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

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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 [1].
- This technique is suitable when there is strong background signal with a nonwhite spectral density and when oscillations are not repeatable enough to use a triggered ensemble average.
- A band-pass filter centered on the 1-MHz modulation frequency with ±10% pass band results in a SNR improvement factor of I_{BP}~53 for the Hall thruster spectral density, or I_{BP}~4 for white noise.
- Phase-Sensitive Detection gives a further improvement factor of I_{PSD} ~2, for a total improvement >100 from signal conditioning.

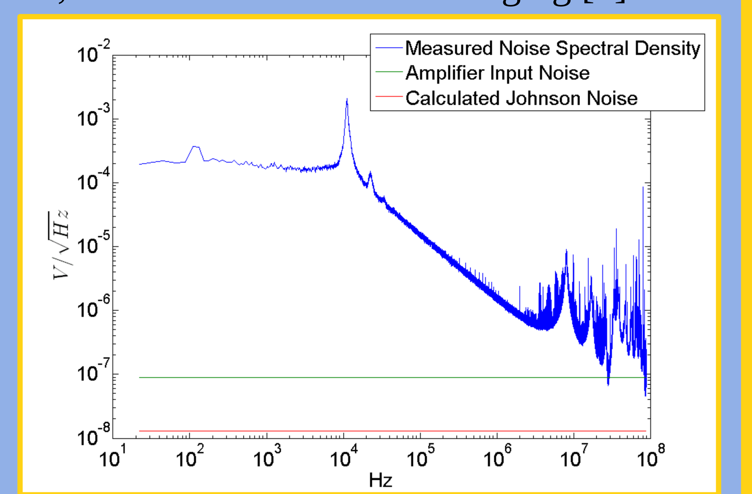

Fig. 1. Noise linear spectral density in LIF signal of a Hall thruster.

- We will apply the new system to Hall thrusters to study breathing and rotating spoke modes (~10kHz).
- The system has a bandwidth limit of about 1 MHz, which is sufficient to interrogate such oscillations.
- Relative to other LIF techniques developed for similar studies, our technique using the above combination of signal processing can be faster and more flexible.
  - The dwell time used was 60 s per wavelength, compared with several minutes for similar studies using different techniques (and plasma sources) [2],[3].
  - Triggering for averaging in the time domain is unnecessary, leading to other advantages:
    (1) Our measurements are made at normal operating conditions without any perturbation to create a reliable phase reference to trigger averaging. In reference [3], for example, measurements were made in a Hall thruster by periodically turning off the discharge current, which was shown to change the VDF.
    (2) If the oscillation is not repeatable and triggered ensemble averaging is used, then the average waveform may not be physically meaningful. For example, if the oscillation period varies, then the ensemble average waveform will have a unphysically decaying amplitude.

Experimental Configuration

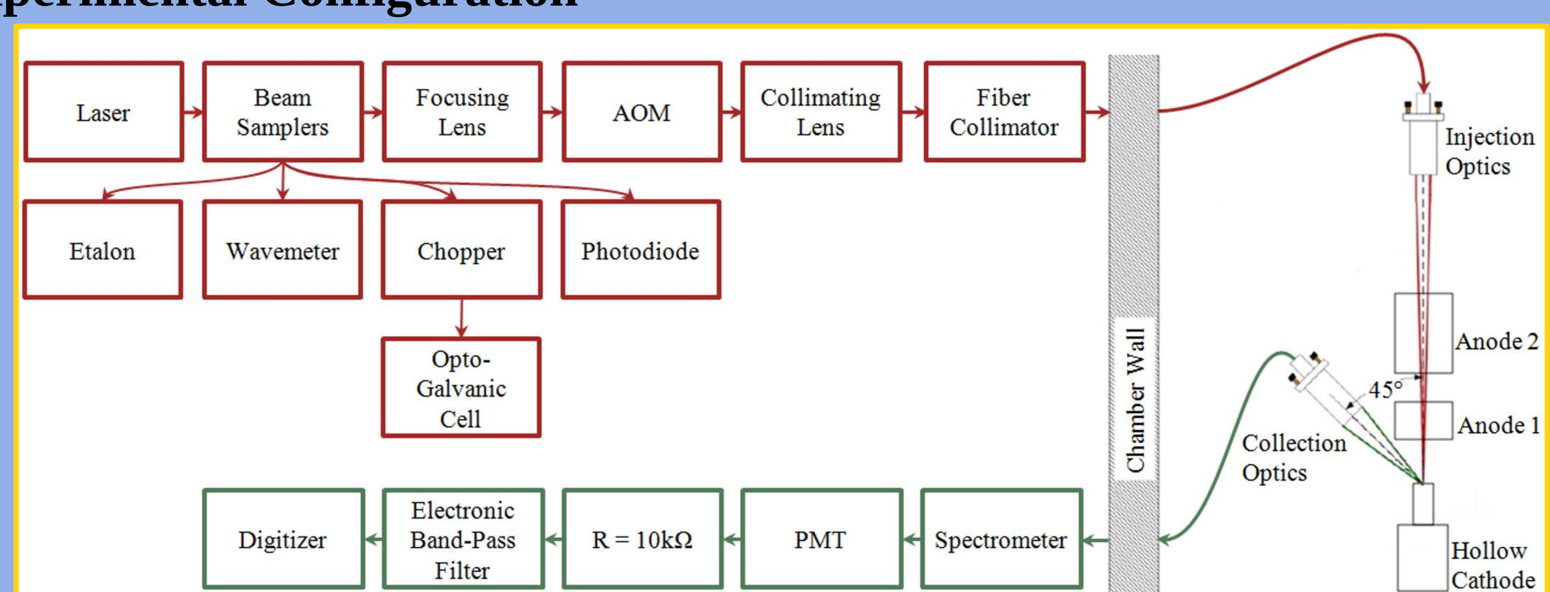

Fig. 2. Diagram of the experimental setup.

- Power amplifiers in current control mode drive a 10-kHz sinusoidal current oscillation.
- The laser is injected axially and light was collected from outside the keeper plate.
- The Xe II transition at 834.953 nm is probed and fluorescence from 541.9 nm is collected.

Signal Processing

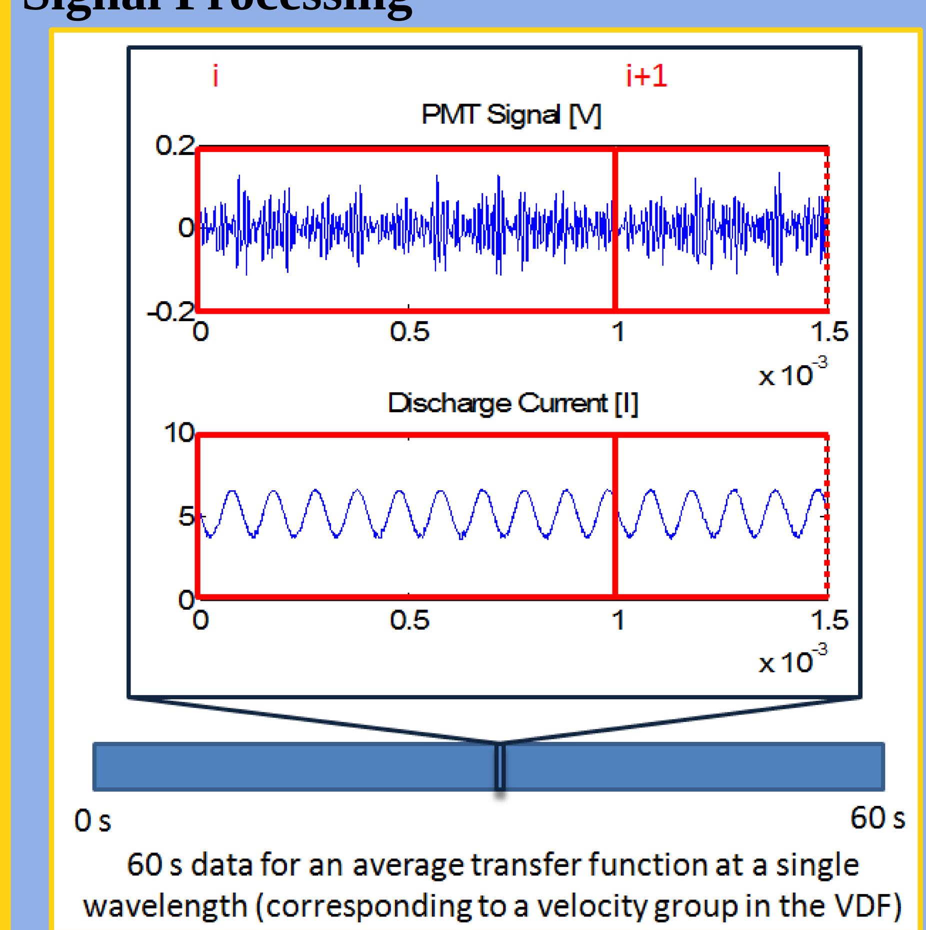

Fig. 3. Diagram illustrating the 60-s acquisition and the 0.001-s chunks taken from the data.

- 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_{BP}~53.
- The filter output and discharge current are sampled at f_{sa} = 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 Processing (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_{PSD} ~2.
  - Transfer function averaging provides the main SNR improvement factor of more than 100.
  - The transfer function describes the response of LIF signal to any discharge current signal.
  - We synthesize the characteristic TRLIF signal by multiplying the average transfer function <H[k]> by the spectrum of a discharge current trace I_D*[n] and transforming to the time domain.
  - We build up the complete VDF by repeating for all wavelengths.

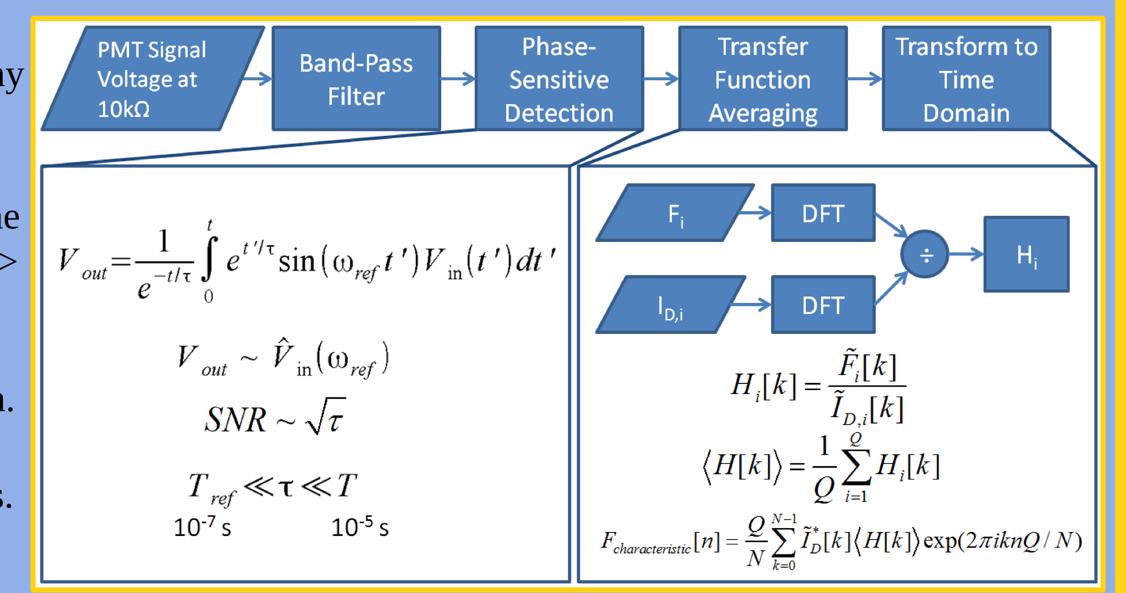

Fig. 4. Flowchart of the algorithm for the novel TRLIF technique.

Validation Argument

- The strategy is to test both the average VDF profile and time-resolved features by comparing the results of the new technique with two independent measurements:
  - Compare to the VDF profile from a lock-in amplifier integrating over a long time constant τ = 100 ms ("conventional LIF"). The large τ effectively averages the VDF profile in time.
  - Compare time-resolved features to results from an average over an ensemble of traces triggered at zero phase in the discharge current oscillation ("triggered ensemble averaging").
- Since we compare the same measurements made with independent analysis techniques, any systematic error that only one technique introduces will be apparent.

Triggered Ensemble Average

- Using the same data, filtering, and phase-sensitive detection, traces are triggered based on the phase of the discharge current and then an ensemble of traces are averaged elementwise to recover the average waveform after each trigger (in lieu of transfer function averaging).
- This comparison isolates the effect of transfer function averaging because that is the most uncommon part of the algorithm and the most open to doubt.

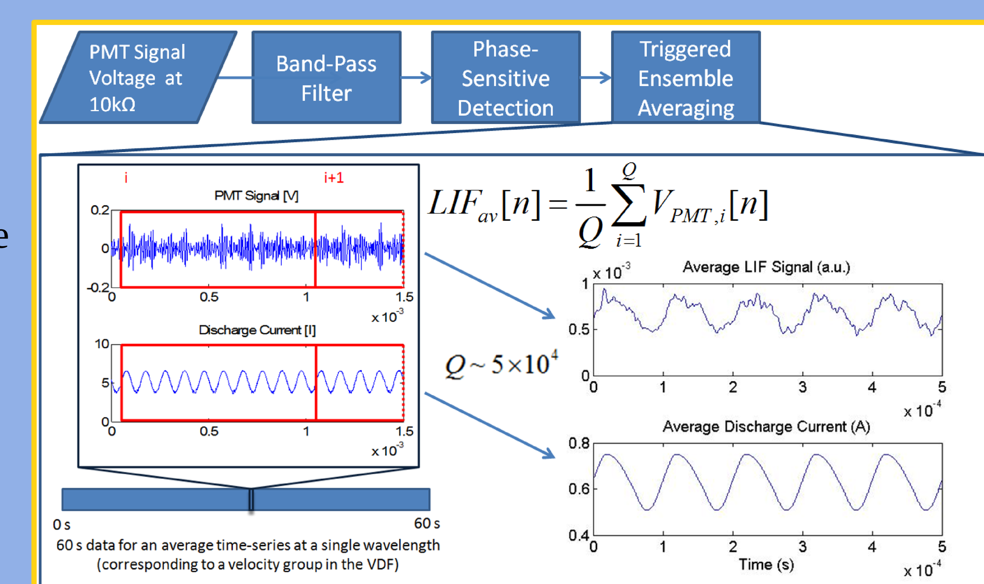

Fig. 5. Flowchart of the post-processing algorithm for the triggered ensemble averaging technique.

Example of a time-resolved VDF measurement

Fig. 6. Animation of the ion VDF profile in the interrogation volume as a function of time.

Does time-averaged TRLIF agree with conventional LIF?

- Figure 7 shows that there is no significant error in the time-averaged VDF profile from TRLIF data.
  - The average VDF profile from the transfer function technique agrees with the lock-in amplifier to within the error of the lock-in measurement.
  - The averages of the two time-resolved techniques agree to within about 0.1%.

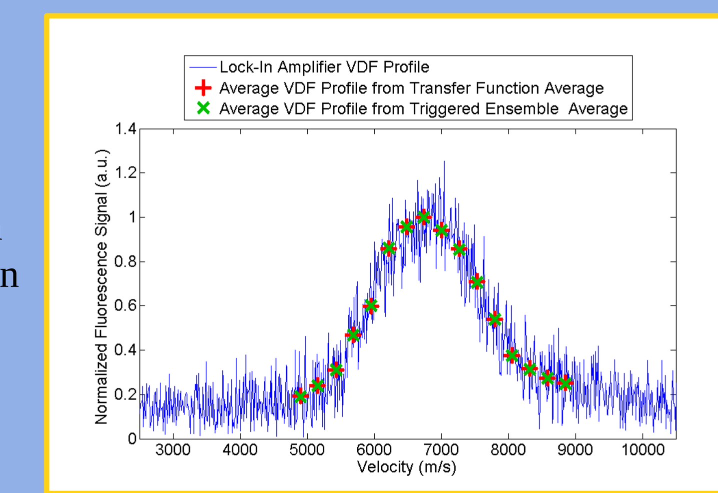

Fig. 7. Time-averaged VDF profiles from lock-in amplifier (blue line), transfer function averaging (red '+'), and triggered ensemble average (green 'x').

Does TRLIF capture the expected time-resolved features?

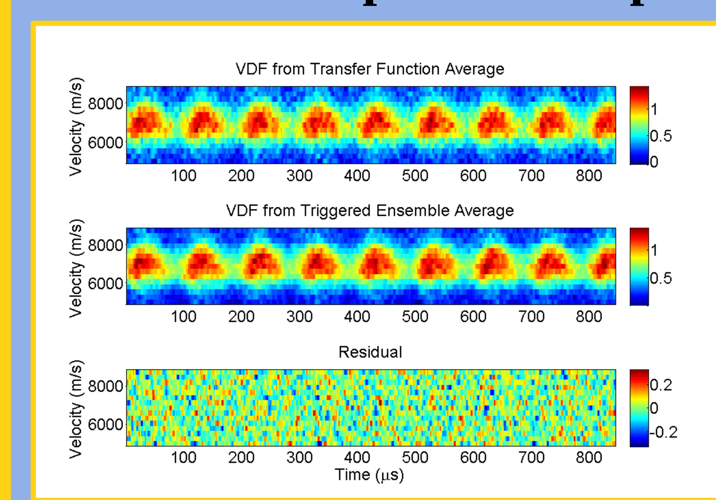

Fig. 8. Heat maps of normalized TRLIF signal as a function of velocity and time for transfer function averaging (top) and triggered ensemble averaging (middle), and a heat map of the residual between them (bottom).

- The TRLIF ion VDF profiles from the two techniques are nearly identical.
- There is no systematic pattern in the residual, confirming that the residual is 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 peak value.
- The final SNR was:
  SNR_{TE}=18 for the triggered ensemble average and SNR_{TF} = 11 for transfer function average
- The SNR improvement factor was:
  I_{TE} = 238 and
  I_{TF} = 148

- 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.

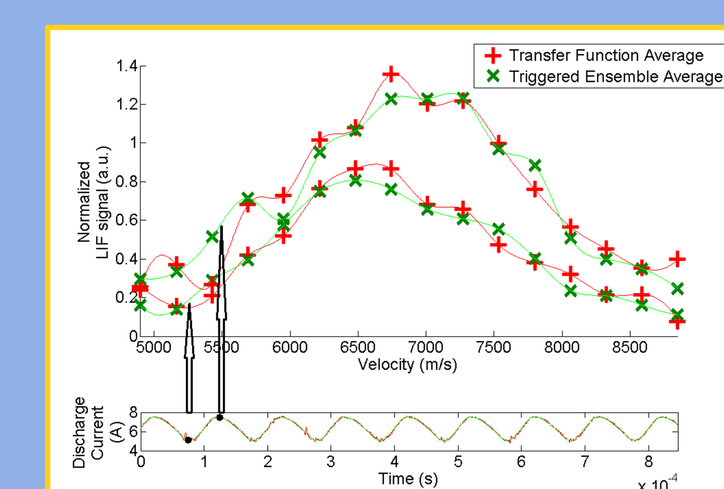

Fig. 9. "Snapshots" of the VDF profile for the transfer function average (red "+") and triggered ensemble average (green "x").

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 orificed hollow cathode.
- Measurements were validated by comparison to independent measurements from a typical lock-in amplifier and from triggered ensemble averaging.
- A journal paper detailing the development and validation of this technique is in review [4].
- Experiments are planned to interrogate breathing and rotating spoke oscillations in Hall thruster plumes.

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