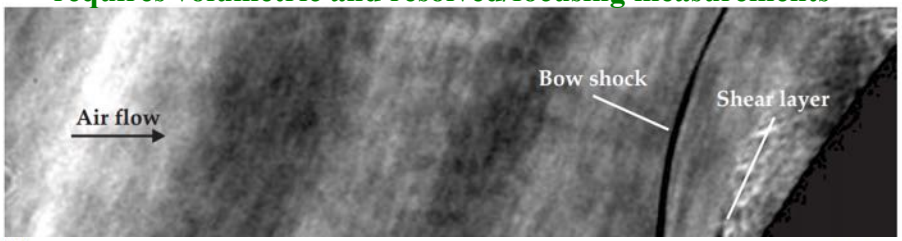
Supersonic-Hypersonic measurements are crucial to understand underlying physics

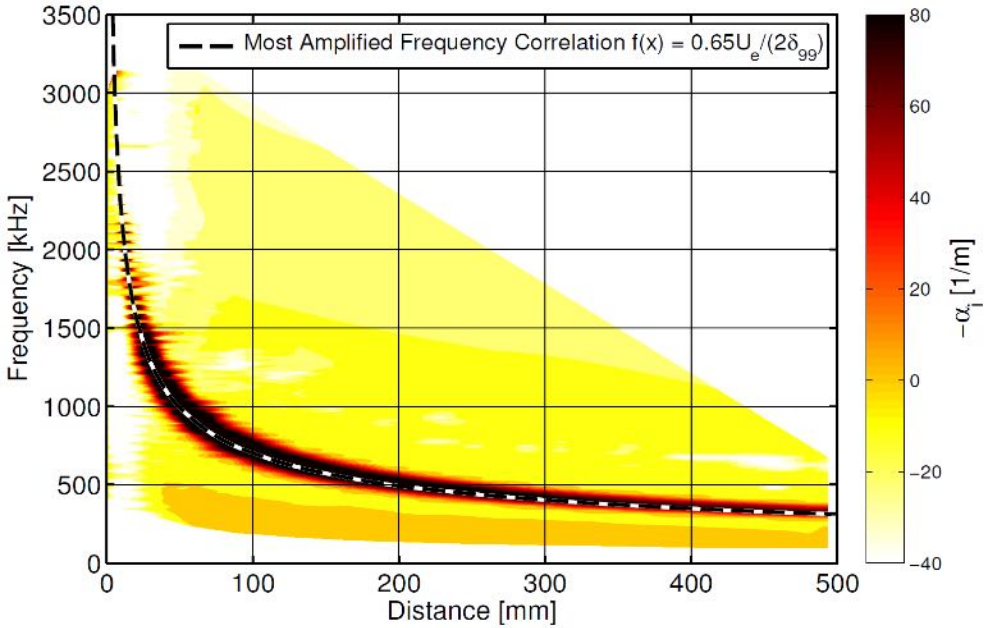
Boundary layer transition measurement and prediction is critical for control surface authority and heating load predictions.

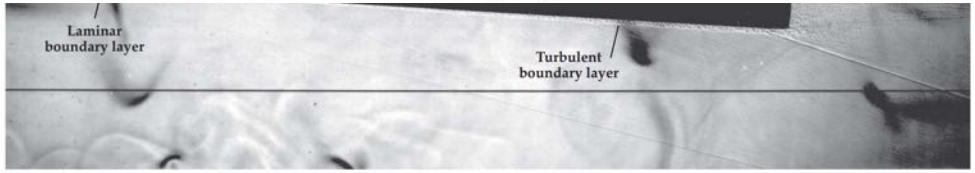
Shock wave / boundary layer interactions are major source of flow unsteadiness and responsib for creating "hot spots" that can lead to catastrophic fin/wing/flap failure.

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

Shock-boundary layer interaction: can be highly 3-D; requires volumetric and resolved/focusing measurements





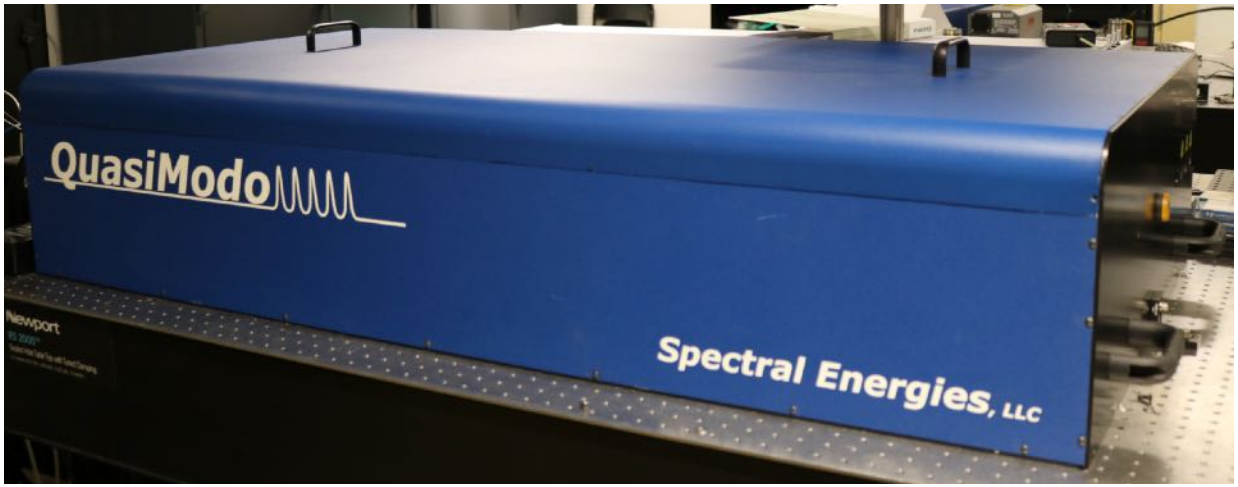


Measurement Need:

high-rep-rate (100 kHz or greater), noninvasive diagnostics to characterize flow structure *(small and large) with high spatial and temporal resolution*, *V*, ρ, *T*, … in supersonic-hypersonic environments

S. P. Schneider, *Prog. Aerosp. Sci.* **40**, 1, (2004), in I.A. Leyva, *Physics Today* **70**, 11, 30 (2017).

High-repetition-rate, High-energy Burst-Mode Laser



Standard burst-mode laser @ 10 kHz Energies:
1 J per pulse 1064 nm for nanosecond operation (10 ms burst duration)
200 mJ per pulse 1064 nm for picosecond operation (10 ms burst duration)

Upgraded burst-mode laser @ 1 MHz Energies:
150 mJ per pulse 1064 nm for both picosecond and nanosecond operation (1.5 ms burst duration).

Pulse Burst Laser Flow Visualization at the NASA Langley Unitary Plan Wind Tunnel

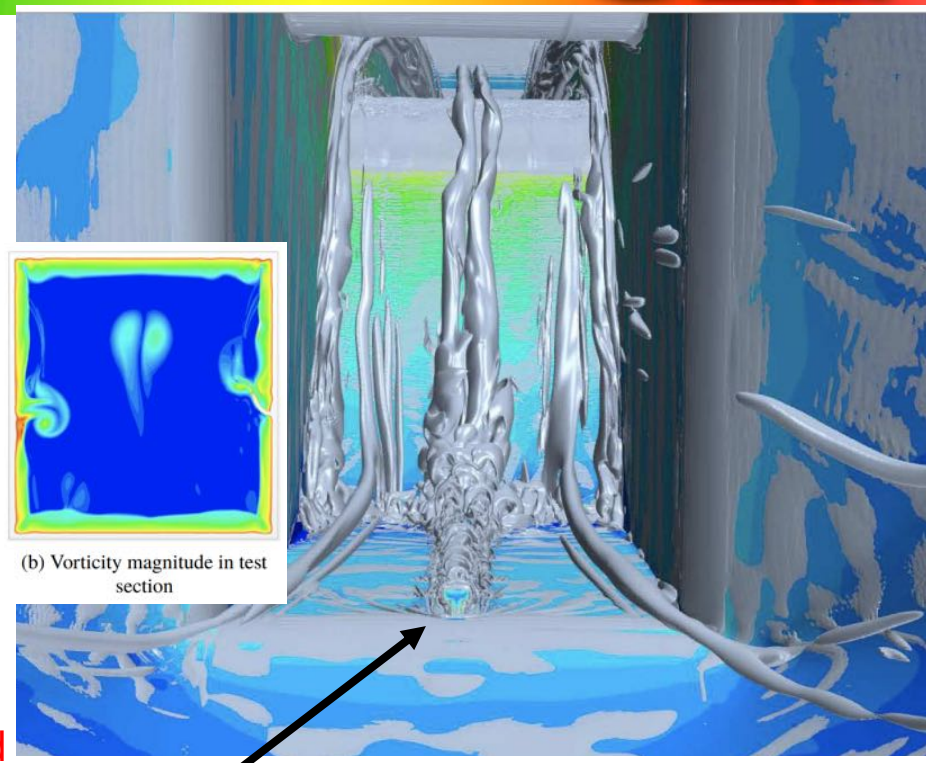
Computational study involving multiple researchers and codes predicted unexpected counter-rotating vortices in the NASA Langley 4' Unitary Plan Wind Tunnel.

- Vortices appeared to originate from the T-shaped rail on which the nozzle block slides.
- Side-wall vortices also observed in CFD.
- Conventional measurements (probes, time-averaged flow visualization, schlieren) didn't directly see evidence of vortices

– Models tested in UPWT did show unexpected moments.

– Burns, Fahringer, Danehy were asked to visualize these vortices with the pulse burst laser using planar laser Mie scattering.

- Scattering from ice crystals produced by injecting liquid water downstream of the test section. Ice crystals form in supersonic expansion.



(b) Vorticity magnitude in test section

***T* rail**



AIAA AVIATION Forum
August 2-6, 2021, VIRTUAL EVENT
AIAA AVIATION 2021 FORUM

10.2514/6.2021-2963

Check for updates

Flow Characterization of the NASA Langley Unitary Plan Wind Tunnel, Test Section 2: Computational Results

R.E. Childs* , P.M. Stremel† , V.M. Hawke‡ , and J.A. Garcia§
NASA Ames Research Center, Moffett Field, CA 94305

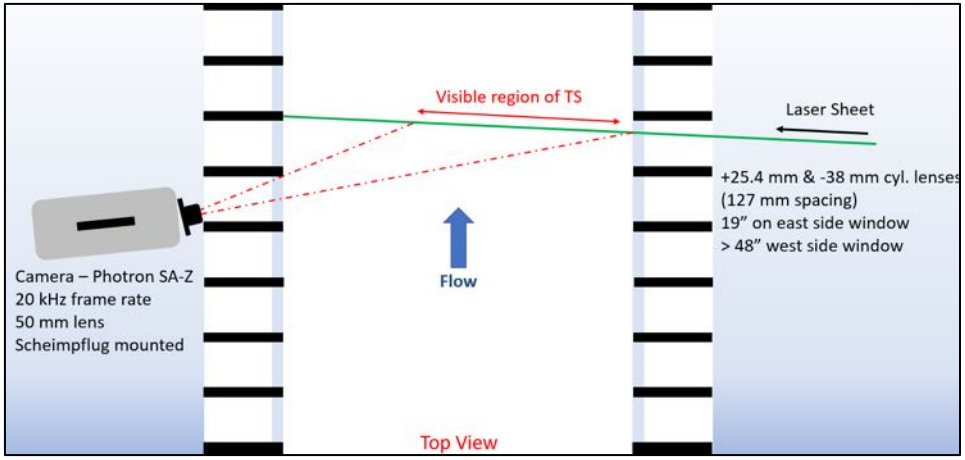
S.J. Alter¶ , C. Hunter‖ , W.L. Kleb** , P. Parikh†† , M. Patel‡‡ , and M.N. Rhode§§
NASA Langley Research Center, Hampton, VA 23666

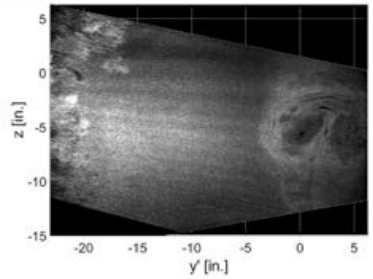
K. Salari¶¶
Lawrence Livermore National Lab., Livermore, CA 94550

Pulse-burst Planar Laser Mie Scattering (PLMS)

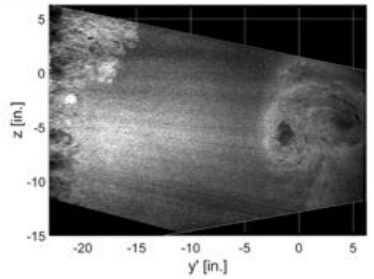
- **Pulse-burst Planar Laser Mie Scattering (PLMS) visualized centerline and sidewall vortices, confirming computations.**
  - **Reported in CFD paper (right)**

- **Quantitative velocity measurements also obtained using variation of PLMS (*Planar Investigation of a CobraMRV Reentry Flowfield Using Pulse-Burst, Cross-Correlation DGV*, Burns, Fahringer, Danehy in this SciTech meeting)**

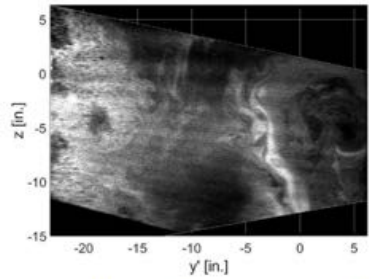




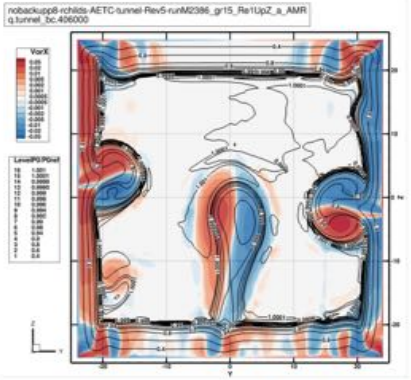
a) Instantaneous T-rail vortex pair (right side of image), $M = 2.386, Rey = 10^6/ft$



(b) T-rail vortex pair at different time; observe change in location



(c) Side-wall vortex (left of image) and T-rail vortex, $M = 2.5, Rey = 10^6/ft$

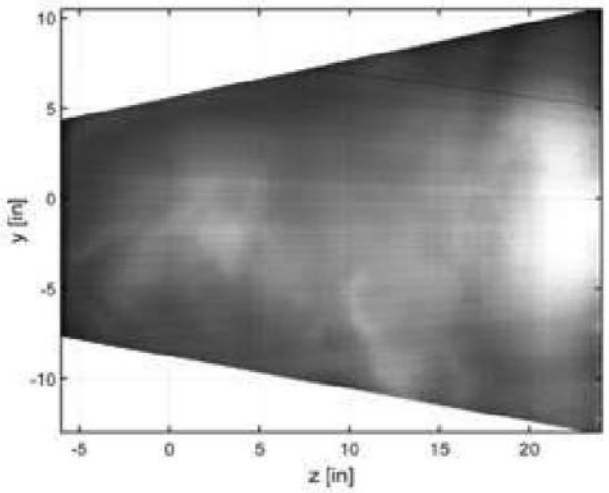


(d) Color vorticity and $P0$ contours, instantaneous CFD solution

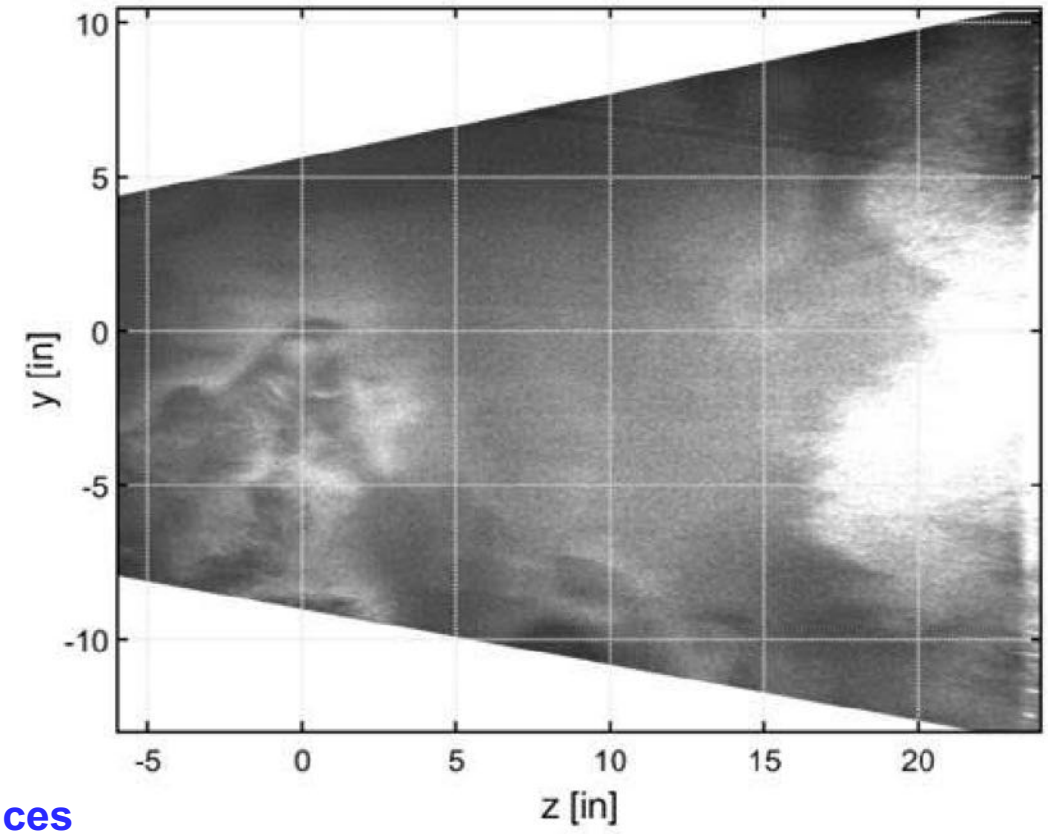
Fig. 13 Instantaneous flow visualizations using Planar Laser Mie Scattering at $X = 47.5''$ (courtesy R. Bur and P. Danehy) and X–vorticity contours from CFD at $X = -60''$

This effort was funded by NASA ARMD AETC and TTT programs

PB-PLMS Flow Visualization Results



50-pulse mean



Animated sequence (acquired at 20 kHz, shown at 10 fps) Mach 2.5, Re 1e6/ft

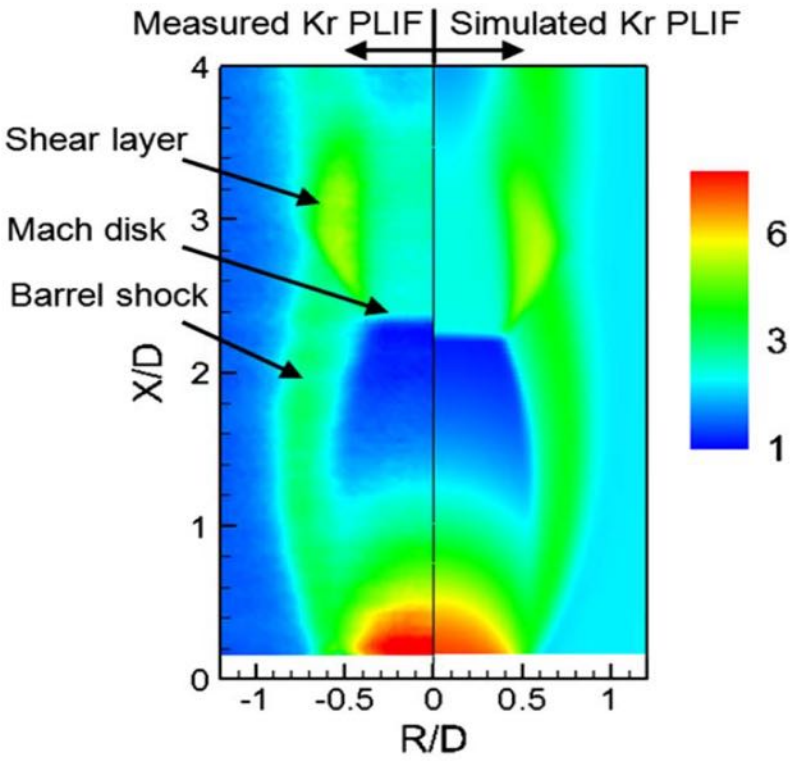
- **Averaged image does not show vortices**
- **Time resolution allows movement and lifetime of vortices to be assessed.**
- **A fairing for the T-rail has been proposed to reduce vortex strength.**
  - **PLMS will be used to verify flow quality improvement of modified T-rail**

PLIF Imaging for Flow Structure Measurements

Advantages of PLIF:

- High spatial and temporal resolution
- Measurement in model with arbitrary shape (e.g., inside the cavity. etc.)
- Species concentration detection

Comparison of Kr PLIF and CFD simulation in a Mach 4.5 jet flow



Burn et al., AIAA paper 2011-3936, 41th AIAA Fluid Dynamics Conference and Exhibit (2011).

Visualization of the shear layer using NO PLIF



Apollo-geometry capsule tests

Danehy et al., " PLIF investigation of hypersonic flowfield in a Mach 10 wind tunnel," AIAA 2006-3442

Challenges for NO PLIF imaging of boundary layer in large-scale wind tunnels

- Laser beam absorption during long propagation distance (> 1 m depending on probe location)

-NO seeding in freestream, localized seeding is not available

- High-spatial-resolution imaging of wide wavelength UV NO LIF emission over long distance (for boundary layer imaging, BL thickness few mm)

-Limited long focal length UV camera lens

- High energy UV LIF beam at high repetition rate (100 kHz – MHz)

–Sufficient laser energy is required for exciting molecules under low pressure hypersonic environments

CUBRC Mach 10 Wind Tunnel



MHz Burst-mode OPO and NO Line Selection

- **Burst-mode laser and OPO system for NO PLIF**
- **~0.25%–0.5% NO seeding in entire flow**

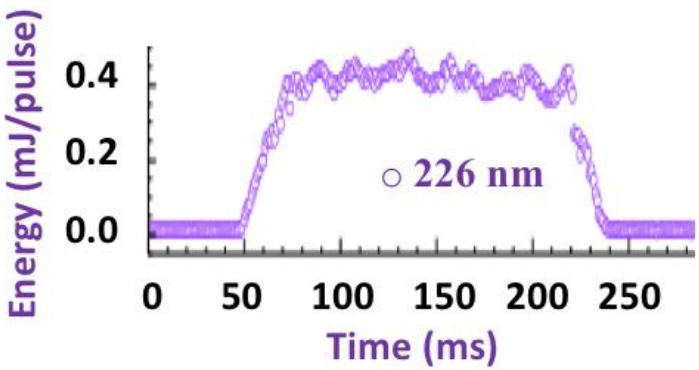
Challenges:

- **Long absorption path length in freestream**
  –Laser needs to transmit ~ 1 m of freestream to reach the boundary layer (the distance from shockwave to BL is ~0.5")

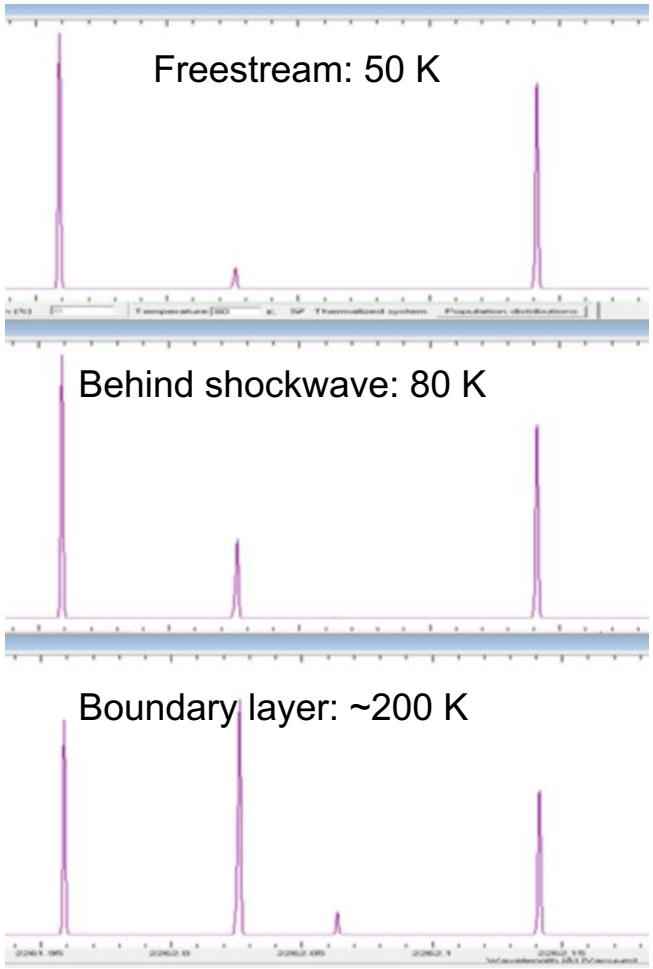
Solutions

- **Select an ideal NO absorption line that has low absorption in freestream (~50 K) and high absorption in BL (~200 K).**
- **Q1(8) in *A*–*X* (0,0) transition was selected**
  -Q1(8) line almost has no absorption in freestream, and strongest absorption in boundary layer
  -Based on our calculation, the 1-m long freestream absorption of the laser energy loss is <2%.

Burst Profile of 1 MHz pulse train



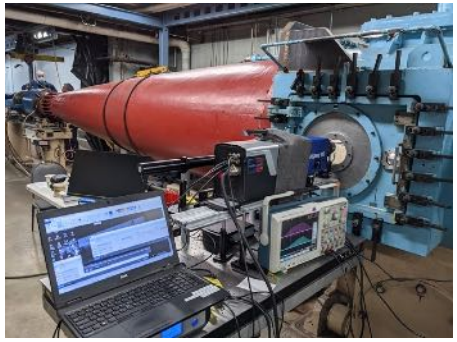
NO absorption line selection

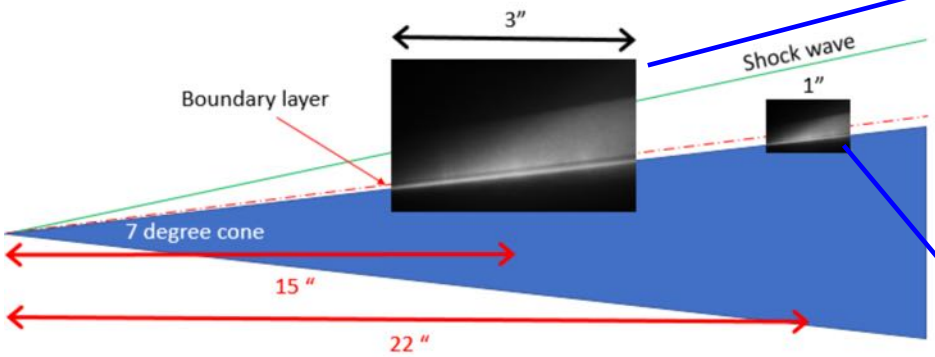


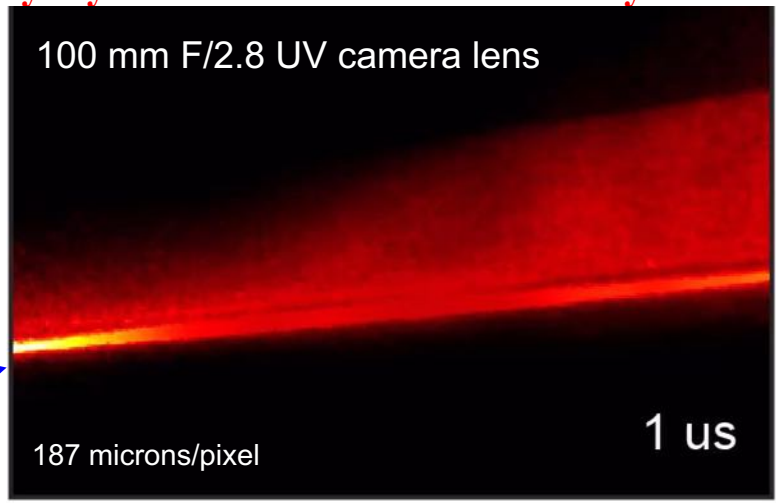
MHz NO PLIF in CUBRC 48” Mach 10 Shock Tunnel

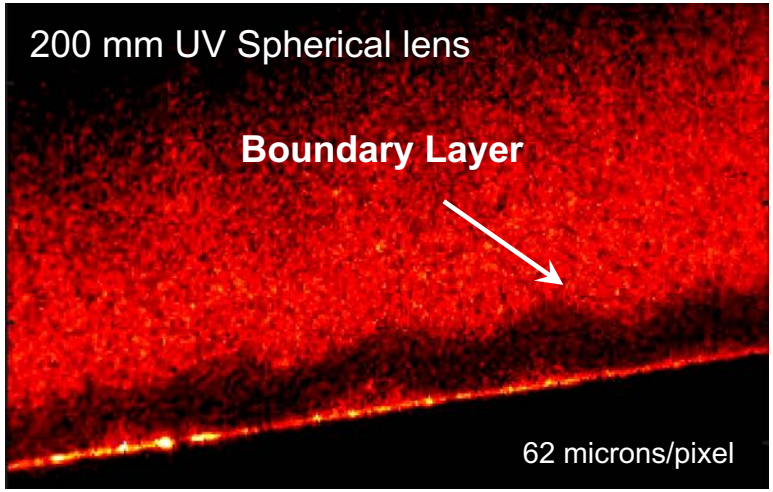
1-MHz rate NO PLIF imaging in a Mach 10 flow boundary layer for the 2nd mode instability detection











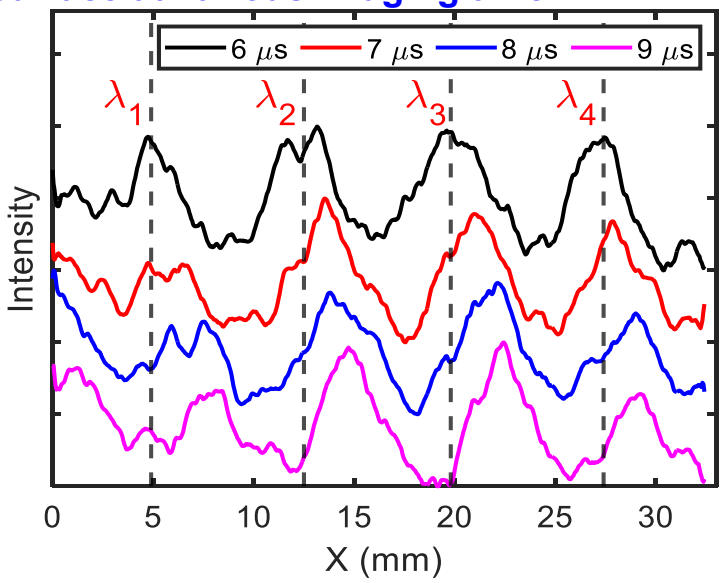
- **Burst-mode laser and OPO system for NO PLIF**
- **Two positions: 15” and 22” from a 7-degree cone tip**
- **Flow speed: ~1520 m/s**
- **Reynolds number: 1×10^6/ft, and 2×10^6/ft**
- **Simultaneous MHz rate FLDI measurement**
- **2nd mode instability induced wave packet λ=~6–8 mm from NO PLIF images**
- **NO fluorescence emission 230-285 nm**

For 200 mm Spherical lens Effective imaging distance

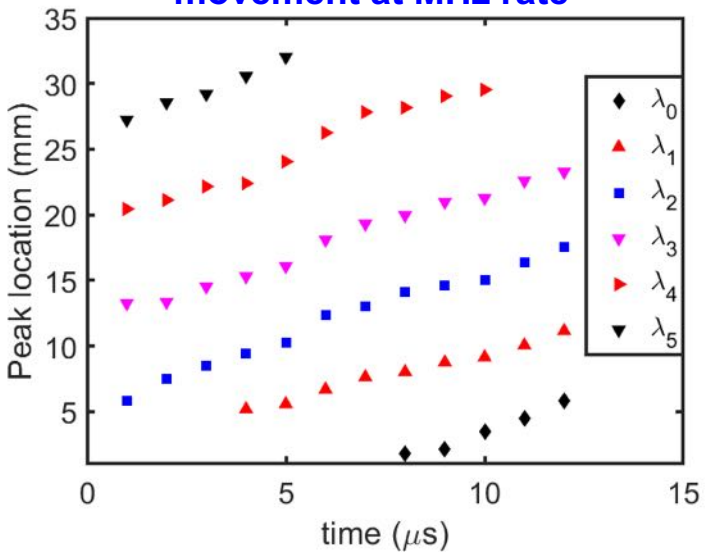
- **At 230 nm, image distance = 172.5 mm**
- **At 255 nm, image distance = 177.9 mm**
- **At 280 nm, image distance = 181.8 mm**

MHz NO PLIF in CUBRC 48” Mach 10 Shock Tunnel

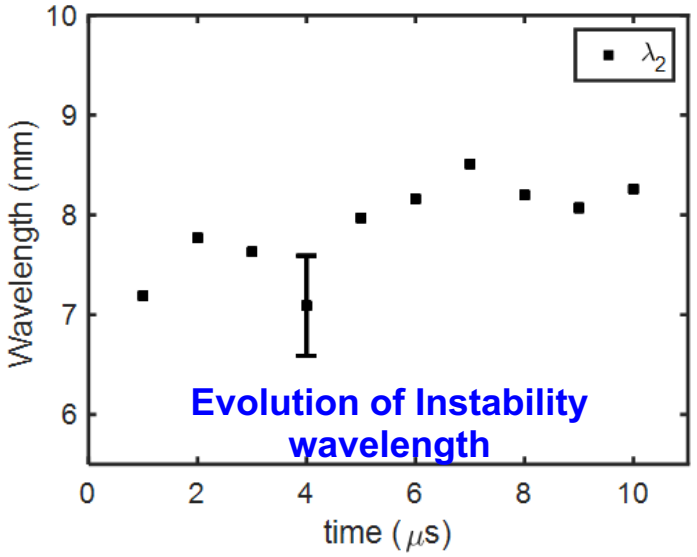
Instability wave packet along the model surface at various imaging time



Peak of the wave packet movement at MHz rate



- **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.**
- **With an average wavelength of 7.5 mm, the 2nd mode instability frequency is ~ 200 kHz.**

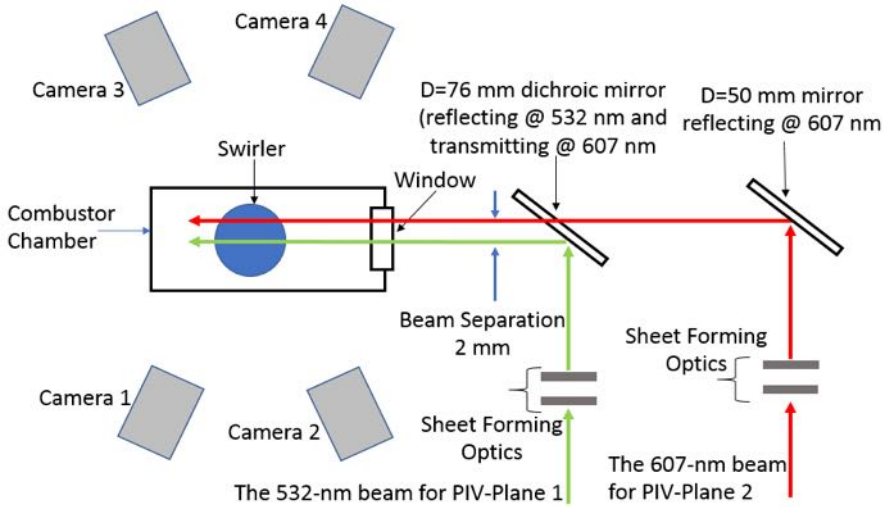


Dual-plane SPIV for large-scale Canonical Flow

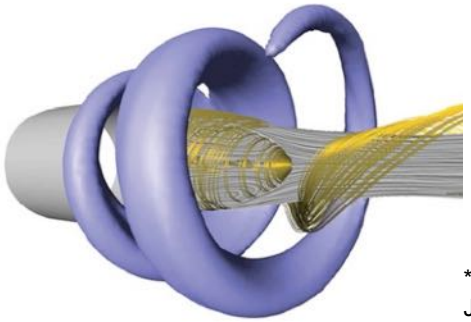
- Turbulent swirling combustion has advantages of **high power density, fast fuel/air mixing, and robust flame stabilization**, and has been widely used in aircraft engines and land-based power-generation engines.

How to resolve 3D flow pattern with large field of view and high spatial and temporal resolution?

- Dual-plane Stereo PIV
- Burst-mode DSPIV for 10 kHz or higher data acquisition speed
- Two-color scheme helps to improve PIV signal purity (no cross talk between the cameras)

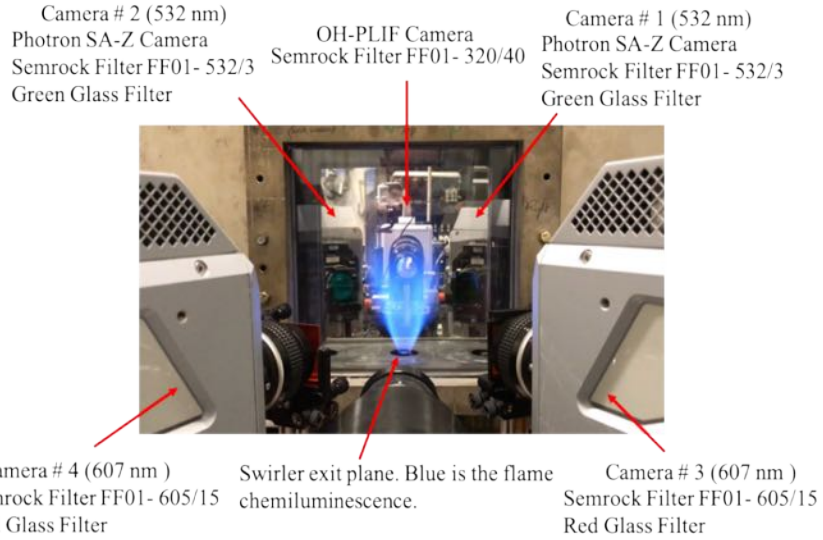


- 3” FOV, SA-Z 20 kHz 1024x1024 pixels, 80 micron/pixel
- 15 microsecond interpulse spacing



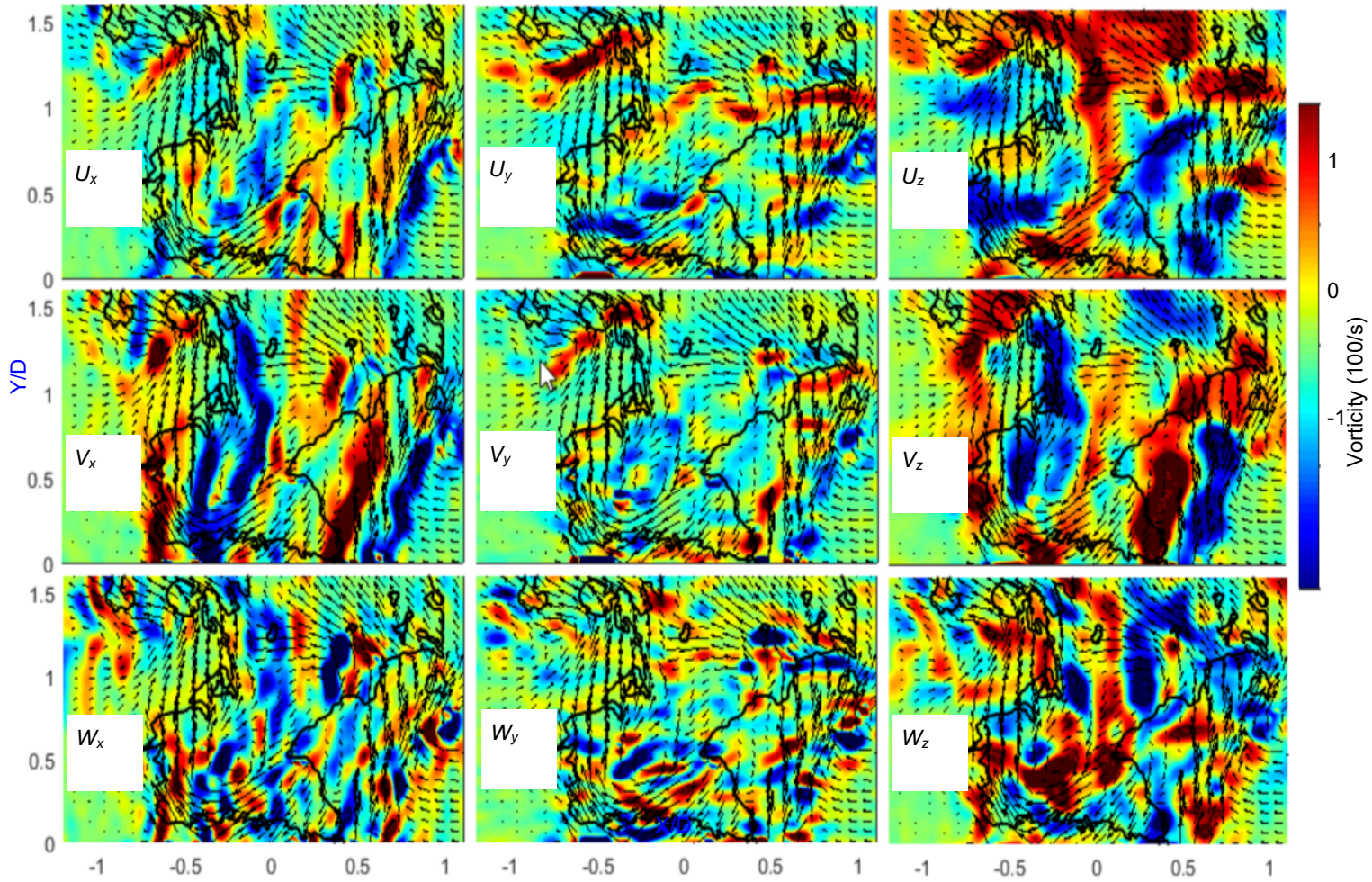
Swirl flow highly 4D. Capturing interactions such as flame stretch or extinction requires multi-dimensional diagnostics. These experimental tools didn’t exists until recently

*K. Oberleithner, et al, Jour. Fluid. Mech., 2011.



10-kHz Two-color DSPIV

An example of nine-component velocity-gradient tensor (background contour color) overlapped with in-plane velocity vectors and the flame front (black lines) for a turbulent swirling flame.



- out-of-plane velocity *W* is a result of the strongly swirling flow

Summary

- **High-speed burst-mode Mie scattering helps to understand NASA facility instability problem**
- **MHz NO PLIF for high-resolution BL flow measurement in a large wind tunnel**
  - **Second mode hypersonic flow instability in boundary layer is successfully measured by both NO PLIF**
  - **MHz PLIF imaging allows to track BL turbulence and dynamics**
- **Produce 3D insight from two-color DSPIV to measure swirling reacting jets**

– A strategy for verification and refinements of the PIV-plane separation has been developed, which allow accurate determination of the three out-of-plane velocity gradients