Background Gas Pressure Effects in the Cylindrical Hall Thruster

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A weakly collisional plasma discharge of the cylindrical Hall thruster with the cusp magnetic field and the thruster plume are strongly affected by variations of the low background pressure from 3 μtorr to 50 μtorr. High speed imaging measurements revealed that the increase of the background pressure leads to the suppression of two key modes of low frequency discharge oscillations in this thruster, including longitudinal breathing mode and rotating spoke mode. These effects occur in spite of insignificant changes of the plasma collisionality in this pressure range.

I. Introduction

The principle of operation of the cylindrical Hall thruster (CHT)[1] is based on a closed E×B electron drift and electrostatic acceleration of non-magnetized ions in quasineutral plasma in a hybrid magneto-electrostatic trap (Fig. 1). The magnetic field configuration of the CHT can be cusp-type and magnetic mirror-type (so called direct-type). Comprehensive studies of the miniaturized low power CHT are reported elsewhere.[2] In recent papers, we described the existence of two principle modes of low frequency oscillations of the CHT discharge, including longitudinal breathing mode and E×B rotational mode (the so-called rotating spoke).[3,4] The breathing mode manifests itself in large amplitude oscillations of the discharge current (~ 10 kHz).[3] These oscillations are also

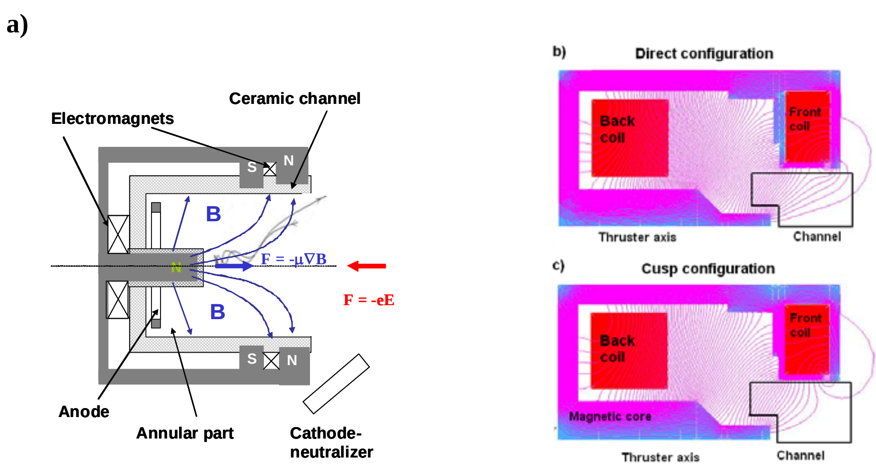

Figure 1. Schematic of a cylindrical Hall thruster (CHT) (a) and magnetic field configurations: direct (b) and cusp (c). In the direct configuration, the electromagnet coils currents are in the same direction, while for the cusp configuration, the coils currents are in the opposite direction (opposite polarity).[2]

observed in conventional annular Hall thrusters and usually associated with ionization instability.[5,6] Breathing oscillations are easy detectable on oscilloscope traces of the discharge current. Using a high speed camera, we succeed to detect the rotating spoke as a region of increased visible light emission that propagates azimuthally.[4] The spoke was seen only in the magnetic "cusp" configuration (Fig. 1b) and was not seen in the "direct" configuration (Fig. 1c). A sequence of images from the high speed camera is shown in Fig. 2. Correlated high speed imaging and

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probe measurements indicated that stronger spoke oscillations are localized in the region near the anode. It was also determined that the spoke travels in the E ×B direction with a speed that ranges from 1.6-2.8 $\times 10^3$ m/s (20-35 kHz). This is an order of magnitude smaller that the azimuthal E×B speed expected in the near anode region.[4] Unlike breathing oscillations, the rotational mode oscillations are not seen in the discharge current traces,

Note that similar rotational oscillations were previously detected and well characterized for the annular Hall thrusters,[7] including low frequency spoke, which usually occurs at the non-saturated part of the thruster V-I characteristic (e.g. at low discharge voltages <200 V).[8,9] It is believed that the spoke is responsible for the

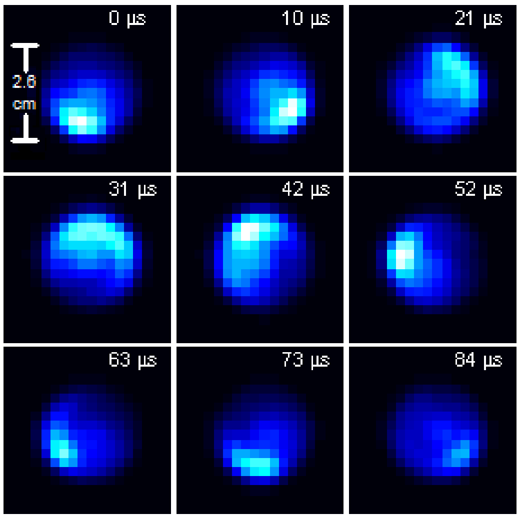


Figure 2 Sequence of camera images show counter-clockwise rotation, in the ExB direction, in the cusp configuration of the 2.6 cm CHT thruster. This spoke was not observed for the direct magnetic configuration of the CHT.[4]

anomalously large electron conductivity across the magnetic field measured in these regimes. Apparently, this is also the case for the CHT thruster with the cusp configuration of the magnetic field. In fact, it was recently demonstrated that the suppression of the spoke with the increase of the cathode electron emission (non-self-sustained current overrun regime) correlates with the reduction of the electron cross field current. However, key differences of the rotating spoke observations for the CHT thrusters is that 1) the spoke occurrence has a non-local nature - it occurs in the near anode region with a strong magnetic field, while being turn on/off by the magnetic field topology away from the anode at the thruster exit (cusp vs. direct, Figs. 1b and 1 c), 2) it occurs in the thruster regimes with a highly ionized plasma flow.

A detailed analysis of spoke oscillations in the CHT and their dependence on the cathode electron emission is described in Ref. 4. Moreover, the effect of the cathode electron emission on the CHT operation is described elsewhere.[3] With the enhancement of the cathode electron emission (for a hollow cathode, by running an auxiliary cathode-keeper discharge of 2-3 A[3]), the CHT operates more efficiently and produces a narrower plasma plume.[10] However, these improvements can be affected by the background gas pressure in the vacuum chamber (Fig. 3).[11] In particular, the increase of the background pressure causes the increase of the discharge current and also diminishes the plume angle advantage

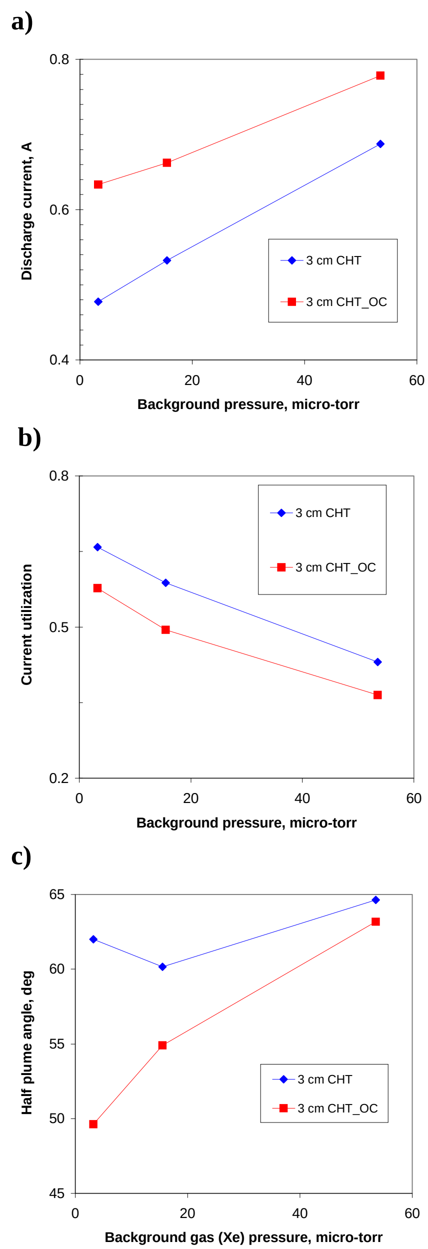


Figure 3. Effect of the background pressure on operation of the 3 cm CHT in the self-sustained and non-self sustained overrun current (hollow cathode-keeper current is 2-3 A) regimes: (a) discharge current, (b) current utilization efficiency and (c) half plume angle for 90% of the total ion flux.[11]

of the non-self-sustained regime with the enhanced cathode electron emission (with an auxiliary cathode-keeper discharge) as compared to the conventional self-sustained operation (without the cathode-keeper discharge). In the present paper, we describe the effect of the background pressure on the breathing and spoke oscillations for the self-sustained operation of the CHT with the cusp magnetic field.

II. Experimental setup

The 2.6 cm diam. CHT was operated in the large PPPL Hall Thruster facility.[12] Xenon gas was used in all experiments. The anode and cathode gas flow rates were 4 sccm and 2 sccm, respectively. The background pressure in a 28 m^3 vacuum vessel equipped with cryopumps was varied by flowing an additional Xenon gas flow (up to 100 sccm) through the gas feedthrough on one of the vessel flanges. Without an additional gas flow, the background pressure did not exceed 3 μtorr. A commercial Heatwave 250 model hollow cathode electron source was used as the cathode-neutralizer. The cathode keeper electrode was used to initiate the main discharge between the cathode and the thruster anode, and to maintain the discharge current. In the current overrun regime, the cathode- keeper current was 2.5 A.

III. Procedure and analysis of high speed imaging

A Phantom Camera V7.3 camera was used to obtain the high-speed images of unfiltered emissions in the visible spectrum range. This camera is capable of recording up to 400,000 frames per second at 32x32 pixel resolution. The camera is located outside the vacuum vessel looking in through a viewport about 7m away from the thruster, and aligned approximately along the thruster axis.

The following signal processing procedure was applied for the analysis of images.[13] To determine the breathing mode signal, the algorithm averages the brightness of all the pixels contained within the outer radius of the thruster in a single frame, resulting in a single scalar value. Performing this average for each frame, a scalar valued function of time is obtained – the average brightness of the plasma discharge over time. This function is the breathing mode signal. The breathing mode has two properties of interest – the coefficient of variation (COV) and the frequency of oscillation. The COV is a dimensionless parameter that gives the strength of the breathing mode. It can be calculated as COV = $\sigma/\langle x\rangle$, where σ and $\langle x\rangle$ are the standard deviation and the mean value of the signal, respectively. Breathing mode strength decreases as COV value decreases. A well defined breathing mode usually disappears for COVs below 0.15 as there is no longer a clearly dominant frequency. To obtain the frequency of oscillation, a spectrogram and a periodogram of the signal are created. The spectrogram shows if the signal's frequency content changes with time, while the periodogram gives a time-averaged view of the frequency content of the signal. By locating the highest peak in the periodogram, the dominant frequency in the breathing mode signal can be determined, giving the frequency of the breathing mode. However, the accuracy of this frequency determination decreases with decreasing COV value because the breathing mode has a less clearly defined frequency and other oscillations, such as the spoke, may become the dominant oscillation in the plasma and the breathing mode signal.

Fig. 4 illustrates the cross-correlation procedure, which was used to analyze the recorded images of CHT

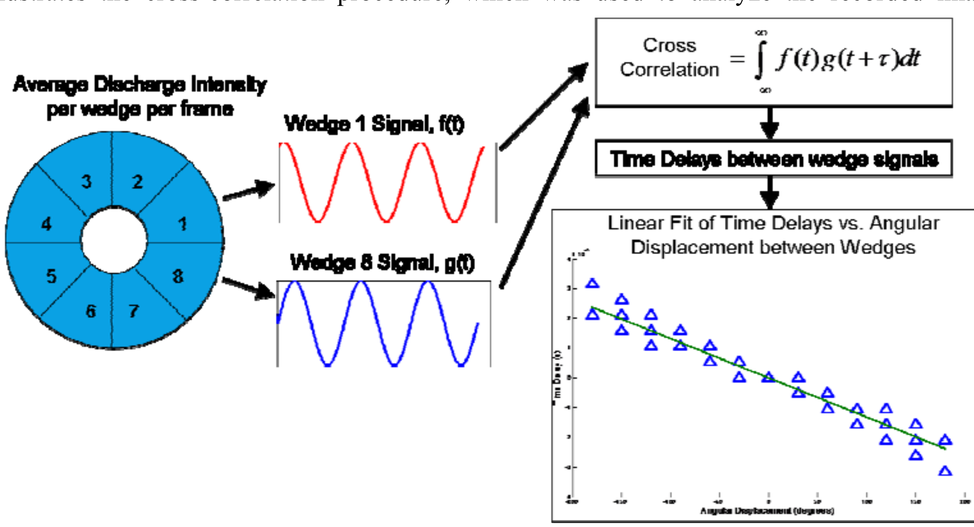


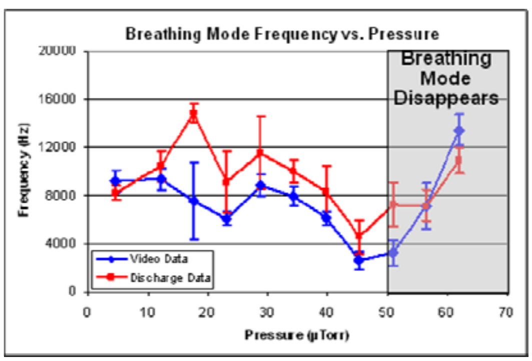
Figure 4. Cross-correlation analysis procedure to measure spoke frequency.[13]

rotational oscillations. The images of the thruster from the camera were loaded into the MATLAB software for analysis. Each pixel has a brightness or intensity level at every time. First, the image of the thruster is divided into annular wedges. The intensity of the pixels within each wedge are averaged, yielding a brightness of the wedge as a function of time. The wedges are annular because the spoke of interest is near the outside radius, so excluding the center region reduces noise. Consider the case when there is a spoke moving clockwise. The intensity in wedge 1 would peak to a maximum just before the intensity in wedge 8 peaks, as shown in the figure. The travel time, which manifests as the time delay between the signals of wedge 1 and wedge 8, could be used to calculate the spoke frequency. The cross correlation function is used to find the time delay. The cross correlation, which is a function of the time delay, is maximum when the functions are most similar. Taking the time delay of the maximum of the cross correlation yields the spoke travel time. Cross-correlations are performed between all pairs of wedges. If there is a spoke of constant rotation, then the points of all the time delays vs. angular distances of wedges should fall on a straight line. A least squares linear fit gives an estimate of the spoke frequency, and the R^2 value from the linear fit quantifies the degree to which the observed pattern fits a rotation. The error from the calculated frequency was estimated to be about 20%. This estimate came from the difference in frequency when using different input parameters to the method, such as wedge size.

IV. Experimental results and discussions

A detailed analysis of the effect of the background pressure on the discharge characteristics and the plasma plume is described in Ref. 11. Both the discharge current and the ion current increase with the increase of the background pressure from 3 µtorr to 60 µtorr (Fig. 3). However, the current utilization, which characterizes how well the magnetic field suppresses the electron cross-field transport, decreases (Fig. 3b). Fig. 5 illustrates changes of the breathing oscillations with the background pressure. The breathing mode is suppressed with increasing background pressure, with significant suppression occurring at pressures as low as 20 µTorr. Above 50 µTorr, a well-defined breathing mode disappears and higher frequency, lower amplitude oscillations arise. The amplitude drops below an arbitrarily defined lower limit (0.15), below which a well-defined breathing mode generally disappears.

a)



b)

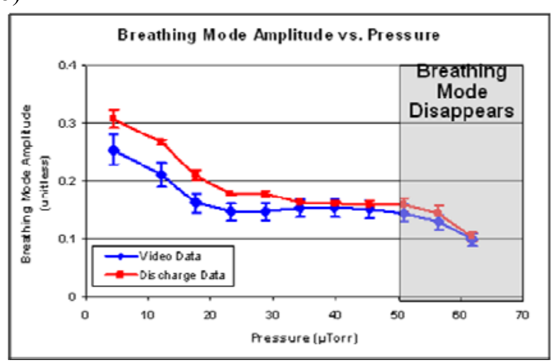


Figure 5. Variations of the frequency (a) and COV (b) of the breathing oscillations with the background pressure.

As for the rotating spoke, its frequency increases dramatically with the background pressure (Fig. 6). However, the spoke speed (~10^3 m/s) is still well below the electron ExB velocity (~ 10^4- 10^5cm/s in the near anode region). The spoke disappears with the increase of the pressure above 50 µTorr. Note that the increase of the pressure from 3 µTorr to 50 µTorr may lead to the increase of the electron transport

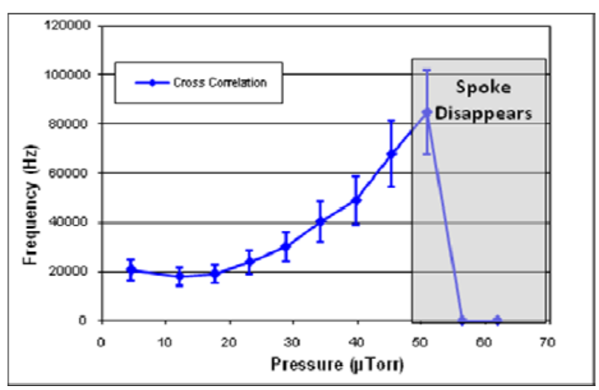


Figure 6. Variations of the frequency of the rotating spoke oscillations with the background pressure.[13]

collision frequency (due to electron-atom collisions) from 10^5 s^{-1} – 10^6 s^{-1}. This is still much lower than the anomalous collision frequency (10^8 s^{-1}), which is usually required to explain the measured plasma properties and electron current in the CHT discharge.[2] It appears therefore, that the observed effects of the background pressure on steady state discharge and plasma plume, characteristics, and as well as on breathing and spoke oscillations cannot be simply explained by a linear increase of the electron transport frequency with the background pressure. Future studies are required to precisely indentify possible physical mechanisms which could be responsible for these effects.

Finally, we note also that when the spoke occurs in the thruster discharge, a significant fraction of the electron current may be directed through this spoke. The disappearance of the spoke may constitute a large change in effective current-carrying area in the thruster. Such changes should be taken into account while comparing the electron cross-field transport levels (for calculations of the effective Hall parameter[2,3,5,9]) in the thruster discharge.[4] According to our high speed imaging and probe measurements,[4,13] the increase of the effective current-carrying area in the CHT may occur with the increase of the background gas pressure, the enhancement of the cathode electron emission[3]and the change of the magnetic field configuration from the cusp-type to the direct-type[14]. Nevertheless, because the effective Hall parameter is inversely proportional to the current-carrying area, our previous conclusions on the reduction of the electron cross-field mobility in the CHT thruster under the corresponding variations of the background gas pressure, cathode keeper current and the magnetic field are qualitatively correct.

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