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Mach 18 Flow Velocimetry with 100-kHz KTV and PLEET in AEDC Tunnel 9

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Krypton Tagging Velocimetry (KTV) and Picosecond Laser Electronic Excitation Tagging (PLEET) velocimetry at 100-kHz rate were demonstrated in Mach 18 flow conditions at AEDC Tunnel 9 employing a burst-mode laser system and a custom optical parametric oscillator (OPO). The measured freestream flow velocities from both KTV and PLEET agreed well with the theoretical calculation. The increase in repetition rate provides better capability to perform time-resolved velocimetry measurements in hypersonic flow environments.

Hypersonic flow, at a speed of Mach 5 and above, is attracting significant interest in flow dynamics studies. The information gained from these studies are essential for high-speed air vehicle development, spacecraft re-entry, and many defense-related research areas [1, 2]. However, experimental hypersonic flows studies, which are important for computational fluid dynamic (CFD) model validation and evaluation, are very challenging due to: 1) the limited hypersonic facilities, and 2) the available measurement techniques. Most hypersonic wind tunnels are small-scale tunnels (test section diameter less than 0.3 m) in universities and research institutes for academic studies. Only a few large-scale hypersonic facilities exist (test section diameter near or greater than 1 m), which limits the number of practical hypersonic experimental studies. Most of the large-scale facilities rely on traditional pressure/temperature intrusive probes to measure flow parameters. Non-intrusive spatially and temporally resolved laser-based measurement techniques, however, can provide higher quality data in these facilities by directly measuring flow parameters without protruding the flow field. Temporally resolved diagnostics, in particular, require extremely fast repetition rates (greater than 100 kHz) to resolve flow dynamics in hypersonic wind tunnels because of extremely high flow speeds (often greater than 1 km/s). Many laser diagnostic techniques developed in the past few decades have limited applicability in hypersonic facilities. For example, particle-seeded techniques such as particle imaging velocimetry (PIV) [3, 4] and planar Doppler velocimetry (PDV) [5] could contaminate the wind tunnel and potentially produce inaccurate velocity measurements because of particle response time issues. Rayleigh, Filtered Rayleigh, Interferometric Rayleigh, and Raman scattering based techniques are limited in hypersonic conditions because of the weak signal intensities associated with extremely low pressures [6, 7]. Hence, laser diagnostic techniques need to be specifically tailored to be used in hypersonic conditions. To our knowledge, several laser diagnostic techniques have

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been utilized in hypersonic flow studies, including planar laser-induced fluorescence (PLIF) [8], molecular tagging velocimetry (MTV) [9], femtosecond laser electronic excitation tagging (FLEET) [10, 11], picosecond laser electronic excitation tagging (PLEET) [12], and focused laser differential interferometry (FLDI) [13, 14].

Non-intrusive velocimetry techniques have been applied in AEDC Tunnel 9 [10, 11, 15] including 10-Hz krypton tagging velocimetry (KTV) and 1-kHz FLEET. To resolve the temporal dynamics in hypersonic flow speeds, measurements with high repetition rate at 100 kHz or higher are needed. The main challenges in applying high-repetition-rate laser-based measurement techniques in large scale wind tunnels, such as Tunnel 9, include long focal length (low fluence at probe volume), small collection solid angle (lower signal than laboratory setting), relatively low laser pulse energies at high repetition rate (low signal), long laser beam path (alignment stability issues), unstable facility temperature (unstable laser operation), limited number of tests (high cost for tunnel operation and long preparation time), etc. The ability to make high-repetition-rate laser-based measurements with high spatiotemporal resolution in such environments is an extremely challenging endeavor. In this work, we demonstrate 100-kHz KTV and 100-kHz PLEET velocimetry for Mach 18 flows in the AEDC Tunnel 9 using burst-mode, laser-based systems.

Experiments

Tunnel 9 was run at Mach 18 condition with a Reynolds number of ~1.5×10^6/ft. N_2 was pumped into a reservoir with a pressure and temperature of 130 MPa and 1844 K, respectively. Upon breaking the diaphragm, Mach 18 conditions were produced for ~5 seconds. The freestream flow speed was ~1.9–2.1 km/s. The static temperature and pressure are ~35K and ~0.4 torr, respectively. For KTV measurement, ~1% Kr (in mass) was seeded into the reservoir prior to filling with N_2. For the PLEET measurements, the test gas was pure nitrogen. The tunnel was able to be operated approximately 2 times per day for two days, limiting the number of test runs for this measurement campaign. The test section had a circular cross section of ~1.5 m.

Figure 1 shows the schematic for KTV and PLEET measurements, and the photograph of the experimental setup. KTV was conducted using a burst-mode laser with a high-speed optical parametric oscillator (OPO) to generate a 100 kHz pulse train at the Kr absorption wavelength of 212.6 nm using the same excitation scheme as described in Ref. [16]. The high-intensity ns-duration 212.6 nm beam can efficiently ionize Kr via 2+1 resonance-enhanced multi-photon ionization (REMPI), a process consisting of two-photon excitation followed by one-photon ionization [17]. According to the experimental work of Richardson et al. [18] and the theoretical work of Shekhtman et al. [19], the 212.6 nm excitation line has the largest excitation cross-section and is therefore optimal for single-laser techniques. The long-lived emission (a few μs) in the near infrared wavelength regime (700-900 nm) is produced as a result of electron–ion recombination and the resulting radiative cascade to several emitting Kr states [16, 20, 21]. Previous work indicated that the long working distances prohibited efficient 2+1 REMPI while only using a single 212 nm beam [23]. In that work, the residual 355-nm beam that was used for sum-frequency-mixing was re-combined with the 212-nm beam to enhance 2+1 REMPI. A similar scheme was used in this work to promote REMPI. Furthermore, a 769.45-nm continuous wave (CW) diode laser was used in this work to re-excite the metastable Kr state ($5P[3/2]_1$) to further enhance the KTV signal, as done in [24], the first-ever implementation of KTV in a high enthalpy shock tunnel. The 212 and 355 nm beams were both focused into the test section using a spherical f =+1000 mm lens and the beams were directed through a 75 mm-diameter window located on the side of the tunnel as shown in Figure 1a. The 769 nm beam was expanded in the stream-wise direction using a cylindrical f = -750 mm lens. Approximately 3 mJ/pulse at 212 nm (25 mJ/pulse at 355 nm) and 1 W at 769 nm were used in this work.

The experimental setup for the 100-kHz PLEET measurements was very similar to the KTV setup, as shown in Figure 1b. In this experiment, the burst-mode-laser output the fundamental 1064 nm beam and eliminated the need for the OPO. For the PLEET work, the burst-mode laser outputs 100-ps pulses for 10 ms at 100-kHz repetition rate. An f = +1000 mm spherical lens was used to focus the laser beam into the test section. Approximately 150 mJ/pulse were used in this work.

A high-speed camera (Photron SA-Z) and visible intensifier (LaVision IRO) were secured on top of the tunnel and imaged the signal through a port window positioned at the top of the tunnel. The IRO was equipped with an 85-mm *f*/1.8 lens (Nikon). The camera was operated at the laser repetition rate (100 kHz), but the intensifier was operated at 500 kHz for KTV and 200 kHz for PLEET to obtain multiple exposures of the tagged lines within a single image. The gate width was 200 ns for KTV and 500 ns for PLEET. The IRO gain settings were 70% for KTV and 60% for PLEET. The first exposure for KTV and PLEET imaging was taken at 100 ns and 1μs, respectively, after laser excitations.

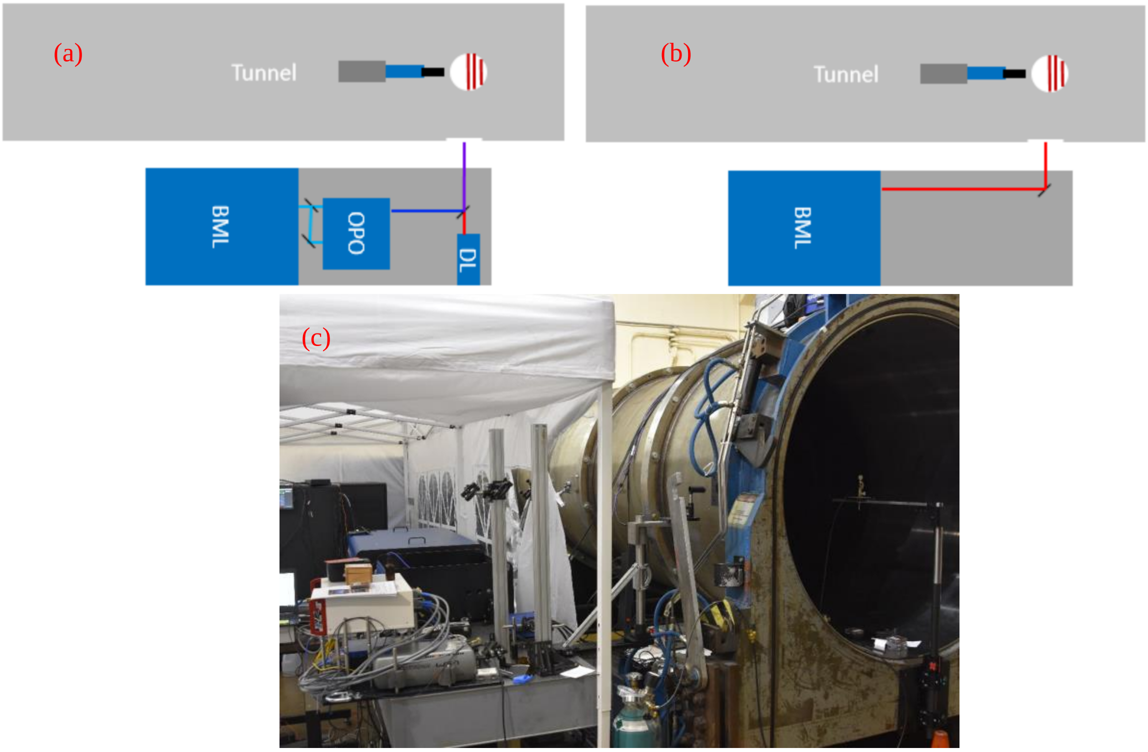


Figure 1. Top-view schematic of (a) 100-kHz KTV measurement, and (b) 100-kHz PLEET measurement in AEDC tunnel 9; (c) a photograph of experimental setup in Tunnel 9.

Results

KTV Results

To date, KTV has only been conducted using either 214 nm write with 760/769 nm read beams [15], 212 nm write beam without a read beam [16, 22], or 216 nm write beam with a 769 nm read beam [24]. However, the combination of 212 nm write and 769 nm read beams has not yet been used in a ground test facility, but has been explored in a test cell [20]. To evaluate the effect of the 769 "read" beam after a 212 nm "write" beam, a static cell of pure Kr at 10 torr was setup in the probe volume within the test section. Figure 2 shows the comparison between the two configurations with and without the 769-nm CW beam. For these tests, the exposure time was set to 200 ns, and the delay was 100 ns after laser excitation. With the 212-nm excitation beam only, the signal intensity is ~1500 counts, however, the intensity increased to ~10x higher with the 769-nm read beam. In Figure 3, time-resolved measurements in 99% N_2/1% Kr gas mixture using the setup described in [19, 20] support a ~5-10x improvement in signal using the 769 nm read beam at pressures of 1 torr and 10 torr at delays of 100-750 ns. For this reason, the 769 read beam was implemented for the tunnel runs.

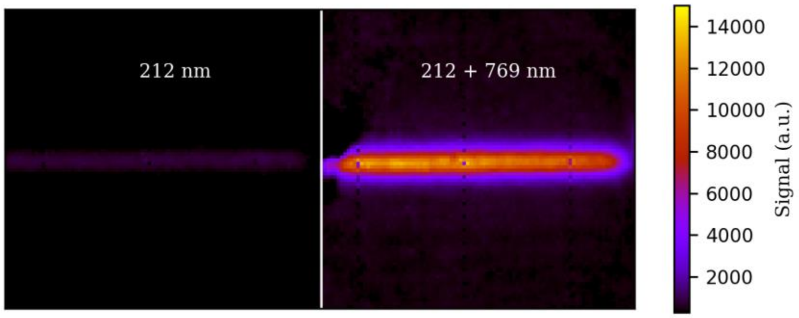


Figure 2. Comparison of "read" beam effect in a static cell with 10-torr pure Kr. The result shows the "read" beam has 10x signal enhancement for a delay time range of 100ns–300ns.

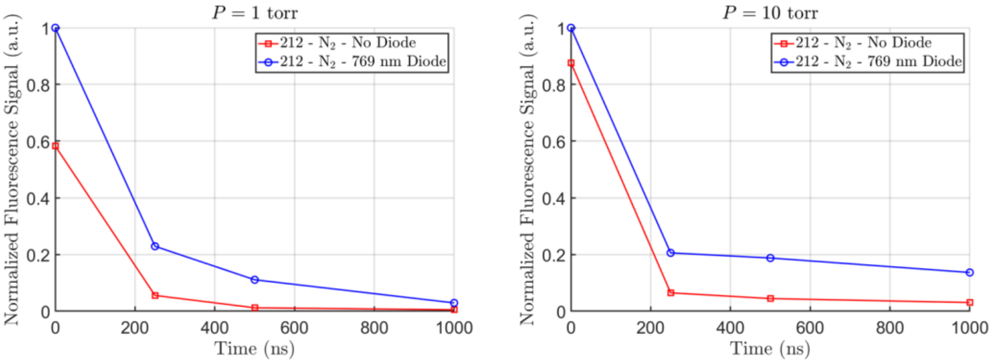


Figure 3. Time-resolved Comparison of "read" beam effect in a static cell with 99% N_2/1% Kr at Pressures of 1 torr and 10 torr. The "read" beam enhances the 212 nm excitation signal a factor of 4-10, depending on the delay time.

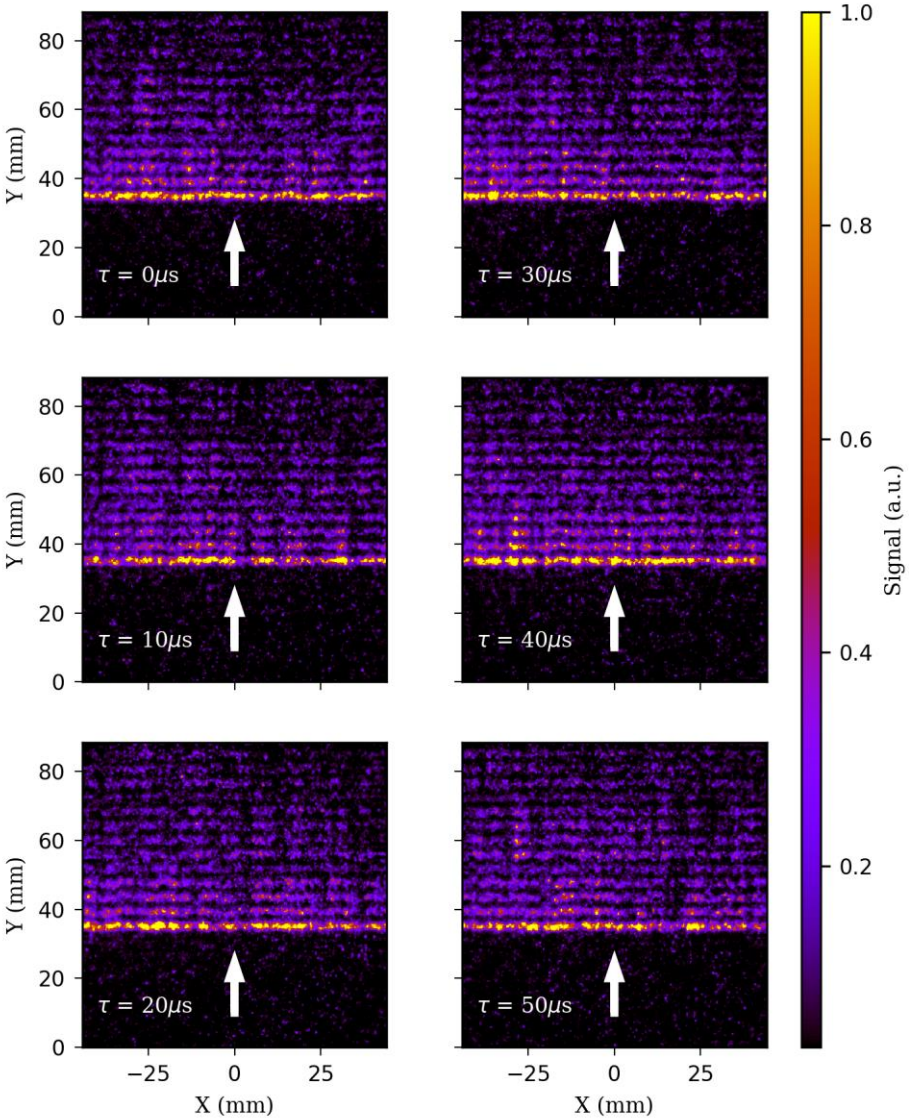
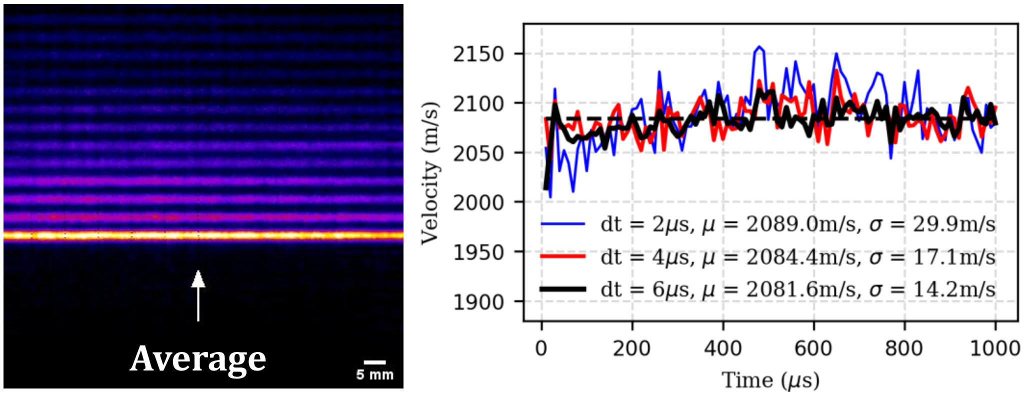


Figure 4. A 6-image sequence of 100-kHz KTV in Tunnel 9 freestream measurement of Mach 18.

Figure 4 shows a 6-image sequence of the 100-kHz KTV signal in the freestream of Tunnel 9 in Mach 18 flow conditions. In the images shown throughout this manuscript, the X-axis is parallel with the laser propagation direction with the laser propagating from right to left. The Y-axis is parallel with the flow direction. An arrow is drawn in Figure 4 to show the flow direction. Although the laser has 10-µs interpulse spacing, the intensifier was operated with 500 kHz. Therefore, the KTV tagged sample convected within the flow and was imaged every 2 µs to show the tagged line movement. Figure 3 shows that the KTV signal has a long lifetime, and more than 10 lines could be detected, (*i.e.*, 20 µs after the laser excitation). The width of the KTV fluorescence signal, shown in Figure 4, is on average 1.38 mm. The signal-to-noise ratio (SNR) was ~15 for the 0.1-µs time delay and ~10 for images taken within the first 10 µs. The signal nonuniformity across the lines are likely due to either uneven Kr seeding in low temperature conditions or conglomeration, considering the freestream temperature is much lower than the freezing point of Kr.

Similar to other MTV velocimetry techniques, the flow velocity was calculated by measuring the displacement of the signal lines over the Δt between exposures. To calculate the flow velocity, the image was horizontally binned and the signal from each exposure was fit to a Gaussian profile. Other methods were tested, including segmenting the image into smaller regions, calculating the velocity within each segment, and averaging the data. These results were in very close agreement (~2%) as using the horizontally binned image. The peak of the Gaussian fit was used to define the tagged gas position in each image. Figure 5 shows an average KTV image and a time series of the flow velocities measured by a single burst of 1 ms. The measured average flow velocity is ~2085 m/s with a measurement precision of 0.7%–1.5%.



(a) (b)

Figure 5. An average 100-kHz KTV image (a), and a time series of the flow velocities measured by a single burst (b) in AEDC tunnel 9.

PLEET Results

100-kHz PLEET was also accomplished at Tunnel 9 in Mach 18 conditions. Figure 6 presents a 6-image sequence of 100-kHz PLEET in a Tunnel 9 freestream measurement at Mach 18. The interpulse spacing between the laser pulses is 10 µs, but the time spacing between two lines (in the Figure 6) is 5 µs because the intensifier was running at 200 kHz. The first PLEET line was imaged 1 µs after laser excitation. PLEET has also been demonstrated earlier in the AFRL Mach 6 Ludwieg tube [12]. In those previous measurements, the signal was detectable for more than 20 µs, however, in this work only three lines (i.e., ~ 15 µs) are shown before the tagged sample exits the camera field-of-view. In all previous PLEET work [12], a small (~10 mm long) tagged sample was produced. In this work, however, the tagged sample spanned the entire camera field-of-view (~ 83 mm long). Moreover, the location of the focal point of the PLEET beam shows the lowest signal compared to the remainder of the line. This is also different than previous experiments and is not quite clear from this demonstration. One hypothesis is that the focal point may reach a high enough fluence that ionizes the nitrogen molecules, in addition to dissociation, which leads to weaker signal.

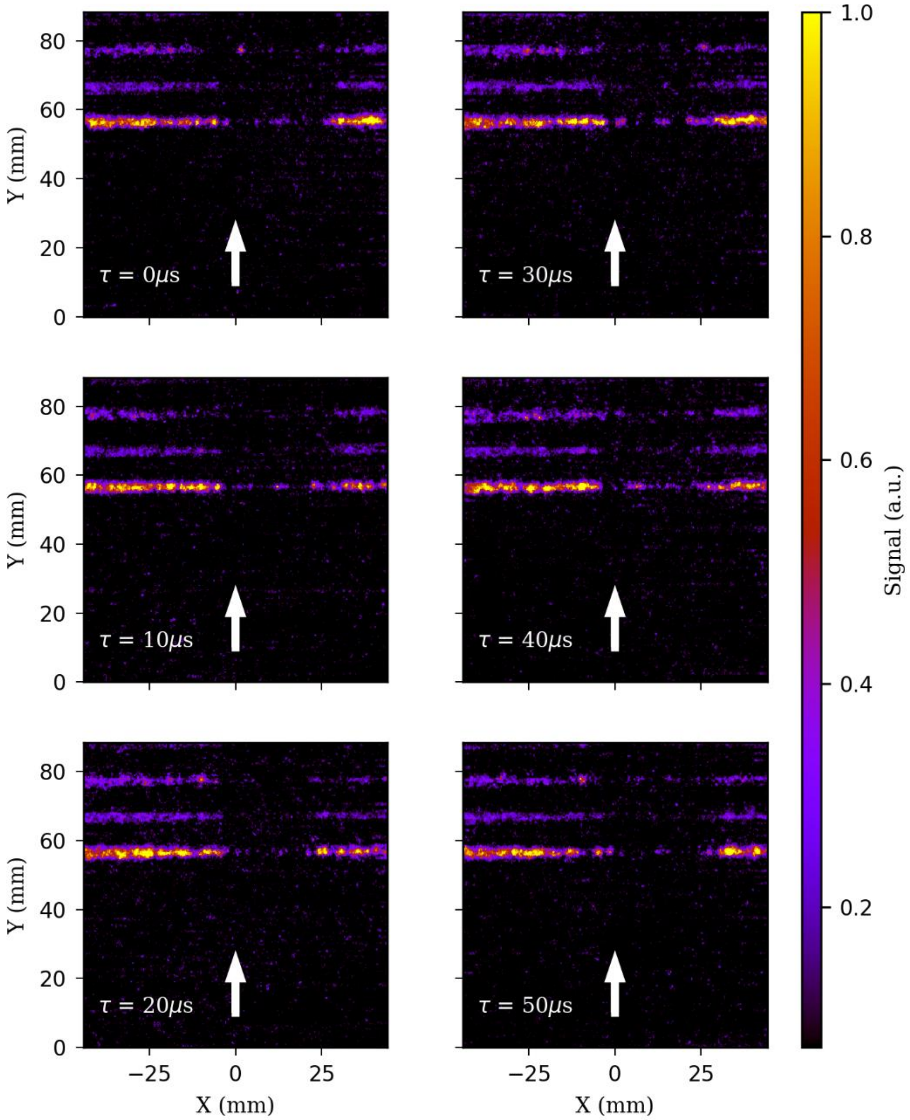
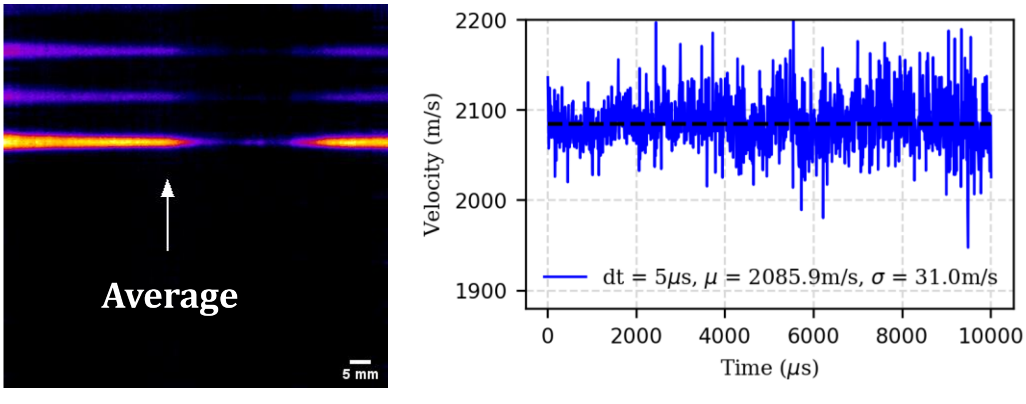


Figure 6. A 6-image sequence of 100-kHz PLEET in Tunnel 9 freestream measurement of Mach 18.



(a) (b)

Figure 7. An average 100-kHz PLEET image (a), and a time series of the flow velocities measured by a single burst (b) in AEDC tunnel 9.

Similar to KTV analysis in Figure 5, Figure 7 shows an average PLEET image and a time series of the flow velocities measured using the PLEET signal in each frame within the10-ms burst. The measured average flow velocity is ~2086 m/s – in close agreement with the KTV results – with an average measurement uncertainty of approximately 1.5%. The measured average freestream flow speed of ~2085 m/s by both 100-kHz KTV and 100-kHz PLEET are in close agreement with the estimated flow velocity using the pressure data.

Conclusion

100-kHz rate KTV and PLEET velocimetry have been demonstrated in Mach 18 flow conditions at AEDC Tunnel 9 employing a burst-mode laser system and a custom optical parametric oscillator (OPO). This demonstration overcame the challenges associated with applying velocimetry in large-scale hypersonic tunnels, such as low pressure, long focal length, and small collection solid angle. KTV was demonstrated using 212 and 355 nm beams to promote 2+1 REMPI as the "write" beams and a 769-nm "read" beam. One study indicated that the KTV signal was enhanced by ~ 10x by employing the "read" beam in low-pressure Kr cell. Single-shot KTV measurements were successfully demonstrated at these extremely low pressures (0.3 torr) with only 1% Kr seeding. Single-shot 100-kHz PLEET was also demonstrated in these conditions (without Kr seeding). The measured freestream flow velocities from both KTV and PLEET agreed well with the velocities estimated using pressure data. The increase in repetition rate provides high data sample rates and the capability to perform better time-resolved velocimetry measurements in hypersonic flow environments.

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