20 kHz tracer-based PLIF of a jet in crossflow in an expansion tube

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Abstract This manuscript describes 20 kHz cinematographic tracer-based (toluene) planar laser-induced fluorescence (PLIF) imaging of an underexpanded jet in an expansion tube. A pulsed, Nd:YAG laser at 266 nm delivering 0.8–0.9 mJ per pulse at 20 kHz repetition rate is used for excitation, and a CMOS camera coupled to a high-speed intensifier images the resulting fluorescence. Mach 0.9 flow is generated in an expansion tube operated in shock-mode, and an underexpanded jet of hydrogen is issued perpendicularly from a flat plate; toluene is uniformly seeded into the free stream. Significant background signals are observed (> 15% of peak LIF signal) resulting from reflected fluorescence, which falsely elevate signal levels in the acquired images; this background signal is removed by deconvolving the acquired images with a kernel that describes the reflection of fluorescence off the walls. The resulting PLIF image sequences are presented, visualizing jet start up process and the dynamics of the jet in crossflow.

1. Introduction

This work demonstrates the use of relatively practical, turn-key laser and imaging systems for tracer-based planar laser-induced fluorescence (PLIF) imaging of a practical flow field, an underexpanded jet in crossflow in an expansion tube [1, 2].

The transverse jet in crossflow (or JICF) is a basic configuration used to mix fuel (the injectant) with oxidizer (the crossflow) in an air-breathing engine. The entrainment, turbulent transport, and mixing characteristics of the jet in crossflow can play a major role in the performance of a combustion engine, and these characteristics are largely controlled by a complex system, of large-scale vortical structures [3]–[6].

The specific configuration studied in this work, the jet in nearly sonic crossflow, is relevant to next-generation, high-speed aerospace propulsion systems; in particular, the dynamics and transients of the JICF immediately behind shockwaves might be found in a starting or unstarting scramjet (where the cross-flow may be supersonic) or during normal operation of a non-premixed rotary-detonation-engine (RDE [7]) where the crossflow will be nearly sonic or supersonic). In a non-premixed RDE, fuel is injected into a subsonic crossflow or co-flow of air, and an unsteady detonation wave burns the mixture. This detonation wave also interacts with the jet of fuel and air, contributing to their mixing, and sufficient mixing must occur before the next arrival of the detonation wave. In the present work, the flow field generated in an expansion tube resembles the situation immediately behind the RDE detonation wave, and high-repetition-rate (20 kHz) tracer-based PLIF enables visualization of the dynamics and time-history of the shock wave and free stream flow interacting with the jet.

Recently available high-repetition-rate light sources and UV-sensitive cameras have enabled the application of high-repetition-rate (i.e., > 1 kHz) tracer-based PLIF to the study of a variety of flow fields, such as biacetyl PLIF used to image mixture fraction in direct-injection engines at 12 kHz [8], acetone PLIF to image mixture fraction in a bench-top setting at 9.5 kHz [9], and toluene PLIF to image temperature stratification near walls (10 kHz [10]) and inside an internal combustion engine (6 kHz [11]). Toluene PLIF has also been used for single-shot imaging of supersonic flows generated in an impulse facility [12], and applied specifically to study the mixing of a jet in supersonic crossflow [13] in the context of scramjet propulsion. In this work, we use a high-repetition-rate light source to acquire image sequences in an impulse flow facility.

Impulse flow facilities generate short-duration flows (~1ms) and offer the capability to ground test the next-generation of aerospace propulsion systems. A variety of laser-based diagnostics have been used to study flows generated in these facilities, but many of the techniques have not been capable of kHz acquisition rates until recently, primarily due to a lack of sufficiently high-repetition-rate light sources; Jiang et al. [14] provides an excellent overview of diagnostic
techniques applied to flows generated in impulse facilities. Custom burst-mode lasers [15], [16] have been successfully designed and built for kHz rate PLIF imaging, and Jiang et al. [14] have used such a system for NO PLIF imaging of a jet in crossflow within the 48-inch CUBRC shock tunnel; this work is a complementary demonstration of high-repetition-rate PLIF in an impulse facility, but instead of using a custom-built burst mode laser, an optical parametric oscillator, and imaging of NO, this work uses toluene as a tracer molecule and an easy-to-use, off-the-shelf, continuously pulsed 266 nm light source.

High-repetition-rate PLIF imaging within confined environments, like the test section of a shock tunnel or expansion tube, presents other experimental challenges as well. The high average power of high-repetition-rate lasers can burn windows and present safety hazards, and so beam handling and blocking must be a priority for the experimentalist. Additionally, imaging tracer-laden flows, which produce large regions of high LIF signal within the field of view, can lead to significant background signals from the LIF signal reflecting off the internal walls and windows of the test section. Using the background correction method described in [2], these background signals can be quantified and removed in post-processing, and this process is detailed within this manuscript and in [2].

This manuscript also details the extension of practical high-repetition-rate tracer-based imaging to an impulse flow facility. This extension may not initially seem particularly novel because this technique has already been demonstrated in applied settings such as internal combustion engines, however, due to the demanding nature of larger scale flow facilities capable of generating high-speed or supersonic flows and the additional personnel and resources required to manage and operate these facilities, the turn-key nature of the laser and imaging systems used in this work create new opportunities to use high-repetition-rate PLIF to study these practical flow configurations relevant to aerospace propulsion within impulse facilities.

2. Experimental Set up
A schematic of the experimental setup is provided in Figure 1. An expansion tube serves as the impulse flow facility used to generate the flow field in this work. Expansion tubes [17] can generate a wide range of conditions by utilizing an unsteady expansion to process shock-treated gas to a final, test-gas condition. Typically, expansion tubes are used to generate short bursts (< 1 ms) of high-enthalpy gas with accurate free stream chemistry (i.e., low dissociation), but by changing gases and fill pressures, relatively long duration (= 1 – 2 ms), cold flows (= 500K) can also be produced [12]. An expansion tube can also be operated as a shock tube by removing the secondary diaphragm to produce long duration (= 20ms) flows behind the incident shock wave, which is how the tube is operated in this work. We refer to this mode of operation as ‘shock-mode’.

In this shock-mode configuration, the incident shock wave propagates down the tube, heating, pressurizing, and accelerating the gas behind it, and this incident shock and the test gas flow terminate in a large-volume dump tank. The tube is outfitted with arrays of piezo-electric time-of-flight shock sensors (referred to as shock counters) that are used to measure the shock speeds and dictate the timing of data acquisition; the shock speeds are also used to infer the test gas conditions. For this work, the driver gas is argon (6.8 bar fill pressure), and the driven gas is a mixture of helium and toluene (= 5% toluene by volume mixed manometrically in a separate mixing tank, 130 mbar fill pressure), resulting in relatively weak shocks and low post-shock temperatures. The resulting post-shock free stream pressure, temperature, and Mach number are approximately 500 mbar, 480 K, and 0.9, respectively.

A flat plate (100 mm wide by 155 mm long) is mounted in the test section of the expansion tube; Figure 1 includes a schematic of the plate, which is positioned at the exit of the expansion tube. A 2 mm diameter contoured nozzle is machined into the plate 64 mm downstream from the leading edge. A regulated tank of hydrogen is connected to the plate via stainless plumbing, and a fast-acting solenoid valve (Valvetech model 15060-18) controls the flow of the jet fluid.
The imaging systems consists of a VisionResearch Phantom v710 CMOS camera and LaVision high-speed intensified relay optic (HS-IRO) with a Gen II photocathode, a ‘slow’ P46 phosphor, and a Sodern f/2.8 100mm UV lens. A Schott glass 2 mm-thick WG280 long-pass filter is placed in front of the camera to block the majority of scattered 266 nm light; the filter transmission is roughly 1% at 266 nm, 86% at 300 nm, and greater than 99% from 300 nm to 2 μm; toluene fluorescence peaks near 280 nm and extends out to about 340nm [18]. The phosphor in the intensifier has a relatively slow decay, and significant residual signal, roughly 6%, is observed in the first subsequent image at an acquisition rate of 20kHz. The residual signal of a single image is measured and corrected for using a walk-forward algorithm (see [1] for more details).

**Fig. 1** Schematics of the experimental facility and setup (not to scale). Figure from [1].

**Fig. 2** Schematic of timing of laser, camera, and expansion tube operation. Figure from [1].
The light source is an EdgeWave HD40II-E Nd:YAG laser delivering 6 ns pulses of 266 nm light. The laser outputs between 0.8 and 0.9 mJ per pulse, corresponding to an average power between 16 and 18 W. A beam splitter, photodiode, UG11 filter, and integrating sphere are used to monitor shot-to-shot variation in laser energy and timing of the laser and intensifier gate. Windows of pressure vessels or static cells can be irreparably damaged due to the adsorption and subsequent burning of tracer molecule if subject to high average power for long periods of time; for this work, due to the extremely high average power, windows burn in just a couple seconds if containing a mixture of test gas, so a mechanical shutter (Electro-Optical Products Corporation model SH-20) blocks the beam during the majority of the time to prevent damage to the test section windows, which are UV-grade fused silica.

For all images acquired in this work, gate times are 1000 ns, and the laser pulse is positioned (in time) 100 ns after the opening of the intensifier gate; fluorescence lifetimes of toluene are well under 100 ns [19]. The image size is 592 × 512 (W × H) pixels, resulting in a spatial resolution of 10.5 pixels per mm or 95 µm per pixel. A 400 mm planoconvex cylindrical lens focuses the beam into a sheet, which is approximately 700 µm thick at full-width half-max and 1.75 cm wide.

Two separate fields of view are imaged and then stitched together to form the full field of view visible in the presented images. The different fields of view are imaged during different expansion tube shots by moving the final reflecting and focusing optics downstream 1.25 cm between runs. 5mm of overlap is maintained between the two fields of view. Only the light sheet is moved to image the different fields of view, and so the camera stays in the same position resulting in simple image registration between upstream and downstream views. Roughly half of the laser energy per pulse is lost across the first optic due to the drop in reflectivity induced by the high temperatures created by the incident beam; mirrors downstream of the first optic perform near total reflecting and focusing optics downstream 1

Timing of the laser, camera, shutter, and expansion tube operation is summarized in Figure 2. Time zero (t₀) occurs when the shock wave passes over a shock sensor located near the primary diaphragm station. Before a run, the laser and camera systems are clocked by a SRS delay and pulse generator at 20 kHz. A run is initiated by venting a double-diaphragm section in the tube (see [21], [22] for details of the expansion tube facility and its operation), causing the primary diaphragm to burst and the shockwave to form. The mechanical shutter (the EOPC model SH-20 described above) opens concurrently with the vent; the shutter takes 40 ms to fully open. At this time, the laser pulses illuminate the field of view, but no images are acquired. Roughly 200 ms after the venting of the double-diaphragm, a mechanical relay switches the laser and camera clock to a BNC Model 555 delay and pulse generator, which waits to be triggered by the t₀ signal from the first shock counter; at this time, the laser is not being triggered so no light is emitted from the laser. Once the shockwave arrives at the first shock counter, the BNC delay generator is triggered, clocking the laser and camera at 20 kHz until 360 images are acquired. At this same time (t₀), the solenoid valve in the flat plate is also opened, allowing jet fluid to flow through the plate and out into the test section. The test gas arrives in the test section at around t = 6 ms, and images are acquired until 18 ms.

2.1 Image Corrections and Background Signal Removal

 Corrections are made to all images in the following process: first, all images are dark noise subtracted (50-image averages), and then signals from slow phosphor decay are removed (see details in [1]). Then, background signals resulting from reflections in the confined environment (i.e., test section) are corrected for using the procedure outlined above and in [2].

PLIF imaging in confined environments can result in large background signals due to the reflection of fluorescence off of surfaces (e.g., the back wall), especially when the free stream is seeded with the tracer as it is in this work (opposed to, for example, OH imaging where signal is only visible in reaction zones). To convert the fluorescence signal to physical quantities, an accurate measure of the actual fluorescence signal must be acquired. Imaging systems have certain limitations and characteristics that must be considered and corrected for in order to accurately measure the fluorescence signal. For example, a CCD may have varying response (i.e., signal out versus photons in) as a function of the wavelength of the incident light; a measure of the relative
spectral response of an imaging system is used to correct for this effect when imaging fluorescence spectra. Clemens [23] summarizes image corrections for flowfield imaging; we can model the fluorescence signal acquired $S_{\text{meas}}$ at a location $(x, y)$ in the field of view by a camera with exposure time $t_i$ and camera readout time $t_{ro}$ to be

$$S_{\text{meas}} = w(x, y) [L(x, y) S_f (x, y) + S_{\text{back}}(x, y, t_i)] + S_{\text{dark}}(x, y, t_{ro})$$  \hspace{1cm} (1)$$

where $w(x, y)$ is the whitefield response of the camera, $L(x, y)$ is the spatial distribution of laser sheet intensity, $S_f(x, y)$ is the actual fluorescence signal per unit of incident laser energy, $S_{\text{back}}(x, y, t_i)$ is the background signal, and $S_{\text{dark}}(x, y, t_{ro})$ is the signal resulting from dark current. Given a measure of $S_{\text{meas}}$, $S_f$ is found in Eq. 1 after correcting for the other terms: $S_{\text{dark}}$ is measured by capping the camera and acquiring the image; laser sheet intensity $L(x, y)$ can be assumed constant with the use of beam shaping optics, or an in situ measure of intensity can be made using a cuvette; and whitefield response of the imaging system $w(x, y)$ can be measured by imaging a uniformly illuminated plane. For non-luminous flows, background signals $S_{\text{back}}$ are often estimated by acquiring an image with the laser on but in the absence of tracer, which makes it possible to correct for aberrations such as reflections of incident laser light; however, this background correction technique does not correct for non-negligible background signals due to reflections of fluorescence off surfaces. Measures can be taken to minimize reflections of fluorescence, such as imaging in free space and painting or dying surfaces black, but certain studies require that imaging be done on flowfields inside chambers or cells with walls (e.g., a wind tunnel or an internal combustion engine), where fluorescence can reflect off these walls. Fluorescence is emitted isotropically through $4\pi$ steradians; some of that light is collected by the imaging system, and some of that light inevitably impinges on surfaces. If the wall behind the fluorescence image is reflective, diffusively or specularly, fluorescence reflections off the back wall can contaminate the measurement of actual fluorescence.

Two techniques that have been developed to determine $S_{\text{back}}$ (or $S_f$, which is usually the actual quantity of interest) are structured light illumination for planar imaging (SLIPI) or acquiring-image deconvolution with a background kernel (correction with a background kernel). Structured light illumination [24], [25] utilizes modulated and spatially shifted excitation light to determine the location and amount of additional scattered or reflected signal. This structured light technique is particularly useful when imaging sprays or droplets using LIF, or when the source of scattering changes in time (e.g., droplets within a spray).

The background kernel technique [2] deconvolves the acquired image with a background kernel that is computed using the geometry of the test section and imaging system. Essentially, this background kernel describes the signal contribution of neighboring pixels to the measured signal of a given pixel, and the acquired image is the sum of the real fluorescence and the convolution of the real fluorescence signal with the background kernel (after accounting for dark noise $S_{\text{dark}}$ and whitefield response $w$ in Eq. 1)

$$S_{\text{meas}} = S_f + S_f * \psi$$ \hspace{1cm} (2)$$

where $\psi$ is the background kernel. The real fluorescence signal can be found by taking the inverse Fourier transform of the ratio of $S_{\text{meas}}$ with $1 + \psi$

$$S_f = \mathcal{F}^{-1} \left( \frac{S_{\text{meas}}}{1 + \psi} \right)$$ \hspace{1cm} (3)$$

Additional details and description of the background kernel correction can be found in [2].

In this work, as is also presented in [2], a background kernel is determined by imaging a uniform tracer field while blocking the incident laser beam (similar to structured light illumination), and the kernel is first estimated given the geometry of the experimental configuration, and then iterated on to find one that best corrects the uniform tracer field such that LIF signal is zero in regions where the beam is blocked and signals in the unblocked regions match for different amounts of beam blockage. The final background kernel in this work has a radius of 150 pixels and a maximum value in the center of $7.5 \times 10^{-6}$. Figure 3 shows a representative uniform tracer field with a portion of the blocked beam, the uncorrected signal profiles (for
additional cases with different amounts of beam blockage), and the corrected traces using the optimal kernel. We can see that in the uncorrected traces, there are background signals up to almost 20% of the peak LIF signal, and significant disagreement in the wings. With the correction, signals are zero in the blocked region, and agreement between signal profiles improves significantly in the wings.

![Uncorrected and Corrected Signal Profiles](image)

**Fig. 3** Uniform tracer field with beam blocked, uncorrected, and corrected signal profiles from dotted line in uniform tracer field image. Image on left corresponds to dotted green lines in middle and right plots.

This kernel-based correction technique is useful for high-repetition-rate imaging of dynamic flow fields with static background (e.g., no particles or droplets) because it can be applied entirely during post-processing without the need of additional hardware or simultaneous acquisition of structured light images. As we see in Figure 3, background signals of nearly 20% of the maximum signal in the image are observed and successfully removed via the kernel-based correction. Figure 4 displays the acquired image ($S_{\text{meas}}$, left), the background signal ($S_{\text{bgnd}}$, middle), and background-kernel-corrected image ($S_f$, right), all for the upstream field of view. We can see that the background signal contributes nearly uniformly over the dark, non-fluorescing, underexpanded bulk of the jet near the plate. For qualitative imaging like that presented here, this correction is perhaps less important than in a quantitative imaging application, however, this correction should still be performed in order to obtain more accurate zero-signal levels for the construction of isosurfaces or contours of signal.

![Uncorrected, Background, and Corrected Images](image)

**Fig. 4** Uncorrected image, background signal, and corrected image. Differences are subtle between acquired and corrected images, but can play a significant when constructing when constructing isosurfaces in qualitative imaging or for quantitative LIF imaging.

After correcting for phosphor decay and background signals, images are corrected for laser-sheet spatial non-uniformity by normalizing each image by an average of the top 10 rows of the first 5 images, using images for which no flow can be observed. Lastly, for images presented as stills and in the movie, shot-to-shot variations in laser energy and tracer number density are
performed by normalizing each image by a measure of average LIF signal from a 10 × 10 pixel region near the top of each image (marked in Figure 3a). By correcting for shot-to-shot variation in laser energy via a measure of energy from the image itself, variations in signal due to non-uniformities within the 10 × 10 pixel window will affect the normalization of each image and may result in small differences in the relative signal between images within a sequence of images; even so, the scheme adopted in this work is convenient and enables an entire sequence of images to be visualized on the same relative color scale.

3 Imaging Results

In this section, we present a series of images and corresponding pressure and signal-to-noise ratio (SNR) time-histories. A movie displayed at 10 frames per second containing all acquired images can be found in supplementary materials of [1].

As mentioned, image acquisition and the flow of jet fluid begins well before the arrival of the shockwave and crossflow (Figure 2). A sequence of images of the jet start-up process and undisturbed jet are presented in Figure 5a (and the supplementary movie in [1]). The two fields of view are highlighted in the figure by the blue dotted box (upstream) and purple dotted-dashed box. These two fields of view are acquired during subsequent shots in the expansion tube and stitched together in post-processing. The average of all images from \( t = 1.5 \) to 5.0 ms (75 images) of the undisturbed jet is shown on the far right of Figure 5a. We observe the starting transient of the jet, the rough location of the barrel shock and Mach disk can be inferred, and downstream unsteady dynamics and instabilities are visualized (e.g., \( t = 0.80 \) ms in Figure 5a).

At time \( t = 5.9 \) ms, the shock and subsequent crossflow arrive, as shown in Figure 5b (and the supplementary movie [1]). Smith and Mungal [5] provide a thorough investigation and description of the behavior of jets in crossflow; for this configuration, the jet-to-free stream momentum flux \( J \), velocity \( r \), and density \( s \) ratios are 5.5, 1.5, and 2.5, respectively, at \( t = 6 \) ms. The Reynolds number \( Re_D \), using the diameter of the jet (2 mm) and the properties of hydrogen at the throat of the jet is about 800,000.

The upstream half of the first image in Figure 5b shows the jet immediately after the shock has passed through the field of view, and around \( x/D = 10 \), the shock can be seen in the downstream field of view. To reiterate, the sequence of images in the upstream and downstream fields of view are acquired during different expansion tube shots, and in both shots, the shock was in roughly the same position. The underexpanded jet fluid far from the plate (i.e. near \( y/D > 10 \)) appears to be translated by the drift velocity of the passing shock, whereas closer to the issuing orifice, the jet has not yet changed trajectory. We also observe the shock is no longer perpendicular to the plate, having been affected by underexpanded jet structure near the plate.

For the rest of the test time, some unsteadiness in the free stream and overall jet trajectory are observed, and typical features of a jet in crossflow are visualized, specifically jet shear-layer vortices on the windward side of the jet and some tornado-like wake vortices in the far field (visible in the supplemental video of [1]). The high acquisition-rate provides a smooth time-average of the jet (far right of Figure 5b). A significant difference in the near- and far-field signal intensities are observed, corresponding to the barrel shock and Mach disk (near field) and the mixing of the crossflow with the injectant (far field).

Time-histories of pressure (measured at the location of the last shock counter in Figure 1), temperature inferred from pressure (i.e., isentropic expansion after the passing of the shock wave), relative fluorescence signal \( S_f \) and spatial SNR are provided in Figure 6. Pressure and temperature time-histories are displaced in time to align with the arrival of the shock in the images. Signal is measured in a 10 × 10 pixel region in the image before correction for number density and laser energy are made (the red box in Figure 5a); the spatial SNR is computed as the average signal in the same 10 × 10 pixel region divided by the standard deviation of the signal. Signal \( S_f/S_{\infty} \) is normalized by the measured signal at \( t = 0 \).

The LIF signal of toluene is dependent on both temperature \( T \) and toluene number density \( n_{\text{toluene}} \) and in the weak excitation limit is described by

\[
S_f \propto n_{\text{toluene}} \sigma(T) \phi(T) \frac{E}{h^2 \pi \eta}
\]

where \( \sigma \) and \( \phi \) are the absorption cross-section and fluorescence quantum yield of toluene, \( E \) is the
laser fluence, $h$ is Planck’s constant, $c$ is the speed of light, $\lambda$ is the wavelength of excitation light (266 nm), and $\eta$ is the collection efficiency of the imaging system. For toluene, $\sigma$ is weakly dependent on temperature whereas $\phi$ is an exponential function of temperature, dropping two orders of magnitude from 300 to 900 K [18]. The number density of toluene depends on both pressure and temperature ($n = \rho/RT$). Therefore, the gas dynamic processes that occur in the expansion tube during the course of a run change both the temperature and pressure, which have opposite effect on LIF signal; a reduction in pressure will decrease signal due to decreased number density of toluene, but a reduction in temperature will increase LIF signal (at constant tracer number density) due to an increase in quantum yield. This effect is directly observed in the first image in Figure 5b, as the temperature increase across the shock has a larger detrimental effect on the LIF signal compared to the increase in number density across the shock. The region behind the shock appears darker relative to the upstream half of the field of view due to the method chosen to correct for variations in laser energy and LIF signal due to changes in tracer number density and temperature.

![Image](image_url)

**a)** Instantaneous and time-average (far right) images of starting jet. Red square indicates 10 by 10 pixel region in which average signal level and SNR are calculated.

![Image](image_url)

**b)** Instantaneous and time-average (far right) images of jet in crossflow. At $t = 5.9$ms, the shock wave can be seen around $x/D = 10$.

**Fig. 5** Image sequences of jet start up and and jet in crossflow. Images are not spaced evenly in time. All presented images are composite of upstream (blue dashed box) and downstream (purple dashed-dotted box) fields of view described in Section 2 and Figure 1. Far right image in both sequences are averages over the indicated time. SNR and average signal values are taken from the 10 by 10 pixel region marked in the left-most image of Figure 3a. Both **a** and **b** are from [1].
These changing free stream conditions (i.e., pressure and temperature) enable us to observe changes in the relative LIF signal level and corresponding changes in spatial SNR. Upon arrival of the shock, signal and SNR decrease, largely due to an increase in temperature and the high sensitivity of toluene quantum yield to temperature; the decrease in SNR is evident to the eye in Figure 5b for \( t = 8.4 \) ms, as this image is notably more grainy than images acquired at other times. Fluorescence lifetimes are short (< 100 ns) for toluene and the excitation laser pulse width is 6 ns, and so degradation in image quality is a result of decreased SNR and not motion blur. Around 8.5 ms, an expansion fan arrives (having reflected off the end wall of the driver section of the expansion tube), dropping both the temperature and pressure, while LIF signal and SNR simultaneously increase until all the toluene-seeded test gas has passed through the test section (\( t = 18 \) ms). SNR up to 30 is observed, and SNR does scale roughly nearly with \( \sqrt{SNR} \), suggesting the system is approaching the shot-noise-limit, in terms of its spatial noise characteristics.

Jet trajectories in previous works have typically been quantified using measures of jet fluid concentration or velocity within the plume of the jet [5]. This work qualitatively marks the jet trajectory using a contour of signal, which may be decreased due to a decrease in temperature or tracer number density, which we cannot distinguish with uncalibrated, single-camera tracer-based PLIF. Therefore, the scientific impact on the fluid mechanics of the jet in crossflow is limited in this particular demonstration. By utilizing a dual-band or multi-camera high-repetition-rate tracer-based PLIF imaging strategy ([10], [12], [18]), quantitative images of temperature can be acquired, and the ease of use of high-repetition-rate tracer-based PLIF imaging enables these techniques to be used to study flows generated in impulse facilities. The operation of expansion tube facilities at low-enthalpy conditions in standard operating mode or ‘shock-mode’ produces long-duration compressible flow fields, and these relatively long duration flows provide ample time to establish steady-state conditions for many flows, and high-repetition-rate systems allow meaningful statistics to be collected. Because these facilities allow for custom mixtures of test gases, tracer-based PLIF is a useful technique to study these flows. The combination of high-repetition rate, quantitative tracer-based imaging techniques with impulse facilities yields opportunities to further study canonical fluid mechanics topics (e.g., jets in supersonic crossflow) or applied configurations (e.g., the geometry of a pylon injector in a scramjet).

4 Conclusions and Implications
This work demonstrates the use of turn-key laser and imaging systems to continuously image and visualize an underexpanded jet in crossflow generated in an impulse facility using tracer-based PLIF. A jet of fuel injected into nearly sonic crossflow behind an incident shock-wave was imaged using a turn-key 20 kHz, pulsed, 266 nm light source and an off-the-shelf high-speed, CMOS camera coupled to an intensified relay optic. Background signals due to the fluorescence are
removed using the background-kernel method. Lastly, signal-to-noise ratios between 10 and 30 are observed. The methodology demonstrated within can be extended to quantitative imaging (e.g., thermometry) through the use of dual-camera techniques ([10], [12], [18]). High-repetition-rate PLIF imaging enables the study and characterization of a variety of practical flows, including high-speed or supersonic flows. Lastly, the ease-of-use of the equipment used in this work will enable the study of more complex flow fields due to the decreased demand on the experimentalist to manage both the diagnostics and the experimental facilities.

4 Acknowledgements
This work was supported by the U.S. Department of Energy sponsored Predictive Science Academic Alliance Program (PSAAP) at Stanford University as well as the Air Force Office of Scientific Research (AFOSR) with Dr. Chiping Li as technical monitor. V. A. Miller is supported by the Claudia and William Coleman Stanford Graduate Fellowship, and V. A. Troutman is supported by the Gabilan Stanford Graduate Fellowship.


