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14. 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.					
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GEC-XXXX

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



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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



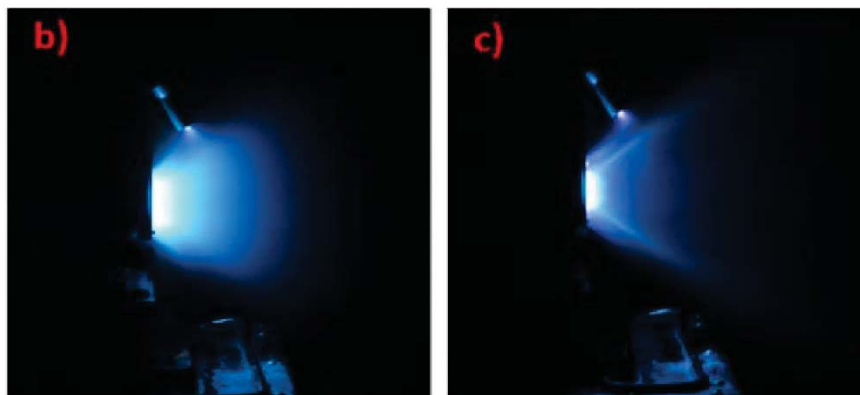
MIT Diverging Cusped Field thruster

Motivation

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

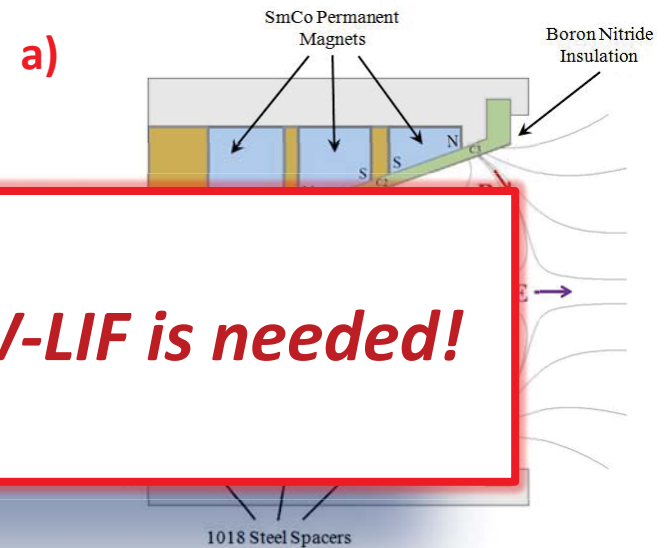
A Time-Synchronized method of CW-LIF is needed!

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

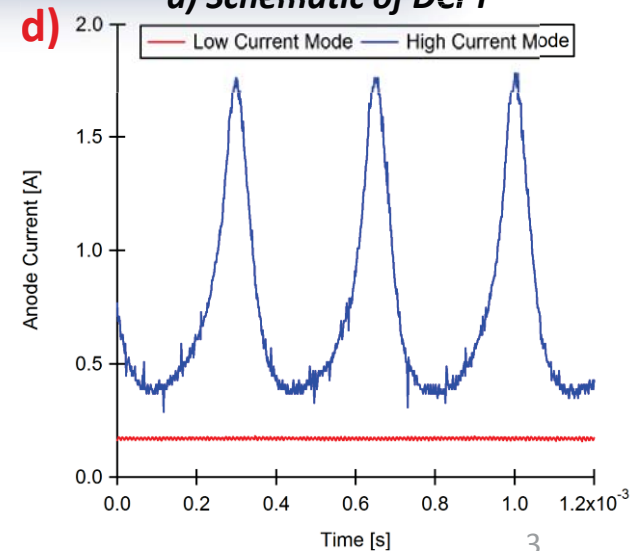


DCFT operating in: **b) High current mode,**
c) Low current mode

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a) Schematic of DCFT



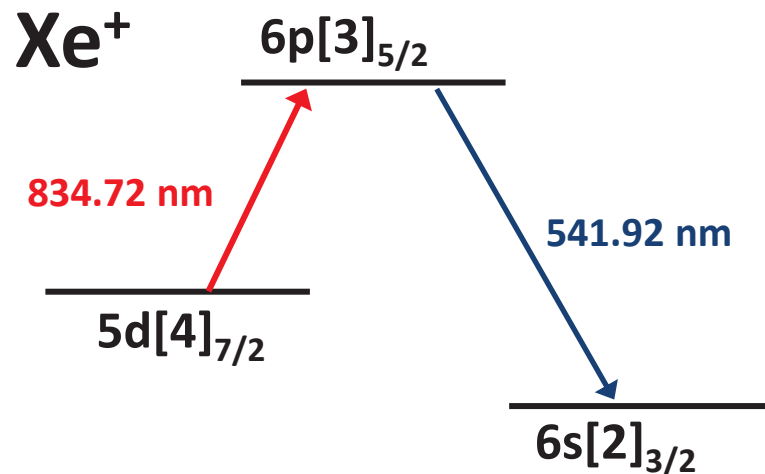
d) DCFT Current Traces

Laser-induced Fluorescence Velocimetry

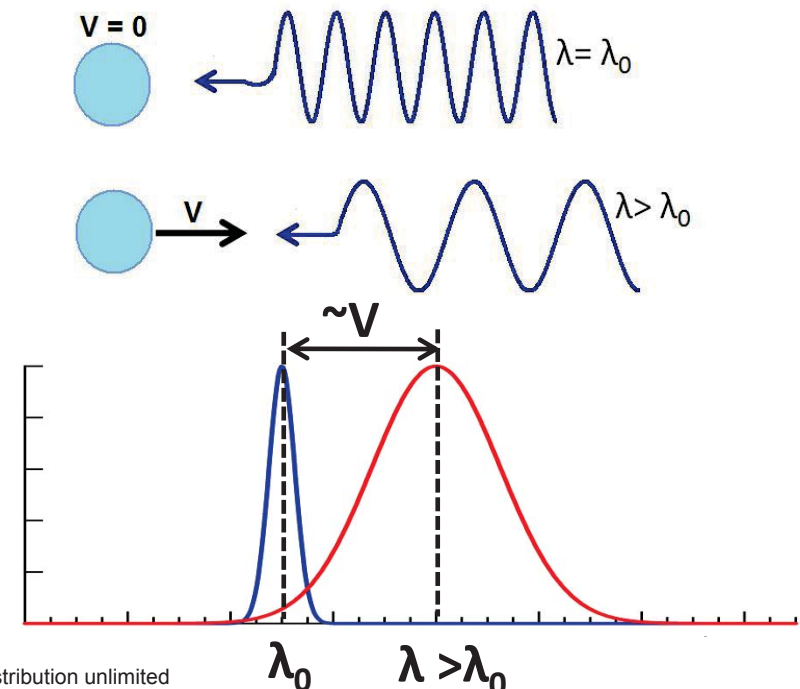
LIF is used to measure the velocity of ions in the thruster plume

- Laser beam tuned across electronic transition in Xe ions
 $5d[4]_{7/2} - 6p[3]_{5/2}$ at 834.72 nm
- Ions spontaneously emit photons resulting in their relaxation from its excited state to a lower state (fluorescence)
 $6s[2]_{3/2} - 6p[3]_{5/2}$ at 541.92 nm
- Fluorescence excitation spectrum = convolution of ion velocity distribution function (VDF), and transition lineshape (inc. hfs, etc.)
- Shape (broadening/shift) dominated by Doppler effect:

$$\delta v_{12} = \frac{V}{c} v_{12}$$



Non-resonant fluorescence scheme



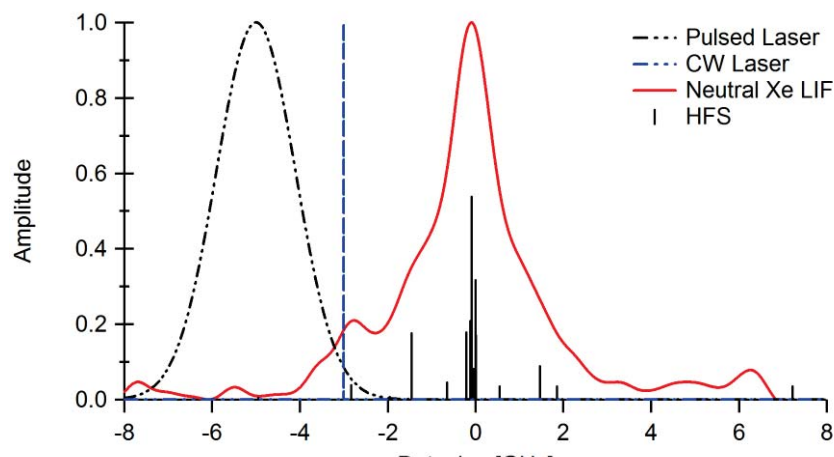
Approaches to Time-Synchronization

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



Lineshape of the 834.68 nm Xe transition compared to widths of a pulsed laser and a CW laser. Hyperfine structure (HFS) shown as reference.

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 thruster¹
 - Magnetic field reconnection in a toroidal shaped plasma device²
 - Helicon generated pulsed argon plasma³
- 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

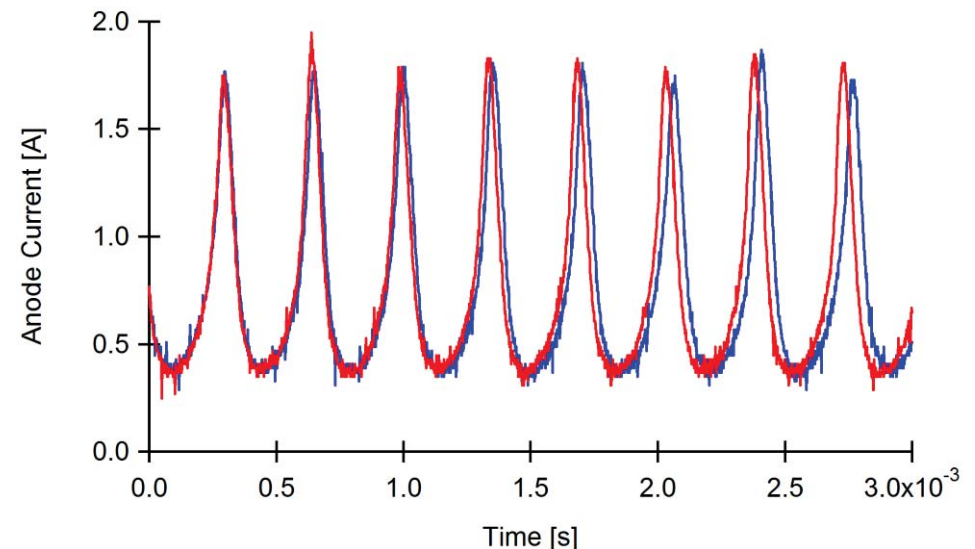
References:

1. S. Mazouffre, D. Gawron, and N. Sadeghi. Phys. of Plasmas **16**, 1 (2009).
2. A. Stark, W. Fox, J. Egedal, O. Grulke, and T. Klinger. Phys. Rev. Lett. **95**, 1 (2005).
3. I. A. Biloiu, X. Sun, and E. E. Scime. Rev. Sci. Instrum. **77**, 10F301-1 (2006).

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Sample-Hold

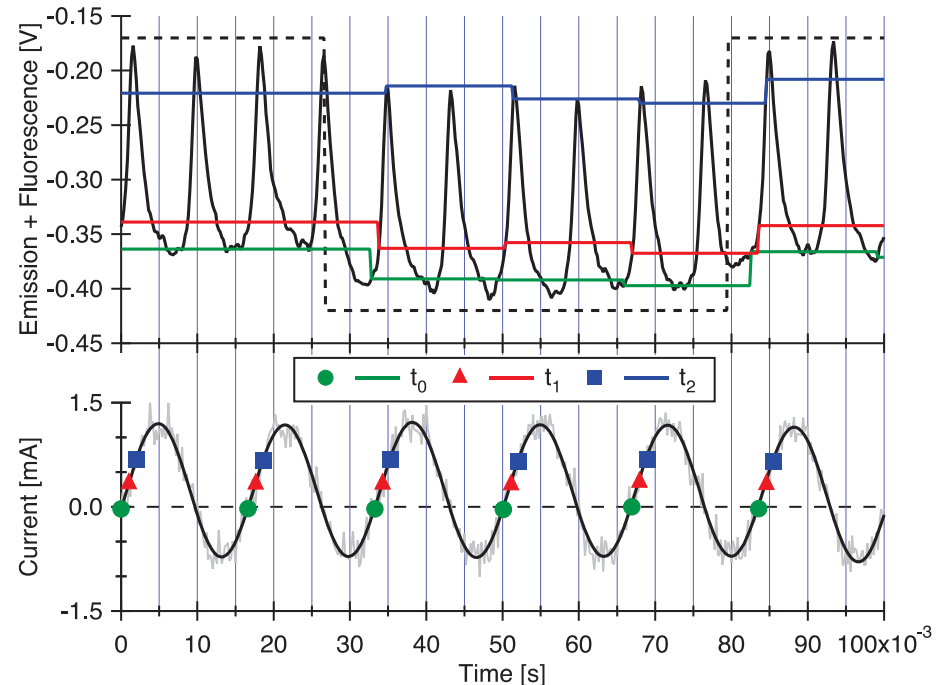
- Phase sensitive detection allows for jitter in frequency of discharge current
- Sample-hold method can get good result with fewer scans
- For small signals that can't be pulled out by boxcar averager method or digital lock-in, hardware version of sample-hold is available
 - High dynamic reserve of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



DCFT current traces, taken approx. 30 seconds apart. Note: slight change in frequency ⁶

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 re-sampled 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

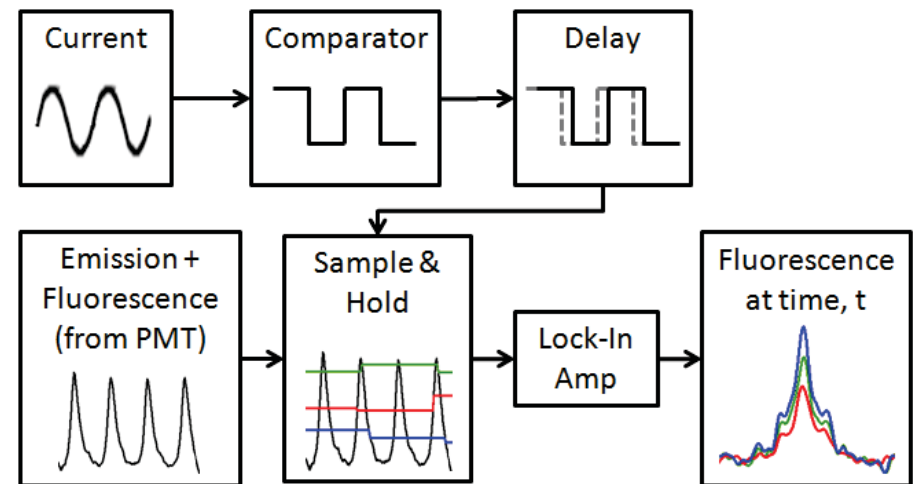


*Discharge current, with points for time t_0 through t_2 (bottom).
Raw PMT signal ---, chopper on/off - - -, and sample-held
signals for t_0 through t_2 (top).*

- 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 μ s
 - 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

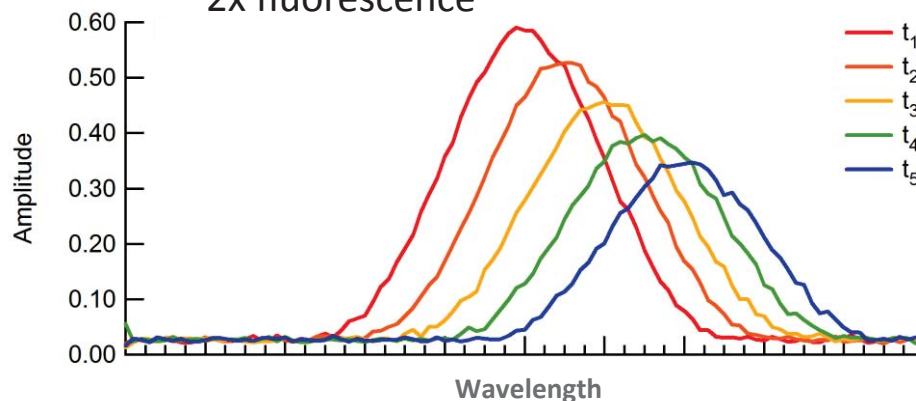


Block diagram of hardware sample-and-hold method

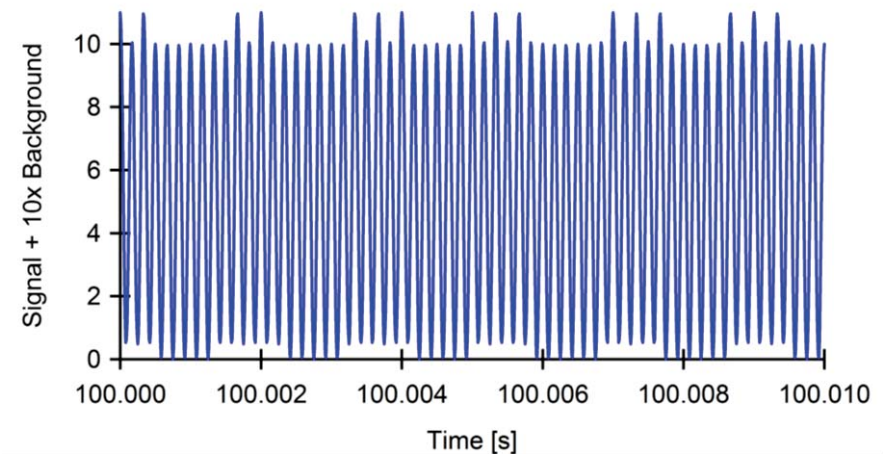
- Sample-held output is fed directly into an SRS SR-850 Lock-in Amplifier
 - Phase sensitive detection at chopper reference frequency
 - Output is a fluorescence excitation lineshape synchronized to time t_0 in the current discharge cycle
- To sample additional times along the current cycle, built in time delay in the SR-250 is used to adjust the sample trigger

Modeling of Time-Sync Method

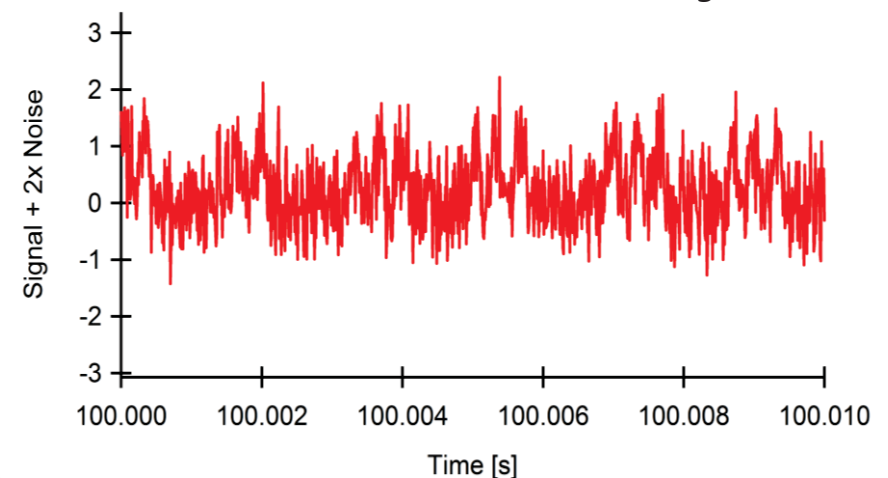
- 3 kHz model – Similar to velocity and amplitude changes expected in DCFT
 - 5 levels of Gaussian profiles with different height and centerline frequency imbedded in chopper on/off signal
 - Background added to fluorescence signal to test noise rejection
 - Successfully rejects noise, including:
 -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



Results of sample-and-hold method on 3kHz model with 2x noise

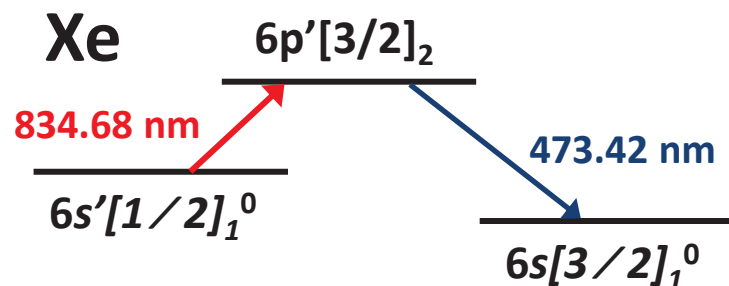
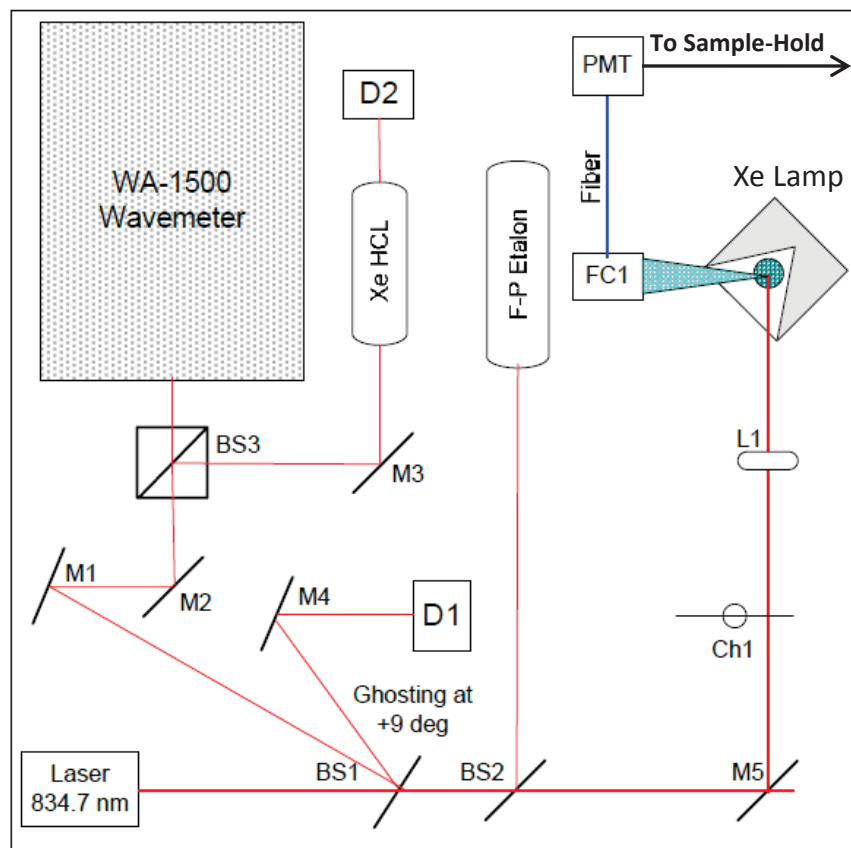


3kHz model with 10x sinusoidal background



3kHz model with 2x noise

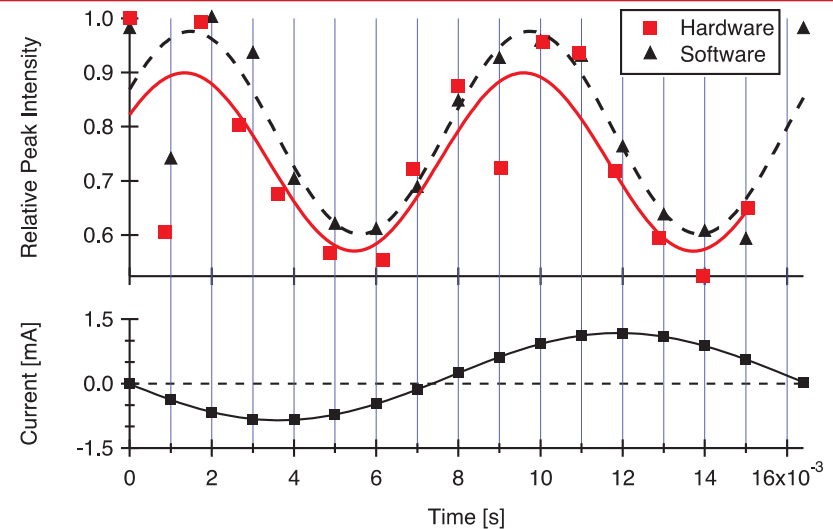
Table-Top Experiment



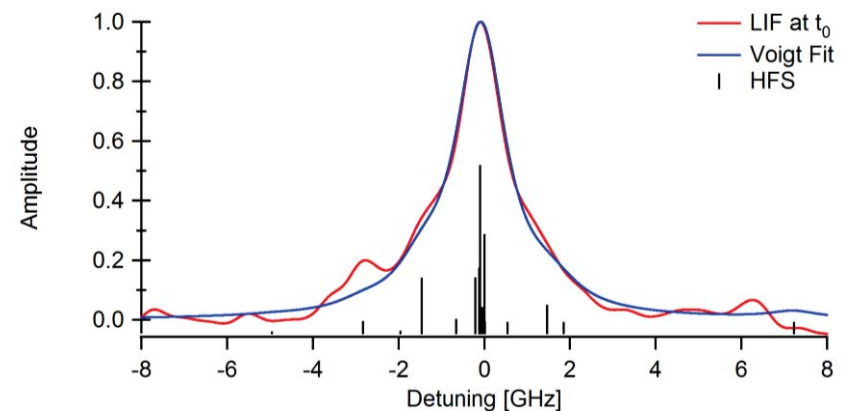
- Measurements on 60 Hz Xe spectral lamp
 - Measuring change in lower state population rather than shift in wavelength
 - Population inferred by time-sync LIF intensity
- Neutral (Xe I) transition at 834.68 nm probed
 - $6s'[1/2]_1^0 - 6p'[3/2]_2$
- Non-resonant fluorescence collected at 473.42 nm
 - $6s[3/2]_1^0 - 6p'[3/2]_2$
- 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-and-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



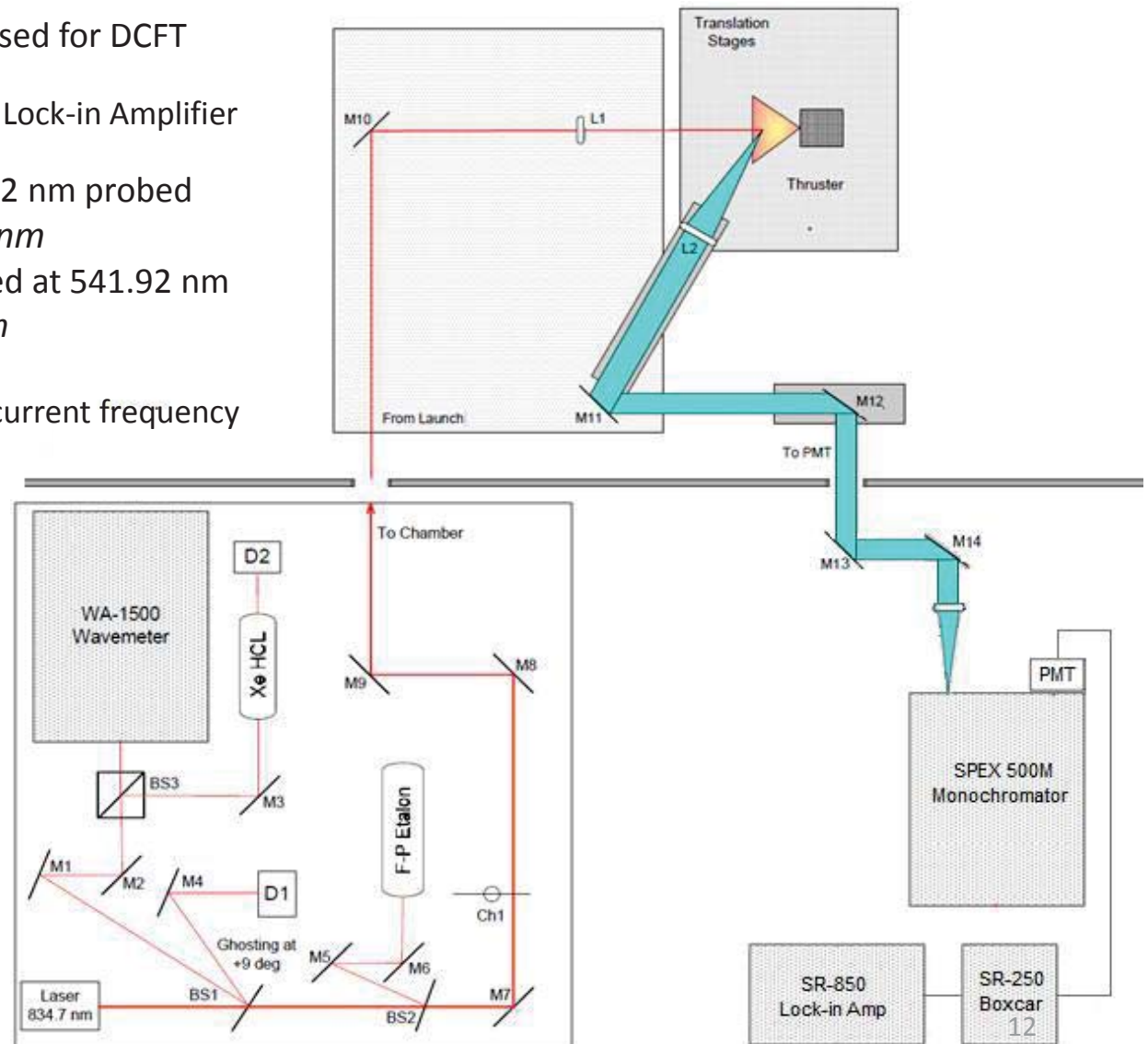
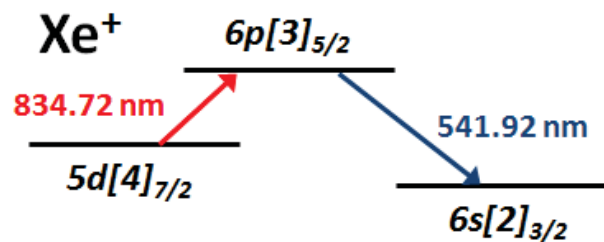
Time evolution of the peak intensities of the fluorescence excitation lineshape over a single current cycle



Best Voigt fit of transition at time t_0 assuming Doppler temperature of 300 K and $a = 2.7$

Time-Sync DCFT Experiment

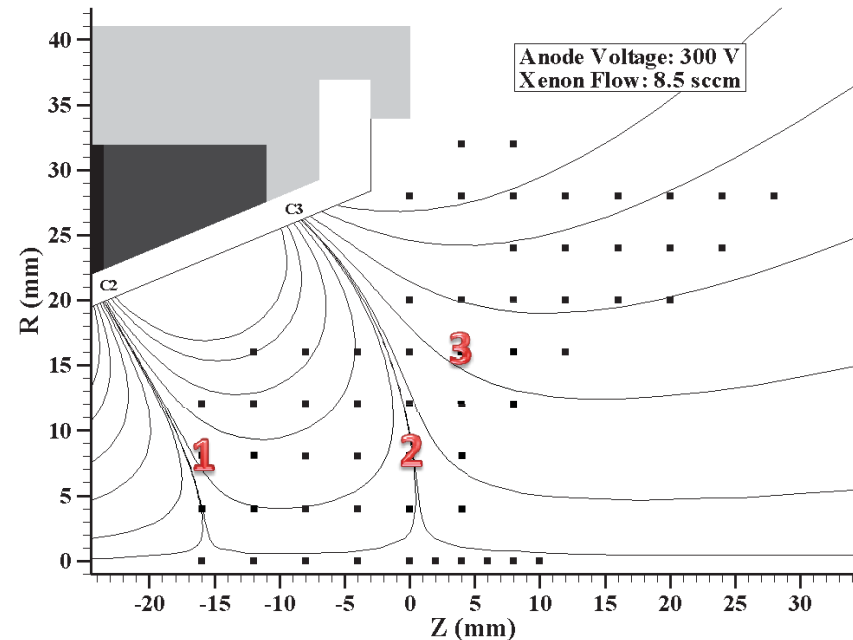
- Hardware version of sample-hold used for DCFT experiments
 - High dynamic reserve of SR-850 Lock-in Amplifier gives better noise rejection
- Xenon ion (Xe II) transition at 834.72 nm probed
 - $5d[4]_{7/2} - 6p[3]_{5/2}$ at 834.72 nm
- Non-resonant fluorescence collected at 541.92 nm
 - $6s[2]_{3/2}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



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Time-Sync DCFT Experiment

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

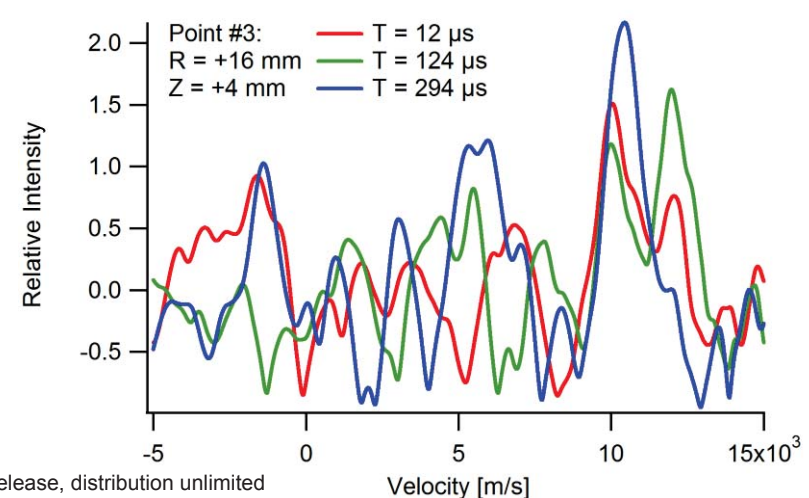
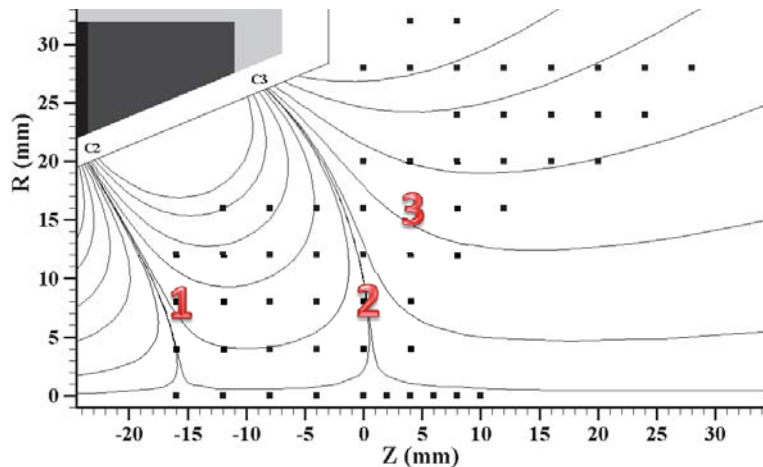
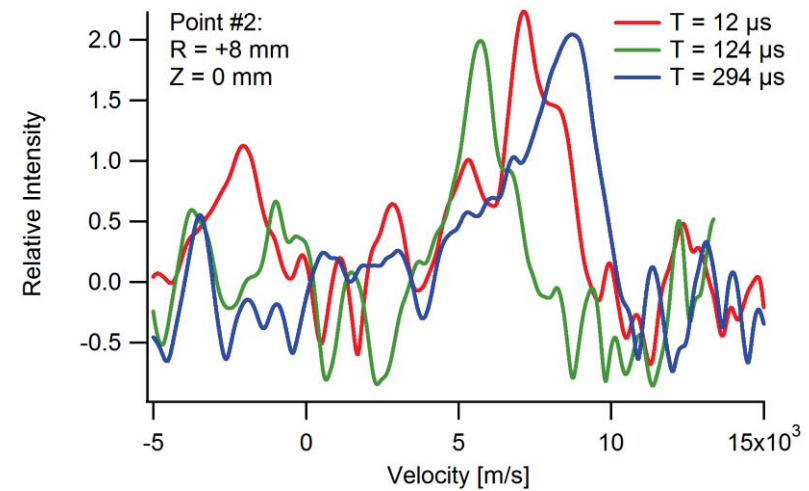
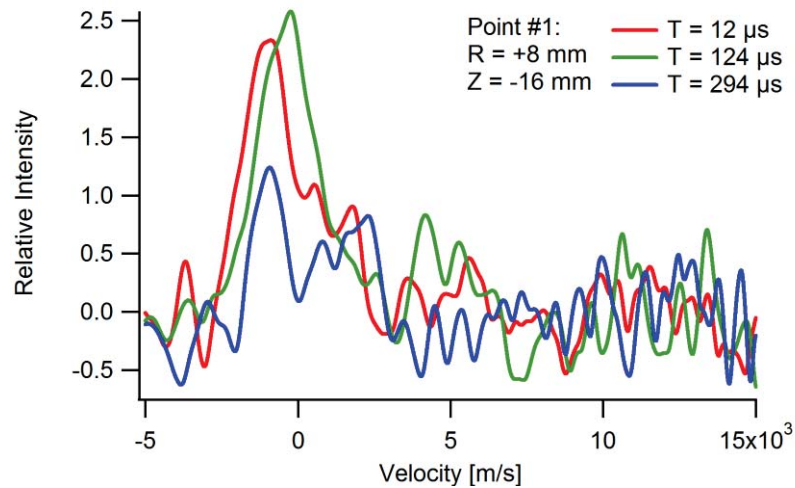


Measurement locations for time-sync LIF on DCFT

DCFT Operating Conditions	
Anode Flow Rate:	830 $\mu\text{g/s}$ Xe (8.5 sccm)
Anode Potential:	300 V
Anode Current:	0.49 A
Background Pressure:	5×10^{-6} torr

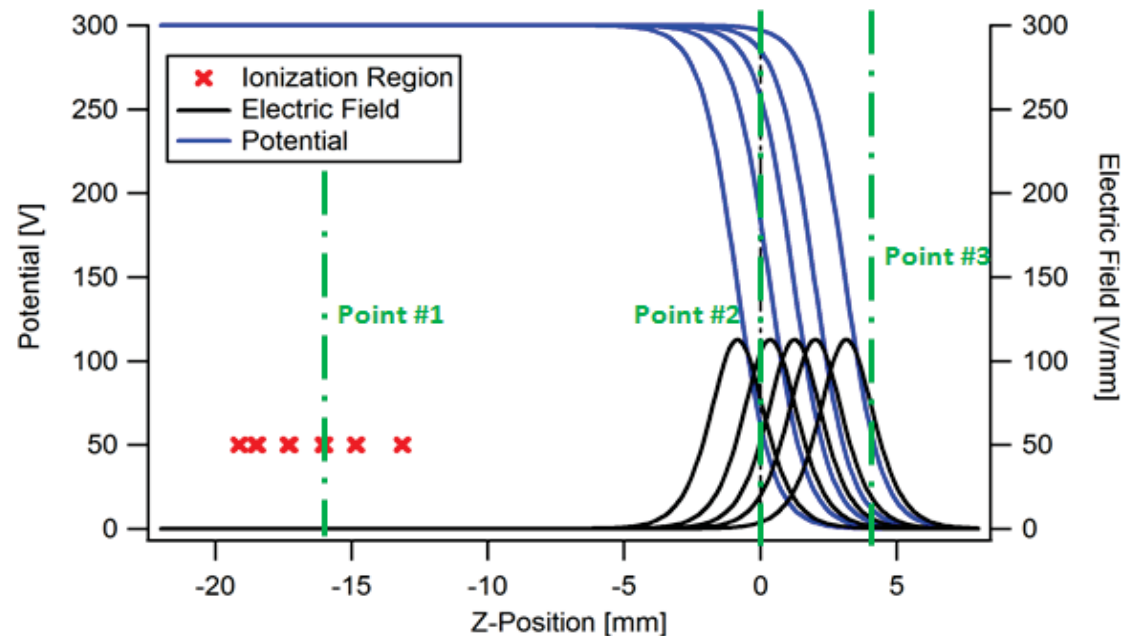
Time-Sync DCFT Results

- 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?



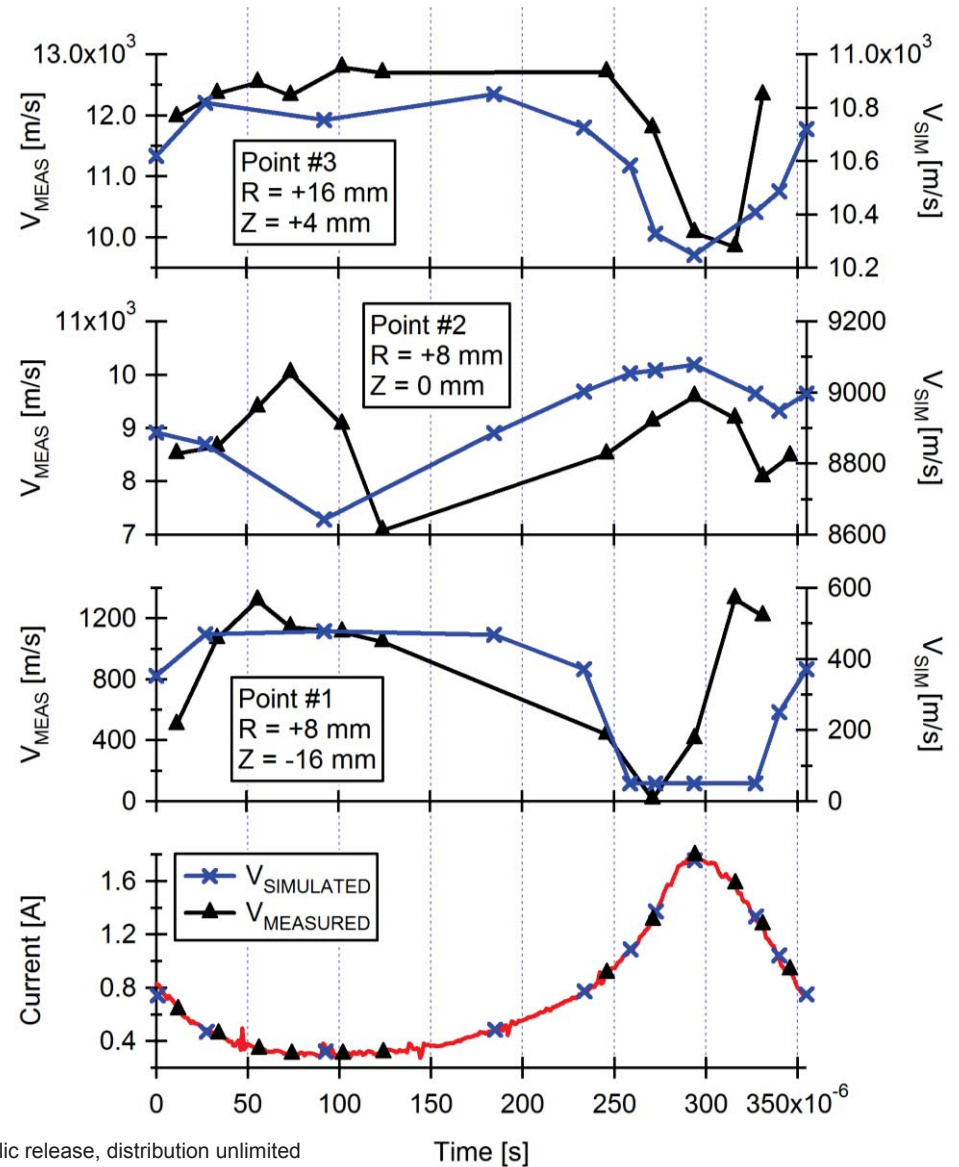
Simulation of DCFT Results

- 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

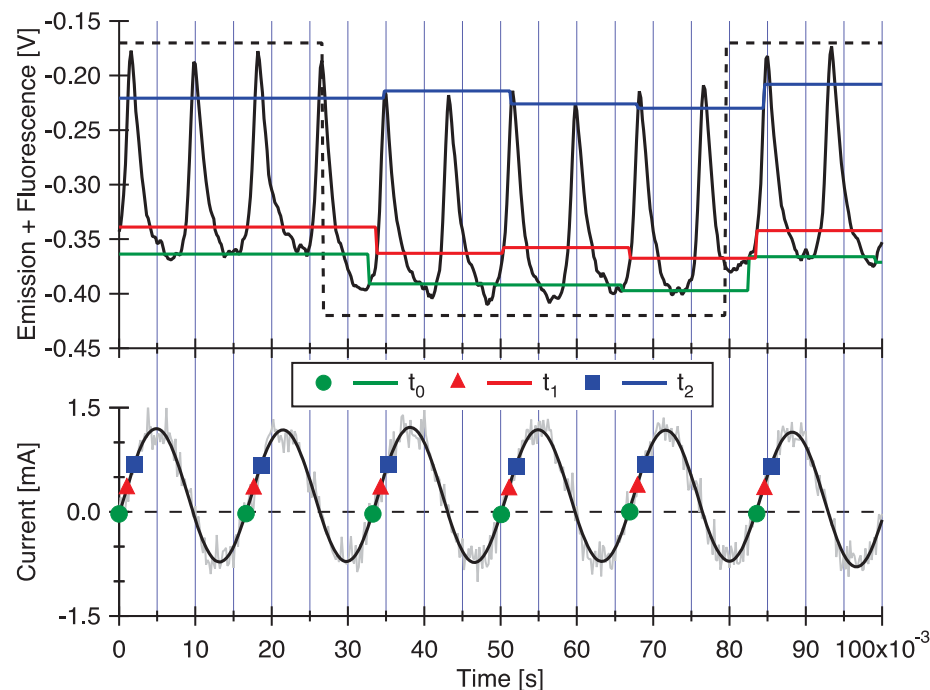
Gated Integration vs. Phase Sensitive Detection

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
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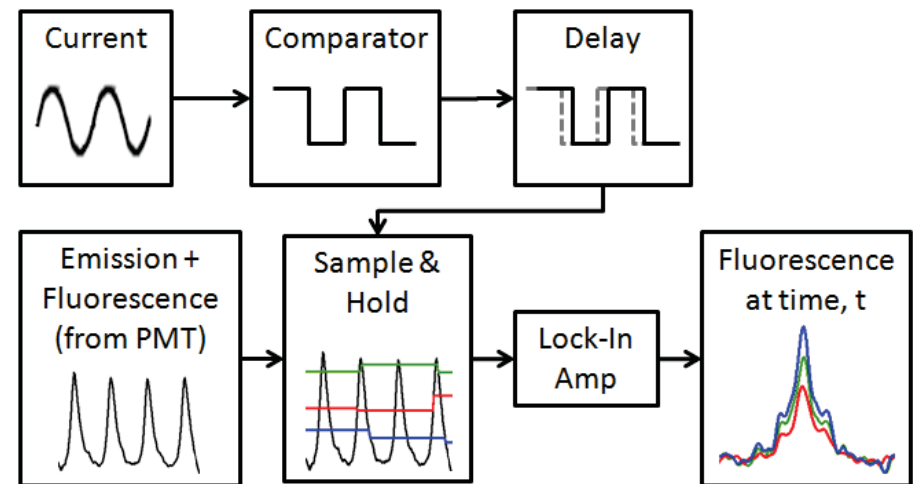


*Discharge current, with points for time t_0 through t_2 (bottom).
Raw PMT signal ---, chopper on/off - - -, and sample-held
signals for t_0 through t_2 (top).*

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

Hardware Sample-Hold Method

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Block diagram of hardware sample-and-hold method

- 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

Signal to Background Calculation

- Collection volume for background emission much larger than for fluorescence

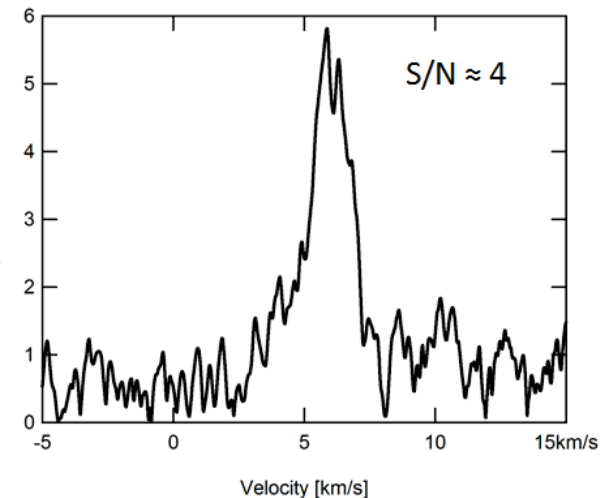
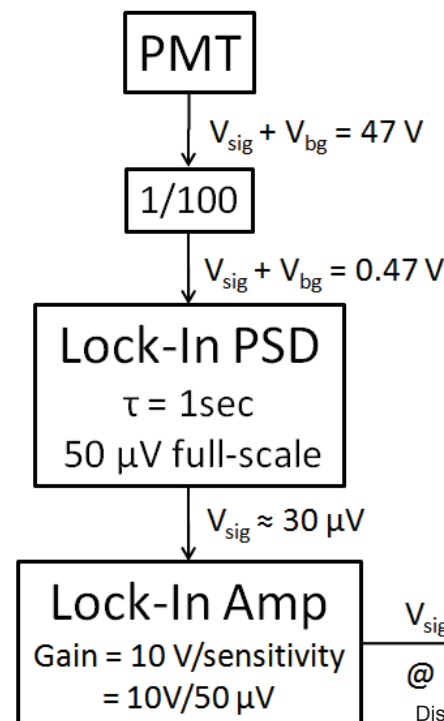
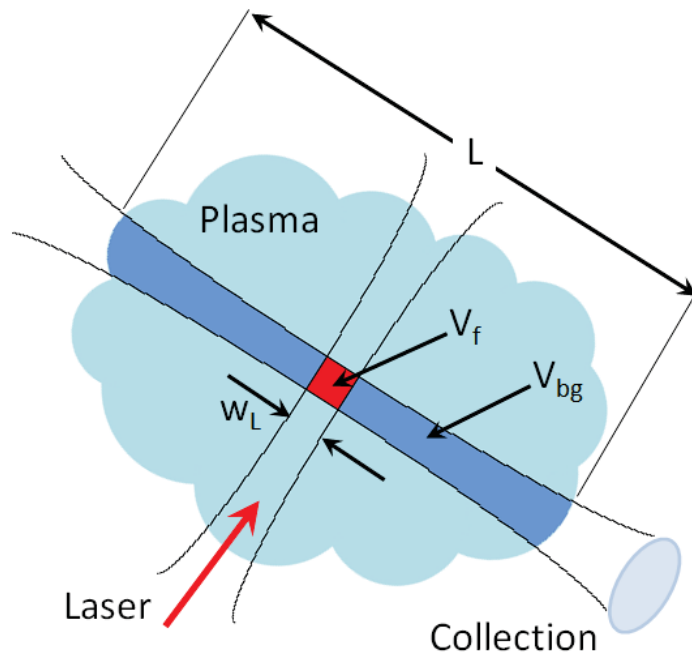
$$\frac{S_f}{S_{bg}} = \frac{n_{2,f} V_f}{n_{2,bg} V_{bg}} = \frac{n_{2,f} w_L}{n_{2,bg} L}$$

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

$$\frac{w_L}{L} \approx \frac{1}{10}$$

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

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



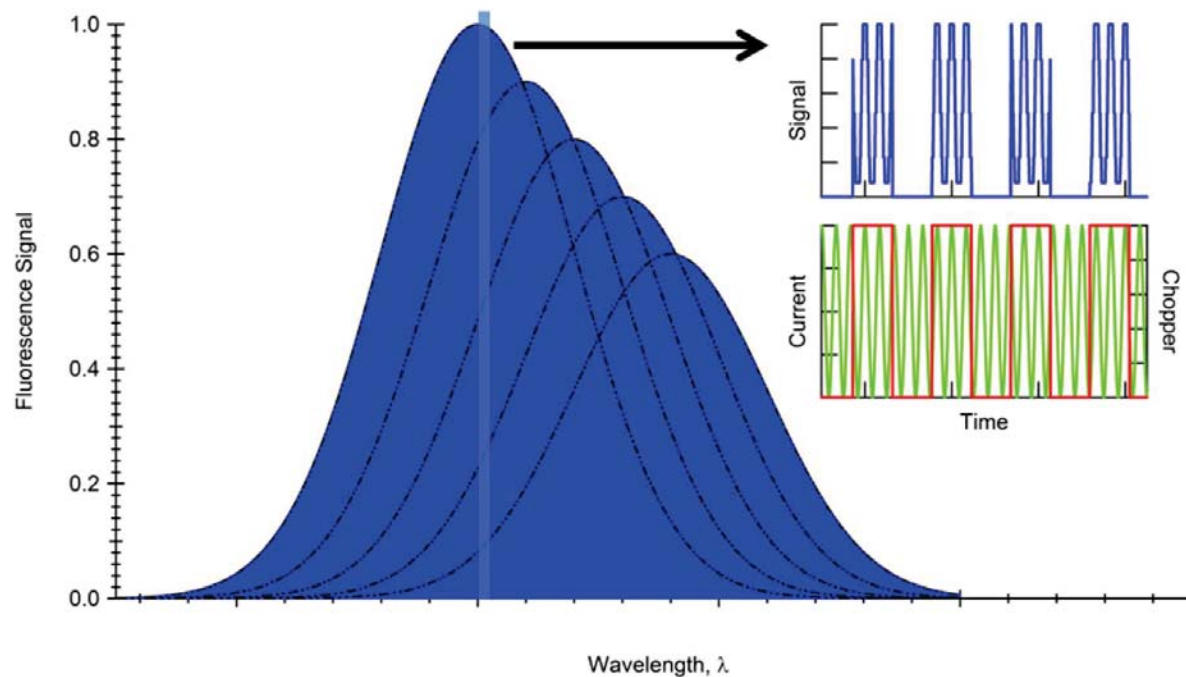
$V_{sig} \approx 6 \text{ V on } 10 \text{ V scale}$

@ 10 mW laser power

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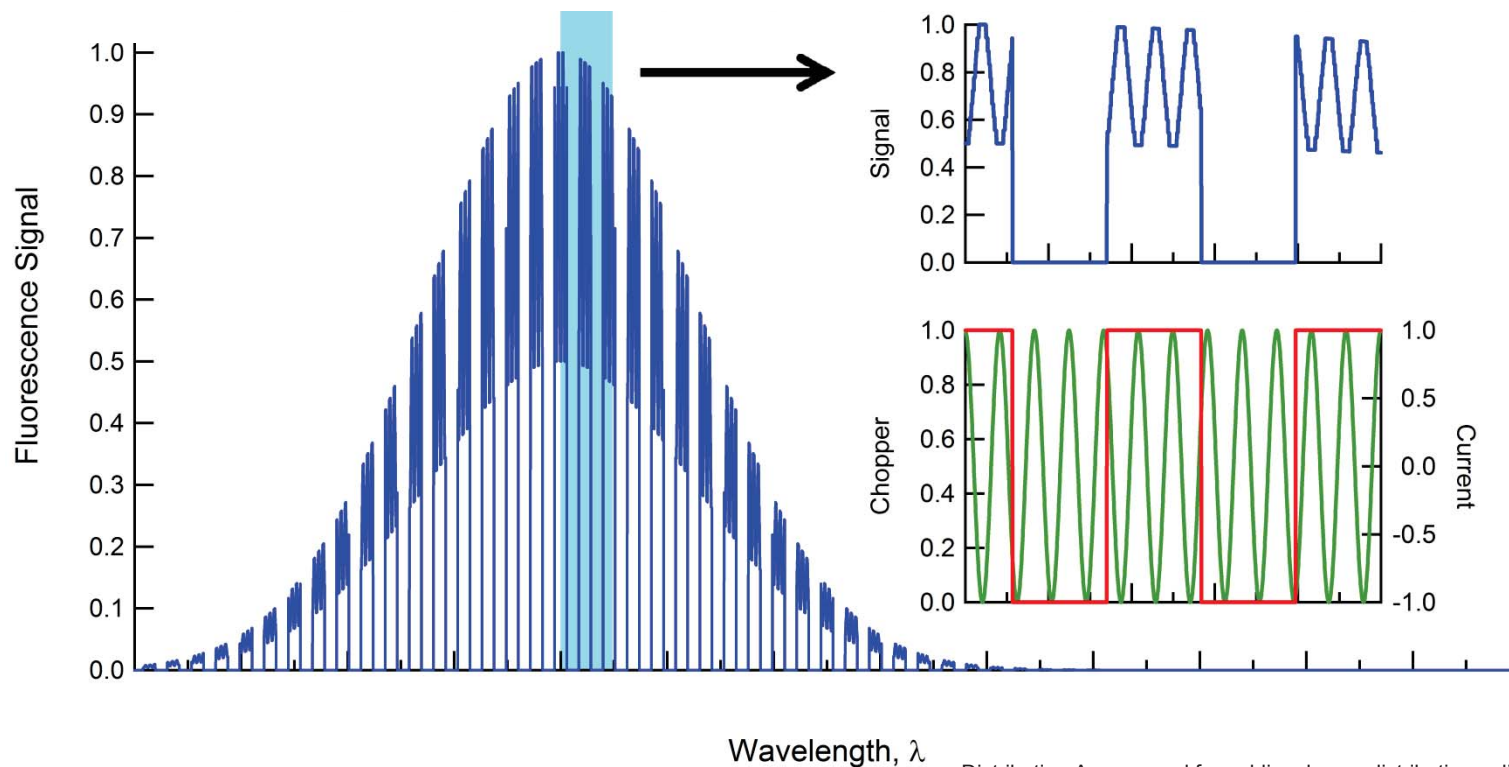
Modeling of Time-Sync Methods

- 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



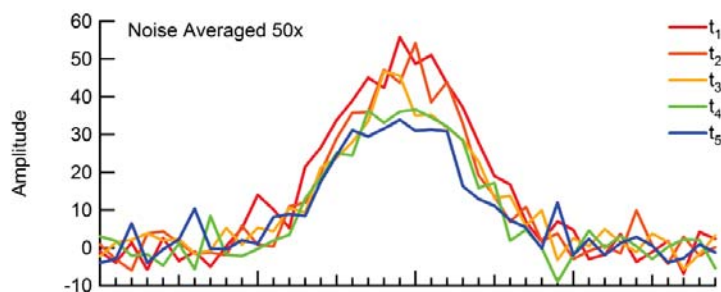
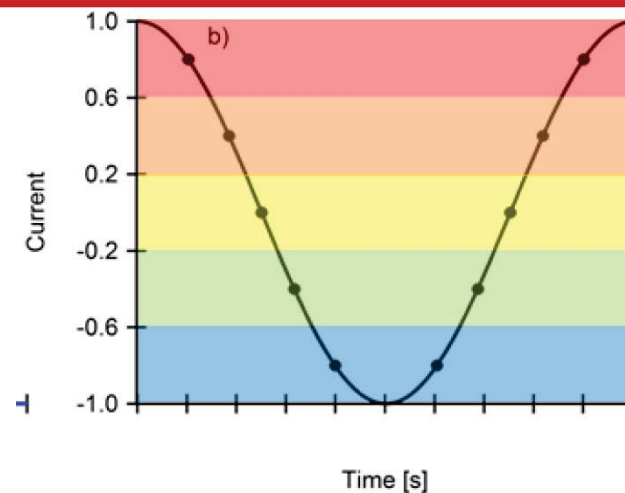
Modeling of Time-Sync Methods

- 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



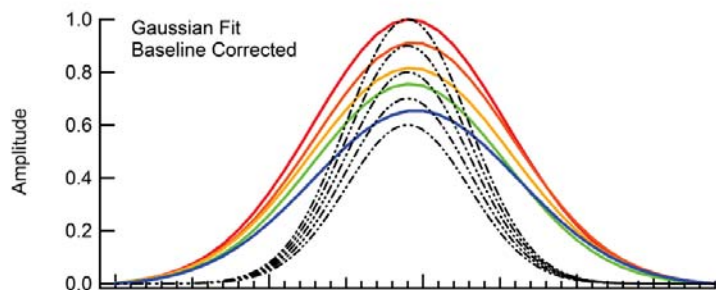
Modeling of Time-Sync Methods (cont.)

- 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

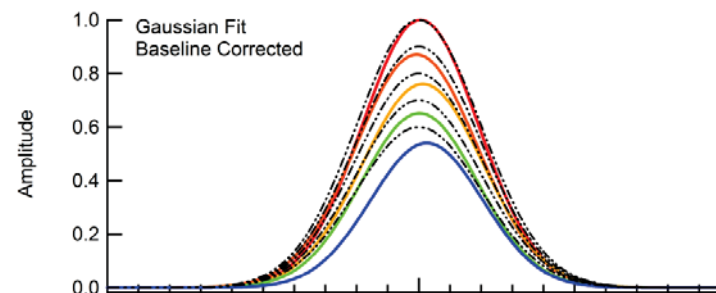
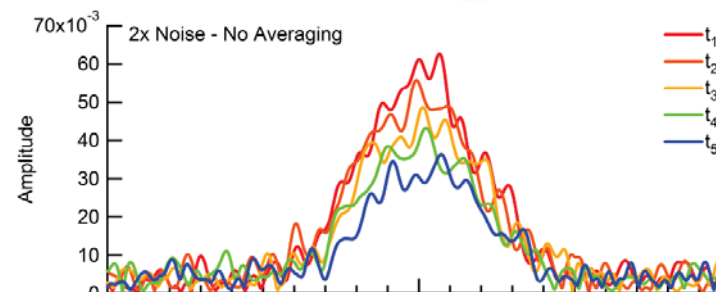


Boxcar Averager Method

Sample-Hold Method



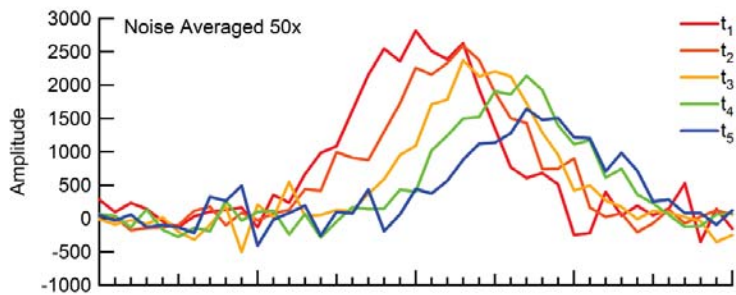
Wavelength



Wavelength

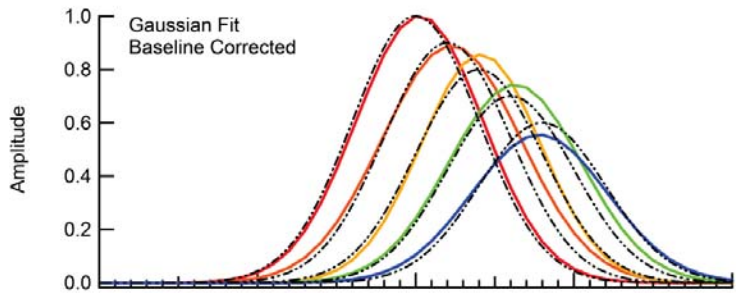
Modeling of Time-Sync Methods

- 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

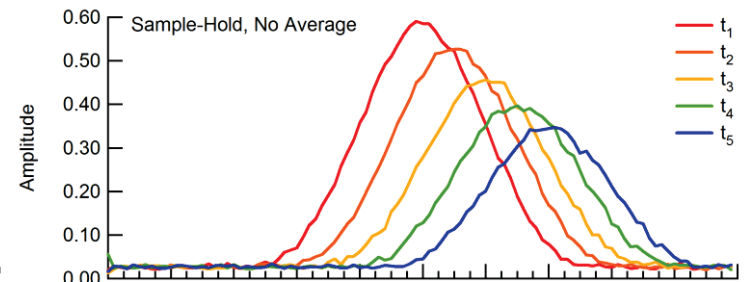


Results of 3kHz model

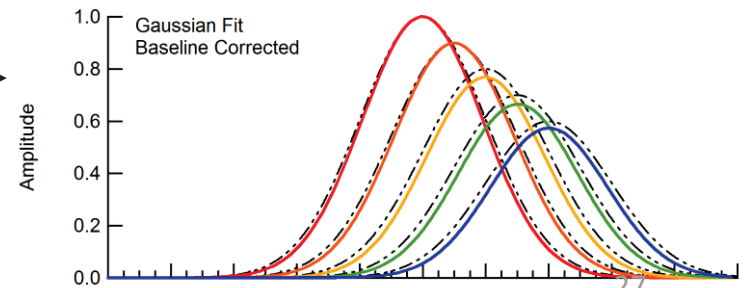
Boxcar Averager Method



Wavelength



Sample-Hold Method



Wavelength

Pressure vs. Broadening in Xe Lamp

- From Cedolin thesis
 - Voigt parameter, $a = 2.7$ in our lamp corresponds to ≈ 7 torr

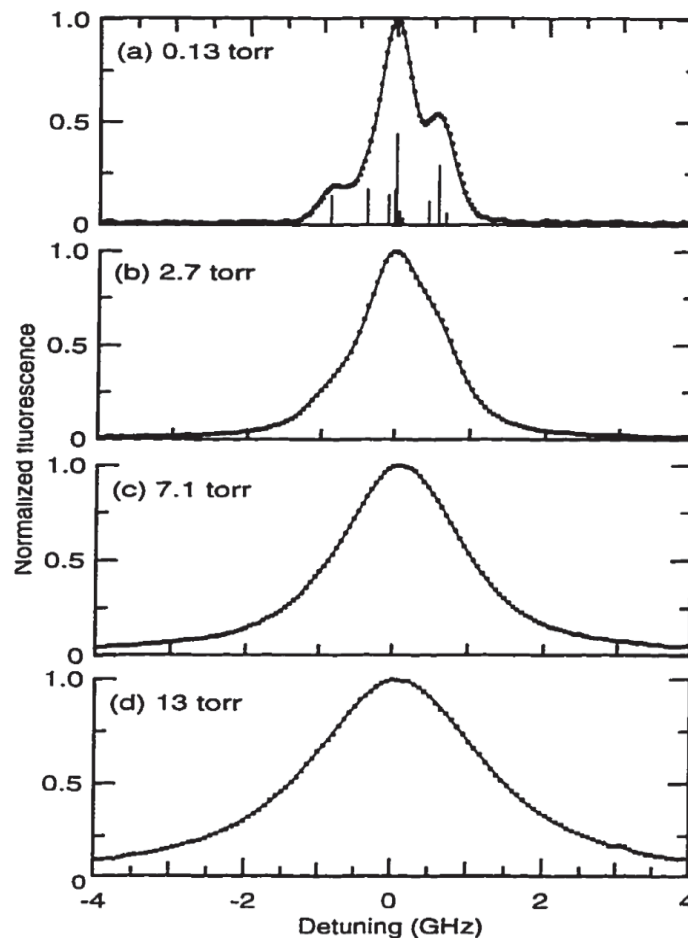


FIG. 4-4. Evolution of reduced 828-nm LIF excitation line shapes (•) and curve-fit results (—) with density: (a) $3.9 \times 10^{21} \text{ atoms m}^{-3}$ with contributing hyperfine lines (l), only every sixth point plotted for clarity, Voigt $a = 0.16$; (b) $8.4 \times 10^{22} \text{ atoms m}^{-3}$, every tenth point plotted, $a = 1.2$; (c) $2.2 \times 10^{23} \text{ atoms m}^{-3}$, every tenth point plotted, $a = 2.8$; (d) $4.0 \times 10^{23} \text{ atoms m}^{-3}$, every twenty-fifth point plotted, $a = 4.9$.