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**Instantaneous Velocity Profiles of Wall-Bounded Shear Flows in  
Thermochemical Non-Equilibrium**

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## **Final Report for Award #: FA9550-16-1-0262**

# **(YIP) Instantaneous Velocity Profiles of Wall-Bounded Shear Flows in Thermochemical Non-Equilibrium**

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# 1 Summary of Influence by YIP Award

## 1.1 Academic Products

- Many conference papers [1–19]
- 11 peer-review publications [20–30]
- Drew Zahradka Master’s Thesis [31]
- Matthew Hunt’s Master’s project
- Muhammad Mustafa’s Master’s project
- Muhammad Mustafa’s PhD Thesis [32]

## 1.2 Professional Development

- Parziale appointed as a fellow in the Air Force (AF) Summer Faculty Fellow Program (SFFP) from 2014 and 2017.
- Muhammad Mustafa (PhD Student) appointed as Air Force (AF) Summer Faculty Fellow in 2017, hot his PhD and is now working at Inoveering.
- Matthew Hunt (Master’s Student) appointed as Air Force (AF) Summer Faculty Fellow in 2016, currently with Engineer at Lockheed.
- Drew Zahradka (Master’s Student), currently working at Con Edison.
- Several undergraduate researchers have cycled into and out of the lab taking part in KTV related research. The focus has been improved shock-tube performance.
- Parziale’s group and Spectral Energies are selected for USAF SBIR Phase I and Phase II contracts titled “Non-intrusive, Time Resolved Measurement of Density and Velocity Perturbations in Supersonic and Hypersonic Wind Tunnels” (USAF Contract No. FA9101-17-P-0094 and FA2487-19-C-0013). Emphasis is on enhancing the repetition rate of the KTV technique.
- Parziale’s group is selected for an AFOSR DURIP grant (FA9550-19-1-0182) titled “DURIP: Solid State Read Step for Simple, High-Speed Krypton Tagging Velocimetry.” That work will use a laser diode to replace the read step in KTV.
- Parziale wins Stevens Provost Early Career Award for Research Excellence for 2019
- Parziale is appointed to North Atlantic Treaty Organisation (NATO) Research and Technology Organisation (RTO) Applied Vehicle Technology (AVT) Panel; subtask lead for collaborative efforts between NATO member countries on high-enthalpy hypersonic boundary-layer instability and transition

## 1.3 Research Objectives

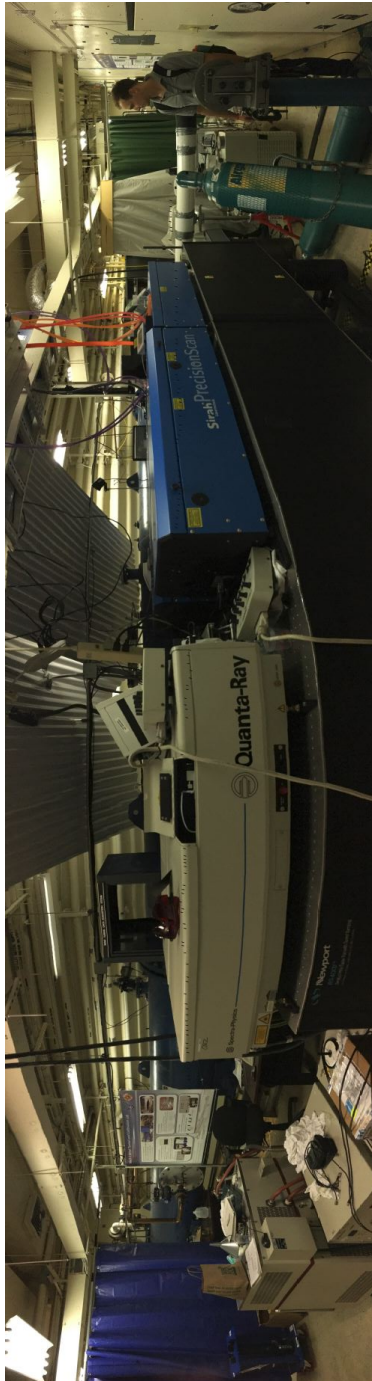
- Successful collaborative research effort with AEDC White Oak investigating the use of Krypton Tagging Velocimetry (KTV) to measure freestream velocity in AEDC Tunnel 9. Progress strong. First round of results accepted by AIAA J as tech note without revision. See Figures 6 and 7.
- Collaborative research effort with Arnold Engineering Development Complex (AEDC) White Oak investigating Mach 3 turbulent boundary layers and shock-wave/turbulent boundary-layer interaction. Progress is strong. Results discussed at AIAA Scitech 2017/2018 and Aviation 2018. Progress made on one-dimensional KTV data in a Mach 3 turbulent boundary layer and shock-wave/turbulent boundary-layer interaction. Four angles of compression corner were tested. POD analysis and turbulence amplification was the focus of the study. See Figures 10, 11, and 12. This work was accepted to JFM.
- Single-laser KTV was performed in 2018 and results were accepted to Physical Review Applied in 2019
- Progress made towards using a solid state source for the read step for KTV. See Figure 9 for a brief. Results accepted to Optics Letters.
- Successful experiments at Caltech, article accepted to Experiments in Fluids.

#### 1.4 Educational Objectives

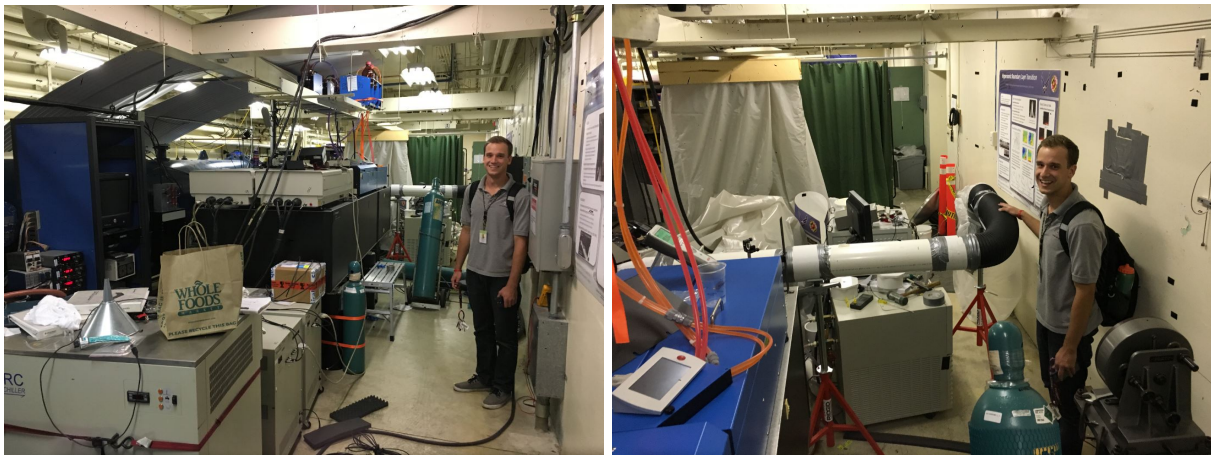
- Incorporate DoD related current events into the introduction to subjects in *ME354 Heat Transfer* and *ME545 Introduction to Aerospace*. Zahradka, Hunt, and Mustafa were all students in these courses which led to their recruitment into the graduate program and AF SFFP program.
- *ME679 Mechanics of Compressible Fluids* offered for the first time in many years at Stevens.
- Parziale has mentored students of City Knoll Middle School situated in the Hell's Kitchen Neighborhood of New York City. (Title I school, >40% of students below poverty line). This effort is part of an on-going interdisciplinary unit connecting social studies and science as applied to the Space Race. The unit is called Teen Thursdays and takes place on the Intrepid Sea, Air, & Space Museum Complex aboard the USS Intrepid on the west side of New York City.

## 2 Results and Photos

### 2.1 KTV Equipment in AEDC Calibration Lab



**Figure 1:** KTV Equipment in AEDC Calibration Lab. Student for scale on right.



**Figure 2:** KTV Equipment in AEDC Calibration Lab. Student for scale on right.

## 2.2 KTV Equipment in AEDC Tunnel 9 Lab

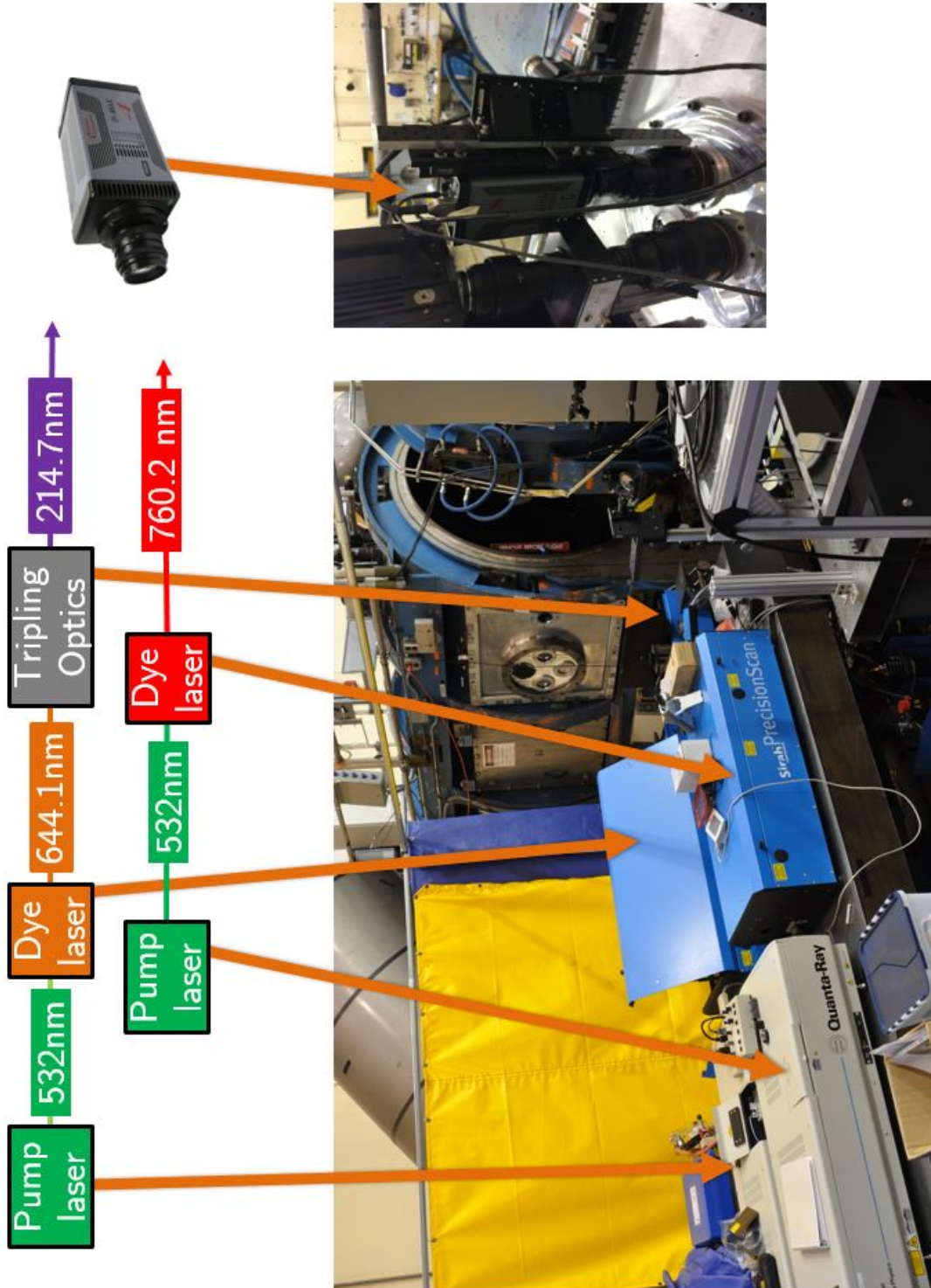
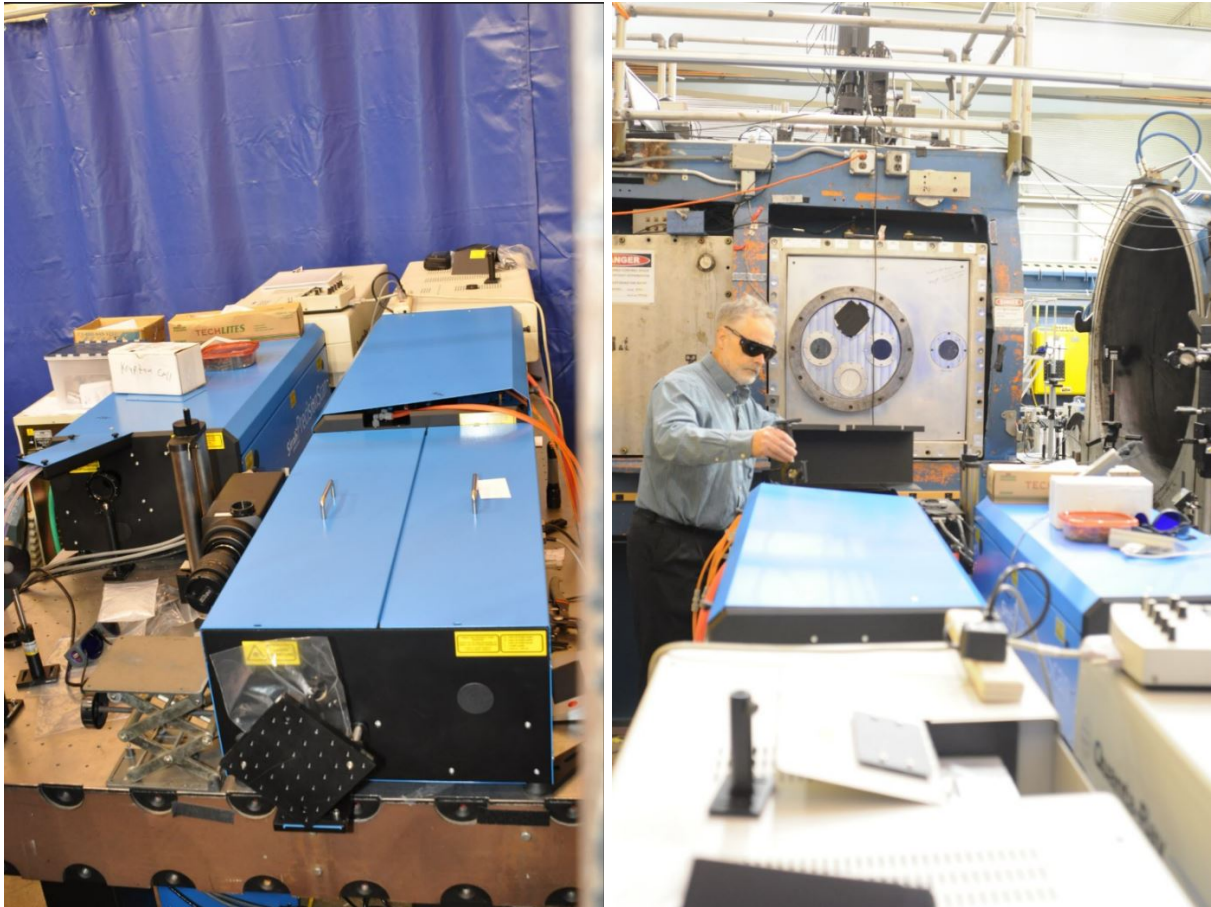


Figure 3: KTV Equipment in AEDC Tunnel 9 Lab. Annotated.



**Figure 4:** KTV Equipment in AEDC Tunnel 9 Lab. Laser system.



**Figure 5:** KTV Equipment in AEDC Tunnel 9 Lab. Camera mounted on top of the test section.

### 2.3 AEDC Tunnel 9 Results Highlights

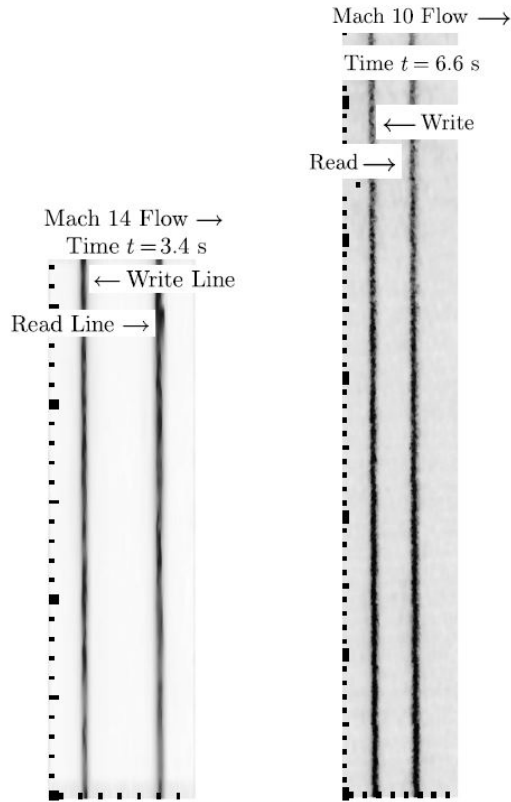


Fig. 3 Time stamp denotes tunnel starting trigger. Composite of write and read KTV exposures from Tunnel 9 condition A (left) and condition B (right). Conditions in Table 1. Tick marks denote millimeters. Inverted intensity scale. Write/read delay of 2  $\mu$ s.

Figure 6

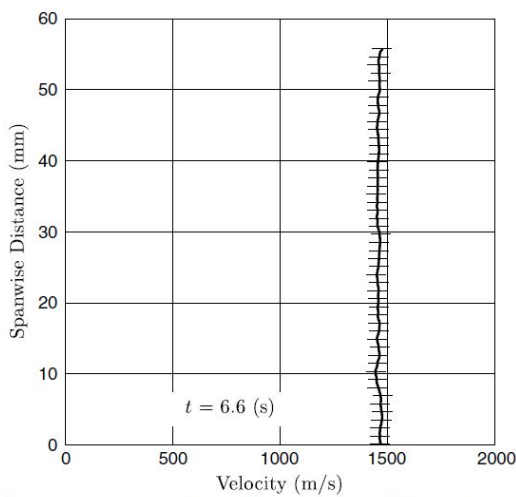


Fig. 6 Freestream-velocity profile for condition B. Error bars are horizontal thin black lines. The timestamp notes the time from camera trigger and is shared with Fig. 8.

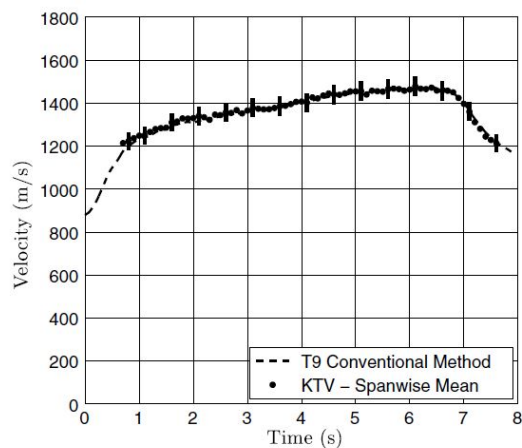


Fig. 8 Comparison of Tunnel 9 freestream velocity as calculated by conventional methods in Sec. III (dashed line) and measured by KTV (solid dots, spanwise average) vs time for condition B. Error bars are vertical thin black lines. The timestamp notes the time from camera trigger and is shared with Fig. 6.

Figure 7

## 2.4 KTV Work at Stevens Institute of Technology



Figure 8: KTV Equipment in the new Parziale lab.

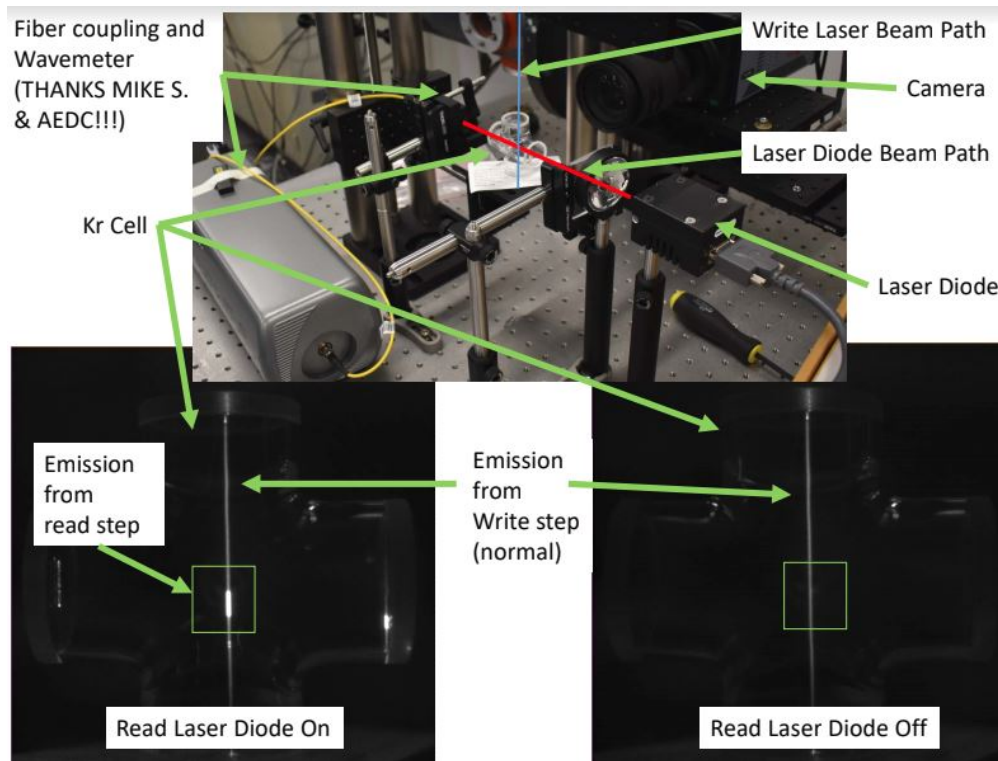
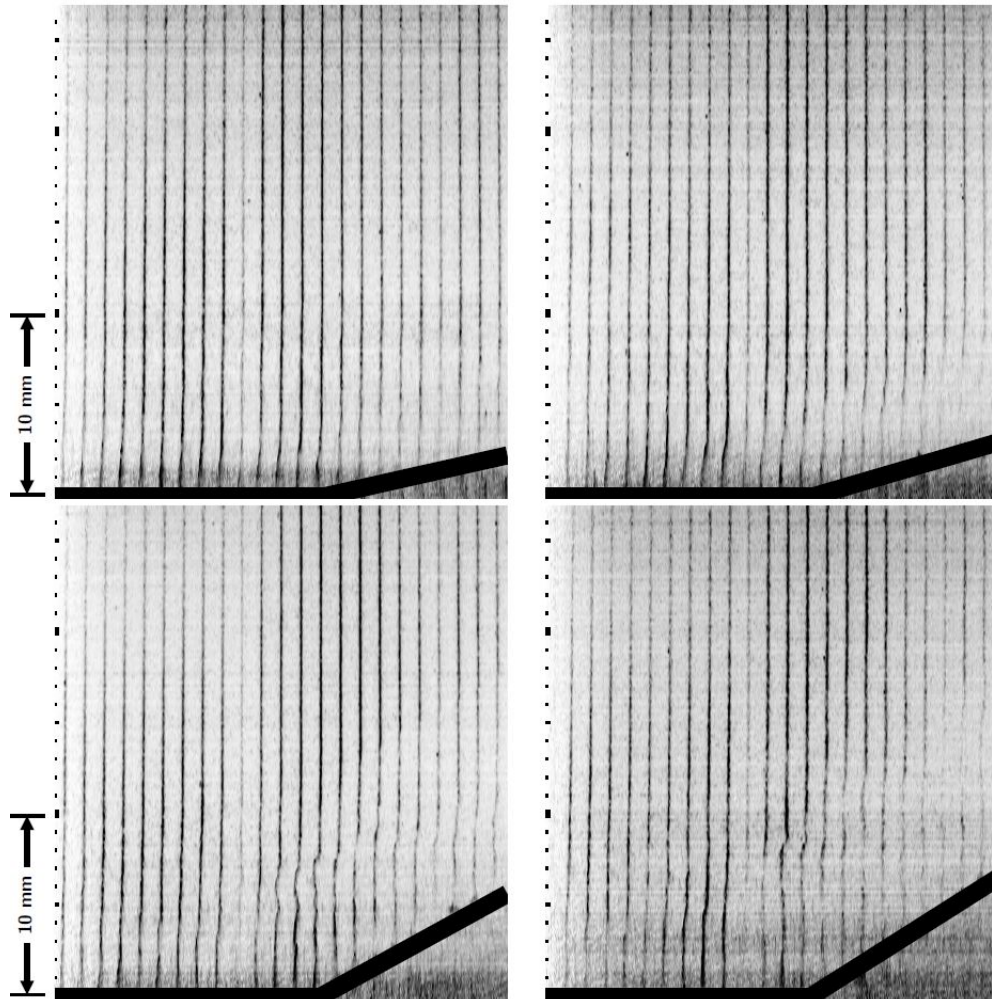
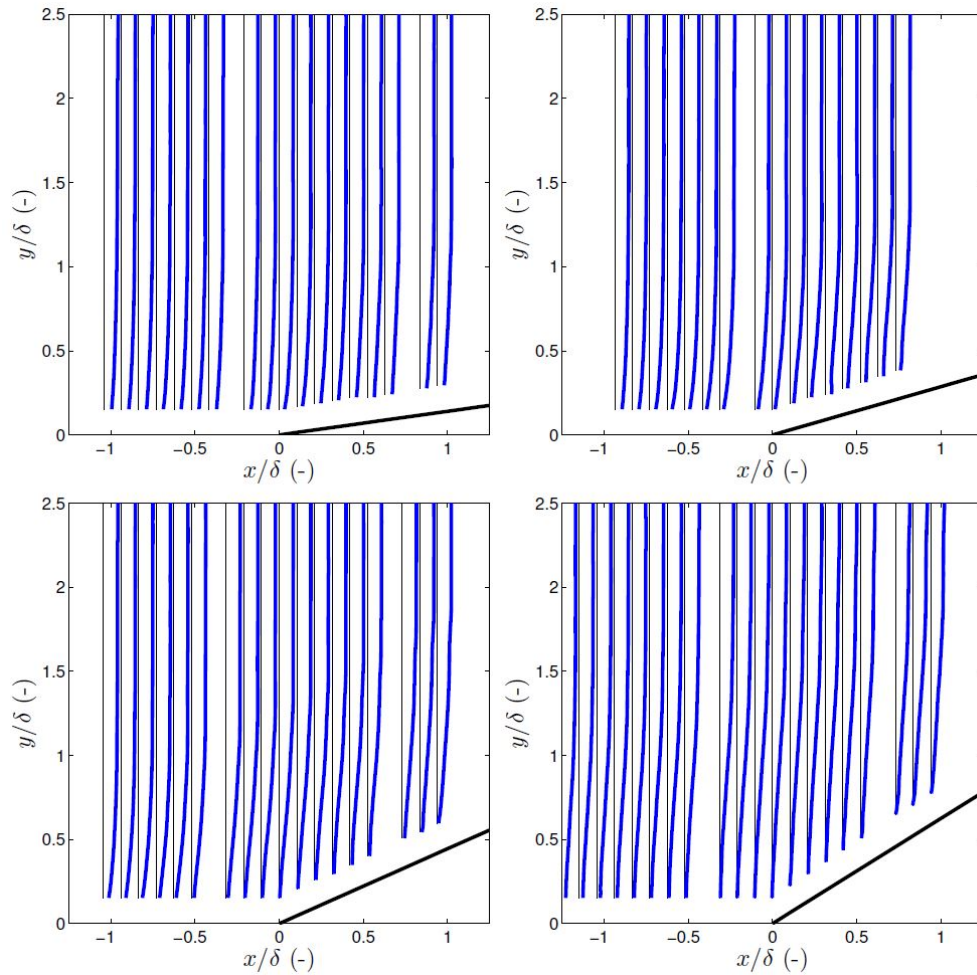


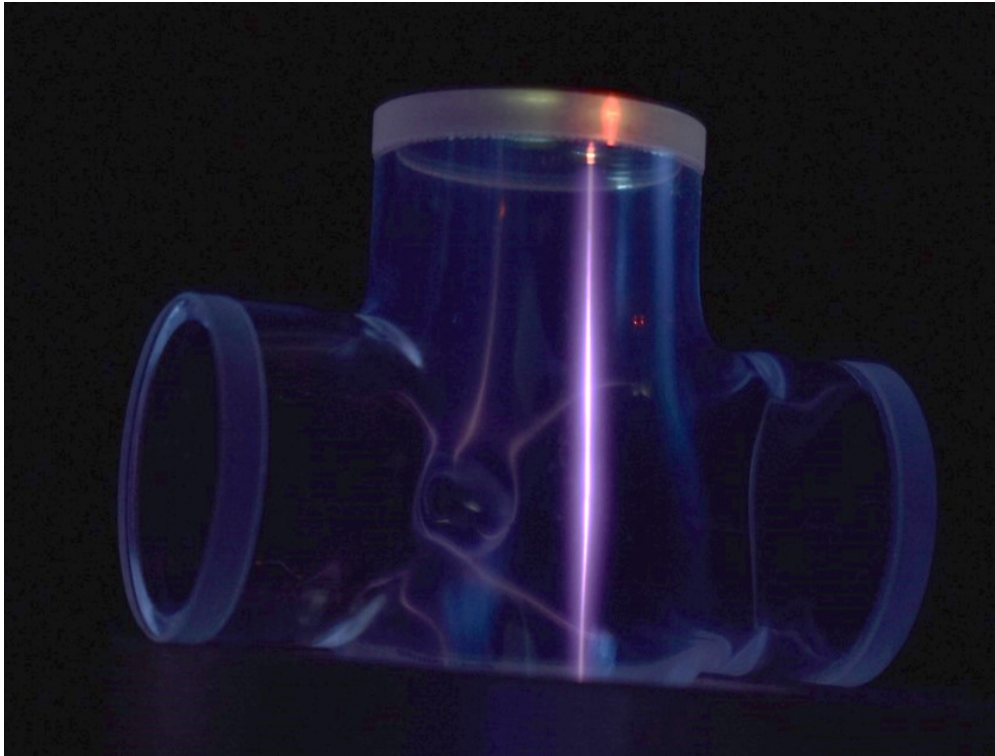
Figure 9: Read step with a laser diode.



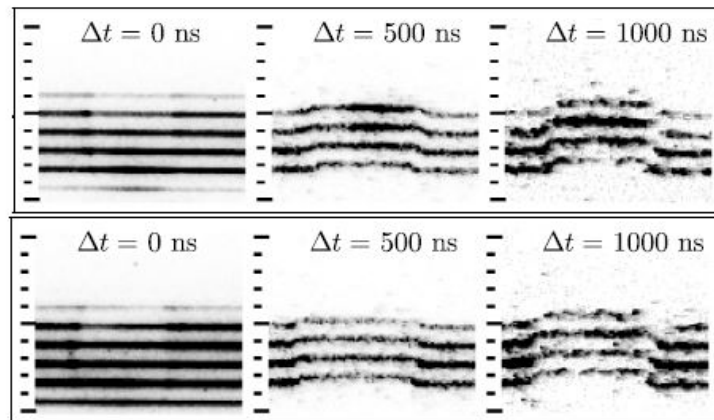
**Figure 10:** Clockwise from top-left are sample instantaneous shock-wave/turbulent boundary-layer interaction fluorescence exposures for the 8, 16, 32 and 24 degree corners, respectively. These are ostensibly boundary-layer profiles traces with a 500 ns prescribed delay between the write and read step. Major tick marks are 10 mm. Flow is left to right. Inverted intensity scale. Wall marked as black.



**Figure 11:** Clockwise from top-left are two sample non-dimensional ( $u/(12U_\infty)$ ), instantaneous shock-wave/turbulent boundary-layer interaction velocity profiles represented in blue and red for the 8, 16, 32 and 24 degree corners, respectively. Thin vertical black line represents the write location. Flow is left to right.



**Figure 12:** Laser-Induced Fluorescence in a Kr cell.



**Fig. 4.** Single-shot fluorescence exposures for 95% air/5% Kr jet experiments with laser diode (top) and single-laser scheme (bottom). Tick marks are 1 mm. Flow is bottom to top. Inverted intensity scale.

**Figure 13:** Underexpanded jet results from Optics Letters. In this work we showed for the first time that the read step from KTV can be simplified (laser diode) or eliminated completely.

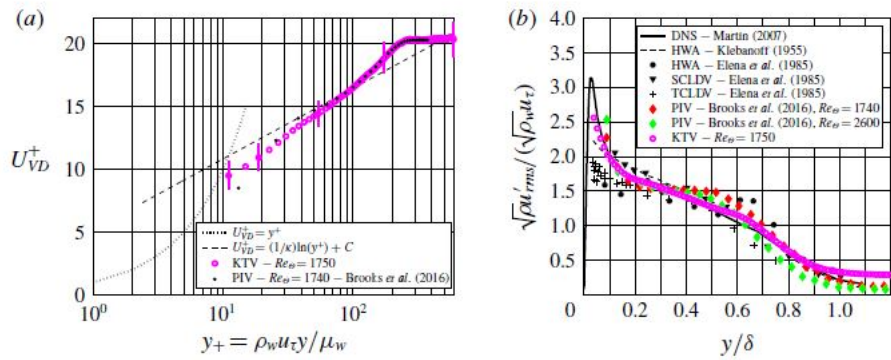


FIGURE 6. (Colour online) (a) The van Driest scaling of the mean velocity. (b) Morkovin scaling of streamwise fluctuations.

**Figure 14:** Mach 3 turbulent boundary-layer results from JFM. These results show that the incoming boundary layer in the Mach 3 Calibration Tunnel at AEDC White Oak is a canonical supersonic turbulent boundary layer, enabling the study of shock-wave/turbulent boundary-layer interactions.

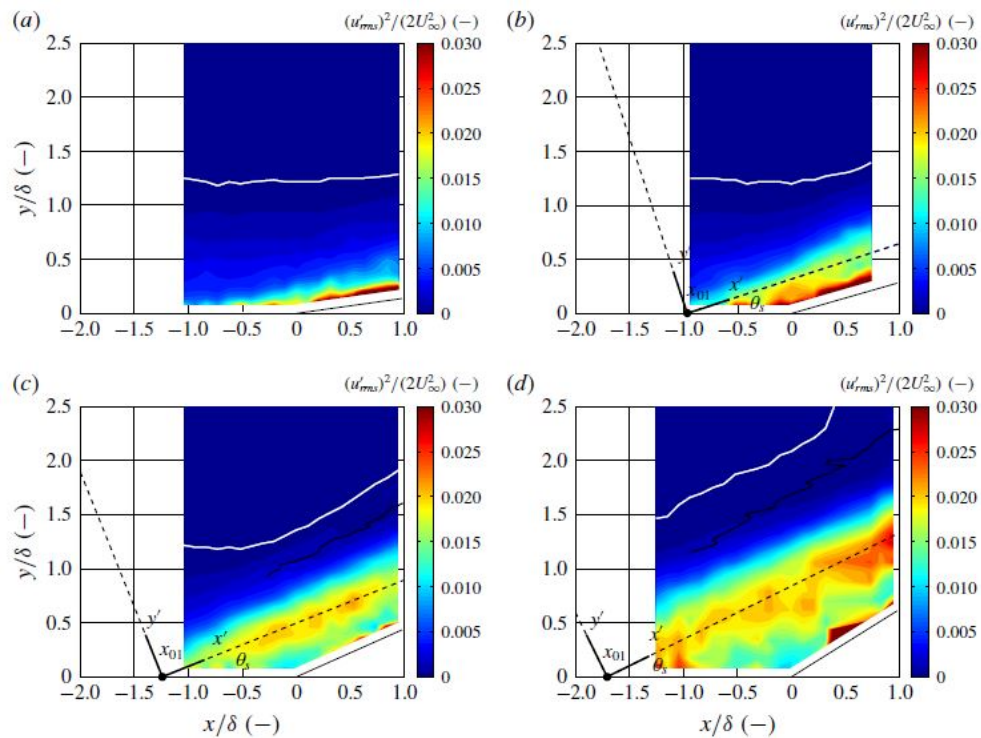


FIGURE 12. (Colour online) Contours of the non-dimensional streamwise turbulent kinetic energy (sTKE)  $(u'_{rms})^2 / (2U_\infty^2)$  for the (a) 8°, (b) 16°, (c) 24° and (d) 32° corners, respectively. The shear-layer coordinate system fitted to the maximum sTKE is overlaid. Flow is left to right. Mean shock position shown in black. White line marks  $y_u/\delta$  which is the wall-normal location above which the streamwise-velocity fluctuations are less than 2% of the free-stream velocity, or  $u'_{rms} = 0.02U_\infty$ .

**Figure 15:** Mach 3 shock-wave/turbulent boundary-layer interaction results from JFM. Here we show maps of the turbulent intensity as a function of turning angle.

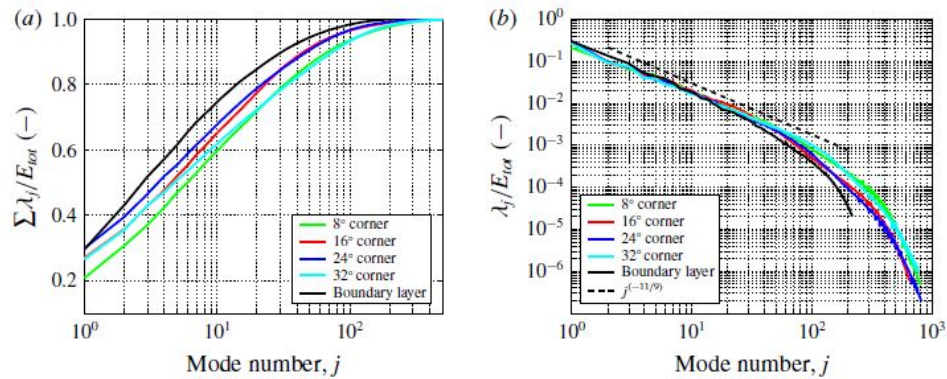


FIGURE 15. (Colour online) (a) The cumulative fraction of energy,  $\sum \lambda_j / E_{tot}$ . (b) The fraction of energy of each mode,  $\lambda_j / E_{tot}$ . The black line is the mode number raised to the  $(-11/9)$  power as suggested by Knight and Sirovitch (Knight & Sirovich 1990).

**Figure 16:** Mach 3 shock-wave/turbulent boundary-layer interaction results from JFM. Here we show that there is a common inertial range for each case, including the boundary layer. Interestingly, after the first few modes, which define the mean flow, the smaller scale turbulence is basically the same among each case.

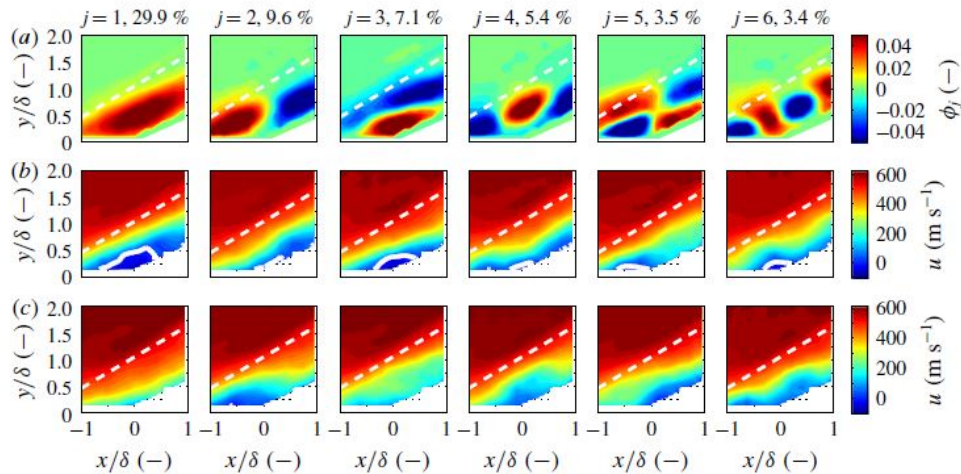


FIGURE 17. (Colour online) Snapshot POD analysis for the 24° corner flow. Each column corresponds to one of the first six POD modes marked by the mode number  $j$  and the fraction of energy associated with each mode in %. (a) POD modes for the 24° corner flow are shown as contours of  $\phi_j$ . (b) The mean streamwise velocity of snapshots with the largest positive mode coefficients (samples falling to right of  $+1.5\sigma$  in in figure 16). (c) The mean streamwise velocity of snapshots with the largest negative mode coefficients (samples falling to left of  $-1.5\sigma$  in in figure 16). A solid white line denotes the boundary between positive and negative streamwise velocity. A dashed white line denotes the mean shock location.

**Figure 17:** Mach 3 shock-wave/turbulent boundary-layer interaction results from JFM. Here we show the most energetic modes and the effects on the mean flow.

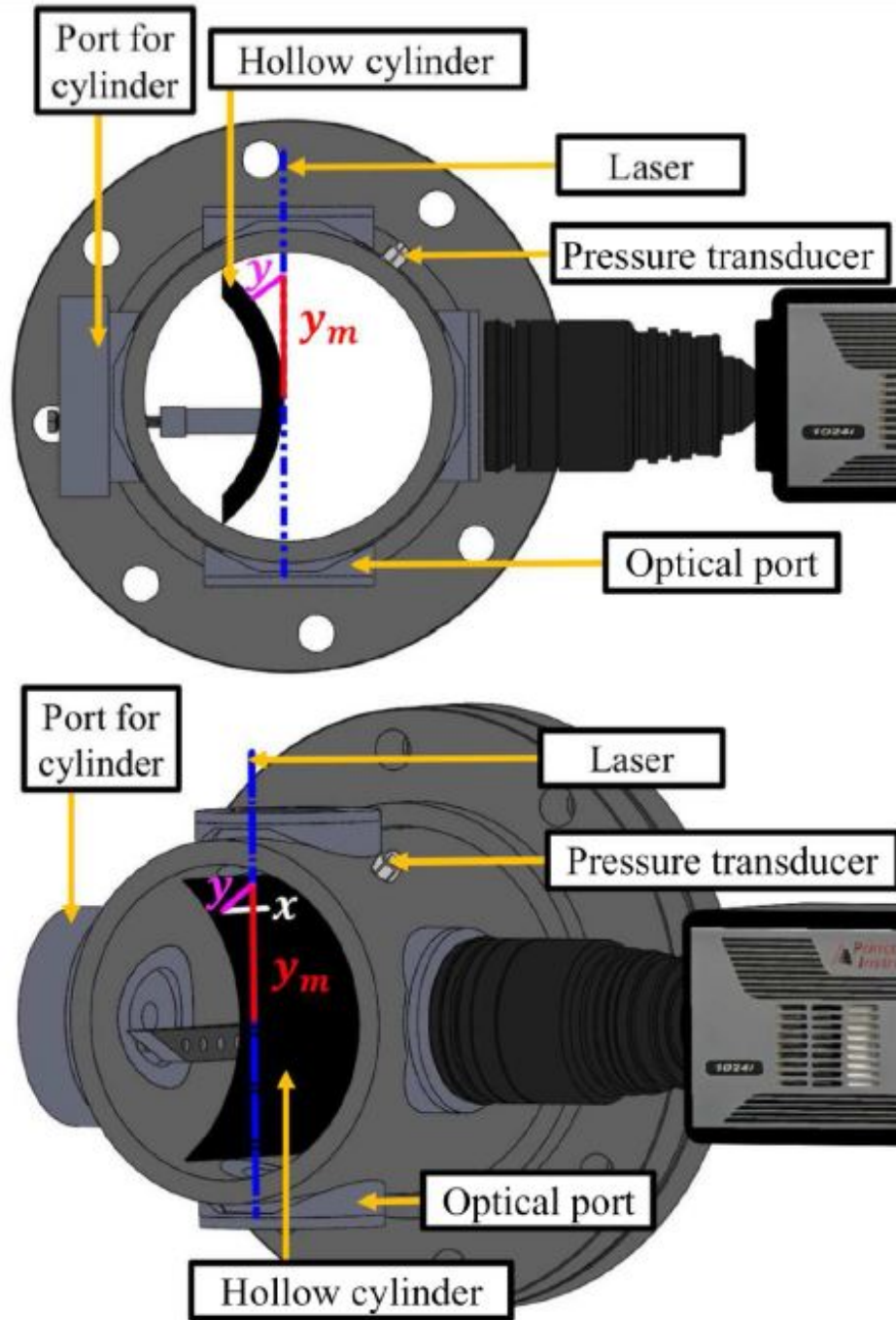


FIG. 5. Schematic of the test article in the shock tube. Top: Front view. Flow direction and  $x$  (streamwise) coordinate are into the paper and along the surface of the cylinder. Bottom: Isometric view.  $y$  and  $y_m$  are as in Fig. 8.

**Figure 18:** This is the schematic for the single-laser KTV experiments we performed in the Stevens Shock Tube.

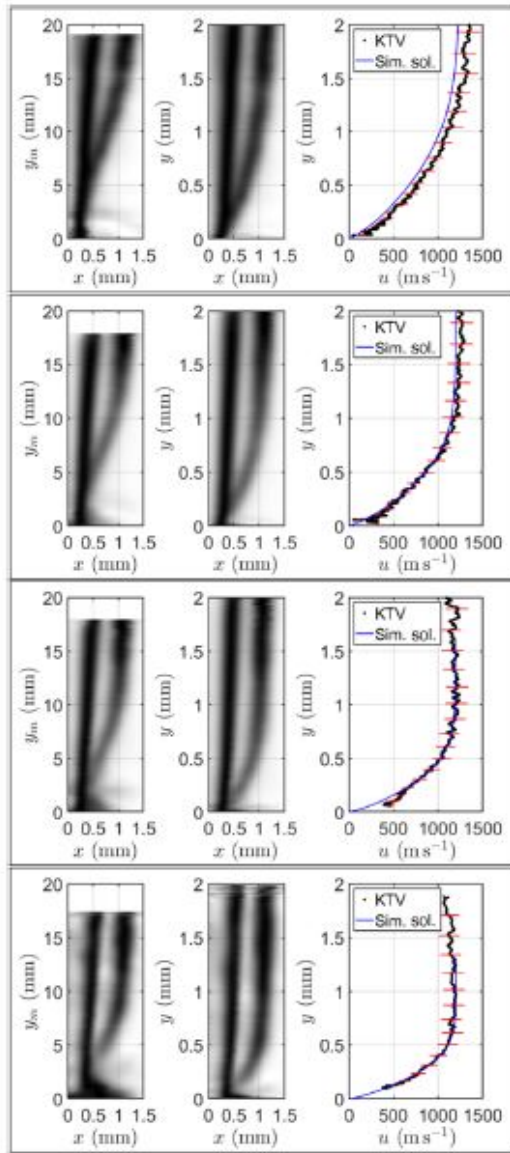


FIG. 11. Results for KTV experiments in 75%  $N_2$ /20%  $O_2$ /5% Kr. From the top,  $Re_2^{unit} = 1.55 \times 10^5 m^{-1}$  (shot 163),  $Re_2^{unit} = 3.80 \times 10^5 m^{-1}$  (shot 162),  $Re_2^{unit} = 7.63 \times 10^5 m^{-1}$  (shot 159),  $Re_2^{unit} = 1.15 \times 10^6 m^{-1}$  (shot 157). Left: Superposition of raw write and read KTV images (inverted scale). Center: Superposition of write and read images mapped from  $y_m$  to  $y$  (black). Right: Similarity solution in blue and KTV derived velocity profile in black with error bars in red.

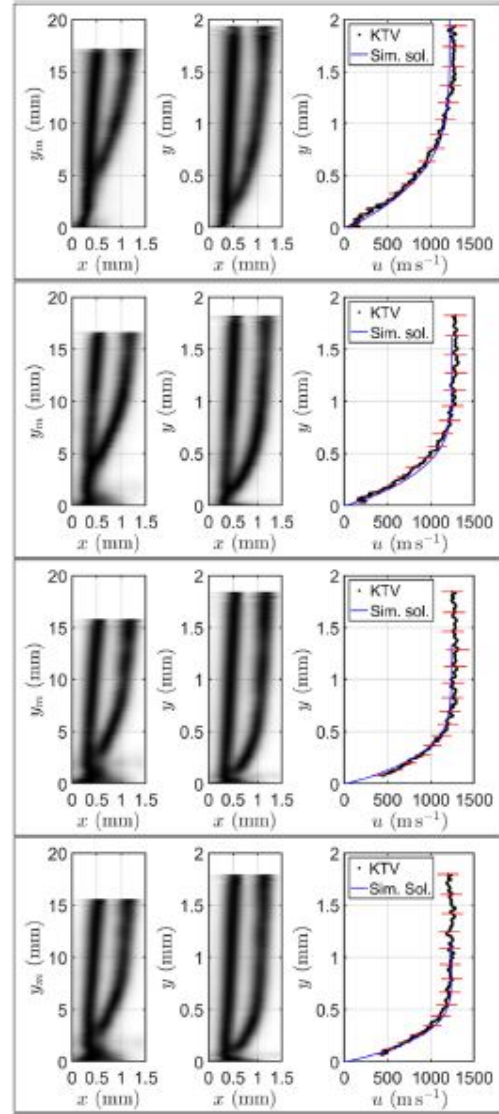
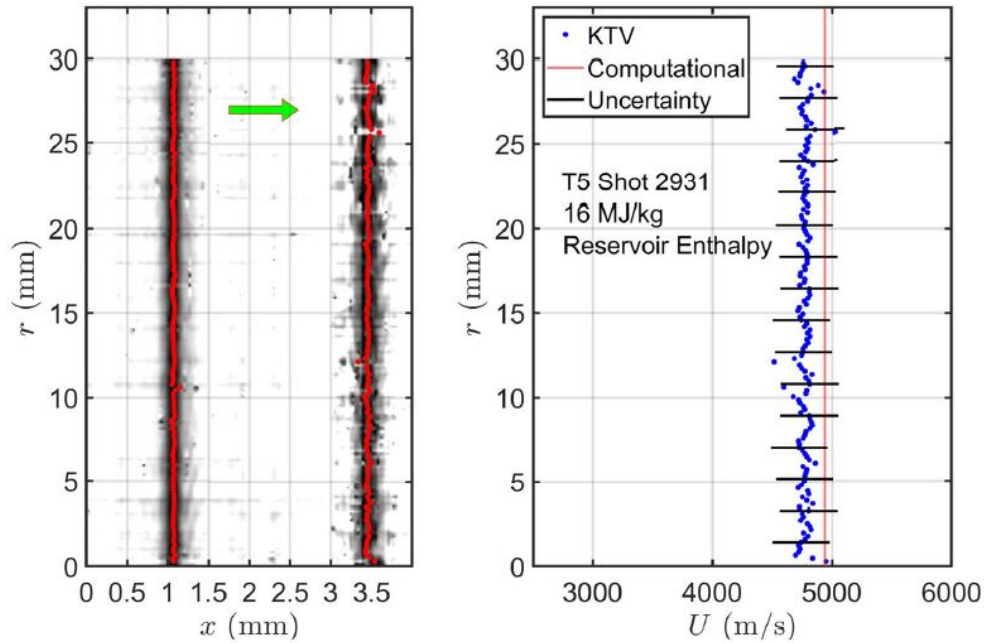


FIG. 12. Results for KTV experiments in 99%  $N_2$ /1%. From the top,  $Re_2^{unit} = 3.88 \times 10^5 m^{-1}$  (shot 165),  $Re_2^{unit} = 7.68 \times 10^5 m^{-1}$  (shot 166),  $Re_2^{unit} = 1.15 \times 10^6 m^{-1}$  (shot 168),  $Re_2^{unit} = 1.53 \times 10^6 m^{-1}$  (shot 159). Left: Superposition of raw write and read KTV images (inverted scale). Center: Superposition of write and read images mapped from  $y_m$  to  $y$  (black). Right: Similarity solution in blue and KTV derived velocity profile in black with error bars in red.

Figure 19: These are the single-laser KTV results in air and  $N_2$ .



**Figure 20:** We apply Krypton Tagging Velocimetry (KTV) to measure velocity profiles in the freestream of a large, national-scale high-enthalpy facility, the T5 Reflected-Shock Tunnel at Caltech. The KTV scheme utilizes two-photon excitation at 216.67 nm with a pulsed dye-laser, followed by re-excitation at 769.45 nm with a continuous laser diode. Results from a nine-shot experimental campaign are presented where  $N_2$  and air gas mixtures are doped with krypton, denoted as 99%  $N_2$ /1% Kr, and 75%  $N_2$ /20%  $O_2$ /5% Kr, respectively. Flow conditions were varied through much of the T5 parameter space (reservoir enthalpy  $h_R \approx 5 - 16$  MJ/kg). We compare our experimental freestream velocity-profile measurements to reacting, Navier-Stokes nozzle calculations with success, to within the uncertainty of the experiment. Then, we discuss some of the limitations of the present measurement technique, including quenching effects and flow luminosity; and, we present an uncertainty estimate in the freestream velocity computations that arise from the experimentally derived inputs to the code.

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