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14. ABSTRACT The breathing mode of a xenon 600W Hall effect thruster has been studied using both temporally resolved experimental data and numerical modeling. Fluctuations in xenon neutral NIR (810-835 nm) emission in the near field thruster plume have been measured at 1 μ s resolution using a high-speed intensified charge coupled device (ICCD). Oscillations in electron temperature, 3-9 eV, have been inferred using a collisional-radiative model and a two-line ratio method. The time-resolved emission and electron temperature measurements are then used to assess the accuracy of the numerical model HPHall. Simulations were found to be consistent with a -6 phase delay measured between discharge current and electron temperature cycles, but were unable to predict the magnitude of oscillations observed.					
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Comparison of Numerical and Experimental Time-Resolved Near-Field Hall Thruster Plasma Properties

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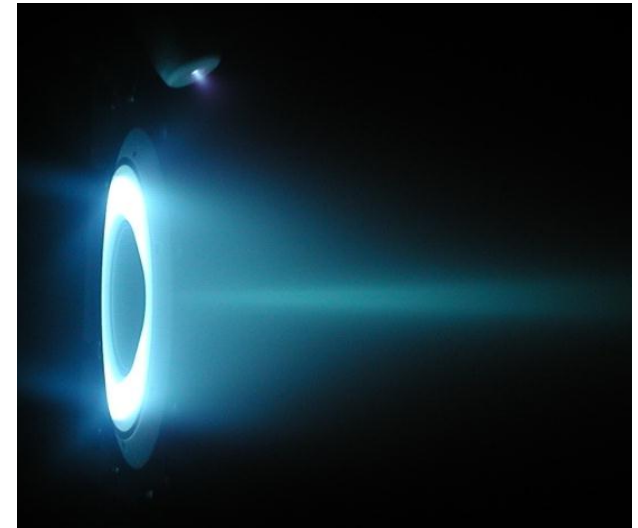
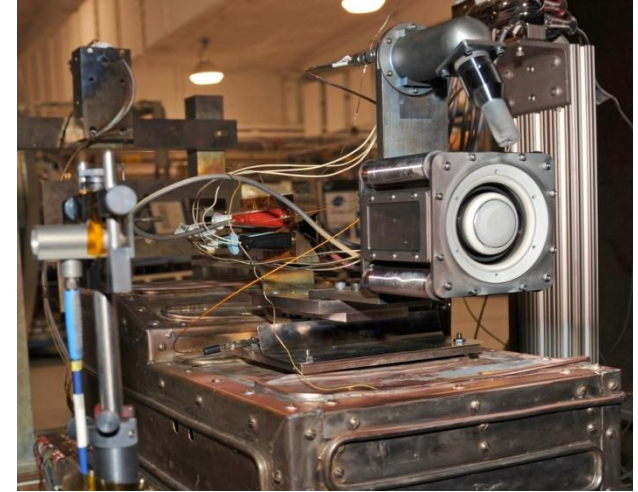




Overview

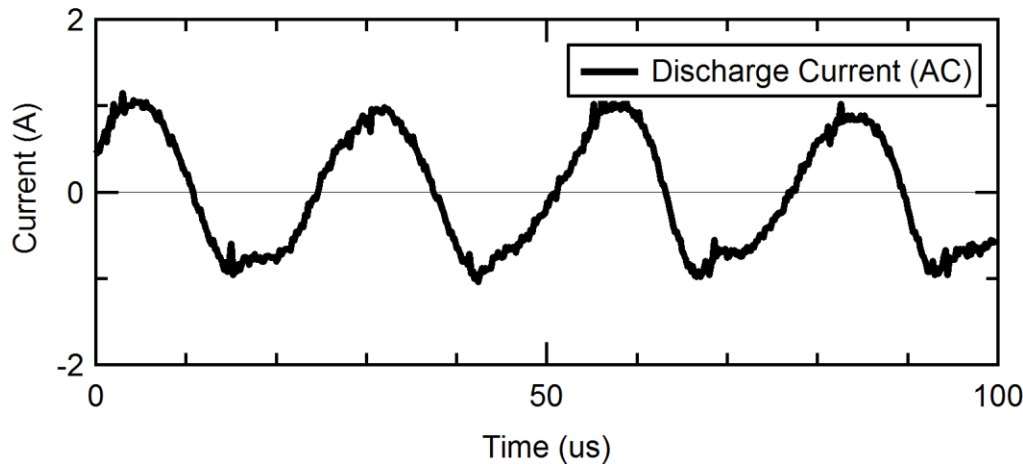


- **Background**
- **BHT-600 Thruster**
- **Experimental Work**
- **Collisional Radiative Modeling**
- **HPHALL Simulations**
- **Numerical /Experimental Comparison**





Background: Breathing Mode



- Seen through low frequency (10-50k Hz) oscillations in discharge current (I_d)
- Periodic depletion & replenishment of neutrals at exit¹
- Also referred to as neutral transit time instability- scales with $L_{channel} / V_{neutrals}$
- Previous time averaged measurements unable to quantify oscillations in plasma properties

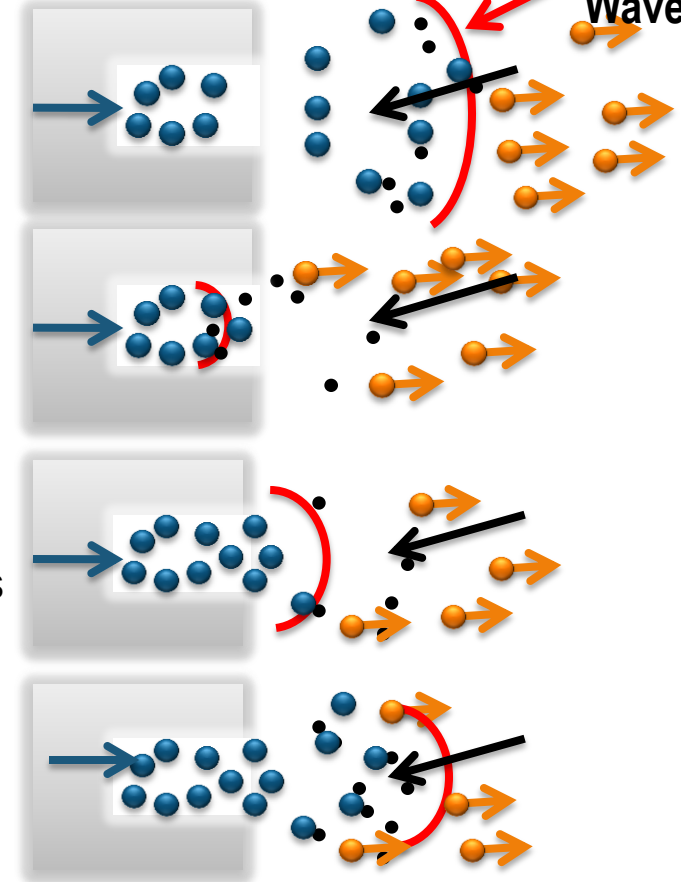
[1] Boeuf, J. P.; Garrigues, L. , *Journal of Applied Physics* , vol.84, no.7, pp.3541-3554, Oct 1998

Constant
neutral flow

Quasi-neutral

● = ●

Ionization
Wave

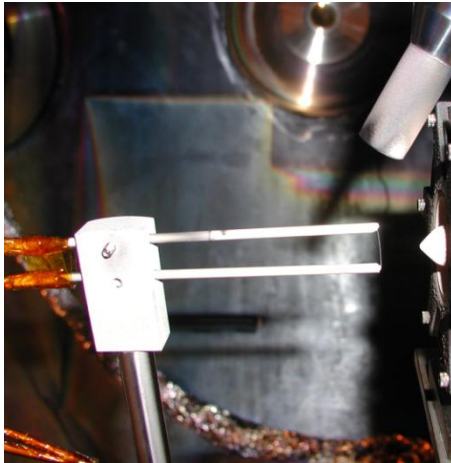




Background: Diagnostics

Probe

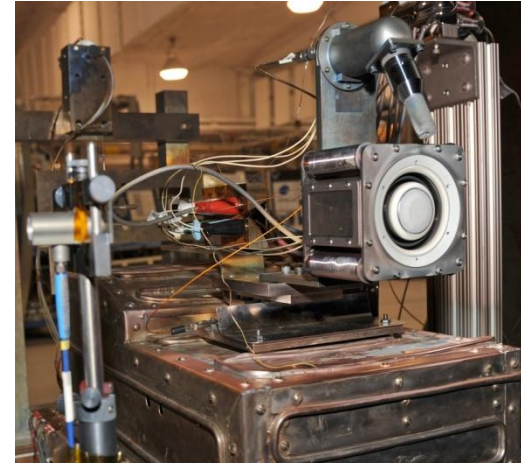
- Measurements
 - Langmuir- T_e , density, e^- EDF
 - RPA – ion EDF
 - Faraday- thruster beam current
 - Intrusive- spatially limited
 - Temporally limited due to sweeps
 - Lobbia² (10 μ s resolution)
- [2] Lobbia, RB and Gallimore, A.D. , *Rev. Sci. Instrum.* 81, 073503, 2010



Electrostatic Probe

Emission

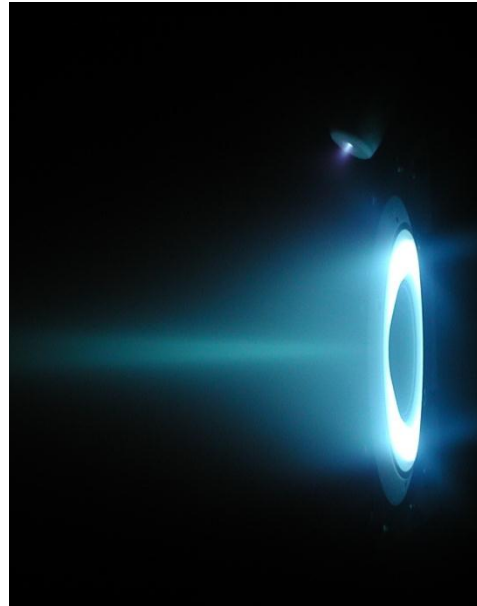
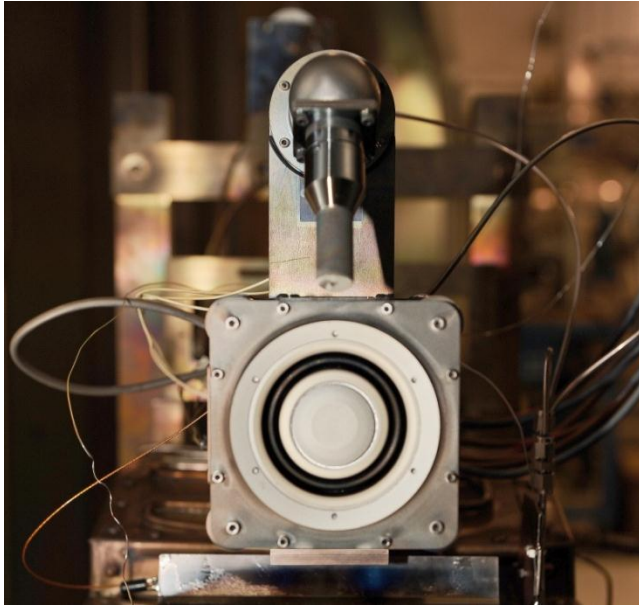
- Measurements
 - Line Intensity ratio- T_e
 - Absolute Intensity - Density
 - Doppler Shift - velocity
- Non-intrusive- capable of near field measurements
- Line of sight averaging
- Measurements on ns timescales



Emission Beam Coupler



BHT-600 Hall Effect Thruster



BUSEK

Dimensions

R_{inner} 24 mm

R_{outer} 32 mm

Channel Depth 10 mm

Nominal Conditions

Anode Flow Rate 2.45 mg/s

Cathode Flow Rate 197 μ g/s

Anode Potential 300 V

Anode Current 2.05 A

Magnetic Current 2.0 A

Performance

Thrust 42 mN

Specific Impulse 1650 s

Anode Efficiency 55.0%

- Thruster tested w Xe at nominal conditions
- Extensive previous experimental work
 - Probe- RPA, Faraday, ExB³⁻⁶
 - Optical measurements-LIF^{6,7}

[3] Ekholm et al, *JPC*, 2006.

[6] Hargus et al, *JPC*, 2008.

[4] Niemela et al, *JPC*, 2006.

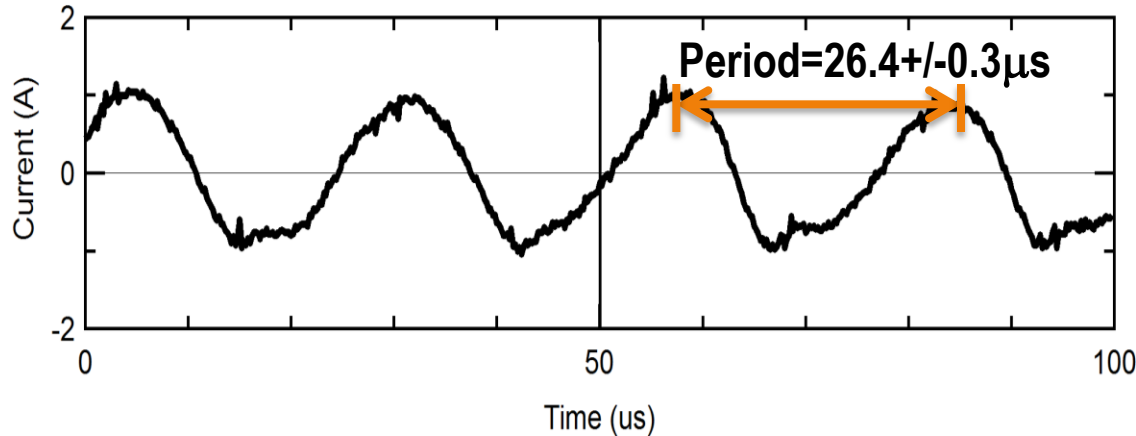
[7] Nakles et al, *JPC*, 2008.

[5] Nakles et al, *IEPC*, 2009.

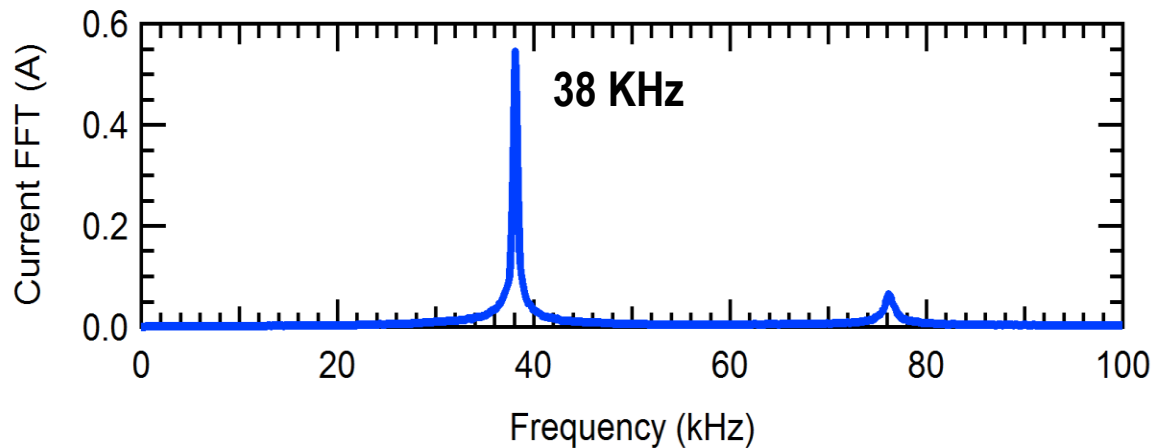
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BHT-600 : Breathing Mode Oscillations



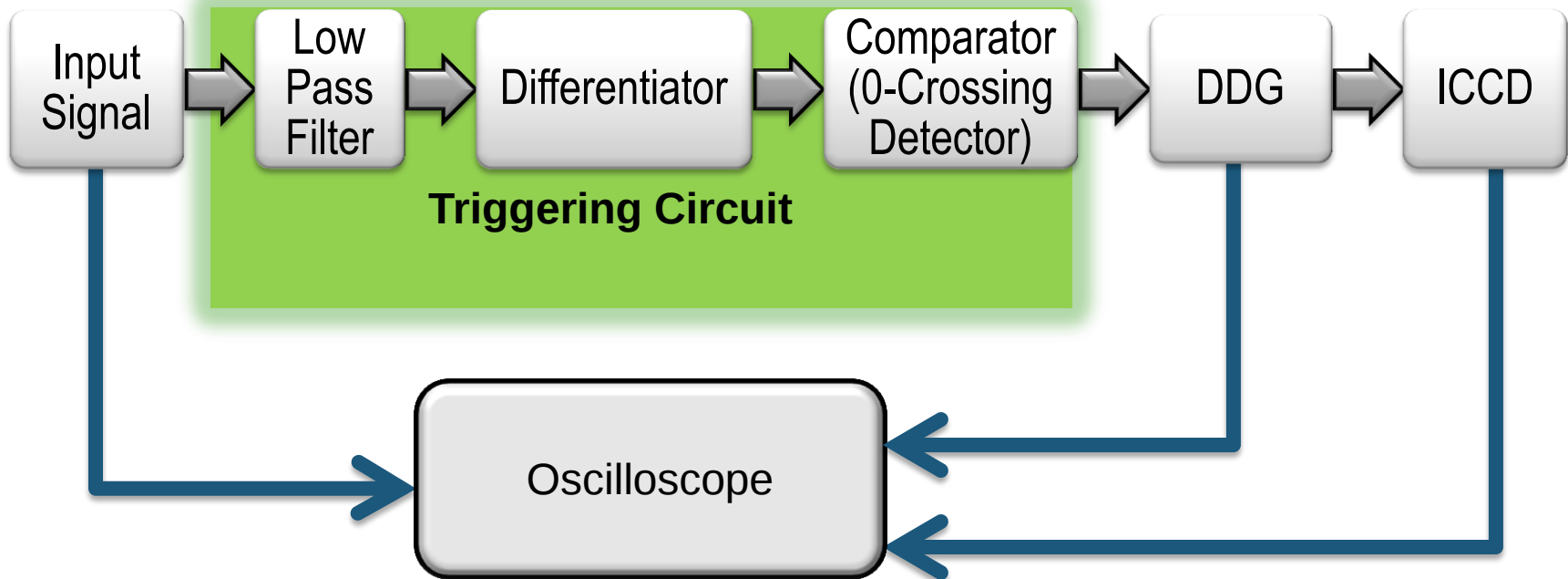
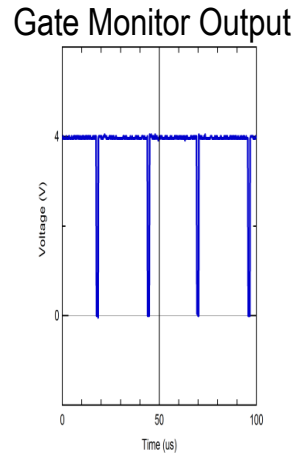
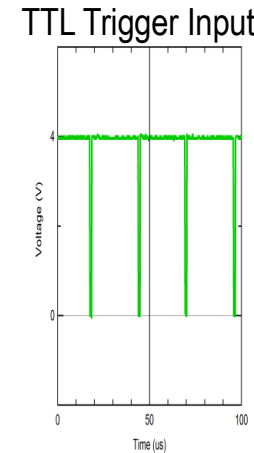
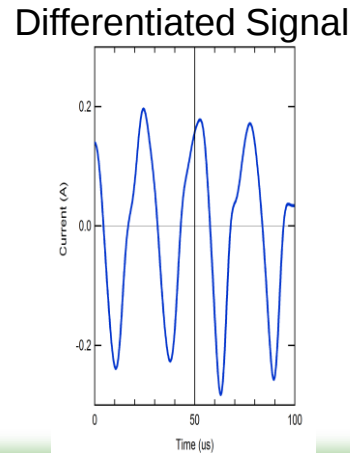
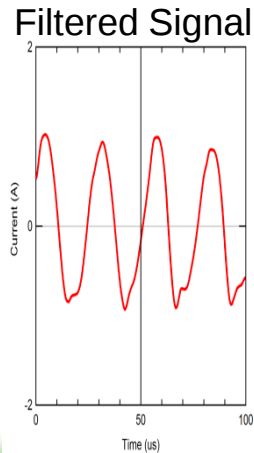
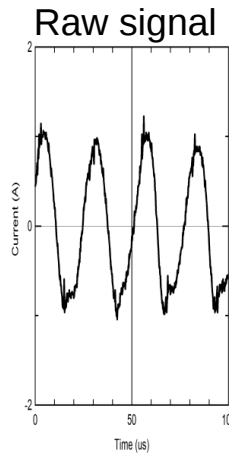
Discharge Current (AC)
Passive inductive probe
Band pass: 120Hz- 20MHz



Discharge Current FFT
Spectrum Analyzer
with FFT averaging

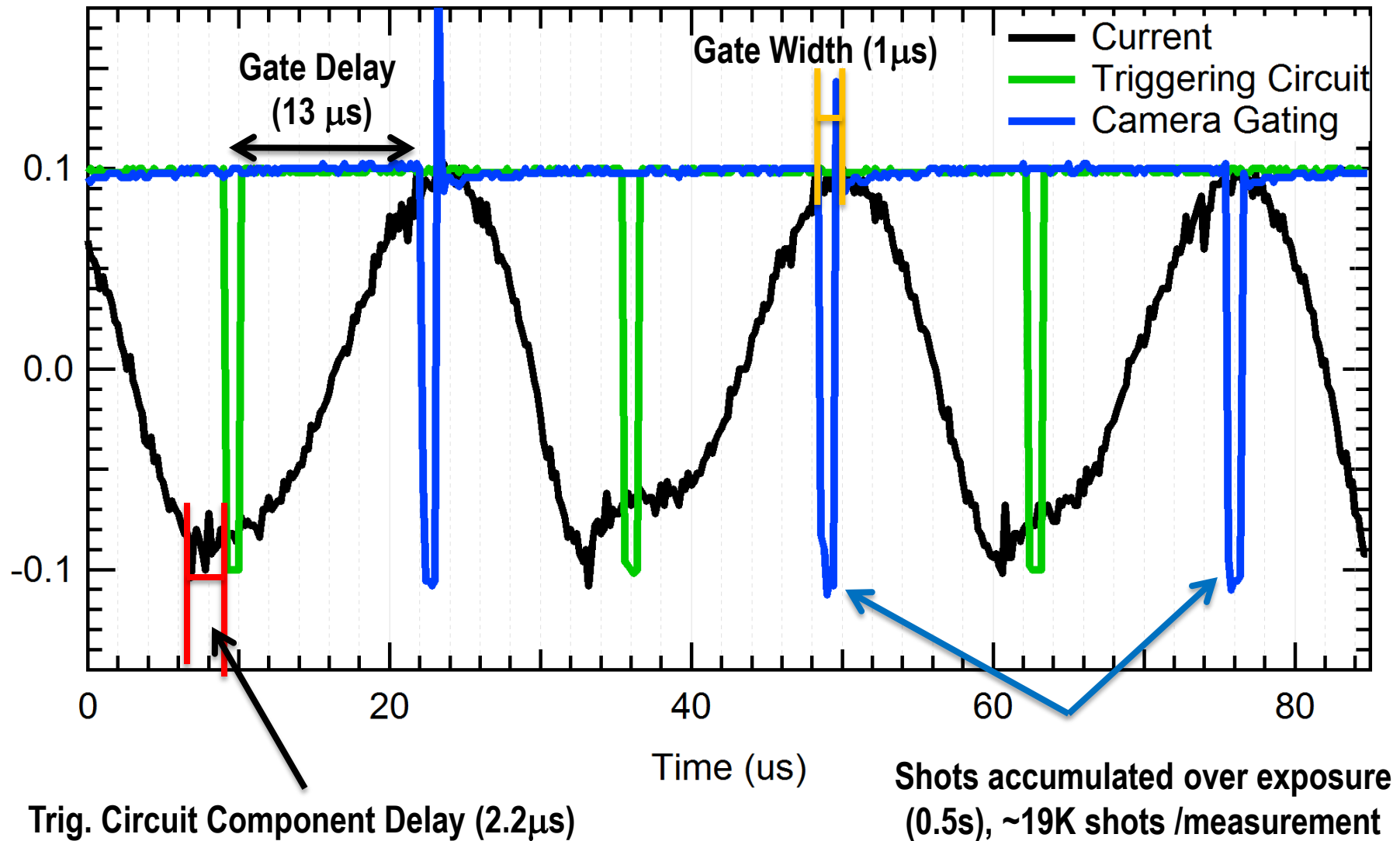


Timing System



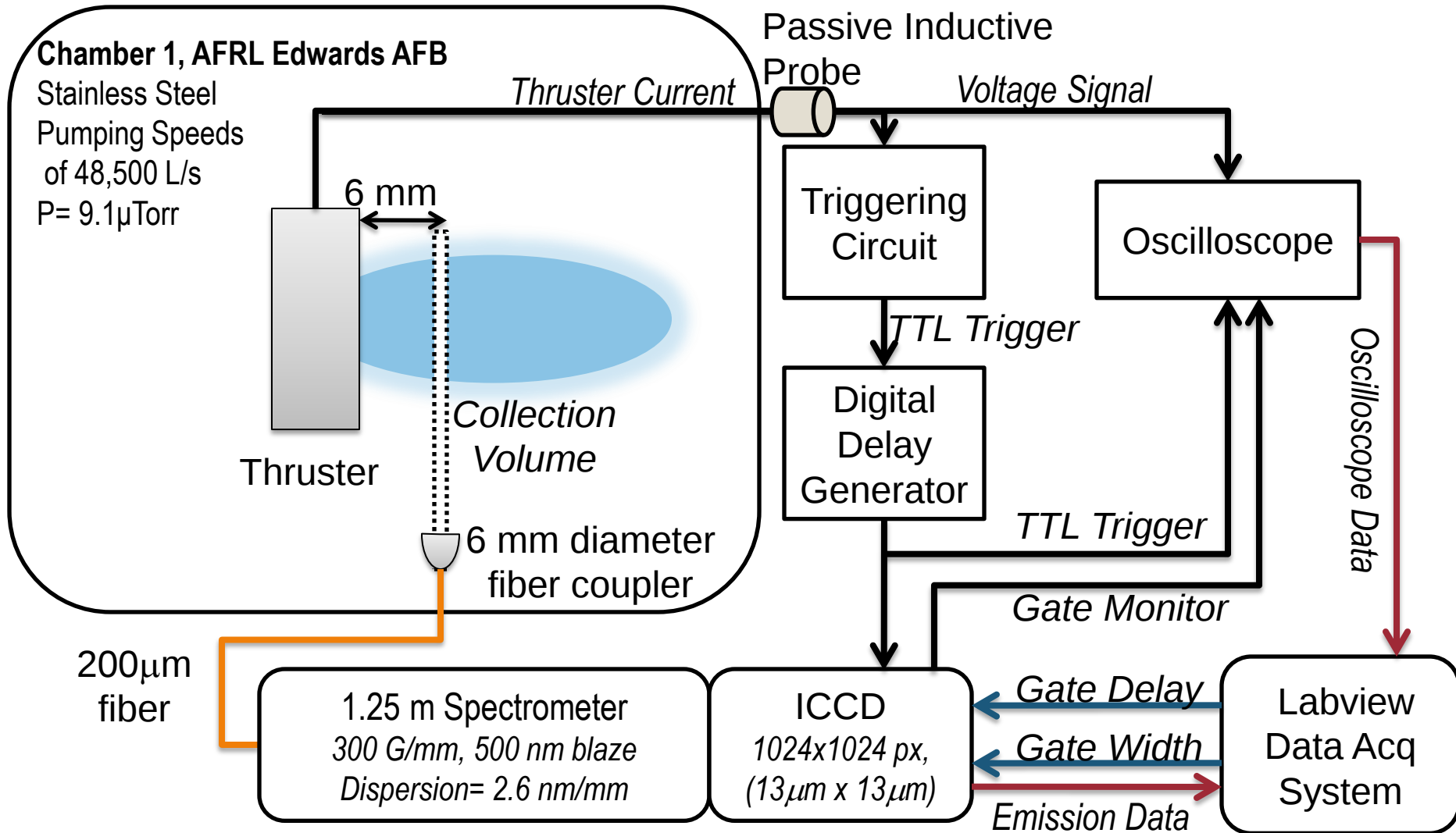


Timing System



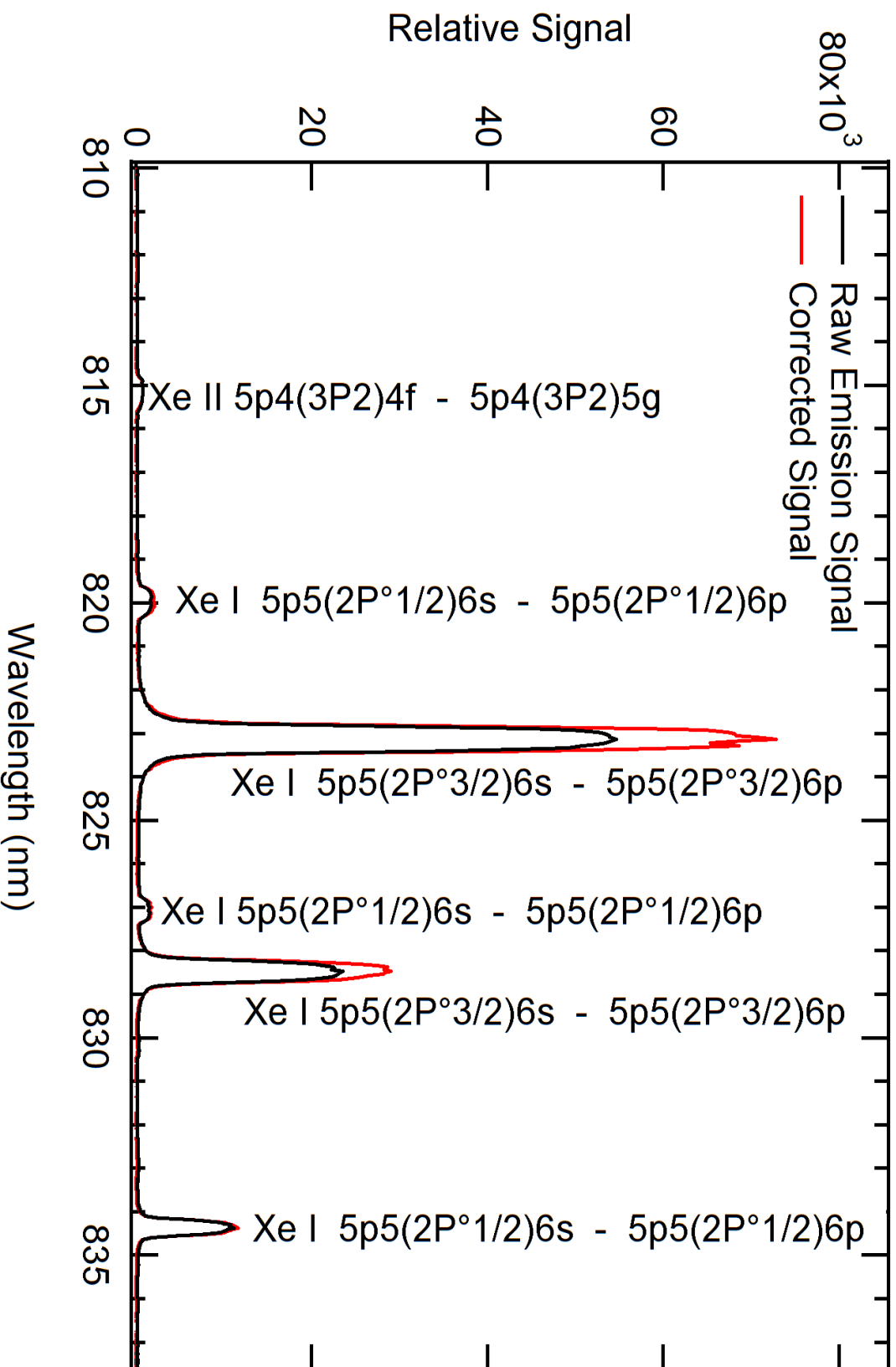


System Schematic





Sample Emission Measurement



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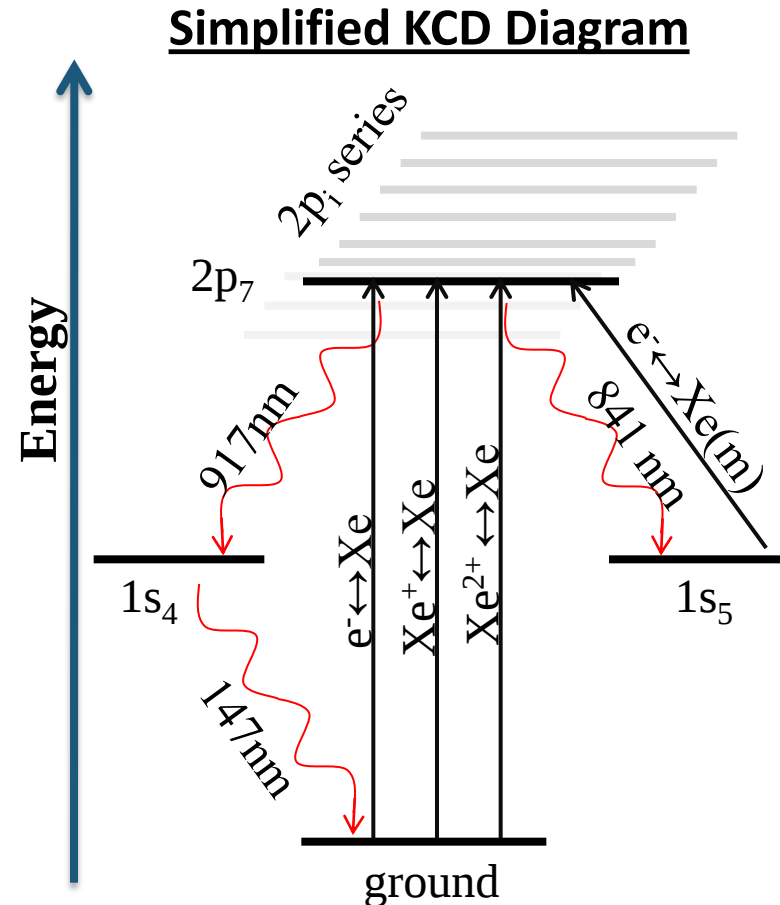
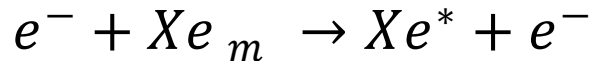
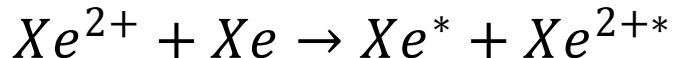
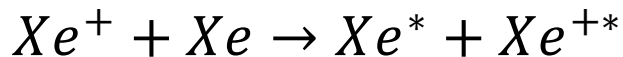
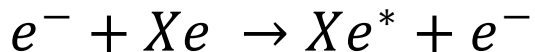


Collisional Radiative Modeling (CRM)



- Predicts emission by modeling collisional excitation and allowed radiative decay paths
- KCD⁸ Metastable Modeling
 - Treated as virtual ground
 - Assumed in equilibrium

Simplified Xe Collisional Excitation Processes



[8] Karabadzhak et al., *Journal of Applied Physics* , 2006



CRM: KCD Model

$$I_{XeI}(\lambda) = \frac{hc}{4\pi\lambda} (N_0 N_e) \left[\underbrace{k_{e0}^\lambda}_{\text{E x B probe measurements}} + \underbrace{\alpha k_{10}^\lambda}_{\text{E x B probe measurements}} + \frac{1-\alpha}{2} \underbrace{k_{20}^\lambda}_{\text{E x B probe measurements}} + \left\{ \frac{N_m}{N_0} \right\} \underbrace{k_{em}^\lambda}_{\text{Metastable rate approximations}} \right]$$

$$\underbrace{k_{i0}^\lambda}_{\text{E x B probe measurements}} = \int_0^\infty \underbrace{f_i(E_i)}_{\text{Ions- uniform velocity, LIF}} \underbrace{\sigma_{i0}^\lambda(E_i)}_{\text{Empirical excitation cross sections}^{9,10}} u_i dE_i$$

*Metastable rate approximations

$f(T_e, \alpha) \approx 0.01\% - 0.3\%$

*Equilibrium assumption

- Ions- uniform velocity, LIF
- e^- - Maxwellian EDF= $f(T_e)$

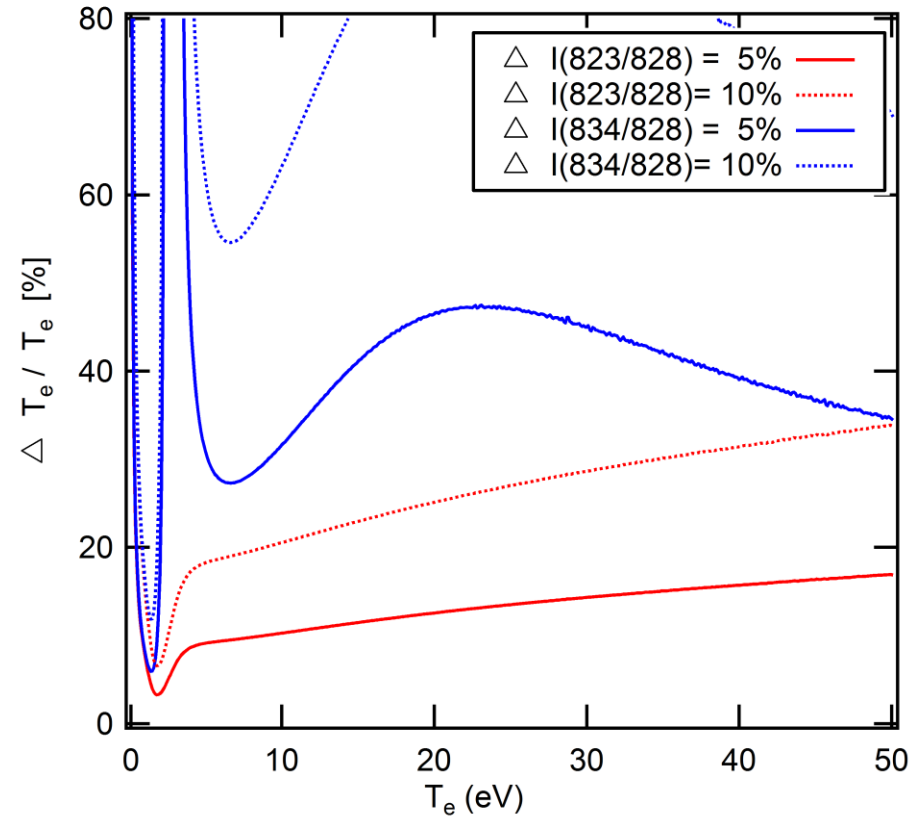
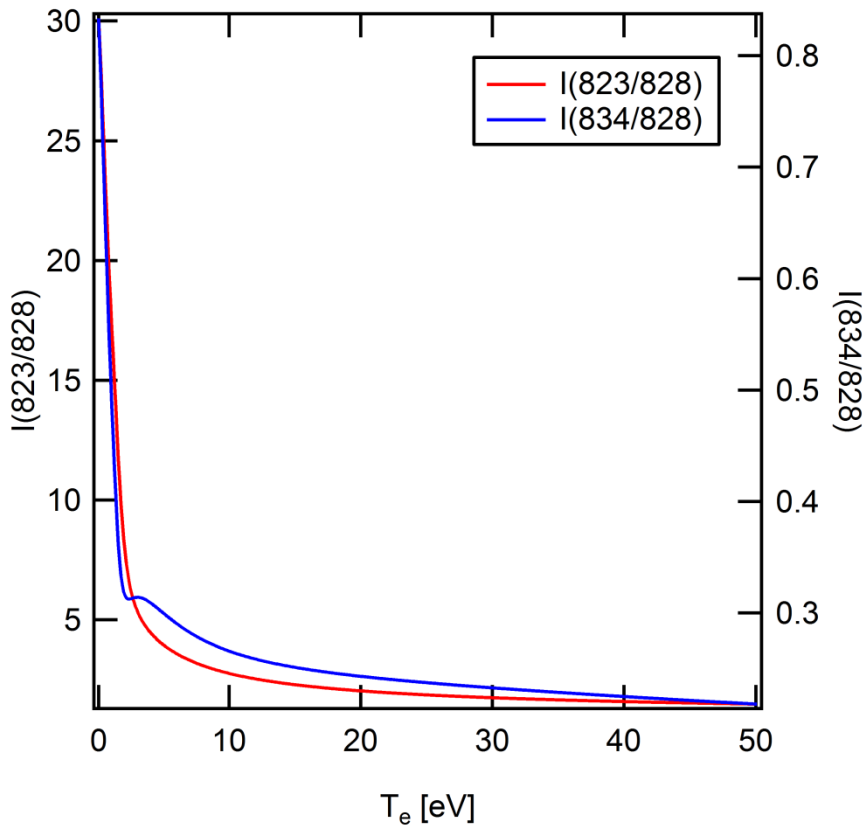
$$\frac{I_{XeI}(\lambda_1)}{I_{XeI}(\lambda_2)} = f(\alpha, u_1, T_e)$$

[9]Chiu et al, *Journal of Applied Physics* , 2006.

[10] Sommerville et al, *Journal of Prop. & Power*, 2008.



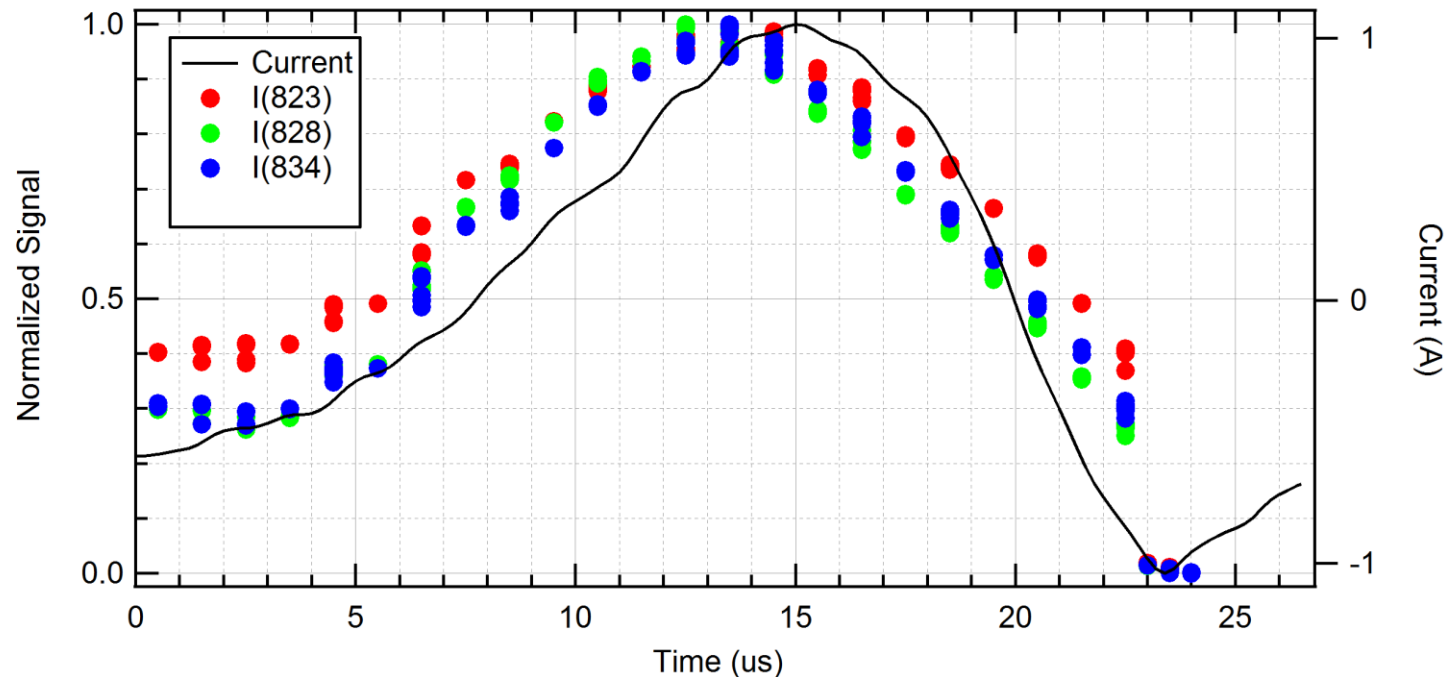
CRM: KCD Model



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Normalized Emission Measurements



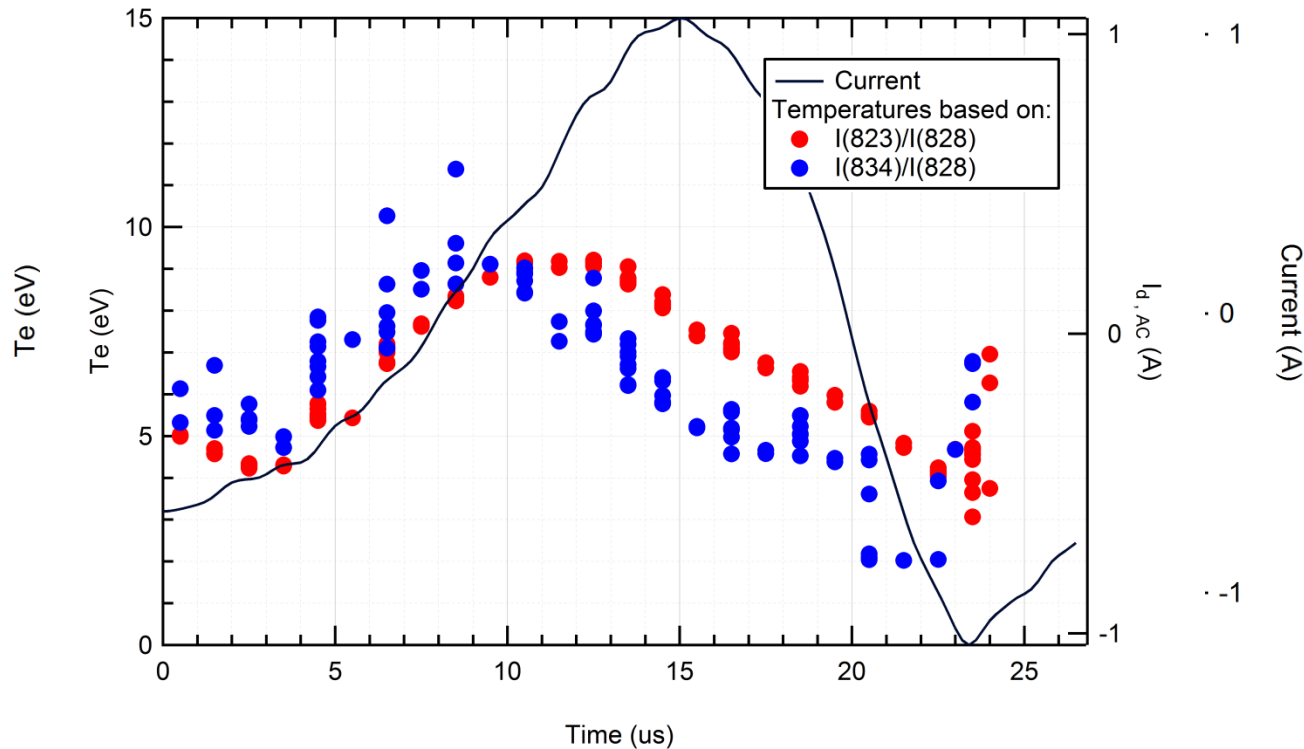
- **Intensity in phase with discharge current oscillations**
- Similar visible emission fluctuations seen by Liu et al.¹¹ in thruster high speed imaging
- Small phase shift ($\sim 2 \mu\text{s}$) seen between intensity and discharge current
 - Corresponding to a 8 km/s electron axial velocity
 - In agreement with 5-10 km/s electron axial velocity predicted by HPHall¹²

[11] Liu et al., *IEEE T. Plasma. Sci.*, (in press)

[12] Scharfe, M K, Koo, J W, personal communication, 2011



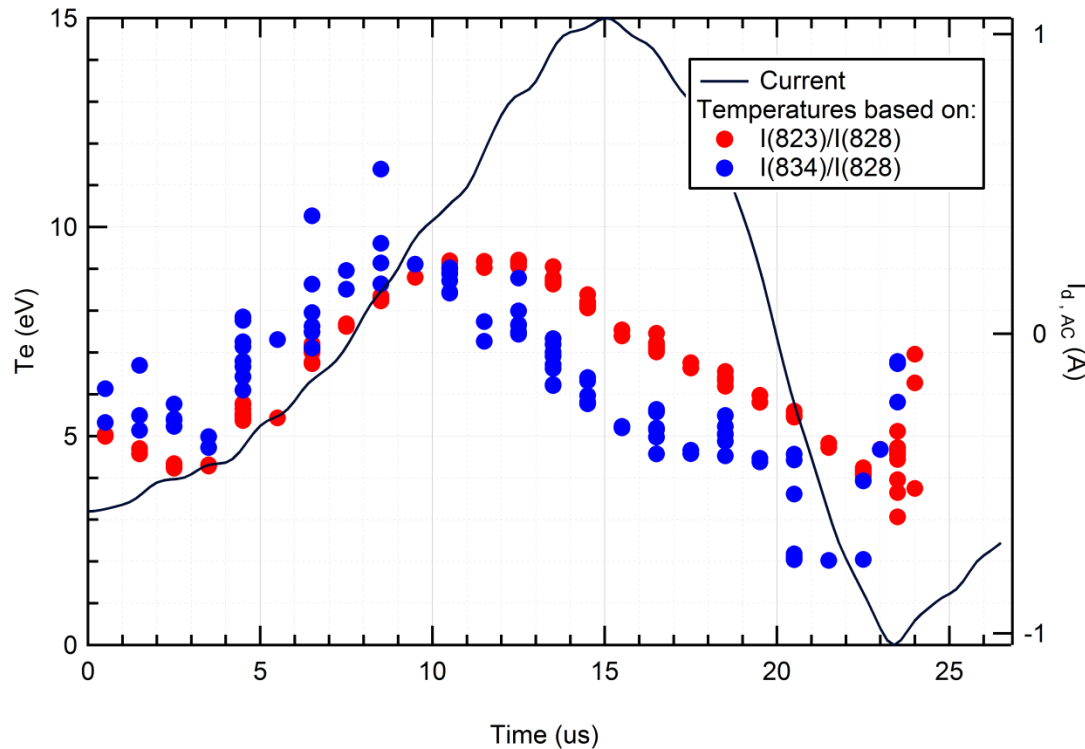
Electron Temperature



- **Line ratio method divergence in cooling phase of the cycle may be due to:**
 - Non-maxwellian EEDF
- **Low emission signal (SNR=1.9 dB) in low I_d portion of cycle**
 - Higher uncertainties in T_e



Electron Temperature



		I_{823}/I_{828}	I_{834}/I_{828}
$\overline{T_e}$	eV	6.6 ± 0.6	6.2 ± 1.8
$\widetilde{T_e}/\overline{T_e}$	%	27 ± 4	38 ± 15
τ_d	μs	-4	-6

Comments

- High SNR
- Lower T_e uncertainty
- Low SNR
- Higher T_e uncertainty
- Independent of metastable approximation

Distribution A: Approved for public release; distribution unlimited.



HPHall: Overview

- **Radial-axial hybrid particle-in-cell (PIC)**

- Fluid electrons
- PIC ions and neutrals
- Quasineutral
- Electron mobility- axially varying effective mobility

- **Simulations**

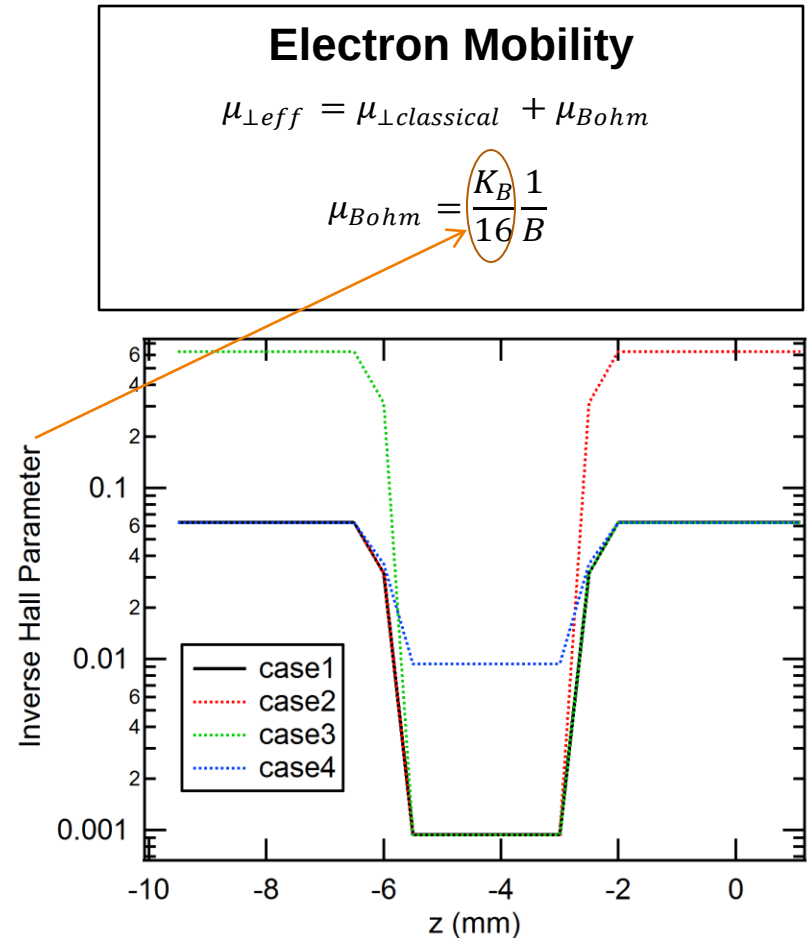
- Time step = 0.25 μs
- Varying Inverse Hall Parameter $K_B/16$
- Properties evaluated at 4 axial locations:

A) Channel Near Anode
B) Channel Near exit

C) Near Plume
D) Far Plume

- **Experimental/numerical comparison:**

- Time-averaged quantities
- Breathing mode behavior





HPHall: Case Comparison

	Units	Measured	HPHall Case 1	HPHall Case 2	HPHall Case 3	HPHall Case 4
T	mN	39	38	38	38	41
I_{SP}	s	1530	1530	1510	1530	1660
f_{BM}	kHz	38	34 ± 5	54 ± 5	31 ± 5	22 ± 5
$\bar{I}_d$	A	2.05	2.18	2.21	2.20	3.64
$\widetilde{I}_d / \bar{I}_d$	--	32%	7 %	11 %	7 %	6 %
$\overline{T_e}$	eV	6.6 ± 0.6	12.4	10.4	12.7	25.8
$\widetilde{T_e} / \overline{T_e}$	---	$32 \pm 8 \%$	4%	6%	4%	2%

- **Accurate thruster performance—within 10%**
- **Difficulty with predicting breathing mode behavior**
 - Oscillations in I_d and T_e significantly lower than observed
 - Higher than observed T_e – possible mechanism to increase mobility
- **Inverse Hall parameter-strong influence on breathing mode**
 - Variation in breathing mode frequency and amplitude of oscillations



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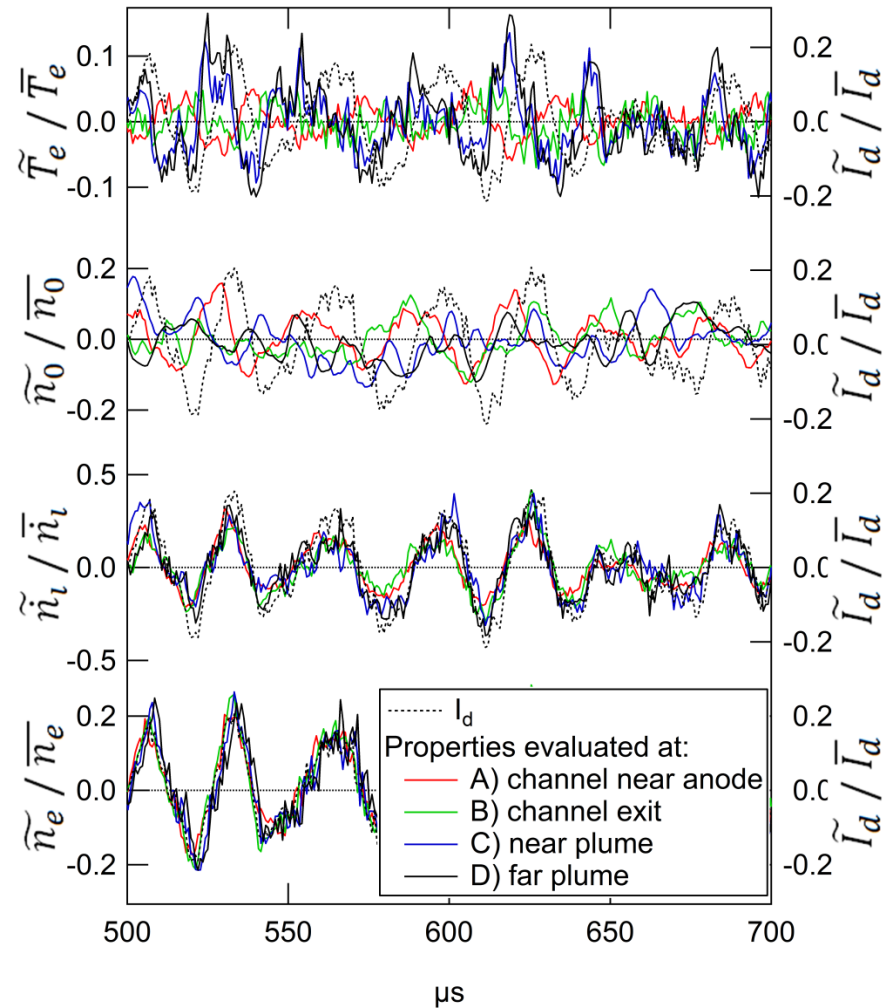
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 - Higher than observed T_e – possible mechanism to increase mobility
- **Inverse Hall parameter-strong influence on breathing mode**
 - Variation in breathing mode frequency and amplitude of oscillations
- **Further analysis based on Case 1**



HPHall Results: Time-Resolved



- T_e – Slight correlation with I_d seen in plume, and near anode
 - Out of phase with discharge current—similar to experimental observations
- N_0 – Little correlation with I_d except for near anode
- N_i/N_e – strong correlation with I_d at all axial locations
 - Oscillations nearly in phase with discharge current oscillations

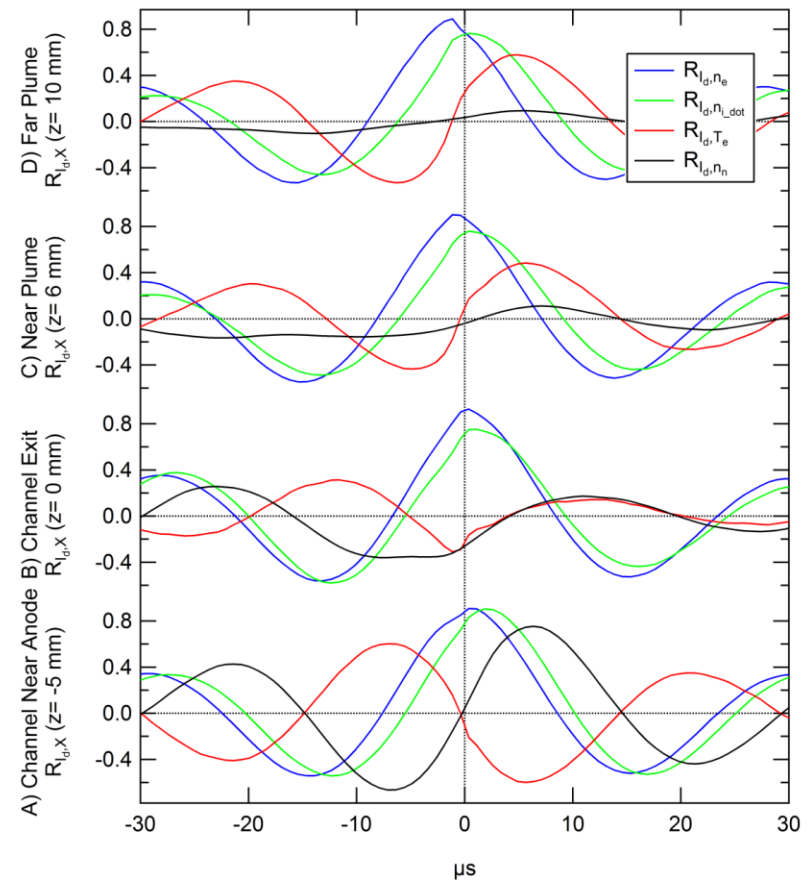




HPHall Results: Cross Correlation

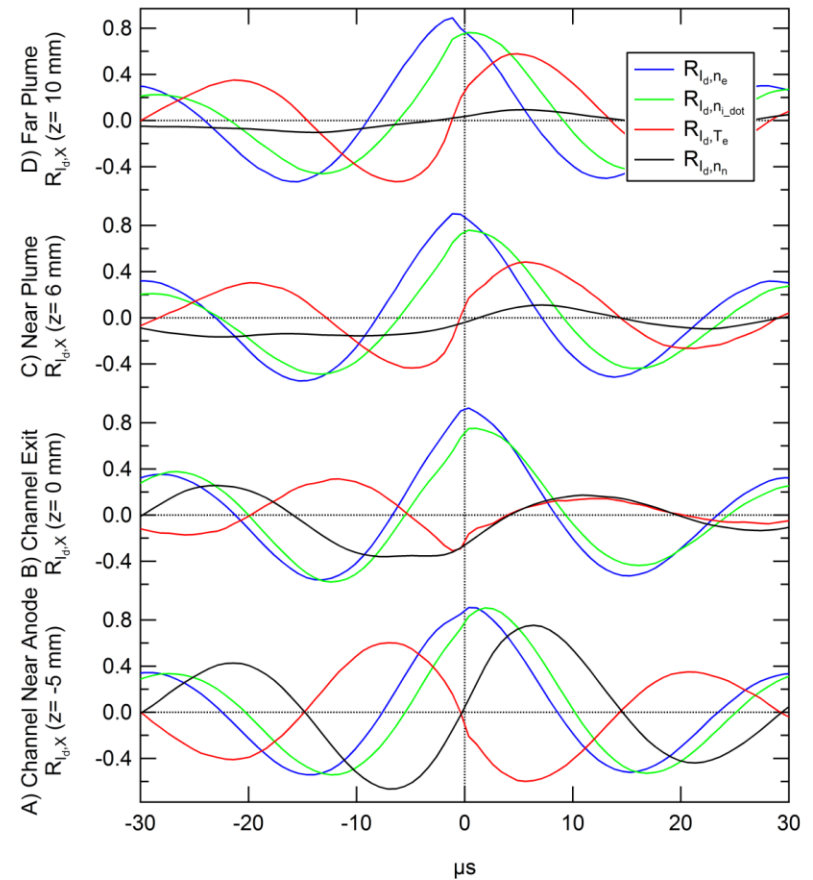
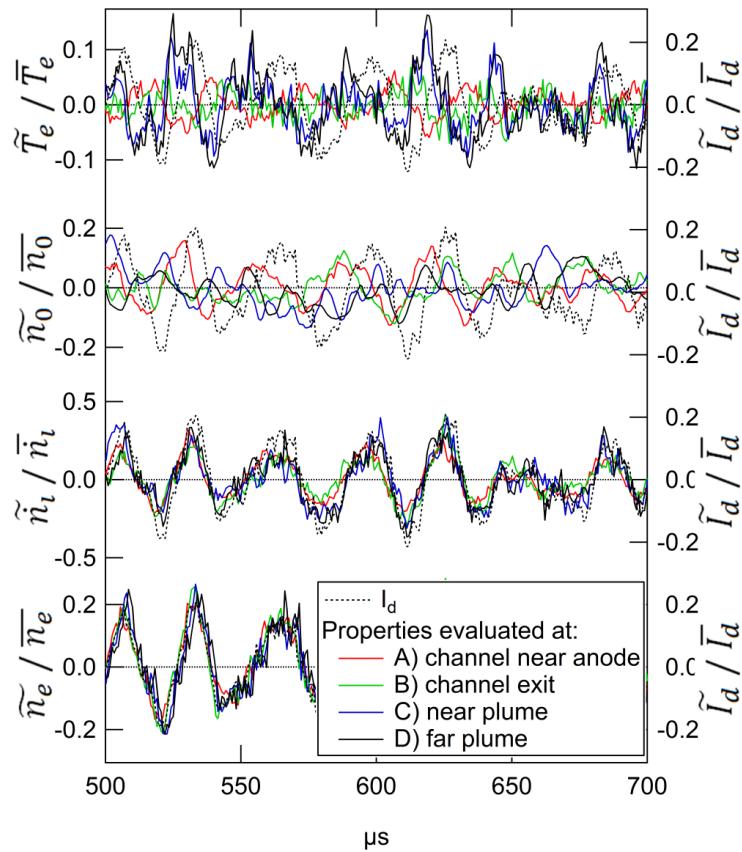


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 - Oscillations nearly in phase with discharge current oscillations





HPHall Results



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HPHall Results

	Axial Location	$\bar{X}$	$\tilde{X}/\bar{X}$	freq (kHz)	τ_{delay} (μs)	$\phi_{I_d, X}$ (degrees)	R
Discharge Current I_d	--	2.2 A	7%	34	--	--	1.00
Neutral Density n_0	A	9.5E+18 m ⁻³	4%	33	6.4	77	0.75
	B	2.1E+18 m ⁻³	5%	33	-22.9	-275	0.26
	C	5.6E+17 m ⁻³	7%	28	7.1	73	0.11
	D	3.9E+17 m ⁻³	7%	33	5.6	68	0.09
Ionization Rate $\dot{n}_i$	A	1.2E+24 m ⁻³	8%	33	1.9	23	0.90
	B	1.7E+23 m ⁻³	9%	34	1.1	14	0.75
	C	1.9E+22 m ⁻³	12%	34	0.4	5	0.76
	D	6.3E+21 m ⁻³	13%	33	0.4	5	0.76
Electron Density n_e	A	1.1E+18 m ⁻³	7%	34	0.4	5	0.91
	B	6.4E+17 m ⁻³	8%	34	0.4	5	0.93
	C	3.5E+17 m ⁻³	8%	34	-1.1	-14	0.90
	D	2.4E+17 m ⁻³	9%	33	-1.1	-14	0.89
Electron Temperature T_e	A	27.3 eV	2%	34	-7.1	-87	0.60
	B	23.0 eV	2%	34	-11.6	-143	0.31
	C	16.5 eV	4%	34	5.6	68	0.48
	D	12.5 eV	5%	34	4.9	59	0.58

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Summary

- **Time resolved emission measurements:**
 - Emission of 823, 828, and 834 nm lines found to fluctuate nearly in phase with I_d
 - T_e fluctuations of $32\% \pm 8\%$, $-5 \pm 1 \mu\text{s}$ out of phase with I_d
- **HPHall simulations run with varying effective mobility profiles:**
 - Profile choice strong influence on breathing mode oscillations (frequency, amplitude)
 - Little effect on overall performance, all cases w/in 10% of observed values
- **HPHall Breathing mode predictions:**
 - Significantly under predict oscillation magnitude for both I_d and T_e
 - Higher than observed T_e values maybe be result of need for increased mobility
 - Phase shifts found to be consistent with current observations

	Units	Measured	HPHall Case 1
T	mN	39	38
I_{SP}	s	1530	1530
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$\bar{I}_d$	A	2.05	2.18
$\widetilde{I}_d/\bar{I}_d$	--	32%	7 %
$\bar{T}_e$	eV	6.6 ± 0.6	12.4
$\widetilde{T}_e/\bar{T}_e$	---	$32 \pm 8 \%$	4%
ϕ_{I,T_e}	deg	$68^\circ \pm 14^\circ$	68°