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Driving Low Frequency Breathing Oscillations in a Hall Thruster

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Coherent m = 0 breathing oscillations in a cylindrical Hall thruster are driven by imposing a sinusoidal modulation of the applied anode potential. Using high speed imaging and total discharge current measurements to monitor fluctuations, 11 kHz oscillations are driven at 13 V_{AC}. The resulting discharge provides a test-bed to perform laser-induced fluorescence measurements of the time-dependent ion velocity distribution using a novel heterodyne approach. Development of the diagnostic and characterization of induced oscillations could be relevant steps to understand the naturally occurring breathing mode and rotating spoke oscillations in Hall thrusters.

I. Introduction

Hall thrusters are useful in propulsion applications such as station keeping and orbit transfers of satellites.[1] The cylindrical Hall thruster (CHT) is a type of Hall thruster designed for low power applications (∼100 W) by eliminating the central annular component in the near-exit region. The reduced surface-to-volume ratio lessens the effects of plasma-surface interactions, which shorten the lifetime of the thruster and lead to wall power losses.[2]

Operation of conventional annular Hall thrusters and CHTs is characterized by a number of low frequency oscillations, including m = 0 breathing oscillations and m = 1 azimuthal oscillations. Breathing oscillations are observed as discharge current oscillations,[3] and have been suggested to be the result of an instability of the ionization region.[4] High speed imaging studies coupled with probe data have confirmed the existence of an azimuthally rotating spoke (i.e., a region of increased density and light emission), which is also observed in the individual segment currents of a segmented anode.[5−8] While these disturbances have received much attention for their possible influence on Hall thruster operation, efficiency, and plume divergence, the underlying physical causes of these phenomena have not been fully understood.[8,9] Extensive experimental campaigns using an annular thruster have been undertaken to characterize the propagation of the instabilities, as well as the various mode transitions that arise from adjustment of the operating parameters.[10,11] Increased background pressure levels have also been found to suppress breathing and spoke oscillations.[12] Furthermore, 3D PIC simulations have been applied to simulate the ion dynamics in a CHT, and results suggested that the presence of a rotating spoke is coupled with an azimuthally asymmetric depletion of the neutral gas.[13]

In this study, we induce breathing oscillations within a CHT with aims to investigate how disturbances form as well as to provide a coherent operating regime to develop and test diagnostics that will better characterize instabilities in plasma discharges more broadly. Ref. 14 showed that modulation of the cathode keeper potential leads to temporal coherence of breathing oscillations in a Hall thruster. Additionally, results in Refs. 9 and 15 showed that the boundary conditions along the anode of a CHT have the ability to either amplify or attenuate oscillations, as well as manipulate their frequency and structure. By modulating the potential at the anode, an artificial analogue of the breathing mode is investigated. In particular, a novel heterodyne approach to perform time-resolving laser-induced fluorescence (TR-LIF) measurements of the ion velocity distribution function (IVDF) for discharges exhibiting periodic disturbances is outlined and tested.

In this paper, the experimental setup including the LIF diagnostic is described in section II. Results are presented in section III with concluding remarks summarized in section IV.

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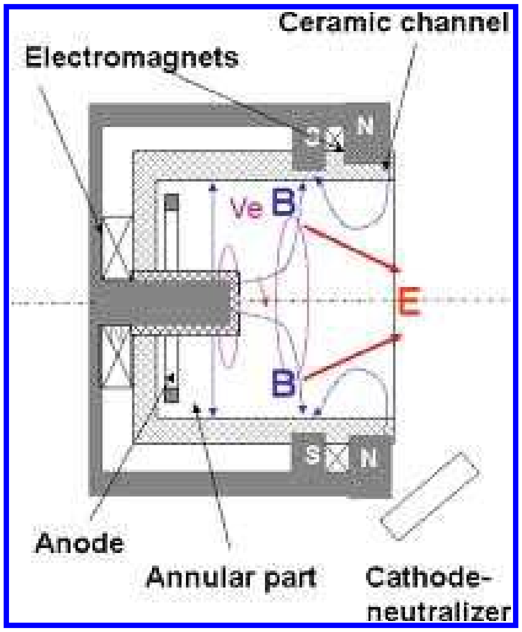

Figure 1. A schematic view of the cylindrical Hall thruster.

II. Experimental Setup

Experiments were conducted at the small Hall thruster facility (SHTF) at the Princeton Plasma Physics Laboratory using a 2.6 cm diameter CHT, shown schematically in Fig. 1 and described elsewhere in detail.[2,16] A plasma cathode-neutralizer attached ~5 cm from the channel exit serves dual functions as an electron source and a neutralizer for ions ejected out of the thruster. 1 A of keeper current was applied to sustain the discharge upon startup, along with a heating current of 18 A. The thruster runs using a xenon propellant, while flow rates of 3.5 and 2.0 standard cubic centimeters per minute (SCCM) were applied to the CHT and the cathode, respectively. Background xenon pressure was maintained at roughly 6×10^{-5} Torr through the steady-state balance of gas flow and expulsion using a turbo-molecular pumping system. The magnetic field profile was established in the discharge channel using a set of electromagnetic coils (see Fig. 1), with currents of 2.4 and 0.5 A through the rear and front coils, respectively. The magnetic field was tuned to minimize the level of rotational activity observed in the discharge. A Phantom v7.3 high-speed camera, separated from the thruster by an optical path length of roughly 2 m, was focused at the exit channel to measure the axially integrated light intensity of the CHT discharge. Images were produced at a resolution of 64 × 64 pixels with a 60,606 fps capturing rate.

In order to impose the modulation, an AC power supply was connected in series to the main thruster power supply. A sinusoidal waveform with an amplitude of 13 V was applied directly to the anode with a DC level of 220 V. The modulation was strong enough to ensure coherence for the LIF measurements, while still keeping within a linear discharge regime to prevent excessive perturbation of the plasma and maintain the same time-average behavior as without the modulation.

A flow chart of the LIF system is provided in Fig. 2. The setup includes a tunable diode laser, directed along the thruster centerline, which is used to excite singly ionized xenon from the metastable 5d $^2F_{7/2}$ level into the 6p $^2D^\circ_{5/2}$ excited state. As the electrons drop into their low energy states, fluorescence is emitted in all directions proportionally to the density of ions in the velocity classes probed. The laser beam is chopped, typically at 100 kHz, to establish a background noise level for reference. Collection optics focused on the CHT exit plane lead to a photomultiplier tube (PMT) to produce an electrical signal for processing. Typical time-resolving methods require a significant amount of time (up to several hours) in order to obtain a full set of measurements due to the poor signal-to-noise ratio of the electrical output from the PMT.[17] In order to circumvent this difficulty for discharges that exhibit periodic behavior, the distribution function f as a function of configuration $\mathbf{x}$ and velocity $\mathbf{v}$ space is harmonically decomposed in time t:

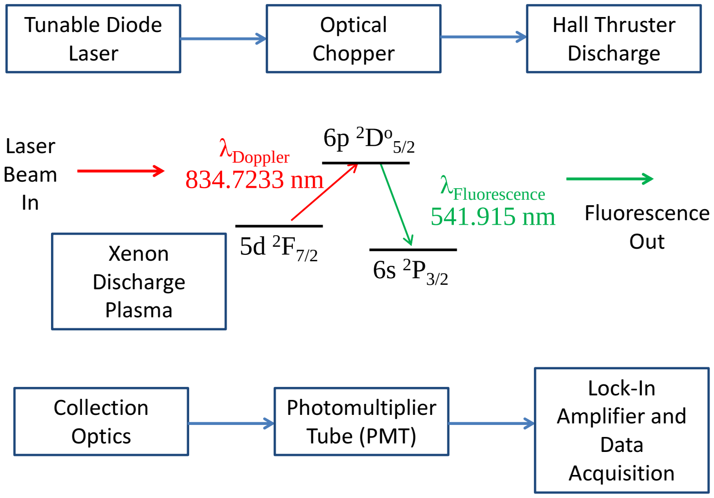

Figure 2. A block diagram of the LIF system.

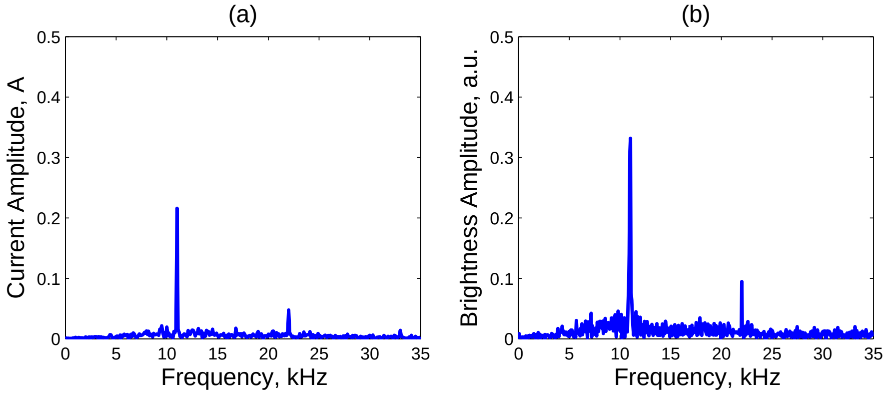

Figure 3. Fast Fourier transform (FFT) of the (a) total discharge current and (b) total image brightness traces produced by a modulated applied voltage of the CHT.

$$f(\mathbf{x},\mathbf{v},t) = A_0 + \sum_{n=1}^{\infty}[A_n(\mathbf{x},\mathbf{v})cos(\omega_D t) + B_n(\mathbf{x},\mathbf{v})sin(\omega_D t)] \tag{1}$$

where ω_D represents the angular driving frequency. The coupling between the chopping of the laser beam (angular frequency ω_C) and the modulation of the discharge produces a signal that varies as the sum and difference of the two frequencies involved. By locking into the frequencies $\omega_C \pm n\omega_D$, the amplitudes of the Fourier components A_n and B_n may be measured. Equivalently, the decomposition may be expressed using the total amplitude $R_n = \sqrt{A_n^2 + B_n^2}$ and a relative phase $\theta_n = tan^{-1}\left(\frac{B_n}{A_n}\right)$ to relate the time-dependence across different velocities. Further details of the LIF system and methods used may be found elsewhere,[18] while a detailed validation of the approach will be presented in an upcoming journal paper.

III. Results

In order to characterize the oscillations produced in the Hall thruster discharge, frequency decompositions of the (a) total current and (b) brightness are provided in Fig. 3. The perturbation amplitude was maintained as high as possible while keeping the measured ratios between the second and first harmonic components at about 25 % for the current and brightness traces. As a result, a first-order LIF scan of the resulting perturbation in the IVDF is expected to provide a sufficient test-bed for the heterodyne measurement

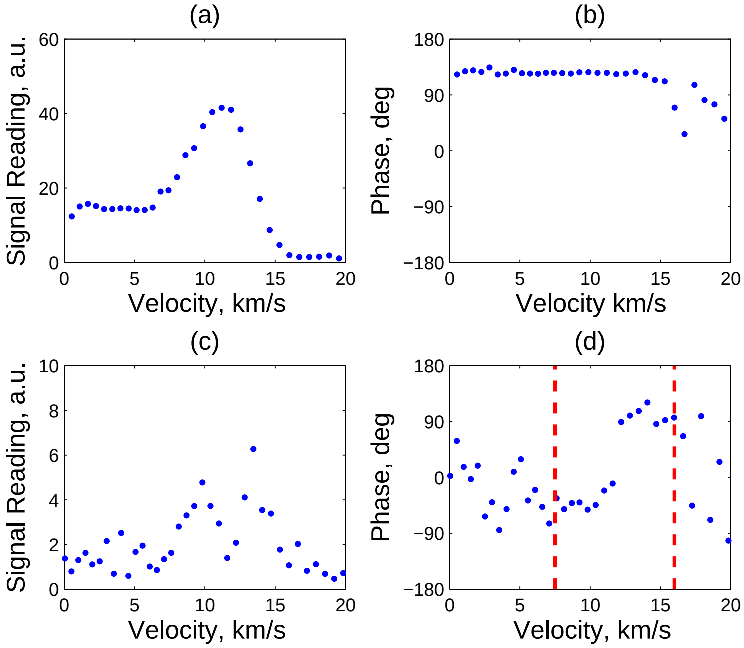

Figure 4. (a) Amplitude and (b) phase of the time-average coefficient measurements of the IVDF. (c) and (d) show the amplitude and phase information, respectively, needed to calculate the first-order perturbed coefficients of the distribution function. The region between the red lines in (d) denotes velocities where the first-order signal measurement is coherent.

approach.

The time-average of the IVDF depicted in Fig. 4(a) is measured by the typical means of locking into the chopping frequency. Locking of the relative phase measurement at a constant level suggests that a coherent signal reading is detected. After about 16 km/s as the amplitude drops off to its zero level, the phase becomes scattered as the noise component begins to dominate. The number of ions travelling at velocities over 16 km/s may thus be considered negligible. Likewise, measurement of the perturbation, shown in Fig. 4(c-d), exhibits phase locking between velocities of roughly 7.5 and 16 km/s. The oscillation amplitude in this region of velocity space exhibits a double hump feature, and the relative phase between the characteristic velocities of these humps is shifted by roughly 180 deg. This suggests that the oscillations in the distribution function are time-lagged by a half-period when comparing velocities of different humps. Measurements of the second-order perturbation detected only noise, which confirms the predominantly linear behavior of the discharge.

IV. Conclusion

Results show that modulation of the applied voltage of a CHT has the ability to induce oscillations of the discharge current and plasma properties, including the IVDF. Preliminary analysis of the resulting waveforms indicate not only similarities, but also differences with respect to those of natural breathing oscillations, including an increased phase lag in oscillations of the plasma properties. The imposed periodicity allows for the resulting velocity distribution to be decomposed into a Fourier series, which allows time-resolving LIF measurements to be made using phase-sensitive detection by locking into either the sum or difference of the laser chopping and discharge modulation frequencies. These results validate the methodology better than previous work, where oscillations were driven using a square-wave modulation, as opposed to a sinusoid. Results also suggest that the approach is applicable to second and higher harmonics of the distribution. A detailed investigation of the driven breathing mode activity, along with comparisons to the natural breathing mode and a thorough validation of the heterodyne approach to LIF will be presented in forthcoming publications.

Acknowledgments

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