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Dotted-Line FLEET for Two-Component Velocimetry

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Femtosecond Laser Electronic Excitation Tagging (FLEET) is a powerful unseeded velocimetry technique typically used to measure one component of velocity along a line, or two or three components from a dot. In this letter we demonstrate a dotted-line FLEET technique which combines the dense profile capability of a line with the ability to perform two-component velocimetry with a single camera on a dot. Our setup uses a single beam path to create multiple simultaneous spots, more than previously achieved in other FLEET spot configurations. We perform dotted-line FLEET measurements downstream of a highly turbulent, supersonic nitrogen free jet. Dotted-line FLEET is created by focusing light transmitted by a periodic mask with 1.6 × 40 mm^2 rectangular slits and 0.5 mm edge-to-edge spacing, then focusing the imaged light at the measurement region. Up to seven symmetric dots spaced approximately 0.9 mm apart, with mean full-width at half maximum diameters between 150 μm and 350 μm, are simultaneously imaged. Both streamwise and radial velocities are computed and presented in this letter.

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Femtosecond Laser Electronic Excitation Tagging (FLEET)[1] is a propitious addition to the molecular tagging velocimetry (MTV) diagnostic suite due to its simplicity and the ubiquity of nitrogen. The broadband FLEET emission is produced as a result of the ionization, dissociation and recombination processes following femtosecond laser excitation of nitrogen-containing gases. The emission, typically taking the form of a line or spot, is swept with the flow and can be tracked with a gated camera to give velocity.

Many recent efforts with MTV methods have focused on extending the measurement region from a single 1D line. Experimentalists demonstrated mounting optics onto motorized translation stages [2, 3] and using beamsplitters to write multiple lines [4] to map out larger flowfields. While some MTV setups have directed a beam through the measurement region several times to produce larger measurement areas [5], FLEET is subject to numerous nonlinear effects including supercontinuum generation and self-focusing that preclude the focused beam from being redirected multiple times through a measurement region.

Splitting or multi-passing beams can incur challenges from power reduction and space constraints imposed by the presence of multiple focusing optics. Other methods of increasing the coverage include imaging a single line multiple times onto a frame at different delays as it convects with the flow, often referred to as "burst mode" imaging [6]. This type of imaging suffers from signal decay with time, and distortion by molecular diffusion and turbulent mixing. It also cannot be used for spatial correlations in the primary flow direction. A simpler method for multi-line formation utilizes beam blocks with periodic slits and was demonstrated to write fluorescing grids using seeded biacetyl [7]. Multi-line FLEET using a periodic mask was demonstrated recently in a supersonic jet flow [8, 9]. This method retains FLEET's simplicity as an unseeded, one-laser, one-detector system with a single beam path.

However multi-line FLEET suffers from the same drawbacks as traditional line FLEET—it cannot be used to capture multiple dimensions of velocity. A homogeneous tagged line is not only unable to resolve velocity components parallel to the laser propagation, but also suffers from projection ambiguity in the streamwise direction. Highly multi-dimensional turbulent flows can produce significant errors in the measurement if streamwise velocity is the sole component resolved, since contamination from other velocity components will be present. This contamination is derived from the assumption that convection follows a known bulk flow direction, typically the streamwise trajectory. Several authors have attempted corrections using an iterative approach [10, 11] but the universality of such corrections is unknown. Previous demonstrations of FLEET spots for two- or three-component velocity measurements have been limited to tracking a single spot [12], or one to three spots written with separate beam paths, which increases the optical complexity and risks beam degradation [4, 11, 13, 14]. Moreover, the spacing of these spots is limited by the optical arrangement.

In the present work, periodic masks are used to create a line of FLEET spots with even spacing using a single beam path, in contrast to previous multi-beam implementations. One-dimensional, two-component velocimetry measurements are made downstream of the same over-expanded supersonic jet as in Ref [8]. Up to seven dots are simultaneously produced from a single beam to demonstrate the capability of dotted-line

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FLEET. The advantages of dotted-line FLEET are highlighted by combining the additional radial velocity component found from FLEET dots with the profile capability of a FLEET line.

To capture the mechanisms responsible for dotted-line formation, dotted-line and multi-line FLEET are modeled using LightPipes [15], a beam modeling tool for coherent light with diffraction and phase tracking. The beam is modeled as a monochromatic 800 nm Gaussian intensity distribution that is propagated through space using the Fresnel near-field approximation. To assess the accuracy of this simplified model, a comparison is made to the intensity distribution measured in a nonlinear Young's double slit experiment using 120 fs pulses centered at 790 nm [16]. Good qualitative agreement between Figure 4 of Ref [16] and this current model's intensity distribution is found, although the closest matching intensity distribution occurred at a different position downstream. We attribute this discrepancy to the lack of nonlinear phenomena, such as self-focusing, and the monochromatic nature of the current model. To model the current experiment, the monochromatic beam is passed through a mask (Figure 1) and the respective focusing optics, modeled as perfect lenses, for the two FLEET permutations.

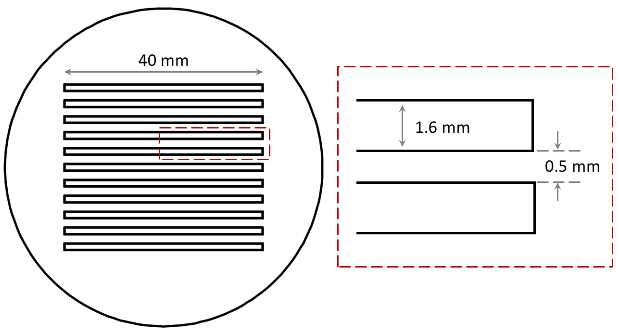


Fig. 1. Mask dimensions.

To determine line spacing from the model, the intensity at the image plane is fitted with Gaussian distributions to find the line peaks, and the difference between those centers is used to determine spacing. For brevity, the ray-tracing figures may be found in supplemental material with their implications discussed here. The model under-predicts multi-line FLEET spacing by up to 5%. Since this difference is small, the model adequately describes the mechanism for multi-line FLEET formation. However for dotted-line FLEET, the experimental mean spacing between adjacent dots is 0.90-0.95 mm, and the standard deviation is 0.03-0.13 mm, while the model results in a value between 0.7 and 0.8 mm, under-predicting by about 20%. The higher contribution of nonlinear effects in dotted-line FLEET due to stronger beam focusing are likely to cause this discrepancy. While nonlinear and chromatic effects are not represented in this simplified diffraction model, the model accurately predicts the formation of high-intensity regions at the imaging plane that correspond to multi-line FLEET signals. The formation of FLEET spots was modeled to identify the key parameters in the optical setup and choice of mask dimensions. Further experimental optimization of these parameters can be found in Ref [9] and presently the optimal values are used. The different optical configurations of Ref [9] also may be used to design dotted-line FLEET implementations for enclosed experimental facilities in which longer focal lengths are necessary.

Figure 2 shows the experimental schematic used to demonstrate dotted-line FLEET. Femtosecond pulses are generated by a Ti:sapphire regenerative amplifier seeded with 30-nm of bandwidth centered at 800 nm, and pumped at a 1 kHz repetition rate by a Q-switched Nd:YLF laser. A single-pass Nd:YLF-pumped Ti:sapphire amplifier provides additional gain to produce energies up to 10 mJ in the compressed 50-fs pulses at the laser exit. The $1/e^2$ diameter is measured to be 12.5 mm. The beam is first expanded using two spherical lenses with $f = -150$ mm and $f = +200$ mm, passed through a thin periodic mask with 1.6×40 mm^2 rectangular slits and 0.5 mm edge-to-edge spacing (as shown in Figure 1), and focused using spherical plano-convex (PLCX) $f = +125$ mm and cylindrical plano-convex (CYL) $f = +200$ mm lenses. The cylindrical lens's power axis is parallel to the mask slots. The cylindrical lens focuses the beam into a thin "dashed" sheet in the image plane and the spherical lens further compresses the "dashes" into dots. This optical arrangement differs from [8] such that it focuses the post-mask beam image tightly to generate dots rather than lines. The evolution of the beam profile through the lens configuration is given as supplemental material, determined using the ray tracing model.

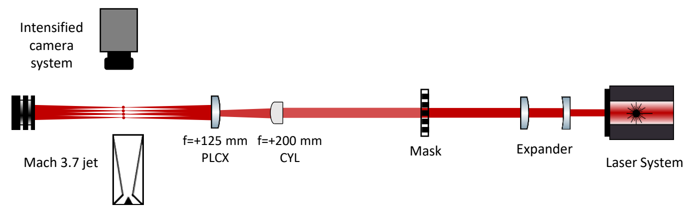


Fig. 2. Experimental diagram for dotted-line FLEET measurements. PLCX = spherical plano-convex lens, CYL = cylindrical plano-convex lens.

All the data are taken downstream of a free jet with a design Mach number of 3.7 and a 6.35 mm exit diameter (D), positioned where quenching is low before the jet flow mixes strongly with atmospheric air. The jet is operated in an overexpanded configuration with a 1034± 3 kPa plenum pressure. An intensified high-speed CMOS camera system coupled with a 105 mm, 1.8/f focal length lens is used to image the FLEET signal perpendicular to the direction of laser propagation.

Without the use of the beam expander, only five dots at the ambient condition, rather than seven, could be observed. The critical element to dot formation rather than lines [8] was the use of faster focusing downstream of the mask. 9.8 mJ of energy is incident to the beam expander and 5.9 mJ is measured downstream of the focusing optics. The mask is responsible for approximately 25% of the energy attenuation. Two to three dots at ambient conditions could still be seen using only 6 mJ incident to the optical setup but the full 9.8 mJ beam is used to maximize signal in the experiment. The potential ramifications of energy deposition are explored in Ref [17].

There are several notable length scales in this setup. The distance between the mask and the cylindrical lens is approximately 66 cm, and the separation between the $f = +200$ mm CYL and $f = +125$ mm PLCX lenses is 4.5 cm. The standoff distance between the last focusing optic, the $f = +125$ mm PLCX lens, and the formation of the FLEET signal is approximately 20 cm, altered from the collimated case by the presence of the mask. As with multi-line FLEET formation [9], some variability in the optics spacing is permitted.

Figure 3 shows mean FLEET images approximately $3D/2$ downstream of the jet exit, between $-r/2$ and $r/2$ where $r =$

$D/2$, at different delays. Each panel shows the average of 300 single-shot images plotted using false color to visualize both the bright dots near the center and the weaker dots at the periphery. The spots in the $d = 1 - 4$ μs panels appear larger than that in the leftmost panel because they are taken in nitrogen flow rather than air where quenching is reduced, expanding the perimeter over which detectable signal may be found.

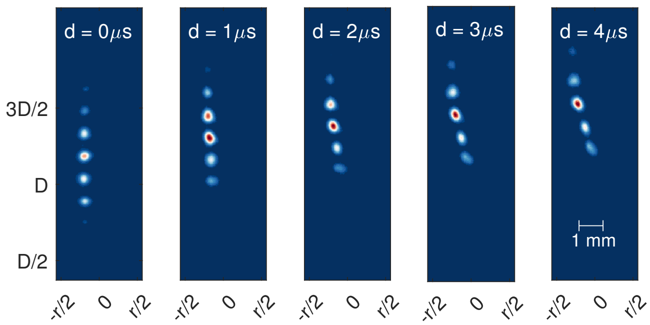
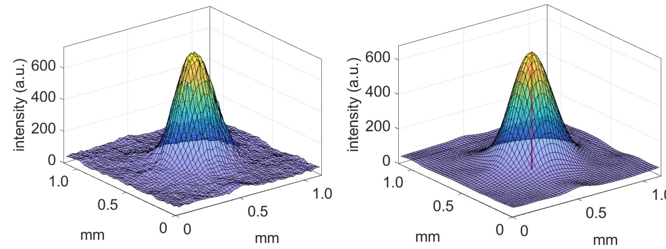


Fig. 3. Mean images at different delays. The gate is 10μs for the first panel (in static air) and 0.5μs for the four delayed panels (with nitrogen flow on).

Dotted-line FLEET presents several challenges to data processing, as the spot shapes and intensities are sensitive to the local flow conditions. Spots can become distorted in regions of high velocity gradients, and disappear entirely where the fluid density is low. The spots are also extremely bright in their centroid, with higher signal levels than traditional line FLEET. In this experiment, five dots with mean single-shot signal-to-noise (SNR) levels from 4 to 13 can be tracked for up to 5μs using gates of 0.5μs and 1μs. SNR is computed as the ratio of the average signal over a 6 x 6 pixel^2 region centered at each dot to the standard deviation of the signal. Figures 4a and 5a show the raw intensity distributions of a single-exposure FLEET dot in static air and 2 diameters downstream of the jet with flow on, respectively. The background noise level in Figure 4a is non-zero because of ambient lighting used to illuminate the jet nozzle exit, while it is zero in all the cases with the flow on.

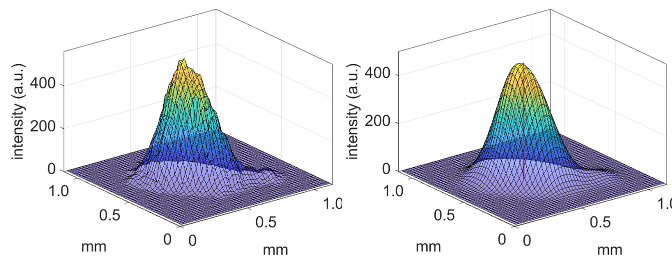
The signal is first smoothed via convolution with a Gaussian kernel size equal to the average spot FWHM in the r-direction, as shown in Figures 4b and 5b and the resulting images are fitted with two-dimensional Gaussian surfaces (as used in Ref [14, 18]) to find their spot centers typically within 2 μm. This filter reduces the effects of spurious intensifier noise, which can be observed at background conditions while the laser is off, and is selected because the initial (unsaturated) intensity distribution resembles a Gaussian. Similar FLEET post-processing techniques have been employed by others to remove artifacts caused by intensifier noise and the sensor's electronic readout [4, 18]. As a quality control, signals and fitted centers are spot-checked by comparing the filtered image to the raw image, as in Figure 5, and the two-component velocities computed using the smoothed and raw datasets are compared. The resultant single-shot streamwise velocities differ by 0.5% and radial velocities, by 2% on average. Because the smoothing process helps to remove camera artifacts without introducing detectable bias into the measurement, it is used in the subsequent data presentation.

In addition to the high signal levels offered by dotted-line FLEET, the spots are nearly axisymmetric, aiding the accuracy of the surface fit. Figure 6 depicts the streamwise and radial



(a) raw **(b)** smoothed

Fig. 4. Intensity distribution of a single dot at $d = 0\mu s$, $g = 10\mu s$ in static air; red line marks the fitted center.



(a) raw **(b)** smoothed

Fig. 5. Intensity distribution of a single dot at $d = 3\mu s$, $g = 0.5\mu s$ with nitrogen jet on; red line marks the fitted center.

full-width at half maximum (FWHM) dimensions, and their corresponding aspect ratios, for each of the seven dots at a zero delay where dot 1 is located at the most upstream location. Due to the vertical alignment of the beam profile with the periodic mask, dots 1 and 7 are located most peripherally and are consequently the smallest and lowest signal spots. The worst aspect ratio of seven spots is 0.75 and their mean ratio is 0.92. Previous FLEET spot experiments have only achieved comparable aspect ratios by imaging in the direction of beam propagation in a quasi-boresight configuration [11]. The spot size, number and axisymmetry of intensity distribution offer a distinct advantage over other multiple-spot FLEET configurations attempted previously.

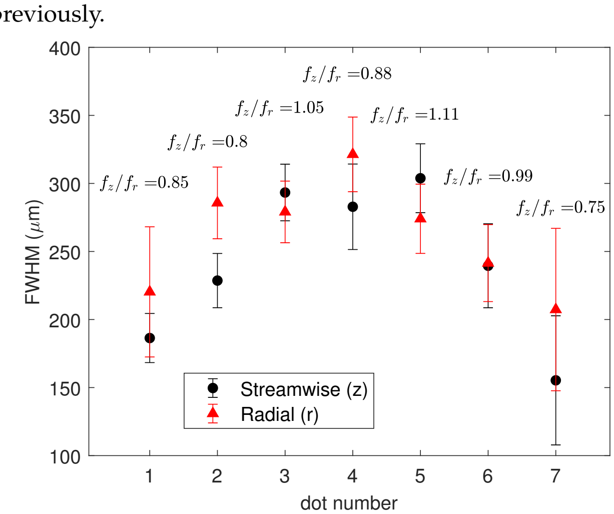


Fig. 6. Dot aspect ratio at a zero delay.

Mean velocity is computed from dotted-line FLEET using de-

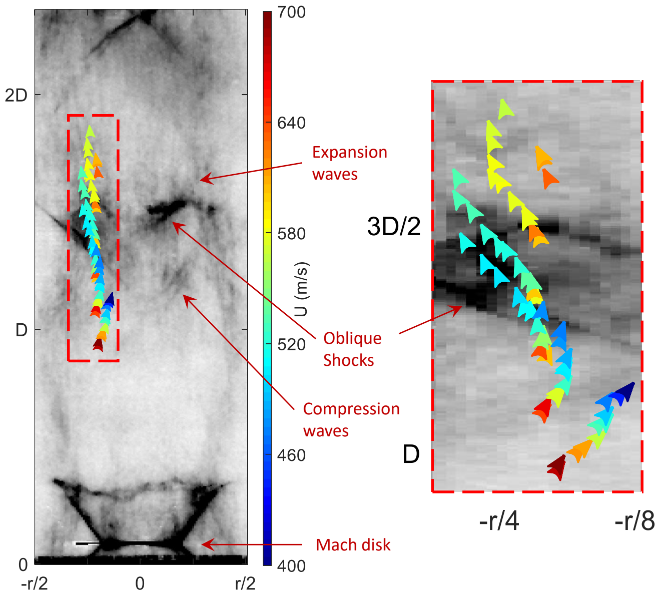


Fig. 7. Mean velocity overlaid on Schlieren (5 μs exposure)

lays of $1 - 8\mu s$ and gates of 0.5 and $1.0\mu s$ to form the composite map in Figure 7. Velocity vectors are superposed on schlieren images with the jet flow features annotated; a larger, more detailed schlieren view is found in supplemental materials. The color and angle of the arrows correspond to velocity magnitude and direction, respectively, and capture lateral movement that is not observable with line FLEET. In all cases, velocities (from 300 shots at each delay) are plotted at the mean position between the initial and displaced spots [19]. The velocity profile shows some of the expected features in an over-expanded free jet, including the flow turning with the compression and expansion fans. Faster flow is observed upstream in the first shock cell, slowing through the shock structures and accelerating again through the expansions as it approaches the second cell structure.

In summary, dotted-line FLEET with up to seven symmetric dots spaced 0.9 mm apart are formed by focusing light transmitted by a simple periodic mask placed into a single beam. The simplicity of the arrangement and quantity of dots is more attractive than previous generation of multi-point FLEET. The FLEET dots are small, with mean streamwise and radial FWHM values less than 350 μm, and exhibit a relatively high mean single-shot SNR between 4 to 13. The measurement is limited by a balance between the number of spots that can be imaged and signal saturation where beam intensity is concentrated. Dotted-line FLEET relies on a single laser path to make simultaneous two-dimensional measurements at multiple points, a feat unattainable by line FLEET, and may be extended to three-component measurements if an additional camera were used.

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DISCLOSURES

The authors declare no conflicts of interest. See Supplement 1 for supporting content.

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