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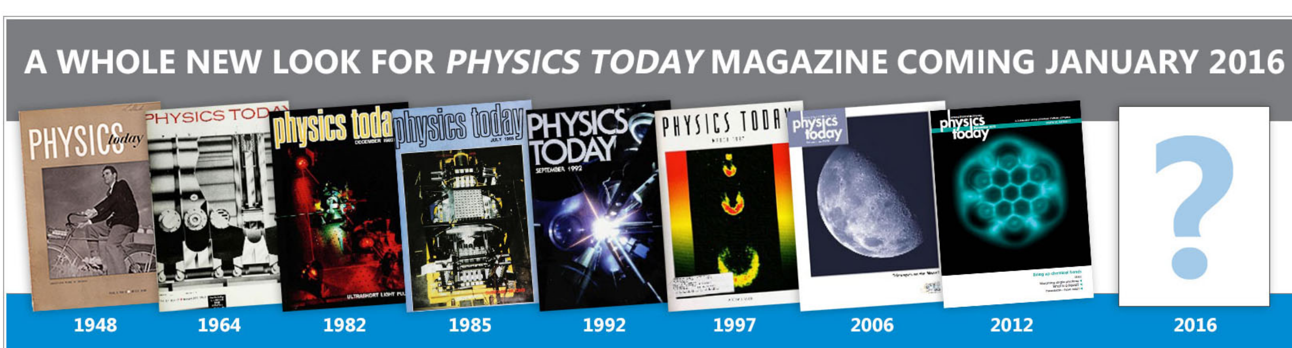

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Experimental evidence of E × B plasma rotation in a 2.45 GHz hydrogen discharge

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An experimental observation of a rotating plasma structure in a 2.45 GHz microwave-driven hydrogen discharge is reported. The rotation is presumably produced by $E \times B$ drift. The formation of the rotating plasma structure is sensitive to the strength of the off-resonance static magnetic field. The rotation frequency is on the order of 10 kHz and is affected by the neutral gas pressure and applied microwave power. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4938033]

I. INTRODUCTION

Rotating structures are commonly observed in magnetized low-temperature plasmas of $\boldsymbol{E} \times \boldsymbol{B}$ devices such as Hall thrusters for satellite propulsion[1] and magnetron discharges applied, e.g., for sputtering applications.[2,3] In typical $\boldsymbol{E} \times \boldsymbol{B}$ devices the external magnetic field is perpendicular to an electric field applied between two electrodes, which drives a discharge current $\boldsymbol{J}$. Although numerous experimental and simulation studies[4–6] on the characteristics of the rotating structures have been published, their formation is not yet fully understood. Research on this topic has been carried out in a wide context ranging from plasma processing applications to thermonuclear fusion[7] and even planet formation,[8] to mention a few.[9]

In laboratory plasmas two effects, namely, instabilities and dissipation, govern the formation of rotating structures[4] and, thus, studying them can provide information about fundamental plasma physics. Here, we report an experimental observation of a rotating plasma structure in a cylindrically symmetric electrode-less magnetized hydrogen discharge driven by pulsed 2.45 GHz microwave radiation in off-resonance condition. Rotating vortices in similar discharge geometry, but at substantially higher microwave power, have been observed earlier by Nagaoka *et al.*[10,11] who reported the formation of a plasma hole surrounded by a Burgers vortex under the electron cyclotron resonance condition. The main qualitative difference between the rotating structure presented here and the one reported in Refs. 10 and 11 is the spatial distribution of the discharge. In our experiment the rotating structure was observed to be open in the direction of the drift unlike typical "closed-drift-configurations" observed, e.g., in Hall-thrusters.[2,3] Hence, the collective drift velocity can be determined from the spatial movement of the ionization front.

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II. EXPERIMENTAL SETUP

The experimental data were taken with the T.I.P.S. (Test-bench for Ion-source Plasma Studies) plasma generator driven by a 3 kW adjustable power magnetron operated in pulsed mode at 50 Hz. The system is essentially similar to microwave ion sources intended for the production of intense proton beams.[12,13] The plasma generator is shown schematically in Fig. 1 and its detailed description can be found in Refs. 14 and 15. The main optical diagnostics tool of the T.I.P.S. setup is an Image Intensified CCD frame camera system for temporally and spatially resolved diagnostics. The CCD Camera System made by Cordin Corporation (model 220A) is described thoroughly in Refs. 15 and 16. The setup enables taking up to four images with independently adjusted exposure times and delays between each shot. Typical exposure time has been on the order of 1 μs while the delay between pictures has been adjusted depending of the set of plasma parameters. The MCP and CCD gains can

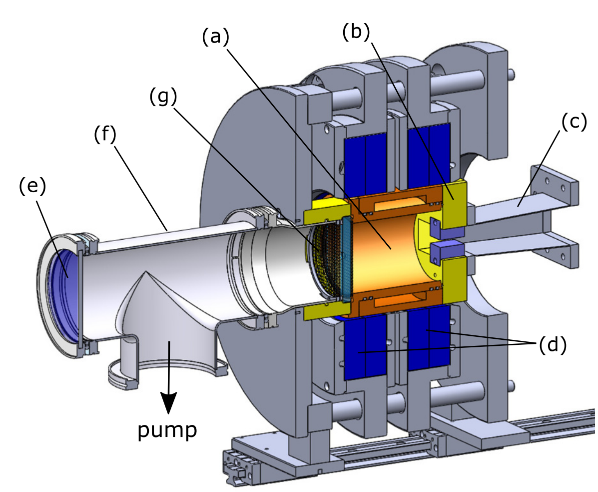

FIG. 1. A cross section view of the plasma reactor: (a) plasma chamber, (b) microwave coupler, (c) microwave guidewave adaptor, (d) coil pancakes, (e) quartz window placed in front of the camera, (f) vacuum tee, and (g) optical window with shielding grids.

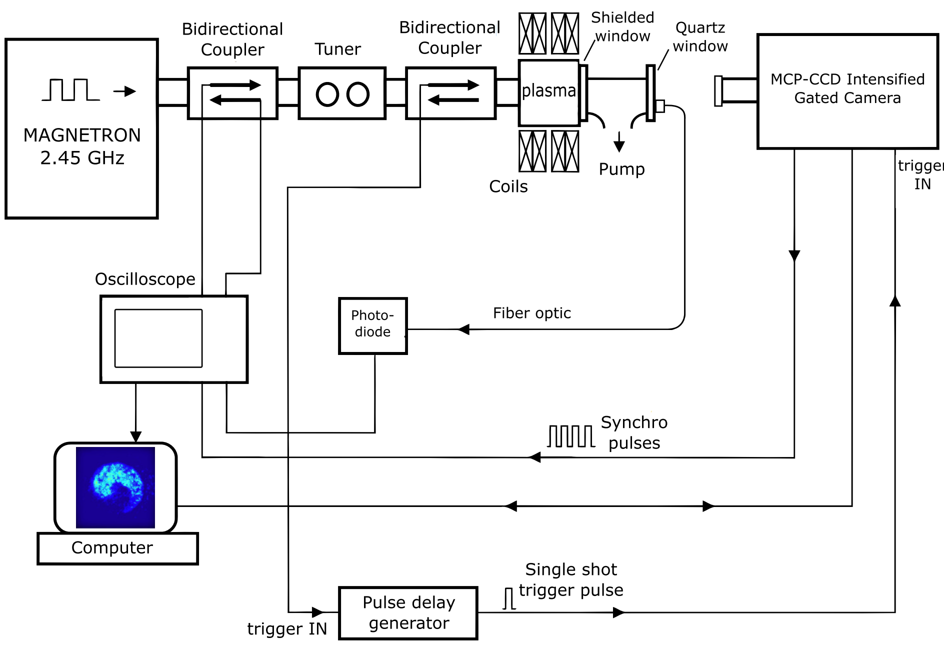

FIG. 2. Schematic representation of the experimental setup where timing strategy is shown by using a pulse delay generator and the applied power signal as a master pulse for synchronizing the discharge and ultra-fast camera.

be adjusted depending on the incident light intensity. The auxiliary diagnostics include bidirectional couplers for the measurement of applied and reflected microwave power signals and a fast photodiode connected to the discharge through an optical fiber port placed at the periphery of the plasma chamber. The layout of the diagnostics setup is presented in Fig. 2.

III. EXPERIMENTAL RESULTS

Several plasma morphologies (or more precisely planar projections) have been documented with the T.I.P.S. plasma generator.[15,16] It has been observed that the magnetic field strength and topology define the structure while the applied power and neutral gas pressure play less significant roles in both static and transient distributions.[15,17] A rotating *YinYang*-structure displayed in Fig. 3 appears in off-resonance conditions, i.e., when $B < 87.5$ mT everywhere in the plasma chamber volume. Figure 4 shows a simulation (FEMM 4.2)[18] of the magnetic field distribution corresponding to the appearance of the rotating plasmoid. In such condition the microwave–plasma coupling is rather weak, i.e., $(P_i - P_r)/P_i$, where P_i is the applied power, and P_r the reflected power is only about 5%. Reversing the direction of the static magnetic field causes the direction of the rotation to change, which implies that the rotation is most likely driven by the $\boldsymbol{E} \times \boldsymbol{B}$-drift. However, some reports on $\boldsymbol{E} \times \boldsymbol{B}$ show the ionization waves going in the $-\boldsymbol{E} \times \boldsymbol{B}$ direction,[19] and others researchers report that direction reversal can depend of discharge conditions.[20]

It is worth noting that the magnetic field setting corresponding to the rotating *YinYang*-plasmoid is drastically different from the magnetic field setting corresponding to stationary *YinYang*-structure recently reported.[15]

The frequency of the rotation can be monitored with the photodiode owing to the positioning of the collimated diagnostics port at the lower left sector of the plasma chamber. This is demonstrated in Fig. 3 showing the oscillograms of the applied microwave power signal, the photodiode current signal, and the timing of the frame camera system (corresponding to pictures in Fig. 3). The periodic ripple of the photodiode signal was utilized to measure the applied power and pressure dependencies of the plasma rotation frequency in the range of 500–2300 W and 3–9 $\times$ 10^{-3} mbar, respectively. The results are shown in Fig. 5. The rotation frequency decreases monotonically with increasing pressure (data taken with 1500 W applied microwave power) but remains within $\pm$10% from the average in a wide range of applied microwave powers (data taken at 8.7 $\times$ 10^{-3} mbar pressure). Fig. 6 shows the average light intensity (photodiode signal) in corresponding range of operating parameters.

IV. DISCUSSION

We have reported an experimental observation of rotating plasma structure in electrode-less microwave discharge. To our knowledge the existence in rotating structures in plasma generators similar to typical high-current proton sources have not been reported before. The motion of the rotating spoke is presumably driven by $\boldsymbol{E} \times \boldsymbol{B}$-drift emerging from the static magnetic field and plasma potential induced electric field across the plasma sheath forming between the plasma and the neutral gas volume (as well as the plasma and the conducting wall of the plasma chamber). The formation of the rotating spoke is assumed to be related to rather poor microwave–plasma coupling which causes the plasma ignition to take place only near the maximum of the cavity electric field, i.e., on-axis.[14] In such condition, the plasma column and the conducting wall of the plasma chamber form a coaxial structure that resembles that of a magnetron. Finally the coaxial structure develops into a rotating *YinYang*-projection shown in Fig. 3. The described sequence of events was confirmed by studying the plasma breakdown (of the corresponding morphology) with high temporal resolution.[17] It is difficult to define the direction of the electric

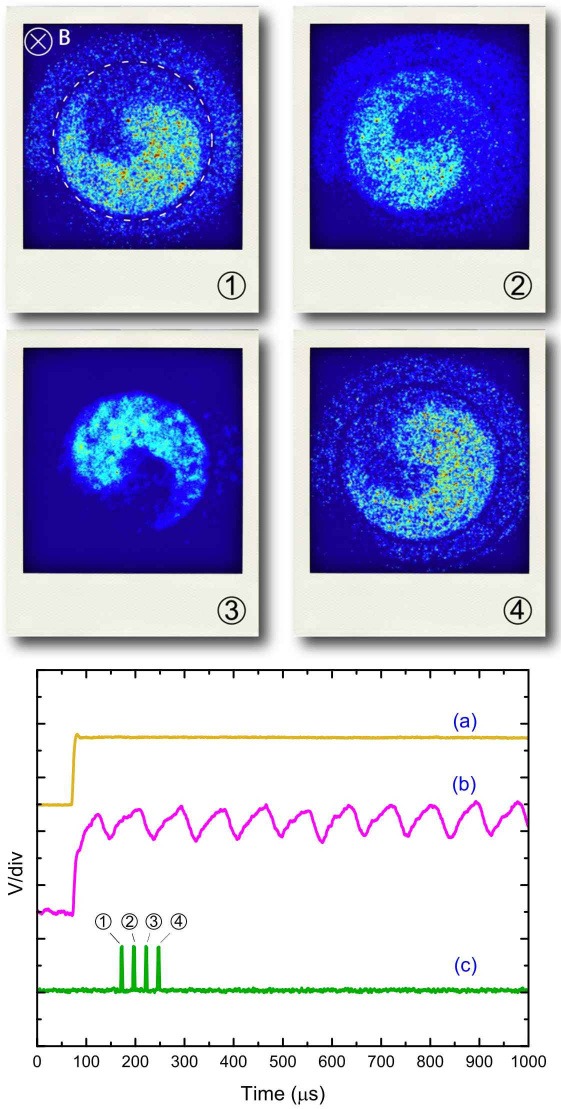

FIG. 3. Sequence of visible ultra-fast MCP-CCD camera pictures of the rotating *YinYang* plasma structure. The diameter of the plasma chamber (85 mm) and the magnetic field direction are marked on the first image. The oscillogram shows: (a) the applied microwave power, (b) the light intensity recorded with a photodiode, and (d) the camera trigger monitor signal.

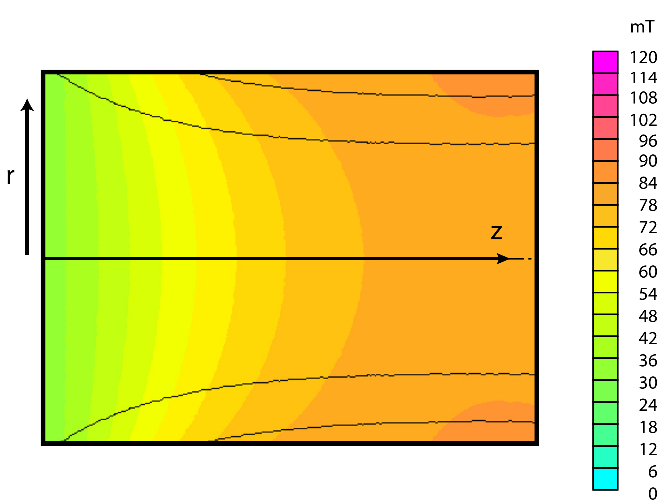

FIG. 4. Magnetic field distribution inside the discharge chamber for the rotating *YinYang* plasma distribution.

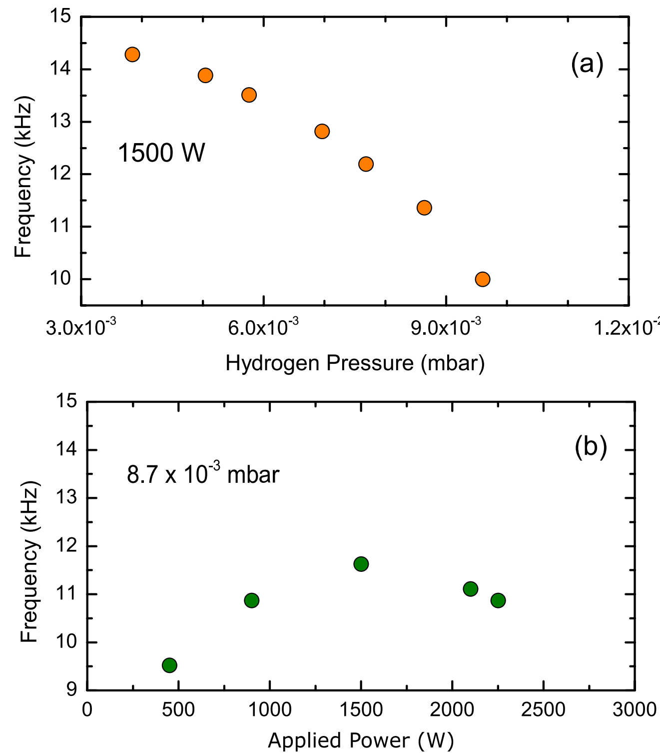

FIG. 5. Rotation frequency vs. hydrogen pressure (a) and vs. applied power (b) for the rotating *YinYang* plasma distribution.

field driving the rotational motion because the pictures taken with the CCD camera are 2D-projections of the complex plasma morphology. However, it is argued that the primary component of the static magnetic field being axial requires the electric field to be predominantly radial in order to drive a rotational plasma drift.

According to collisional electron transport theory the contribution of the $\boldsymbol{E} \times \boldsymbol{B}$-drift on the electron velocity in the direction perpendicular to the magnetic field can be expressed as

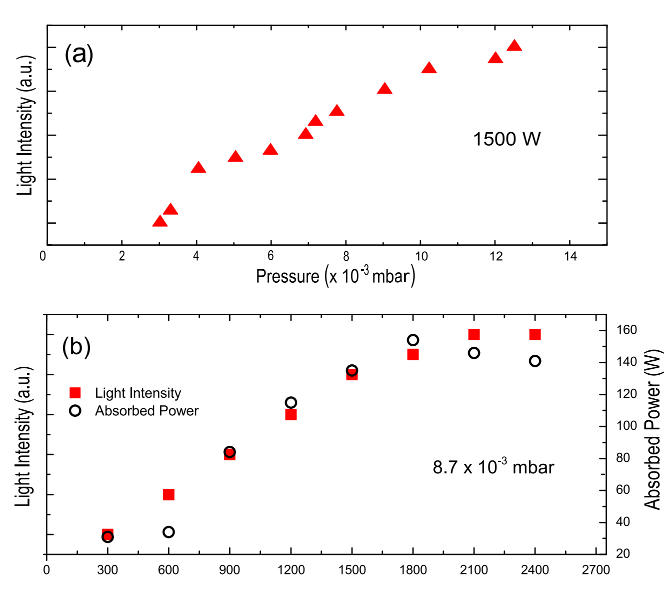

FIG. 6. Plasma light intensity vs. hydrogen pressure (a) and vs. applied and absorbed power (b).

$$v_{E\times B} = \frac{\omega_{ce}^2\tau^2}{1+\omega_{ce}^2\tau^2}\frac{E}{B}, \tag{1}$$

where $\omega_{ce} = \frac{eB}{m_e}$ is the electron gyrofrequency in the external magnetic field and $\tau = \frac{1}{\nu}$ is the mean time between electron collisions, i.e., the inverse of the electron collision frequency. The drift velocity is typically expressed with the Hall parameter $h = \omega_{ce}\tau$ as

$$v_{E\times B} = \frac{h^2}{1+h^2}\frac{E}{B}. \tag{2}$$

In typical plasmas (including the microwave discharge discussed here) the electron Hall parameter is much greater than unity, i.e., $h \gg 1$. The drift velocity in quasineutral plasmas of "closed-drift-configurations" is determined by the electron drifty velocity.[5] However, in open-drift structures in which there is a distinct boundary between the rotating ionization front and neutral gas, the drift velocity is reduced due to a build-up of an ambipolar potential retarding the electron motion across the boundary. In such condition the drift velocity is dictated by ions being the slower plasma species and the Hall parameter can be written as $h_i = \frac{eB}{m_i\nu_{ii}}$. It is assumed here that the plasma consists of singly charged ions and the only collision type contributing to ion momentum transfer and diffusion is ion–ion collisions. The ion–ion collision frequency in single species (hydrogen), singly charged (maximum ion charge state 1+) plasma can be expressed as[21]

$$\nu_{ii} = 4.8\times10^{-8}\frac{n_e}{T_i^{3/2}A^{1/2}}\ln\Lambda, \tag{3}$$

where n_e is the plasma density, T_i is the ion temperature, A is the effective mass number of ions (H^+, H_2^+, and H_3^+), and $\ln\Lambda$ is the Coulomb logarithm. In this formulation, the ion temperature is given in units of eV and electron density in units of cm^{-3}. The dominating plasma species in the microwave discharge for *YinYang* mode[22] is H_3^+ and the ion temperature is estimated on the order of 1 eV. The electron density in the T.I.P.S. plasma generator has been reported to be on the order of 10^{10}–10^{11} cm^{-3}. Furthermore, the value of the Coulomb logarithm can be assumed to be on the order of 10. The given numbers translate to the ion–ion collision frequency being on the order of 10 kHz which implies that the positive ions are strongly magnetized and also the ionic Hall parameter is much greater than unity, i.e., $h_i \gg 1$. Thus, the rotation velocity of the ionization front corresponds to the $\boldsymbol{E}\times\boldsymbol{B}$-drift velocity which reduces to

$$v_{E\times B} \approx \frac{E}{B}. \tag{4}$$

This expression for the rotational velocity can be used to estimate the electric field strength driving the azimuthal motion of the plasma. Such estimate is based on the magnetic field strength ranging from (approximately) 30 to 70 mT and measured rotation frequencies ranging from 9.5 to 14.5 kHz. Taking into account the radius of the plasma chamber (42.5 mm), these frequencies translate to maximum rotational velocity ranging from 2.5×10^3 to 3.9×10^3 m/s, which is approximately an order of magnitude less than the minimum ion velocity (1 eV H_3^+ ions), i.e., the rotational velocity is dictated by the drift velocity. Consequently, the strength of the electric field is estimated to be in the range of 70–270 V/m, which implies that the radial variation of the plasma potential within the plasma is on the order of 5 V in the present experiments. This value refers to the internal variation of the plasma potential, not to the potential drop across the plasma sheath. The calculated electric field is approximately an order of magnitude weaker than the electric field reported in Refs. 10 and 11, which is reasonable since the absorbed power in our experiment is on average at least an order of magnitude lower.

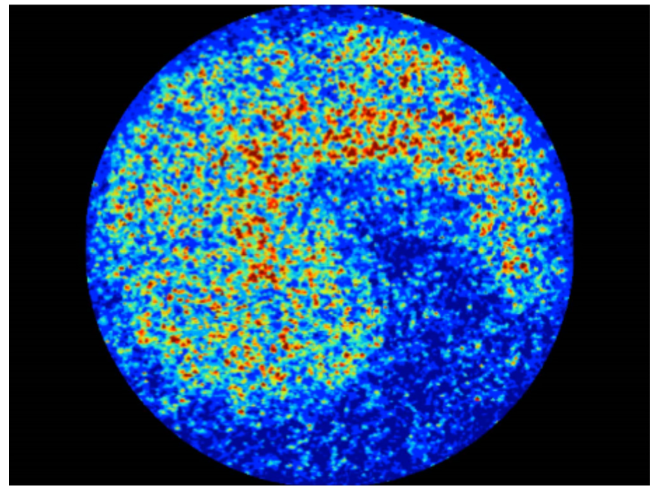

FIG. 7. Slow motion movie of the rotating *YinYang* plasma distribution. (Multimedia view) [URL: http://dx.doi.org/10.1063/1.4938033.1]

The dependence of the rotational frequency on the neutral gas pressure shown in Fig. 5(a) is similar to typical dynamics of a moving ionization-front, observed in laboratory experiments[23] in which a pressure increment slows down the front despite of increased plasma density implied by the increased light emission intensity shown in Fig. 6(a) (inelastic collision rate). The saturation of the rotation frequency with the applied microwave power implies weaker microwave–plasma coupling at high power. Such trend is also seen in Fig. 6(b) where the slope of the light intensity increase becomes less steep at microwave powers exceeding 1500 W in a good agreement with the absorbed power.

The experimental results reported in this paper can support particle-in-cell simulations of rotating structures discussed, e.g., in Ref. 5.

Finally Fig. 7 (Multimedia view) presents a slow motion video composed by a large number of pictures taken during different experiments and combined in order to illustrate the phenomenon.

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