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Calibration and Certification of Molecular Tracking for the Measurement of Near Wall Stresses in High Speed Unseeded Air and Nitrogen

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Abstract

The Femtosecond Laser Electronic Excitation Tagging (FLEET) method is used for unseeded velocimetry in air and in other nitrogen-containing flows. FLEET enables tracking of the flow by writing and following line patterns as the move. Velocity measurements of a turbulent boundary layer were obtained for the calculation of skin friction. Comparisons between FLEET and hot wire anemometry, and analyses of turbulence statistics obtained with FLEET were performed in order to quantify perturbative effects of the tagging on small-scale turbulence. On the computational side, models were developed to follow the kinetics and to simulate the emission as a heated filament to better understand the effects of energy deposition and laser heating on the measurements. Efforts to enhance the FLEET tagging signal in different gas mixtures resulted in the discovery of argon as a promoter of higher signal intensities as well as new insight on the molecular processes. Zero-dimensional kinetics models were developed to determine the governing processes in the FLEET emission in different gas flows. Spin-off efforts at the Arnold Engineering Development Complex Tunnel 9 and NASA Langley have successfully demonstrated premiere boundary measurements in hypervelocity flows, and reflect FLEET's growing popularity as a diagnostic tool in the aerospace community.

I. Relevant Publications

a) Peer Reviewed Publications

DeLuca, Nicholas J.; Miles, Richard B.; Jiang, Naibo; Kulatilaka, Waruna D; Patnaik, Anil K; Gord, James R "FLEET velocimetry for combustion and flow diagnostics", APPLIED OPTICS Volume: 56 Issue: 31 Pages: 8632-8638 Published: NOV 1 2017 (https://doi.org/10.1364/AO.56.008632)

Christopher M. Limbach, Richard B. Miles, "Rayleigh Scattering Measurements of Heating and Gas Perturbations Accompanying Femtosecond Laser Tagging" AIAA Journal, 2017, Vol.55: 112-120, 10.2514/1.J054772

Yibin Zhang, Mikhail N. Shneider, Richard B. Miles, “Femtosecond Laser Excitation in Argon–Nitrogen Mixtures”, AIAA Journal: 1-12, (2 Feb 2018) 10.2514/1.J056084

Zhang, Y. and Miles, R.B. “Femtosecond laser tagging for velocimetry in argon and nitrogen gas mixtures.” Opt. Lett. 43, 551 (2018)

Yibin Zhang, Paul M. Danehy, Richard B. Miles, “Femtosecond Laser Tagging in R134a with Small Quantities of Air,” AIAA Journal: 1-8, 10.2514/1.J057156 (2018)

L. E. Dogariu, A. Dogariu, R. B. Miles, M. S. Smith, and E. C. Marineau, "Femtosecond Laser Electronic Excitation Tagging Velocimetry in a Large Scale Hypersonic Facility", AIAA Journal, submitted (2018)

b) Published Conference Manuscripts

Yibin Zhang, Nathan Calvert, Arthur Dogariu, Richard B. Miles, “Towards shear flow measurements using FLEET” (AIAA 2016-0028) 54th AIAA Aerospace Sciences Meeting, 2016, 10.2514/6.2016-0028

Nathan Calvert, Yibin Zhang, and Richard B. Miles. "Characterizing FLEET for Aerodynamic Measurements in Various Gas Mixtures and non-Air Environments", 32nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2016 AIAA Aviation Forum

Yibin Zhang, Nathan Calvert, Mikhail N. Shneider, Richard B. Miles, “Enhancement of FLEET in Argon Gas Mixtures,” (AIAA 2016-3249) 32nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2016 AIAA Aviation Forum

Christopher J. Peters, Richard B. Miles, Ross A. Burns, Paul M. Danehy, Brett F. Bathel, Gregory S. Jones, “Femtosecond Laser Tagging Characterization of a Sweeping Jet Actuator Operating in the Compressible Regime,” (AIAA 2016-3248) 32nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2016 AIAA Aviation Forum

Yibin Zhang; Richard B. Miles, “Characterizing the Accuracy of FLEET Velocimetry Using Comparison with Hot Wire Anemometry,” (AIAA-2017-0256). 2017 AIAA SciTech Forum, Grapevine Texas, Jan 9-13, 2017

Matthew R. New-Tolley; Mikhail N. Shneider; Richard B. Miles , Modeling of the FLEET Filament Interaction with a Nonuniform Gas Flow, (AIAA-2017-0257), 2017 AIAA SciTech Forum, Grapevine Texas, Jan 9-13, 2017

Yibin Zhang; Mikhail N. Shneider; Richard B. Miles. “Characterization of Intermediate Reactions Following Femtosecond Laser Excitation in Argon-Nitrogen Mixtures,” (AIAA-2017-0841), 2017 AIAA SciTech Forum, Grapevine Texas, Jan 9-13, 2017

Yibin Zhang, Mikhail N. Shneider, Richard B. Miles, "An experimental and theoretical investigation of femtosecond laser excitation in N2 + O2 mixtures," (AIAA 2017-3899) 33rd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2017,

Yibin Zhang, Richard B. Miles, "Shear layer measurements along curved surfaces using the FLEET method," (AIAA 2018-1768 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-1768 Correction: Shear layer measurements along curved surfaces using the FLEET method (AIAA 2018-1768.c1)

Matthew R. New-Tolley, Mikhail N. Shneider, Richard B. Miles, "Evolution of the hot channel and blast wave structure generated from femtosecond tagging in quiescent air," (AIAA 2018-2990) 2018 Aerodynamic Measurement Technology and Ground Testing Conference, 2018, 10.2514/6.2018-2990

Yibin Zhang, Paul M. Danehy, Richard B. Miles, "Femtosecond laser tagging in 1,1,1,2-Tetrafluoroethane with trace quantities of air (AIAA 2018-1027), 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-1027

Laura E. Dogariu, Arthur Dogariu, Richard B. Miles, Michael S. Smith, Eric C. Marineau, "Non-Intrusive Hypersonic Freestream and Turbulent Boundary-Layer Velocity Measurements in AEDC Tunnel 9 Using FLEET", (AIAA 2018-1769), 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-1769

c) Conference Presentations

Stephan Reuter, Benjamin M. Goldberg, Yibin Zhang, Arthur Dogariu, Richard B. Miles, "Single Shot Diagnostics of Atmospheric Plasmas at the Liquid Interface, " (poster presentation) Gordon Research Conference on Fundamental Insights in Plasma Processes August 5 - 10, 2018

L. Dogariu, A. Dogariu, M. S. Smith, E. C. Marineau, and R. B. Miles, "Hypersonic Flow Velocity Measurements Using FLEET," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest ATu4I.4 (2018)

Richard Miles, "Optical Diagnostics for Partially Ionized Plasmas," (invited) BM3.00002: Optical Diagnostics, Plasma Diagnostics Workshop, American Physical Society Gaseous Electronics Conference, Portland, Oregon. Nov 5-9, 2018

d) Patents

#9,863,975 Femtosecond Laser Excitation Tagging Anemometry, Richard Miles, Arthur Dogariu, James Michael, Mathew Edwards. (January 9, 2018)

II. Outline of Projects and Objectives

Direct and accurate measurement of velocity and other transport related quantities in hypersonic flows has remained elusive for long time. Established flow velocimetry techniques, such as those based on probe type measurements (e.g., hot wire, Pitot tubes), Laser Doppler Velocimetry (LDV) and Particle Imaging Velocimetry (PIV), all provide indirect measurements of flow transport quantities. In addition, probe type velocity measurements are intrusive and of limited use in high speed flows, whereas the use of LDV and PIV in large scale and/or high speed facilities faces many challenges due to strict requirements on flow seeding. Proper seeding is often very difficult to achieve and expensive to implement, and in some cases, affects the desired measurements due to seed material interactions with combusting processes and test articles. For FLEET, the flow is not seeded and only a single laser and a single time gated camera are required for flow velocity measurements. A femtosecond laser is used for multiphoton dissociation of molecular nitrogen to create long lived fluorescent tracers that are imaged several microseconds later with a single time-gated intensified camera. Real-time quantitative velocities are obtained by measuring the displacement of the tagged lines. The potential to capture these data at kilohertz rates and follow the real time evolution of continuous line patterns at intervals as short as microseconds bring a new capability for high speed flow dynamic measurements. The application of FLEET in nitrogen based ground test facilities is particularly promising since FLEET emission lines in nitrogen are significantly stronger than in air.

Work conducted by Calvert[1] and Zhang[2] demonstrated the feasibility of using FLEET to measure velocity profiles within tens of microns to the wall in an open supersonic jet as well as in an in-draft wind tunnel facility. This promising application has motivated this project to address the uncertainty and limitations involved as well as to seek potential methods to increase the accuracy of measurements. The effects of optical properties (wavelength, pulse energy, beam focusing), imaging properties (camera delay, exposure time, averaging, magnification) and flow medium (air, pure nitrogen, argon) on small-scale velocity measurements are studied. The effort to quantify the perturbations introduced by the laser energy deposition involved both experimental and theoretical approaches and a study of the behavior of FLEET diagnostic in different gas mixtures. In summary, the investigation of near-wall velocity measurements include the following sub-projects:

a) Direct measurement of boundary layers and flow properties
b) Investigation of FLEET viability in non-air flows
c) Optimization of FLEET parameters for turbulent flows
d) Computational and modeling efforts to quantify the laser interaction in boundary layer flows
e) Spin off efforts in AEDC Tunnel 9

This report is divided into these five sections with each detailing the progress made and status of the corresponding effort.

A. Experimental Boundary Layer Measurements

FLEET has recently been demonstrated for boundary layer interrogation in supersonic flows up to several wall units from the surface, paving the way towards skin friction measurements. Out of the three different configurations tested, measuring the velocity gradient tangential to a curved surface, where the beam is oriented in the direction normal to the flow, best resolves the laminar sublayer[3]. A clear advantage of this set-up is the ability to resolve close to a surface without ablating the wall material, limited only by the thickness of the FLEET line at the beam's focal region. Turbulent boundary layer structures across curved surfaces have not been studied as frequently as across

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[1] Calvert, N. D., Dogariu, A., & Miles, R. B. (2013). FLEET Boundary Layer Velocity Profile Measurements. In *AIAA 44th Plasmadynamics and Lasers Conference*.

[2] Zhang, Y., Calvert, N., Dogariu, A., & Miles, R. B. (2016). Towards shear flow measurements using FLEET. In *54th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum (AIAA 2016-0028)*.

[3] Zhang, Y., Calvert, N., Dogariu, A., & Miles, R. B. (2016). Towards shear flow measurements using FLEET. In *54th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum (AIAA 2016-0028)*.

canonical boundary layers, such as that across a flat plate in zero pressure gradient. The curved plate configuration avoids clipping the laser beam, making it particularly suitable for near-wall measurements. In the case of flat and low-curvature surfaces, the law of the wall scaling is obeyed and the zero-pressure gradient assumption in the wall-normal direction holds. This configuration demonstrates the feasibility of resolving near-wall fluctuations along irregular, curved surfaces by passing a beam tangential to the curve. Measurements using this grazing incidence approach have previously been obtained in an open jet down to a reported 20μm from the surface[4].

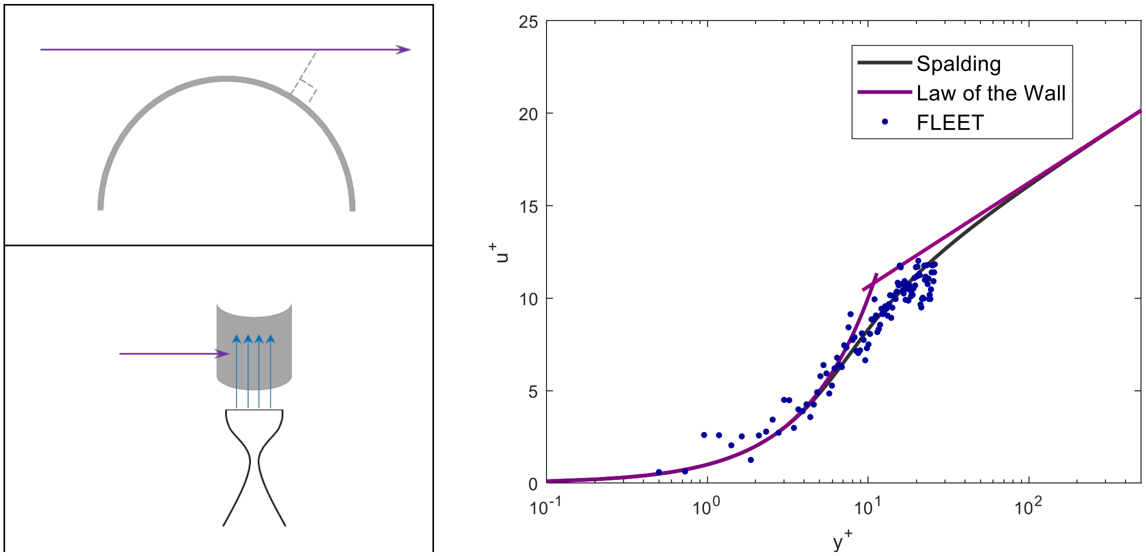

Figure 1. Left: Experiment schematic for the curved surface configuration, top-down view and frontal view. Right: Comparison of the van Driest transformed velocity for FLEET and theory by Spalding

The first image of Figure 1 depicts the experimental schematic for the grazing incidence experiment, where the purple arrow represents the laser beam path relative to the curved surface. The second image shows the van Driest transformed velocity calculated from FLEET in a Mach 1.15 flow, $Re_D \sim 10^5$ and compared to theory. The preliminary data shows good fit as compared to theory by Spalding.

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[4] Calvert, N. D., Dogariu, A., & Miles, R. B. (2013). FLEET Boundary Layer Velocity Profile Measurements. In *AIAA 44th Plasmadynamics and Lasers Conference*.

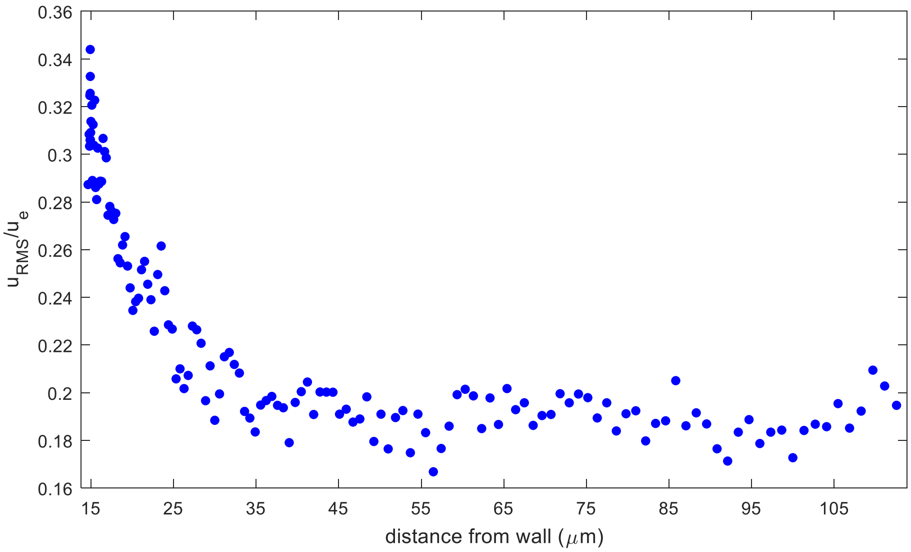

Figure 2. Streamwise normalized RMS velocity as a function of wall normal distance

Figure 2 shows the streamwise RMS velocity fluctuations in the same Mach 1.15 flow and demonstrates our ability to capture large turbulent velocity structures in the near-wall region.

B. Enhancement of signal, robustness and viability through a study of FLEET physics

Equations 1-5 describe the probable method by which femtosecond laser dissociation of molecular nitrogen produces atomic nitrogen, which collisionally recombines over hundreds of microseconds to produce electronically excite nitrogen molecules in the $B^3\Pi_g$ state. The transition from the nitrogen $B^3\Pi_g$ to $A^3\Sigma_u^+$ state produces visible and infrared fluorescence that can be tracked with a camera for velocimetry purposes.

$$N_2 + h\nu \rightarrow e^- + N_2^+ \tag{1}$$
$$e^- + N_2^+ \rightarrow N + N \tag{2}$$
$$N + N + N_2 \rightarrow N_2\left({}^5\Sigma_g^+\right) + N_2 \tag{3}$$
$$N_2\left({}^5\Sigma_g^+\right) + N_2 \rightarrow N_2\left(B^3\Pi_g\right) + N_2 \tag{4}$$
$$N_2\left(B^3\Pi_g\right) \rightarrow N_2\left(A^3\Sigma_u^+\right) \tag{5}$$

Previous studies conducted by Edwards et al[5] have determined noticeable heat deposition in the flow by the laser filament, so current work seeks to decrease perturbative effects of FLEET. The accuracy and effectiveness of FLEET velocimetry is limited by the emission signal intensity and lifetime, which in turn are functions of experimental conditions including gas mixture. Signal intensity and lifetime become limiting factors when flows, such as in a wind tunnel testing facility, experience large pressure and density drops. We also seek to extend the viability of FLEET velocimetry to in non-air mixtures, including mixtures of nitrogen with argon, helium, carbon dioxide and methane, which have experimentally yielded mixed results. We achieved the best signal enhancement in argon-nitrogen

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[5] Edwards, M. R., Limbach, C. M., Miles, R. B., & Tropina, A. (2015). Limitations on High-Spatial Resolution Measurements of Turbulence Using Femtosecond Laser Tagging. In *53rd AIAA Aerospace Sciences Meeting* (pp. 2015-1219).

gas. Argon gas is an important working gas in aerodynamics studies due to its natural abundance and inert behavior. It is often flowed through supersonic and hypersonic wind tunnels, and shock tubes, or used as a plasma medium.

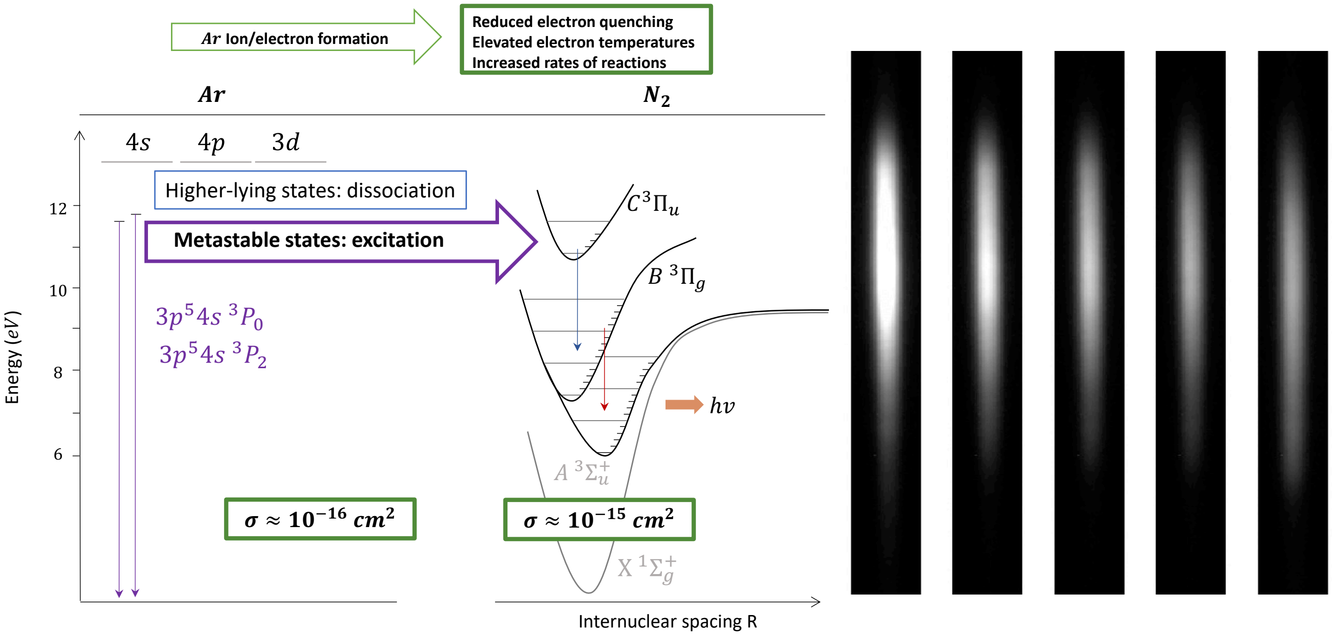

Figure 3.Potential energy diagram of argon with respect to excited electronic states of molecular nitrogen. The main mechanisms for enhancement of nitrogen radiation are annotated on the diagram. Right: FLEET signal imaged in different mixtures of nitrogen and argon. From left to right, the mixtures are 6% N2, 20% N2, 30% N2, 40% N2 and 100% N2.

It is experimentally observed that the inclusion of argon gas in a pure nitrogen flow enhances the signal intensity at short delays of several microseconds, which is typically the delay used for supersonic boundary layer measurements. Argon gas is demonstrated to enhance FLEET at atmospheric pressure and temperature for unseeded velocimetry applications, primarily through 2-4 orders of magnitude increase of excited species that may radiate through nitrogen's second positive system at early timescales of interest. The first positive system continues to play an important role in maintaining this emission at longer delays. A detailed kinetic model is implemented to explain this observed behavior in nitrogen and argon mixtures. Dominant processes governing the creation of $\mathrm{N_2(B^3\Pi_g)}$ and $\mathrm{N_2(C^3\Pi_u)}$ include a slower decay of electron temperature through increased ionization processes, reduced nitrogen quenching of electrons, nitrogen atom creation and recombination, the formation and dissociation of N_4^+ and several argon-nitrogen direct and indirect excitation pathways. The pooling of $N_2(A^3\Sigma_u^+)$ to form B- and C-state nitrogen play minor roles in the formation of radiating species at timescales useful for measurements in the FLEET-argon plasma chemistry. In mixtures where nitrogen is dominant, metastable argon species are less instrumental in direct nitrogen excitation transfer, $Ar^*(4^3P_2) + N_2 \rightarrow Ar + (N_2(B^3\Pi_g), N2(C^3\Pi_u))$, than in facilitating further reactions through maintaining a higher electron temperature, whereas this excitation transfer begins to play a larger role as the percentage of argon is further increased. It is concluded that not one single process can be credited for the enhancement, but a combination of ionization and heating produces the increased emission observed in argon mixtures as shown in Figure 3.

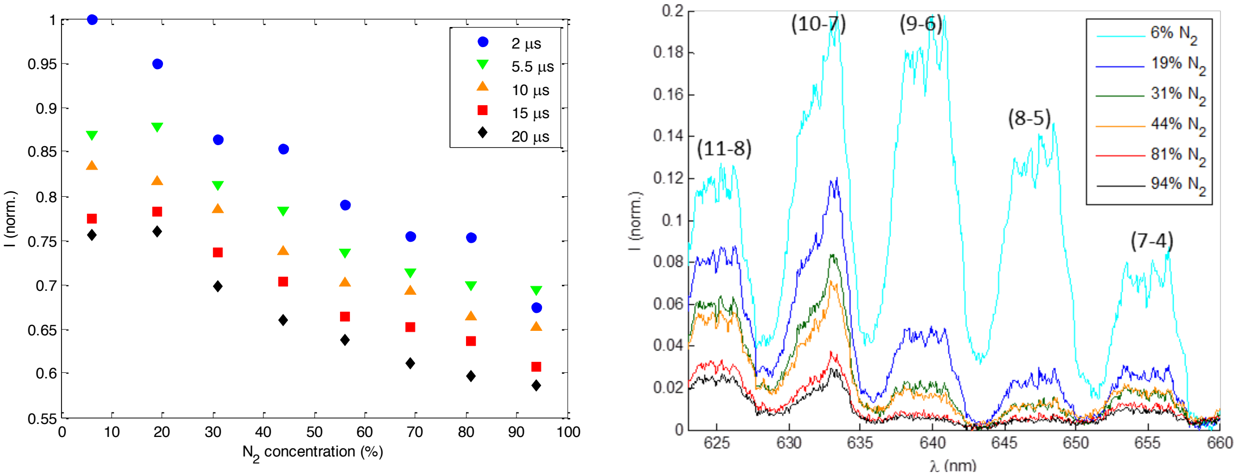

Figure 4.Left: FLEET emission for different time delays while varying the Ar:N_2 *relative concentration.*
Right: Nitrogen spectrum as FLEET emission for varying the Ar:N_2 *relative concentration.*

The enhancement with the addition of Argon is quantified in Figure 4. Fig. 4 (left) shows how the FLEET emission at different time delays increases proportionally with the partial pressure of Argon. Fig. 4 (right) shows that the emission spectrum is that of the nitrogen even for very small amounts on N_2 in Ar:N_2 mixtures, proving the enhancement mechanism outlined in Figure 3.

We have also investigated FLEET in mixtures of nitrogen and oxygen at atmospheric pressure and temperature. Previous studies have shown that the FLEET signal is strongest at all delays in pure nitrogen and decreases by about an order of magnitude in air, a phenomenon attributed to the loss of nitrogen atoms to reactions with oxygen species[6]. The main ion species following laser excitation is O_2^+, which has an ionization energy of 12.07eV, compared to 15.58eV for nitrogen. Thus, reactions involving oxygen species, especially odd oxygen species (O, O_3) at high pressures are expected to be dominant. Oxygen is furthermore found to be a more efficient quencher of excited nitrogen states than molecular nitrogen, especially for higher vibrational states.

As shown in Figure 5, the introduction of small percentages of oxygen into the nitrogen mixture causes the signal to drop steeply by a factor of two or three, forming a local signal intensity minimum. The signal intensity in industrial-grade air under the same experimental conditions at a 5µs delay (not shown) falls approximately on the curve indicated by the 5.5µs delay line at 78% N_2. At 12% mole fraction, the ratio of oxygen to nitrogen in air unfortunately falls close to that minimum well, affecting FLEET's attractiveness as a non-seeded diagnostic method for air flows. The signal appears to have a local maximum in a mixture of 50% nitrogen and 50% oxygen before dipping to immeasurable values as the mole fraction of nitrogen in the mixture continues to decrease. From the spectral analysis and kinetics simulations of these mixtures, it is hypothesized that nitric oxide is an important participant in producing increased emission in the UV, and small contributions from atomic oxygen are observed in the near-infrared. High levels of long-lived NO across different mixture ratios suggest that optimal conditions for FLEET to be used in combination with NO-LIF occur at approximately 50% N_2 + 50% O_2.

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[6] Michael, J. B., Edwards, M. R., Dogariu, A., & Miles, R. B. (2012). Velocimetry by femtosecond laser electronic excitation tagging (FLEET) of air and nitrogen. In *50th AIAA Aerospace Sciences Meeting* (Vol. 1053).

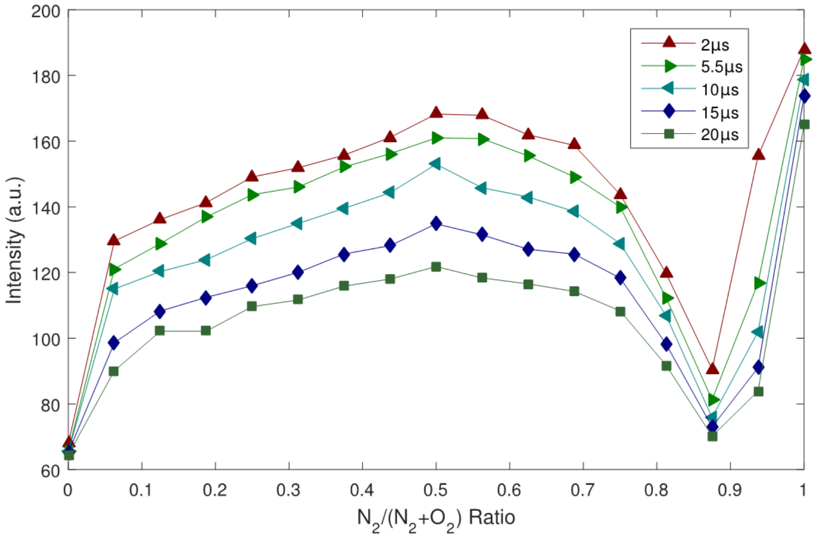

Figure 5. FLEET emission intensity as a function of time and mole fraction, 400nm, 1atm total pressure

Combining the two diagnostics open opportunities for enhanced signal intensities and lifetimes, as well as extended capabilities to combustion applications.

C. Optimization of FLEET parameters for turbulent flows

Table 1. FLEET parameter space

Incident beam properties	**Imaging parameters**	**Experimental Conditions**
Pulse energy density (energy, focusing)	Camera/Intensifier properties	Pressure
Pulse duration	Gating/Delay	Temperature
Wavelength (800, 400, 267)	Sensor spectral range	Gas Mixture (air, N_2, Ar)

Two separate experiments were conducted to study the optimization of FLEET parameters for turbulent flows. In the first, well-developed turbulent flow is produced in a pipe using industrial-grade air and nitrogen. Fully developed turbulent pipe flow requires an L/D ratio of greater than ~ 30; this setup provides an L/D ~130 to ensure well-developed flow for the desired turbulent conditions. A custom pressure transducer - pressure tap array is used to characterize the flow, and the flow rate is varied between 1 cubic foot per minute (CFM) to 4 CFM to determine the transition from laminar to turbulent flow. Measurements are taken at $Re_D=3.5*10^4$ and $Re_\lambda=400$. FLEET and Constant Temperature Anemometry measurements are taken simultaneously and averaged over thousands of data points. In the second configuration, FLEET measurements are taken 38 exit diameters downstream in a vertical free jet of dry air for comparison with RELIEF measurements taken by

Noullez et al[7]. Structure functions of order p are frequently used to describe properties of turbulence. They are generally defined as $S_p(r) = \langle[\Delta u(r)]^p\rangle \sim r^{\zeta(p)}$, where Kolmogorov's predicted scaling is $\zeta(p) = p/3$ not taking into account intermittency. Hot wire probes measure the longitudinal structure functions, whereas FLEET and RELIEF measured the transverse structure functions. From the mean-square transverse velocity gradients computed from the transverse velocity structure function, we may normalize the second order structure function such that it approaches unity as separations approach infinity.

We looked for nonphysical relationships between two point measurements that can be attributed to our imaging equipment and diagnostic parameters, and not present in an unperturbed flow. Figure 6 shows the normalized second order structure function for FLEET velocity measurements using the 400nm laser wavelength with different focusing, and subsequently, different tagging energy density. Hot wire measurements are not shown here because spatial averaging across the length of the sensing element of the probe render the data invalid for scales below 1 mm. These results show good agreement between theory and experiment for separation scales r in the inertial range and increased correlation associated with the dissipation range beginning at separations around 0.2mm. In the dissipation range, the slope should converge to 2 when the Kolmogorov scale is reached (corresponding to a parabolic correlation curve). Fitting of data is accomplished best in pure nitrogen flow and at higher focusing (overall higher tagging energy density) with higher camera magnification. For the particular plotted cases, unphysical data points are rarely encountered due to the high signal-to-noise ratio, so less than 1% of the data is discarded.

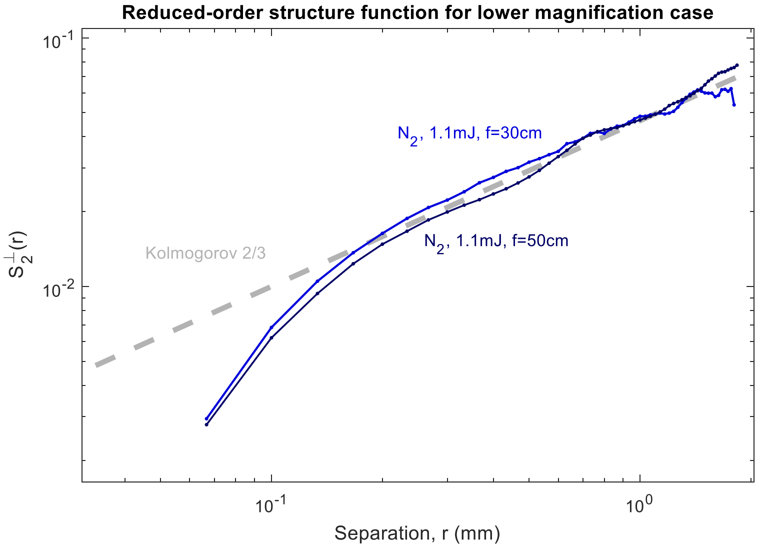

Figure 6. Normalized second order structure function for FLEET velocity measurements taken at the exit of a nitrogen subsonic pipe flow using a magnification of M_3=33µm/pixel, and 400nm beam, 1.1mJ/pulse at 1kHz focused with a f=30cm or 50cm lens. The predicted Kolmogorov scaling is indicated by the grey dotted line.

Typical magnification used for FLEET velocimetry varies between 10µm/pixel to about 40µm/pixel. Increased magnification typically increases our ability to resolve scales in the dissipation subrange regardless of other incident beam variables.

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[7] Noullez, A., Wallace, G., Lempert, W., Miles, R. B., & Frisch, U. (1997). Transverse velocity increments in turbulent flow using the RELIEF technique. *Journal of Fluid Mechanics*, *339*, 287-307.

FLEET using 267nm

Another experiment uses excited metastable argon to collisionally excite nitrogen. This permits the use of lower pulse energies and reduce gas heating. Initial experiments have shown slight enhancement of signal in nitrogen and argon in an open jet flow using less than 10 μJ per pulse at a wavelength resonant to argon. During this effort we have demonstrated tagging in a nitrogen-argon mixture using a femtosecond laser with pulse energies of approximately 75μJ through a multi-photon ionization process at 267nm in a gas cell. A 5.6mJ pulse at the fundamental wavelength (800nm) is converted to an 85μJ pulse at 267nm. An additional 10% loss of pulse energy occurs as the beam passed through the 3.1mm thick optical-grade fused silica window, leaving ≤80μJ of tagging beam energy. We can capture the signal fluorescence lifetime in pure argon, but not nitrogen-argon mixtures using our tagging energies due to the attenuation of the beam by the cell. Lower energy density and narrower tagged lines are produced using 267nm as compared to femtosecond laser tagging in argon or argon and nitrogen using 400nm or 800nm. Using zero-time-delay measurement of focused beam waist, we determine the energy density necessary to produce emission at each excitation wavelength in the gas cell. At λ=400nm, a minimum pulse energy of ~ 0.8mJ at 1kHz focused with a f=30cm lens is necessary to produce visible emission lasting several microseconds. At λ=267nm, the minimum pulse energy at 1kHz focused with a f=10cm lens is 80μJ, resulting in higher tagging efficiency.

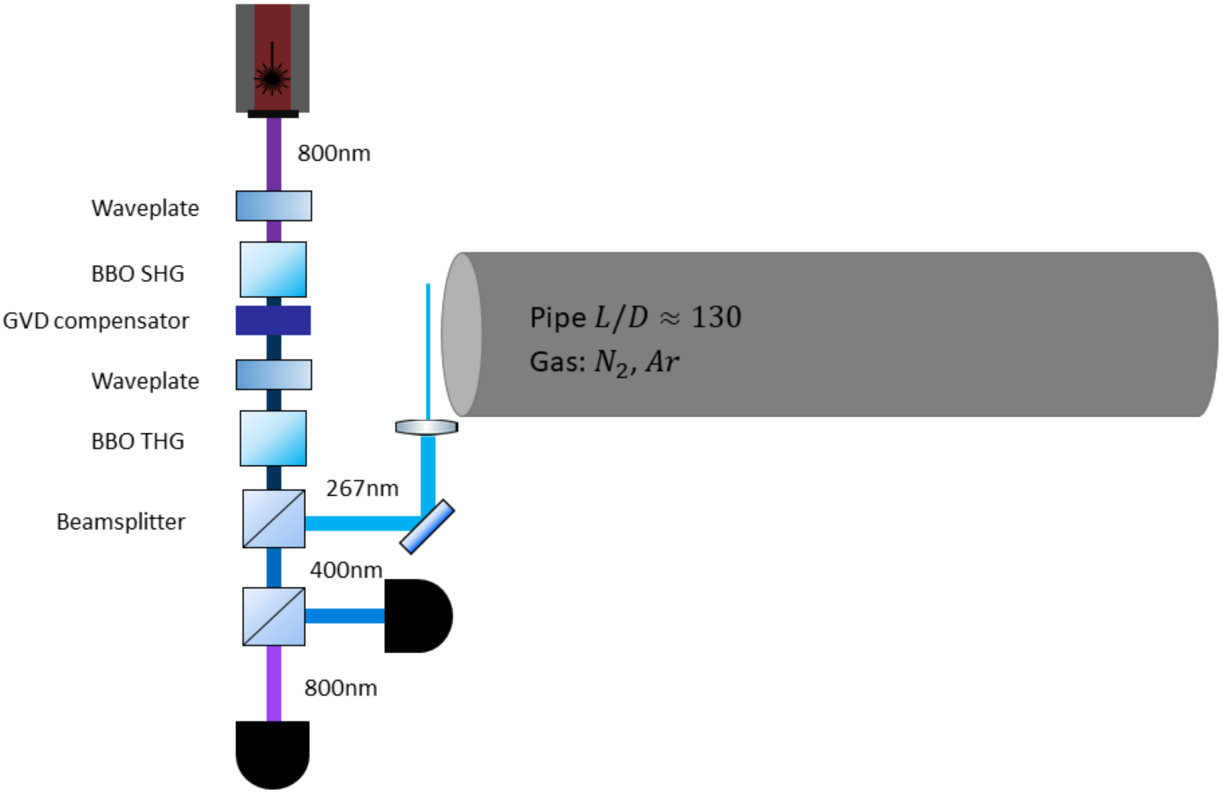

Figure 7. Experimental schematic for velocimetry using the third harmonic at 267nm

We have also demonstrated velocimetry in pure nitrogen gas and pure argon gas using pulses centered at 267nm using the schematic in Figure 7. Measurements were taken in the same subsonic, fully-developed turbulent pipe flow as in section C. A 5.6mJ pulse at the fundamental wavelength (800nm) is converted to a 60 μJ pulse at 267nm and focused with a f=25cm UV lens. Compared to the previous experiment, the pipe flow (nitrogen, argon) is not separated from the air in the experimental room.

D. Computational and Modeling Studies of FLEET

Efforts were made to model the FLEET filament interaction with a nonuniform gas flow to determine the validity of using FLEET for boundary layer velocimetry. Both 2D and 3D simulations are produced, governed by unsteady Navier-Stokes flow. The boundary layer model for the simulation is derived from the Navier-Stokes equations and FLEET is modeled as a heated channel with Gaussian beam distribution. The goal of this study was to understand the temperature distribution in the FLEET filament and its interaction with the measured shear velocity. simulations of FLEET measurements in ~~of~~ a turbulent boundary layer are created for the situation of supersonic flow over a flat plate. In this simulation, the FLEET signal is approximated as a cylindrical hot channel. This approximation is justified by previous computational analyses using an unsteady three-dimensional Navier-Stokes solver, which indicated that radial perturbations of the FLEET signal are negligible compared to its translation through the flow.

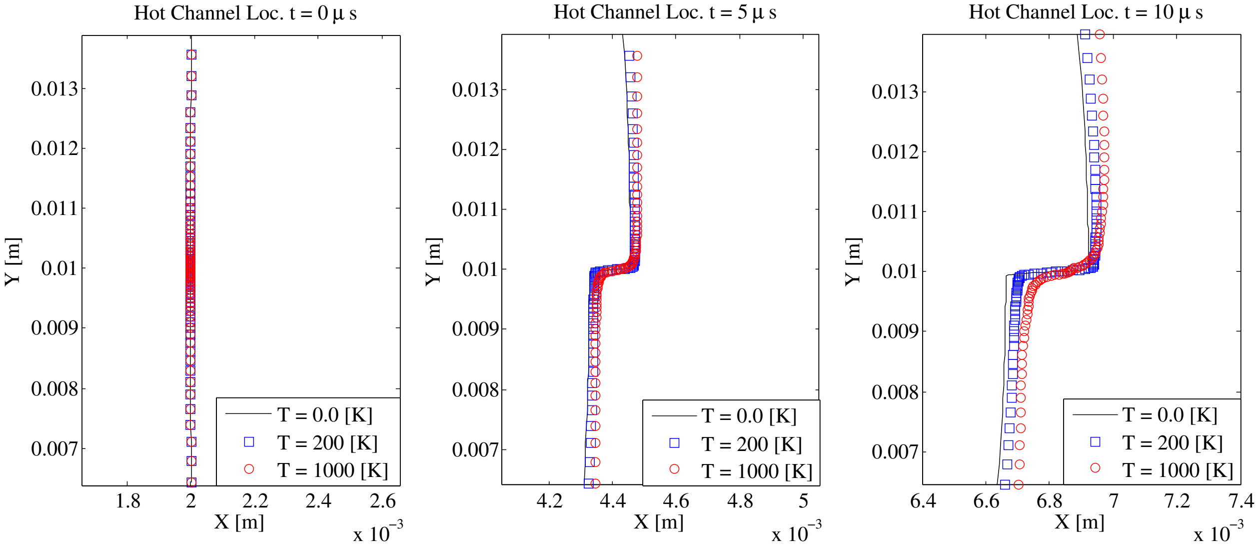

Figure 8. Representative images from modeling efforts. These three images show the evolution of the hot channel centroid in a shear layer as a function of delay and gas temperature (indicated by the different colors in legend).

Each plot in Figure 8 shows the location of the modeled FLEET hot channel centroid in a shear layer formed by juxtaposing two different freestream flows. The upper flow has a Mach number of 1.9 while the lower flow has a Mach number of 1.8. The modeled boundary is located at approximately Y=0.01m. We note that the 1000 K channel rounds out the edges associated with the shear layer, indicating that if the temperature is high, the increase in viscosity impacts the ability of the FLEET line to track the flow. This effect is expected to limit the ability of FLEET to accurately track the small scales in a turbulent flow and motivates research on the minimization of the increase in temperature associated with the FLEET tagging process for measurements of small scale phenomena.

E. Spin-Off Efforts in AEDC Tunnel 9

i. Plasma TEC- Air Force Phase II SBIR

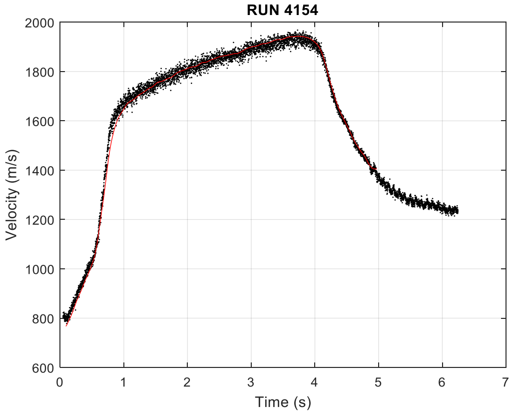

Figure 9. FLEET measured velocity as a function of time for a Mach 14 run in Tunnel 9. The red line is the predicted velocity profile and the black dots are FLEET measurements, taken at 1kHz.

Through SBIR funding, FLEET has been demonstrated in unseeded nitrogen flows at the AEDC Hypervelocity Wind Tunnel 9. FLEET velocity measurements in both the free-stream and across a boundary layer were taken during twenty-one tunnel runs at Mach 10 and Mach 14. Figure 9 shows a comparison of the FLEET measured free stream velocity in a Mach 14 run compared to predicted velocity for a complete wind tunnel run including start up and shut down transients. The flow velocity increases during the three-second constant Mach number run due to the increase in temperature of the nitrogen in the wind tunnel settling chamber. This was the first time a direct measurement of the flow velocity has been achieved in this facility. Figure 10 shows images taken across the turbulent boundary layer at Mach 10.

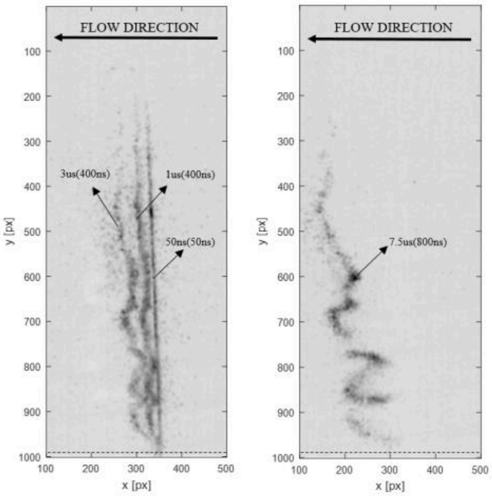

Figure 10: Representative boundary layer FLEET images obtained at Mach 10. The laser is tangent to the surface of a cylindrical model. The same line is imaged four times as it moves from right to left. (Left image): First 3 microseconds. (Right image): Line at 7 microseconds, recorded in a separate image with camera operating in the double shutter mode. The time delay of each line and the corresponding gate duration are indicated on each image. Spatial scale for the x-axis is 17.07 px/mm

The FLEET measurements taken in the hypersonic boundary layer provide qualitative images of the flow structures and spatially resolved velocity profiles. Figure 11 compares the boundary-layer FLEET velocity measurements between several tunnel runs, and shows that the boundary layer can be determines close to the test article. Overall, good agreement was obtained between the experimental profiles and RANS CFD simulations of the boundary layer.

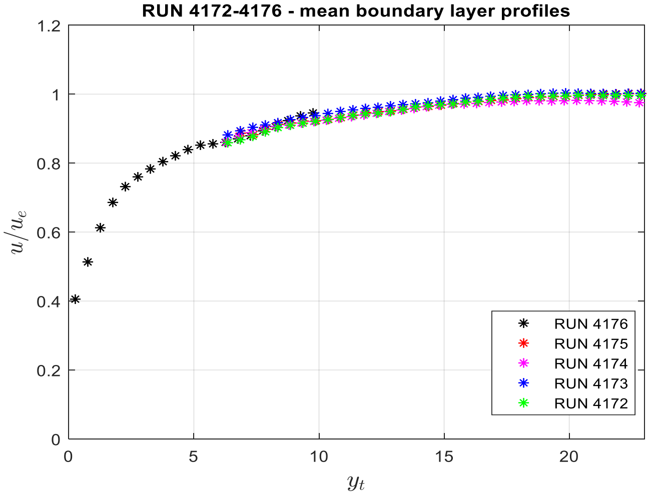

Figure 11. Mean boundary layer profile measured using FLEET for several Tunnel 9 runs

This work was presented at the 2018 AIAA SciTech and CLEO meetings[8], and was submitted for publication in the AIAA journal[9].

ii. NASA – NSTRF support for Ph. D student, Christopher Peters, including on site collaboration at NASA Langley with Dr. Paul Danehy
iii. Spectral Energies, Inc. - NASA – Phase II SBIR - A FLEET system is being developed for the NASA National Transonic Facility at NASA Langley.
iv. MetroLaser, Inc. – NASA Phase II SBIR with NASA Ames for measurement of flow in high enthalpy facilities.

III. Summary

During this project we worked to quantify the accuracy of FLEET velocity measurements and increase robustness of the method through a combination of experiments and models. A number of different parameters govern the viability of the FLEET method in turbulent, high Reynolds number flows with difficult optical access. We have explored some of these variables in the previous studies and continue to strive for a robust, minimally-intrusive diagnostic method whose accuracy can be verified against an established measurement tool. By expanding our laser capability through second and third harmonic generation, we are able to produce tagging with lower energy densities. We aim to apply some of these new capabilities and understanding to the measurement of skin friction in supersonic and hypersonic flows.

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[8] L. E. Dogariu, A. Dogariu, R. B. Miles, M. S. Smith, and E. C. Marineau, “Non-Intrusive Hypersonic Freestream and Turbulent Boundary-Layer Velocity Measurements in AEDC Tunnel 9 using FLEET,” in *56th AIAA Aerospace Sciences Meeting,* 1769 (2018); L. Dogariu, A. Dogariu, M. S. Smith, E. C. Marineau, and R. B. Miles, "Hypersonic Flow Velocity Measurements Using FLEET," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest ATu4I.4 (2018)

[9] L. E. Dogariu, A. Dogariu, R. B. Miles, M. S. Smith, and E. C. Marineau, "Femtosecond Laser Electronic Excitation Tagging Velocimetry in a Large Scale Hypersonic Facility", AIAA Journal, submitted (2018)

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Abstract

The Femtosecond Laser Electronic Excitation Tagging (FLEET) method is used for unseeded velocimetry in air and in other nitrogen-containing flows. FLEET enables tracking of the flow by writing and following line patterns as the move. Velocity measurements of a turbulent boundary layer were obtained for the calculation of skin friction. Comparisons between FLEET and hot wire anemometry, and analyses of turbulence statistics obtained with FLEET were performed in order to quantify perturbative effects of the tagging on small-scale turbulence. On the computational side, models were developed to follow the kinetics and to simulate the emission as a heated filament to better understand the effects of energy deposition and laser heating on the measurements. Efforts to enhance the FLEET tagging signal in different gas mixtures resulted in the discovery

of argon as a promoter of higher signal intensities as well as new insight on the molecular processes. Zero-dimensional kinetics models were developed to determine the governing processes in the FLEET emission in different gas flows. Spin-off efforts at the Arnold Engineering Development Complex Tunnel 9 and NASA Langley have successfully demonstrated premiere boundary measurements in hypervelocity flows, and reflect FLEET's growing popularity as a diagnostic tool in the aerospace community.

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Archival Publications (published) during reporting period:

a) Peer Reviewed Publications

DeLuca, Nicholas J.; Miles, Richard B.; Jiang, Naibo; Kulatilaka, Waruna D; Patnaik, Anil K; Gord, James R "FLEET velocimetry for combustion and flow diagnostics", APPLIED OPTICS Volume: 56 Issue: 31 Pages: 8632-8638 Published: NOV 1 2017 (https://doi.org/10.1364/AO.56.008632)

Christopher M. Limbach, Richard B. Miles, "Rayleigh Scattering Measurements of Heating and Gas Perturbations Accompanying Femtosecond Laser Tagging" AIAA Journal, 2017, Vol.55: 112-120, 10.2514/1.J054772

Yibin Zhang, Mikhail N. Shneider, Richard B. Miles, "Femtosecond Laser Excitation in Argon–Nitrogen Mixtures", AIAA Journal: 1-12, (2 Feb 2018) 10.2514/1.J056084

Zhang, Y. and Miles, R.B. "Femtosecond laser tagging for velocimetry in argon and nitrogen gas mixtures." Opt. Lett. 43, 551 (2018)

Yibin Zhang, Paul M. Danehy, Richard B. Miles, "Femtosecond Laser Tagging in R134a with Small Quantities of Air," AIAA Journal: 1-8, 10.2514/1.J057156 (2018)

L. E. Dogariu, A. Dogariu, R. B. Miles, M. S. Smith, and E. C. Marineau, "Femtosecond Laser Electronic Excitation Tagging Velocimetry in a Large Scale Hypersonic Facility", AIAA Journal, submitted (2018)

b) Published Conference Manuscripts

Yibin Zhang, Nathan Calvert, Arthur Dogariu, Richard B. Miles, "Towards shear flow measurements using FLEET" (AIAA 2016-0028) 54th AIAA Aerospace Sciences Meeting, 2016, 10.2514/6.2016-0028

Nathan Calvert, Yibin Zhang, and Richard B. Miles. "Characterizing FLEET for Aerodynamic Measurements in Various Gas Mixtures and non-Air Environments", 32nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2016 AIAA Aviation Forum

Yibin Zhang, Nathan Calvert, Mikhail N. Shneider, Richard B. Miles, "Enhancement of FLEET in Argon Gas Mixtures," (AIAA 2016-3249) 32nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2016 AIAA Aviation Forum

Christopher J. Peters, Richard B. Miles, Ross A. Burns, Paul M. Danehy, Brett F. Bathel, Gregory S. Jones, "Femtosecond Laser Tagging Characterization of a Sweeping Jet Actuator Operating in the Compressible Regime," (AIAA 2016-3248) 32nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2016 AIAA Aviation Forum

Yibin Zhang; Richard B. Miles, "Characterizing the Accuracy of FLEET Velocimetry Using Comparison with Hot Wire Anemometry," (AIAA-2017-0256). 2017 AIAA SciTech Forum, Grapevine Texas, Jan 9-13, 2017

Matthew R. New-Tolley; Mikhail N. Shneider; Richard B. Miles , Modeling of the FLEET Filament Interaction with a Nonuniform Gas Flow, (AIAA-2017-0257), 2017 AIAA SciTech Forum, Grapevine Texas, Jan 9-13, 2017

Yibin Zhang; Mikhail N. Shneider; Richard B. Miles. "Characterization of Intermediate Reactions Following Femtosecond Laser Excitation in Argon-Nitrogen Mixtures," (AIAA-2017-0841), 2017 AIAA SciTech Forum, Grapevine Texas, Jan 9-13, 2017

Yibin Zhang, Mikhail N. Shneider, Richard B. Miles, "An experimental and theoretical investigation of femtosecond laser excitation in N2 + O2 mixtures," (AIAA 2017-3899) 33rd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2017,

Yibin Zhang, Richard B. Miles, "Shear layer measurements along curved surfaces using the FLEET method," (AIAA 2018-1768 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-1768 Correction: Shear layer measurements along curved surfaces using the FLEET method (AIAA 2018-1768.c1)

Matthew R. New-Tolley, Mikhail N. Shneider, Richard B. Miles, "Evolution of the hot channel and blast wave structure generated from femtosecond tagging in quiescent air," (AIAA 2018-2990) 2018 Aerodynamic Measurement Technology and Ground Testing Conference, 2018, 10.2514/6.2018-2990

Yibin Zhang, Paul M. Danehy, Richard B. Miles, "Femtosecond laser tagging in 1,1,1,2-Tetrafluoroethane with trace quantities of air (AIAA 2018-1027), 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-1027

Laura E. Dogariu, Arthur Dogariu, Richard B. Miles, Michael S. Smith, Eric C. Marineau, "Non-Intrusive Hypersonic Freestream and Turbulent Boundary-Layer Velocity Measurements in AEDC Tunnel 9 Using FLEET", (AIAA 2018-1769), 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-1769

New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

Yes

Please describe and include any notable dates

#9,863,975 Femtosecond Laser Excitation Tagging Anemometry, Richard Miles, Arthur Dogariu, James Michael, Mathew Edwards. (January 9, 2018)

Do you plan to pursue a claim for personal or organizational intellectual property?

Yes

Changes in research objectives (if any):

None

Change in AFOSR Program Officer, if any:

None

Extensions granted or milestones slipped, if any:

None

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

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Equipment/Facilities			
Supplies			
Total			

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Appendix Documents

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