Development of a Novel Time-Resolved Laser-Induced Fluorescence Technique

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Abstract

A novel technique has been developed to measure time-resolved laser-induced fluorescence (TRLIF) signals in plasma sources with a high degree of confidence. The technique utilizes a combination of lock-in amplifiers and phase-sensitive detection algorithms to improve signal-to-noise ratio (SNR) and reduce systematic errors. This allows for the accurate measurement of ion velocity distribution functions (VDFs) in steady-state plasma sources, which is crucial for understanding plasma dynamics. The technique has been validated through comparison with conventional LIF methods and has shown significant improvements in SNR and systematic error reduction.

Introduction

• We have developed a technique using laser-induced fluorescence (LIF) to measure the time-resolved ion velocity distribution (VDF) in plasma sources that have a relatively constant Fourier spectrum of oscillations in steady-state operation, but do not have periodic oscillations.
• Signal modulation is on the order of 1 MHz and we recover the time resolved signal using a combination of band-pass filtering, phase-sensitive detection, and transfer function averaging.

Signal Modulation

• The dwell time used was 60 s per wavelength, compared with several minutes for similar studies using different techniques (and plasma sources) [2][3].
• The drift rate was sufficiently slow that the SNR due to random noise and that transfer function averaging does not introduce a systematic error.
• The mean of the absolute value of the residual is 7% of the total acquisition is split into many smaller chunks of 0.001 s long.

Experimental Configuration

• Power amplifiers in current control mode drive a 10-kV sinusoidal current oscillation.
• The laser is injected axially and light was collected from outside the keeper plate.
• The Xe II transition at 384.95 nm is probed and fluorescence from 541.9 nm is collected.

Signal Processing

• The voltage drop across the 10-kΩ terminating resistor is filtered with a band-pass filter centered on the modulation frequency with a pass band of ±10%, raising SNR by a factor I<sub>SNR</sub>/53.
• The filter output and discharge current are sampled at t<sub>s</sub> = 20 MHz for a total acquisition of 60 s per wavelength. This total acquisition is split into many smaller chunks 0.001 s long.

Signal Modulation (continued)

• For each chunk in each 60-s acquisition:
  • Phase-sensitive detection with time constant τ = 2 μs demodulates the signal and improves SNR by a factor of I<sub>SNR</sub>/2.
  • Transfer function averaging provides the main SNR improvement factor of more than 100.

The SNR improvement factor was:

\[ \text{SNR improvement factor} = I_{SNR}/53 \]

For each chunk in each 60-s acquisition:

• The transfer function describes the response of the LIF signal to any discharge current signal.
• The transfer function is estimated using the lock-in amplifier output and the discharge current.

The dwell time

• The filter output and discharge current are sampled at t<sub>s</sub> = 20 MHz for a total acquisition of 60 s per wavelength.

Example of a time-resolved VDF measurement

• Figures 6 and 9 demonstrate that at any given time the VDF profiles differ only by relatively small random noise.
• Both techniques capture the same general features in the VDF profile, such as mean and spread, including a small acceleration.

Conclusion

• A novel technique to measure time-resolved laser-induced fluorescence (TRLIF) signals was developed and a system implementing the technique was validated using an orificted hollow cathode.
• Measurements were validated by comparison to independent measurements from a typical lock-in amplifier and from triggered ensemble averaging.

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References


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Figures 6 and 7: Animation of the ion VDF profile in the interrogation volume as a function of time.

Fig. 6. Heat maps of normalized TRLIF signal as a function of velocity and time for transfer function averaging (top) and triggered ensemble averaging (middle), and a heat map of the residual between them (bottom).

Fig. 7. Time-averaged VDF profiles from lock-in amplifier (blue line), transfer function averaging (red line), and triggered ensemble average (green ‘x’).

Fig. 8. Snapshots of the VDF profile for the transfer function averaging and (red ‘+’) and triggered ensemble average (green ‘x’).

Fig. 9. Snapshots of the VDF profile for the transfer function averaging and (red ‘+’) and triggered ensemble average (green ‘x’).

Fig. 1. Noise linear spectral density in LIF signal of a Hall thruster.

Fig. 2. Diagram of the experimental setup.

Fig. 3. Diagram illustrating the 60-s acquisition and the 0.001-s chunks taken from the data.

Fig. 4. Flowchart of the algorithm for the novel TRLIF technique.

Fig. 5. Flowchart of the post-processing algorithm for the triggered ensemble averaging technique.

Fig. 8. “Snapshots” of the VDF profile for the transfer function averaging and (red ‘+’) and triggered ensemble average (green ‘x’).