Direct measurement of spoke-induced, cross-field electron transport in a cylindrical Hall thruster

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Cross-field electron transport has been a longstanding, important issue in Hall thruster research. The degradation of efficiency due to the anomalous electron mobility makes understanding the transport mechanisms crucial. Along with electron-wall interactions, fluctuations have been suggested as contributing to the cross-field transport. In addition to small-scale, turbulent fluctuations, a multi-centimeter rotating spoke has been observed in numerous $\mathbf{E} \times \mathbf{B}$ devices and has been suggested to contribute to cross-field electron transport. To directly quantify the cross-field transport induced by the rotating spoke oscillation, a segmented anode has been constructed and installed on a cylindrical Hall thruster. The anode has four segments, allowing measurement of current as a function of azimuthal position. Synchronized measurements with a Phantom v7.3 fast camera reveal upwards of 50% of the current being conducted through the rotating spoke. Supplementing the segmented anode are electrostatic probe measurements to determine the phase of plasma potential and density fluctuations relative to the enhanced current. The fluctuations are properly phased for a net current enhancement via an axial $\mathbf{E} \times \mathbf{B}$ electron drift towards the anode.

Nomenclature

A = electrostatic probe area
c_s = ion sound speed
I_d = discharge current
I_{drift} = electron drift current
I_k = cathode keeper current
I_{sat} = ion saturation current
n_e = electron density
q_e = elementary charge
v_d = drift velocity
v_{spoke} = rotating spoke velocity

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I. Introduction

A low-frequency, rotating spoke of light has been observed in a variety of devices including annular Hall thrusters,[1–4] cylindrical Hall thrusters,[5] and more general $\mathbf{E} \times \mathbf{B}$ devices.[6] Understanding the basic fluctuation mechanism is important for basic plasma science, including possible relations to the critical ionization velocity,[1,6] as well as applied physics consequences, such as Hall thruster efficiency. In particular, the possibility of enhanced electron current to the anode via the mechanism responsible for the rotating spoke implies the oscillation may degrade thruster efficiency. Indeed, early studies used electrostatic probes to measure fluctuating density and potential, and inferred the spoke to be contributing to the cross-field transport[1] on the correct order to explain the anomalously high transport. More recently, fast camera measurements identified the rotating spoke on a cylindrical Hall thruster, and transitions in oscillation regimes suggested the rotating spoke enhanced electron mobility.[5]

In this paper, we directly measure the current conducted across the magnetic field through the mechanism of the rotating spoke by installing a segmented anode on a 2.6 cm cylindrical Hall thruster. The cylindrical Hall thruster (CHT) is a compact design intended for efficient thruster scaling to low power and small diameter.[7] Typically, the discharge current is monitored using a continuous anode (apparatus details may be found in Ref.[8]), but only longitudinal oscillations are apparent in this data. To improve the diagnostic, the anode was segmented into four azimuthal components allowing synchronized measurements with a high-speed camera to directly measure the current at the spoke location.

In the CHT, the spoke has been observed to rotate at 15-35 kHz, corresponding to a speed of 1.2 - 2.8 km/s,[5] which is substantially less than the local ExB speed but in the same direction as the ExB drift. A characteristic series of images acquired using a Phantom v7.3 fast camera is shown in Fig. 1. While the frequency of the spoke oscillations is similar to the breathing mode ionization oscillations, enhanced keeper current has been found to suppress the breathing mode oscillations while retaining the rotating spoke, so the phenomena are independent. In-channel Langmuir probes determined the strongest correlation between the density fluctuations and visible light emissions was near the anode.[5]

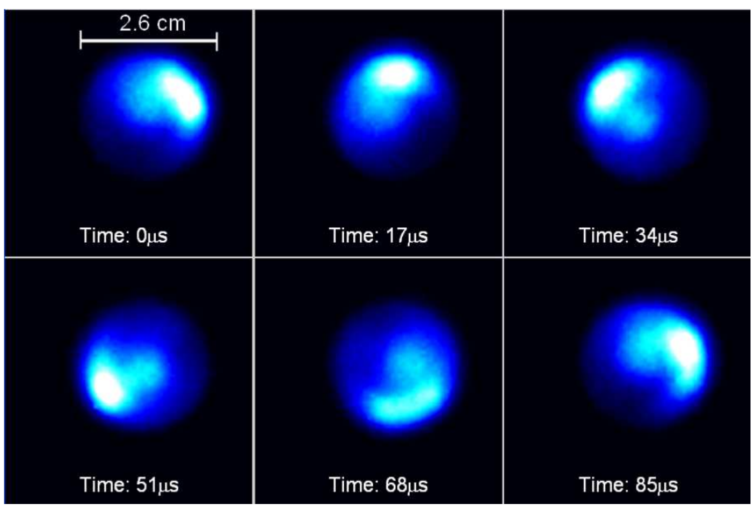

Figure 1. A series of frames displaying the visible light emission from the rotating spoke instability in the 2.6 cm cylindrical Hall thruster. The 15-35 kHz spoke can be seen to rotate in the counter-clockwise direction, which corresponds to the $\mathbf{E} \times \mathbf{B}$ direction. Color is artificial.

In this paper, we demonstrate the mechanism of the rotating spoke does alter the cross-field electron transport. Preliminary findings using a segmented anode were presented in Ref.,[9] and a more detailed description of these results may be found in Ref.[10] Using the segmented anode, we find over half of the total discharge current traverses the rotating spoke, which is large considering the spoke occupies ∼25% of the channel area. To supplement the identification of enhanced cross-field current, the transport mechanism is investigated using emissive and Langmuir probes to determine the phase of the fluctuating potential and density relative to the phase of the spoke. The spoke is determined to possess an azimuthal electric field, and a quantitative estimate is provided of the axial electron drift contribution to the enhanced current.

II. Methods

The experiments were performed at the Large Hall Thruster facility at the Princeton Plasma Physics Laboratory, as described elsewhere.[8] The vacuum vessel is equipped with cryogenic pumps and the background pressure does not exceed 3 μtorr during operation. The basic schematic for the 2.6 cm diameter CHT is shown in Fig. 2.[8] Typical operating parameters include a 4 cm^3/s at standard temperature and pressure (sccm) xenon mass flow to the anode, 2 sccm xenon flow to the cathode, 250 V discharge voltage, 2.5 A for the back coils and -2.0 A for the front coils. The opposite polarity of the fields forms a magnetic cusp near the channel exit and enhances the radial field, as shown in Fig. 3. The field strength near the anode is 850 G. The hollow cathode was operated with a keeper current, I_k, of 1.5 - 1.8 A. Keeper current is a significant parameter, given the wide variety of oscillatory behavior observed for different settings.[5,11] By enhancing the electron emission from the cathode, the ionization-based breathing mode may be suppressed. Given the close frequency of the breathing mode and rotating spoke, suppression of the breathing mode simplifies analysis by ensuring the dominant oscillation in the low frequency range is the rotating spoke. At higher keeper current (3.0 A), the spoke oscillation is also suppressed and high frequency (MHz) oscillations appear. A 1.5 A keeper current has been found to be a satisfactory mid-range value for clear spoke observation.

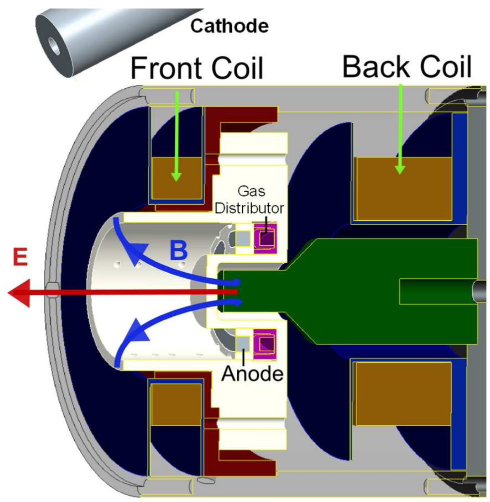

Figure 2. Cross-section view of a cylindrical Hall thruster. Electrons are magnetized and are confined by a combination of the mirror force and the electric field. Ions are not magnetized and are accelerated by the electric field. Segmented anode shown.

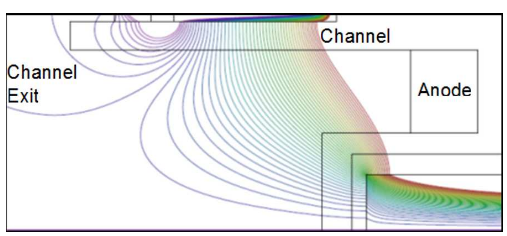

Figure 3. Simulation of the magnetic field in the cusp configuration, with +2.5 A in the back coils and -2.0 A in the front coils. The enhanced cusp shape forms a stronger mirror field. Image is shown about the axis of symmetry. The maximum magnetic field is 875 Gauss and occurs 6 mm from the anode.

A Vision Research Phantom v7.3 fast camera has been used extensively while studying the rotating spoke. The camera is capable of up to 500,000 frames per second (fps), though typical spoke observations were performed near 200 kfps to achieve a resolution of 64x64 pixels. Observations are made 7 m from the thruster and along the axis.

Whereas previous configurations[5,8] have used a combined anode and gas distributor, the apparatus for this experiment uses distinct anode and gas distribution components. For a more detailed description, refer to.[10] A boron nitride base electrically isolates the four anode segments from the gas distributor while allowing xenon to enter the channel via holes on the inner and outer diameter, as shown in Fig. 4. The holes around the outer and inner diameter allow the gas to reach the channel from the distributor. The anode segments are 21.6 mm from the channel exit and a 250 V bias is applied across the anode segments and the cathode. To verify the segmented anode did not perturb thruster operation, we confirmed similar behavior in discharge current and oscillation regimes, and ensured no current was being collected by the gas distributor.

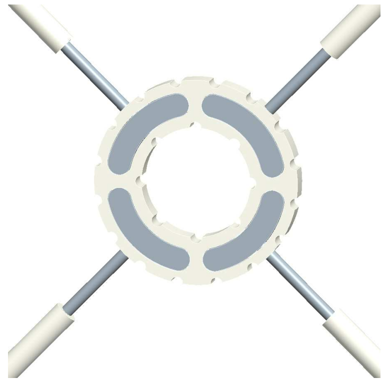

Figure 4. CAD model of the segmented anode assembly. Boron nitride houses the four stainless steel segments. Threaded rods extrude radially to affix the segments and connect the current path. The 8 internal and 16 external semi-circle holes allow gas distribution.

For the electrostatic probe measurements, two emissive and two Langmuir probes were placed 5 mm from the anode through radial holes in the channel wall, as shown in Fig. 5. The emissive probes extrude a thoriated tungsten filament 1mm x 0.5mm into the plasma while the Langmuir probes are positioned flush with the channel wall with an area of 1 mm^2. The emissive probe was heated until additional increase in the current did not increase the floating potential. Visible emission from the probe further confirmed it to be operating in the 'strongly emitting' regime. Recent measurements indicate the emissive probe floats nearly 2 electron temperatures below the plasma potential,[12] as may be expected in the presence of a space-charge saturated sheath.[13] The Langmuir probes were biased +48 V above ground to operate in the ion saturation current regime, which is a negative bias compared to the 175 V - 200 V space potential. Plasma density as a function of time was calculated using the ion saturation current to the planar probe, using the expression for the Bohm ion flux at the sheath edge as follows:

$$I_{sat} = 0.6 q_e n_e A c_s \tag{1}$$

Where q_e is the electron charge, n_e the electron density in the bulk plasma, A the probe area, and c_s is the ion sound speed. The electron temperature is taken to be 16 eV as identified in previous CHT studies.[14] Equation 1 assumes a small, planar sheath compared to the probe dimensions and takes the ions to be drifting to the biased probe with the Bohm velocity while repelling all electrons. All signals were digitized using LeCroy Waverunner 350 MHz and 500 MHz oscilloscopes. A function generator was used to trigger the fast camera and oscilloscopes.

Probe measurements inside the channel must be performed carefully to prevent perturbing the plasma environment.[15] Biasing the Langmuir probe at the wall alters the floating sheath geometry and collects particles which would otherwise be in the plasma. The extruding emissive probe extends into the bulk of the plasma, and (despite floating) can alter the electron distribution function through emissions. Emissive probes are also delicate and may be quickly be destroyed in the harsh plasma. Probe measurements were possible because of the near-anode axial location, as has been achieved in previous studies.[13,14] This region is before the acceleration zone, and thus the plasma is less likely to harm the probes and thruster operation will be less sensitive to small space potential perturbations. The discharge current remained near 0.85 amps, even with the emitting probes and while collecting ion saturation current. To test for azimuthal perturbations, we measured the floating potential of a probe directly adjacent to the emitting probe in the in the $\mathbf{E} \times \mathbf{B}$ direction. The floating potential showed no change with the probe emitting or cold, confirming no significant perturbation to the steady state potential.

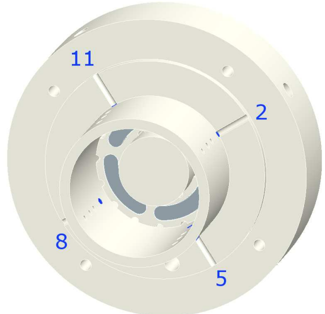

Figure 5. Probe holes in the ceramic channel are visible in this figure. Only those nearest the anode were used in this experiment, and may be seen by the circular grooves in the face of the channel and blue highlights. Numbers refer to approximate positions on a clock. Emissive probes were placed at positions 2 and 11 while Langmuir probes were placed at 5 and 8.

III. Results

The fast camera, segmented anode, and electrostatic probes allowed direct measurements of the cross-field current conducted through the rotating spoke for the first time. The spoke was found to enhance the current as camera and segmented anode measurements indicate over half of the total current traverses the spoke. Observations of the density and potential fluctuations supplement the current measurements by suggesting properties of the transport mechanism. The breathing mode was successfully suppressed using enhanced cathode keeper current, isolating the rotating spoke as the dominant oscillation. Electrostatic probe measurements near the anode provided more detailed measurements of the phenomena, providing characteristic density and potential fluctuations relative to the enhanced current. The phase of the density and potential relative to the spoke current indicate a perturbed electron drift towards the anode. As a simple qualitative model of the transport mechanism, a drift current was estimated using the perturbed $\mathbf{E} \times \mathbf{B}$ velocity and the density profile. At the peak of the characteristic waveform, the drift current accounts for roughly half of the current to the anode segment at the spoke location.

Using the segmented anode, the current through the spoke has been measured to be over 50% of the anode current, as shown in Fig. 6. Specifically, we find 56% of the total current to be conducted through the spoke with a standard deviation of 13%. Due to variation in the spoke behavior and the possibility of a low amplitude breathing mode, the waveform of the spoke current was determined by averaging over several hundred cycles and averaged across the four segments of the anode. The spoke was identified digitally by finding peaks in the smoothed current, requiring a minimum peak spacing of half the average spoke frequency, and checking that the anode segment with the peaking current was also collecting the most current of the four segments. The time axis has been normalized to the spoke period, which ranges from 30 μs to 80 μs. During an individual 10 ms data set, the spoke frequency and period is relatively constant (varies 25% of the mean), but operation over several hours can include spoke behavior over the entire frequency range, likely due to changes in thruster temperature and impurity levels. Thus, comparisons across datasets are most insightful if normalized to the spoke period.

The current to the individual segments was found to be highly correlated with the local intensity as observed by the fast camera. The time series of the average brightness over the quarter of the thruster centered on a given segment was compared to the time series of the segment current. The cross correlation was typically 0.9, indicating the strong similarity of the signals, so relying purely upon the segmented anode current proved effective at identifying the spoke location, and the fast camera was not used in electrostatic probe measurements.

The measurement of enhanced cross-field transport represents the first direct measurement of the fluctuation-induced current. Over half of the total current localized to one quarter of the channel area is a significant increase. While the measurements of enhanced current are interesting in themselves, probe measurements were used to investigate the transport mechanism. For the density profile, biased Langmuir probes were used. The probes were biased +48 V above ground to be sufficiently negative compared to the $\sim$ 175 V space potential. A similar averaging process is performed with the ion saturation current traces by identi-

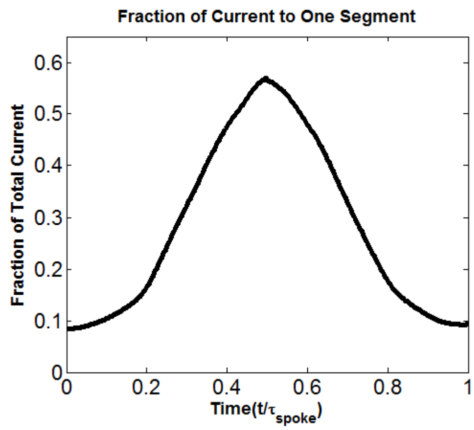

Figure 6. Characteristic waveform of the current through the rotating spoke to a single segment of the anode. The current rises and falls as the spoke becomes centered over the segment, then passes onto the next. The trace was determined by averaging over several hundred spoke cycles. The time axis is normalized to the spoke period, which ranges from 30 μs to 80 μs. The maximum is 0.57 with a standard deviation of 0.13.

fying the peaks of the spoke current, then taking a time window around the peak and averaging over many cycles. Substituting our measured ion saturation currents as a function of time into Eqn. 1, we are able to solve for the density profile, as shown in Fig. 7 (a). We calculate a density with a mean of 4×10^{11} cm^{-3} and a maximum of 1.4×10^{12} cm^{-3}.

To calculate electron flux due to the rotating spoke, the plasma potential profile of the spoke must be known in addition to the density profile. Emissive probe measurements confirmed an azimuthal electric field across the spoke, in phase with the density fluctuation such that electrons would $\mathbf{E} \times \mathbf{B}$ drift to the anode with a net contribution to the current. The emissive probes were heated until the floating potential would not increase. This was assumed to be 2 T_e below the plasma potential.[12] As the spoke rotates past the probe, the potential distribution of the rotating spoke is measured. The characteristic waveform of the potential is shown in Fig. 7 (a).

To extrapolate the azimuthal component of the electric field given the potential profile, we assume the spoke velocity and parameters to be constant (on average) as the spoke moves across the emissive probe. An azimuthal electric field may then be calculated by using the spoke velocity to get from a time derivative to a space derivative:

$$E = -\frac{dV}{dx} = -\frac{dV}{dt}\left(\frac{dx}{dt}\right)^{-1} = -\frac{1}{v_{spoke}}\frac{dV}{dt} \tag{2}$$

Where E is the component of the electric field along the direction of the spoke velocity (azimuthal), V is the space potential of the spoke, and v_{spoke} is the velocity of the spoke. The azimuthal electric field of the spoke as determined using this technique is shown in Fig. 7 (b).

Ultimately, the density and electric field fluctuations are combined to make a simple quantitative estimate of the perturbed current mechanism. The perturbed electric field will cause an axial $E \times B$ drift towards the anode. The drift velocity may then be calculated using the measured azimuthal field and the radial component of the magnetic field, taken to be constant at 760 G, as determined using field simulation software. Indeed, we find a significant drift velocity directed towards the anode when the spoke is present. The drift velocity peaks at 18 km/s, which is fast enough to traverse the 5 mm gap between the measurement location and the anode during the spoke presence. The current caused by this drift may then be estimated as $I_{drift} = e v_d n_e A$, with v_d the drift velocity and A the area of the anode segment. At the maximum spoke current (namely, the spoke is centered at the anode segment of interest), we estimate a drift current of 0.26 A, which is roughly half of the 0.48 A spoke current.

The characteristic electric field, density, and spoke current are shown in Fig. 7. The phasing and magnitude reveal the perturbed $E \times B$ drift significantly enhances the cross-field transport. The peaks of the density, electric field, and their product occur within a several microsecond window of the peak in the spoke current. In this finding, we emphasize the phase of the measurement more so than the magnitude. The possibility of fluctuating electron temperature, for instance, increases the uncertainty in the magnitude of the maximum plasma density, whereas the phase information is more clear. The density and electric field peak at similar times. Given the drift current estimate only accounts for half of the spoke current, it is clear that additional transport mechanisms are at work within the thruster, such as microturbulence, classical transport, and electron-wall interactions.

The phase of the density and electric field appear slightly delayed compared to the spoke current. This could be due to the spoke having a tilted profile through the thruster, as past studies have observed a tilt of 15°.[1] Using a spoke velocity of 1.2 km/s, a delay of 10 μs, and the 5 mm separation between the electrostatic probes and the anode, a tilt of 23° is determined using:

$$\tan\theta = \frac{z}{tv_{spoke}} \tag{3}$$

Where θ is the tilt and z the separation between the anode and the probe. While 23° is our best estimate, clear variation in the timing exists in Fig. 7, varying from the estimate by 50% in either direction. We infer a larger spoke tilt on average than Ref.[1]

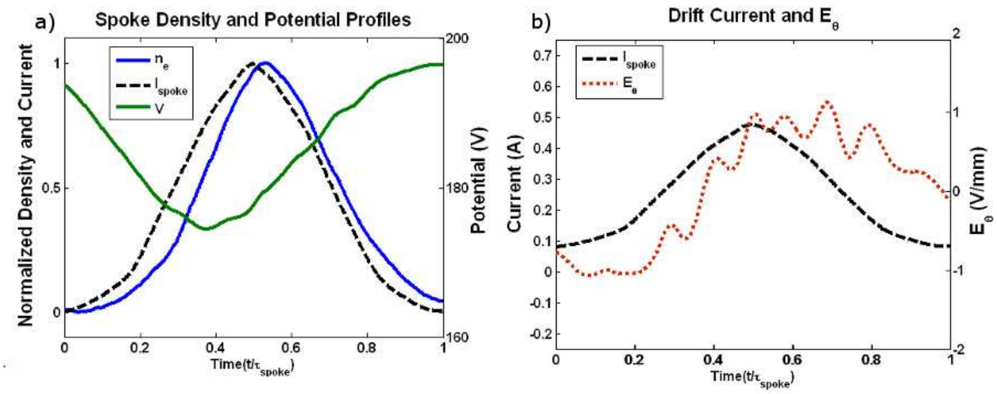

Figure 7. a) Normalized electron density and potential profile of the rotating spoke. The density has a maximum of 1.4×10^{12} cm^{-3}. b) Measured azimuthal electric field of the rotating spoke. Spoke current shown to provide reference for the relative phase.

IV. Conclusion

In summary, the cross-field electron transport induced by the rotating spoke was directly measured for the first time using a segmented anode. On average, over 50% of the total current is conducted by the spoke, which is large given the spoke area of one quarter the channel area. The transport mechanism was estimated using electrostatic probes and a drift-induced current model. Given the relative phasing of the density and the potential, approximately half of the spoke current may be explained by this drift current. The impact on thruster efficiency makes additional study of the rotating spoke phenomena worthwhile for both basic and applied plasma science. For a more complete discussion, refer to Ref.[10]

Acknowledgments

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