# Optimization of Confocal Laser Induced Fluorescence


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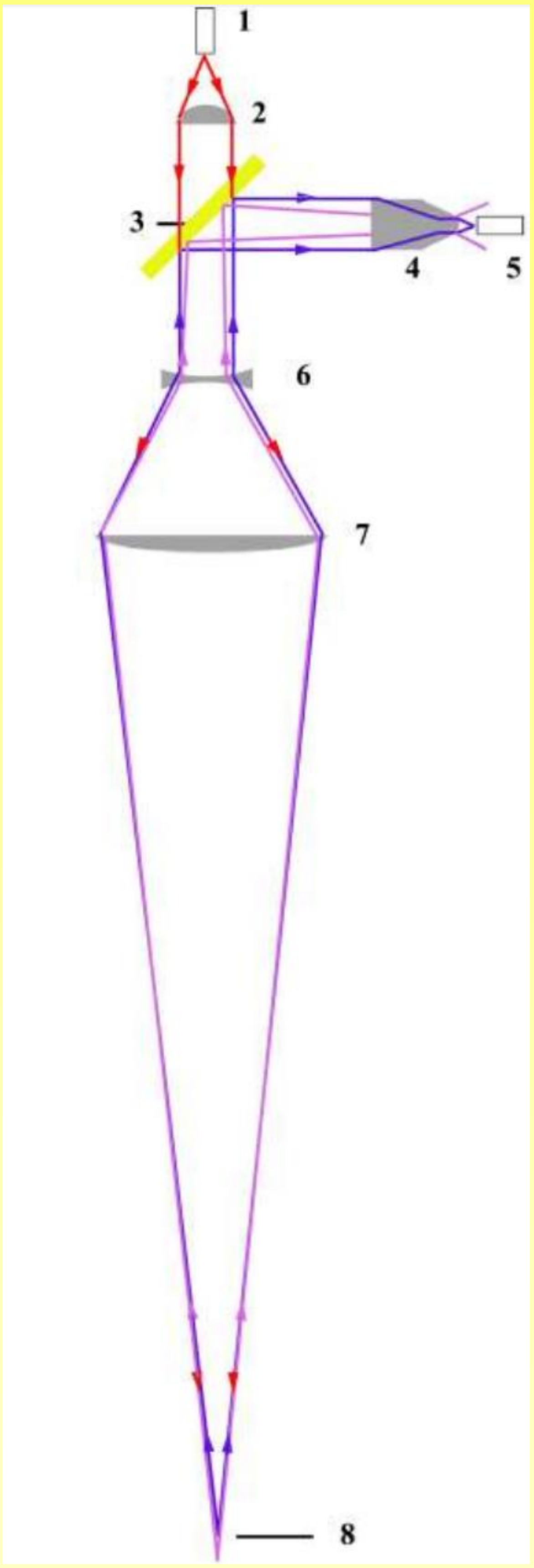
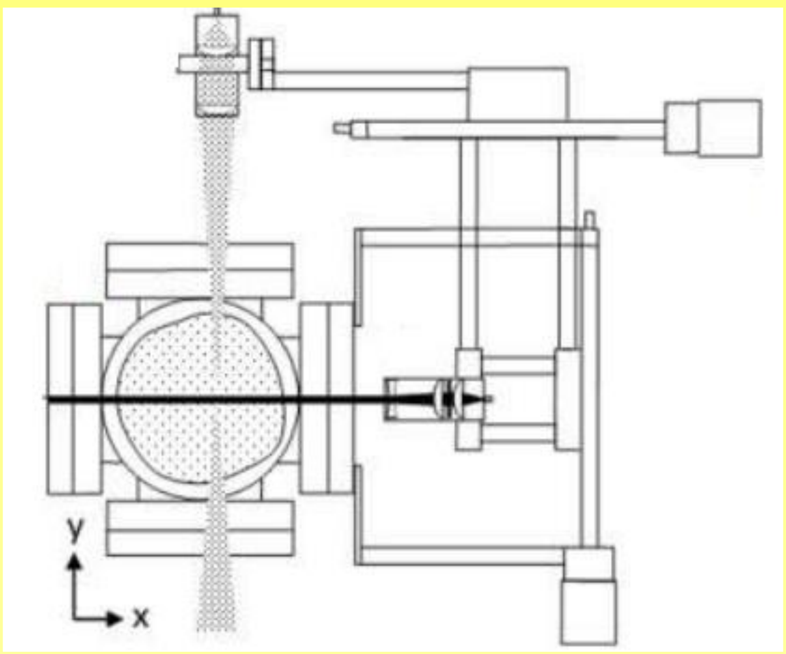
## Abstract

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 remains fully aligned at all times; confocal LIF. Our confocal optical design employs a single two inch diameter lens to both inject the laser light and collect the stimulated emission from an argon plasma. A dichroic mirror is used to separate the injected laser light from the collected emission. The measurement location is scanned radially by manually adjusting the final focusing lens position. In the initial version of the confocal optical system, measurements were poorly resolved radially because they were integrated over a fairly large path length (~4 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.

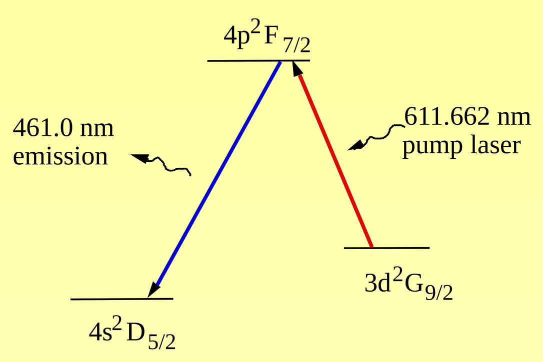

## Confocal Optical Configuration




## Conventional Optical Configuration



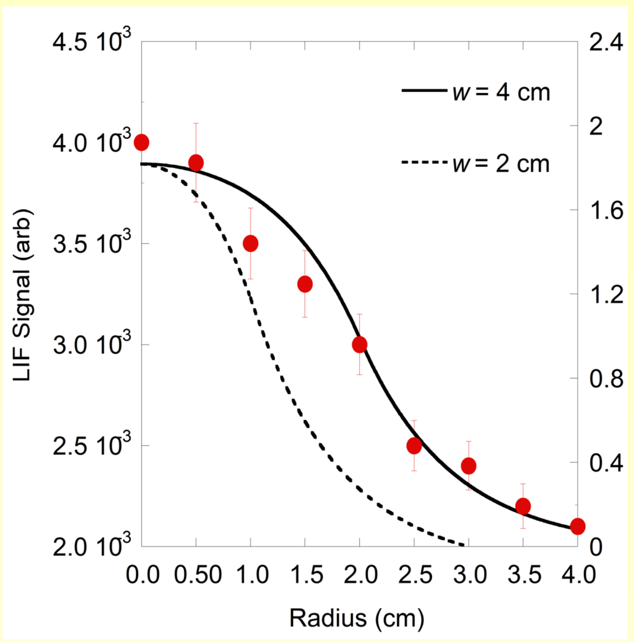

## Ar II LIF Scheme




## Plasma Parameters

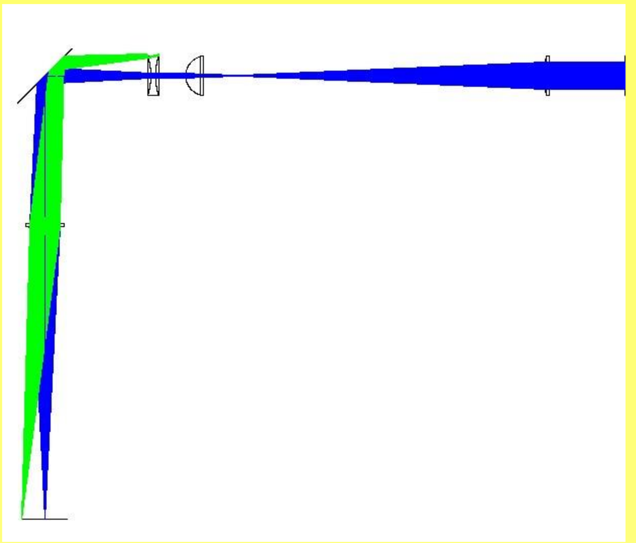
$B = 750$ G
$n \sim 1 \times 10^{13}$ cm$^{-3}$
$P = 3.5$ mTorr
$Power_{RF} = 900$ W

## Previous Confocal Measurements




The red filled circles are the LIF amplitude measurements obtained with the first confocal scheme on 18 October 2013. The solid black curve is the predicted confocal measurement scaling assuming an integrating bin equal to half the plasma diameter that is centered on the measurement location. The dashed curve assumes an integrating bin width 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, > 4 cm, of the plasma along the collection line-of-sight.

## Depth of Field of the Confocal Apparatus



The above figure is a Zemax™ model of the confocal collection apparatus. Through modeling we identified optical configurations with a very small depth of field. At the bottom left of the figure are two point sources. The point source with green rays is off the optical axis. The point source with blue rays is on the optical axis. In this configuration, light collection is limited to points very close to the optical axis and very close to the focal point of the objective lens (obscured by the green and blue ray paths in the figure).

The previous confocal Laser Induced Fluorescence (LIF) apparatus suffered from a large region of integration along the optical axis centered about the focus. To minimize the integration length scale, we used the Zeman™ optical modeling software to identify a better optical configuration. More localized measurement require that the optical depth of field (DoF) be reduced. The optical depth of field is given by [1]

$$DoF = \frac{2f \times (1+\frac{1}{m})}{\frac{f \times m}{F \times c} - \frac{F \times c}{f \times m}}$$

where $F$ is the $f$-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 $f$-number, $F$, of an optical system is given by [2]

$$F = \frac{f}{D} \approx \frac{1}{2NA} \qquad f > D$$

where $D$ is the limiting aperture of the lens. The circle of confusion was estimated to be limited by diffraction. Using Abbe's resolution [3].

$$c = \frac{\lambda}{2NA}$$

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

$$m = \frac{S_{image}}{S_{object}}$$

where $S_{image}$ is the height of the image of the fiber core, and $S_{object}$ is the height of the fiber core.

The confocal apparatus has two different optical paths, injection and collection. Both of these paths have their own focus, $f$-number, circle of confusion and magnification. Hence each calculation is carried out twice.

$$F_{collection} = \frac{f}{D} = \frac{181.293mm}{5mm} = 36.26 \qquad m_{collection} = \frac{S_{image}}{S_{object}} = \frac{0.5mm}{3\mu m} = 167$$

$$F_{injection} = \frac{f}{D} = \frac{181.293mm}{25.4mm} = 7.14 \qquad m_{injection} = \frac{S_{image}}{S_{object}} = \frac{0.5mm}{0.050mm} = 10$$

$$DoF_{collection} = \frac{2f \times (1+\frac{1}{m})}{\frac{f \times m}{F^2 \times \lambda} - \frac{F^2 \times \lambda}{f \times m}} = \frac{2 \times 181.293mm \times (1+\frac{1}{167})}{\frac{181.293 \times 167}{(36.26)^2 \times .461} - \frac{(36.26)^2 \times .461}{181.293 \times 167}} = 7.3mm$$

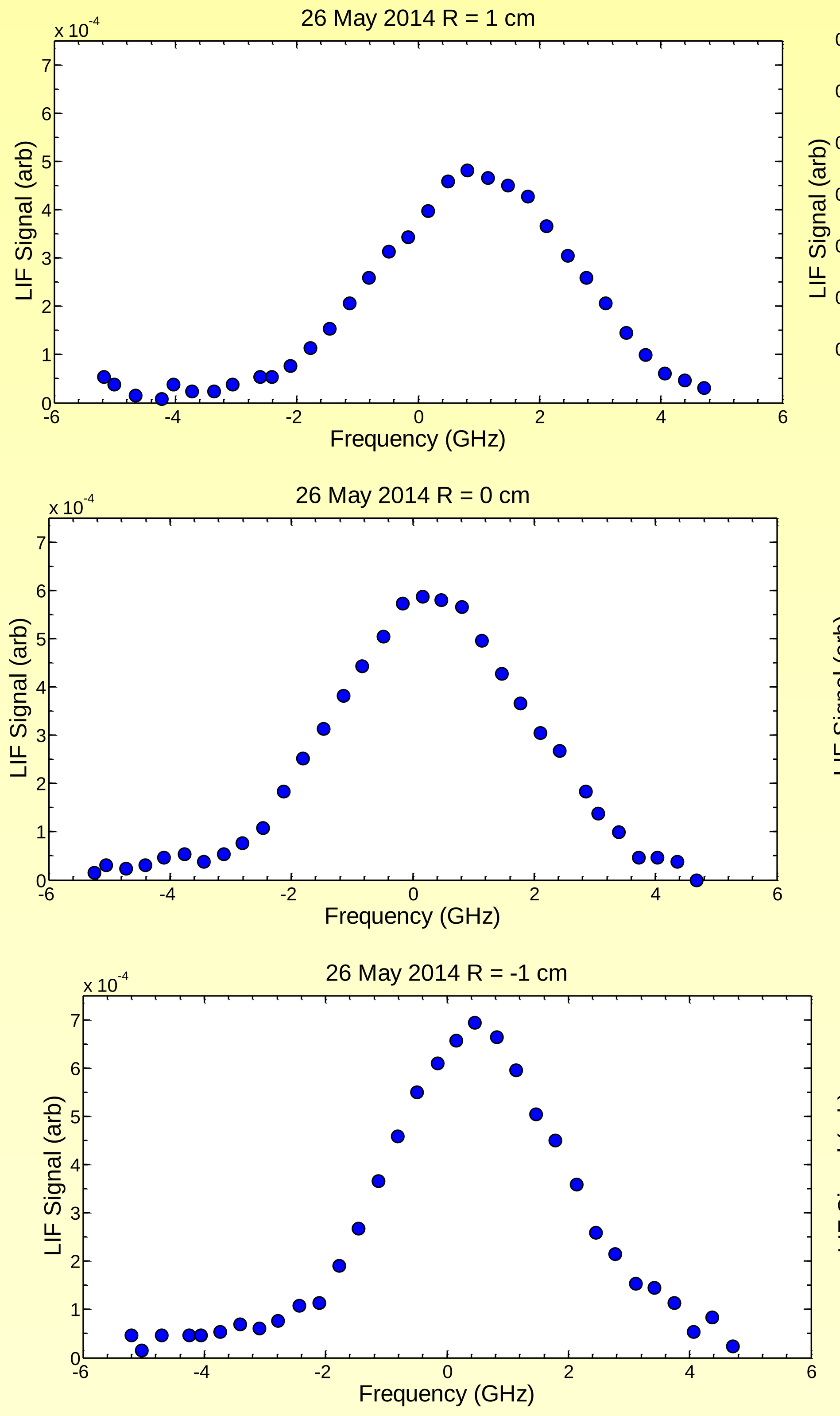
$$DoF_{injection} = \frac{2f \times (1+\frac{1}{m})}{\frac{f \times m}{F^2 \times \lambda} - \frac{F^2 \times \lambda}{f \times m}} = \frac{2 \times 181.293mm \times (1+\frac{1}{10})}{\frac{181.293 \times 10}{(7.14)^2 \times .61166} - \frac{(7.14)^2 \times .61166}{181.293 \times 10}} = 6.86mm$$


[1] Conrad, Jeff. "Depth of Field in Depth." Large Format Page. 2004,2006. <http://www.largeformatphotography.info/articles/DoFinDepth.pdf>

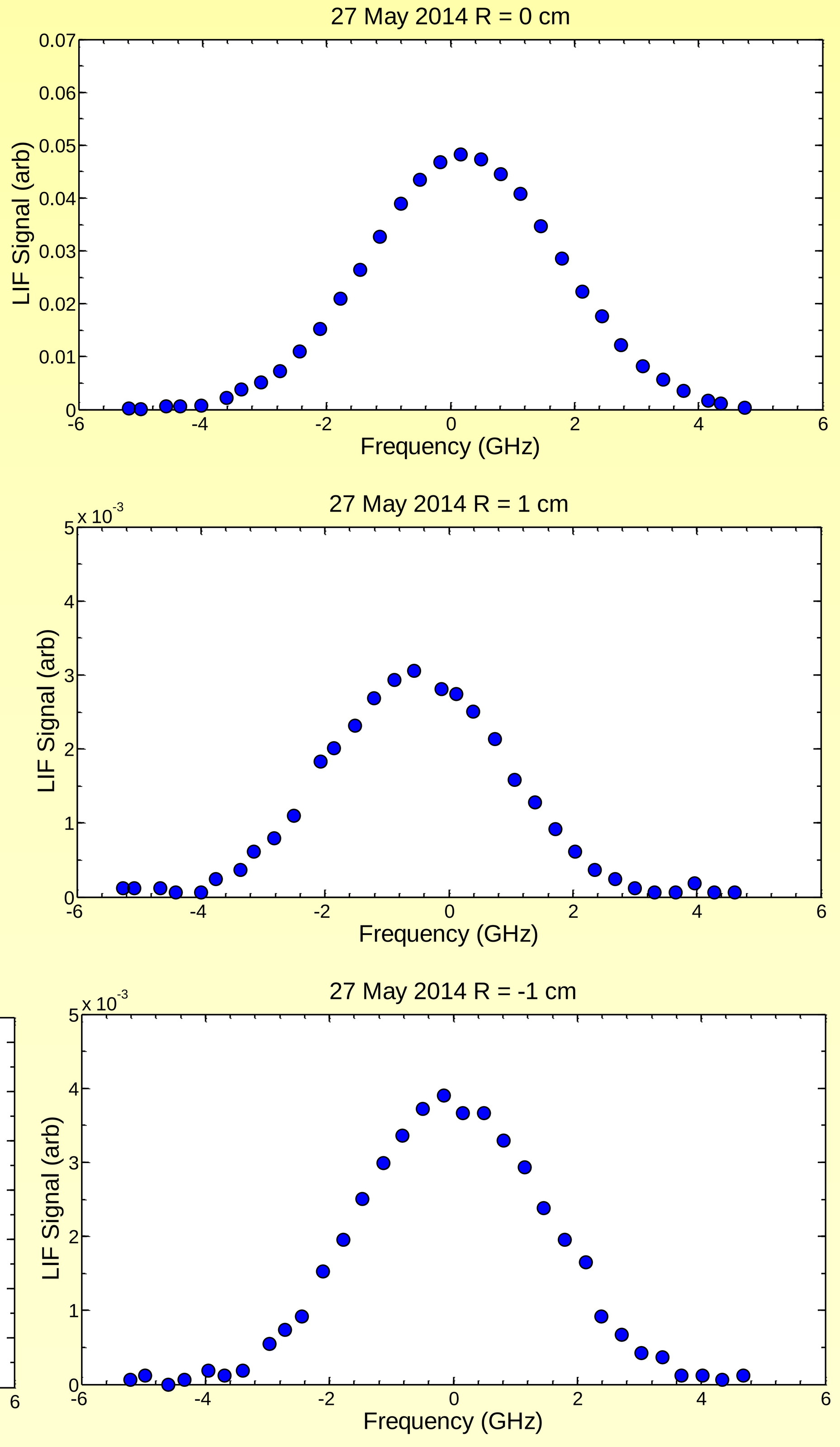
[2] Newport <http://www.newport.com/Tutorial-Light-Collection-and-Systems-Throughput/381845/1033/content.aspx>

[3] Silfies, Joel and Schwartz, Stanley, and Davidson, Michael. "The Diffraction Barrier in Optical Microscopy." Nikon. Microscopy U. <http://www.microscopyu.com/articles/superresolution/diffractionbarrier.html>


## Confocal LIF Measurements

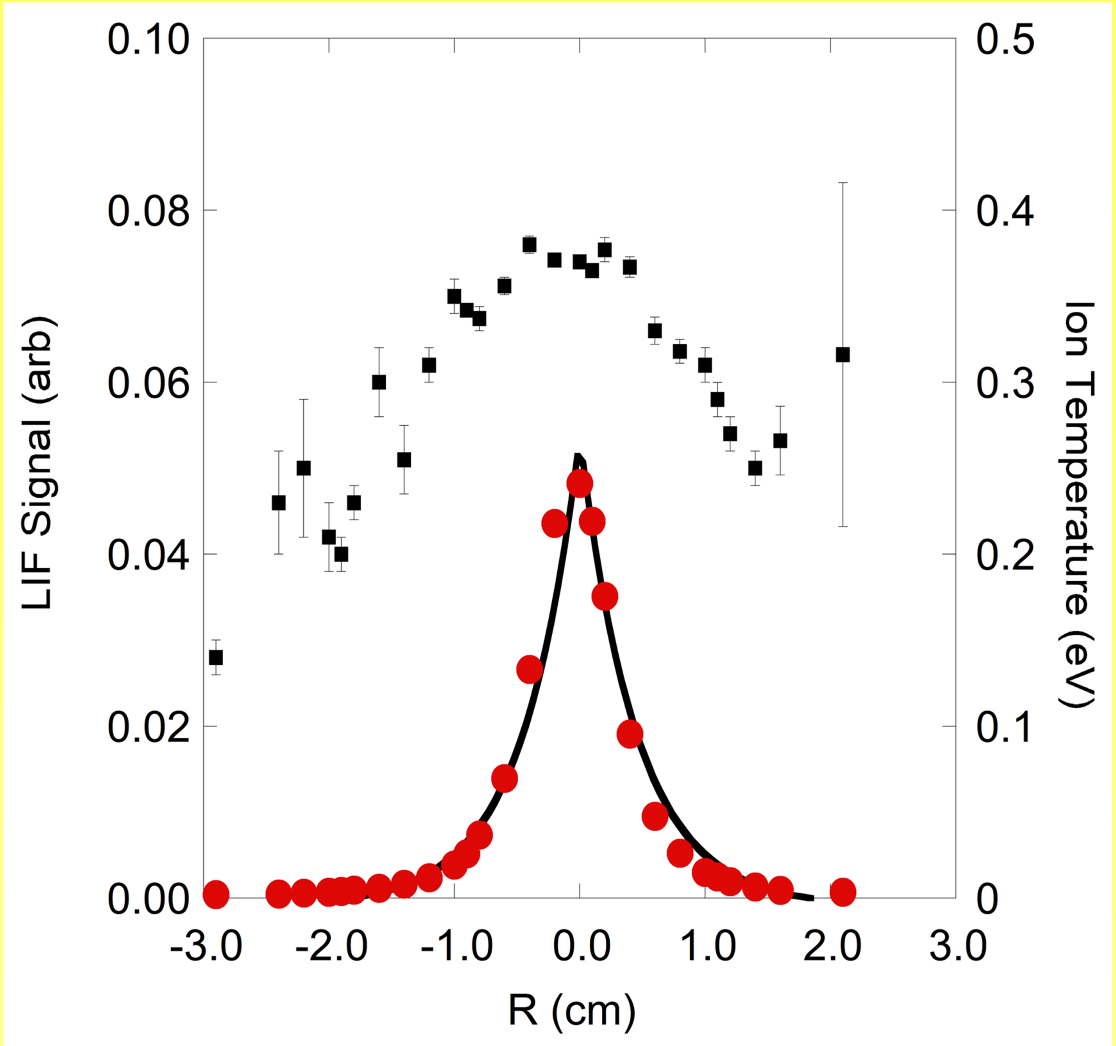



## Conventional LIF Measurements




*Both the conventional and confocal LIF measurements have similar signal-to-noise ratios and line widths*

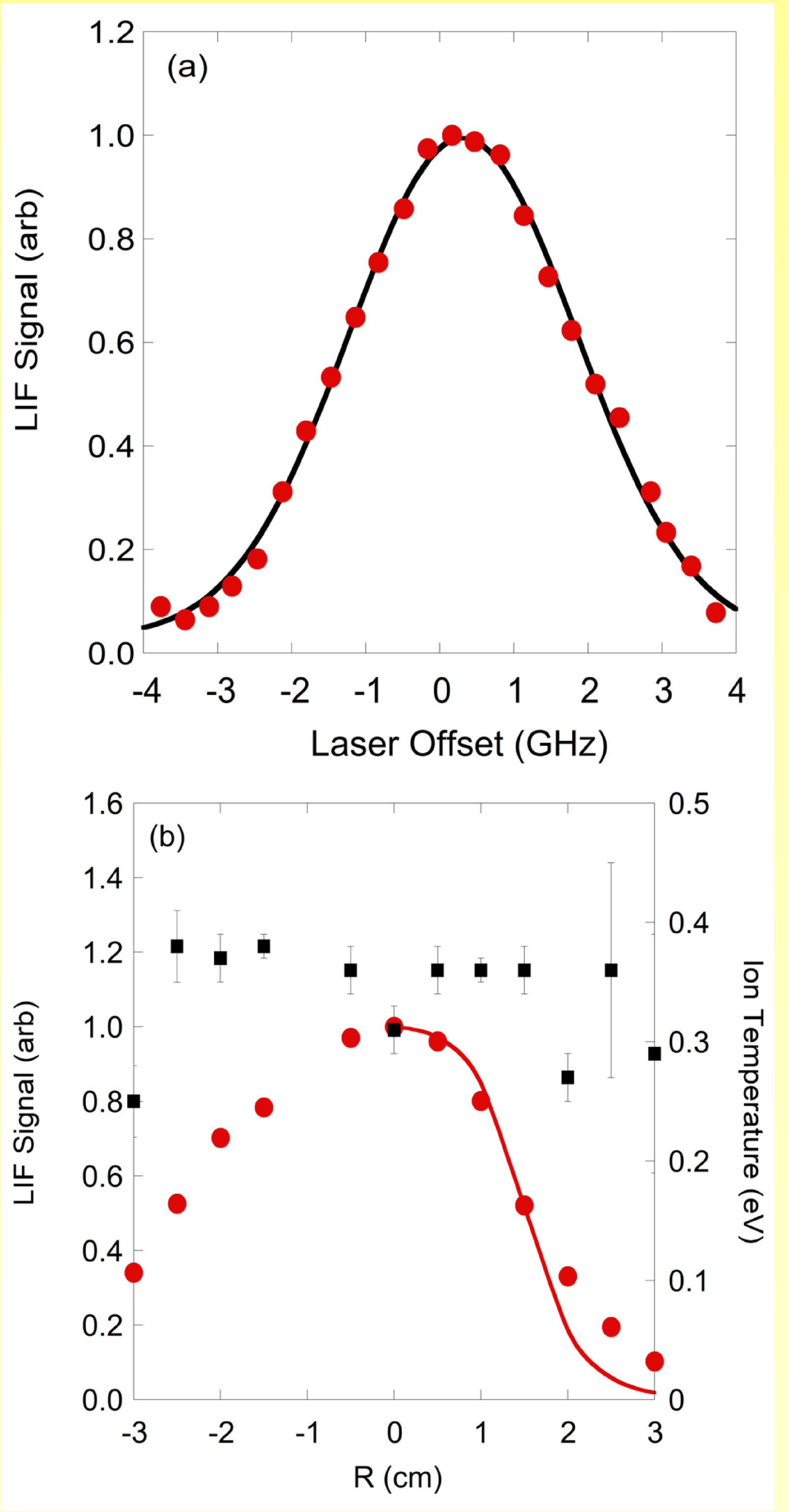
## Traditional LIF Measurements At Different Radial Locations




The high spatial resolution LIF measurements obtained with the 2D apparatus indicate a very narrow, high density core plasma with an ion temperature (squares) that peaks at about 0.4 eV over the inner 2 cm of the plasma.

The metastable ion density (circles) is well fit with a simple decaying exponential curve.

## Confocal LIF Measurements At Different Radial Locations




The upper plot is an example of a confocal LIF measurement obtained near the axis of the plasma source. 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 ~ 0.4 eV.

The lower curve shows the ion temperature (squares) and the metastable 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 metastable ion density profile is also less sharply peaked and shows evidence of asymmetry for measurements made beyond the center of the plasma.

Using exponential fits to the high spatial resolution LIF measurements obtained with the 2D stage, we can analytically integrate over a fix length along the line of sight, $w$. The resultant density signal is given by:

$$0 \le x \le R_0 - w/2$$

$$s(x) = \frac{1}{\alpha w}(2 - e^{\alpha(x-w/2)} - e^{-\alpha(x+w/2)})$$

$$w/2 \le x$$

$$s(x) = \frac{1}{\alpha w}(e^{-\alpha(x-w/2)} - e^{-\alpha(x+w/2)})$$

$\alpha$ is obtained from the exponential fit and the integration length scale was assumed to be 3 cm. 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.**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