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Abstract

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Keywords

laser induced fluorescence, telescopes, plasmas, lenses, geometrical optics

Disciplines

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Confocal laser induced fluorescence with comparable spatial localization to the conventional method

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We present measurements of ion velocity distributions obtained by laser induced fluorescence (LIF) using a single viewport in an argon plasma. A patent pending design, which we refer to as the confocal fluorescence telescope, combines large objective lenses with a large central obscuration and a spatial filter to achieve high spatial localization along the laser injection direction. Models of the injection and collection optics of the two assemblies are used to provide a theoretical estimate of the spatial localization of the confocal arrangement, which is taken to be the full width at half maximum of the spatial optical response. The new design achieves approximately 1.4 mm localization at a focal length of 148.7 mm, improving on previously published designs by an order of magnitude and approaching the localization achieved by the conventional method. The confocal method, however, does so without requiring a pair of separated, perpendicular optical paths. The confocal technique therefore eases the two window access requirement of the conventional method, extending the application of LIF to experiments where conventional LIF measurements have been impossible or difficult, or where multiple viewports are scarce. *Published by AIP Publishing.* <https://doi.org/10.1063/1.4991637>

I. INTRODUCTION

Laser induced fluorescence (LIF) is an established active spectroscopy technique for acquiring non-perturbative measurements of neutral particle or ion velocity distribution functions (N/IVDFs) in plasmas. Velocity moments of these distributions provide the relative density, temperature, and average flow speed of the probed species. Since Stern and Johnson introduced LIF in 1975,¹ it has become a workhorse diagnostic for both low and high temperature plasmas. The implementation of LIF has expanded from simple single crossed injection and collection optical paths to include planar LIF,^{2,3} multiplexed LIF,⁴ tomographic LIF,⁵ and two-photon LIF.⁶ While these implementation methods have provided LIF measurements of numerous atomic and ionic species in a wide range of plasma discharges, some plasma configurations have not been diagnosable by LIF because of limited optical access. In some cases, fiber coupled insertable probes have provided such access,⁷ but for high-density, high-power, plasma sources such as coaxial Hall thrusters, access through probes is infeasible. A confocal optical configuration which employs a single optical path provides a new means of performing LIF measurements of such systems.

The confocal optical arrangement emerged around 1940 when it was developed for use in ophthalmology.⁸ Confocal microscopy was subsequently introduced to the biomedical sciences in 1957.^{9,10} Confocal microscopy improves contrast and reduces scattered light compared to conventional microscopy,¹¹ allowing thin slices of biological tissue to be imaged. These images are then be combined to construct 3D images of the sample.¹² Similar methods are used in

semiconductor production¹³ and material science.¹⁴ The first prototype of a confocal microscope incorporating laser illumination is attributed to Davidovits and Egger in 1969.^{15,16} Detailed accounts of the history and evolution of confocal microscopy have been published by, among others, Pawley *et al.*¹⁷

The first published application of confocal optics for plasma laser spectroscopy sought to measure hydrogen neutral densities in the edges of high temperature plasma devices using two-photon absorption laser induced fluorescence (TALIF).¹⁸ The technique is still used to measure neutral densities in magnetically confined plasmas.¹⁹ In TALIF, the signal scales with the square of the laser intensity, causing the sampled region to be highly localized to the focal point. Obtaining high spatial localization with single-photon confocal LIF is difficult because the signal scales with laser intensity and sampling volume. As a result, the sampling volume must be constrained by the depth of field of the optics—a difficult task for distant sources. Previous attempts to measure ion velocity distributions with confocal single-photon LIF have been reported, with longitudinal spatial localization estimated to be approximately 3 cm using an objective focal length of 20 cm.²⁰

The purpose of this work is to report for the first time, confocal, single-photon LIF measurements that achieve longitudinal spatial localization of the same order of magnitude as conventional LIF methods. The new technique overcomes two major limitations in previous designs: it removes the need for two, spatially separated sightlines required by conventional LIF schemes and extends the short, millimeter-scale observing distance limitation of conventional confocal microscopy to hundreds of millimeters. The optical and experimental arrangements used in demonstrating confocal LIF are described in Sec. II. Section III introduces temperature and

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flow profile measurements obtained by the two optical systems. Final results and a summary are presented in Sec. IV. A model used to estimate the localization of the measurements from a comparison of the two integrated spectrum profiles is described in the Appendix.

II. EXPERIMENTAL ARRANGEMENT

A. The HELIX facility

Operation of the confocal telescope was demonstrated on the HELIX plasma source, which was described in detail in a recent review.²¹ A diagram of the HELIX source is shown in Fig. 1. The facility is capable of producing $n \approx 10^{16} - 10^{19} \text{ m}^{-3}$ plasma, with $T_e = 3\text{--}5 \text{ eV}$ and $T_i = 0.2\text{--}0.5 \text{ eV}$. Plasma is generated using up to 1 kW of RF power in fill pressures of 0.1–20 mTorr and magnetic fields up to 0.12 T. Optical access to the plasma is provided by a 4-way cross port 69 cm downstream of a copper strap half-turn $m = +1$ helicon antenna. Optics for conventional LIF are aligned to the center of the cross port and have the ability to scan in all three directions.

B. Laser induced fluorescence

Detailed descriptions of the conventional 3-state single photon LIF method, in which collection and injection optical paths are perpendicular to each other, are available in the literature.^{22,23} In LIF, the frequency of a narrow-bandwidth laser sweeps through an absorption resonance of a known transition of the target species (ideally beginning with a metastable state), exciting the absorber to a second, higher energy state. This excited state subsequently relaxes to a third state, emitting a photon of known frequency in the process. Measuring the fluorescent emission produces a Doppler-broadened absorption spectrum around the resonance. Analysis of the spectrum provides the temperature, mean velocity, and relative absorbing state density. Components of the spectrum far from resonance are used for background subtraction.

For probing singly ionized argon, the $3d^2G_{9/2}$ Ar-II metastable state ($\lambda_{\text{vac}} = 611.6616 \text{ nm}$) is observed via the

$4p' \ ^2F_{7/2}^0 - 4s' \ ^2D_{5/2}$ fluorescence transition ($\lambda_{\text{vac}} = 461.086 \text{ nm}$). The laser is injected with a linear polarization parallel to the background field, eliminating the sixteen σ ($\Delta m = \pm 1$) components of the Zeeman-broadened spectrum. The broadening associated with the eight π ($\Delta m = 0$) transitions is known.^{24,25} For the plasma conditions of these measurements, this broadening is estimated to be $<4\%$ of the Doppler-broadening and is omitted in this analysis. Stark broadening, line-width, and hyperfine splitting are negligible for these plasma conditions, contributing $\ll 1\%$ to the broadening of the spectrum. Power broadening is not typically observed for these conditions. To ensure that no spurious broadening arises, multiple IVDFs were recorded at the same location while varying the injected laser power. The integrated signal of these IVDFs scales linearly with laser power up to the maximum injected power. In addition, the ion temperature T_i was constant over the range of laser powers. For single-photon LIF, these two measures indicate that absorption saturation did not occur and that power broadening is ignorable. The minimum velocity resolution for this scheme is set by the linewidth of the excitation transition and is reported to be $\Delta \bar{u} \geq 12 \text{ m/s}$.²³ Shot noise and statistical uncertainties typically dominate, with $\Delta \bar{u} = 50 - 100 \text{ m/s}$ common.

A diagram of the optical arrangement used in the measurements reported here is shown in Fig. 2. An actively stabilized Sirah Matisse DR (dye ring) laser provides approximately 1300 mW (CW) of laser power over a 30 GHz mode-hop free sweep. As a spectral reference, a branch of the laser beam passes through a stable, room temperature iodine cell that has a strong transition near the Ar-II resonance^{22,26} prior to injection into the plasma. A second branch of the beam is directed into a Bristol 621 wavemeter, which records laser wavelength and power during the sweep with $\Delta \lambda_{\text{las}} = \pm 0.0001 \text{ nm}$ and $\Delta P_{\text{las}}^{\text{w.m.}} = \pm 15\%$.

C. Conventional LIF optics

A diagram of the conventional optical arrangement used in these experiments is shown in Fig. 3. The laser is transmitted to the injection optics on HELIX via an NA = 0.22, 200 μm

FIG. 1. Top view: Confocal telescope in place on the HELIX plasma source.

FIG. 2. Diagram of the optical path and data acquisition arrangement.

core multimode optical fiber. The light from the fiber passes through a parabolic reflective collimator, which converts the fiber output to a 4 mm diameter (5% level) Gaussian beam. The collimated beam passes through a wire-mesh gridded linear polarizer and enters the plasma with approximately 350 mW of laser power.

The collection optics consist of a pair of plano-convex lenses that image fluorescent light from the center of the

FIG. 3. Schematic of a conventional LIF optical arrangement with coordinate directions marked. Red lines show the path of the injection laser. Blue lines show the path of the collection optics. FP—fiber port for multimode collection fiber, L1— $f = 50$ mm plano-convex lens, L2— $f = 200$ mm plano-convex lens, COL—reflective collimator, POL—wire grid linear polarizer.

injection beam onto the orifice of a second multimode fiber through which it passes to a Hamamatsu photomultiplier tube (PMT). Background light is strongly attenuated by a narrow-band notch filter ($T_{\max} \approx 72\%$, FWHM ≈ 1 nm) centered at 461 nm placed in the collection path. To isolate the fluorescent emission from electron impact excitation and stray light, the PMT signal is correlated with a mechanical chopper in the laser path by a Stanford Research Systems SR830 lock-in amplifier. Saturation in the plasma, in the PMT, and in the lock-in amplifier is carefully avoided.

The LIF optics on HELIX are mounted to a pair of coupled translational stages which are driven by remotely controlled stepper motors. Positioning is confirmed using linear scales with $\Delta x = 0.5$ mm. The injection beam and collection focus are aligned with targets to define an origin on the chamber axis at the center of the cross port. The axis of the collection optics is perpendicular to both the collimated injection beam and the plasma axis.

D. Confocal telescope

For confocal measurements, the laser, wavemeter, mechanical chopper, reference iodine cell, and detection components are the same components used for conventional LIF and are described above. Only the injection and collection optics differ. A rendering of the confocal optical assembly is shown in Fig. 4. The injection beam passes from the laser to the confocal optics via a $5 \mu\text{m}$ core, single mode optical fiber. The small core size provides a point-like illumination source for a parabolic reflective collimator, which converts the fiber output to a 2 mm diameter (5% level) Gaussian beam. The collimated beam passes through a wire-mesh gridded linear polarizer, which withstands the power density of the narrow beam.

The polarized beam reflects off a $\varnothing 12.7$ mm minor axis 45° elliptical mirror and exits the telescope through the objective lens. The objective lens is a $\varnothing 50.8$ mm positive meniscus/plano-convex doublet that mitigates spherical aberration and reduces the focal spot size. Both lenses of the doublet have 300 mm focal lengths, establishing a theoretical $f = 150$ mm for the telescope. The measured focal length for this arrangement is 148.7 mm. The polarization is confirmed during experimental preparation by placing a second linear polarizer in the beam path. The transmitted power is observed to be $\ll 1\%$ of the maximum power when the polarization axis of the second polarizer is oriented perpendicular

FIG. 4. Schematic of the confocal optical assembly with coordinate directions marked. Red lines show the path of the injection laser. Blue lines show the path of the collection optics. FP—multimode fiber port, L1— $f = 25$ mm plano-convex lens, PH—pinhole, L2— $f = 75$ mm plano-convex lens, L3— $f = -50$ mm plano-concave, L4— $f = 300$ mm plano-convex lens, COL—reflective collimator, POL—wire grid linear polarizer, MIR— 45° elliptical mirror, OBJ—plano-convex/meniscus objective doublet, FOC—shared injection/collection focus.

to the intended linear polarization axis of the beam parallel to the background magnetic field.

The collection path of the confocal telescope consists of six lenses, which are mounted coaxially with the injection beam. The objective doublet collimates the fluorescent light from the sample volume, and the next three lenses in the optical path form a beam reducer that draws the diameter down from $\varnothing 50.8$ mm to $\varnothing 25.4$ mm. The last of these lenses focuses the light onto a pinhole, which sits at a plane optically conjugate to the confocal plane of the telescope and which serves as an aperture stop. The final lens in the optical assembly images the pinhole onto the entrance orifice of an NA = 0.22, $\varnothing 200$ μ m core multimode fiber. As in conventional LIF, the multimode fiber transmits the fluorescent light through a notch filter to the PMT. All lenses in the assembly are constructed from N-BK7 glass with an anti-reflective coating optimized for wavelengths $\lambda = 350$ – 700 nm. The transmission coefficient of the optical components changes during the sweep due to wavelength variation. The variation in the transmitted laser power due to wavelength changes is estimated to be $< 0.005\%$ and is neglected.

Three features are critical to the order of magnitude advance of the new confocal design. First, the large objective lenses reduce the depth of field of the collection optics. Second, the pinhole spatial filter constrains the depth of field. Finally, the mirror in the injection path is mounted to a flat window and inserted just behind and coaxial with the objective lens. This arrangement creates a circular obscuration at the center of the collection path. The laser passes through the exclusion cone created by this obscuration, ensuring that the laser and the collected light cone do not overlap except in the intended sample volume near the shared focus. To our knowledge, this is the first use of an obscuration in this manner for confocal LIF.

The pinhole and obscuration create a trade-off between spatial localization and signals. Increasing throughput by decreasing the size of the obscuration, or by increasing the diameter of the pinhole, increases the depth of field of the collection optics and improves the longitudinal localization. Reducing the pinhole diameter improves longitudinal localization, but throughput and signal-to-noise ratio (SNR) decrease as a result.

The confocal telescope is translated as a unit via an optical stage. Once the focal plane is determined relative to the objective lens, the change in location of the focal plane is determined from a scale placed next to the stage. Uncertainty in the location of the focal plane is $\Delta x^{\text{scale}} = 0.5$ mm, arising primarily

from the resolution of the scale. In conventional LIF, small variations in sample volume arise as injection and collection optics move independently, requiring careful, consistent alignment along the entire sample chord. An important advantage of the confocal arrangement for relative intensity measurements is that the injection and collection optics move together, and the sample volume remains unchanged after initial alignment. In this way, systematic uncertainty in the intensity measurement is minimized and the uncertainty becomes predominantly statistical in nature.

E. Beam profiler

LIF signal is very sensitive to the overlap of the injection focal spot and collection fiber image at the focal plane. Verifying that the injection beam intersects with the image of the collection fiber at the focal plane requires 100 μ m-scale positioning. Inspection of the beam shape and collection path is accomplished using a Newport LBP HR beam profiler. The beam profiler consists of a 7.6 mm $\times$ 6.2 mm active area CCD with 4.65 μ m $\times$ 4.65 μ m pixels. During alignment, the collection optics are backlit using a 450 nm wavelength pen laser to approximate the 461 nm fluorescent emission. The spatial separation between the focal plane of the 450 nm wavelength backlight laser and the 461 nm wavelength fluorescent source region due to chromatic effects is expected to be ≤ 0.24 mm and is neglected. Coarse alignment is achieved by altering the pitch of the elliptical mirror, which can be adjusted $\pm 2^\circ$. Fine alignment is achieved by tuning the kinematic tip/tilt optical mount that holds the parabolic collimator. The profiles are observed real-time during alignment and are recorded on a lab computer.

III. RESULTS AND DISCUSSION

A. Beam profiles

Beam profile measurements were recorded at several locations near the focal plane, as shown in Fig. 5. In these measurements, the image of the backlit collection optics appears as a circle, contracting as the sensor moves toward the focal plane and expanding after passing through the focal plane. When the collection and injection optics are aligned, the injected beam appears as a disk with a Gaussian profile at the center of the circle. When the optics are out of alignment, the focused collection image will not overlap with the injection image and the profile at the focal plane will appear as two distinct disks. Misaligned optics reduce the fraction of fluorescent emission

FIG. 5. Beam profile images at several locations along the confocal optical axis. Locations of each profile are given with respect to the focal plane. The contracting and expanding ring is the image of the backlit collection fiber. The central, higher intensity object is the injection laser profile. (Black background is subtracted for clarity. Levels are not normalized between frames.)

that is able to pass through the spatial filter and reach the detector, resulting in diminished SNR and a poorly defined sample volume.

B. LIF profiles

For the data reported here, 650 W of RF power at 9.5 MHz injected into 3.5 mTorr high-purity argon generates a helicon plasma in the HELIX chamber. In the measurement region at the center of the cross port, the background magnetic field is 700 ± 5 G. Typical plasmas exhibit densities of $n \approx 5 \times 10^{18} \text{ m}^{-3}$ and electron temperatures of $T_e \approx 3$ eV. A typical on-axis Ar-II IVDF recorded using confocal LIF is shown in solid blue in Fig. 6, with a Gaussian fit to the argon data shown as a blue dashed line. The spectrum from the iodine gas cell is shown in black dots.

The vertical line in Fig. 6 identifies the expected location of the spectrum peak for a metastable population at rest. A shift of the observed peak indicates an average bulk flow of the metastables. The ion temperature is obtained from a Maxwellian fit to the spectrum. For the spectrum shown in Fig. 6, $\bar{u}_i = 9$ m/s, as expected for a perpendicular flow measurement at the plasma center. The ion temperature is calculated to be $T_i = 0.24$ eV.

A precision pinhole of $50 \pm 3 \mu\text{m}$ provides sufficient signal-to-noise for these experiments. $\text{SNR} = \mu_{\text{sig}}/\sigma_{\text{nse}}$, where μ_{sig} is the mean of the signal and σ_{nse} is the standard deviation of the noise, which is estimated by subtracting a Gaussian fitting function from the data. Under this definition, SNR is as high as 15 at peak integrated LIF signal. At the same location, SNR for the conventional LIF measurement is 22. The SNR can be increased by enlarging the objective lens or the pinhole. Further work is needed to quantify the dependence of SNR and spatial localization on spatial filtering, obscuration size, and telescope focal length.

By translating the optical assembly, measurements of the spatially resolved metastable velocity distribution at the focal plane are obtained. Figure 7 compares the temperature and bulk flow profiles obtained with the two optical arrangements, measured across the HELIX midplane. Negative radial locations are closer to the injection window. At

FIG. 6. Typical ion velocity distribution measured with the confocal telescope. Ar-II LIF signal (solid line) with a Gaussian fit (dashed line) is shown in blue. Iodine reference distribution ($\cdots$) and fit (solid line) are shown in black. For this spectrum, $\bar{u}_i = 9$ m/s and $T_i = 0.24$ eV.

FIG. 7. Comparison of confocal (●) and conventional (□) LIF Ar-II metastable temperature (a) and mean velocity (b) profiles. Laser injection enters from the left. $v_{T_i} = \sqrt{T_i[\text{eV}]/m_i} \approx 700$ m/s.

a focal length of 148.7 mm, the confocal sample volume is limited to $x \lesssim 10$ mm, beyond which the optical assembly is in contact with the glass window of the vacuum chamber.

The horizontal bars in Fig. 7 reflect $\Delta x^{\text{scale}} = 0.5$ mm for the translation stages. The vertical bars reflect shot-to-shot variation and fit uncertainty. Near the core, approximately for $-10 \leq x \leq 8$ mm, $\text{SNR} \geq 10$, $\bar{u}_i^{\text{conf.}} = 21 \pm 53$ m/s, $\bar{u}_i^{\text{conv.}} = -21 \pm 41$ m/s, $\bar{T}_i^{\text{conf.}} = 0.26 \pm 0.05$ eV, and $\bar{T}_i^{\text{conv.}} = 0.23 \pm 0.03$ eV. SNR can be improved by averaging several spectra; however the measurements reported here are for a single IVDF at each location.

The temperature profile, as shown in Fig. 7(a), is flat or slightly peaked. The ion temperature decreases significantly on both sides of the core outside approximately 10 mm. The average flow in the plasma center is small compared to the thermal speed— $v_{T_i} = \sqrt{T_i[\text{eV}]/m_i} \approx 700$ m/s—and gradually reverses the direction around the plasma axis. That any flow as seen in Fig. 7(b) may indicate that the plasma axis is slightly separated from the chamber axis, resulting in the injection direction being slightly tangential instead of purely radial. The differences between the conventional and confocal methods are small, with the confocal mean flow 42 m/s faster and temperature 0.03 eV higher on average. These discrepancies are within typical measurement uncertainty for LIF.

Integrating each spectrum provides the relative density of the absorbing species at the focus of the optics. Figure 8

FIG. 8. Comparison of confocal (●) and conventional (□) LIF Ar-II metastable integrated spectra for a helicon plasma generated by 650 W of RF power in 3.5 mTorr argon at 700 G. A reconstruction of the conventional LIF profile from convolving the estimated metastable emission profile with the response of the conventional optics is shown in a black dashed line. The reconstructed confocal profile is shown in solid red.

compares the relative density profiles recorded across the HELIX midplane. Each profile is normalized to its maximum, and the spectra are corrected for changes in laser power. The profiles shown in Fig. 8 exhibit the sharply peaked emission profile typically observed in helicon discharges.²⁷

C. Spatial localization

Spatial localization is calculated from an optical response model. Specifically, the spatial localization is determined from the full width at half maximum (FWHM) of the response function that, when convolved with a simulated ideal profile, best fits the profile data in a minimized χ^2 sense. The optical model is described in the Appendix. Several candidate confocal response functions generated by the model are shown in Fig. 9. The optimal response function is shown as the red, innermost solid line. This response function produces the reconstructed profile shown by the solid line in Fig. 8. The goodness-of-fit is quantified by the reduced chi-squared, $\chi^2_\nu = \chi^2/\nu$, where ν is the number of fit parameters subtracted from the number of data points. A good fit is indicated by $\chi^2_\nu \lesssim 1$.³⁶ The reconstructed profile compares well to the

experimentally measured profile, with reduced chi-squared $\chi^2_\nu = 0.74$.

The FWHM of the confocal optics response is 1.4 mm, which is a factor of only 1.3 broader than the 1.1 mm FWHM of the conventional method. This result constitutes a dramatic improvement over previously published confocal techniques, which optically smooth over several centimeters during collection. 97.3% of the normalized intensity is contained within the FWHM of the conventional response function. The FWHM of the confocal response contains 65.8% of the normalized intensity, reflecting the contributions farther from the focus. The e -folding distance gives a spread of 1.12 mm for the conventional optics, encompassing 98.8% of the normalized intensity, and 1.73 mm for the confocal optics, encompassing 70.2% of the normalized intensity. By this measure, the new confocal method achieves a spatial localization approximately 1.5× the excellent spatial localization offered by the conventional method. These results conform to an intuitive interpretation of the experimental results of Figs. 7 and 8 which show that the profiles from the two methods nearly overlap despite the sharp gradients present in the source profile.

FIG. 9. Normalized optical response of the conventional and confocal optics. b_{excl} is a geometric factor in the optical response model (see the Appendix for details). Vertical dashed and dotted-dashed lines mark the full width at half maximum of the conventional and confocal optical configurations, respectively.

IV. SUMMARY

We have demonstrated a single-photon confocal laser induced fluorescence technique that achieves an order of magnitude advance in spatial localization compared to previously published implementations. Temperature and bulk flow profiles differ on the order of measurement uncertainty. The confocal arrangement is achieved at moderate loss in signal-to-noise, which in these measurements was 68% of the conventional SNR. At the 148.7 mm focal length of these experiments, an optical model indicates a FWHM of 1.4 mm for the confocal optical response in the direction of laser injection. An upper bound is placed on the lateral localization by the beam waist of the laser, which is approximately ± 1.0 mm. This localization constitutes a significant improvement over previous confocal implementations, which achieved axial localization of several centimeters at comparable focal lengths, and compares well with conventional LIF configurations, which typically achieve approximately 1 mm along the laser and 2 mm laterally. Profiles recorded in a high-density helicon plasma show close agreement in relative intensity, including on the far side the bright plasma core, corroborating narrow spatial binning.

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APPENDIX: OPTICAL MODEL

The theoretical model developed to determine the localization of the confocal LIF optics proceeds in four steps as follows:

1. Linear system theory is used to simulate the response of the conventional optics.
2. The simulated conventional optics response and the measured metastable profile are combined to determine the “true” metastable profile.
3. The “true” metastable profile is convolved with the simulated response of the confocal optics.
4. The free parameters in the confocal model geometry are determined using χ^2 -minimization to match the simulated profile with the measured confocal profile.

Laser induced fluorescence is incoherent, allowing the use of linear system theory,²⁸ in which the light from multiple point-source emitters is summed without interference. The image space irradiance is generated by object space point source emitters whose fluorescent emission has been modified by the point spread function (PSF) of the optics. The optics are assumed to be aberration-free and space invariant over the sample region.

During the acquisition of an LIF spectrum, the PMT converts incident radiant flux (time-averaged optical energy per unit time, in watts) into photoelectric current.²⁹ We refer to the distribution of sources around the focal plane that contribute to the radiant flux as the response function of the optics. Significant contributions to the radiant flux from sources far from the focal plane correspond to a broadened axial optical response

function and a consequent degradation in spatial localization in that direction.

Coordinates in the image space, Σ_i , are defined such that $\tilde{\mathbf{x}} = (\tilde{x}, \tilde{y}, \tilde{z}) \in \Sigma_i$ and are centered at the image of x_o . The corresponding object space, Σ_o , has coordinates $\mathbf{x} = (x, y, z) \in \Sigma_o$, with the origin at $x = x_o$ centered at the focus of the collection optics. The x -axis is defined by the laser axis and x increases in the injection direction. y and z are defined relative to the optical axis, as shown in Figs. 3 and 4.

When the focal plane is at x_o , the response function describes the radiant flux recorded by the PMT as the sum of the object space irradiance originating from points that map through the optics into the fiber acceptance cone,

$$S_{x_o}(x) = G \iint \left[\int_H (\mathcal{L}(\mathbf{x}) \mathcal{P}(\mathbf{x}; \tilde{\mathbf{x}})) d\mathbf{x} \right] d\tilde{y} d\tilde{z}. \quad (\text{A1})$$

Here, the object space irradiance distribution (in brackets) is equal to the local power flux of the laser beam, $\mathcal{L}(\mathbf{x})$, which is symmetric about x_o , distorted by the 3-dimensional PSF of the optical arrangement, $\mathcal{P}$. H restricts the signal to the region of object space that maps to the fiber acceptance cone. The recorded signal is subject to the combined electronic and optical gain, G .

1. Conventional optics model

$H_{\oplus}$, the collection volume for the conventional optics, is estimated by observing the image of the backlit collection fiber with the beam profiler at the focal plane. The collection optics focus to a finite diameter circular spot, establishing a collection volume that is approximated by a conical region before and after the focus, with the two cones connected around the focal plane. This shape is a connected circular hyperboloid, described by³⁰

$$H_{\oplus} = \left\{ \mathbf{x} : \frac{x^2 + z^2}{(r_{\oplus}^{\text{foc}})^2} - \frac{y^2}{b^2} \leq +1 \right\} \subseteq \Sigma_o, \quad (\text{A2})$$

$$b^2 \equiv \frac{f_{\oplus}^2}{(r_{\oplus}^{\text{obj}}/r_{\oplus}^{\text{foc}})^2 - 1}.$$

In Eq. (A2), $r_{\oplus}^{\text{obj}}$ and $r_{\oplus}^{\text{foc}}$ are the objective lens radius and focal spot radius, respectively, and $f_{\oplus}$ is the objective lens focal length. The laser beam is modeled as an ideal, collimated Gaussian beam with rotational symmetry about the x -axis,³¹

$$\mathcal{L}_{\oplus}(y, z) = \frac{1}{2\pi(r_{\oplus}^{\text{las}})^2} \exp \left[-\frac{y^2 + z^2}{2(r_{\oplus}^{\text{las}})^2} \right].$$

The absolute power of the laser is included in the modified gain, $G'_{\oplus}$. The values of all geometric quantities are given in Table I.

The collection axis is centered along y as indicated in Fig. 3. For a point-source emitter in the object plane, the lateral

TABLE I. Measured conventional optics parameters used in model. All quantities are in mm.

$f_{\oplus}$	$r_{\oplus}^{\text{las}}$	$r_{\oplus}^{\text{obj}}$	$r_{\oplus}^{\text{foc}}$
180.0	1.97	12.7	0.60

PSF of the collection optics produces an Airy disk at the image plane,^{32,33}

$$\mathcal{P}_{\oplus,\perp}(x, z; \tilde{x}, \tilde{z}) = O_{\perp,o} \left[\frac{2J_1(\rho)}{\rho} \right]^2,$$

where

$$\rho = \frac{2\pi r_{\oplus}^{\text{obj}}}{\lambda f_{\oplus}} \sqrt{(\tilde{x} - x)^2 + (\tilde{z} - z)^2}.$$

The normalized PSF along the collection axis is³³

$$\mathcal{P}_{\oplus,\parallel}(y; \tilde{y}) = O_{\parallel,o} \left[\frac{\sin(\pi y^*)}{\pi y^*} \right]^2.$$

Here $y^* = (y - \tilde{y})/\Delta y$, where Δy is the depth of field of the collection optics. $O_{\perp,o}$ and $O_{\parallel,o}$ set the maximum of each PSF to unity. The normalization constants of the two PSFs have been incorporated into $G'_{\oplus}$, which is the only fit parameter of the conventional optics model.

2. Confocal optics model

The collection optics of the confocal system are modeled by a pair of hyperboloids: an outer acceptance volume determined by the numerical aperture of the objective lens, and an inner exclusion cone established by the central obscuration. These regions are denoted $H_{\oplus}^{\text{NA}}$ and $H_{\oplus}^{\text{excl}}$, respectively. The collection volume defined by the numerical aperture is³⁰

$$H_{\oplus}^{\text{NA}} = \left\{ \mathbf{x} : \frac{y^2 + z^2}{(r_{\oplus}^{\text{foc}})^2} - \frac{x^2}{b_{\text{NA}}^2} \leq +1 \right\} \subseteq \Sigma_o,$$

$$b_{\text{NA}}^2 \equiv \frac{f_{\oplus}^2}{(r_{\oplus}^{\text{obj}}/r_{\oplus}^{\text{foc}})^2 - 1},$$

where $r_{\oplus}^{\text{foc}}$ is the spot radius at the focal plane and $r_{\oplus}^{\text{obj}}$ is the radius of the objective lens. A visualization of the model near the shared focal plane is shown in Fig. 10.

The exclusion region lies inside $H_{\oplus}^{\text{NA}}$ and is symmetric about the focal plane. A small region around the focal plane is not excluded in the confocal arrangement, so the exclusion volume is represented as two separate volumes. This geometry is referred to as a two-sheet circular hyperboloid, described by³⁰

$$H_{\oplus}^{\text{excl}} = \left\{ \mathbf{x} : \frac{y^2 + z^2}{(r_{\oplus}^{\text{excl}} b_{\text{excl}})^2 / (f_{\oplus}^2 - b_{\text{excl}}^2)} - \frac{x^2}{b_{\text{excl}}^2} \leq -1 \right\} \subseteq \Sigma_o.$$

FIG. 10. Close-up of the focal region: 1—blue outer cone representing outer limit of collection cone; 2—blue inner cone representing exclusion volume, with $2b_{\text{excl}}$ region marked; 3—focused laser beam. Shaded rectangles mark yz cut planes at -5 , -2 , and 0 mm (focal plane).

TABLE II. Measured confocal optics parameters used in the model. All quantities are in mm.

$f_{\oplus}$	$R_{\oplus}^{\text{las}}$	$w_{\oplus}^{\text{las}}$	$r_{\oplus}^{\text{obj}}$	$r_{\oplus}^{\text{foc}}$	$r_{\oplus}^{\text{mir}}$
148.7	1.00	0.16	25.4	0.60	6.35

(Note in particular the change in sign of the right hand side of the inequality.) Here, $r_{\oplus}^{\text{excl}}$ is the maximum radius of the exclusion cone, which occurs at the objective lens, and b_{excl} is the distance from the focal plane to the closest point of the exclusion cone. The region of separation between the two exclusion zones therefore has width $2b_{\text{excl}}$, as marked in Fig. 10. All of the emission created in this separation region reaches the PMT. However, b_{excl} is difficult to measure directly and is left as one of the two free parameters of the confocal model, along with the system gain $G'_{\oplus}$. The measured quantities used for the confocal model are given in Table II.

In the model, the collection volume observed at yz cut planes (see Fig. 10) resembles the annular cross sections seen in the corresponding frames of the backlit profiles in Fig. 5. This volume condenses until it forms a disk of radius $r_{\oplus}^{\text{foc}}$ at the focal plane. The confocal injection laser beam geometry is similar to the conventional beam, except that it focuses coplanar to the collection optics down from an initial diameter of $\varnothing 2$ mm, so that

$$r_{\oplus}^{\text{las}}(x) = w_{\oplus}^{\text{las}} + \frac{R_{\oplus}^{\text{las}} - w_{\oplus}^{\text{las}}}{f_{\oplus}} |x|,$$

where $w_{\oplus}^{\text{las}}$ is the laser beam waist radius, $R_{\oplus}^{\text{las}}$ is the maximum beam radius, and $f_{\oplus}$ is the focal length of the objective lens.

The lateral PSF for optics that contain a central obscuration is^{34,35}

$$\mathcal{P}_{\oplus,\perp}(y, z; \tilde{y}, \tilde{z}) = \frac{O_{\perp,o}}{(1 - \epsilon^2)^2} \left[\frac{2J_1(\rho)}{\rho} - \epsilon^2 \left(\frac{2J_1(\epsilon\rho)}{\epsilon\rho} \right) \right]^2,$$

where ϵ is the obscuration ratio, $\epsilon = d/D$. d is the diameter of the obscuration, and D is the diameter of the objective lens. $\rho = \rho(y, z; \tilde{y}, \tilde{z})$, analogous to the conventional optics model. The axial PSF is³³

$$\mathcal{P}_{\oplus,\parallel}(x; \tilde{x}) = O_{\parallel,o} \left[\frac{\sin(\pi x^*)}{\pi x^*} \right]^2,$$

with $x^* = (x - \tilde{x})/\Delta x$, where Δx is the depth of field. As in the conventional optics model, the normalization constants of the

two PSFs are incorporated into $G'_{\odot}$, which remains along with b_{excl} as the two fit parameters for the confocal model.

Candidate response curves for each optical system are obtained by calculating Eq. (A1) for a range of fit parameter values. The response of the conventional optics depends on fit parameter $G'_{\odot}$, and the response of the confocal optics depends on fit parameters $G'_{\odot}$ and b_{excl} .

The actual relative metastable emission profile, ξ , is not measured directly but is only observed after modification by the optics. ξ is estimated by scaling the conventional profile data with $G'_{\odot}{}^{-1}$ and convolving the result with the conventional optical response to obtain a candidate profile, ξ_{sim} , such that $\xi_{\text{sim}}(x) = (\xi * S_{\odot})(x)$. As the scaling of ξ varies, ξ_{sim} and the conventional profile data are compared using χ^2 -minimization. The optimal reconstructed conventional LIF profile is shown as a black dashed line in Fig. 8, and the corresponding response function is shown in Fig. 9.

$G'_{\odot}$ and b_{excl} are determined in a similar way, by generating a range of candidate profiles via $[\xi * S_{\odot}(G'_{\odot}, b_{\text{excl}})](x)$ and comparing the resulting candidate profile with the confocal profile data. Figure 9 shows the response functions for several values of b_{excl} . A comparison of the reconstructed profile and the experimental data when $b_{\text{excl}} = 0.18 \pm 0.01$ mm produces $\chi^2_{\nu} = 0.74$, indicating a good reconstruction of the experimental data.

This model is intended to provide a coarse estimate of the localization characteristics of the confocal optical arrangement. Further work is needed to refine the model and incorporate magnification and aberrations, which are expected to be significant at longer focal lengths.

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