Strongly Eccentric Rotational Plasma Lamina Observed in a 2.45-GHz Hydrogen Discharge

Osvaldo Daniel Cortázar and Ana Megía-Macías

***Abstract*— A novel strongly eccentric rotating plasma lamina structure subtending approximately an angle of 120° is reported in a 2.45-GHz driven electron cyclotron resonance hydrogen discharge in the proximity of the chamber wall. Shape and rotation frequencies depend critically on the embedded magnetic field distribution in the plasma chamber as well as on neutral gas pressure and microwave power. The discharge denominated test-bench for ion-sources plasma studies includes a transparent doubled shielded quartz window that keeps the microwave resonance condition. An ultrafast microchannel plate charge-coupled device frame camera is used to obtain four pictures of 1-μs exposure time each during a single plasma pulse in the visible emission range. $E \times B$ drift is pointed as that responsible for driving the rotational behavior of a thick plasma sheath, where the scale of the quasi-neutrality breaking is estimated ten times greater than that in a typical plasma sheath.**

***Index Terms*— $E \times B$, electron cyclotron resonance (ECR) plasma source, hydrogen, ion source, rotational plasma.**

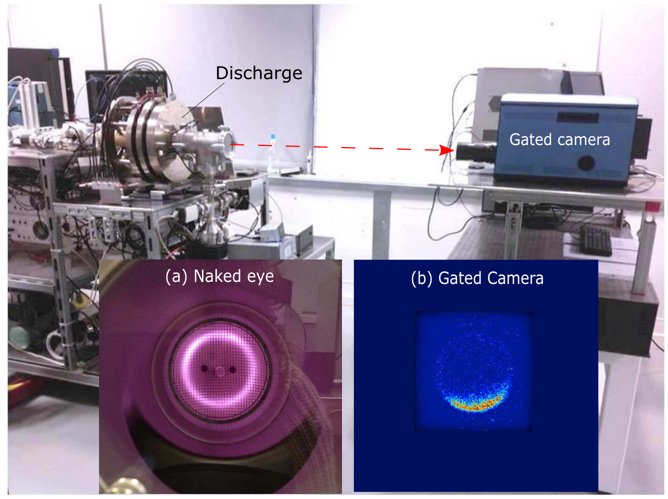

Fig. 1. View of the experiment with two embedded pictures of the discharge. (a) Naked eye (time integrated) recorded with a regular digital camera at 1/60 s of exposure time. (b) Picture obtained with the MCP-CCD-gated camera at 1 μs of exposure time, where the rotating lamina structure is observed.

I. Introduction

THE macroscopic collective rotational behaviors of different kinds of plasmas have been studied with deep interest for decades in the community [1]–[4]. A wide range of research works from nuclear fusion to astrophysical plasmas has been conducted with some controversy about their origin and the relationship between laboratory-produced plasmas, plasmoids, and astrophysical phenomena [5], [6]. Significant advances have been recently reported in the simulation of rotating structures by particle-in-cell Monte Carlo collision techniques [7]–[9] observed in $\boldsymbol{E} \times \boldsymbol{B}$ devices [4]. Furthermore, several cases of vortex structures have been reported at relatively high microwave powers with large plasma volumes (14 kW, 141 L) by Okamoto *et al.* [2] and Nagaoka *et al.* [10], [11]. Moreover, photographic techniques are an important tool for characterizing laboratory electron cyclotron resonance (ECR)-type plasmas [12]–[14], and a rotating spoke plasma structure was recently reported by this technique [15].

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This paper has supplementary downloadable multimedia material available at http://ieeexplore.ieee.org provided by the authors. This includes a supplementary file that contains a slow motion video composed of a large number of pictures taken during different experiments and combined in order to illustrate the phenomenon. The total size of the file is 15 MB.

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II. Experimental Setup

The experiments have been performed with the plasma discharge denominated testbench for ion-source plasma studies, a device driven by a 3-kW adjustable power magnetron of 2.45 GHz operated in the pulsed mode at 50 Hz. The system is similar to the popular microwave ion sources intended for the production of intense proton beams [16], [17]. A detailed description of the plasma source system has been published recently in [18]. The experimental setup was originally designed to perform studies on pulsed hydrogen plasmas especially on the transient processes, such as breakdown and decay [14], [19], [20]. Images are acquired with an intensified frame charge-coupled device (CCD) camera system made by Cordin Corp. (model 220A). A Pentax 67 mm $\times$ 150 mm telephoto lens with a focus ring to reduce the minimum focus distance is attached. The setup enables taking up to four images with independently adjusted exposure times and delays between each shot. Typical exposure time has been of 1 μs, while the delay between pictures has been adjusted depending on the plasma dynamics. The microchannel plate (MCP) and CCD gains can be adjusted depending on the incoming light intensity. The images are transformed through the calibration into a representation where red corresponds to the highest intensity and blue, the lowest. The auxiliary diagnostics include the measurement of incident and reflected microwave power signals recorded from bidirectional couplers. The time-resolved light emission is also obtained through an optical fiber placed at the periphery of the observation quartz window and connected to a fast photodiode. Fig. 1 shows the picture of

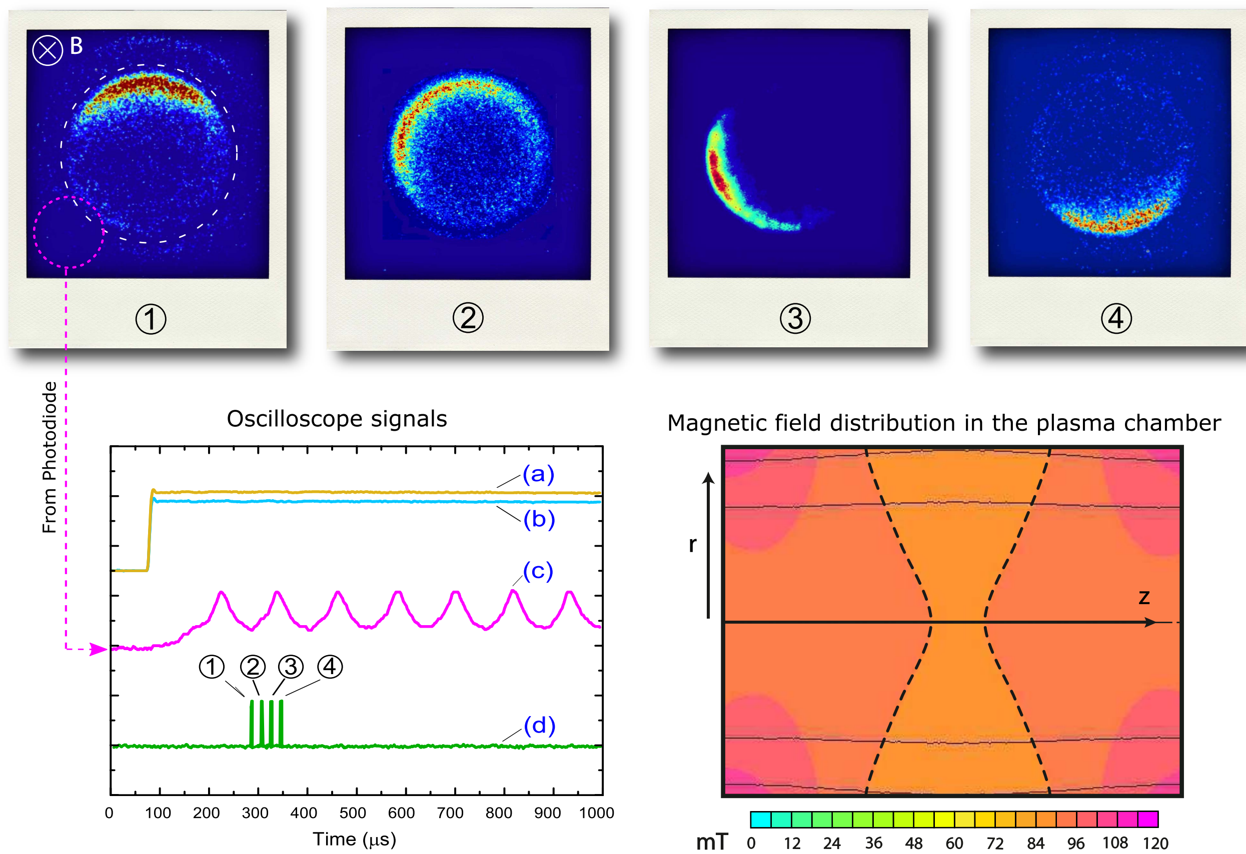

Fig. 2. Sequence of visible ultrafast pictures in the Half Moon mode. The diameter of the plasma chamber (85 mm) and the magnetic field circulation are marked on the first image. The oscillogram shows the timing control signals. (a) and (b) Incoming and reflected microwave powers. (c) Light intensity recorded with a photodiode. (d) Timing monitor pulses where the picture number is indicated. The magnetic field distribution inside the plasma chamber is also shown with the dashed lines representing the ECR value surface.

the experiment, where the discharge and the gated camera are shown. Two pictures of the plasma are embedded to illustrate the differences between the naked eye view (time integrated) and the time-resolved pictures. Fig. 1(a) was obtained with a regular digital camera at 1/60-s exposure time and Fig. 1(b) with the MCP-CCD-gated camera at 1 μs of exposure time, showing the plasma structure behind the apparent ring shape.

III. Results

A thin eccentric rotational plasma lamina is observed in the proximity of the chamber wall covering approximately at an angle of 120°. The central part of the structure shows a thickening, where the intensity of the emitted light is relatively higher. This plasma distribution denominated Half Moon was observed at 1020 W of incoming power, 4.4×10^{-3} mbar of hydrogen pressure, and 10% of coupling factor.

Fig. 2 shows a typical sequence of four pictures obtained during a single plasma pulse. The first picture shows the plasma chamber radius as a white dashed circle and the magnetic field direction in the top-left corner. The small circle in the bottom-left corner indicates approximately the detection area of the photodiode light collector.

The oscilloscope signals show the temporal-resolved information acquired during the experiment corresponding to the pictures, where (a) and (b) in Fig. 2 are the incoming and reflected microwave powers, respectively, (c) is the light intensity recorded by the collimated fiber optics with photodiode, and (d) is the pulse corresponding to each picture obtained from the MCP-CCD-gated camera monitor output. The number on each picture indicates the timing order, as is shown in Fig. 2(d) signal. The light collimator for obtaining the light intensity signal is placed in the bottom-left border of the observation quartz window. The light signal of Fig. 2(c) is due to the photodiode position and the plasma rotation that allow to measure the rotational frequency and its stability. Note the picking shapes denoting the pass of the relatively high intensity light emission plasma zone at the front of photodiode detection area.

The magnetic field distribution inside the discharge chamber is also shown in Fig. 2, where the ECR = 87.5-mT surfaces are indicated as black dashed lines. The surfaces perform a meniscus-like volume, in which the magnetic field drops under the ECR value. It is noticeable how a very symmetrical magnetic field distribution (with respect to the center of the plasma chamber) can produce such a marked asymmetrical plasma distribution in contrast with the previous studies [14].

For the set of experimental conditions, the rotation has been recorded in the counterclockwise, but whether the magnetic field distribution is inverted by inverting currents in the coils, the rotation is also inverted. The rotation frequency is ~10 kHz as can be appreciated by a typical period of 100 μs in Fig. 2(c).

If the exposure time is long enough or if the plasma is directly observed by the naked eye, it looks like a ring distribution [14], as is shown in Fig. 1(a). It is noticeable that for this case, the experimental settings are critical not accepting any variation. It means that the rotational Half Moon structure was only observed under the described fixed set of experimental parameters with a remarkable reproducibility and stability.

IV. Discussion

A novel rotational eccentric plasma lamina distribution is reported under a critical set of experimental parameters in a 2.45-GHz electrodeless hydrogen discharge. The stable rotation frequency and the inversion of the direction with the magnetic field reversal suggest that this phenomenon may be related to $\boldsymbol{E} \times \boldsymbol{B}$ drift. The combined effect of the external static magnetic field and plasma potential-induced electric field in the plasma chamber could drive the rotation. Although the electric field distribution is hard to predict considering that the images are 2-D projections, we propose an estimation on the base of the light intensity distribution and the formation of a thick plasma sheath.

Assuming for this plasma distribution the same conditions estimated in the previous reported work [15] where the rotation velocity of the ionization front that corresponds to the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity is reduced to

$$v_{E\times B} \approx \frac{E}{B} \tag{1}$$

this expression can be used to estimate the electric field strength with the magnetic field strength ranging from 70 to 100 mT, as shown in Fig. 2, and the measured rotation frequency of 10 kHz. Using the plasma chamber radius of 42.5 mm, the maximum rotational velocity is 2.7×10^3 m/s, which is approximately an order of magnitude lower than the minimum ion velocity (1-eV H_3^+ ions) pointing to rotational velocity as dictated by the drift velocity. The strength of the electric field is estimated to be in the range of 190–270 V/m, which implies that the radial variation of the plasma potential within the plasma is on the order of 10 V. The calculated electric field is approximately an order of magnitude weaker than the electric field reported in [10] and [11], which is reasonable since the absorbed power in our experiment is on average at least an order of magnitude lower.

Moreover, due to the plasma shape and the proximity to the chamber wall, we could consider the plasma lamina as a thick plasma sheath, where the quasi-neutrality is broken in a large scale that can reach 1000 λ_D (where λ_D is the Debye length), as was reported in [21], in other similar ECR plasma generator for a vortex structure.

Assuming such hypothesis, we can think in a radial unbalanced charge distribution $e\ (n_i - n_e) \geq 0$ (due to the difference of mobility between electrons and ions) that produces an electrostatic potential ϕ to reduce the electron loss rate. Such a potential obeys to Poisson's equation

$$\varepsilon_0 \nabla^2 \phi = -e\ (n_i - n_e). \tag{2}$$

On the other hand, assuming that the plasma is optically thin, the emitted light intensity can be considered proportional to the ion density [22] and the light intensity distribution can be used as a pattern of the charge distribution. So, we can propose a typical image as a positive free charge density distribution for solving (2), such that the maximum value of the distribution can be adjusted to match with the rotation velocities and potential previously estimated with (1).

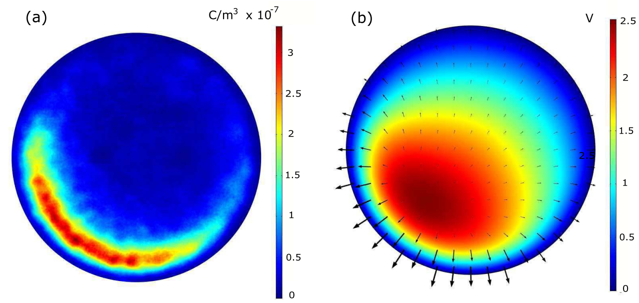

Fig. 3. Results of Poisson's equation solution obtained with a picture used as electric free charge distribution $(n_i - n_e)$. (a) Distribution and (b) potential distribution with the vector map of the electric field superimposed.

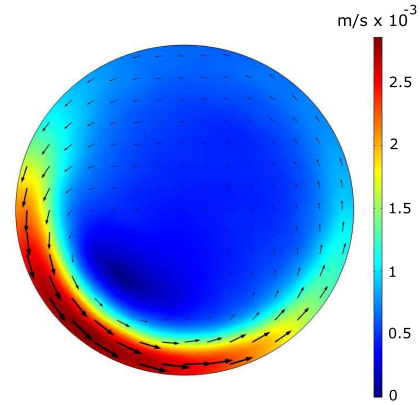

Fig. 4. $\boldsymbol{E} \times \boldsymbol{B}$ velocity distribution. The velocity norm is superimposed represented by the color distribution key.

Fig. 3 shows the results of (2) solution obtained by using the COMSOL Multi-physics software with a picture used as electric charge distribution input and the boundary conditions $\phi(R) = 0$ V and $d\phi/dr(R) = 0$ V/m, where R is the plasma chamber radius. The charge distribution is shown in Fig. 3(a), and the vectorial electric field distribution has been superimposed on the potential in Fig. 3(b). The electric field direction shows to be radial outward. Fig. 4 shows the map of $\boldsymbol{E} \times \boldsymbol{B}$ calculated with an homogeneous magnetic field entering in the page, as shown in Fig. 2, and the previously calculated $\boldsymbol{E}$ by (2). Note that Fig. 4 is a representation of the vectorial velocity distribution superimposed on the electric field norm.

Taking a charge density peak of 3×10^{-7} C/m^3 for the distribution of Fig. 3(a), the values of the electric field reach a maximum of 250 V/m, the potential of 2.5 V, and the tangential velocity of 2.7×10^3 m/s in reasonable concordance with the above calculations with (1). It means that the free nonneutralized charge particle density $(n_i - n_e)$ could reach 10^{12} m^{-3}, which implies the four orders of magnitude drop

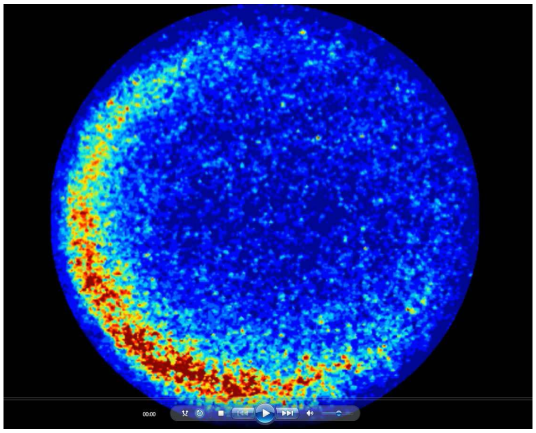

Fig. 5. Screen capture of the Half Moon plasma distribution slow-motion video (multimedia view available at http://ieeexplore.ieee.org).

in n_e with respect to typical measured values. Considering a typical $\lambda_D \approx 0.1$ mm for this kind of plasmas at quasi-neutrality condition and the previous calculations, the length scale for the present case of quasi-neutrality breaking is estimated in 100 $\lambda_D \approx 10$ mm in good agreement with the lamina thickness.

In resume, this plasma lamina rotating mode could be interpreted in terms of $\boldsymbol{E} \times \boldsymbol{B}$ drift driving a thick plasma sheath, where the scale of quasi-neutrality breaking is ten times greater than in a typical plasma sheath.

Finally, Fig. 5 shows a screen capture of a slow-motion video composed by a large number of pictures taken during different experiments and combined in order to illustrate the phenomenon. The video is available at http://ieeexplore.ieee.org.

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