Time-resolved Electron Energy Distribution Functions: Preliminary Results and Development of a Rapidly Swept Langmuir Probe System

Robert B. Lobbia[(a)] and Alec D. Gallimore[(b)]

The University of Michigan, Ann Arbor, [(a)] Postdoctoral Research Fellow, lobbia@umich.edu, [(b)] Arthur F. Thurnau Professor, alec.gallimore@umich.edu

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Motivation for High-speed Langmuir Probing

Plasmas exhibit wide bandwidth of oscillatory modes:

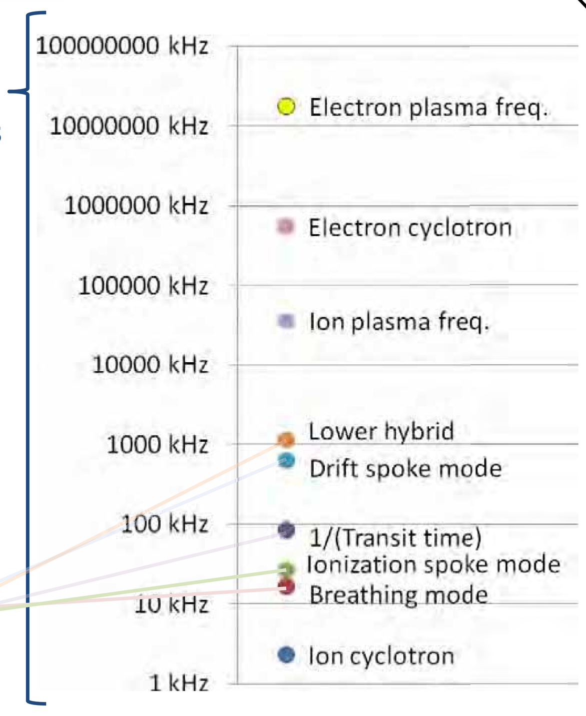
- 1 kHz – 10 GHz, typical
- Modes arise from electromagnetic interactions between particles and the imposed magnetic and electric fields
- For Hall effect thrusters, prior research has identified several modes experimentally and theoretically; but with limited temporally and spatially resolved plasma measurements

Limited pre-existing measurements

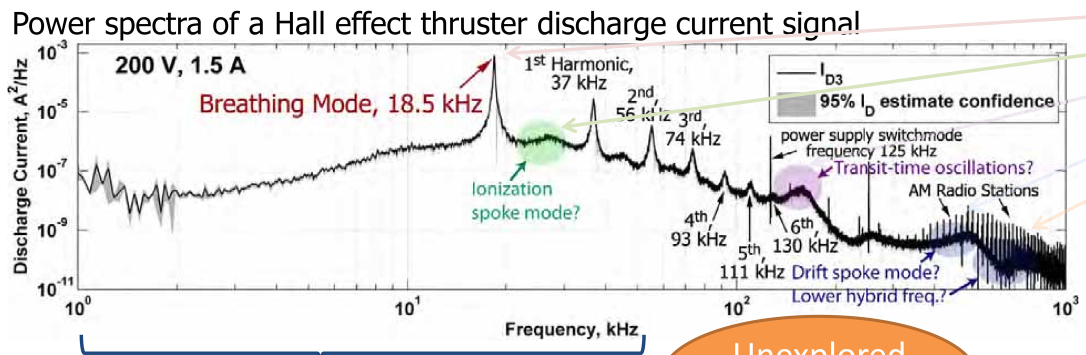
- High-speed plasma measurements are difficult due to fast timescales, high-voltages, and low-currents

Effects of transient plasma processes poorly understood

- Breathing mode oscillations in Hall thrusters have previously been seen as detrimental to thruster performance, however recent [Ref. 5] measurements suggest that these oscillations give rise to transient electron temperature fluctuations that may actually improve thruster performance
- Understanding of Electron Energy Distribution Functions (EEDF) temporal variations during Hall thruster breathing mode transients and other unsteady plasma discharges is critical to improving device performance



Power spectra of a Hall effect thruster discharge current signal



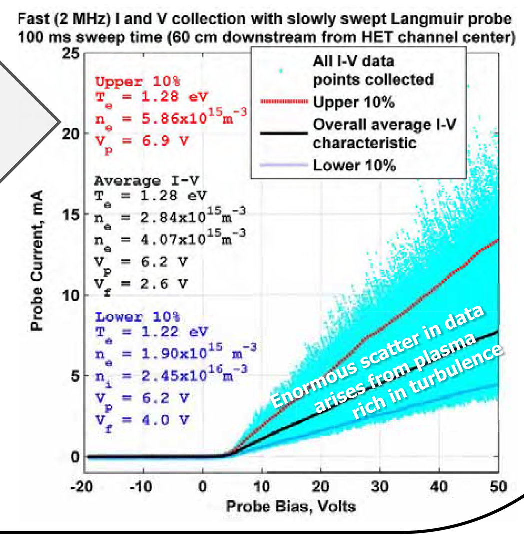
Current state-of-the-art High-speed Dual Langmuir Probe (100 kHz)

Unexplored physics

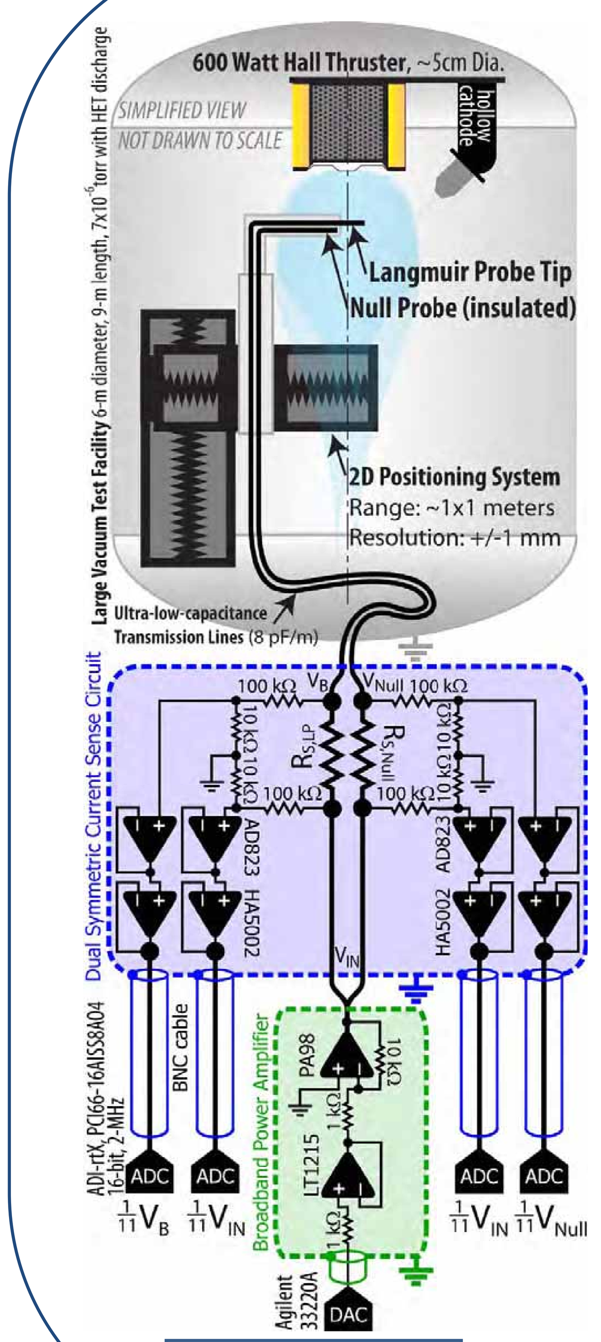
Next generation HDLP under development (1 MHz)

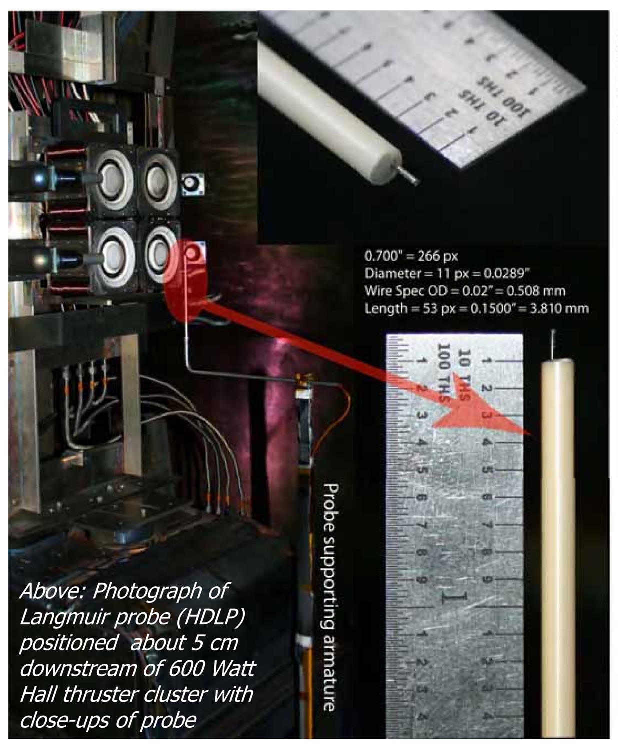
Direct and truly time-resolved simultaneous measurements of EEDFs, T_e, V_p, V_f and n_e have yet to be obtained at a rate of 1 MHz within any plasma.

Broad spectrum of plasma oscillations corrupt slowly swept (*conventional*) Langmuir probe measurements

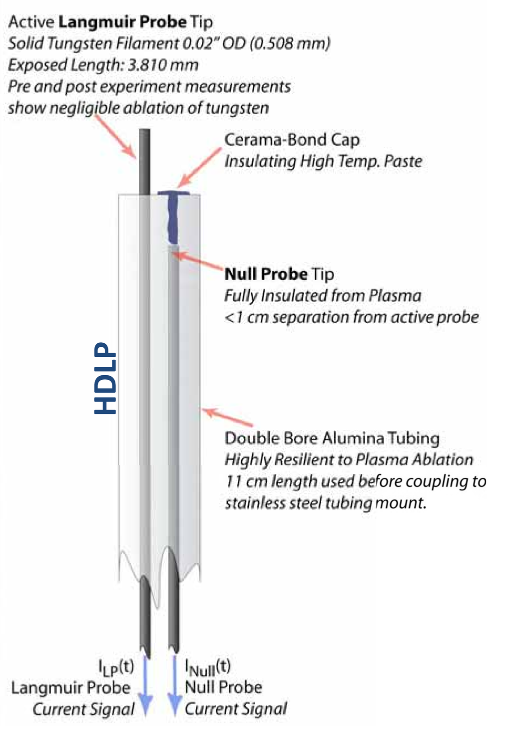


Experimental Approach

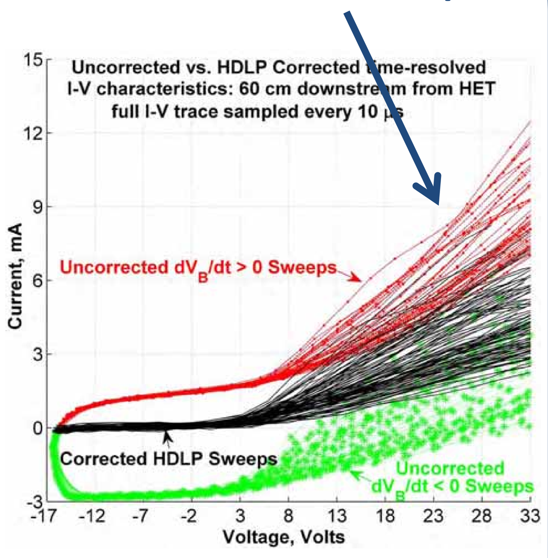




Above: Photograph of Langmuir probe (HDLP) positioned about 5 cm downstream of 600 Watt Hall thruster cluster with close-ups of probe

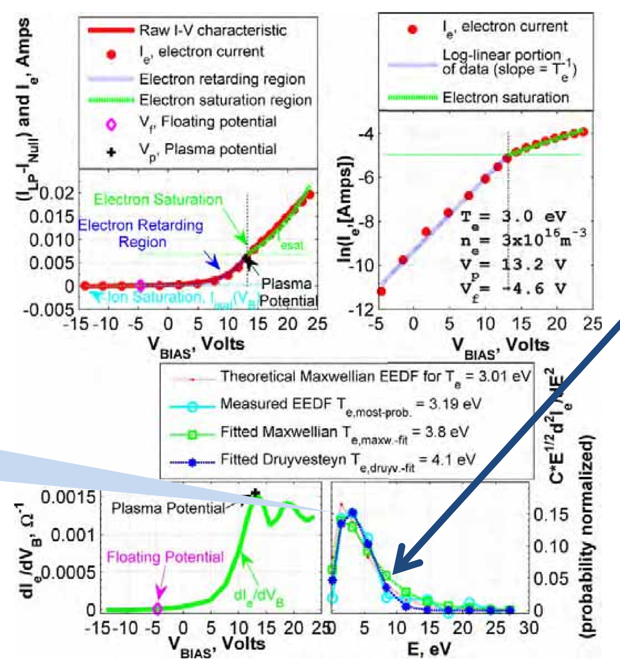


100 kHz sweeps



High-speed Dual Langmuir Probe (HDLP):

- Unique method employs insulated compensation electrode to boost bandwidth (Ref. 1)
- Pre-existing HDLP system (shown in this box) enables 100 kHz sweep rate
- Time-resolved EEDFs from 100 kHz HDLP have poor energy resolution (≈3 eV) and poor dynamic range (≈80 dB)
- Traditional thin-sheath Langmuir probe theory (valid up to ≈10 MHz sweep rate, Ref. 2)

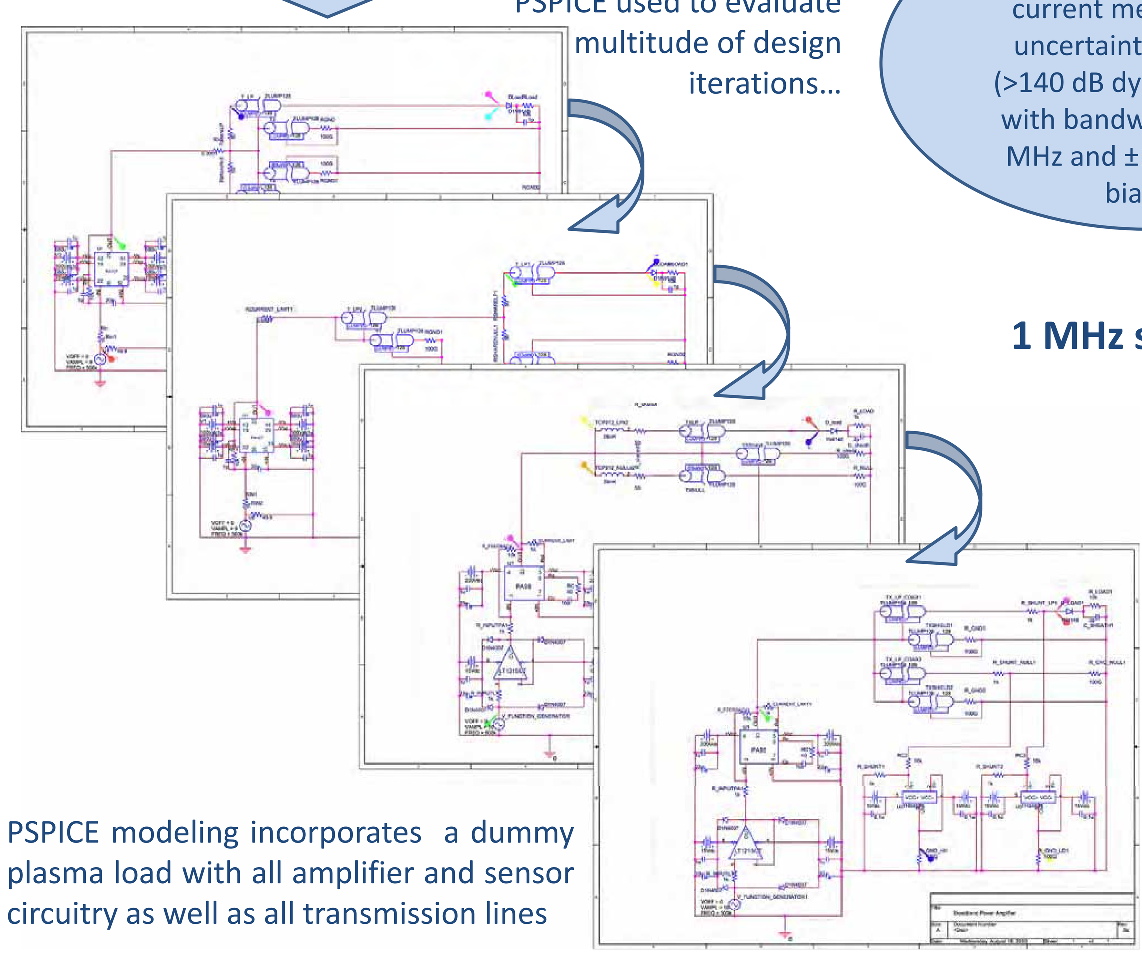


Preliminary time-resolved EEDFs using 100 kHz HDLP system

Raw electron current trace is directly differentiated numerically WITHOUT ANY SMOOTHING via Druyvesteyn method

Redesign of electronics to gain 100x bandwidth and 1000x dynamic range

PSPICE used to evaluate multitude of design iterations…

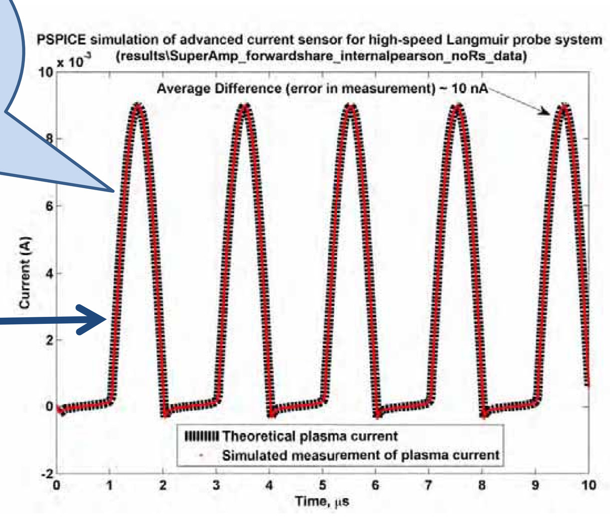


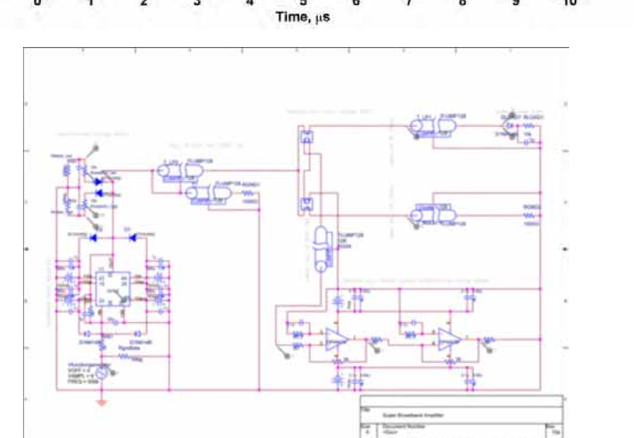
PSPICE modeling incorporates a dummy plasma load with all amplifier and sensor circuitry as well as all transmission lines

PSPICE amplifier and sensor simulation predicts current measurement uncertainty of ±10 nA (>140 dB dynamic range) with bandwidth DC-100 MHz and ±100 V probe biasing

1 MHz sweeps

Final Design



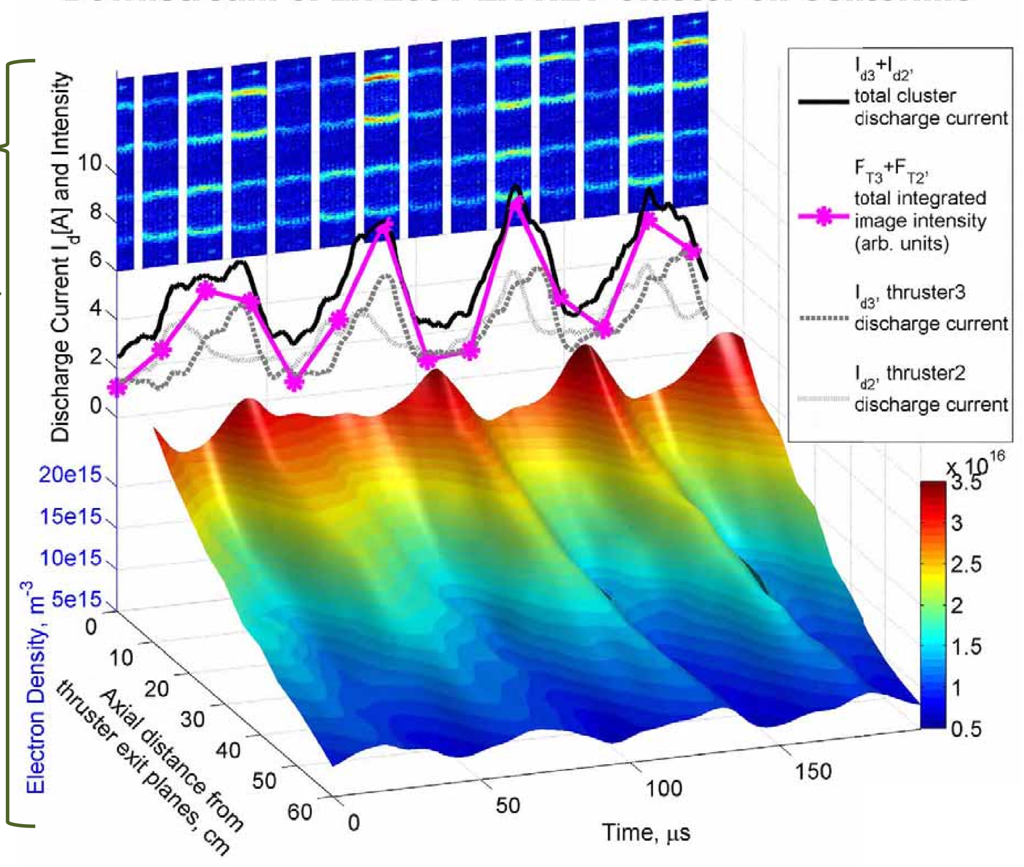


Final design simulations meet experimental requirements

Time-resolved Plasma Properties

Simultaneous Time-resolved Plasma Measurements Downstream of 2x 200V 2A HET Cluster on Centerline

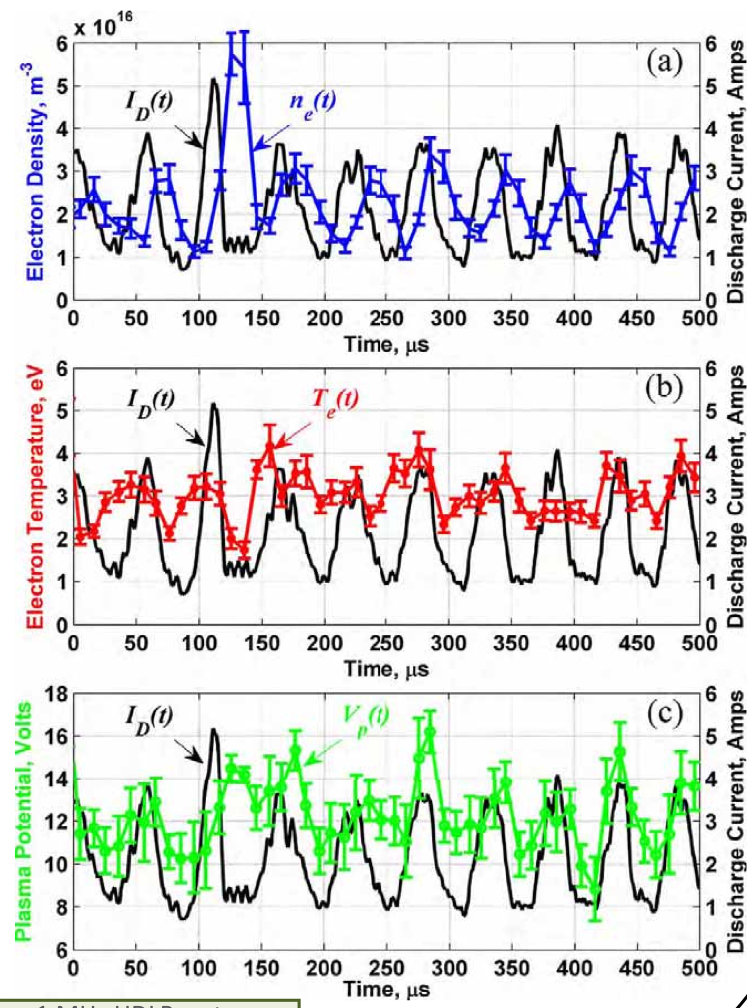
Large magnitude plasma oscillations observed in Hall thruster cluster plume by various high-speed sensors (FASTCAM, magneto-resistively measured discharge currents, and HDLP)



Above: axially propagating (>10 km/s) waves of electron density measured with 100-kHz HDLP (Ref. 3). Spatiotemporal methods of data fusion (Ref. 4) are used to combine single-point HDLP data. Below: simultaneously measured Hall thruster discharge current along with 100-kHz HDLP measured electron density (a), electron temperature (b), and plasma potential (c) from Ref. 1.

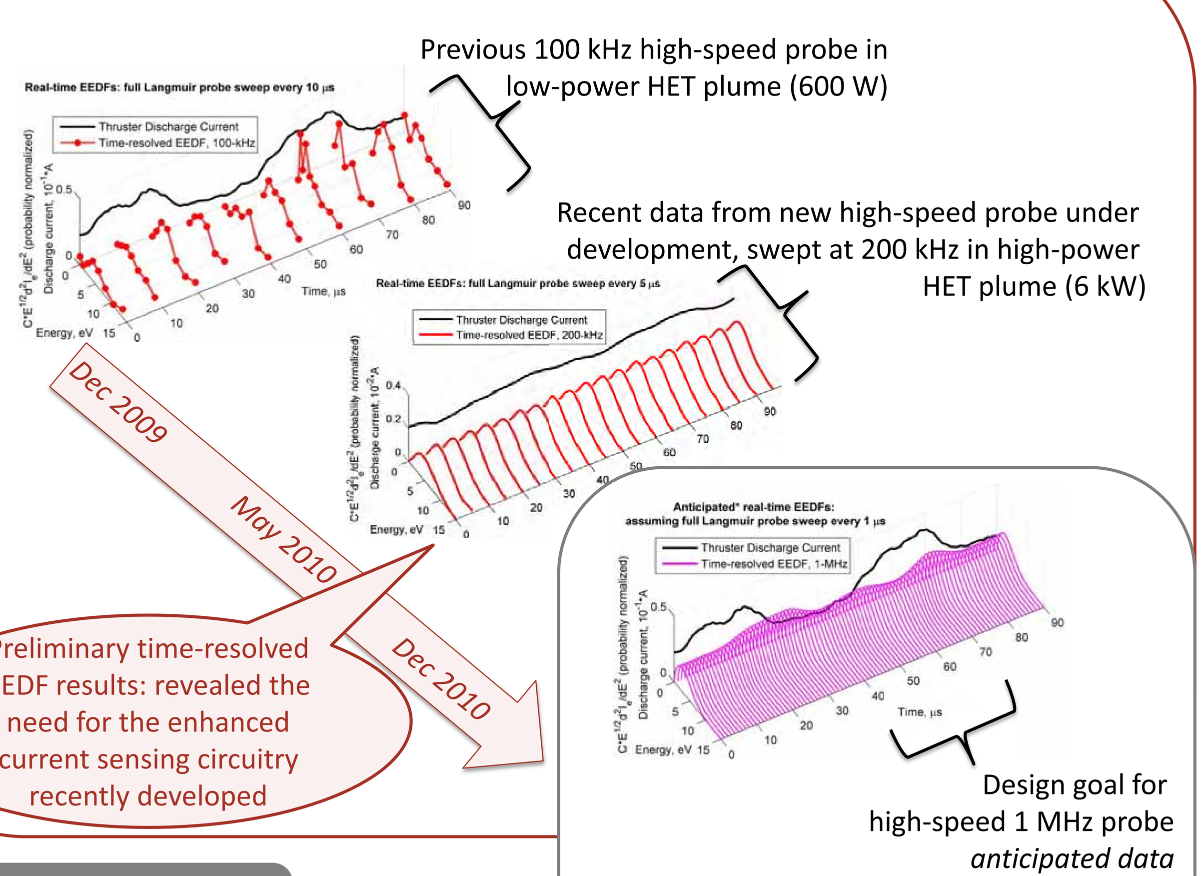
HDLP Measured Plasma Properties:

- Fully swept probe traces enable determinations of $n_e(t)$, $n_i(t)$, $T_e(t)$, $V_f(t)$, $V_p(t)$, and $f_e(E,t)$
- Rapid sweep rates reveal *I-V* probe characteristics nearly devoid of the "noise" apparent at slower sweep rates
- Extensive data acquired in Hall thruster plume at 100 kHz
- Higher speed (1 MHz) HDLP system presently under development and only limited preliminary data acquired thus far
- Improvements to current sensing circuitry (additional +60 dB of dynamic range) should dramatically enhance time-resolved electron energy distribution function data



1 MHz HDLP system under development will provide time-resolved plasma property measurements (n_e, n_i, T_e, V_p, V_f) as well as EEDFs

Time-resolved EEDFs



Preliminary time-resolved EEDF results: revealed the need for the enhanced current sensing circuitry recently developed

Goal and Impact

The goal of this work is to obtain high-resolution time-resolved measurements that will reveal transient efficiency losses and performance enhancing processes in quasi-steady state and pulsed plasmas.

→ Enables device and EEDF optimization/control in the temporal domain, *bolstering EEDF control scheme development.*

→ Provides spatially and temporally detailed experimental data to use in *validating advanced plasma simulation efforts* by other MIPSE collaborators.

References

[1] R. Lobbia and A. Gallimore, Review Rev. Sci. Instrum., 073503, Vol. 81, Issue 7, July 2010.
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[3] R. Lobbia and A. Gallimore, 31st International Electric Propulsion Conference, IEPC-2009-106, Ann Arbor, MI, Sept. 20-24, 2009.
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[5] R. Lobbia "A Time-resolved Investigation of the Hall Thruster Breathing Mode," Ph.D. Dissertation, University of Michigan, 2010.

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