Rotating Spoke Instabilities in Hall Thrusters

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***Abstract*—High-speed imaging of a Hall thruster plume reveals near-omnipresent rotating regions of elevated light emission, dubbed rotating spokes, in the annular thruster discharge channel. Azimuthal oscillations have long been suggested to induce cross–field electron transport in Hall thrusters, but conclusive experimental identification of such oscillations with probes is often challenging. However, simple processing of high-speed images taken at a few tens of thousands of frames per second clearly reveals long-wavelength rotating spokes at very low frequencies, corresponding to velocities of only a few hundred meters per second.**

***Index Terms*—Image sequence analysis, plasma devices, plasma diagnostics, plasma waves.**

HALL thrusters are space propulsion devices that use electromagnets to create a strong radial magnetic field across a generally annular discharge channel, suppressing axial electron mobility toward the anode at the base of the channel and thus sustaining strong axial electric fields for ion acceleration without acceleration grids. While Hall thrusters have a flight heritage of nearly 40 years, the high cost of vacuum chamber testing to optimize performance and validate lifetimes for ever higher power thruster designs increasingly motivates development of predictive Hall thruster models.

The primary hurdle to a predictive Hall thruster plasma model is our poor understanding of the mechanisms of electron transport across the strong magnetic fields in the thruster plasma. One theory often suggested to drive cross-field transport is the formation of axial $E \times B$ drift currents due to the applied radial magnetic field and induced azimuthal electric field components in plasma instabilities. Such instabilities have been measured at low frequencies using *in situ* plasma probe arrays [1] and at high frequencies with collective light scattering laser techniques, [2] but both methods are inherently local, making it difficult to accurately estimate global levels of electron transport by this mechanism.

High-speed imaging can nonintrusively capture a wealth of qualitative information about the entire thruster plasma at a glance, for example, fluctuations in total image brightness summed over all image pixels correlate strongly with discharge current oscillation spectra, a common diagnostic assessment of thruster operating stability. The combination of high-speed imaging with local plasma probes has the potential to enable quantitative global thruster calculations as well, by scaling visible wave structures on camera to match measured plasma properties such as potential and density. Plasma density fluctuations have already been observed in rotating spokes in a small cylindrical Hall thruster using synchronous high-speed imaging with *in situ* Langmuir probes, [3] at frequencies similar to those measured with plasma probes alone in [1].

Here, we present images of a nominal 6-kW class laboratory Hall thruster showing the clear presence of coherent rotating spoke structures, with frequencies in the low single kilohertz and linear velocities in the $E \times B$ direction ranging from about 400–1000 m/s, depending on the operating condition (Fig. 1). Similar videos of several Hall thrusters ranging in power level from the 600-W class Busek BHT-600 to the pictured 6-kW thruster all exhibit spokes at various operating conditions, suggesting that this is a general Hall thruster phenomenon. All images shown were captured by a Photron FASTCAM 1024PCI camera at 27 000 frames per second (fps) at 128×128 pixel resolution.

The thruster shown has been well characterized across a range of operating conditions with a nominal anode efficiency of over 60% [4]. The spokes are the strongest and the most stable at higher discharge voltages (Figs. 2 and 3), corresponding to higher efficiency operating conditions, while they tend to turbulently break apart and reform at lower voltages. Thruster operation in these images was at a constant 10-mg/s xenon flow rate or approximately 10-A discharge current, with varied discharge voltage and magnetic field optimized to minimize discharge current at each voltage.

Neglecting radial variation in image brightness, a 2-D Fourier analysis of the azimuthal variations in brightness over time permits clear identification of the spoke amplitude, frequency, and number of spokes simultaneously present. The spoke amplitude is generally on the order of 5%–10% of the mean background image, with two to three spokes generally visible at one time, corresponding to wavelengths on the order of 10 cm. While the spoke rotational frequencies are not reflected in current spectra, our own measurements and those in [3] link spoke formation with significant changes in the thruster discharge current level. We attribute this to our use of a ring-shaped anode, such that discharge current measurements effectively integrate current over the full 2π of the ring, washing out azimuthal variations.

The common appearance of these long-wavelength low-frequency instabilities across several Hall thruster platforms ranging over an order of magnitude in power level indicates a ripe area for more detailed investigation with high-speed imaging supported by *in situ* plasma measurements.

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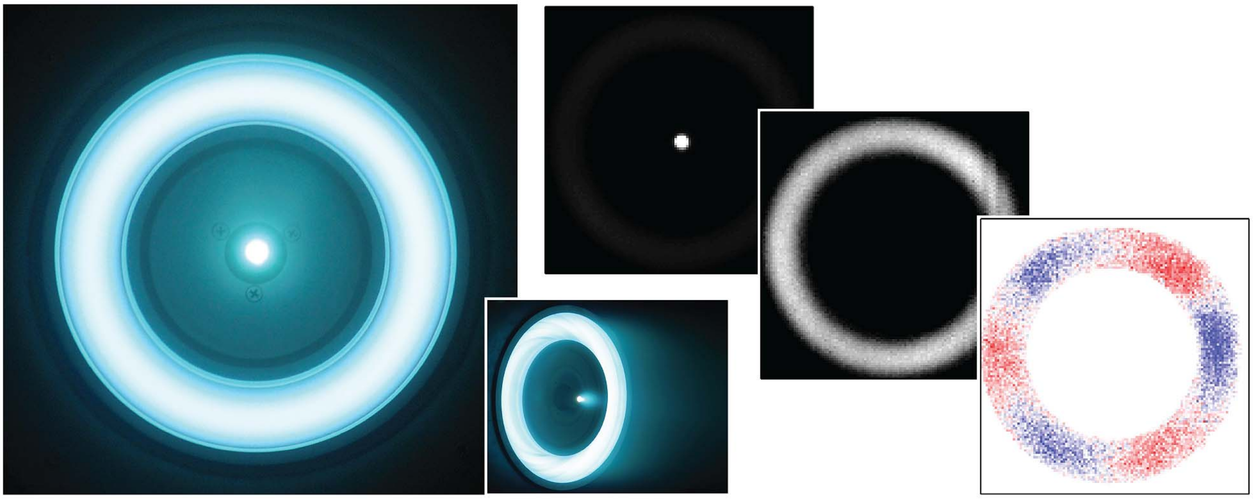

Fig. 1. At the far left, the large axial view and inset side view of the 6-kW laboratory Hall thruster show the annular thruster channel and central cathode. Along the diagonal, at the upper left, a single black-and-white raw high-speed video frame shows the thruster channel and bright central cathode. During processing, the cathode spot is removed to improve apparent contrast, shown in the middle frame. This image is ac coupled by subtracting off the mean image taken over a full video and shown in false color at the bottom right, where red and blue show regions of brighter- and dimmer-than-average emissions, respectively.

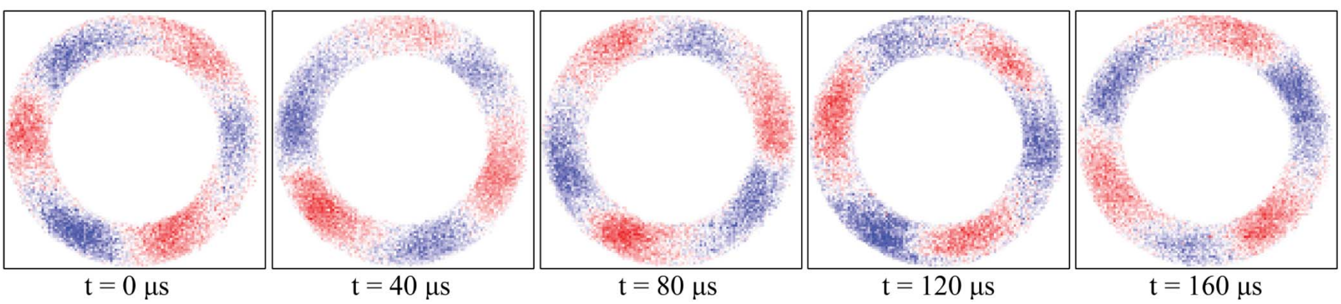

Fig. 2. False-color ac-coupled video of a 600-V 10-A operating condition at 27 000 fps shows a coherent threefold spoke structure rotating in the counterclockwise direction. The frequency of spoke passage by a given point on the channel is approximately 3 kHz, but each spoke's individual rotational frequency is only one-third this value, or 1 kHz, corresponding to a velocity of about 500 m/s.

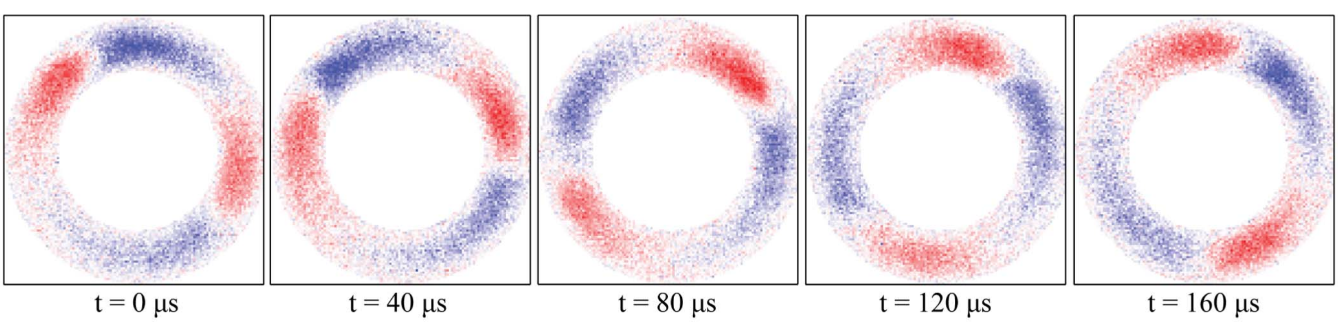

Fig. 3. Type of spoke mode varies with operating condition; at 300 V, only two spokes are present, passing a fixed point at 2.5 kHz for an approximate individual spoke frequency of 1200 Hz and a speed of about 600 m/s.

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