Temperature Measurements through Femtosecond Nitric Oxide LIF

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This study demonstrates a method to measure gas temperature using femtosecond (fs) Nitric Oxide (NO) Laser-Induced Fluorescence (LIF). A cell was used with a pressure ranging from $100-1500$ mtorr, and a 2 % NO mixture buffered in nitrogen. A femtosecond (fs) laser system, tuned to excite the NO A-X (0,0) transition, provided the necessary LIF signal. The experiment was conducted in two stages. In the first stage, a resistor and thermocouple were used to heat a NO gas mixture within the cell, establishing a correlation between the LIF 225-to-227 nm LIF signal ratio and temperature. In the second stage, an air inductively coupled plasma (ICP) system generated variable temperature conditions to demonstrate the proof of concept for this technique. The air mixture was maintained at the same pressure range as in the first stage. Results showed a linear relationship between the 225/227 LIF signal ratio and temperature. Simulations and experimental data aligned well, indicating that the 225 nm LIF signal increases with temperature relative to the 227 nm signal. The method was validated under two ICP conditions, showing that it is possible to obtain gas temperature measurements through the use of fs NO LIF.

I. Introduction

II. Experimental Setup

Figure 1 illustrates the setup diagram. This experiment comprises two stages. In the first stage, a resistor and a thermocouple are used to heat a nitric oxide gas mixture by a known amount to establish a relationship between the LIF signal ratio and temperature. The second stage involves using an inductively coupled plasma (ICP) to demonstrate that precise gas temperature measurements can be achieved.

In the first stage of this experiment, a resistor and a thermocouple are placed inside a vacuum cell. The resistor, powered by a HY3003-3 DC Power Supply, heats the gas within the cell, while the thermocouple measures the temperature. An Edwards nXDS20i Vacuum Pump maintains the cell pressure between $100-1500$ mtorr. The cell is filled with a 2 % NO mixture buffered in nitrogen, with the goal of altering its temperature while keeping the pressure constant.

A Spectra-Physics Solstice Ace femtosecond (fs) laser system operating at 800 nm was adjusted to a range of $222-228$ nm using a Topas prime and Niruvis optical parametric amplifier to excite the NO A-X (0,0) transition. Detection was performed using a Pco.Edge 5.5 Camera and a Stanford Computer Optics Quantum Leap intensifier. These were equipped with a band pass filter centered at 253 nm and a bandwidth of 40 nm to capture the LIF signal. The fs pulse occurred at $t = 0$ ns, while the camera had a gate duration of $\tau_{\text{gate}} = 14$ ns and no delay relative to the laser was chosen. This configuration was selected to maximize signal collection and temporal resolution while avoiding any possible quenching. It is also worth noting that for each condition tested, a region of interest containing the laser was selected and averaged. As a result, any spatial information was averaged out.

At a specified temperature determined by the resistor, the laser frequency was adjusted to 225 nm and 227 nm, and their corresponding LIF signals were recorded. The ratio of these signals correlates with the gas temperature, as determined by the thermocouple. The higher the temperature the higher the 225/227 ratio. By conducting these measurements across various temperatures, a relationship between the ratio of the 225 nm and 227 nm signals and

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temperature can be established. This facilitates temperature measurements under unknown conditions, such as those generated by a plasma.

Once the relation between the 225/227 signal ratio and temperature is established the second stage of the experiment can be achieved. An ICP system can be utilized to create the desired unknown conditions. The ICP is generated by a 13.56 MHz signal, which is amplified and adjusted through a matching network. The signal is generated by a Rohde&Schwarz signal generator, amplified by an EIN 325LA RF Power Amplifier, and matched by an MFJ Intellituner. This system is capable of supplying up to 50 W of forward power into the plasma. The gas mixture used is air at the same 100 – 1500 mtorr pressure range.

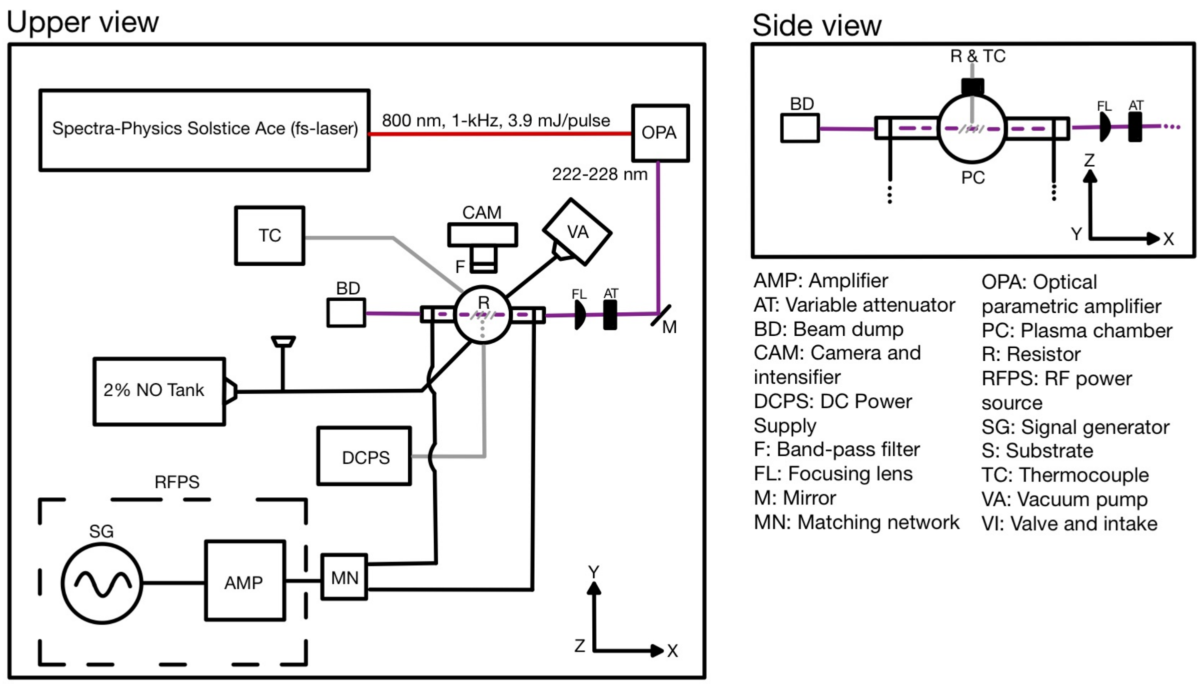

Fig. 1 Experimental setup diagram.

III. Results and Discussion

To avoid saturation, the behavior of the NO LIF signal as a function of laser energy was initially tested. The cell was set to 120 mtorr and filled with a 2 % NO mixture at room temperature. No heat was added, as the resistor was not used. The pulse energy was varied using a variable attenuator, ranging from 1.8 to 11.9 μJ, and the NO LIF signal was recorded. Figure 2 demonstrates that the NO LIF signal exhibits a linear response across the entire investigated range. An energy of 4 μJ per pulse was selected as it falls within the linear regime.

Figure 3 displays the decay of the NO LIF signal over the accumulated wavelength range of 233 – 273 nm. The figure clearly indicates a single exponential decay with a lifetime constant of 175 ns. To minimize quenching effects, a pressure of 115 mtorr was used. Additionally, a 3 ns camera gate was employed in this specific case to maximize temporal resolution.

LIFBASE was used to simulate the LIF accumulated emission (233 – 273 nm) for the NO A-X (0,0) transition at a pressure of 1000 mtorr across different temperatures. Figure 4 shows the accumulated LIF signal for temperatures of 300 K, 600 K, and 900 K as a function of laser frequency. The curves were normalized to the 227 nm point, where the slope remains consistent across all temperatures, indicating that the accumulated LIF signal at this frequency does not vary with temperature. However, the slope at the 225 nm point does change, leading to an increase in the 225-to-227 nm LIF signal ratio with temperature. Therefore, it is possible to tune the laser to these two wavelengths to collect their respective LIF signals and obtain a gas temperature measurement.

Figure 5 presents the same three curves from Fig. 4 after being convolved with a broadband femtosecond pulse. This

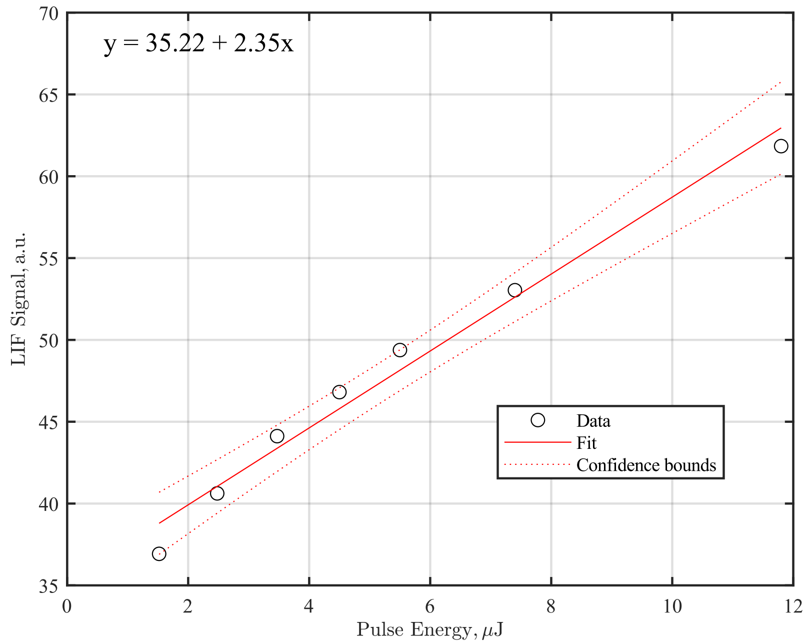

Fig. 2 LIF signal as a function of pulse energy.

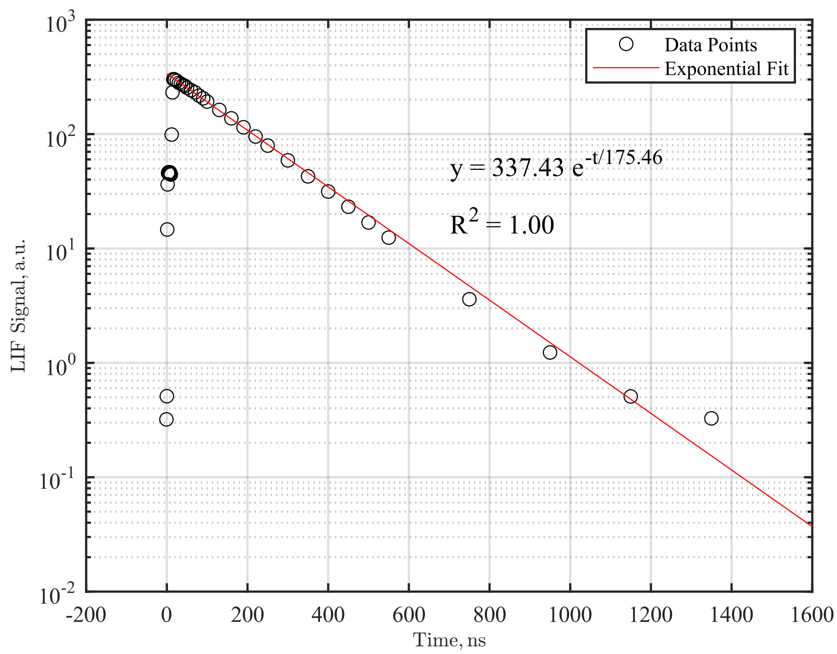

Fig. 3 LIF signal lifetime.

convolution was necessary because LIFBASE assumes a laser pulse with an infinitely small bandwidth, whereas the laser used in this experiment was a broadband femtosecond pulse. The femtosecond pulse was modeled as a Gaussian with a bandwidth of 1 nm FWHM. These simulated curves can now be compared with the experimentally obtained ones shown in Fig. 6. Figure 6 displays the experimentally obtained accumulated LIF signal curves for two different operating ICP conditions and one without ICP. It should be noted that the curves in Fig. 6 were acquired using the air ICP (for the 16 W and 30 W cases) and with the 2 % NO nitrogen-buffered mixture at room temperature for the no plasma case. Additionally, the pressure for all three cases in Fig. 6 was maintained between 100 – 125 mtorr.

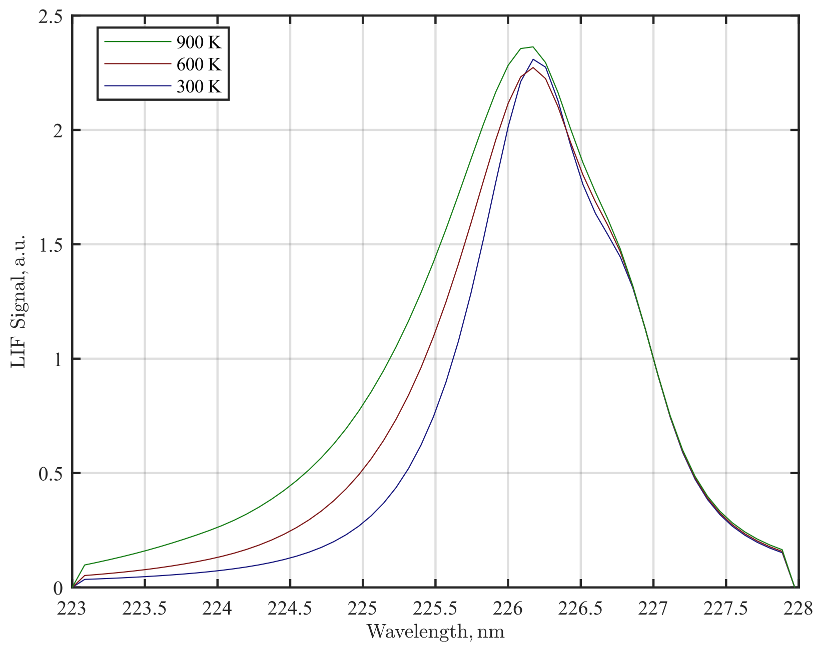

Fig. 4 Simulated LIF signal as a function of laser frequency at various temperatures. Curves are normalized at 227 nm.

The red arrow in Fig. 6 indicates the same trend of increasing LIF signal at 225 nm shown in Fig. 4 and Figure 5. Therefore, this figure experimentally shows that as the plasma gets hotter the LIF signal at 225 nm increases when compared to its 227 nm counterpart. Nonetheless, this assumes that a hotter plasma is obtained the higher its supplied power, which may not always be the case.

Lastly, Figure 7 shows the 225/227 ratios as functions of thermocouple temperature. The blue and black circles represent data obtained using the 2 % NO mixture, where the current in the resistor was varied, the gas temperature was measured with the thermocouple, and the LIF signals at 225 nm and 227 nm were captured using the camera. A linear fit was applied exclusively to the blue and black data points. The gray datapoints were obtained using the air ICP at 20 W and 790 mtorr and measuring the gas temperature using the thermocouple, the heating resistor was not employed. It is important to note that the two gray data points were collected on different days, which explains their slight discrepancy in the graph. The fact that these data points lay so close to the linear fit indicates that it is possible to measure the gas temperature in this plasma using only the 225/227 ratio. Therefore, the temperature of the plasma between these two different days ranges from 100 to 140 °C. Furthermore, the fact that the $R^2 > 0.9$ indicates that this relation is close to linear in the given range. Nonetheless, the next step of this work is to explore pressure effects on the 225/227 ratio and validate this linear relation.

IV. Conclusion

The experimental setup detailed in this study demonstrates a method to measure gas temperature using LIF signal ratios. Initially, a resistor and thermocouple were employed to heat a nitric oxide gas mixture, establishing a relationship between the LIF signal ratio at 225 nm and 227 nm and the temperature. The setup ensured precise temperature control

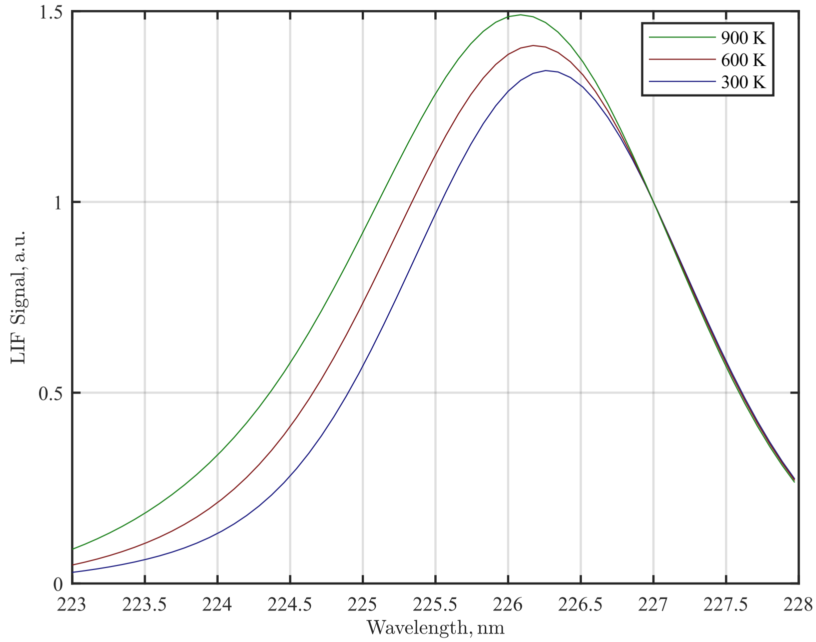

Fig. 5 Simulated LIF signal convoluted with femtosecond pulse as a function of laser frequency at various temperatures. Curves are normalized at 227 nm.

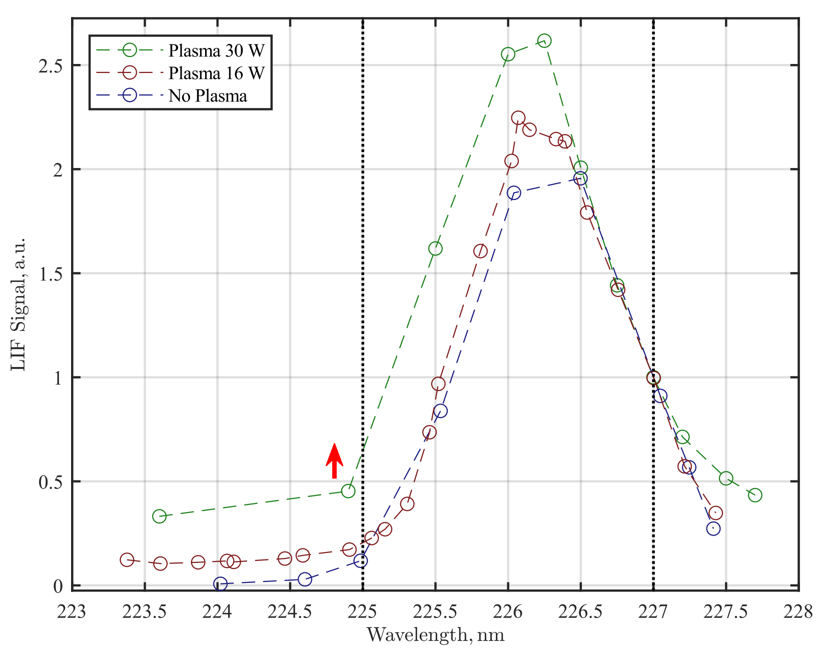

Fig. 6 Measured LIF signal as a function of laser frequency at different operating conditions. Curves are normalized at 227 nm.

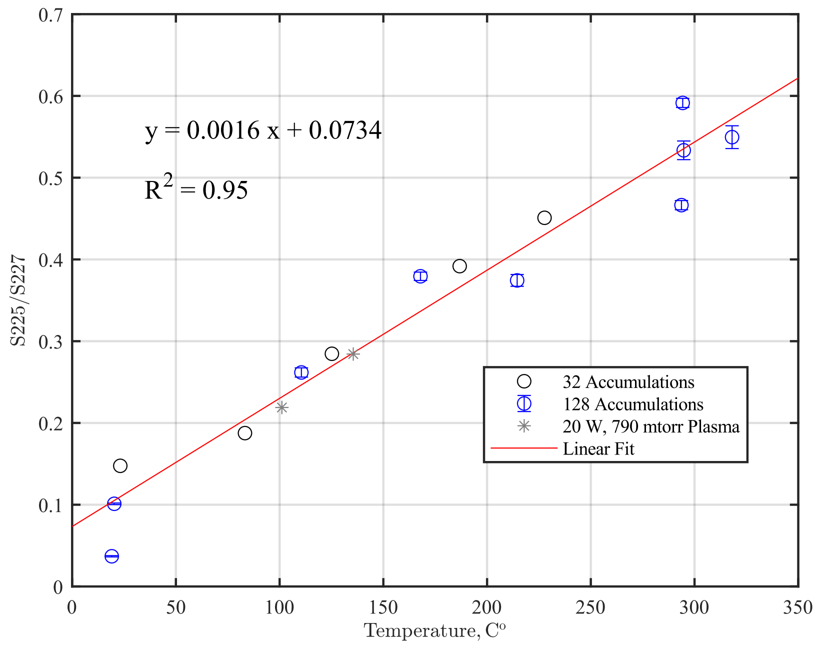

Fig. 7 Temperature measurements.

and measurement within a vacuum cell maintained at 100 − 1500 mtorr. In the second stage, an inductively coupled plasma (ICP) was used to create variable temperature conditions. A femtosecond laser system, adjusted to excite the NO A-X (0,0) transition, and advanced detection equipment ensured accurate LIF signal capture.

The results confirm a linear relationship between the 225/227 LIF signal ratio and temperature. Initial tests with varied laser pulse energy showed a consistent linear response, establishing 4 μJ per pulse as optimal for avoiding saturation. Simulations and experimental data aligned well, showing that the LIF signal at 225 nm increases with temperature compared to the 227 nm signal. ICP operating conditions closely matched the linear fit derived from the resistor-heated setup, validating the temperature measurement approach. This method effectively measures gas temperature in plasma, with future work focusing on exploring pressure effects and further validating this linear relationship.

References