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Feedback Control of an Azimuthal Oscillation in the $E \times B$ Discharge of Hall Thrusters

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Feedback control of a low-frequency azimuthal wave known as a "rotating spoke" in the ExB discharge of a cylindrical Hall thruster was demonstrated. The rotating spoke is an m=1 azimuthal variation in density, electron temperature, and potential that rotates at about 10% of the local $E \times B$ electron rotation speed. It causes increased electron transport across the magnetic field and is suspected to be an ionization wave. Feedback control of this wave required special consideration because, although it causes a rotating azimuthal variation in the current density to the anode, it does not show up as a signal in the total thruster discharge current. Therefore, an extra source of information was needed to track the oscillation, which was addressed by using a special anode that was split azimuthally into four segments. The current to each segment oscillates as the rotating spoke passes over it, and feedback is accomplished by resistors connected in series with each anode segment which cause the voltage on a segment to decrease in proportion to the current through that segment. The feedback resulted in the disappearance of a coherent azimuthal wave and a decrease in the time-averaged total discharge current by up to 13.2%.

INTRODUCTION

The Hall thruster is an $E \times B$ plasma discharge device with a radial magnetic field and an axial electric field[1]. The magnetic field is strong enough to magnetize electrons but not ions so the ions are accelerated axially but the electrons are confined by the magnetic field and rotate in an azimuthal $E \times B$ drift. The presence of the electrons ensures that the plasma stays quasi-neutral throughout the acceleration region and the electrons self-organize to set the electric field in response to a DC bias on the anode and cathode. Recent work suggests that the electron rotation may play an important role in controlling the electric field[2].

In this paper we study an azimuthal wave in the Hall thruster known as the "rotating spoke". It can be observed using Langmuir probes in the thruster channel which measure fluctuations in plasma density and temperature corresponding to an m=1 mode near the anode that rotates at about 10% of the local ExB speed[3,4]. Measurements can also be made with a fast camera, which registers a region of increased visible light emission that rotates at the spoke frequency[4,5]. The fast camera integrates the plasma light emission axially so it is not possible to determine whether the light emission emanates from the same axial location as the plasma fluctuations measured by the probes, but the bright spot in the camera measurements and the density maximum measured by the probes are highly correlated and in-phase[6]. The light emission and density maximum of the rotating spoke are also correlated and in-phase with an azimuthal variation in the current density to the anode, which suggests that the spoke may cause increased electron transport[6]. The spoke has been observed in a variety of Hall thruster configurations including annular[5,7–9] and cylindrical[4,6] Hall thrusters. In this study, we use a cylindrical Hall thruster[10] with a segmented anode[6], but the results should be relevant for other thruster configurations as well including conventional Hall thrusters of annular geometry.

The spoke is one of a variety of oscillations that the Hall thruster supports across a broad frequency range[11]. It is of particular interest because of its connection to electron transport across the magnetic field[3,6]. Anomalous electron cross-field transport is an important problem in Hall thruster physics and it is one of the major impediments to predictive modeling of the thruster[12]. Several phenomena may contribute to anomalous transport including electron-wall interaction[13,14], the rotating spoke, and other oscillations[15,16], but a complete understanding of which processes are important under which conditions is still a subject of research.

Despite thorough observation of the spoke, the mechanism of the oscillation is not fully understood. Several authors[3,7,8,17] have suggested that the spoke is an ionization wave because it is localized near the anode where the gas is ionized and the rotation speed depends on the species of working gas. A recent fluid model[17] that predicts an azimuthal oscillation that is driven by ionization and conducts current to the anode further supports these claims. A numerical model[18] of the thruster recently showed azimuthal variation that might be connected to the spoke, but it is not clear what the mechanism is in this model.

Methods to suppress the spoke are of practical interest because it causes increased electron transport and degrades thruster efficiency. The spoke can be suppressed by choosing an appropriate regime of steady-state operation parameters, for example, by increasing the cathode electron emission current[4], but the ability to suppress the spoke extends the flexibility of the thruster and may be able to improve thruster performance. We did not design the feedback controller based on a physical model; however, previous work on feedback control of a different oscillation in the Hall thruster[19] showed that modifying the anode voltage is an effective way to influence plasma parameters near the location where the spoke exists, on a similar time scale to the spoke. This provided motivation to empirically explore feedback control of the spoke. We implemented simple feedback control by connecting resistors in between each anode segment and the thruster power supply. This caused the voltage on an anode segment to decrease in proportion to the current passing through the segment, which is highly correlated with the density oscillation of the spoke. This method proved to be very effective at destroying coherent spoke oscillations, and reduced the average total discharge current of the thruster.

EXPERIMENTAL SETUP

The cylindrical Hall thruster (CHT)[10] is a plasma device with crossed electric and magnetic fields that creates and accelerates a plume of quasi-neutral plasma. Figure 1 shows a schematic of the nominally 300 W, 2.6 cm diameter CHT employed in this experiment[20]. Neutral gas enters the thruster via a gas distributor at the anode and is ionized through collisions with electrons that are supplied by a hollow cathode mounted outside the thruster. The magnetic field, which reaches a maximum of 875 Gauss 6 mm in front of the anode and

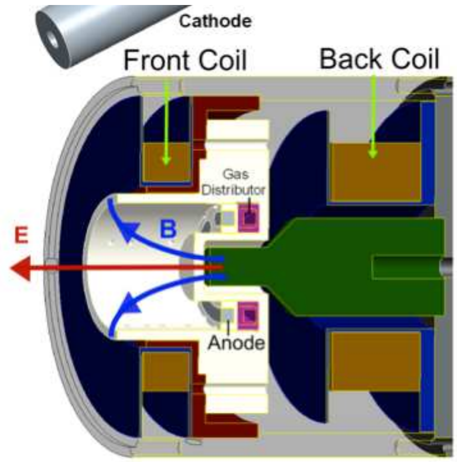

Figure 1. Schematic of a cylindrical Hall thruster.

decreases toward the channel exit, is strong enough to magnetize electrons but not ions. Electrons are confined axially in the thruster channel through a combination of magnetic mirror forces on the anode side and electrostatic forces on the cathode side, and ions are accelerated by a mostly axial electric field.

The spoke was first observed in this thruster with a fast camera and Langmuir probe measurements[4]. The spoke appears on the camera as a spot of increased light emission that rotates at a frequency of 15-35 kHz in the direction of the $E \times B$ drift speed. The translation speed of the spoke ranges from 1.2-2.8 km/s which is significantly lower than the local $E \times B$ speed of 30 km/s[6]. A segmented anode was built to measure anomalous current caused by the spoke[6]. Measurements showed that oscillations in current to each anode segment were strongly correlated and in-phase with the spoke that appeared on the fast camera measurements. The segmented anode is composed of 4 anode segments that are electrically isolated from each other and held in place by a boron nitride structure. The segmented anode is described in detail in an earlier paper[6].

We implemented a feedback mechanism by connecting large resistors between each anode segment and the thruster power supply as shown in Figure 2, so that the voltage on each anode segment would decrease in proportion to the current through that segment. We used three different resistance values in separate experiments: $R_f = 100\,\Omega$, $200\,\Omega$, $300\,\Omega$, but in each case the resistors attached to each segment all had the same value. For typical average operating parameters of 0.25 A current through one segment and 200 Ω resistors, the voltage drop across the resistor is 50 V compared to an anode segment voltage (after the resistor) of

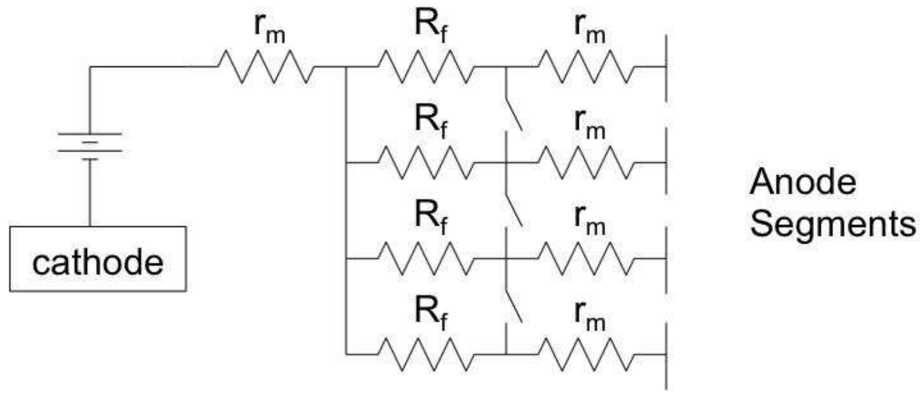

Figure 2. The feedback was implemented by attaching resistors between each anode segment and the thruster power supply. The feedback resistors, R_f, were either 100Ω, 200Ω, or 300Ω and the measurement resistors, r_m, were 1 Ω.

250 V. The anode segment voltage is with respect to the cathode which floats at about +7 V with respect to ground. If the current through an individual segment is doubled to 0.5 A, which is typical when the spoke is present, then the anode segment voltage decreases by 20% to only 200 V, which will reduce the voltage drop between that anode segment and the thruster cathode. When the switches shown in figure 2 are closed, the feedback damping is turned off. In this case, each anode segment is held at the same voltage except for the small differences caused by the measurement resistor, $r_m = 1\ \Omega$, which is used to measure the current. In this case the segmented anode effectively operates as if it were not segmented and there is no voltage variation when the current to the individual segments varies in time. The voltage on the anode will still vary in response to oscillations in the total current, but this did not suppress the spoke oscillation.

RESULTS

Figure 3 shows the current through the anode segments when the damping is off compared to when it is on for the case when $R_f = 200\ \Omega$ resistors were used in the damping circuit. The cathode keeper current, which controls the electron supply to the thruster[21], was set to 1.6 A in order to isolate the spoke by suppressing another thruster oscillation known as the breathing mode. A dramatic reduction in the segment current oscillations is evident and the average total current decreases by 10.1% from 0.89 A to 0.80 A. The magnitude of

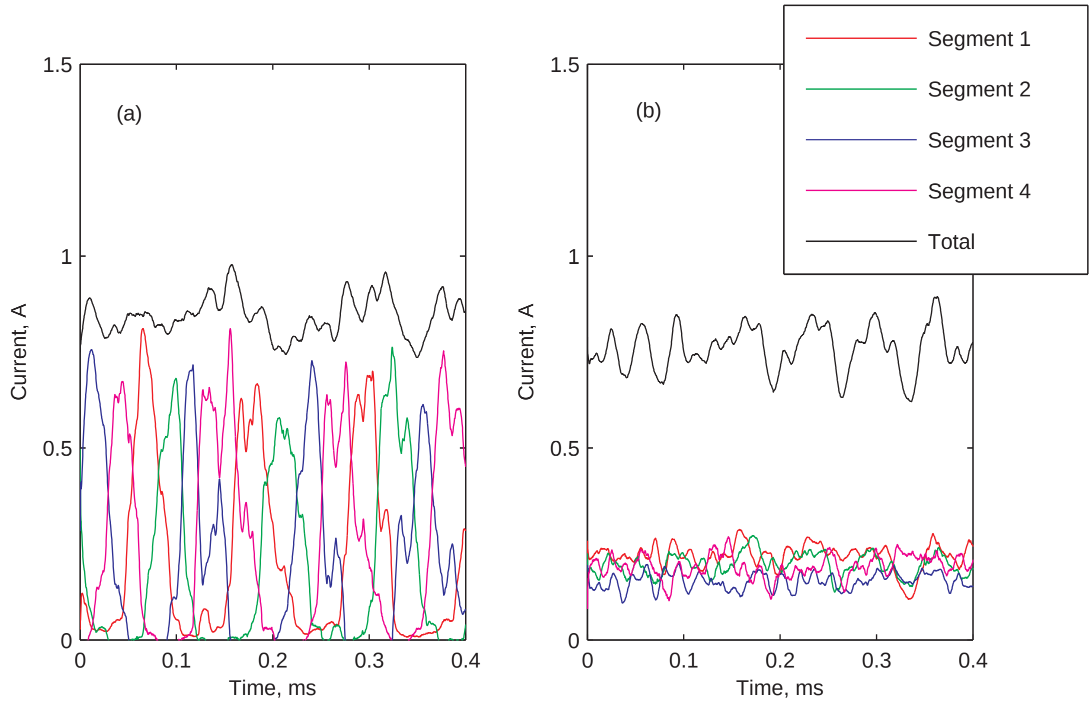

Figure 3. Total discharge current and current through each anode segment for the case when the damping is off (a) and the case when it is on (b). The damping strongly suppresses the oscillations which can be seen in the segment currents when the damping is off.

the decrease in total current from the undamped case to the damped case depended on the thruster parameters including the size of the feedback resistor, the magnetic field strength and the cathode keeper current. With 300 Ω resistors and 1.6 A keeper current, we measured a decrease in the total current of 13.2%. This result confirms the previous finding[6] that the spoke enhances electron transport to the anode. The damping depended on the value of R_f. When 100 Ω resistors were in place, the standard deviation in the current to an anode segment decreased by 78% when the feedback was switched from off to on. This compares to a reduction of 94% when 300 Ω resistors were used. When only the 1 Ω measurement resistors were in place, the spoke was not noticeably damped. We note that the spoke suppression is not caused by a change in the average anode voltage, as this value was held constant.

Figure 4 shows the Fourier transform of the current to segment 1 of the thruster when the damping is off compared to when it is on. It is clear that the coherent oscillation that is seen in the current when the damping is off completely disappears once the damping is turned

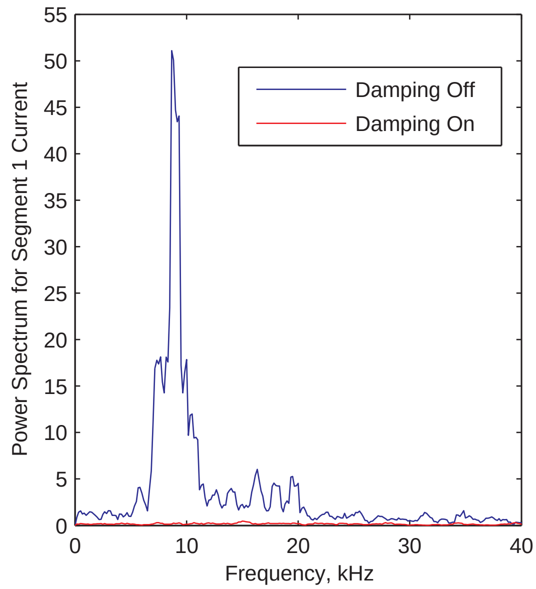

Figure 4. Fourier transform of the current to Segment 1 of the thruster when the damping is off compared to when it is on.

on. The fast camera data shows that azimuthal bright spots still appear intermittently, but these flicker in and out without persisting in a coherent oscillation and the discharge is much more uniform.

This damping only works when the anode is segmented, and cannot be achieved when the anode segments are electrically connected. A segmented anode is needed is because the spoke current oscillations do not show up in the total current of the thruster. Figure 5 compares the power spectrum of the current through segment 1 to that of the total current oscillations.

ANALYSIS

A quantitative analysis of the feedback control is beyond the scope of this paper; however, we offer a qualitative sketch of how the suppression may work. The varying voltage on the anode segments might manipulate the ionization rate in the spoke region in a way that diminishes azimuthal density perturbations faster than the spoke mechanism promotes their growth. The voltage on the anode controls the strength of the axial electric field in the thruster channel. The axial field is a strong source of electron heating, so it influences the

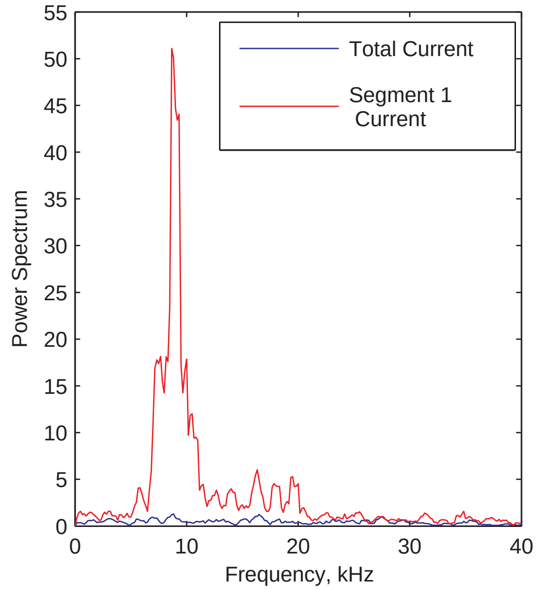

Figure 5. Fourier transform of the total current compared to the transform of the current through an individual segment. The large coherent oscillation at around 10 kHz in the segment current is absent in the total current.

ionization rate through its effect on the electron temperature. In sum, an increase in the anode voltage will result in an increased ionization rate. Furthermore, because our anode is divided into four independent sections that can each have a different voltage, the ionization rate can be manipulated as a function of angle.

Measurements show that oscillations in current to the anode segments are in-phase with density oscillations[6]. Therefore, in our feedback scheme the voltage on an anode segment will decrease as the density peak passes over it because of the increased current to that segment. This will result in a weaker axial electric field downstream of the segment, which reduces the ionization rate in the region of peak density. At the same time, the other anode segments will have a higher voltage that increases the ionization rate in the low-density regions. As the spoke rotates, the anode segment voltages will adjust so that they always lower the ionization rate in regions of high density and increase it in regions of low density. While this could be the mechanism that suppresses the spoke, a quantitative model is needed to prove that this is so.

A previous paper showed that the spoke can be suppressed without feedback by increasing electron emission from the thruster cathode[4]. Increased cathode emission has been shown to increase the electric field inside the thruster[21], so it may be that the increased electric field raises the steady-state ionization rate in the thruster to a level at which the rotating spoke does not develop. If this is the case, then the feedback control might increase the electric field in the portion of the channel where the spoke is not located to suppress growth of the rotating spoke, but the average ionization rate is not raised to the level required to prevent spoke formation in steady-state.

CONCLUSION

We demonstrated that feedback control can effectively suppress the spoke oscillation. The suppression of the spoke leads to a reduction in the total discharge current due to the anomalous current that is carried by the spoke. For typical operating parameters, the discharge current can be reduced from 0.89 A to 0.8 A. This translates into a 11.2% increase in thruster efficiency (not accounting for losses in the circuitry). This is not enough to make up for the power loss in the resistors which is about 15% of the discharge power. However, an efficiency increase may be achieved by implementing the feedback control with more advanced circuitry to avoid the resistive power loss. The spoke can be avoided without resort to feedback control by choosing an appropriate operating regime. However, feedback suppression of the spoke creates added flexibility by increasing the parameter space in which the thruster can stably operate. Furthermore, this method of feedback control with a segmented anode may be applicable to other $E \times B$ discharges that exhibit azimuthal ionization instabilities.

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