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# Time-synchronized continuous wave laser-induced fluorescence on an oscillatory xenon discharge

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A novel approach to time-synchronizing laser-induced fluorescence measurements to an oscillating current in a 60 Hz xenon discharge lamp using a continuous wave laser is presented. A sample-hold circuit is implemented to separate out signals at different phases along a current cycle, and is followed by a lock-in amplifier to pull out the resulting time-synchronized fluorescence trace from the large background signal. The time evolution of lower state population is derived from the changes in intensity of the fluorescence excitation line shape resulting from laser-induced fluorescence measurements of the  $6s'[1/2]_1^0 - 6p'[3/2]_2$  xenon atomic transition at  $\lambda = 834.68$  nm. Results show that the lower state population oscillates at twice the frequency of the discharge current, 120 Hz. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4766958>]

## I. INTRODUCTION

This paper describes a method of time-synchronizing laser-induced fluorescence (LIF) measurements in an oscillatory discharge to points in time along the discharge current cycle. A continuous wave (CW) diode laser is used to probe the  $6s'[1/2]_1^0 - 6p'[3/2]_2$  neutral transition at 834.68 nm in a 60 Hz xenon lamp discharge. A sample-hold circuit and lock-in amplifier is used to pull out fluorescence excitation line shapes that each correspond to a particular point in time along a discharge current cycle.

Motivation for this work is derived from LIF velocimetry diagnostics applied to low-power plasma propulsion devices, such as Hall thrusters and the diverging cusped field thruster (DCFT).<sup>1</sup> These discharges typically operate on xenon and have spectral linewidths and shifts that are too narrow to resolve with pulsed dye lasers. One of the primary operating modes of the DCFT is characterized by strong, quasi-periodic,  $\sim 3$  kHz current oscillations corresponding to fluctuations in the position of the ionization region in the thruster. Time-averaged LIF studies are not capable of resolving such ion dynamics.

Typical time-resolved LIF measurements employ pulsed dye lasers to study properties such as the spectral line broadening of a given transition, reflecting the temperature, velocity distribution, etc. With a Doppler broadened temperatures on the order of 1800 K, the  $6s'[1/2]_1^0 - 6p'[3/2]_2$  Xe transition used in this work has a linewidth of  $\sim 1.3$  GHz.<sup>1</sup> State of the art pulsed dye lasers have linewidths of  $> 1$  GHz<sup>1</sup> at best. Achieving time-synchronized fluorescence measurements, while maintaining the capability of resolving the transition's spectral features, necessitates the use of a CW laser with linewidths  $< 300$  kHz.<sup>2,3</sup>

Several studies have attempted time-resolved LIF measurements in an oscillating plasma discharge using a CW laser. These studies include the measurements of velocity or

energy distributions in a Hall thruster,<sup>4,5</sup> a magnetic field reconnection experiment in a toroidal shaped plasma device,<sup>6</sup> and a helicon generated pulsed argon plasma.<sup>7</sup> In each of these studies, the plasma discharge was driven at a particular frequency and the fluorescence signal was averaged over tens to hundreds of discharge cycles in order to eliminate background noise. In the case of the Hall thruster, measurements were triggered after short interruptions to the thruster discharge power. For the toroidal plasma device, the open cusped shaped magnetic field was periodically driven to reconnect with the vessel's walls through use of an external poloidal field coil. In the pulsed argon plasma, an external function generator was used to add low frequency (5 Hz) pulses to the rf power driving the helicon discharge.

Our method varies from these previous studies in several important ways. First, it is intended for use on a naturally oscillatory mode of a plasma (in particular, the DCFT) that is operating without any forced (and intrusive) interruption to the discharge current. Second, the natural operation of the DCFT is quasi-periodic, with oscillations driven by the accumulation of ions within the thruster channel and subsequent expulsion of the ions due to an applied electric field. This so-called "breathing mode" is not driven at a particular frequency, as seen in the reconnection experiment, and can therefore drift in frequency over the course of a laser scan. By using phase sensitive detection and a sample-hold circuit that triggers time-synchronization when the discharge current passes through a particular level, not at a particular frequency, we are able to extract fluorescence signals correlated to discharge currents that are not perfectly periodic.

## II. EXPERIMENT

These experiments were performed at the Stanford Plasma Physics Laboratory (SPPL) at Stanford University. The experimental apparatus is shown in Fig. 1. The laser is a New Focus Vortex *TLB* – 6017 tunable CW diode laser, with a center wavelength of 834.7 nm. The laser is typically scanned

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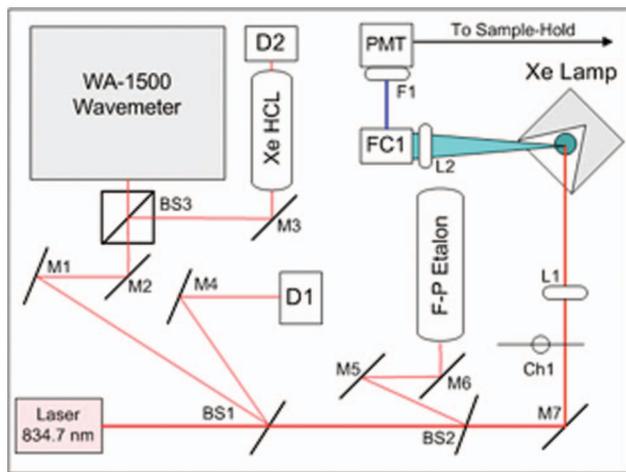


FIG. 1. Top view diagram of the laser optical train and collection optics used to measure fluorescence excitation line shapes for the Xe lamp discharge.

over an  $\sim 20$  GHz frequency range to encompass an entire spectral feature as well as a nearby reference line. The 10 mW beam is passed through several beam pick-offs for diagnostic purposes. The first beam pick-off directs a beam to a photodiode detector (D1) used to provide constant power feedback to the laser. Drift in laser output power is negligible over the course of the  $\sim 3$  min scans used for the Xe lamp, however, monitoring laser power allows for baseline corrections to our signal if necessary (i.e., for future experiments with longer scan lengths). The second beam is divided into two equal components by a 50–50 cube beam splitter. The first component is directed to a Burleigh WA-1000 wavelength meter used to monitor absolute wavelength. The second component is sent through a low pressure xenon hollow cathode discharge lamp (HCL) that provides a wavelength reference through absorption of the neutral xenon  $6s'[1/2]_1^0 - 6p'[3/2]_2$  transition at 834.68 nm.<sup>8,9</sup> The second pick-off sends a beam to a Thorlabs SA200 Fabry-Perot etalon (F-P), with a 1.5 GHz free spectral range and finesse of 200. Combined with the absorption reference, the F-P etalon provides a high resolution frequency measurement that gives a much more accurate measurement of wavelength than the wavemeter as the laser is swept during a scan.

The main portion of the beam is sent through a Stanford Research Systems SR540 chopper, rotating at 11 Hz for phase sensitive detection, and is then focused by a 2 in., 100 mm focal length lens onto the center of a 60 Hz xenon spectral lamp that is run by an SP-200 power supply. This relatively slow chopper frequency is chosen such that the 60 Hz oscillation in the discharge current goes through several cycles for each chopper on/off period. Although there is a small detectable xenon ion population in this particular discharge, a better signal is achieved by probing the  $6s'[1/2]_1^0 - 6p'[3/2]_2$  neutral transition at 834.68 nm. Non-resonant fluorescence from the  $6s[3/2]_1^0 - 6p'[3/2]_2$  transition is collected at 473.42 nm<sup>10</sup> to minimize back-scatter from reflections of the lamp surface.

Light from the lamp, including both the fluorescence signal at 473.42 nm and background emission, is collected at an angle  $90^\circ$  from the incident probe beam by a 1 in., 100 mm focal length lens, then fed into a fiber optic cable via a 1 in.

diameter Thorlabs F810SMA-543 fiber collimation lens. The fiber optic cables used in this set-up are Thorlabs multimode cables with 200  $\mu\text{m}$  silicon core and 220  $\mu\text{m}$  cladding, with a numerical aperture (NA) of 0.22. The cables transport the collected fluorescence through a 10 nm bandpass filter, centered at 470 nm to filter out the majority of background light, and into a photomultiplier tube (PMT). If sent directly into a lock-in amplifier, this set-up would provide a time-averaged measurement of the fluorescence excitation line shape.

To time-synchronize the LIF signal to the discharge current, a sample-and-hold scheme is implemented between the PMT and the lock-in amplifier. The sample-and-hold and lock-in method was first implemented in software. Simultaneous measurements are taken of the discharge current, absorption reference, etalon, chopper reference, and fluorescence signal from the PMT, as the CW laser is scanned slowly in wavelength across the spectral feature. The fluorescence is embedded in background interference and associated noise, the majority of which is produced by emission from the discharge.

The discharge current as a function of time is passed through a low pass filter for noise reduction. Points where the AC from the Xe discharge crosses through zero with a positive slope are then located. The points are considered to be time  $t_0$  within the discharge current cycle. Times  $t_1$ ,  $t_2$ , etc., along the current cycle are then determined based on a delay time with reference to the  $t_0$  points.

The emission plus fluorescence signal is then passed through a digital sample and hold circuit, as shown in Fig. 2. The lower portion of this figure shows the current trace, with points for time  $t_0$  through  $t_2$  shown as dots. The upper portion of the graph gives the raw PMT signal, with the chopper on/off cycle also shown as a black dotted line, for reference. The emission plus fluorescence trace is sampled at the first data point corresponding to time  $t_0$  in the current trace. This value is then held until the current cycle reaches its next positive zero crossing, at which time the emission plus fluorescence trace is re-sampled and held until the next crossing. This process is repeated for data points corresponding to times  $t_1$ ,  $t_2$ , etc., thereby splitting the emission plus

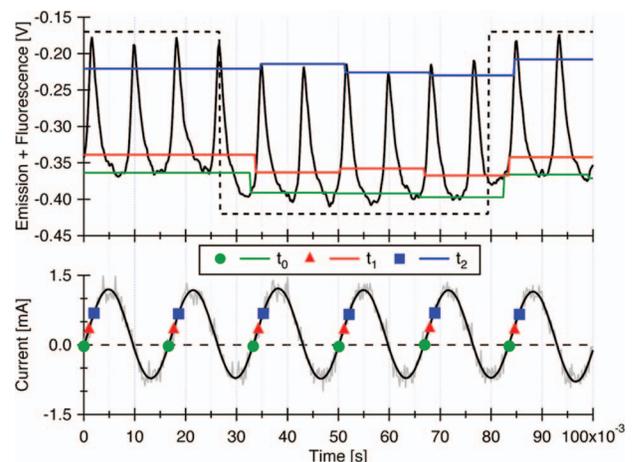


FIG. 2. Example of correlation between points in current cycle (bottom) and sample-held signals from the emission plus fluorescence trace (top) taken from a 60 Hz Xe discharge lamp.

fluorescence signal into  $N$  separate signals corresponding to  $N$  different times within a discharge current cycle. The individual sample-held signals are then passed through a digital lock-in, along with the recorded chopper reference, to extract the time correlated fluorescence excitation line shape out of the background emission. In this way, a single laser scan (taking several minutes for a  $\sim 20$  GHz frequency range) can be used to extract a number of time-dependent fluorescence excitation line shapes.

Although the software version of this procedure is desirable due to the need for only a single scan to time-synchronize the fluorescence to the discharge current, applications of this method can include a hardware version of the sample-hold and lock-in amplifier. The impetus for the hardware version is the much lower signal-to-noise ratio seen in the DCFT as compared to the xenon spectral lamp. To achieve good results for the DCFT, laser scan lengths are typically on the order of 30 min to encompass the  $\sim 20$  GHz frequency range. For a 3 kHz discharge, the number of data samples required to implement the software sample-hold and achieve fluorescence excitation line shapes at ten points in time is at minimum 54 mega samples per channel. This is beyond the capability of the 16 bit Gage scope card used in this work. Also, the high dynamic reserve achieved by a hardware lock-in amplifier, such as the Stanford Research Systems (SRS) SR-850, is computationally expensive to replicate. Figure 3 provides a block diagram describing the hardware version of the sample-hold approach. Although not necessary to pull out time-synchronized signals on the xenon discharge lamp, results provided later in this work will confirm that both hardware and software approaches to the sample-hold give similar results, thereby validating the hardware sample-hold for future use on the DCFT.

For the hardware sample-hold design, the current from the Xe lamp discharge is fed into an LM339 comparator chip to transform it into a series of transistor-transistor logic (TTL) pulses (see Fig. 3). The resulting signal from comparator is a square wave with an approximately 50% duty cycle. With inputs from the comparator and the raw emission plus fluorescence signal from the PMT, an SRS SR-250 Boxcar Averager is used to perform the sample-hold function.

For every positive slope in the comparator signal, the boxcar averager samples the PMT signal for a period of time defined by the gate width. The last sampled value of the PMT

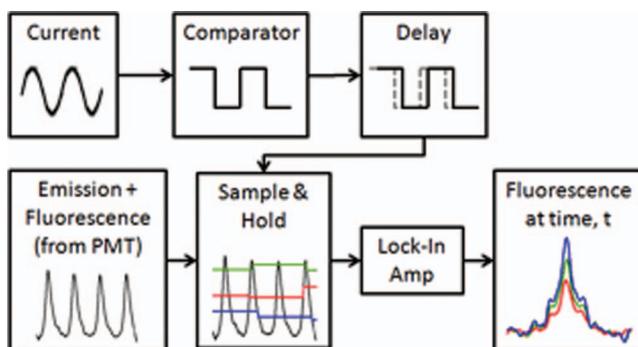


FIG. 3. Block diagram of the sample-hold method of synchronizing the fluorescence trace to various times along a discharge current cycle.

signal is then held until the next comparator trigger, at which point the boxcar averager re-samples the PMT signal and holds the value again. This process repeats itself throughout the length of the laser scan. The output of the boxcar averager (i.e., the sample-held signal) is fed directly into an SRS SR-850 Lock-in Amplifier along with the chopper reference frequency for phase sensitive detection. The result is a fluorescence excitation line shape synchronized to time  $t_0$  in the current discharge cycle. To sample additional times along the current cycle, the built in time delay in the SR-250 is used to adjust the sample trigger, and the laser scan is repeated.

### III. RESULTS AND DISCUSSION

The spectral lamp used to demonstrate this diagnostic consists of a long, thin glass tube filled with xenon gas that has electrodes on each end. With an AC input to the lamp, each electrode takes turns operating as the anode and cathode over the course of a current cycle. The high voltage applied across the electrodes provides the electrons with enough energy to ionize the xenon gas in the tube, creating a plasma discharge. In order to sustain the discharge, the cathode has to maintain the temperature required for thermionic emission through a combination of the supplied current and bombardment of ions from the discharge. The ion current in the discharge is not enough to provide the necessary heating. Therefore, a positive space charge sheath forms at the cathode to accelerate the ions towards its surface, while the cathode surface itself maintains a negative electric potential to accelerate electrons into the discharge.<sup>11</sup>

Referring back to Fig. 2, we see that the raw PMT signal (emission plus fluorescence) oscillates at approximately 120 Hz, double that of the 60 Hz current supplied to the lamp, as expected. With a negatively biased PMT, the peaks in this trace represent the points of minimum amplitude in the emission. These points occur  $\sim 1$  ms after the current signal passes through zero in both the positive and negative direction. The emission signal (i.e., when the chopper is closed) is proportional to the number density of the upper level of the  $6'[3/2]_1^0 - 6p'[3/2]_2$  transition that emits at 473.42 nm as background interference.

Figure 4 provides a fluorescence excitation line shape for time  $t_0$ , obtained with the hardware sample-hold method.

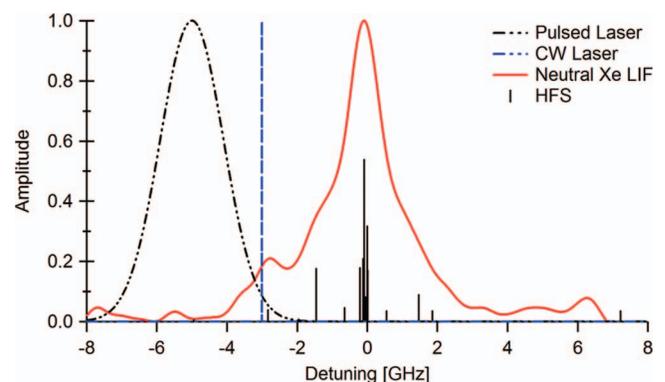


FIG. 4. Fluorescence excitation line shape at time  $t_0$  for the Xe lamp discharge as compared to the width of a typical CW laser and a pulsed dye laser.

The hyperfine structure (HFS) of the transition is shown for reference, as it contributes to the asymmetry of the line shape. A spectral fit of this line shape is made by summing individually broadened hyperfine components of the xenon transition, each weighted by their known relative line strength. Assuming only the natural linewidth and Doppler broadening, a spectral fit to this line shape suggests that the temperature of the xenon in this discharge is  $\sim 1800$  K. We find that the line shape is relatively constant over the course of the current cycle, suggesting that this spectral line may be predominantly pressure broadened. The lack of information available about the xenon fill pressure in the tube leaves us unable to determine the pressure broadening coefficients. Therefore, 1800 K should be seen as an upper limit to the actual temperature in the lamp.

Also shown in Fig. 4 are the linewidths for a CW and a pulsed dye laser. As mentioned above, these line widths illustrate the need for a CW laser when resolving this spectral feature. Furthermore, the use of a continuously scanning CW laser that is modulated by a mechanical chopper with a 50% duty cycle (as opposed to a pulsed laser with small duty cycle), necessitates the use of a lock-in for signal recovery instead of using the SR-250 Boxcar Averager in the gated integrator mode. For this application, gated integration would require active background subtraction and averaging over a large number of signal on/off cycles to achieve similar results as phase sensitive detection. By using the chopper reference frequency for phase sensitive detection, jitter in the frequency of the discharge current has little to no effect on the measurement when using the sample-hold/lock-in method. In contrast, straight addition and subtraction of signals in the time-domain reduce the effectiveness of gated integration when the desired signal is not perfectly periodic.

Figure 5 provides the time evolution of the peak intensities of the fluorescence excitation line shape over the course of a single current cycle. Data points are shown for both the hardware and software versions of the sample-hold and lock-in method. Best fit curves of the data reveal that the peak intensities, indicative of the lower state population of

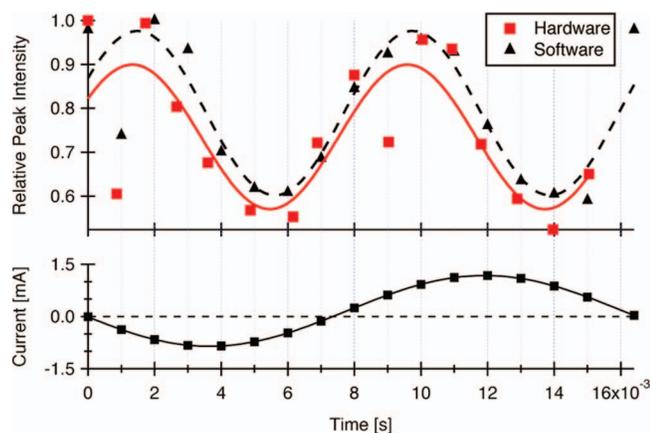


FIG. 5. Peak amplitudes of fluorescence excitation line shapes (top), synchronized in time with the lamp discharge current cycle (bottom). Note: Peaks are normalized such that the maximum in the cycle equals unity to eliminate any difference in the amplification factor between the hardware ( $\square$ ) and software ( $\triangle$ ) versions of the lock-in amplifier.

the  $6s'[1/2]_1^0 - 6p'[3/2]_2$  xenon atomic transition, also oscillate at a frequency of 120 Hz, but with an  $\sim 2$  ms delay from the zero point crossing of the current. This suggests that the lower state population fluctuates with a  $\sim 1$  ms phase delay relative to that of the upper state.

In this type of discharge, the local electric field is directly proportional to the local current density.<sup>11</sup> The nonlinear response in the spontaneous emission from the discharge reflects a strong field dependence in the collisional excitation of the  $6p'[3/2]_2$  upper state. The 1 ms phase lag between the current passing through zero and the maximum emission amplitude can be a consequence of this nonlinearity and also the possible development of the sheath at each electrode as the current oscillates. The additional 1 ms phase shift between the peak in the LIF and the peak in the background emission suggests that the population of the lower  $6s'[1/2]_1^0$  state is established by a mechanism that is different but closely coupled to that of the upper state.

#### IV. CONCLUSIONS

In summary, both software and hardware versions of a sample-hold and lock-in amplifier have been implemented in an effort to time-synchronize CW laser-induced fluorescence measurements on a 60 Hz xenon lamp to its discharge current cycle. The approach introduced allows us to probe spectrally narrow, quasi-periodically varying line shapes that would be inaccessible with a typical tunable pulsed dye laser.

In the spectral lamp probed as a demonstration of this method, results show a strong correlation between the dynamics of the current and measured fluorescence intensities, with both the upper and lower state populations of the probed transition fluctuating at double the discharge current frequency, but slightly out of phase with each other. The width of the spectral line shape in this discharge, while resolved, did not appear to vary strongly with time, presumably due to a strong component of pressure broadening.

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