High-frequency probing diagnostic for Hall current plasma thrusters

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High-frequency oscillations (1–100 MHz) in Hall thrusters have not received sufficient experimental scrutiny. A diagnostic setup, consisting of a single Langmuir probe, a special shielded probe connector-positioner, and an 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 (Ref. 1). © *2002 American Institute of Physics.* [DOI: 10.1063/1.1494857]

I. INTRODUCTION

Hall thrusters are now considered as the preferred candidate for spacecraft propulsion in certain near-Earth missions,[2] One of the important issues that could stand in the way of successful integration of the Hall thruster in spacecraft[3] 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[4] and are still under way.[5]

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 is very limited both theoretically and experimentally.[6] Low-frequency oscillations, in the tens of kilohertz wave band, are critical for the thruster power processing system design and thruster integration with the satellite onboard circuitry[7] and therefore have attracted significant attention. At the same time, lack of experimental data regarding plasma instabilities with the frequencies of a few tens of megahertz is caused by the technical difficulties one encounters in detecting and diagnosing these modes.

This article is organized as follows. The technical problems encountered in diagnosing high-frequency phenomena in a Hall-thruster plasma are discussed in Sec. II. Section III describes the instrument setup, which allows us to detect and characterize high-frequency oscillations inside a laboratory Hall thruster. Section IV describes the calibration and experimental procedures for high-frequency measurements.

II. HIGH-FREQUENCY PROBE DIAGNOSTIC

Measurements of the plasma oscillations in this frequency range have become feasible due to recent progress in the fabrication of miniaturized semiconductor devices. Use of such devices allows placement of signal conditioning electronics inside the vacuum vessel in the proximity of the probe, needed to achieve acceptable signal-to-noise ratio. Such measurements were recently successfully performed, for example, in the Magnetic Reconnection Experiment,[8] however Hall thrusters present additional problems for the use of probe diagnostics. For example, use of the double probe in Hall thrusters is restricted by sputtering of the probe material, which can produce a short circuit between the probe tips. Also, double-probe characteristics are very difficult to interpret in the presence of a magnetic field for a flow of ions with an unknown energy distribution. For larger Hall thrusters, the use of a coil-type antenna for the detection of such oscillations might be feasible, but, in thruster models with an overall channel diameter less than 10 cm, localized measurements will require antenna sizes of ~ 1 mm diameter. Such an antenna would be very difficult to implement technically due to its short lifetime in the harsh environment of Hall-thruster plasma, and may not yield a sufficient level of a detected signal due to the small pickup area of the antenna.

The single Langmuir probe is one of the most commonly used plasma diagnostic tools, but it too has very serious constraints while used to study Hall-thruster plasma. Probes inside the acceleration channel tend to disturb the discharge. While the double probes collecting the ion saturation current tend to introduce less disturbance than the single probe, collecting significantly higher-electron current,[9,10] this disadvantage of the single probes vanishes if the probe is biased negatively and operated in the ion saturation regime.

It is also very difficult to maintain probe integrity inside the high-temperature region.[11] Thus, the only accessible fixed location for such probing is on the outer wall of the ceramic channel close to the channel exit. At the same time, the probe tip size must obey,[10] $r \ll \rho_e$, where r is the probe radius and ρ_e is the electron gyroradius. For the typical laboratory Hall thruster (1 kW power range) with applied magnetic field of 100–200 Gs and discharge voltage of 200–300 V, the diameter of the probe tip should then not exceed 0.5 mm on the outer wall of the acceleration channel. To simplify the analysis of probe characteristics, it is suggested to have the size of the probe tip much larger than the sheath thickness around the tip, which typically is assumed to be a few Debye lengths. Since in the acceleration zone of the Hall-thruster typical plasma densities are if the order of $10^{10}-10^{11}$ cm^{-3}, which corresponds to $\lambda_D \sim 0.03$ mm, this requirement does not contradict the maximum size constraint we mentioned before.

The sputter deposition on the insulating channel wall around the single probe can effectively increase the probe collecting area. Therefore, the interpretation of the experi-

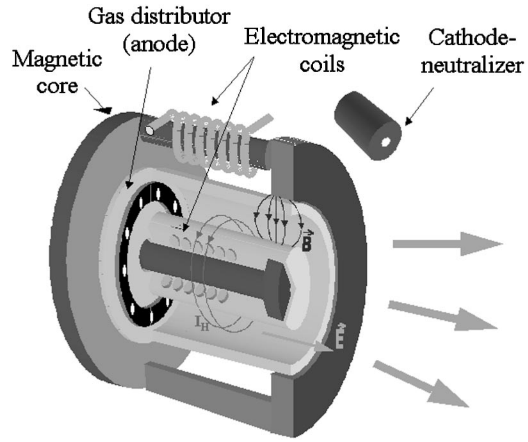

FIG. 1. Typical Hall-thruster schematics.

mental results yielding the absolute values of plasma parameters might not be always correct. However, possible problems of the single probe short circuiting to the metal support structure of the thruster can be easily monitored as well as prevented by the grooves on the channel surface[12,13] if the problem becomes severe.

The amount of current, collected by the surface of such a small probe, even for the steady-state measurements is such that the impedance of the probe-to-plasma interface is of the order of 100 kΩ (the ratio of the probe floating potential to the probe ion saturation current). At the same time, the oscillations in the frequency range around 30 MHz correspond to relatively short wavelengths $\sim$1 m in free space and even shorter in the coaxial cables. This means that all the transmission of the signal from the probes to the recording point (oscilloscope, spectrum analyzer, etc.) should be performed by the way of coaxial shielded transmission lines with matched impedance. This condition is very difficult to meet using standard low-impedance cables. Therefore, a matching circuit should be constructed and placed close to the probe to minimize the effect of impedance mismatch between the probe and the cables.

During the steady-state thruster operation, the probe tip is bombarded by energetic ions which erodes the probe. Therefore, the probe system should accommodate the easy replacement of the probe tip and easy adjustment of its protrusion into the channel.

III. INSTRUMENTAL SETUP

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

The thruster used for the experiments is a 1-kW-range Hall thruster, which has been developed and extensively studied at the PPPL Hall Thruster Experimental facility.[14] 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.

The probe is constructed of tungsten wire 0.25 mm diameter, protruding into the discharge area of the thruster

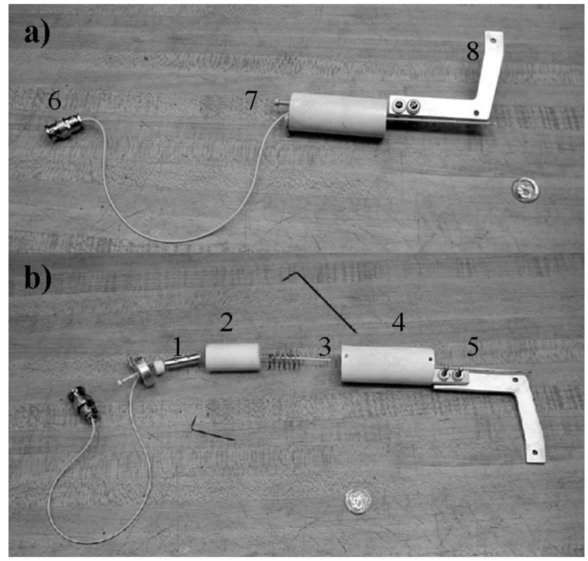

FIG. 2. Probe connector positioner with mounting bracket: (a) fully assembled and (b) disassembled for probe wire change: 1–main lead connector; 2–insulating sleeve; 3–ceramic isulating tube; 4–connector body; 5–shielding sleeve; 6–BNC connector; 7–tip adjustment screw; and 8–mounting.

from the outer ceramic wall of the acceleration channel. On the outside of the thruster, the probe wire is insulated by alumina tube 0.8 mm diameter. To prevent the probe wire from the pickup of electromagnetic noise, outside the thruster, a molybdenum tube shields the alumina, essentially providing a coaxial transmission channel for the signal from the probe. On the other end, the probe wire is coupled to a regular coaxial cable (silicone coated for vacuum compatibility) through a specially designed connector (Fig. 2). This connector by a single bolt on the back 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 a way that the whole transmission line stays coaxially shielded.

Oscillations in the plasma density can be related to the oscillations in the ion saturation current of the probe. After the probe setup (without circuitry) was assembled, the voltage-current characteristics (e.g., Fig. 3) 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. At the same time, the design of the circuit for high-frequency matching of the transmission lines allowed rather simple circuit modification to include additional biasing voltage in the probe circuit in front of the insulating transformer, if necessary.

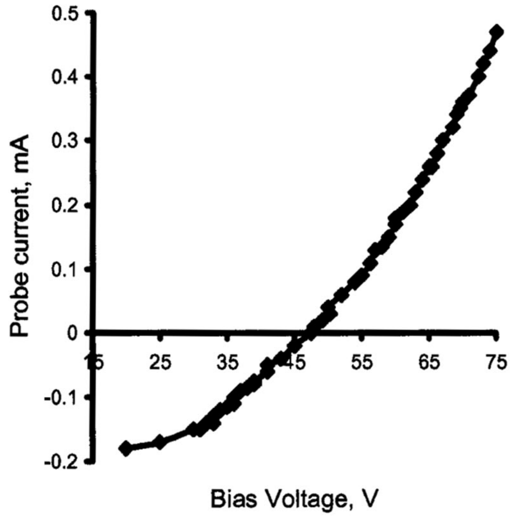

FIG. 3. Typical probe voltage–current characteristic (mass flow 1.7*g* mg/s Xe, $V_d = 200$ V, $I_d = 1.6$ A, $I_{coil} = 1.5$ A).

To match the probe setup to the transmission line (e.g., regular 50 Ω coaxial cable), a matching circuit was designed and assembled (Fig. 4). In this circuit, a commercial high-speed transformer is introduced to insulate galvanically the probe immersed in the high-voltage thruster plasma from the recording digital storage oscilloscope (DSO) and provide necessary bandpass filtering. The transformer, loaded by a low-inductance resistor is connected to the input of the high-speed operational amplifier, which provides matching to the coaxial cable, connected to a data recording commercial DSO with matching input impedance.

The following electronic components were selected: pulse engineering transformer PE-5154CT with the frequency band 0.9–110 MHz, l0 kΩ load resistor, and Burr-Brown Operational Amplifier OPA-682 with 105 Ω input and <1 Ω output impedances, and <250 MHz bandwidth. The signal was recorded using LeCroy LT-264M DSO.

Note, that while this system's impedance is perfectly matched between the matching circuit and the DSO, the impedances between the probe and the circuit change significantly. In order to minimize the effect of such a mismatch on the signal strength and possible noise introduction, the distance between the probe and the matching circuit should be minimized. This was achieved by placing the matching circuit in a capsule inside a well, protruding from the side of the vacuum chamber toward the thruster (Fig. 5).

In order to provide reliable operation of the matching circuitry in a thermally stable regime in a limited volume of the capsule, mildly pressurized air supply is provided to the capsule for convective removal of the any excessive heat, generated by the amplifier.

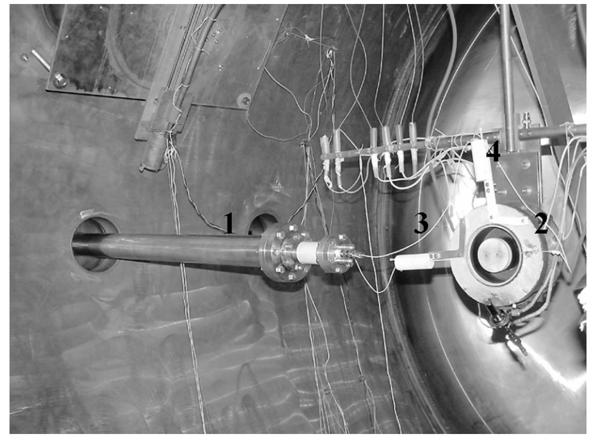

FIG. 5. Two azimuthally separated probes, connected to the matching circuit inside a tube well: 1–well with the capsule inside; 2–thruster; and 3, 4–probe connectors.

IV. EXPERIMENTAL PROCEDURE

The performance of the matching circuit was tested using a commercial Wavetek signal generator. For the input signal frequency range 1–50 MHz and signal amplitude 5–1000 mV, the response was linear with the introduced noise smaller than the oscilloscope digitizing error.

The system was then used to perform experiments characterizing plasma oscillations in the Hall-thruster discharge.[1] 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 μm. The recorded signal was afterwards Fourier analyzed (see, for example, Fig. 6) to obtain data on the oscillatory modes, present in the discharge plasma.

The same setup, but using multiple probes, provided information on the phase velocity and propagation direction of the recorded plasma waves. During multiple experiments with various conventional and nonconventional thruster configurations[12,13,15] high-frequency plasma waves were de-

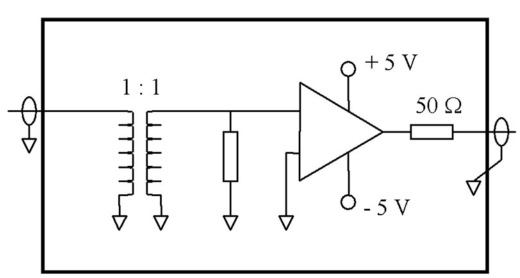

FIG. 4. Impedance matching circuit diagram.

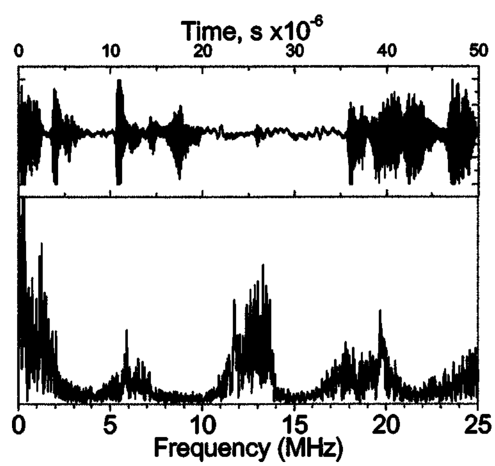

FIG. 6. Typical oscilloscope trace and corresponding frequency spectrum.

tected. The frequencies of the observed waves varied between 5 and 30 MHz depending on the thruster configuration and operating point, and at times several higher-order harmonics were also observed.

The experimental data obtained from multiprobe setup provides a clear indication of the presence of frequency- and phase-correlated oscillations at different locations within the thruster at different operating conditions. The results of the measurements are currently being analyzed to provide a more complete picture of oscillatory processes in Hall plasma, as well as to compare it with the theoretical predictions for the oscillations in this wave band.[16,17]

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