High-speed Dual Langmuir Probe Measurements of the Plasma Properties and EEDFs in a HET plume

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Using an advanced High-speed Dual Langmuir Probe (HDLP) with a 1-µs temporal resolution, the plume of an 11 kW nested-channel Hall Effect Thruster (nested-channel HET or NHET) is investigated. The HDLP employs a single active Langmuir probe that is rapidly swept from -30 V to +30 V over a time as short as 1 µs (an insulated null probe is driven in parallel to compensate for adverse high-frequency effects). The resulting properties of electron (and ion) density, electron temperature, plasma potential, floating potential, and electron energy distribution function (EEDF) are all acquired simultaneously with excellent temporal and spatial resolution. A planar region measuring 2.5 mean channel diameters radially and 2.25 mean channel diameters axially is mapped beginning 2.5 mean channel diameters downstream from the thruster exit plane (410 total grid points). Large collections (0.25 seconds at 0.4 MHz for all plasma properties at each grid point) of the acquired high-speed probe data are combined together using a method of spatio-temporal data fusion that enables the synchronization of all the spatial grid-points to a common temporal evolution. The resulting visualizations of the various plasma transients observed show large amplitude bursts of plasma corresponding to the Hall thruster breathing mode as well as inter-channel coupling between the simultaneously discharging nested channels. The time-resolved EEDFs in the plume of the thruster display distributions that are predominantly Maxwellian and contain transient bursts of higher energy electrons that occur with breathing mode oscillations observed in the total discharge current signal. Overall, these spatially and temporally resolved measurements reveal the strongly electrodynamic nature of HET discharges that permeates all plasma properties at all plume positions investigated in this study with relative fluctuations averaging approximately 10% to 15% .

I. Motivation

Previous high-speed plasma measurements of HETs have revealed an environment rich in dynamics and turbulence.[1] A variety of natural plasma oscillations are excitable within the discharge of a HET[2] ranging from low-frequency azimuthal modes and breathing modes (1 to 40 kHz) to high-frequency lower-hybrid and electron plasma frequency modes (1 MHz to 10 GHz). Earlier work, with a 100-kHz HDLP diagnostic, measured strong plasma transients (nearly 100% of the DC mean in oscillation magnitude) in the near- and far-field plume regions of a low-power HET.[3] While this early work showed the ability to take unsmoothed 2nd derivatives of the raw data, insufficient energy resolution limited the usefulness of the EEDFs computed with this system. The new HDLP

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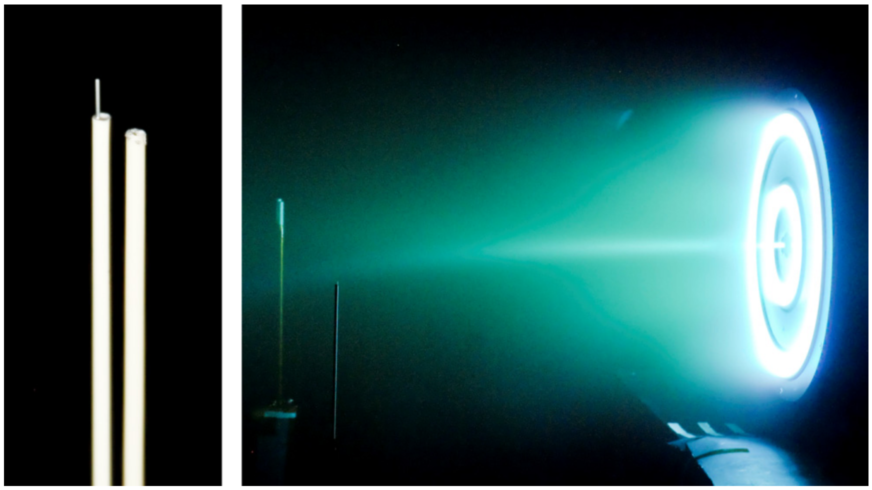
system developed significantly expands the operational regime of the HDLP concept, allowing for one to collect time-resolved EEDFs at rates of 1-MHz and higher. While this new HDLP system was designed with sufficient bandwidth and digitizers to operate at rates as high as 10-MHz, breakdown of thin-sheath theory at these sweep rates (sheath capacitance, polarization currents, sheath formation, and other detrimental effects)[4] limits the usefulness of these data through increased uncertainty. Examination of a broadband HET discharge power spectrum indicates that most (>95%) of the fluctuation energy within the plume is carried by lower frequency (< 1 MHz) fluctuations. Thus, a 1 MHz HDLP is able to probe the vast majority of plasma fluctuations critical to processes involved in the transient transfer of energy within the HET plasma and its environment.



(a) (b)

Figure 1. (a) Close-up photograph of HDLP used in this work (active probe on left; null probe on right). **(b) Photograph of NHET 200 V 23 A_{dc} xenon discharge** (17.4 mg/s + 7 mg/s) with multiple downstream probes in plume (HDLP presented in this paper is the lower probe column) operating inside the LVTF.

II. Experimental Setup

A. Large Vacuum Test Facility and High-Power Nested Channel HET

The University of Michigan's Large Vacuum Test Facility (LVTF), a 9-m long and 6-m diameter cylindrical stainless-steel clad chamber, with seven liquid-N_2 baffled re-entrant cryogenic pumps maintaining 240 kl/s pumping-rate on xenon attains a corrected pressure of 1.5×10^{-5} torr while operating an 11 kW Nested-channel Hall Effect Thruster (NHET). The NHET was operated for this study (see Figure 1(b)) with xenon discharges of 150 V 24 A 24 mg/s (total DC current and mass flow) as well as 200 V 23 A 24 mg/s (total), but only data from the 200 V case has been processed at this time (the 150 V data will be published separately in an additional paper). The cathode and thruster are conditioned and operated steadily for >1 hour prior to data collection to limit water vapor outgassing and other startup transients.[5] Thruster discharge currents are recorded using a wide-bandwidth (DC to 100 MHz for inner channel and DC to 15 MHz for outer channel) split-core Hall probes (Tektronix TCP312, TCP303, and TCPA300) placed downstream of the power supply and discharge filter. Separate laboratory DC power supplies are used for each discharge channel and for each electromagnetic coil. However, the centrally mounted cathode is shared by both discharging channels. Additional test setup and thruster details are published elsewhere.[6,7,8]

B. High-speed, Low-noise, Broadband and Multistage Sensors

Perhaps the greatest challenge in this work was the development of high-performance sensors that provide enormous instantaneous dynamic range. Raw data is collected by some of the fastest 16-bit digitizers in existence today (8 channels running synchronously at 180 MHz), but their 90-dB dynamic range is limited. To attain measurements with more than 100 dB of instantaneous dynamic range, a series of digitizer stages are spanned by each sensor signal. Measured specifications for the developed plasma current sensor are shown in Table 1. These specifications were verified by examining Bode plot frequency responses and other measurements using the full test setup including nearly 20 meters of transmission lines and a dummy plasma load. According to the HDLP approach,[9] a null probe is driven in parallel with the active Langmuir probe. Both probes are virtually identical and in close proximity to one another, but the null probe is insulated from the plasma while the Langmuir probe is exposed to the plasma. A series of custom multi-stage differential current amplifiers are then used to send the true plasma current signal to up to 3 stages of analog-to-digital conversion (each stage running in parallel). A differentially wrapped (e.g. active and null probes are counter-wound) Pearson coil is used as the first high-speed sensor stage providing bandwidth of approximately 300 Hz to 90 MHz (-3 dB). A series of wide-bandwidth ultra-low noise amplifiers can then be employed to provide 20x to 400x amplification of the Pearson sensor output. The coaxial transmission lines running the probe biases into the vacuum chamber are carefully balanced (manually tuned) resistively, capacitively, and inductively including an integrated pair of impedance matching shunts whose voltage drops are fed into a dual-isolated ("flying") instrumentation amplifier to provide a DC to 120 kHz pair of current measurements. Since most signals are sampled at 180 MHz, downsampling of the 120 kHz current signals can provide a theoretical boost in signal-to-noise ratio (SNR) of $20 \cdot \log_{10}\left(\sqrt{180MHz / 0.120MHz}\right) = +32dB$. The signals are also fed though a Keithley 2000 6½ digit multimeter to compute an additional high-resolution pair of DC current measurements for each grid location.

Table 1. Specifications for the developed HDLP current sensor system. *These specifications include the use of the stray capacitance and noise compensating null probe. Multiple sensors (each with 1 or more output stages) are run simultaneously to attain a wider bandwidth and dynamic range.*

Plasma Current Sensor Specifications	
Bandwidth	DC to 90 MHz (-3 dB)
Maximum Probe Voltage	±100 V
Maximum Current	±270 mA
Measurement Resolution	±2 µA (103 dB dynamic range)
Current Measurement Noise *(unfiltered and unaveraged)*	±16 µA (85 dB SNR)

The various multi-rate signals may be fused together after acquisition using standard digital signal processing techniques. The probe biases are sourced by a high-voltage broadband power amplifier (DC to 1 MHz, ±220 V, ±200 mA) that is described in detail elsewhere.[9] The transmission line shunts intentionally form a low-pass filter (-3 dB at about 4 MHz) that causes a small reduction in the amplitude (-0.2%) of the bias waveform (nominally a 200 kHz sinewave which creates a full IV trace every 2.5 µs, see Figure 2) as well as a small phase shift (3.2° or 45 ns at 200 kHz). Since the analog data is digitized every 5.6 ns the 45 ns delay is significant, and when this is combined with other cable length delays the probe current and voltage signals appear out-of-phase. Using both digital filtering and line delay measurements, the I and V signals are amplitude and phase corrected to represent the values seen by the active Langmuir probe at the probe tip.

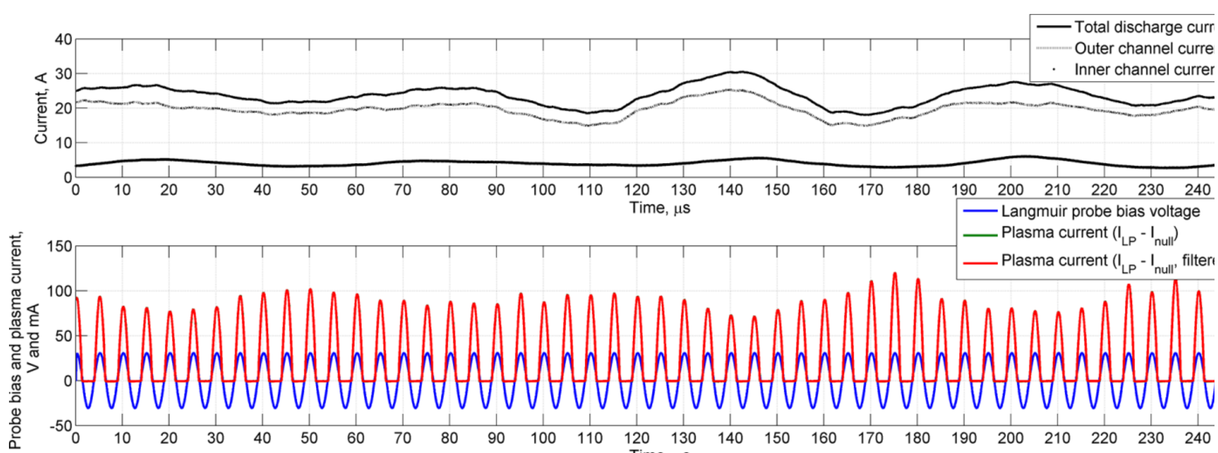


Figure 2. Raw NHET discharge current signals (upper) and HDLP current and voltage signals (lower). *The 200 kHz sinewave probe biasing signal (blue) creates a full IV trace at a rate of 400 kHz.*

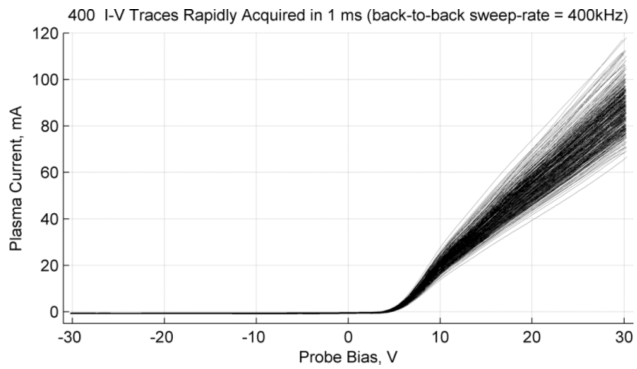


Figure 3. 400 sequential IV traces acquired back-to-back in 1 ms.

C. High-speed Dual Langmuir Probe

The HDLP technique is detailed other works,[4,9] and here is comprised of a cylindrical active Langmuir probe 4.9 mm in length and 0.475 mm in average diameter (mean of pre-test and post-test measurements to account for minor erosion experienced during experiment). Shown in Figure 1(a) is a close-up photograph of the active and null probes. The axes of the probes are perpendicular to the bulk plasma axial flow direction. The resulting IV traces are processed using standard thin-sheath electrostatic probe theory (see Figure 4 for the automated analysis performed on one IV trace).[4] To ensure effective operation of the HDLP system the various transmission lines, sensors, amplifiers, digitizers, and tuning components are modeled in PSPICE prior to assembly. The long cable lengths and high-bandwidth requirements of this work involve careful balancing and tuning to correctly transmit and measure high-frequency IV traces (see Figure 2 and Figure 3). Trimmer capacitors and potentiometers are used to fine-tune the transmission line and sensor setups. An additional planar HDLP was also constructed and run with full IV traces collected at a rate of 1 MHz, but these results are still being processed and shall be published in a future paper.

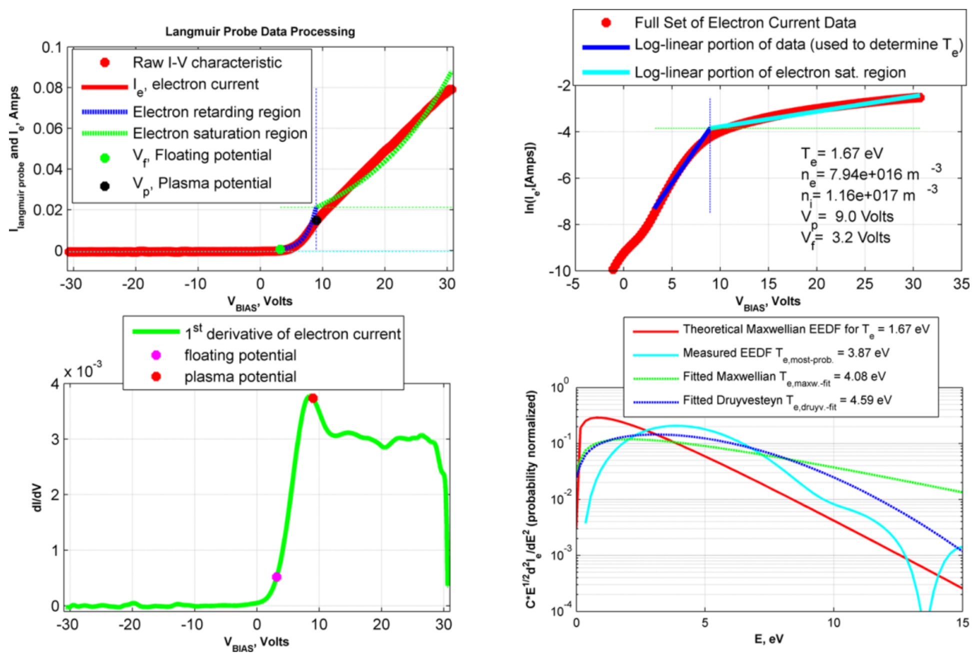


Figure 4. Langmuir probe thin-sheath analysis performed for a single rapidly acquired IV trace. *The first derivative of the electron current determines the plasma potential but this is refined by using the intersection of the two log-linear portions of the IV trace. The computed EEDF (using the 2nd derivative Druyvesteyn method with smoothing) shows an energy distribution that is predominantly Maxwellian.*

III. Results

D. Single-position Time-resolved Measurements

The post-processing of the raw data (over 300 GB per for the full 410-point grid) is computationally intensive and requires days to compute corresponding time-resolved plasma properties when using a highly paralleled code on a specialized high-performance data processing workstation. Only a fraction of the data acquired during this experiment has been processed at this time: the 200 V 23 A_{dc} NHET discharge case for the cylindrical HDLP. First presented in Figure 5, are the time-resolved plasma measurements acquired 2.5 mean channel diameters downstream from the NHET exit plane and radially aligned on the center of the inner discharge channel:

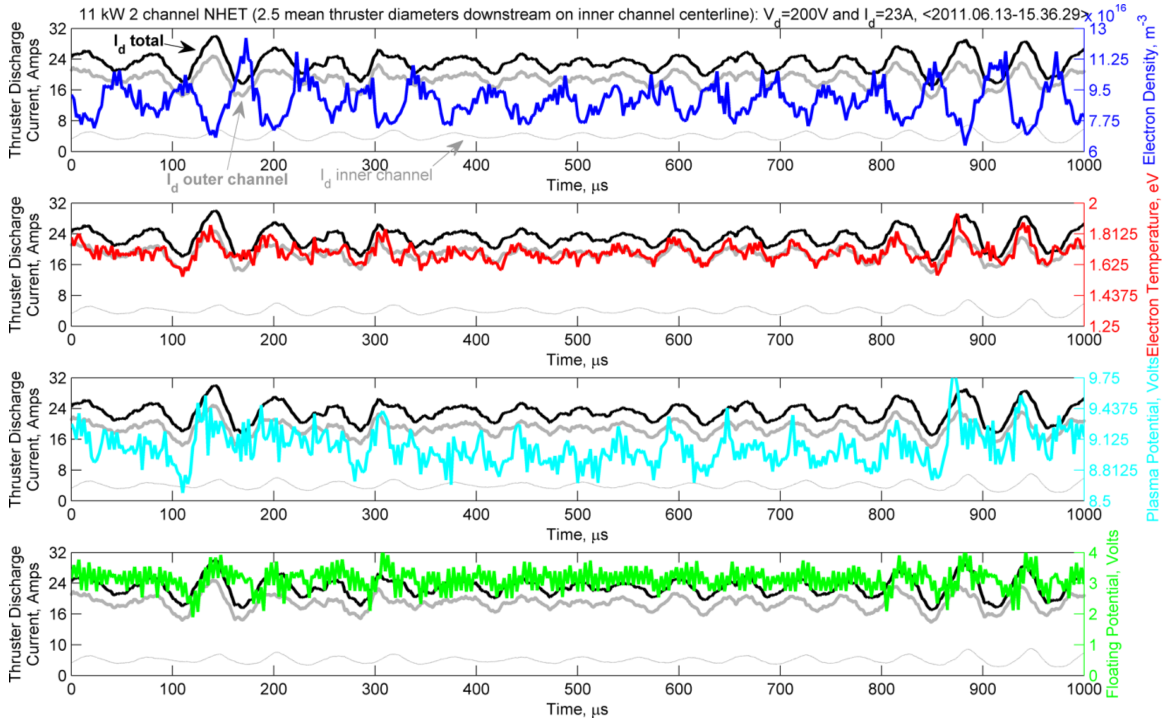


Figure 5. With a temporal resolution of 2.5 μs (0.4 MHz), these are the fastest fully swept Langmuir probe data ever acquired. *The transient nature of these plasma properties downstream from the 11-kW nested-channel HET reveal strong transient oscillations dominated by the Hall thruster breathing mode.*

The data in Figure 5 all exhibit breathing mode oscillations around 18 kHz and both the inner and outer channels appear to oscillate predominantly in phase with one another. The channels are operated with separate discharge power supplies and mass flow controllers, thus downstream plasma interactions near the exit plane must be coupling the discharge oscillations. Similar inter-HET plasma transient coupling has also been observed with closely spaced clusters of low-power HETs.[10] Since breathing mode plasma oscillations are caused by transient bursts in the local ionization rates inside the discharge channel of a HET,[11,12] the close proximity of the concentric channels in the NHET under investigation creates a near-field plume environment where the separate channel plumes overlap and interact with one another. At higher discharge currents (and/or lower discharge voltages) the ionization and acceleration regions are known to move slightly downstream from the HET discharge channel,[13] an effect that would increase plume interaction—especially ionization related processes such as the Hall thruster breathing mode. For the low-voltage high-current 200 V 23 A_{dc} discharge data presented, the ionization and acceleration zones are likely to have some overlap though without very-near-field (or internal) measurements, the degree of overlap is unknown at this time. Additional inter-channel coupling may originate from the use of a shared centrally-mounted cathode (see Figure 1(b)) and partially shared magnetic fields. Since the channels tend to fluctuate in-phase, their total combined discharge current is also plotted (as a solid black trace) in Figure 5. Comparing the fluctuations of the various plotted plume plasma properties to the NHET total discharge current, *$I_d(t)$* total, consistent relative amplitudes of approximately 10-15% (local standard deviation divided by local time-averaged mean):

$$\tilde{I}_d(t)/\overline{I_d(t)} \approx \tilde{n}_e(t)/\overline{n_e(t)} \approx \tilde{V}_f(t)/\overline{V_f(t)} \approx \tilde{V}_p(t)/\overline{V_p(t)} \approx \tilde{T}_e^*(t)/\overline{T_e^*(t)} \approx 10\% \text{ to } 15\%$$

The above observation has an average precision of ±6% for most of the plume (except for T_e which exhibited much greater uncertainty in the far field). This relationship is slightly different than has been observed with a low-power HET,[1] and this might be related to the lower relative amplitude present at this discharge setting where $\tilde{I}_d(t)/\overline{I_d(t)} \approx 11\%$. With the low-power HET, much larger relative amplitude oscillations were observed, namely $\tilde{I}_d(t)/\overline{I_d(t)} \approx 50\%$. However, in both studies the relationship $\tilde{I}_d(t)/\overline{I_d(t)} \approx \tilde{n}_e(t)/\overline{n_e(t)}$ is satisfied, while the low-power HET observed the other properties have relative fluctuations a factor of two smaller. From a conservation of mass standpoint, the observation of discharge current and electron density fluctuations scaling 1:1, is a direct theoretical prediction (at least to a zeroth order approximation). Whereas scaling the electron temperature and potential fluctuations from discharge density fluctuations alone, may not be possible since additional physics is undoubtedly involved.

Another important observation made from Figure 5, is the in-phase relation of the total discharge current fluctuations to electron temperature, plasma potential, and floating potential fluctuations. This contrasts the out-of-phase relation between total discharge current and electron density fluctuations. The apparent 31 µs delay agrees well with the expected theoretical transit time delay for 200-V Xe^+ ions to travel from the thruster to this position 2.5 mean thruster diameters downstream. This delay is not readily present in $T_e(t)$, $V_f(t)$, and $V_p(t)$, strongly suggesting that these properties propagate initially through the plasma at electron thermal (or electromagnetic) speeds (>300 km/s). A closer examination of $T_e(t)$, $V_f(t)$, and $V_p(t)$ also shows smaller peaks that line up with the phase-delayed density peaks, indicating that the dense bursts of plasma also convectively transport smaller temperature and potential fluctuations as they slowly plod downstream at roughly 17 km/s. These results concur with earlier observations that showed similar results.[3]

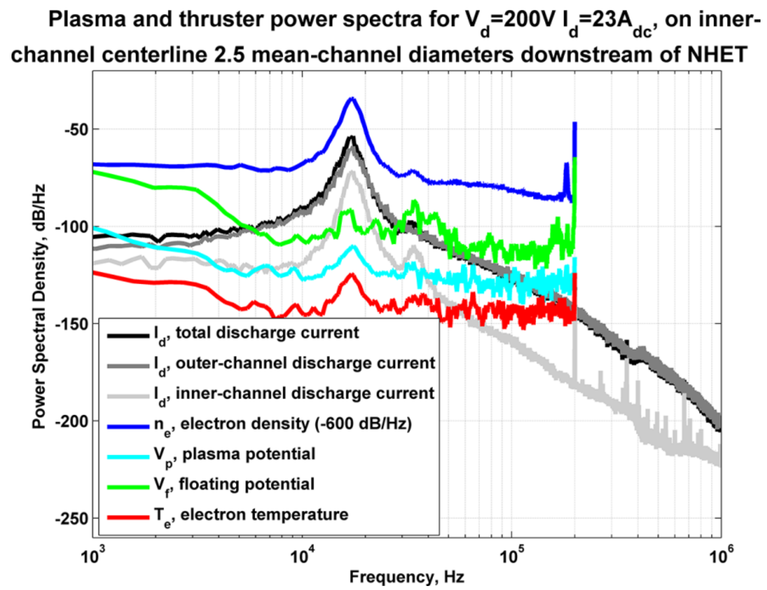


Figure 6. Thruster and downstream plume power spectra. *Breathing mode oscillations at 17.5 kHz contain most of the signal power (with a small harmonic peak at 35 kHz). Both the inner and outer NHET discharge channels appear to have the same peak breathing mode frequency.*

The power spectra of the thruster and plasma properties observed 2.5 mean channel diameters downstream (on inner-channel centerline), are next presented in Figure 6. Both the inner- and outer-channel discharge current spectra are shown as well as their sum. In this experiment discharge voltage was measured using sense lines and the transient nature of this signal (cathode to anode potential) appeared relatively steady having oscillations < 5% of the mean discharge voltage. With an ideal DC power supply (operating in voltage-control mode) having very short cabling to the HET, the voltage would be a constant DC value. However, due to insufficient output stage (or discharge filter) capacitance/regulation and finite line-length inductance, the physical discharge current fluctuations create small electrical voltage fluctuations. With higher power thrusters this effect will become amplified and additional capacitors and filtering in close proximity to the HET may be needed. All signals in Figure

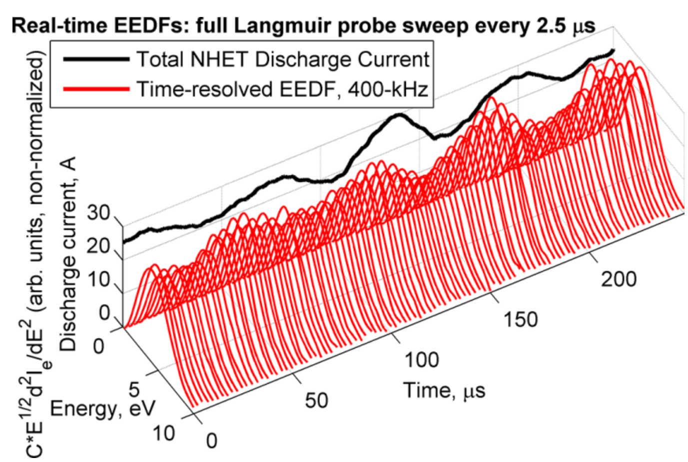


Figure 7. Time-resolved electron energy distributions functions *determined using the Druyvesteyn method applied to smoothed data. The EEDF vertical units are left non-normalized and scaled by an arbitrary amount to match the total NHET discharge current trace included in this plot. Breathing mode oscillations create an unsteady EEDF as a result of varying electron energy populations throughout each breathing mode cycle.*

6 clearly show the dominant breathing mode frequency of 17.5 kHz with a minor 35 kHz harmonic. For the electron temperature and plasma/floating potentials at this position, their spectra contain a broader 1st harmonic peak since the convectively transported properties add two additional frequency features at 32 kHz and 39 kHz; the probe at this location sees two perturbations for every breath of plasma (the first peak is nearly instantaneously transmitted each breathing mode cycle by thermal electrons while the second is carried by the slower dense plasma breath).

The final single-point plasma measurements presented are the time-resolved EEDFs in Figure 7. Once again, the fluctuations mirror the breathing mode fluctuations seen in the total discharge current trace (solid black line of Figure 7). In this case, the EEDF curves have been left non-normalized (but arbitrary scaled) and thus their variation is dependent on the absolute electron populations for each energy level (i.e. non-scaled integration would recover the time-resolved electron density). The amplitude of these EEDFs depends on the total time-resolved electron density, thereby causing a phase delay with the total discharge current similar to the delay seen with electron density in Figure 5. If these EEDF traces were normalized to unit probability (analogous to fixing the electron density to a constant of 1 for all traces), then the EEDFs would instead fluctuate in-phase with the total discharge current fluctuations (as is seen with $T_e(t)$ in Figure 5). However, the temporal variation in electron temperature for this thruster operating condition at this position (2.5 mean channel diameters downstream on inner-channel centerline) is a mere ±0.13 eV. This small change in energy is difficult to resolve in the acquired EEDF data for several reasons: 1) the minimum measured energy resolution is about this same value (450 IV points for a 60 $V_{peak\text{-}to\text{-}peak}$ sinewave bias here gives $|dE|_{max} \approx 0.2$ eV), 2) minute distortions between positive and negative dV/dt bias sweeps, and 3) the necessity of numerical data smoothing (which decreases the energy resolution even further) required to take the second derivative of the electron current. Future work with the HDLP diagnostic is ongoing, and great effort is being placed on eliminating need to numerically smooth the acquired IV traces. Even with the smoothing applied (and the subsequent loss of fine-energy resolution detail that can blur out sharp features in the distribution) the ability to directly acquire EEDFs at a rate of 400 kHz is remarkable and, to the author's best knowledge,[9] these are the fastest fully-swept Langmuir probe and EEDF data ever published.

E. Two-dimensional Time-resolved Measurements

Using a method of spatio-temporal data fusion,[14] the entire 410 element two-dimensional grid of time-resolved data may be combined into a coherent series of time-resolved 2D measurements. A series of spatio-temporarily combined frames portraying the evolution of an electron density transient breathing mode cycle follows in Figure 8:

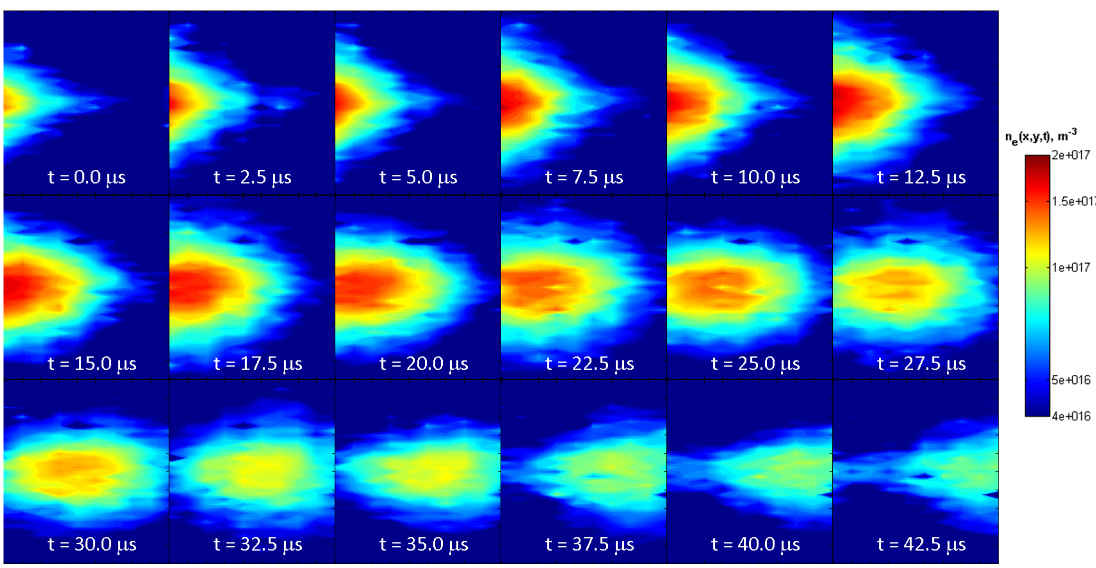


Figure 8. A breath of plasma revealed by a spatio-temporarily fused series of time-resolved 2-D plume electron density color contour maps.

The 2.5 μs temporal resolution provides a detailed downstream progression of plasma originating from an ionization burst by the NHET breathing mode. However, the coarse radial resolution and relatively far-field positions of these data prevent clear discerning of the plasma accelerated out of the individual channels and the central cathode. Focusing in on a single radial profile 2.5 mean channel diameters downstream, Figure 9, shows a sequence of plasma "breaths" exhaled by the NHET breathing mode.

IV. Conclusion

Detailed measurements of the time-resolved state of a plasma discharge downstream from a nested-channel Hall thruster have been acquired and discussed. A unique high-speed dual Langmuir probe and associated sensors have enabled acquisition of the fastest fully-swept Langmuir probe data ever published at 400 kHz (with 1 MHz results also acquired but to be published in a separate work). All the plasma properties were observed to fluctuate in a manner similar to the breathing mode fluctuations seen in the total discharge current (sum of both discharging channel currents), but with phase differences dependant on whether the property is convectively or thermally transported across the plume. The close proximity of the two concentric or "nested" discharge channels exhibit strong transient plasma coupling to each other resulting in predominantly in-phase channel current fluctuations. The amplitudes of the observed fluctuations averaged about 10% to 15% for all properties at the thruster discharge condition of 200 V and 23 A_{dc} examined. Finally, the large grid of single-point time-resolved measurements was fused into 2D time-resolved sequences that highlight the magnitude and prevalence of breathing mode fluctuations throughout the entire plume region investigated.

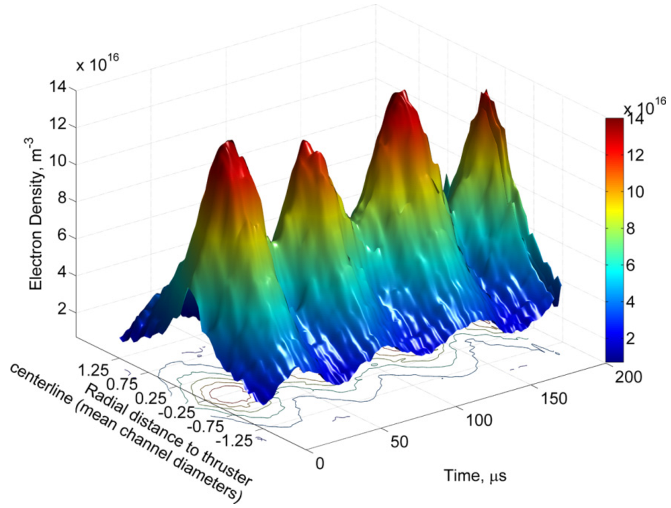


Figure 9. Evolving radial profile of electron density 2.5 mean channel diameters downstream from NHET. *About 3.5 breaths of plasma are portrayed in this sequence.*

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