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Experimental studies of high-frequency azimuthal waves in Hall thrusters

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High-frequency oscillations (1–100 MHz) are drawing significant attention in the recent research of Hall thrusters. A diagnostic setup, consisting of single Langmuir probe, special shielded probe connector-positioner, and electronic impedance-matching circuit, was successfully built and calibrated. Through simultaneous high-frequency probing of the Hall-thruster plasma at multiple locations, high-frequency plasma waves have been successfully identified and characterized. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1634564]

I. INTRODUCTION

Hall thrusters are now considered as the preferred candidate for spacecraft propulsion in certain near-Earth missions.[1] One of the important issues that could stand in the way of successful integration of the Hall thruster in spacecraft[2] is the presence of plasma oscillations, which could interfere with rf communication, or the thruster operation itself. Both theoretical and experimental studies of plasma oscillatory behavior have been performed since the earliest Hall thruster investigations and are still underway.[3]

In spite of widely recognized importance of the oscillations in the high-frequency band for thruster operation, the insight on the physical properties of these modes has been very limited both theoretically and experimentally.[4] The lack of extensive experimental data regarding plasma instabilities with the frequencies of a few tens of MHz is caused by the technical difficulties one encounters in detecting and diagnosing these modes. Due to the recent progress in the high-frequency data acquisition, analysis tools, and equipment, these oscillations attracted more attention.[5]

This paper is organized as follows. The instrument setup, which is employed to detect and characterize high-frequency oscillations inside a laboratory Hall thruster, is discussed in Sec. II. Section III describes the calibration, experimental procedures, and data analysis for high-frequency measurements. Section IV summarizes the experimental results. The analysis of the findings and comparison to theory are presented in Sec. V.

II. HIGH-FREQUENCY PROBE DIAGNOSTIC

Hall thrusters present significant problems for experimental studies of the local high-frequency phenomena in plasma inside the acceleration channel. Despite very serious limitations, a single-tip Langmuir probe can serve as an extremely useful diagnostic tool. While it is considered more difficult to interpret single-probe data than, for instance, for the double probe,[6] it allows significant advantages in terms of probe lifetime, resistance to short-circuiting, and sputtering and measurement localization. At the same time, careful consideration of the probe size selection and operating point allows one to acquire meaningful data using single-tip probes. In the waveband of a few tens of MHz, accurate impedance matching of all diagnostic circuits is essential to achieve acceptable signal to noise ratio. Such measurements have become feasible due in part to recent progress in the fabrication of miniaturized semiconductor devices, allowing placement of signal conditioning electronics inside the vacuum vessel in the proximity of the probe.

To overcome the limitations and technical difficulties of operating high-frequency probes in the harsh Hall thruster environment, a special probe diagnostic was successfully developed and tested.[7]

The thruster used for the experiments is a 900 W range Hall thruster, which has been developed and extensively studied at the PPPL Hall Thruster Experimental facility.[8] The schematic diagram of the thruster, which includes the magnetic circuit with coils, insulating annular acceleration channel, gas-feeding anode, and the cathode neutralizer, is shown in Fig. 1.

A special connector (Fig. 2) was designed and manufactured to connect the tungsten probe tip, protruding into the discharge area of the thruster from the outer ceramic wall of acceleration channel, to the data acquisition circuitry. This connector allows easy regulation of the length of the probe protruding into the plasma. The connector is also easy to disassemble for probe wire replacement. Both of these features are necessary to compensate for fast erosion of the probe tip during thruster operation. At the same time the connector is designed in such way that the whole transmission line stays coaxially shielded from the probe tip to the coaxial electrical vacuum feed through.

To match the probe setup to the outside transmission line (e.g., regular 50 ohm coaxial cable), a matching circuit was designed and assembled. The circuitry for multiple probes was designed, built, and placed in a capsule inside a well, protruding from the side of the vacuum chamber toward the thruster (Fig. 3). Since the transmission line impedance can be perfectly matched between the matching circuit and the data acquisition system, the impedances of the coaxial line between the probe tip and the circuit change significantly. The matching circuit had to be located at a minimum distance from the probe in order to minimize the effect of such mismatch on the signal strength and possible noise introduction.

Oscillations in the plasma density can be related to the

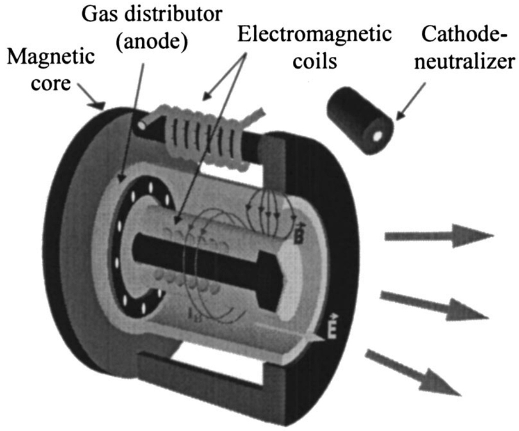

FIG. 1. Typical Hall thruster schematics.

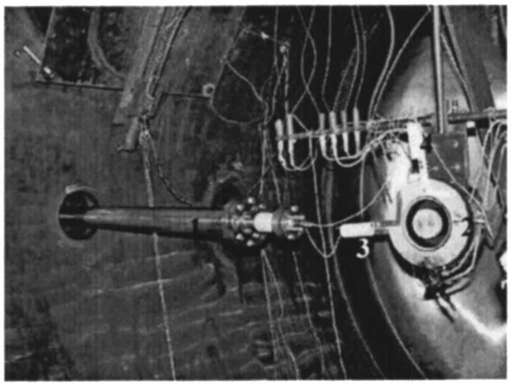

FIG. 3. Two azimuthally separated probes, connected to the matching circuit inside a tube well: (1) well with the capsule inside; (2) thruster; (3, 4) probe connectors.

oscillations in the ion saturation current of the probe. After the probe setup (without circuitry) was assembled, the voltage-current characteristics of the probe were experimentally measured at various operating points. During these measurements the probe was biased relative to the grounded vacuum vessel using a directly connected dc power supply. The analysis of the probe characteristics indicated that, for the probe located in the acceleration zone of the thruster channel, the necessary bias, negative in relation to the probe floating potential, can be provided for all practical thruster operating conditions simply by connecting the probe to the ground through a load, small compared to the probe–plasma impedance, while large enough to detect fluctuations without need for high-amplification techniques.

The output of the matching circuit was connected to a data recording commercial digital storage oscilloscope (DSO, LeCroy LT-264M) with matching input impedance and high-enough sampling rate (up to 2 GS/s).

III. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

During the initial testing of the matching circuit, the response was found to be linear with the introduced noise smaller than the oscilloscope digitizing error for the input signal frequency range 1–50 MHz and signal amplitude 5–1000 mV.

The system was used to perform experiments characterizing plasma oscillations in the Hall thruster discharge. The signal from the probing system was recorded by the DSO at the rate of 1 GS/s with the duration of the samples up to 50 microseconds. The recorded signal was Fourier analyzed (see, for example, Fig. 4) afterwards to obtain data on the oscillatory modes, present in the discharge plasma.

The same setup, but using multiple probes, was used to measure the phase velocity and propagation direction of the plasma waves. The probes were mounted at various azimuthally separated locations (90, 120, and 180 deg). In order to account for possible variations in the delay of the signal passing through separate circuits the synchronization procedure for the probes was performed, using the split signal from the generator. Then, the synchronized signals from the probes were recorded simultaneously and Fourier analyzed for various thruster operating conditions. The frequency spectrum at different locations was virtually identical for all of the operating regimes and thruster configurations (see, for example, Fig. 5).

To obtain the phase relationship between the signals from different probes, the following procedure was implemented. First, the main harmonics in the frequency range between 5 and 50 MHz was identified. After that the signal was digitally bandpass filtered with the center frequency of

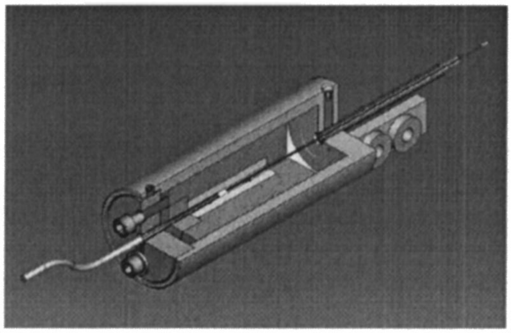

FIG. 2. Probe connector design.

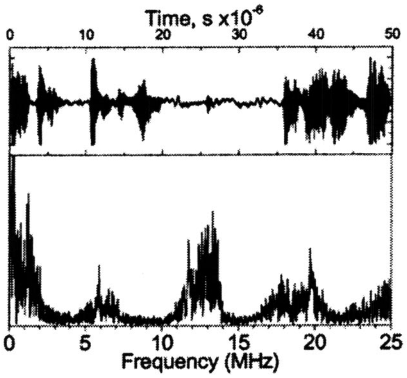

FIG. 4. Typical oscilloscope trace and corresponding frequency spectrum.

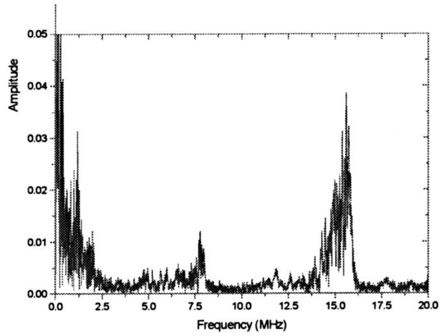

FIG. 5. Typical spectra of the signal from azimuthally separated probes.

the filtering function corresponding to the frequency of identified harmonic.

Such digital filtering produced nearly ideal sinusoidal waves with a certain phase shift (Fig. 6). Sine function was then fitted into the filtered waves and the phase difference between the fitted sinusoidal waves was obtained.

The described technique produced a comprehensive database of the high-frequency plasma waves in the acceleration channel of PPPL Hall thrusters for various operating conditions.

IV. EXPERIMENTAL RESULTS

The results of the phase-correlation technique, described in Sec. III, yield the phase shift of the signal between two probes being exactly equal to the angle between the probe azimuthal locations around the thruster. This indicated that propagation of the observed wave is purely azimuthal.

The amplitude of the detected oscillations was very unstable (Fig. 4), and no trends in the duration, onset, or stabilization of the observed waves could be identified. At the same time, multiple measurements at the same thruster operating point yielded the frequencies of the excited waves to be very repeatable between the measurements and strongly dependent on the thruster operating parameters.

The variation of the maximum magnetic field (controlled by the magnetic coils current) resulted in the variation of the frequency of the observed waves (Fig. 7). An increase in the applied magnetic field resulted in the decrease of the oscillation frequency for any fixed discharge voltage.

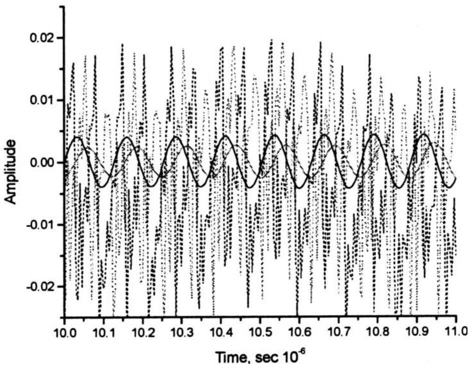

FIG. 6. Recorded and digitally bandpass-filtered signal from two probes.

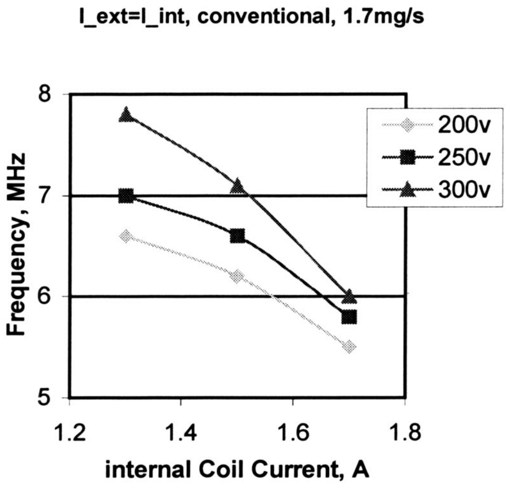

FIG. 7. Frequency of the detected oscillations as a function of the B field for different discharge voltages.

Changes in the profile of the applied magnetic field, which were introduced by the variation of the ratio of the current in the internal and external magnetic coils, have also affected the frequency of the observed waves (Fig. 8). At the same time, for any fixed profile (coil current ratio) and discharge voltage the frequency of the waves was decreasing for the increase of the maximum value of the magnetic field.

The high-frequency waves were also detected in different thruster geometries, both conventional and nonconventional.[9–11] The presence of the segmented electrodes in the thruster channel has also resulted in the change of the main frequency of the unstable mode.

V. DISCUSSION

During the course of experiments for different thruster operating points, the probes were located at different positions to determine the direction of propagation of the de-

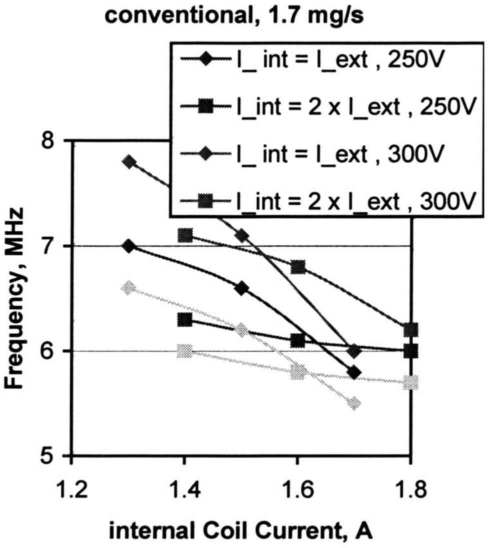

FIG. 8. Frequency of the detected oscillations as a function of the B field for different discharge voltages and B field profiles.

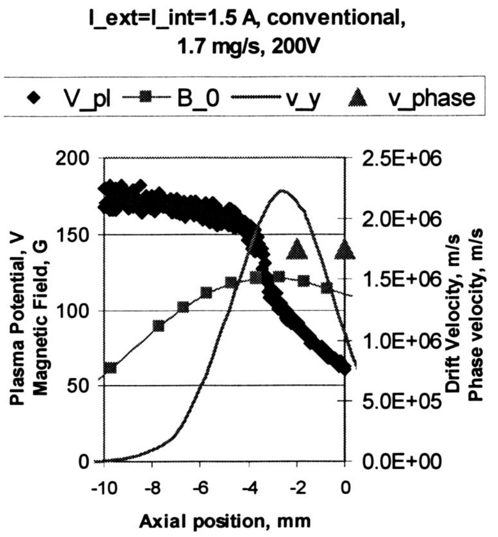

FIG. 9. Electric and magnetic field profile measurements inside the thruster channel, calculated electron drift velocity, and wave phase velocity.

tected waves. While keeping one of the probes at the same location (2 mm from the edge of the acceleration channel), the second probe was both moved azimuthally and located at the edge of the channel. The axial change in the location of the second probe has not changed the spectral characteristics of the probe signal, or the phase relation of the main harmonics to the ones obtained from the unmoved probe. It was therefore concluded that purely azimuthal waves were experimentally detected in the acceleration zone of the Hall thruster.

The phase velocity of the observed waves, determined by the assumption that the channel circumference is equal to full wavelength, demonstrated that it is correlated to the electron drift velocity inside the thruster acceleration channel. The electron drift velocity is proportional to the electric field and inversely proportional to the magnetic field inside the thruster. The frequency of the observed waves also increases with the increase in discharge voltage, which can be considered an integral characteristic of the electric field inside the thruster. The oscillation frequency is also decreasing with the increase of the magnetic field. While the dependence of the frequency on these parameters is not proportional, this can be explained by the changes in the distribution of parameters inside the thruster with the changes in the operating point.

The localized measurements of the electric field inside the thruster, performed separately,[9] provide local data for the electron drift velocity at the location of the high-frequency probes. While these data are available only for a limited number of operating points, they suggest that the measured phase velocity of the azimuthal waves being detected is not equal locally to the electron drift velocity (Fig. 9). This fact, together with the absence of phase velocity dependence of the axial position of the probe, suggests that we were not observing an azimuthally rotating plasma density fluctuation and that azimuthally propagating oscillatory modes are present in the Hall thruster plasma.

For the whole range of thruster operating parameters and configurations, the amplitude of the observed high-frequency waves was highly unstable, since the bursts of high-amplitude oscillation were interrupted by quiescent intervals (see, for example, Fig. 4). The amplitude of the high-frequency oscillations in the bursts was also changing quite rapidly. The time average of this amplitude did not correlate with any of the thruster operating parameters. While the ratio of the ‘‘unstable’’ bursts to the quiescent periods tended to increase with the increase of the discharge voltage, there was no statistically significant correlation between the oscillation onset times or burst durations and the thruster operation regime.

For many operating points, more than one frequency of the azimuthal wave was detected. The amplitudes of higher-frequency waves did not show any correlation to the amplitude of the ‘‘main’’ harmonic or the thruster operating regime. This fact suggests that the presence of the multiple frequency signal was not due to the nonlinear behavior of the same wave but rather due to the presence of multiple waves with the same phase velocity and multiple wavenumbers ($k = n/R$, where k is the wavenumber, R is the channel radius, and $n = 1,2,3,...$).

According to theoretical studies of the Rayleigh instability,[12] it is expected that axial gradients in the magnetic field, plasma density, and electron drift velocity can, under certain conditions, drive an azimuthal quasielectrostatic wave. This wave presents an axially localized mode that propagates in the azimuthal direction in the acceleration zone of the thruster. The phase velocity of this mode does not depend on the axial coordinate and is equal to the electron drift velocity only at a single location where the instability condition is satisfied. Depending on the exact instability condition, azimuthal waves with multiple frequencies could be excited by this instability. Since the experimentally observed waves that are studied in these experiments show all of the characteristic features of Rayleigh instability, namely purely azimuthal propagation, axially independent phase velocity, and qualitative agreement with the electric and magnetic field scaling, it would be logical to conclude that the observed waves could be the manifestation of the Rayleigh instability, which has been theoretically predicted recently.

ACKNOWLEDGMENTS

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