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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 μs 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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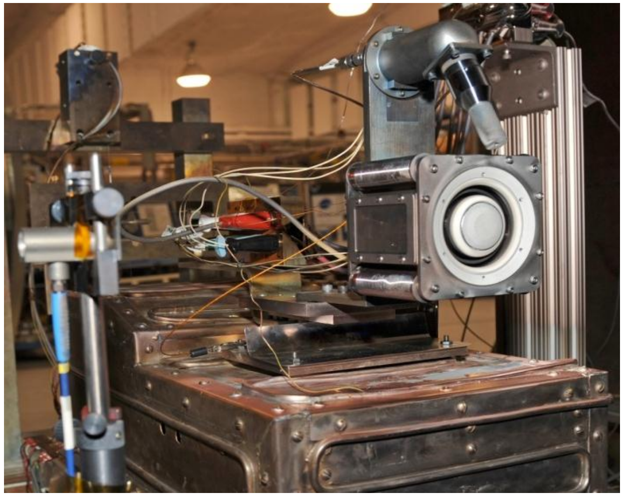
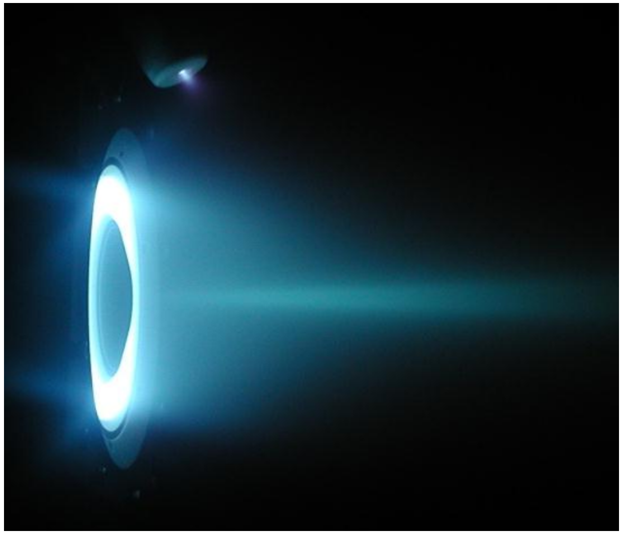
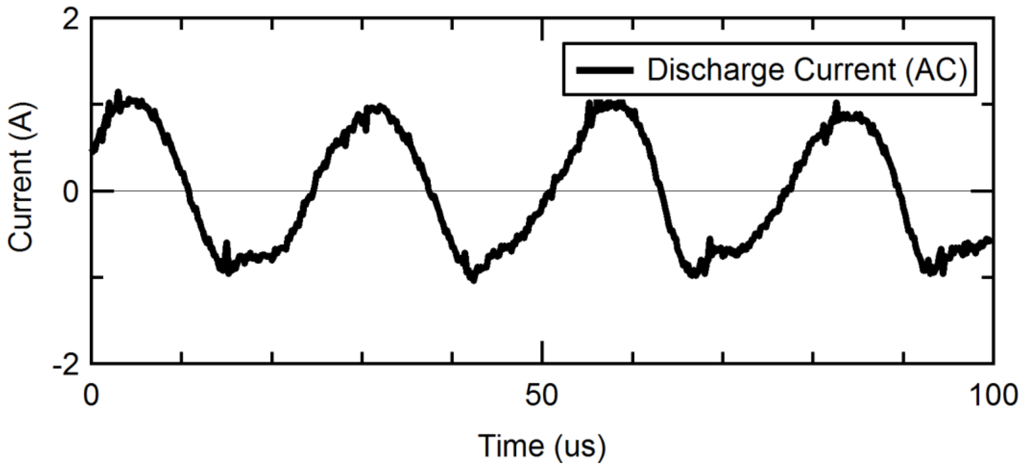
Overview

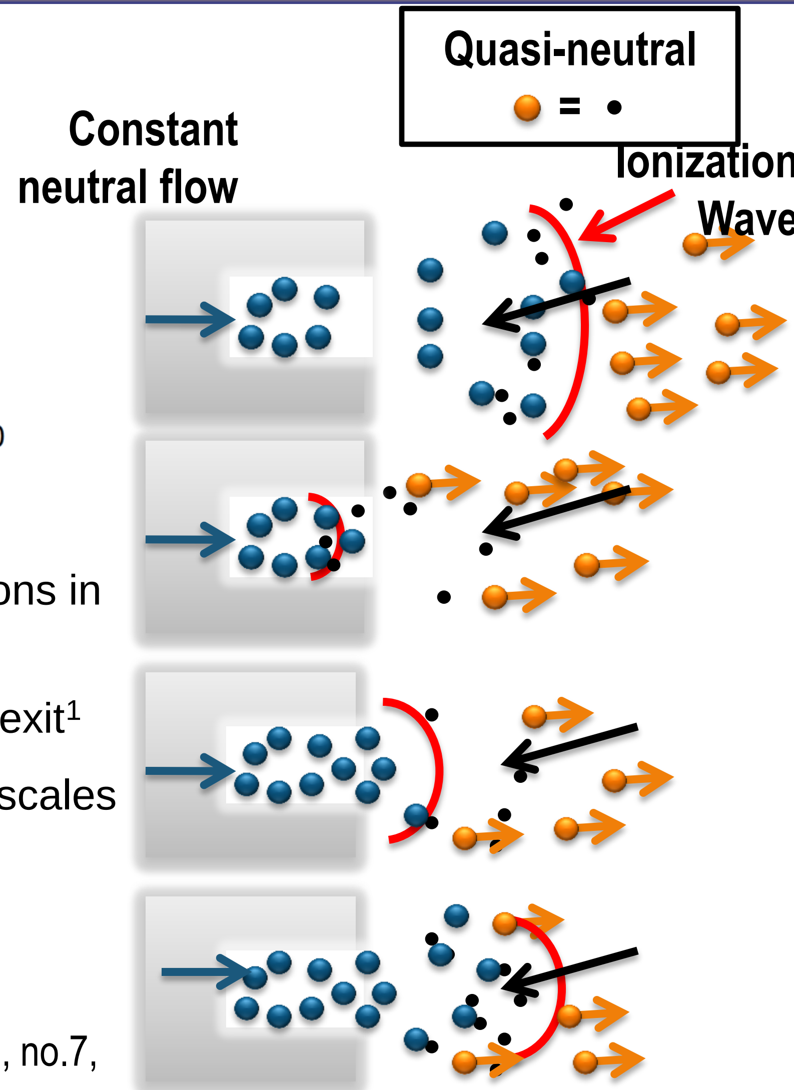
- **Background**
- **BHT-600Thruster**
- **Experimental Work**
- **Collisional Radiative Modeling**
- **HPHALL Simulations**
- **Numerical /Experimental Comparison**





Background: Breathing Mode





- Seen through low frequency (10-50k Hz) oscillations in discharge current (I_d)
- Periodic depletion & replenishment of neutrals at exit[1]
- 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

Background: Diagnostics

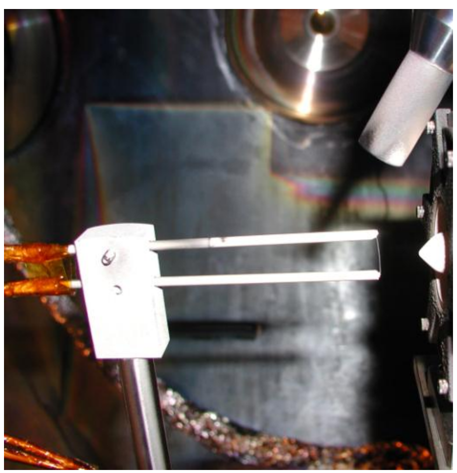
Probe

- Measurements
  - Langmuir- T_e, density, e^- EDF
  - RPA – ion EDF
  - Faraday- thruster beam current
- Intrusive- spatially limited
- Temporally limited due to sweeps
  - Lobbia[2] (10 μs resolution)

[2] Lobbia, RB and Gallimore, A.D. , *Rev. Sci. Instrum*. 81, 073503, 2010

Emission

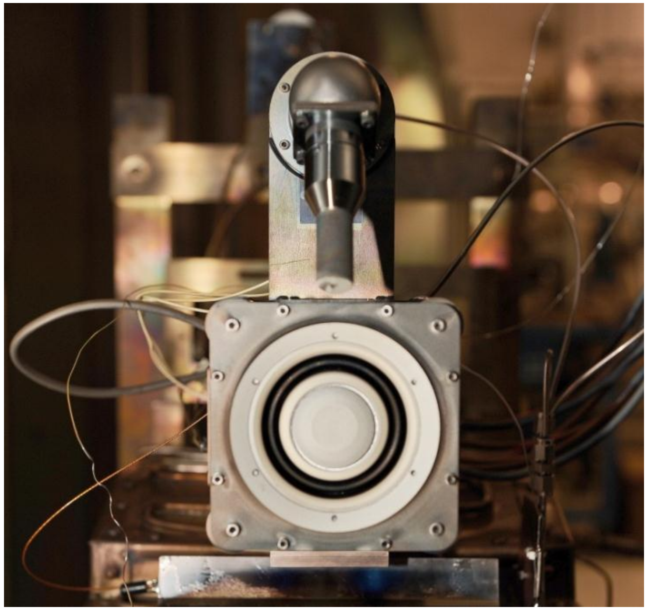
- Measurements
  - Line Intensity ratio- T_e
  - Absolute Intensity - Density
  - Doppler Shift - velocity
- Non-intrusive- capable of near field measurements
- Line of sight averaging
- Measurements on ns timescales

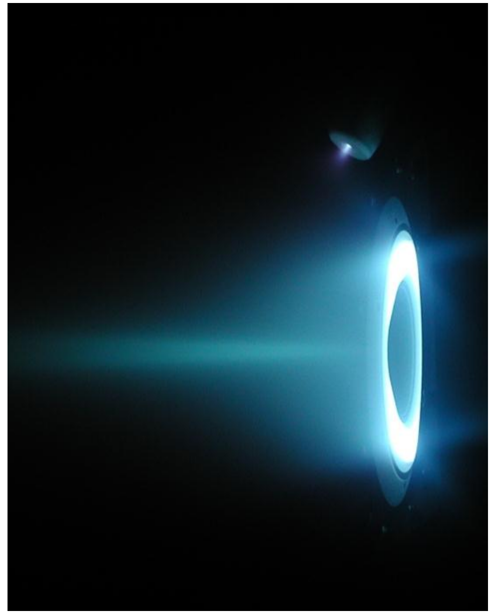


Electrostatic Probe

Emission Beam Coupler

BHT-600 Hall Effect Thruster





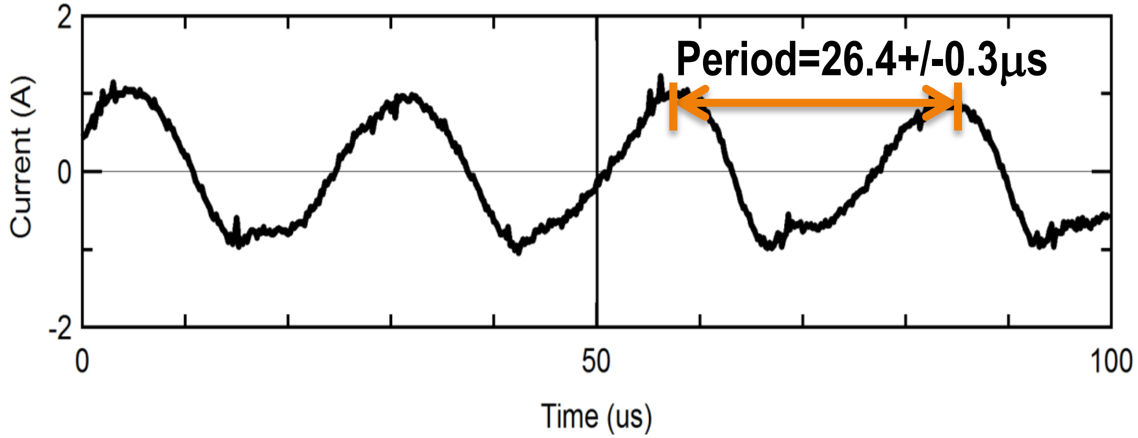
- **Thruster tested w Xe at nominal conditions**
- **Extensive previous experimental work**
  - Probe- RPA, Faraday, ExB[3-6]
  - Optical measurements-LIF[6,7]

BUSEK

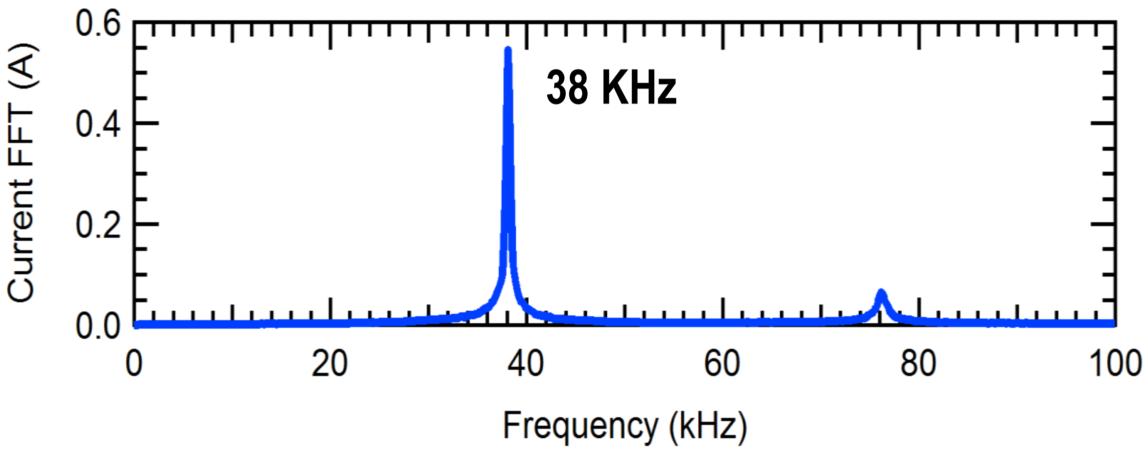
Dimensions	
R_{inner}	24 mm
R_{outer}	32 mm
Channel Depth	10 mm
Nominal Conditions	
Anode Flow Rate	2.45 mg/s
Cathode Flow Rate	197 μg/s
Anode Potential	300 V
Anode Current	2.05 A
Magnetic Current	2.0 A
Performance	
Thrust	42 mN
Specific Impulse	1650 s
Anode Efficiency	55.0%

[3] Ekholm et al, *JPC,* 2006.
[4] Niemela et al, *JPC,* 2006.
[5] Nakles et al, *IEPC,* 2009.
[6] Hargus et al, *JPC,* 2008.
[7] Nakles et al, *JPC,* 2008.

BHT-600 : Breathing Mode Oscillations

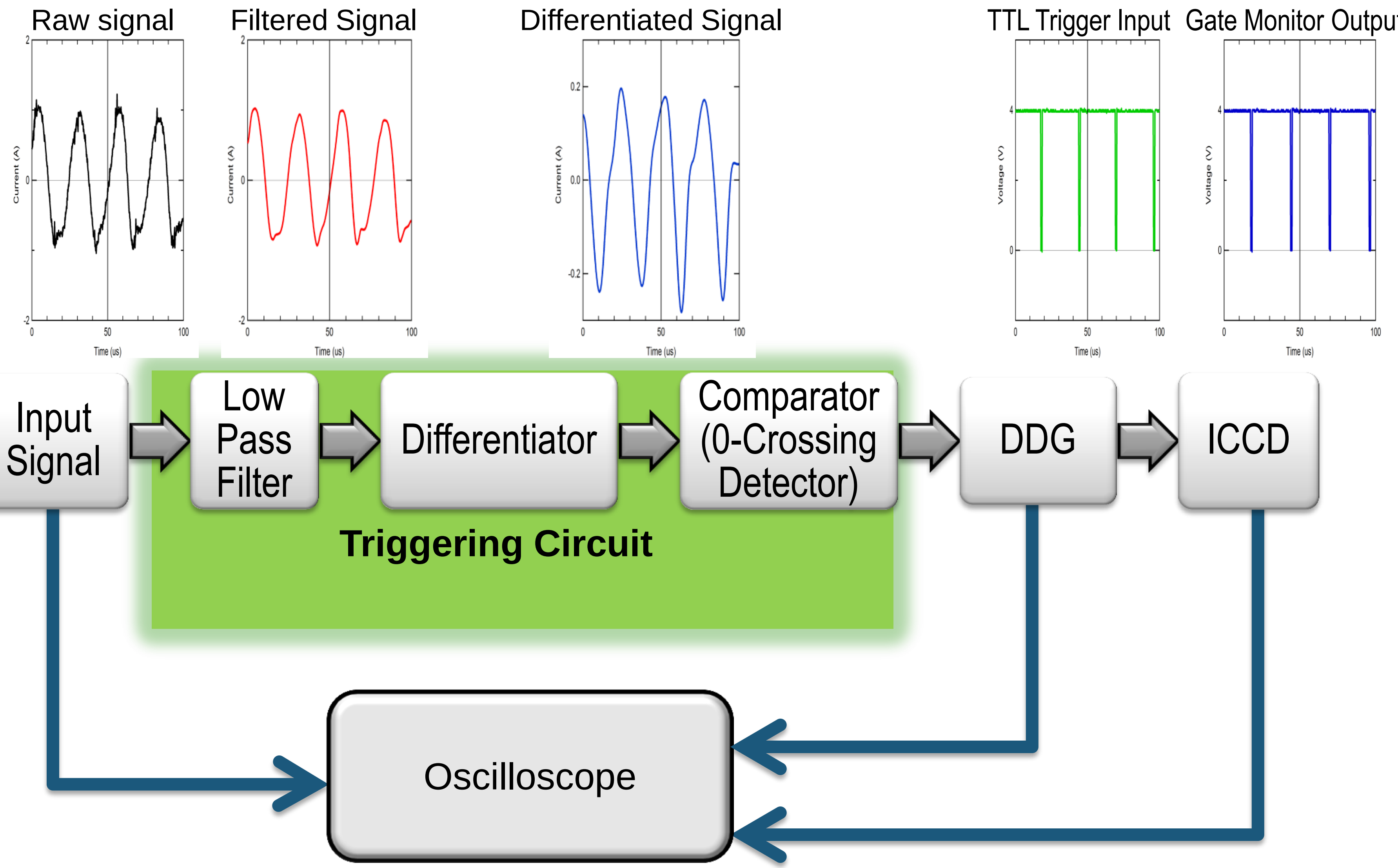


Discharge Currect (AC)
Passive inductive probe
Band pass:120Hz- 20MHz



Discharge Current FFT
Spectrum Analyzer
with FFT averaging

Timing System



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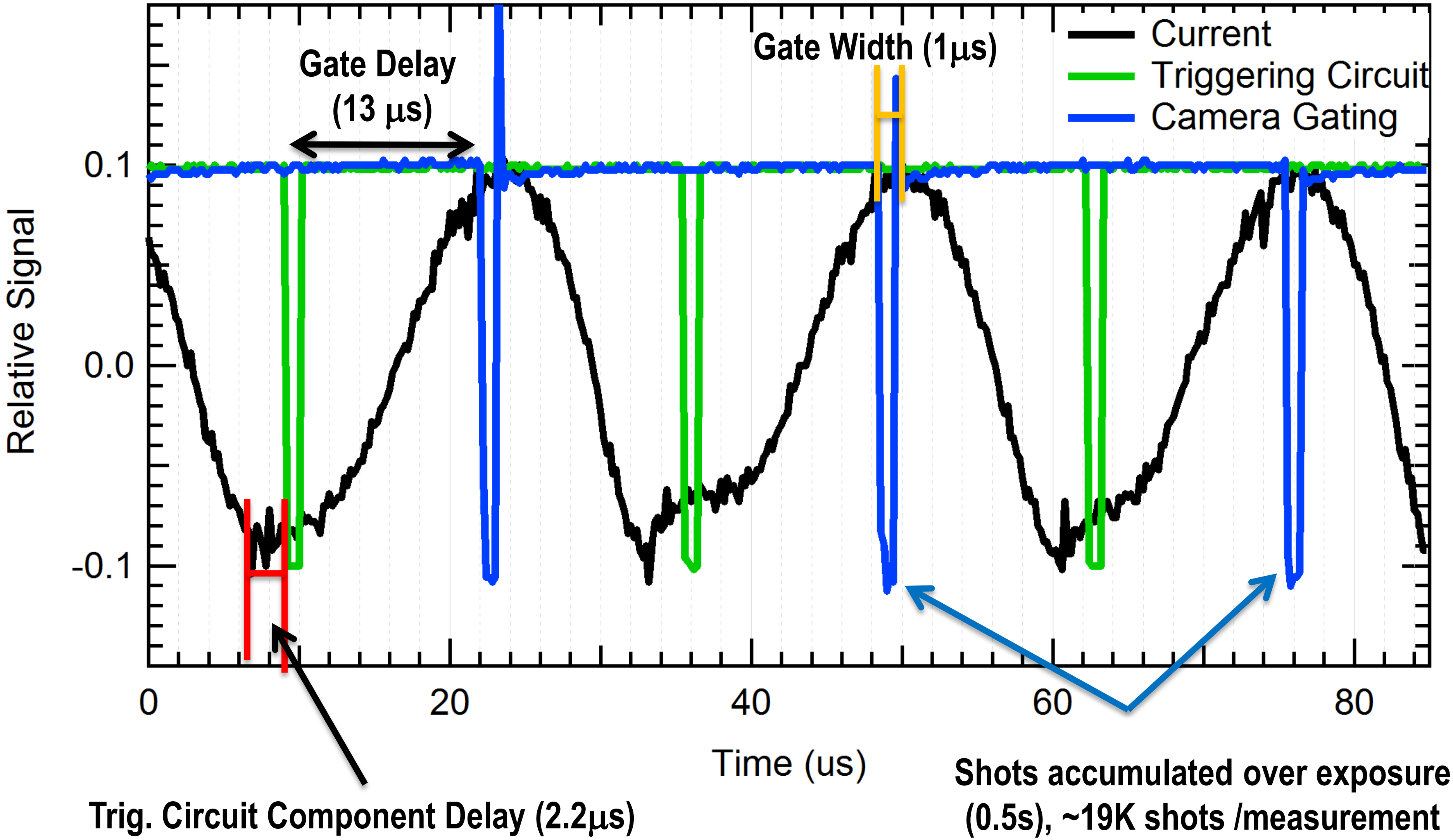
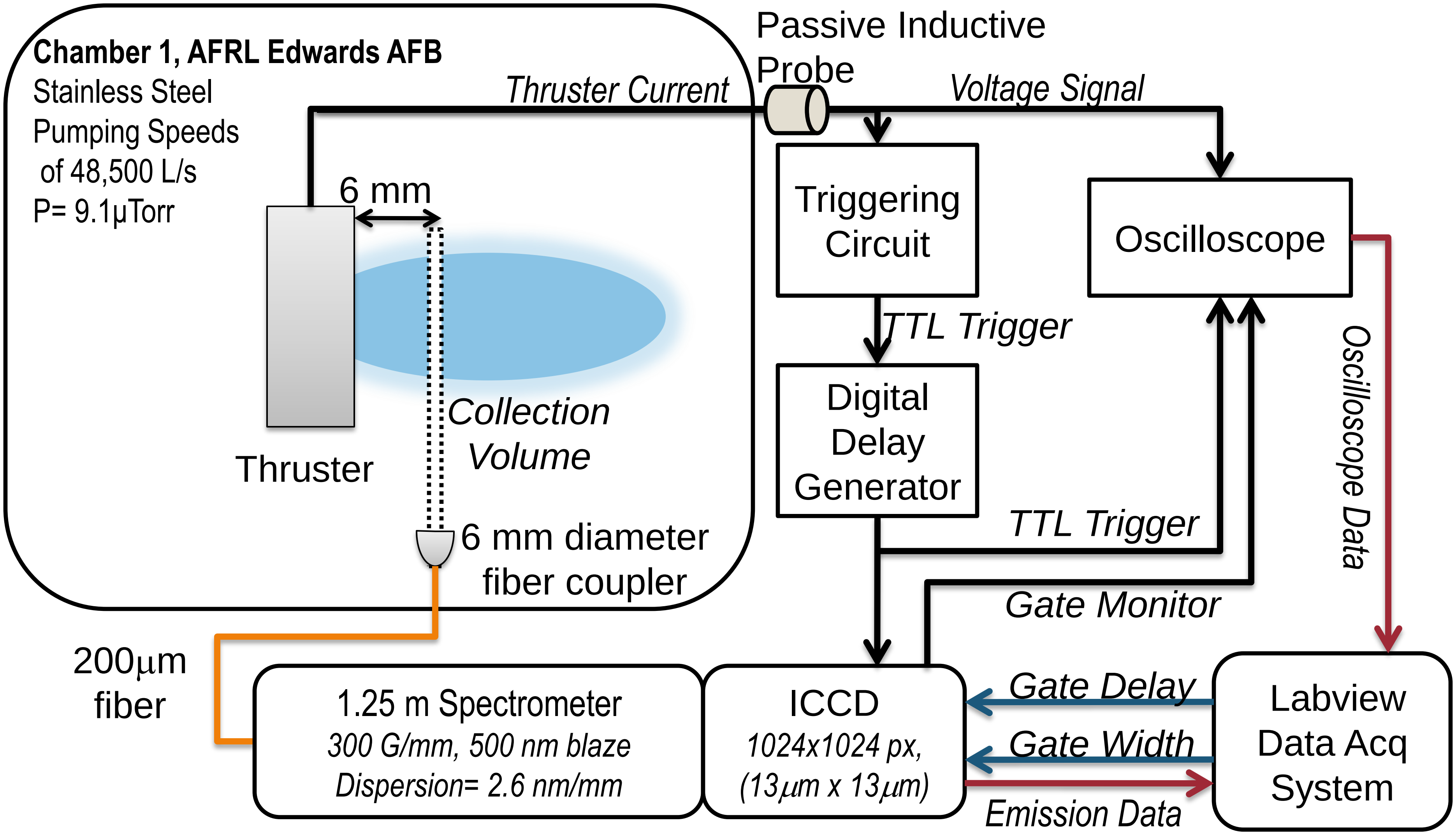


System Schematic



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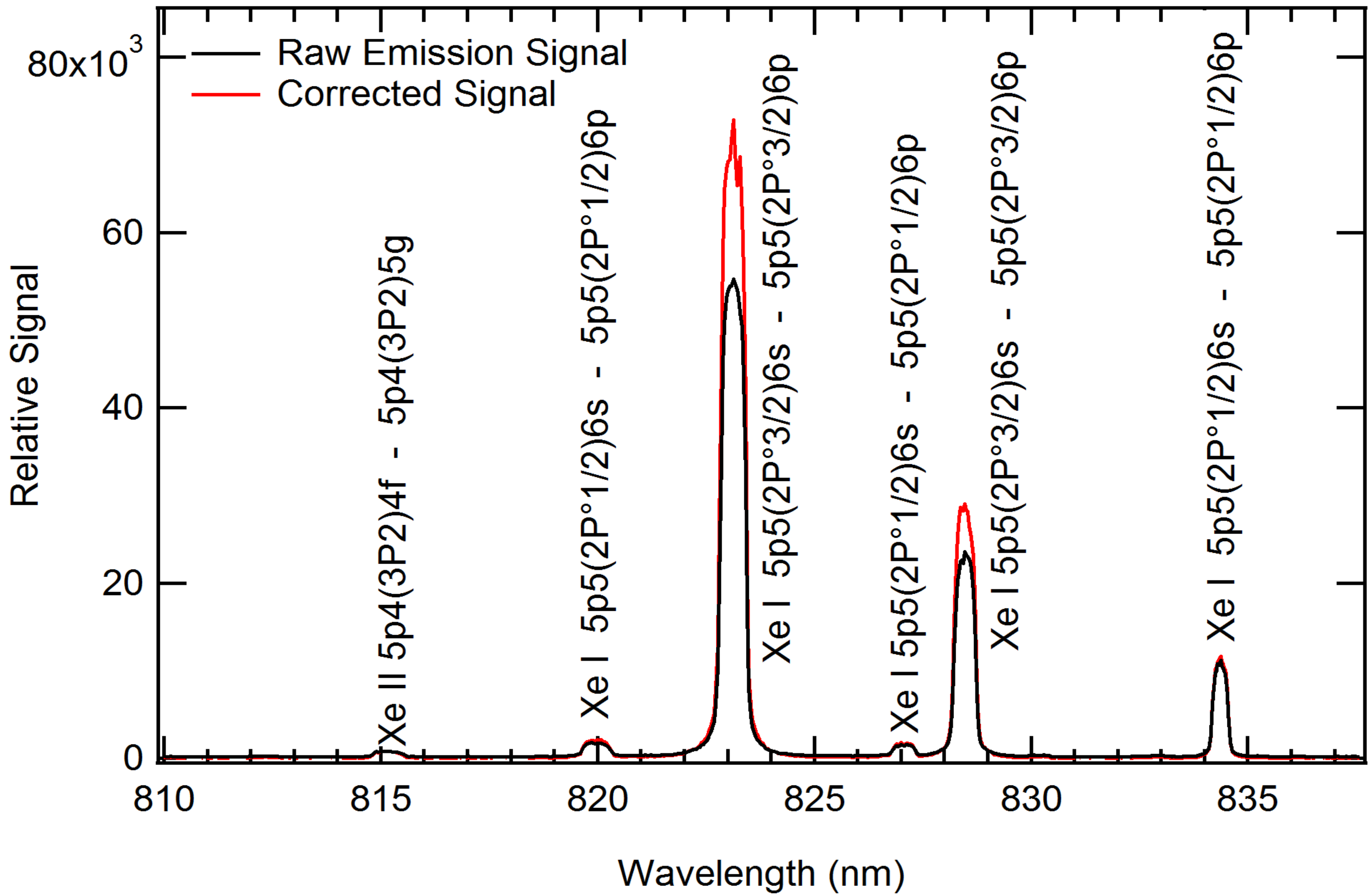
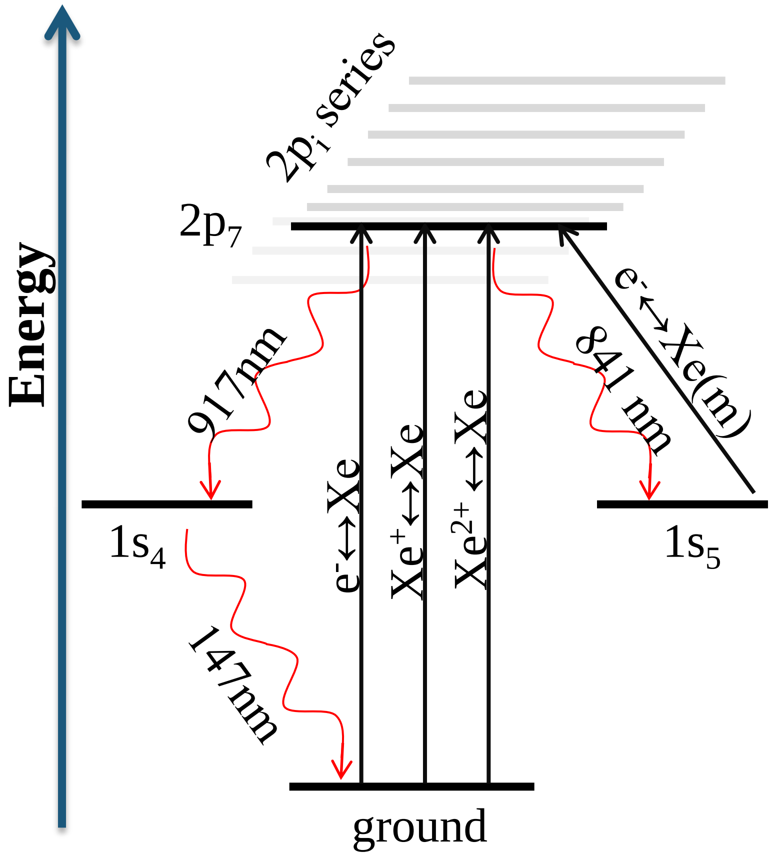
Sample Emission Measurement



Collisional Radiative Modeling (CRM)

- **Predicts emission by modeling collisional excitation and allowed radiative decay paths**
- **KCD[8] Metastable Modeling**
  - Treated as virtual ground
  - Assumed in equilibrium

Simplified KCD Diagram



Simplified Xe Collisional Excitation Processes

$$e^- + Xe \rightarrow Xe^* + e^-$$
$$Xe^+ + Xe \rightarrow Xe^* + Xe^{+*}$$
$$Xe^{2+} + Xe \rightarrow Xe^* + Xe^{2+*}$$
$$e^- + Xe_m \rightarrow Xe^* + e^-$$

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

CRM: KCD Model

E x B probe measurements

*Metastable rate approximations

$$I_{XeI}(\lambda) = \frac{hc}{4\pi\lambda}(N_0 N_e)\left[k_{e0}^{\lambda} + \alpha k_{10}^{\lambda} + \frac{1-\alpha}{2}k_{20}^{\lambda} \quad + \quad \left\{\frac{N_m}{N_0}\right\} \; k_{em}^{\lambda}\right]$$

$$k_{i0}^{\lambda} = \int_0^{\infty} f_i(E_i)\sigma_{i0}^{\lambda}(E_i)u_i \, dE_i$$

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

*Equilibrium assumption

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

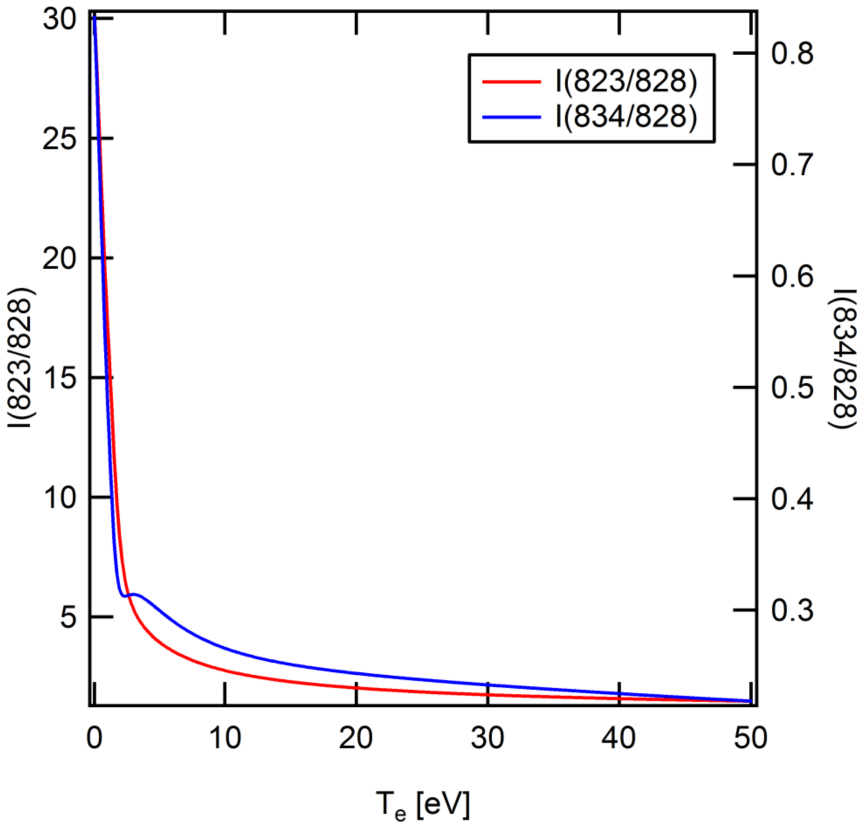
Empirical excitation cross sections[9,10]

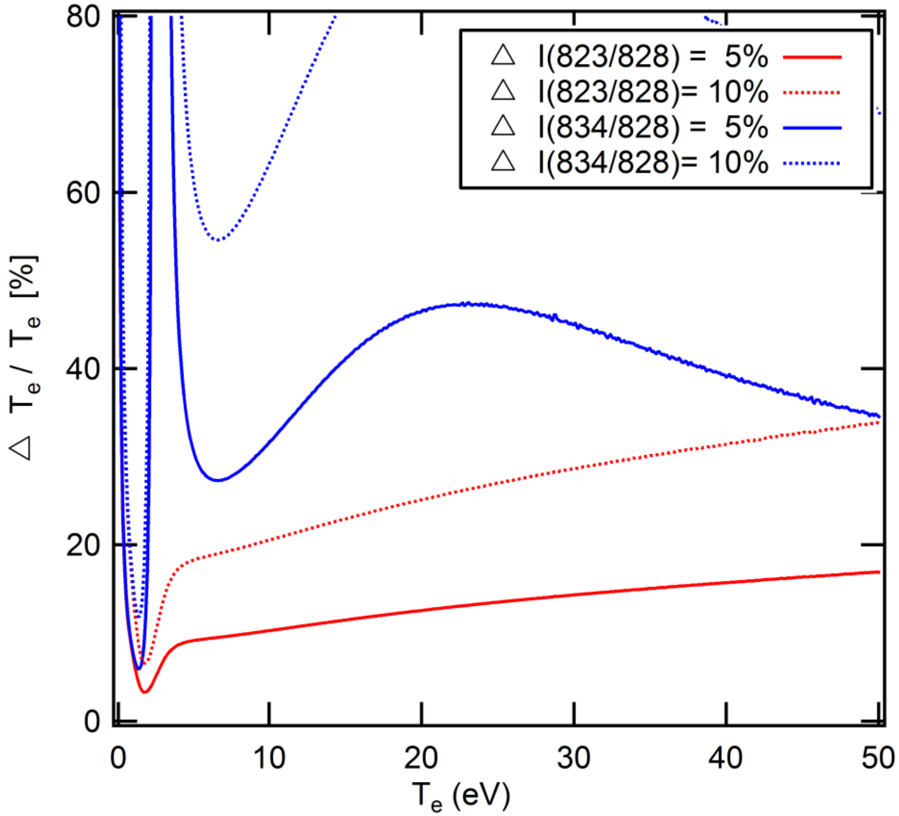
$$\frac{I_{XeI}(\lambda_1)}{I_{XeI}(\lambda_2)} = f(\alpha, u_1, T_e)$$

[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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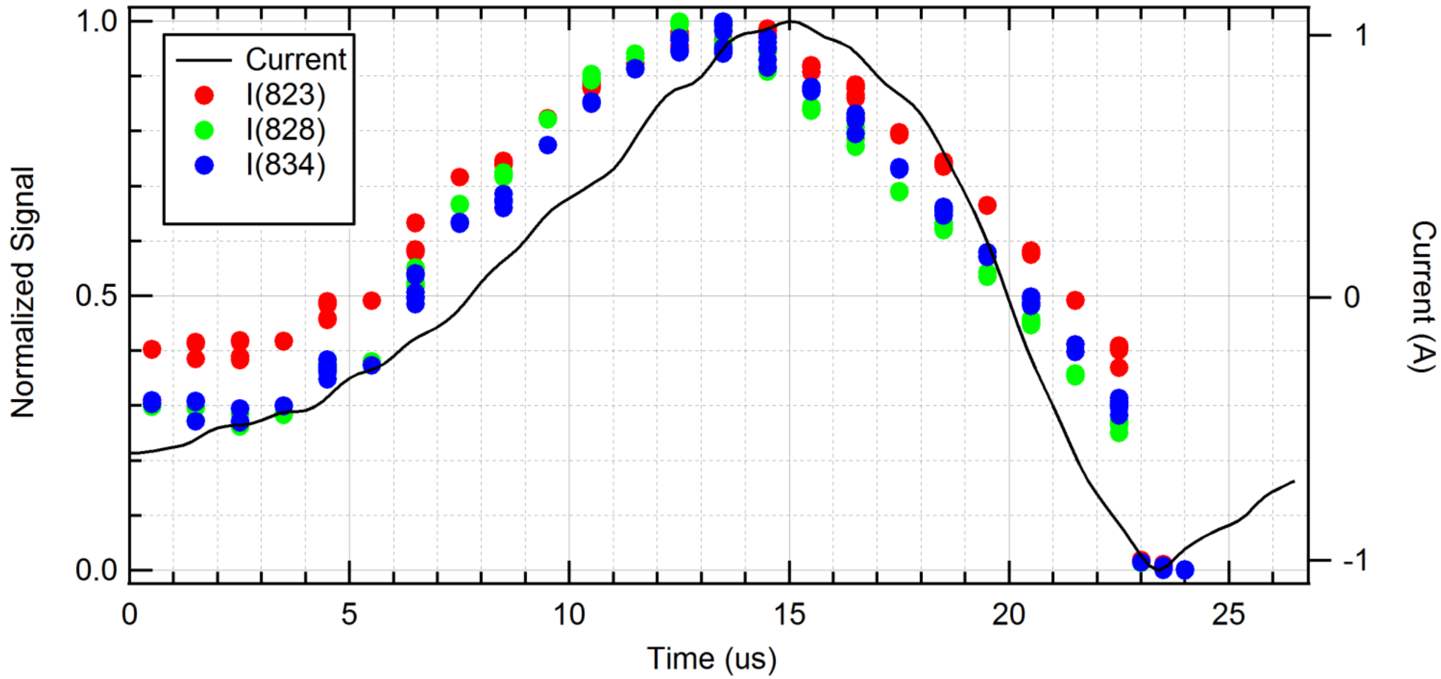
Normalized Emission Measurements

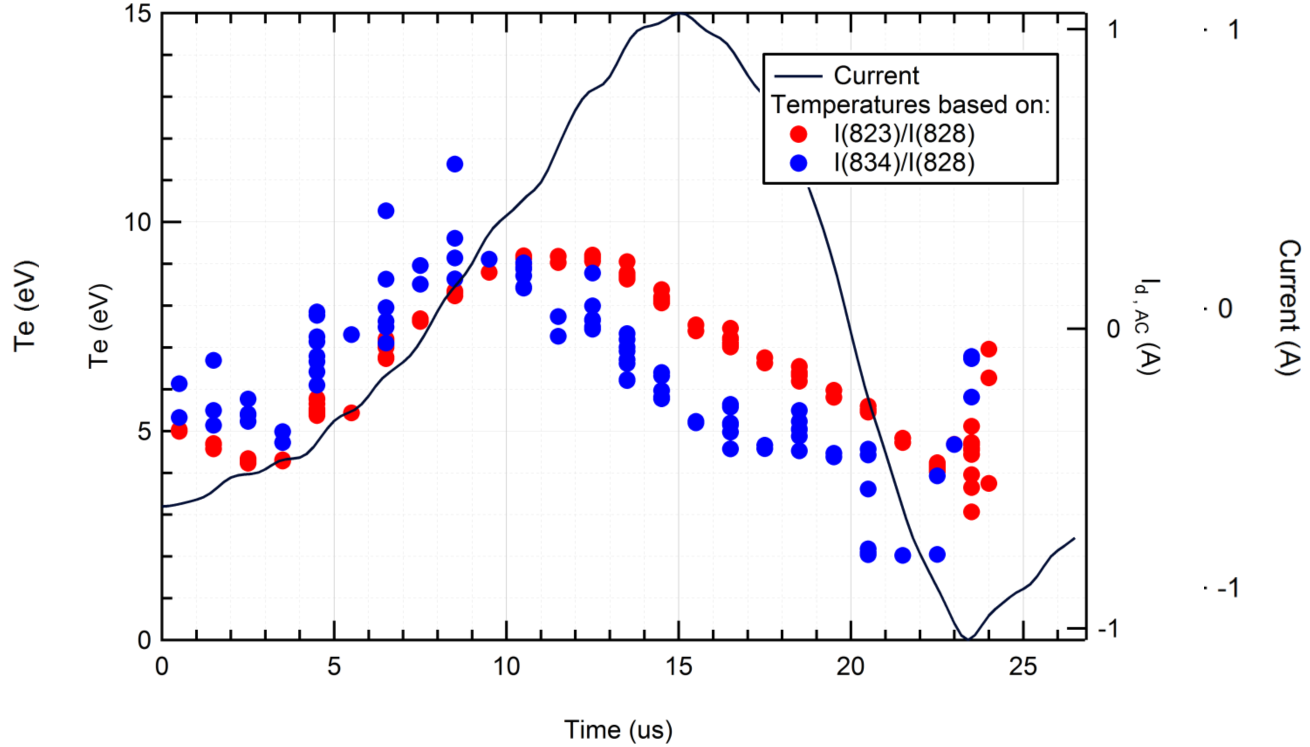


- **Intensity in phase with discharge current oscillations**
- Similar visible emission fluctuations seen by Liu et al.[11] in thruster high speed imaging
- Small phase shift (~2 μs) seen between intensity and discharge current
  - Corresponding to a 8 km/s electron axial velocity
  - In agreement with 5-10 km/s electron axial velocity predicted by HPHall[12]

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

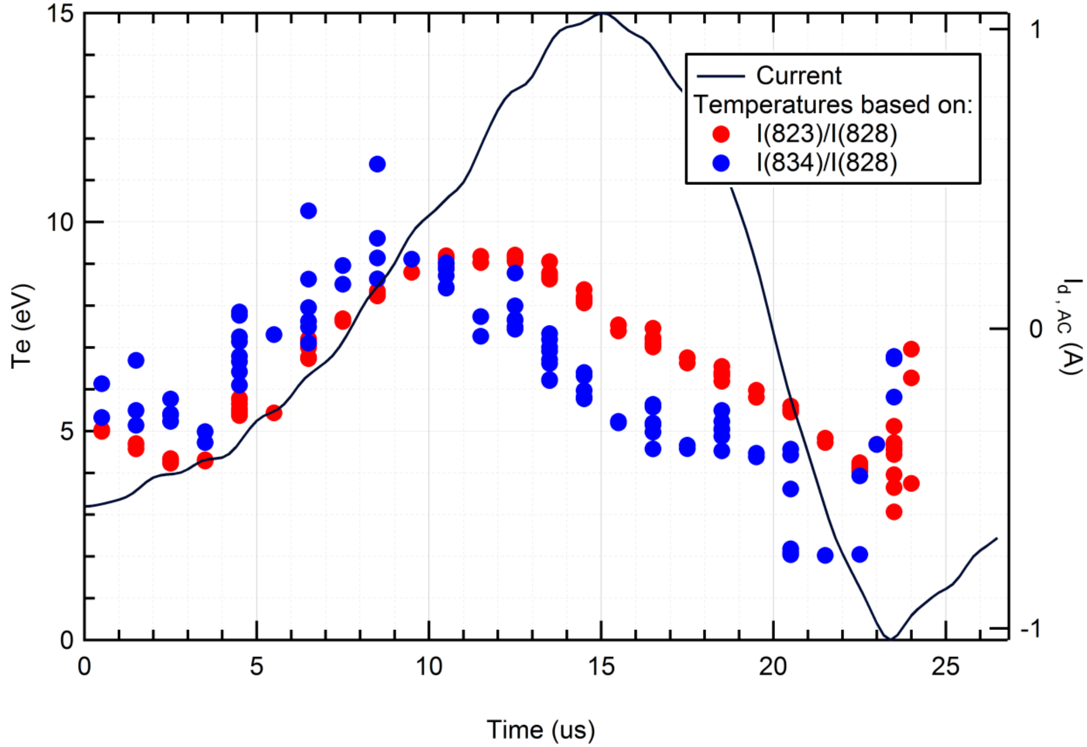
[12] Scharfe, M K, Koo, J W, personal communication, 2011

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

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HPHall: Overview

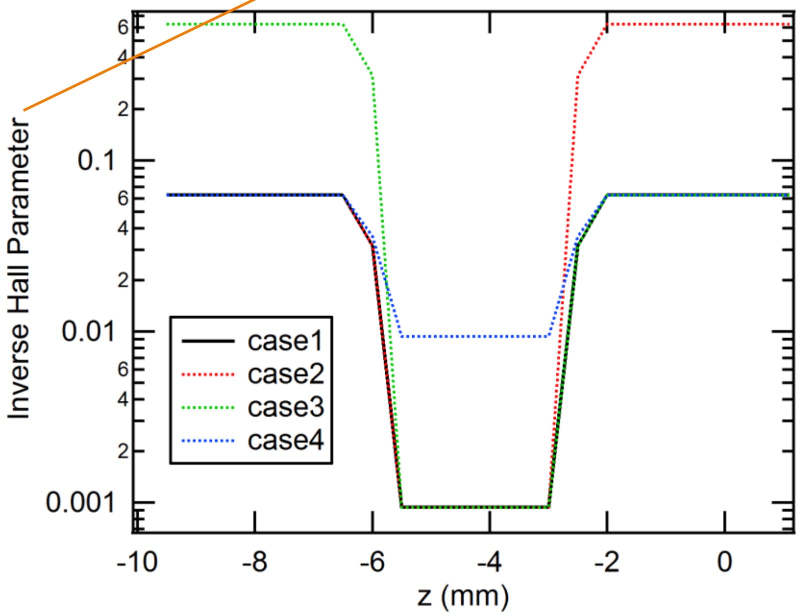
- **Radial-axial hybrid particle-in-cell (PIC)**
  - Fluid electrons
  - PIC ions and neutrals
  - Quasineutral
  - Electron mobility- axially varying effective mobility
- **Simulations**
  - Time step = 0.25 µs
  - Varying Inverse Hall Parameter $K_B/16$
  - Properties evaluated at 4 axial locations:

    A) Channel Near Anode
    B) Channel Near exit
    C) Near Plume
    D) Far Plume
- **Experimental/numerical comparison:**
  - Time-averaged quantities
  - Breathing mode behavior

Electron Mobility

$$\mu_{\perp eff} = \mu_{\perp classical} + \mu_{Bohm}$$

$$\mu_{Bohm} = \frac{K_B}{16}\frac{1}{B}$$



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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 %
$\bar{T}_e$	eV	6.6 ± 0.6	12.4	10.4	12.7	25.8
$\widetilde{T}_e/\bar{T}_e$	---	32 ± 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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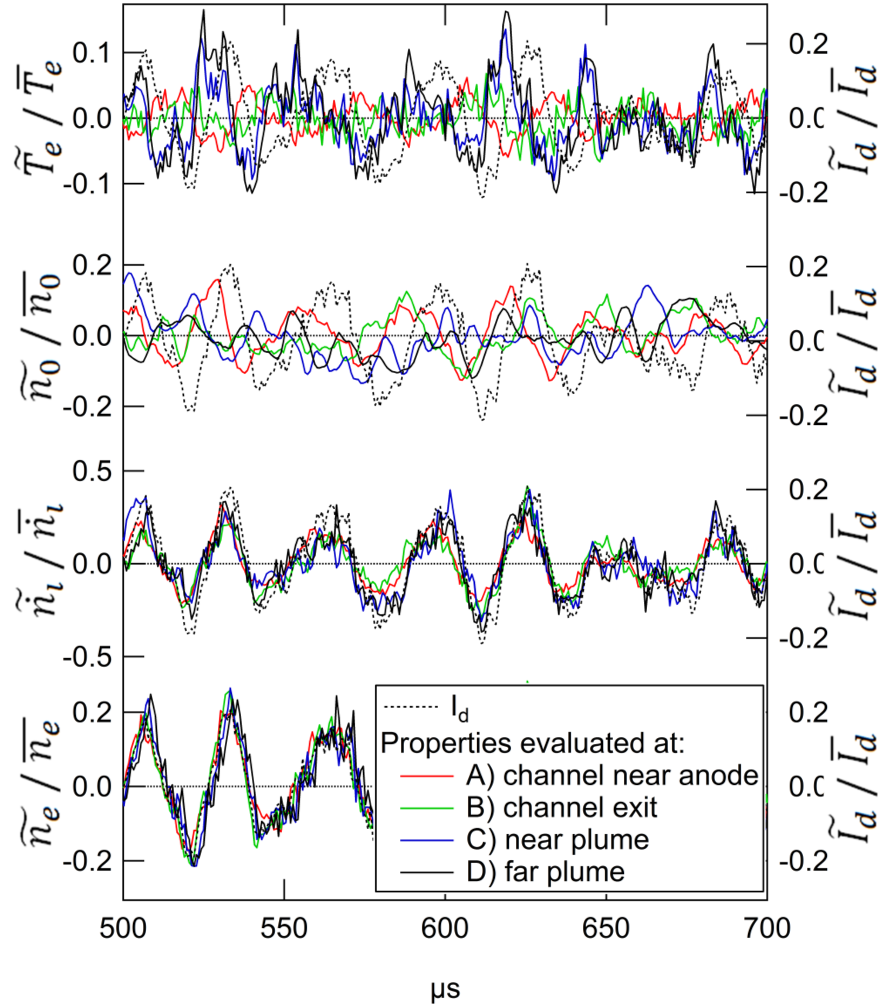
- **Inverse Hall parameter-strong influence on breathing mode**
  - Variation in breathing mode frequency and amplitude of oscillations
- **Further analysis based on Case 1**

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



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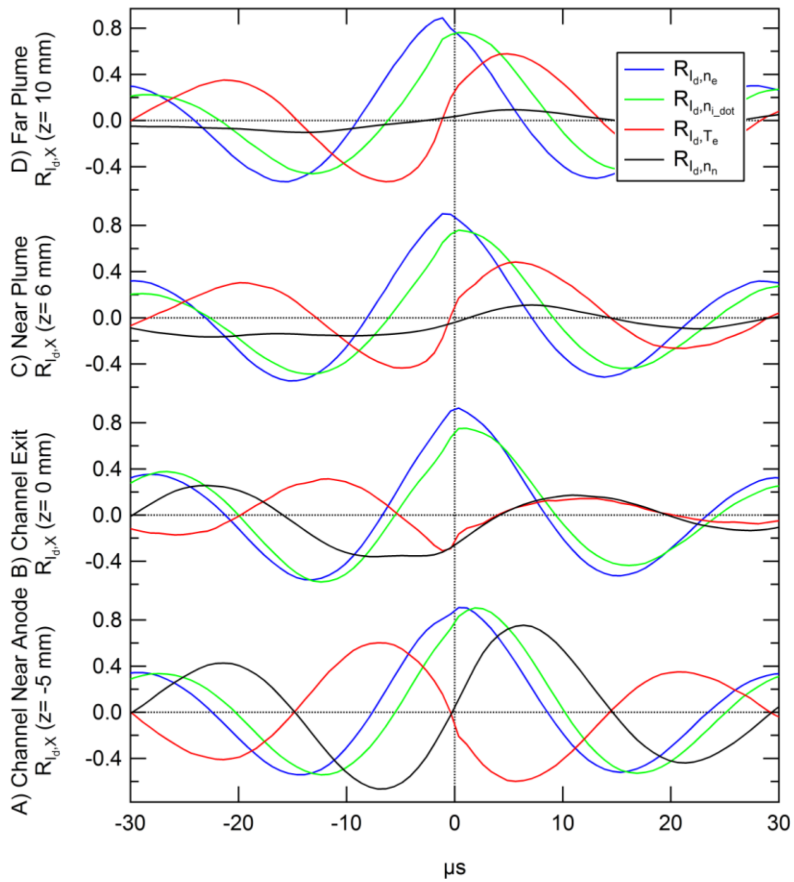
HPHall Results: Cross Correlation

- **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



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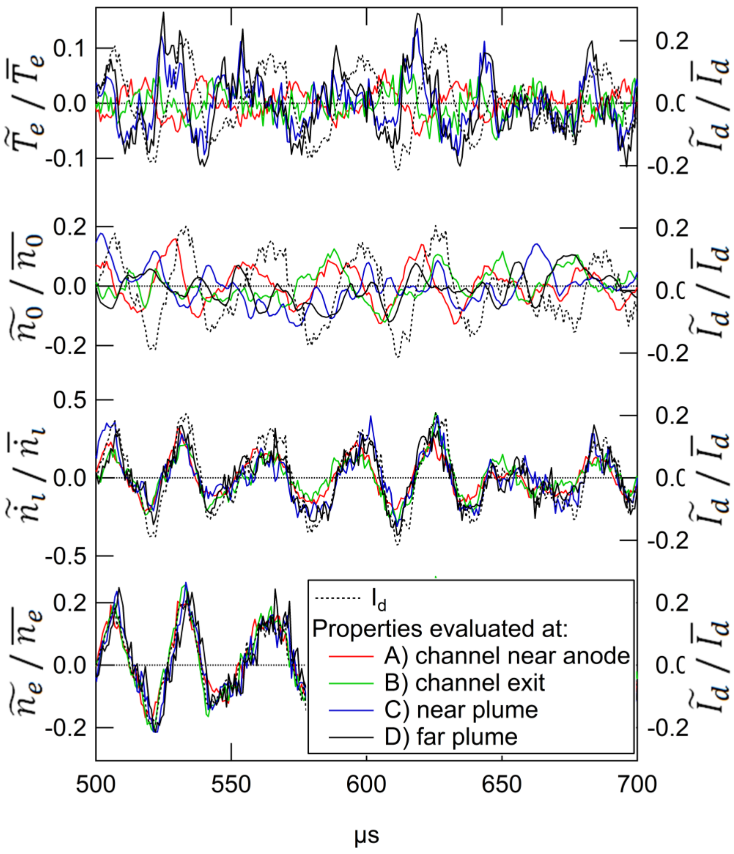
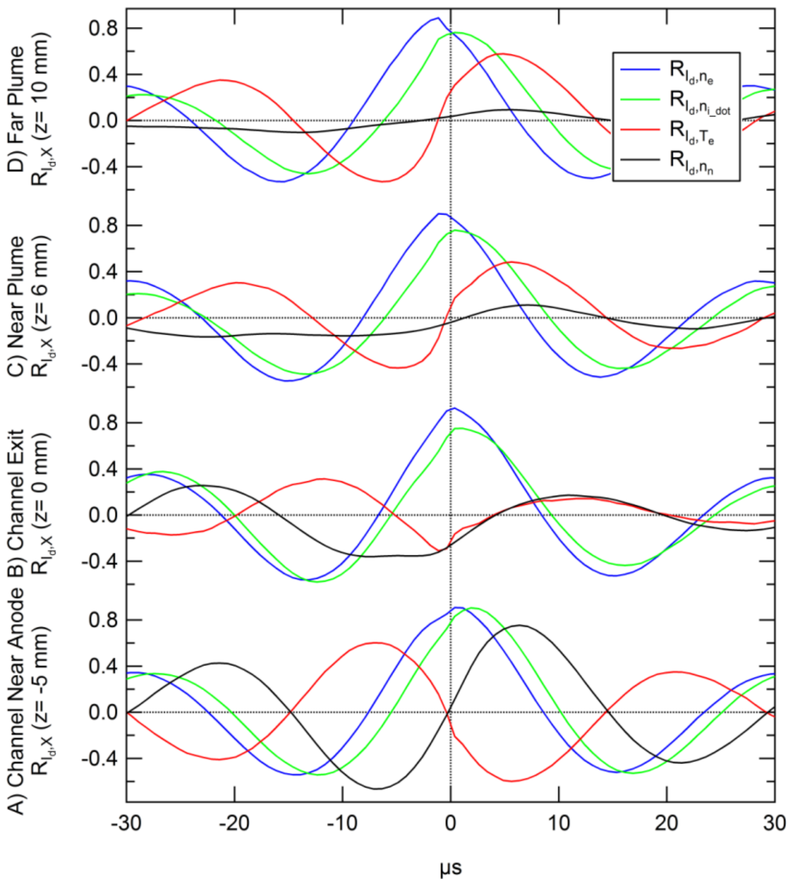
HPHall Results





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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

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% ± 8%, -5 ± 1 μs 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

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$\tilde{I}_d/\bar{I}_d$	--	32%	7 %
$\bar{T}_e$	eV	6.6 ± 0.6	12.4
$\tilde{T}_e/\bar{T}_e$	---	32 ± 8 %	4%
ϕ_{I,T_e}	deg	68° ± 14°	68°