Driving Low Frequency Oscillations in Hall Thruster

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Hall thrusters exhibit usually two types of large amplitude low frequency (10-30 kHz) oscillatory modes, so called breathing mode and spoke mode. In our previous works, it was demonstrated that both these modes can be controlled via the external modulations of the discharge voltage applied to the anode or anode segments. Two regimes of the thruster response, linear and nonlinear, have been revealed depending on the modulation amplitude. There was also observed a resonance-kind behavior - the amplitudes of the excited oscillations of the discharge current and the ion current reach their respective maximum as the modulation frequency approaches the frequency of natural oscillations (breathing or spoke). A one-dimensional model explained this result, in part, due to a decrease of the phase between low-frequency oscillations of the plasma density and the electric field. In this paper, we briefly review recent results on a modulated cylindrical Hall thruster. One important practical implication of these results is that the thruster operation with externally driven breathing oscillations may open a new way to implement enhanced thrust-to-power ratio Hall thrusters.

I. Introduction

Hall thruster technology has become the most mature in the field of spacecraft propulsion, however, its performance capabilities may still be far from its technological and fundamental limits. Further performance improvements may require new designs and operating regimes. One such potential reserve for improvements may be in controlling inherent low-frequency (10-30 kHz) oscillatory modes, so-called breathing mode and spoke mode, which are often observed in Hall thrusters [1]. The breathing mode is the most powerful mode, which manifests itself in oscillations of the discharge current, and can reach in the amplitude of ~ 100% of said current. These oscillations are usually associated with instabilities related to ionization and neutral depletion processes in the thruster channel [2]. The azimuthal mode (m=1,2,..) manifests itself in azimuthal oscillations of the plasma density and the electric field. With the segmented anode, this mode can be detected as current oscillations in the circuit of each anode segment [3]. In recent studies, we demonstrated that breathing and spoke oscillations can be amplified or suppressed depending on the amplitude and frequency of the anode voltage modulation [6-10]. This external modulation can be driven by an external circuit of the anode [6-8, 10]or the anode segments [9]. Experiments have been conducted with 200 W-class

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cylindrical Hall thrusters (CHTs) with electromagnets and permanent magnets [4,5]. For an electromagnet CHT, results of plasma measurements and ion current measurements were reported in Refs. [8,9]. In the resonant regime, when the anode voltage modulations were at the frequency of breathing oscillations, the ion current was shown to increase by 20-40% as compared to a traditional, non-modulated operation [8]. Results of our 1-D simulations suggest that such a resonant behavior is due to decrease of phase shift between the ion velocity and the ion density oscillations, and increase in the amplitudes for both quantities, as well as the contribution of the nonlinear terms. These predictions are consistent with plasma measurements [8]. Moreover, it was also shown that the spoke oscillations can be suppressed by driving breathing oscillations [10]. In this paper, we briefly review these results. We also report initial results on the effect of the external anode voltage modulation in the permanent magnet CHT.

II. Experimental Setup

The experiments were performed at the Princeton Plasma Physics Laboratory, at the small facility of the Hall Thruster Experiment. Two types of the 2.6 cm diameter cylindrical Hall thrusters (CHT) were used, namely, the CHT with electromagnet coils [3,4] and the CHT with permanent magnets [5]. Propellant was xenon-gas with flow rate through anode at 3.5 sccm and cathode at 2.0 sccm. The thruster was into 1.0 m length and 0.8 m diameter vacuum chamber, with vacuum supplied by turbopump, and steady state background pressure at about 6.0 × 10−5 Torr. Thruster was operated at 220 V anode potential; typical values of discharge current were approximately 0.8 A. Current on main magnetic coil current was 2.5 A and on the front magnetic coil current was 0.5 A in “direct” configuration, description of the magnetic field configurations is given in Ref. 4.

Without external driving, the above combination of parameters caused a natural breathing oscillation at frequency around 13 kHz. However, these oscillations are not very coherent in time: frequency and phases change from cycle to cycle. To control the behavior (frequency, phase, and amplitude) of natural oscillations anode potential was modulated. A schematic view of the electrical setup is represented in Fig. 1. Amplifier is installed between the anode power supply and the anode. Sine wave from function generator is feed into it; therefore, anode potential became a shifted sine wave, with base line at 220 V. This procedure is very similar to one that was used in Ref. 6.

The discharge current was constantly monitored during the experiments. Ion density probe was installed at 12 mm from the exit plane, and this data was collected as well. Moreover, spoke and breathing oscillations were monitored using a high-speed camera (Phantom V7.3), which recorded changes in plasma emission intensity within the thruster channel while externally modulating breathing and azimuthal modes.

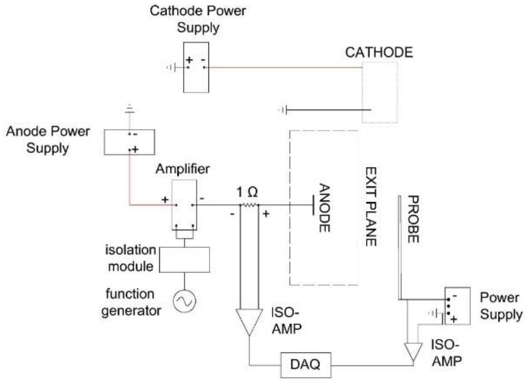

Fig. 1. Electrical schematics of the anode driving system.

III. Recent Results on External Anode Voltage Modulation

A. Suppression of the Spoke Oscillations by Anode Voltage Modulations

In these experiments, we used the 2.6 cm electromagnet CHT operated in the regime mentioned in the experimental part. The main goal of these experiments was an investigation of an interaction between the modulated breathing oscillations and azimuthally rotating spoke. Idea of this study came from an assumption that the azimuthal large-scale instabilities can be coupled with the gradients in axial direction (e.g. via the Simon-Hoh instability mechanism) [11]. Additional coupling mechanism may also come from an interaction of ionization fronts [7,12].

The breathing mode is responsible for changes in plasma parameters profiles, therefore by controlling it, one can change corresponding gradients. Method to control breathing mode via anode potential modulations with different frequencies and amplitudes was shown in previous works [6-8].

Diagnostic was done by means of a high-speed camera, which recorded changes in plasma emission intensity within the thruster channel while externally modulating breathing mode. The recorded signal then was processed with a developed image analysis technique [10,13,14], which allows for identification of coherent axial and azimuthal plasma structures inside the thruster channel and their characteristic frequencies.

For normal operation (no modulations) we identify coherent breathing mode in axial direction at f~13.9 kHz, which frequency remains relatively stationary in time. Analysis of the azimuthally propagating structure (spoke mode) revealed that its frequency varied in 5.8-8.5 kHz range, that shows that the spoke mode is non-stationary, with frequency changing over time. Results are shown in Fig. 2. By varying the amplitude and frequency of the modulation, the suppression of the spoke mode was achieved. External modulations were applied with amplitudes 5 to 30 V peak-to-peak. Modulation frequency was varied from 10 to 15 kHz. Suppression was achieved by the external modulation of the anode potential at frequencies around natural breathing mode, results are shown in Fig. 3. This might be an evidence of the coupling between two modes.

A mode detail description and analysis of these results can be found in Ref. 10.

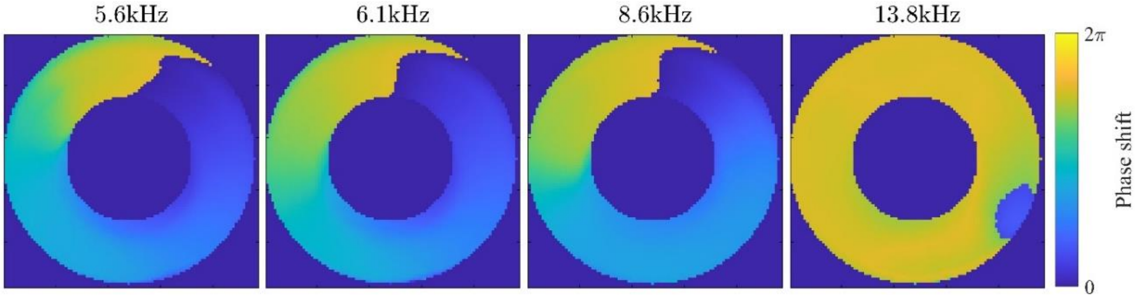

Fig 2. Relative phase shifts for intensity signals from each pixel without modulations. For rotating mode (5.6-8.6 kHz) phases of intensity signals gradually changes from 0 to 2π, for global mode, phases of intensity signals changes uniformly within the channel.

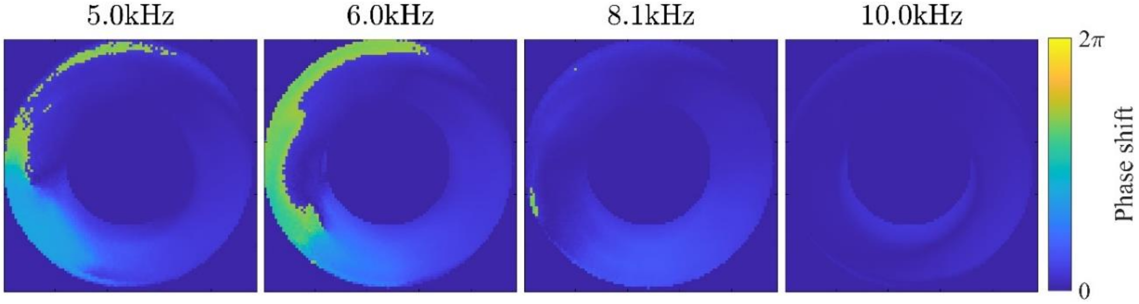

Fig. 3. Relative phase shifts for intensity signals from each pixel with 30 V peak-to-peak, 10 kHz modulations.

B. Permanent Magnet CHT with External Voltage Modulations

All our previous measurements with modulation of the anode voltage were done using the CHT with electromagnetic coils. Here, we report first results obtained by the modulation of the anode voltage in the 2.6 cm CHT with permanent magnets [5]. The thruster was operated at 220V anode voltage with 4 Xenon sccm mass flow and a cathode filament operating in the “current overrun” regime discussed in Ref [15]. A small breathing mode existed in this regime, which can be observed in Figs 4 and 5 where the discharge current and ion current oscillate with some amplitude.

By driving a sinusoidal oscillation on top of the discharge voltage at a frequency close to the natural breathing oscillation frequency (9kHz and 10kHz respectively), it is possible to amplify these discharge oscillations and lock them to the driving frequency. Figure 6 shows a typical modulated anode voltage with 40V amplitude, while Figs. 4 and 5 show the resulting modulated response in discharge and ion current, where there is a clear increase in the current amplitude.

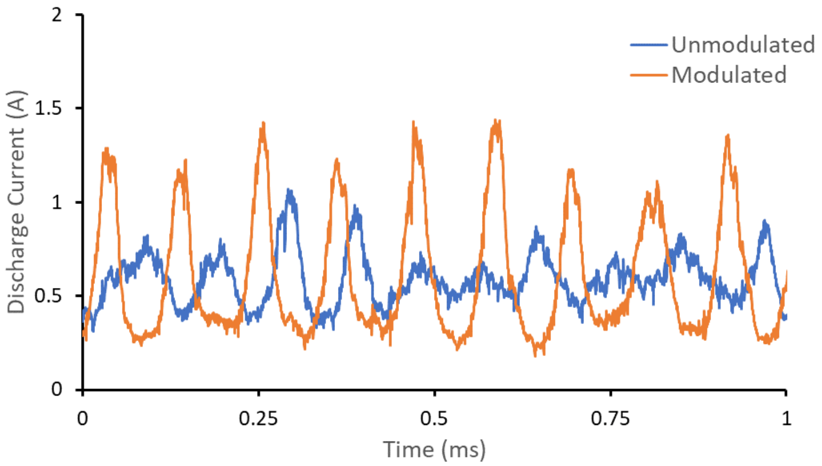

Fig. 4. Discharge Current for a CHTpm with driven Breathing Oscillations

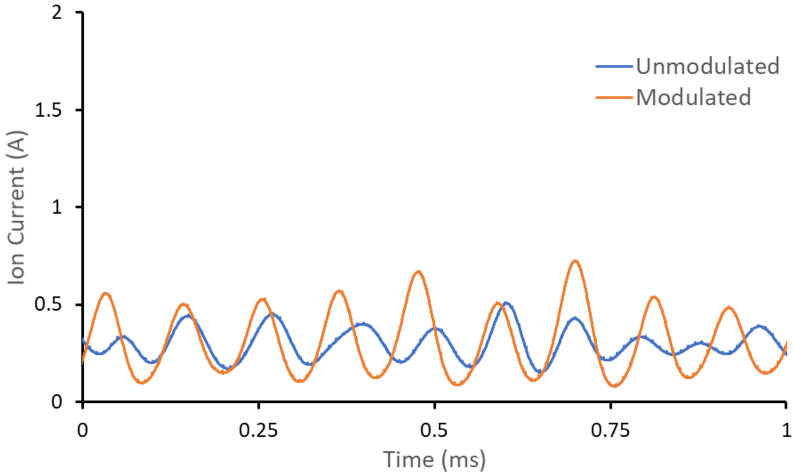

Fig. 5. Ion Current for a CHTpm with driven Breathing Oscillations

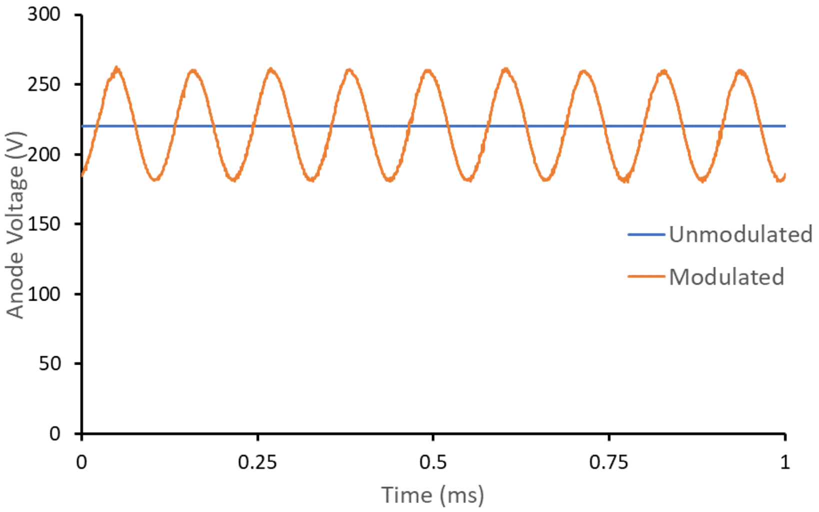

Fig. 6. Anode Voltage for a CHTpm with driven Breathing Oscillations

C. Modeling of Externally Modulated Oscillations

To study these interesting effects of the voltage modulation on the thruster discharge we developed a 1-D transient fluid model [8]. The model allows to study the intrinsic axial modes of oscillations and various effects, including competition of the neutral and ion species depletion, the role of the self-consistent resistive axial current instabilities with effect of the electron diffusion etc. Simiulations succeeded to capture a resonance-kind response of the plasma to the modulation of the discharge voltage near the frequency of natural breathing oscillations. For example, it was shown that when the phase shift between oscillations of the plasma density and the ion velocity decreases to some minimum when the voltage is modilated with the frequency near natural breathing oscillations (Fig. 7). More recently, we found that this prediction of the fluid model is consistent with experimental onbservations which will be reported in a separate paper.

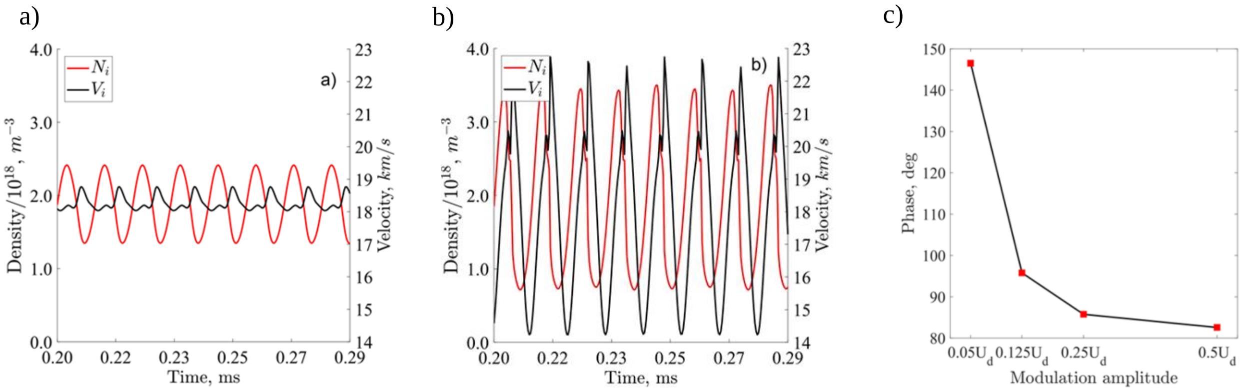

Fig. 7 Modeling of the effect of the external modulation of the anode voltage in the Hall thruster on breathing oscillations, including oscillations the plasma density and the ion velocity: a) linear regime (voltage modulation: +/- 5% of the anode voltage; b) non-linear regime (voltage modulation: +/- 0.25% of the applied voltage); c) effect of the voltage modulation on the phase shift between oscillations of the plasma density and the ion velocity.

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IV. Conclusion

In this paper, we reviewed most recent results on the effect of the external modulations of the anode voltage in the cylindrical Hall thruster on the breathing and spoke oscillations. In particular, the modulation of the anode voltage can help to suppres the spoke oscillations. In addition to the cylindircal Hall thruster with electromagnetc couls, the effect of the breathing oscillations on the discharge current and the ion current has been also demonstrated for the CHT with permanent magnets. Finally, results of our 1-D simulations suggest that the modulation of the anode voltage alter the phase shift between oscillations of the discharge current and the discharge voltage, and the phase shift between the ion velocity and the ion density oscillations. The external modulation of the discharge voltage also changes the amplitudes for these quantities, as well as affect the contribution of the nonlinear terms in the input power and thrust power.

Future theoretical and experimental studies of this new regime of Hall thruster with the external voltage modulations are needed to include a more realaistic thruster model with, for example, 2-D effects, anamlous cross-field trasnport, complex dynamics near the anode, etc.. A more detail experiments including plasma and the thruster performance are currently being conducted and will be reported in a sperate paper.

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