Effects of the Gas Pressure on Low Frequency Oscillations in E×B Discharges

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Abstract: Rotating plasma structures have been observed in a variety of low pressure cross-field discharges of cylindrical geometry, including Penning discharges, cylindrical and annular Hall thrusters, sputtering magnetrons, helicon discharges, and linear plasma devices. These structures can appear in different modes ranging from m=1 to higher order modes which propagate in the direction perpendicular to electric and magnetic fields with velocities of much lower than E×B velocity. Although the phenomenon of such azimuthal non-uniformities or so-called spoke is known for more than four decades, physical mechanisms responsible for its triggering and implications for plasma discharges are still not understood. In recent experimental studies of the cylindrical Hall thrusters and Penning discharge, we demonstrated that the spoke is directly responsible for the enhancement of the electron cross-field transport in these devices. Experiments revealed that for both these devices, the spoke is sensitive to the magnetic field, gas-type and the gas pressure. The increase of the pressure leads to the suppression of the spoke and a larger contribution of classical collisional cross-field transport, which becomes a dominant mechanism.

Nomenclature

B	=	magnetic field
E	=	electric field
Ω_{ce}	=	electron gyrofrequency
Ω_{ci}	=	ion gyrofrequency
ω	=	rotating spoke frequency
M	=	atom mass

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I.   Introduction

Plasmas in cross-field discharge devices exhibit complex nonlinear behavior resulting in variety of turbulent fluctuations and structures that critically affect operation and performance of these devices. E×B rotating structures or so-called rotating spoke oscillations have been observed in a variety of plasma devices with magnetized electrons and non-magnetized or weakly magnetized ions such as Hall thrusters, Penning discharges and sputtering magnetrons. These oscillations are usually low mode number with a characteristic frequency of $\Omega_{ce} \ll \omega \leq \Omega_{ci}$, where Ω_{ce} and Ω_{ci} are gyrofrequency of electrons and ions, respectively. Recent experiments of Hall thrusters and Penning discharges demonstrated that low frequency (1-10's kHz) spoke oscillations are responsible for anomalous electron cross-field transport that limits the maximum achievable electric field and increases power losses in these devices. Our recent measurements in cylindrical Hall thruster[1] (Fig. 1) and Penning discharge (Fig. 2)[2] revealed a strong dependence of spoke oscillations on the input discharge parameters, including gas, gas pressure, the magnetic field, and the electron injection from the cathode.

The principle of operation of the cylindrical Hall thruster (CHT) 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.[3] 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).[4,5] The breathing mode manifests itself in large amplitude oscillations of the discharge current (~ 10 kHz).[3] These oscillations are also observed in conventional annular Hall thrusters and usually associated with ionization instability.[6,7] 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 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 ×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.
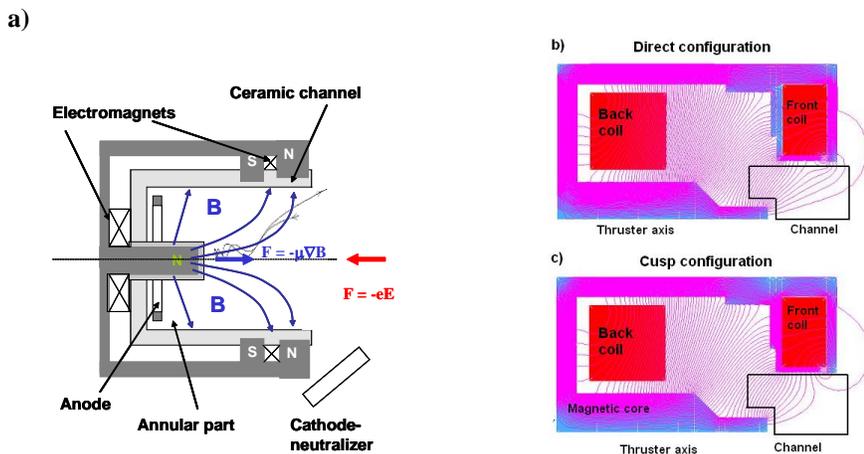

Figure 1. Schematic of a cylindrical Hall thruster (CHT) (a) and magnetic field configurations: direct (b) and cusp (c). In the direct configuration, the electromagnet coils currents are in the same direction, while for the cusp configuration, the coils currents are in the opposite direction (opposite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

The Penning discharge has a cylindrical geometry with applied axial magnetic field and radial electric fields. The plasma is produced by the electron beam from either filament cathode or plasma cathode such as a hollow cathode or RF plasma cathode. The configuration of the Penning discharge (Fig. 3) is more convenient for studies due to easier access for plasma diagnostics. Similarly to Hall thrusters, the Penning discharge system can be a subject to rotating spoke oscillations (Fig. 4).[2]
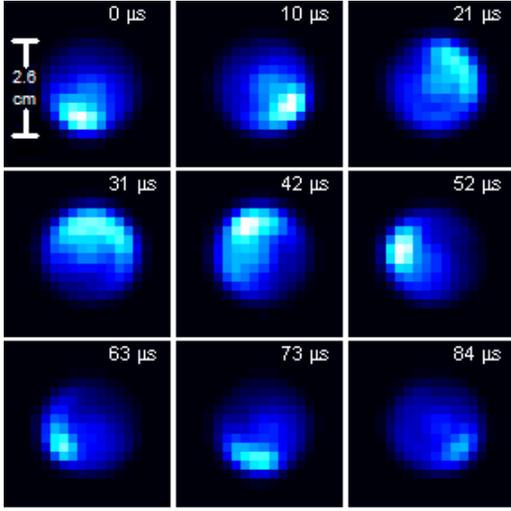
Figure 2. Sequence of camera images show counter-clockwise rotation, in the ExB direction, in the cusp configuration of the 2.6 cm CHT thruster. This spoke was not observed for the direct magnetic configuration of the CHT.[4]
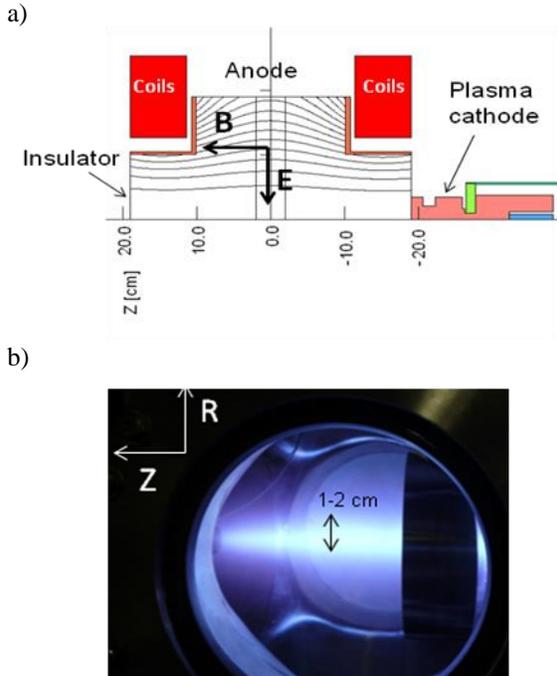
a)

b)

Figure 3. (a) E×B configuration of the Penning DC-RF discharge; b) Xenon operation of the Penning discharge.[2]

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 and for the Penning discharge.
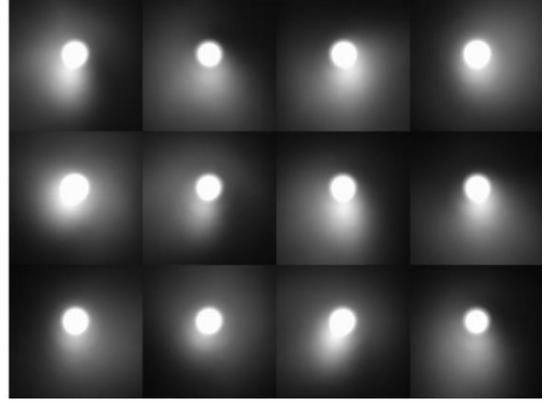

Figure 4. Rotating spoke observed in the Penning discharge at the discharge voltage between the cathode and the chamber of 100 V and the magnetic field of 100 Gauss. Background (xenon) gas pressure is 0.3 mtorr.[2]

II. Experimental setup

The 2.6 cm diam. CHT was operated in the large PPPL Hall Thruster facility.[8] 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.

The Penning discharge system (Fig. 3) is flexible and versatile setup with well controlled parameters of the plasma. In operation, a dc voltage of 20-200 V is applied between the RF plasma cathode and the anode-chamber. The system can be operated with and without magnetic field. Under the variations of the magnetic field of 30-500 Gauss, the Penning discharge system can sustain an efficient ionization of xenon with $n_e^{max} \sim 10^9\text{-}10^{12}$ cm^{-3}, $T_e \sim$ 1-10 eV. With plasma properties of this range are comparable to the plasma properties in the near anode region of the Hall thrusters.

For plasma characterization measurements, Penning discharge system is equipped with an advanced VGPS Langmuir probe station[9], movable biased and emissive probes[10], Laser-Induced Fluorescence diagnostics [11] a trace-rare-gas optical emission spectroscopy (TRG-OES)[12]. Unlike electrostatic probes, TRG-OES is non-invasive plasma diagnostics and therefore, can not disturb the plasma. VGPS station is the state-of-the art probe station dedicated for measurements of electron energy distribution function. In recent experiments, both probe and TRG-OES measurements revealed that the magnetized plasma of the Penning discharge has a non-Maxwellian EEDF with a high-energy tail (Fig. 5). Moreover, Penning discharge system is equipped with various high frequency probes to measure oscillations of the plasma density, electron temperature and plasma potential.

Figure 5. Penning discharge measurements with VGPS probe - spatial variations of the electron energy probably function (EEPF) at the magnetic field of 35 Gauss. Hot electrons near the axis, R ≤ 2 cm, could be due to plasma- beam interaction (electron beam from the cathode).

A Phantom Camera V7.3 camera was used to obtain the high-speed images of unfiltered emissions in the visible spectrum range for both CHT and Penning discharge system. 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 signal processing procedure described in Ref. 13 was applied for the analysis of images.
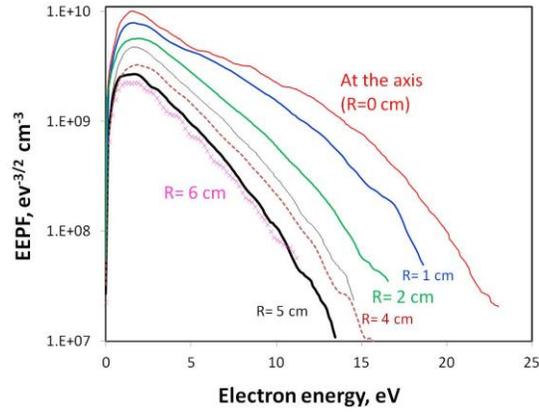
IV. Experimental results and discussions

A detailed analysis of the effect of the background pressure on the discharge characteristics and the plasma in CHT and Penning discharge system will be described in separate paper. Here, we highlight only main results. For the CHT, Fig. 6 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
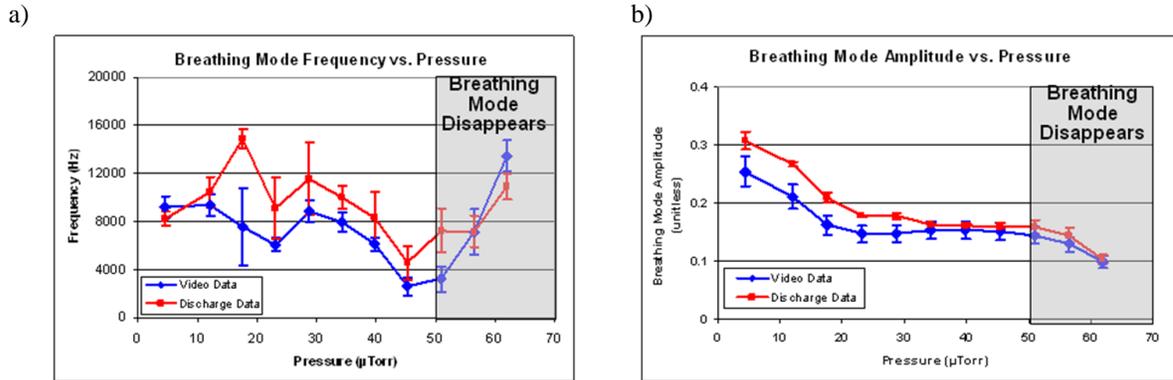
a)

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Figure 6. Variations of the frequency (a) and COV (b) of the breathing oscillations with the background pressure.

The rotating spoke frequency increases dramatically with the background pressure (Fig. 7). 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 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.
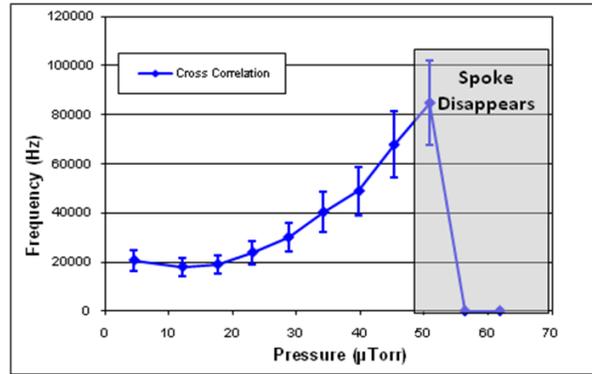

Figure 7. Variations of the frequency of the rotating spoke oscillations with the background pressure.[13]

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 in the thruster discharge. 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 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.

In contrast to the CHT, for the Penning discharge, the rotating spoke frequency reduces with the background pressure (Fig. 8). The spoke frequency follows the scaling of $(B/M)^{0.5}$, where B is the magnetic field and M is the atom mass. The increase of the gas pressure above 10^{-4}-10^{-3} torr leads to the suppression of the spoke oscillations. A more detail analysis of spoke oscillations in the Penning discharge will be described in a separate paper. Results of modeling of the Penning configuration, including theoretical studies of spoke oscillations and 2-D Particle-in-Cell simulations are described in two parallel papers at this conference.[15,16]
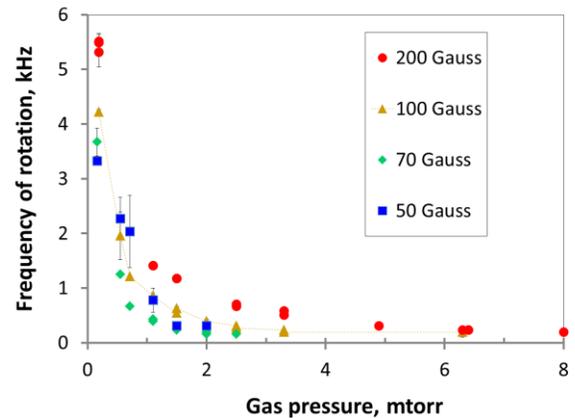

Figure 8. Penning discharge system: The frequency of the rotating spoke oscillations with the background pressure.[13]

Acknowledgments

References

[1] Y. Raitses, Y., and N. J. Fisch, "Parametric Investigations of a Nonconventional Hall Thruster," Phys. Plasmas, Vol. 8, No. 5, May 2001, pp. 2579-2586.

Joint Conference of 30th ISTS, 34th IEPC and 6th NSAT, Kobe-Hyogo, Japan
July 4 – 10, 2015

[2] Y. Raitses, Effect of Magnetic Field on Electron Kinetics in a Weakly-Collisional Plasma, DOE Center for Predictive Control of Plasma Kinetics:Multi-Phase and Bounded Systems, 3rd Annual Meeting, May 17-18, 2012

[3] A. Smirnov, Y. Raitses, and N. J. Fisch, "Experimental and theoretical studies of cylindrical Hall thrusters", Phys. Plasmas 14, 057106 (2007).

[4] Y. Raitses, A. Smirnov, and N. J. Fisch, "Effects of enhanced cathode electron emission on Hall thruster operation", Phys. Plasmas 16 057106 (2009).

[5] J. B. Parker, Y. Raitses, and N. J. Fisch, "Transition in Electron Transport in a Cylindrical Hall Thruster" submitted to Appl. Phys. Lett. (2010).

[6] J. P. Boeuf., and L. J. Garrigues, Appl. Phys. 84, 3541 (1998).

[7] S. Barral and E. Ahedo, Phys. Rev. E 79, 046401 (2009).

[8] Y. Raitses, D. Staack, A. Dunaevsky, L. Dorf and N. J. Fisch, "Measurements of Plasma Flow in a 2 kW Segmented Electrode Hall Thruster", in the proceedings of the 28th International Electric Propulsion Conference, Toulouse, France, March 2003, IEPC paper 03-0139.

[9] V. A. Godyak and V. I. Demidov, J. Phys. D: Appl. Phys. 44, 233001 (2011).

[10] J. P. Sheehan, Y. Raitses, N. Hershkowitz, I. Kaganovich, and N. J. Fisch,, Phys. Plasmas **18**, 073501 (2011)

[11] A. Diallo, S. Keller, Y. Shi, Y. Raitses, and S. Mazouffre, "Time-resolved ion velocity distribution in a cylindrical Hall thruster: Heterodyne-based experiment and modeling", Review of Scientific Instruments 86, 033506 (2015)

[12] V. M. Donnelly, J. Phys. D: Appl. Phys. 37 R217 (2004)

[13] E. Davis, J. B. Parker and Y. Raitses, "High-Speed Imaging Analysis of Discharge Oscillations in the Cylindrical Hall Thruster" to be published in the Journal of Undergraduate Research (2010).

[14] A. Smirnov, Y. Raitses, and N, J. Fisch, "Controlling the Plasma Flow in the Miniaturized Cylindrical Hall Thruster", IEEE Trans. Plasma Sci. 36, 1998 (2008).

[15] W. Frias, A. I. Smolyakov, Y. Raitses, I. D. Kaganovich, I. Romadanov, and M. Umanskiy, "Small scale instabilities and anomalous electron current in Hall plasmas", IEPC-2015-370 paper, the 34th International Electric Propulsion Conference, Hyogo-Kobe, Japan, July 4 – 10, 2015

[16] J. Carlson, I. Kaganovich, A. Khrabrov, Y. Raitses, A. Smolyakov, and D. Sydorenko, "Multi-Dimensional Kinetic Simulations of Instabilities and Transport in ExB Devices", IEPC-pare 2015-373, the 34th International Electric Propulsion Conference, Hyogo-Kobe, Japan, July 4 – 10, 2015.