Optimization of Confocal Laser Induced Fluorescence

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Abstract
Laser induced fluorescence (LIF) provides measurements of flow speed, temperature, and when absolutely calibrated, density of ions or neutrals in a plasma. Traditionally, laser induced fluorescence requires two ports on a plasma device. One port is used for laser injection and the other is used for fluorescence emission collection. Traditional LIF is tedious and time consuming to align. These difficulties motivate the development of an optical configuration that requires a single port and can be easily shaped in all axes. Confocal LIF has confocal optical design employs a single two inch diameter lens to both inject the laser light and collect the stimulated emission from an active plasma. A confocal mirror is used to separate the injected laser light from the collected emission. The measurement location is scanned radially by manually adjusting the focal lens position. In the initial version of the confocal optical system, measurements were poorly resolved radially. Since they were limited over a fairly large path length (~1 cm) centered at the focal point. Here we present optical modeling of and initial results from a modified configuration that significantly improves the spatial resolution of confocal measurements.

The confocal measurements are compared to traditional, two-port, LIF measurements over the same radial range.

Conclusions and Future Work
A confocal LIF optical configuration can provide excellent signal-to-noise.

Confocal LIF configuration eliminates many of the challenges of optical alignment in a traditional LIF measurement.

Measurements indicate that the confocal system averages over a linear region approximately 3 cm in length along the line-of-sight, not the entire possible collection volume.

Depth of Field of the Confocal Apparatus

The previous confocal Laser Induced Fluorescence (LIF) apparatus utilized from a large region of integration along the optical axis oriented about the focus. To minimize the integration length scale, we used the Zemax optical modeling software to identify a better optical configuration. More localized measurements require that the optical depth of field (DoF) be reduced. The optical depth of field is given by

$$D_{oF} = \frac{1}{2} \left( \frac{1}{F/2} \right)$$

where $F$ is the number of the lens, $c$ is the circle of confusion, $m$ is the magnification and $f$ is the focal length of the optical system. The numerator, $F/2$, of an optical system is given by

$$F = \frac{1}{f} \left( \frac{1}{2} \right)$$

where $D$ is the limiting aperture of the lens. The circle of confusion was estimated to be limited by diffraction. Using Airy’s equation,

$$c = \frac{0.61 \lambda}{D}$$

where $\lambda$ is the wavelength and $NA$ is the numerical aperture of the system. The magnification of the system is given by

$$m = \frac{w_o}{w_i}$$

where $w_o$ is the height of the image of the fiber core, and $w_i$ is the height of the fiber core.

Previous Confocal Measurements

The red filled circles are the LIF amplitude measurements obtained with the two confocal scheme on 18 October 2015. The solid black curve is the predicted confocal measurement scaling assuming an imaging lens equal to half the plasma diameter at the measurement location. The dashed curve assumes an integrating lens equal to half the plasma radius. The consistency between the model and measurements suggests that the confocal system is averaging over quite a large region, ~ 3 cm, of the plasma along the collection line-of-sight.

Conventional LIF Measurements

Confocal LIF Measurements

Conventional LIF Measurements at Different Radial Locations

The upper plot is an example of a confocal LIF measurement obtained near the axis of the plasma column. The signal-to-noise is excellent and the ion velocity distribution is well fit by a single Gaussian curve corresponding to an ion temperature of ~ 6 eV.

The lower plot shows the ion temperature (square) and the measurable ion density (circles) as a function of radial location in the plasma column. The ion temperature profile measured confocally is much flatter across the entire plasma column and the measurable ion density profile is also less sharply peaked and shows evidence of anisotropy for measurements made beyond the center of the plasma.

Using exponential fits to the high spatial resolution LIF measurements obtained with the 3D stage, we can analytically integrate over a line of sight in the radial direction.

$$w(t) = \frac{e^{-(t-t_0)^2/2\sigma^2}}{\sqrt{2\pi}\sigma^2}$$

where $w$ is the measured density and $t$ is the line-of-sight position.

The predicted radial profile is shown as a solid line in the figure to the right.

Conclusions and Future Work

- A confocal LIF optical configuration can provide excellent signal-to-noise.
- Confocal LIF collection eliminates many of the challenges of optical alignment in a traditional LIF measurement.
- Measurements indicate that the confocal system averages over a linear region approximately 3 cm in length along the line-of-sight, not the entire possible collection volume.