**Title**: Development of a Time Synchronized CW-Laser Induced Fluorescence Measurement for Quasi-Periodic Oscillatory Plasma Discharges

**Authors**: MacDonald, Cappelli, and William A. Hargus Jr.

**Abstract**: An advanced CW laser induced fluorescence diagnostic technique, capable of correlating high frequency current fluctuations to the resulting fluorescence excitation lineshapes, has been developed. This presentation describes this so-called "Sample-Hold" method of time-synchronization, and provides the steps taken to validate this technique, including simulations and experimental measurements on a 60 Hz Xe lamp discharge. Initial results for time-synchronized velocity measurements on the quasi-periodic oscillatory mode of a magnetic cusped plasma accelerator are also presented. These results show that the positions of the ionization and peak acceleration regions in the device vary over the course of a discharge current oscillation.
Development of a Time Synchronized CW-Laser Induced Fluorescence Measurement for Quasi-Periodic Oscillatory Plasma Discharges

Natalia A. MacDonald
Mark A. Cappelli
Stanford Plasma Physics Laboratory
Stanford University
Stanford, CA

William A. Hargus, Jr.
Spacecraft Propulsion Branch
Air Force Research Laboratory
Edwards Air Force Base, CA

Distribution A: approved for public release, distribution unlimited
Outline

• Introduction
  – Motivation for research
  – Laser Induced Fluorescence (LIF) velocimetry

• Sample-Hold Method
  – Digital
  – Hardware

• Time-synchronized LIF characterization
  – Modeling of time-synchronization schemes
  – Table-top experiment results
  – DCFT experiment results

• Conclusions & Future Work
Motivation

- LIF velocimetry diagnostics applied to the Diverging Cusped Field Thruster (DCFT)
  - Low Current Mode

A Time-Synchronized method of CW-LIF is needed!

- Discharges typically operate on xenon
  - Spectral linewidths and shifts that are too narrow to resolve with pulsed dye lasers

DCFT operating in:  
- b) High current mode,  
- c) Low current mode

A) Schematic of DCFT

D) DCFT Current Traces
Laser-induced Fluorescence Velocimetry

LIF is used to measure the velocity of ions in the thruster plume

- Laser beam tuned across electronic transition in Xe ions
  \[ 5d[4]_{7/2} - 6p[3]_{5/2} \text{ at } 834.72 \text{ nm} \]

- Ions spontaneously emit photons resulting in their relaxation from its excited state to a lower state (fluorescence)
  \[ 6s[2]_{3/2} - 6p[3]_{5/2} \text{ at } 541.92 \text{ nm} \]

Non-resonant fluorescence scheme

- Fluorescence excitation spectrum = convolution of ion velocity distribution function (VDF), and transition lineshape (inc. hfs, etc.)

- Shape (broadening/shift) dominated by Doppler effect:
  \[ \delta v_{12} = \frac{V}{c} v_{12} \]

Distribution A: approved for public release, distribution unlimited
Approaches to Time-Synchronization

**Option 1:**
- Use pulsed laser to make time resolved LIF measurements

**Issues:**
- Typical linewidth of pulsed laser is larger than desired
  - Pulsed Nd:Yag Pumped Dye Laser: > 1.5 GHz
  - Typical Doppler width of transition: < 2 GHz

**Option 2:**
- Use CW diode laser to take time resolved LIF measurements
  - CW Diode Laser: < 300 kHz

**Approach:**
- Take advantage of periodicity of thruster discharge
  - Synchronize acquisition of fluorescence signal with oscillating discharge current
- Two methods considered
  - Boxcar Averager
    - Adds signals in time domain when chopper is open, subtracts when chopper is closed
  - Sample-Hold
    - Uses phase-sensitive detection to remove background
Why Sample-Hold?

**Boxcar Averager**

- Boxcar averager method is more similar to previous studies, including measurements of velocity or energy distributions in:
  - Hall thruster\(^1\)
  - Magnetic field reconnection in a toroidal shaped plasma device\(^2\)
  - Helicon generated pulsed argon plasma\(^3\)
- In previous studies, plasma discharge was driven at a particular frequency
- DCFT is naturally quasi-periodic
  - Straight addition and subtraction of current cycle signals are not effective
  - Signals have to be stretched or interpolated such that they cover the same amount of time, introducing error

**Sample-Hold**

- Phase sensitive detection allows for jitter in frequency of discharge current
- Sample-hold method can get good result with fewer scans
- For small signals that can’t be pulled out by boxcar averager method or digital lock-in, hardware version of sample-hold is available
  - High dynamic reserve of SR-850 Lock-In

References:

DCFT current traces, taken approx. 30 seconds apart. Note: slight change in frequency
Simultaneous measurements of discharge current, emission + fluorescence

Zero point crossings of discharge current with positive slope are located
- Crossing points considered as time = t₀
- Times t₁, t₂, etc. determined based on a delay time with reference to the t₀ points

Emission plus fluorescence trace is sampled at the first data point corresponding to time = t₀

This value is held until the current cycle reaches its next positive zero crossing

Emission plus fluorescence trace is re-sampled and held until the next crossing

This process is repeated for times t₁, t₂, ..., splitting emission plus fluorescence trace into N separate signals corresponding to N times within the current cycle

The individual sample-held signals are passed through digital lock-in amplifier to pull out time-synchronized fluorescence excitation lineshapes
Hardware Sample-Hold Method

- AC current from the Xe lamp discharge is fed into an LM339 comparator chip
  - Comparator output is +5 V when signal from current is above 0.005 V, and 0 V when current signal is below 0.005 V
  - Comparator is configured with a hysteresis circuit to prevent over-triggering
  - Output of comparator is a series of transistor-transistor logic (TTL) pulses with ~50% duty cycle
- TTL Pulses from comparator trigger sample-hold on a Stanford Research Systems SR-250 Boxcar Averager
  - Other SR-250 inputs/settings:
    - Raw emission plus fluorescence from PMT
    - Gate width = 15 μs
    - Delay time = 0 to 160 ms
  - Positive slopes in TTL trigger the boxcar averager to sample the PMT signal for a period of time defined by the gate width
  - The last sampled value of the PMT signal is held until the next TTL trigger
  - Boxcar averager re-samples the PMT signal and holds the value again
- Sample-held output is fed directly into an SRS SR-850 Lock-in Amplifier
  - Phase sensitive detection at chopper reference frequency
  - Output is a fluorescence excitation lineshape synchronized to time t₀ in the current discharge cycle
- To sample additional times along the current cycle, built in time delay in the SR-250 is used to adjust the sample trigger
Modeling of Time-Sync Method

- 3 kHz model – Similar to velocity and amplitude changes expected in DCFT
  - 5 levels of Gaussian profiles with different height and centerline frequency imbedded in chopper on/off signal
  - Background added to fluorescence signal to test noise rejection
  - Successfully rejects noise, including:
    - Sinusoidal background with frequency = 2x current frequency, amplitude = 10x to 1,000x fluorescence
    - Gaussian background noise, amplitude = 2x fluorescence

Results of sample-hold method on 3kHz model with 2x noise
Measurements on 60 Hz Xe spectral lamp
- Measuring change in lower state population rather than shift in wavelength
- Population inferred by time-sync LIF intensity

Neutral (Xe I) transition at 834.68 nm probed
- $6s'[{1/2}]_1^0 - 6p'[{3/2}]_2^0$

Non-resonant fluorescence collected at 473.42 nm
- $6s[{3/2}]_1^0 - 6p'[{3/2}]_2^0$

Collected light is coupled to an optical fiber and onto a PMT and sent to Sample-Hold
- 10 nm BP filter centered at 470 nm

Two implementations of sample-hold
- Digital/Software
- Analog/Hardware
Xe Lamp Results

- Peak intensities of fluorescence excitation lineshapes oscillate at 120 Hz
  - Indicative of the lower state population of the $6s'[1/2]_1 - 6p'[3/2]_2$ Xe transition
  - Digital and analog versions of sample-hold give similar results

- Background emission also oscillates at 120 Hz
  - Indicative of the upper state population of the $6s'[1/2]_1 - 6p'[3/2]_2$ Xe transition

- Phase delay seen between current, emission and fluorescence intensity peaks
  - Emission delays may be caused by development and diminishment of sheaths at each electrode
  - LIF delay may reflect a difference in mechanism for populating lower and upper states, although they appear closely coupled

- Width of transition changes slightly with time
  - Changes in width are not well correlated with current fluctuations
  - Transition appears pressure broadened
    - $P \approx 7$ torr (comparing to results from Cedolin thesis)
  - More information about the lamp is required for temperature estimates

Best Voigt fit of transition at time $= t_0$ assuming Doppler temperature of 300 K and $a = 2.7$
Time-Sync DCFT Experiment

- Hardware version of sample-hold used for DCFT experiments
  - High dynamic reserve of SR-850 Lock-in Amplifier gives better noise rejection
- Xenon ion (Xe II) transition at 834.72 nm probed
  - $5d[4]_{7/2} - 6p[3]_{5/2}$ at 834.72 nm
- Non-resonant fluorescence collected at 541.92 nm
  - $6s[2]_{3/2} - 6p[3]_{5/2}$ at 541.92 nm
- Chopper frequency at 400 Hz
  - Must be slower than discharge current frequency for sample-hold
Time-Sync DCFT Experiment

- Time-sync LIF measurements made at 3 points in plume
  - Point #1: R = 8 mm, Z = -16 mm
    - Inside channel, near separatrix at cusp #2 (C2)
    - Likely a region of ionization
  - Point #2: R = 8 mm, Z = 0 mm
    - At exit plane, near separatrix at cusp #3 (C3)
    - Close to region of maximum potential drop/ion acceleration
  - Point #3: R = 16 mm, Z = +4 mm
    - In “jet” region of plume

**DCFT Operating Conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode Flow Rate</td>
<td>830 μg/s Xe (8.5 sccm)</td>
</tr>
<tr>
<td>Anode Potential</td>
<td>300 V</td>
</tr>
<tr>
<td>Anode Current</td>
<td>0.49 A</td>
</tr>
<tr>
<td>Background Pressure</td>
<td>5x10^{-6} torr</td>
</tr>
</tbody>
</table>

Measurement locations for time-sync LIF on DCFT
Time-Sync DCFT Results

- Current oscillations driven by accumulation and expulsion of ions within the thruster channel
- Axial velocities change over the course of a single current cycle
- Do positions of ionization and acceleration regions shift over time?
Simulation of DCFT Results

• 1-D Matlab code written to simulate acceleration of ions
• Assumptions:
  – Position of ionization and acceleration regions oscillate proportional to current fluctuations
  – Ionization region oscillates around $Z = -16$ mm
  – Peak electric field oscillates around $Z = +2$ mm
  – Electric field only considered in ion acceleration
Analysis of DCFT Results

- **Point #1: R = 8 mm, Z = -16 mm**
  - Ionization region moves back and forth across separatrix at second cusp, correlated in time to current pulses
  - Times when ionization region is deeper in the channel have higher velocity
  - When ionization region starts to pass Z = -16 mm, velocity is slower

- **Point #2: R = 8 mm, Z = 0 mm**
  - Position of largest potential drop/peak electric field moves back and forth across outermost separatrix, correlated in time to current pulses

- **Point #3: R = 16 mm, Z = +4 mm**
  - Past peak acceleration region
  - Ions continue on ballistic trajectories determined in regions similar to Point #1 and #2
Summary

- Sample & hold/phase sensitive detection method has been implemented in software and hardware to synchronize fluorescence signal to discharge current
- Table-top measurements on Xe spectral lamp validated method for both software and hardware versions of sample-hold
- Time-sync measurements made at several positions in the plume of the DCFT
- Current oscillations appear similar to a breathing mode seen in Hall thrusters

Future Work

- Increase S/N for time-sync on the DCFT by using higher power laser
- With increased S/N, make more extensive (spatially) measurements throughout the plume of the DCFT
- Time-synchronized LIF measurement could be applied to other quasi-periodic discharges in fields such as combustion, materials processing, etc.
Thank You!

- Stanford Plasma Physics Laboratory
  - Prof. Mark Cappelli

Collaborations with:
- Air Force Research Laboratory, Edwards AFB
  - Dr. Bill Hargus Jr.

Funding through:
- Science Mathematics And Research for Transformation (SMART) scholarship program
- Air Force Office of Scientific Research, under grant monitor Dr. M. Birkan
Back-up Slides
Gated Integration vs. Phase Sensitive Detection

Note: For CW-LIF, mechanical chopper is used to modulate frequency with a 50% duty cycle

- **Phase Sensitive Detection (PSD)**
  - Locks to chopper reference frequency
  - Maintains noise rejection even if there is jitter in background frequency

- **Gated Integration**
  - Requires active background subtraction
  - With 50% laser duty cycle, averaging over a large number of on/off cycles is needed to achieve similar results as phase sensitive detection
  - More effective for small duty cycle laser modulation – e.g. for pulsed lasers – where background...
Digital Sample-Hold Method

- Simultaneous measurements of discharge current, emission + fluorescence
- Zero point crossings of discharge current with positive slope are located
  - Crossing points considered as time = $t_0$
  - Times $t_1$, $t_2$, etc. determined based on a delay time with reference to the $t_0$ points
- Emission plus fluorescence trace is sampled at the first data point corresponding to time = $t_0$
- This value is held until the current cycle reaches its next positive zero crossing
- Emission plus fluorescence trace is resampled and held until the next crossing
- This process is repeated for times $t_1$, $t_2$, ..., splitting emission plus fluorescence trace into N separate signals corresponding to N times within the current cycle
- The individual sample-held signals are passed through digital lock-in amplifier to pull out time-synchronized fluorescence excitation lineshapes
Hardware Sample-Hold Method

- AC current from the Xe lamp discharge is fed into an LM339 comparator chip
  - Comparator output is +5 V when signal from current is above 0.005 V, and 0 V when current signal is below 0.005 V
  - Comparator is configured with a hysteresis circuit to prevent over-triggering
  - Output of comparator is a series of transistor-transistor logic (TTL) pulses with ~50% duty cycle
- TTL Pulses from comparator trigger sample-hold on a Stanford Research Systems SR-250 Boxcar Averager
  - Other SR-250 inputs/settings:
    - Raw emission plus fluorescence from PMT
    - Gate width = 15 μs
    - Delay time = 0 to 160 ms
  - Positive slopes in TTL trigger the boxcar averager to sample the PMT signal for a period of time defined by the gate width
  - The last sampled value of the PMT signal is held until the next TTL trigger
  - Boxcar averager re-samples the PMT signal and holds the value again
- Sample-held output is fed directly into an SRS SR-850 Lock-in Amplifier
  - Phase sensitive detection at chopper reference frequency
  - Output is a fluorescence excitation lineshape synchronized to time $t_0$ in the current discharge cycle
- To sample additional times along the current cycle, built in time delay in the SR-250 is used to adjust the sample trigger

Block diagram of hardware sample-hold method

Distribution A: approved for public release, distribution unlimited
Signal to Background Calculation

- Collection volume for background emission much larger than for fluorescence

\[
\frac{S_f}{S_{bg}} = \frac{n_{2,f} V_f}{n_{2,bg} V_{bg}} = \frac{n_{2,f} W_L}{n_{2,bg} L}
\]

\[
\frac{S_f}{S_{bg}} = \frac{30 \times 10^{-6}}{0.47} = 6.4 \times 10^{-5}
\]

\[
\frac{W_L}{L} \approx \frac{1}{10}
\]

\[
\frac{n_{2,f}}{n_{2,bg}} = 6.4 \times 10^{-4}
\]

- Dynamic reserve of 84 dB necessary to recover fluorescence signal from background

---

**Diagram: PMT**
- \( V_{sig} + V_{bg} = 47 \text{ V} \)
-你会收到技术测量的信号

**Lock-In PSD**
- \( \tau = 1 \text{ sec} \)
- 50 \( \mu \text{V} \) full-scale
- \( V_{sig} \approx 30 \mu \text{V} \)

**Lock-In Amp**
- Gain = 10 V/sensitivity = 10V/50 \( \mu \text{V} \)
- \( V_{sig} \approx 6 \text{ V on 10 V scale} \)
- @ 10 mW laser power

---

Distribution A: approved for public release, distribution unlimited
Modeling of Time-Sync Methods

- 3 kHz model – Similar to velocity and amplitude changes expected in DCFT
  - 5 levels of Gaussian profiles with different height and centerline frequency imbedded in chopper on/off signal
  - Background added to fluorescence signal to test noise rejection
    - Sinusoidal background with frequency = 2x current, amplitude = 10x to 1,000x fluorescence
    - Gaussian background noise, amplitude =2x fluorescence

Distribution A: approved for public release, distribution unlimited
Modeling of Time-Sync Methods

- 60 Hz model – Similar to amplitude changes expected in Xe Lamp
  - 5 levels of Gaussian profiles with different height imbedded in chopper on/off signal
  - Sinusoidal background with frequency = 2x current frequency and/or random background noise added to signal to test
  - Amplitude of background varied from 10x to 1,000x fluorescence signal
Modeling of Time-Sync Methods (cont.)

- With 2x Gaussian background noise
  - Boxcar averager method has to be averaged over 50 laser scans to achieve similar results to single sample-hold scan
    - Approx. 15,000 current cycles averaged for each wavelength
  - Boxcar averager also results in significant broadening of lineshape
    - Mainly due to breaking up scan into 40 wavelength sections, vs. sample-hold which is continuous in wavelength space
- With up to 1000x sinusoidal background
  - Both achieve similar results that match well with simulated fluorescence levels

![Graphs showing amplitude vs. time and wavelength for Boxcar Averager Method and Sample-Hold Method.](image)
Modeling of Time-Sync Methods

- 3 kHz model – Similar to velocity and amplitude changes expected in DCFT
  - 5 levels of Gaussian profiles with different height and centerline frequency imbedded in chopper on/off signal
- Background added to fluorescence signal to test noise rejection
  - Sinusoidal background with frequency = 2x current, amplitude = 10x to 1,000x fluorescence
  - Gaussian background noise, amplitude = 2x fluorescence
- Both methods achieve similar (very good) noise rejection with purely sinusoidal background noise
- Boxcar averager method required averaging ~50 simulated laser scans to achieve similar results to single laser scan with sample-hold method with 2x Gaussian noise
  - Approx. 750,000 current cycles averaged for each wavelength at 3 kHz

Results of 3 kHz model

Boxcar Averager Method

Sample-Hold Method

Distribution A: approved for public release, distribution unlimited
Pressure vs. Broadening in Xe Lamp

• From Cedolin thesis
  – Voigt parameter, $a = 2.7$ in our lamp corresponds to $\approx 7$ torr

![Graph showing pressure vs. broadening in Xe lamp](image-url)