Review of Spatial Distribution Modes in a 2.45-GHz Hydrogen Plasma

Ana Megía-Macías and Osvaldo Daniel Cortázar

***Abstract*— A comprehensive review of plasma distributions modes found by us in a 2.45-GHz hydrogen ECR discharge is presented for the first time. Regular and ultrafast photographs show very interesting spatial plasma shape modes never observed before for this kind of plasmas. The resonance of the discharge chamber is kept by using an optical transparent but microwave shielded quartz window with two tungsten meshes, one on each side. The experiments reveal a strong dependence of the plasma distributions on the magnetic field where the plasma is embedded. Most distributions are steady but two of them show a rotational behavior connected with $E \times B$ drift.**

***Index Terms*— $E \times B$, ECR plasma source, hydrogen, ion source, rotational plasmas, ultrafast photography.**

I. Introduction

MICROWAVE generated plasmas are very popular for multiple applications related with ion sources in the accelerator community and ion implantation industry [1], [2]. The ECR plasmas play an important role as a one of most popular and reliable ion source core for a wide range of research and applications in both communities. We present herein a comprehensive review of the plasma distributions recently reported in an ECR 2.45-GHz plasma generator using an axial magnetic field produced by coaxial coils. The experiments have been performed with the plasma discharge denominated test-bench for ion-source plasma studiesthat operates in the University of Castilla-La Mancha in Ciudad Real, Spain. The device is driven by a 3-kW adjustable power magnetron of 2.45 GHz operated in pulsed mode at 100 Hz. The system is similar to popular microwave ion sources intended for the production of intense proton beams [1], [3], [4].

II. Experimental Setup

The study of plasma distributions inside of an ECR plasma generator is a difficult task especially by photographic methods [5], [6]. The main constrain is the optical accessibility due to the necessity to keep the plasma chamber full metal integrity. This condition is essential to obtain the resonance capability in order to maximize the electric field strength in the center of the chamber [7]. This full metal integrity does not allow to have a direct sight of the plasma. If a wall of the chamber is replaced by a transparent material (usually a dielectric such as quartz) the resonance of the system is dramatically modified with a direct impact on the plasma [8]. Consequently, the images of the plasma obtained with a such set-up would not be a representative of the operational situation of a full-metal plasma chamber.

To overcome this problem, an optical transparent but microwave shielded window was developed by using two tungsten wire meshes with a 10 mm thick quartz plate in between. The window was placed where usually the extraction electrodes are (in an ion source) and it has a 7 mm diameter hole in the center to pump the chamber while keeping the gas flow dynamics in the same way of a typical ion source. From the microwave electromagnetic point of view, the double shielded transparent window is equivalent to a 10 mm thick solid metal wall but it allows to observe the plasma structures and plasma dynamics. Fig. 1 shows a scheme of the setup where the main subsystems are represented, a picture of the double mesh quartz window has been included. Note that a vacuum tee is used to pump the plasma chamber from the front area as well as it is usually made in ECR ion source allowing the observation of the whole volume from the view port *(i)*. A detailed description of the plasma source system can be seen in references [9]–[11].

III. Plasma Distributions

With the previously described setup, the spatial plasma distributions modes can be observed directly by naked eye. In fact, Figs. 2 and 3 show a *family album*, where the plasma modes are presented as they can be actually seen. The pictures were obtained with a regular digital photographic camera using 1/60-s exposure time. The magnetic field distributions and the other settings for each plasma mode can be found in [10]. The images have been not postprocessed to show the differences of the light intensity emission in each case.

The transitions between the different modes were conducted by changing the currents and axial positions of the coils (magnetic field) as well as hydrogen pressure and incoming microwave power. A microwave tuner is placed between

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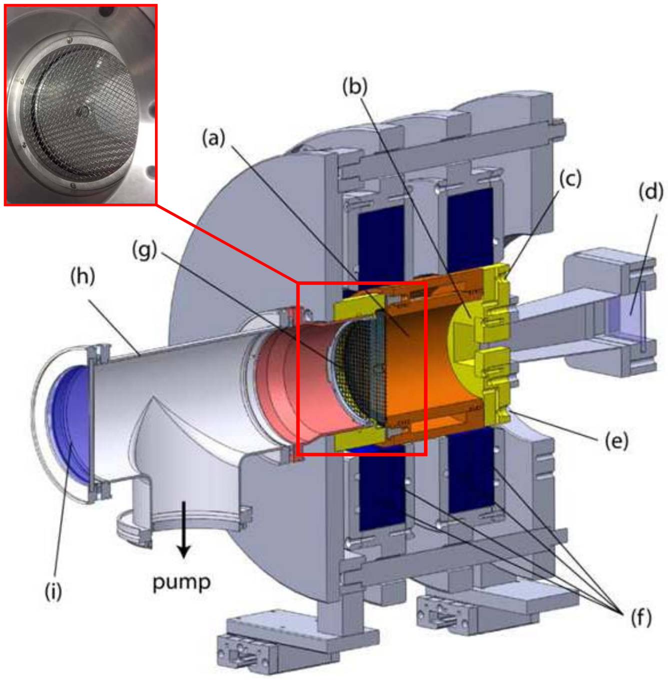

Fig. 1. Setup schematic representation. (a) Plasma chamber. (b) Microwave coupler. (c) Gas pressure gauge port. (d) Rear quartz microwave injection window. (e) Gas inlet. (f) Coils. (g) Tungsten double-mesh window (see picture detail). (h) Pumping tee. (i) View port.

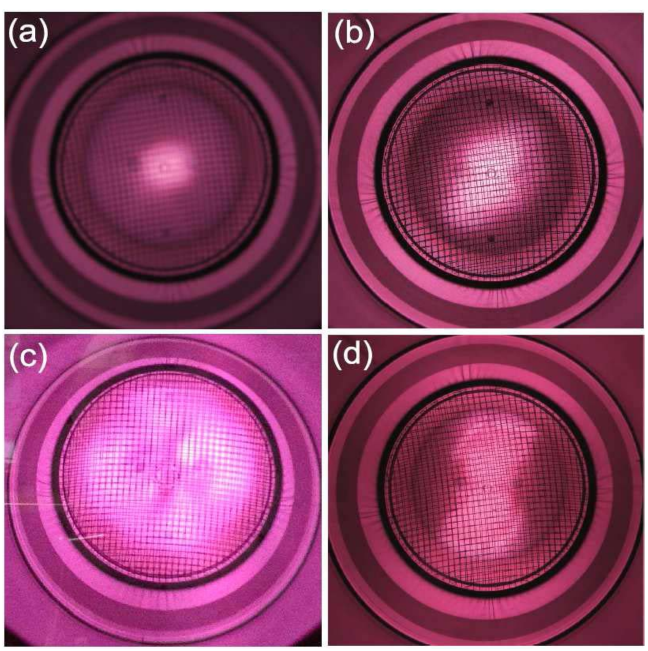

Fig. 2. Spatial plasma modes recorded with regular camera at 1/60 s of exposure time. (a) Column. (b) Slug. (c) Flower. (d) Hourglass.

the magnetron output and the plasma chamber (not shown in Fig. 1). The settings of the tuner are part of the general settings of the system and some structures show some sensitivity to this fine tuning. However, the reproducibility of the plasma modes is remarkable showing a very high stability once the parameters are established.

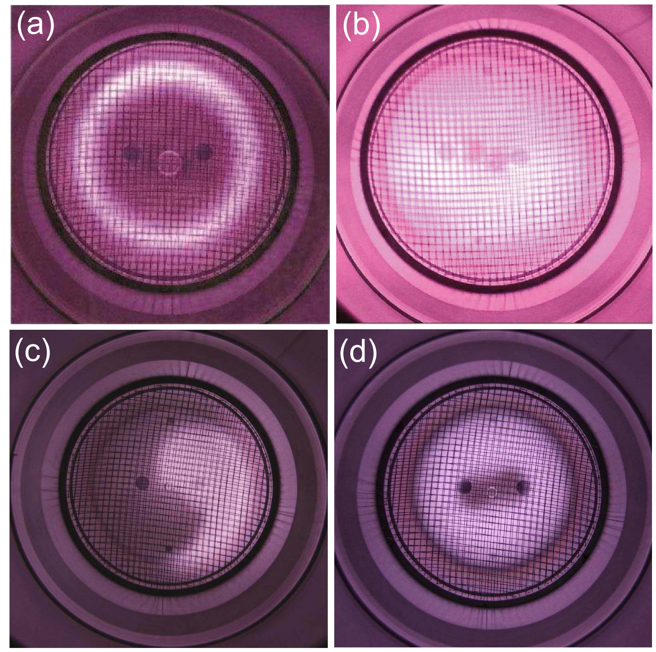

Fig. 3. Spatial plasma modes recorded with regular camera at 1/60 s of exposure time. (a) Ring. (b) Full Chamber. (c) Yin-Yang. (d) Donut.

IV. Temporal Evolution

In order to study the temporal evolution of the modes during breakdown, high-speed pictures were obtained with an intensified frame charge-coupled device (CCD) camera system made by Cordin Corporation (model 220A). The setup enables taking up to four image sequences 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 multichannel plates and the 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 to the lowest.

Figs. 4 and 5 show some typical sequences of four pictures obtained during a single-pulse breakdown of each plasma mode. The first picture shows the plasma chamber radius with a overprinted white dashed circle as reference. The delay between the microwave rising edge and the time when each picture was taken is indicated showing a wide range of variations for the typical formation time of each plasma structure from 10 μs in the case of *Fullchamber* mode to 1 ms in the *Flower* mode. A remarkable structure has been observed in the case of the *Ring*, where a ***S*** shape plasma filament is formed during the first 12 μs and then it vanishes completely by reaching the final and stable ring mode.

Most of the cases show some tendency to produce symmetrical distributions respect to the vertical axis in agreement with the electrical field orientation in the plasma chamber obtained in previous simulations [7]. The distributions of the plasma density can be estimated in the pictures by the distribution of the light intensity. Pictures by using wavelength filters centered in the *Balmer-alpha* line and *Fulcher-band* were obtained

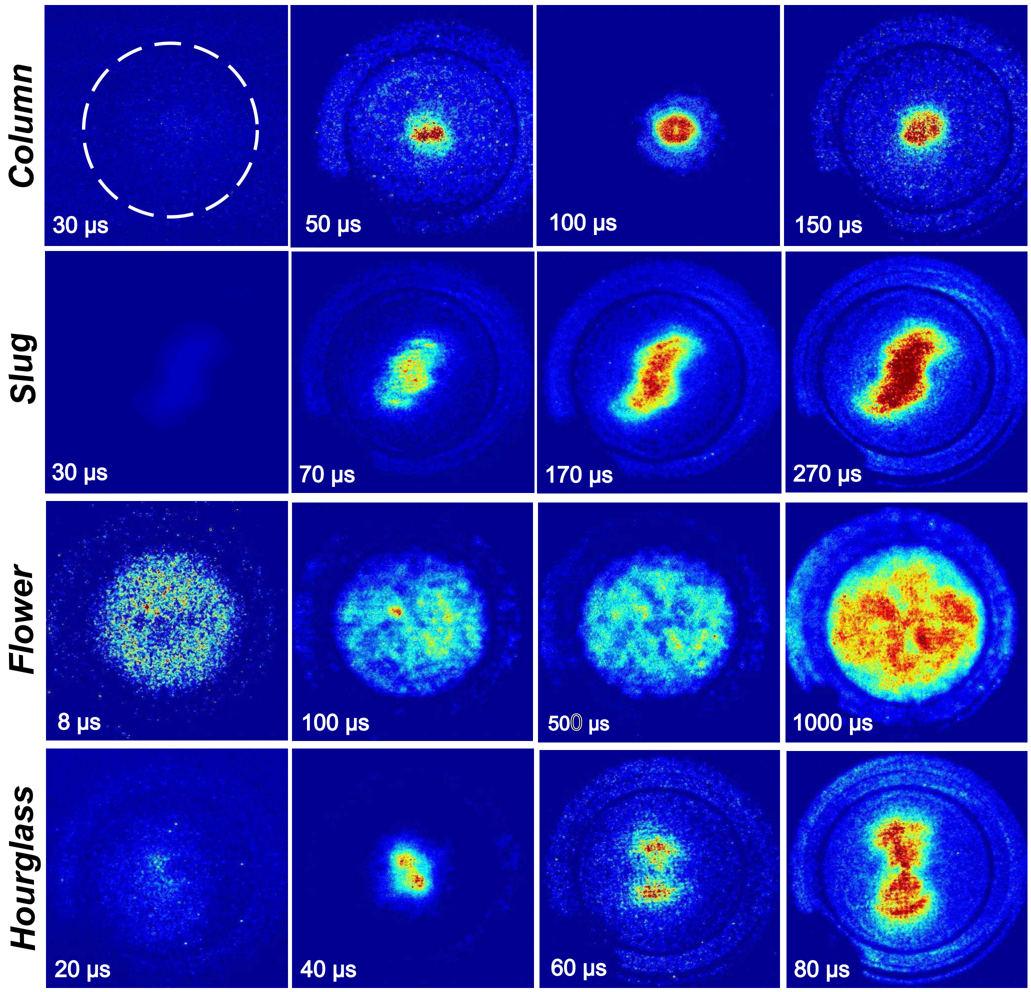

Fig. 4. Breakdown evolution pictures showing the typical evolution times for the *Column, Slug, Flower*, and *Hourglass* plasma modes. The first picture in top left corner shows the inner discharge chamber diameter in as a white dashed line.

in order to help the understanding of H^+, H_2^+ and H_3^+ dynamics [12]. Such images reveal that saturation times for *Balmer-alpha* and the times when *Fulcher-band* reaches its maximum value are different. While the *Balmer-alpha* emission grows slowly, the *Fulcher-band* emission always presents a peak at the very beginning of the breakdown process followed by a slow decay. The maximum of the *Fulcher-band* emission implies that the molecular dissociation rate through the triplet state excitation is also at maximum during the beginning of the plasma breakdown. This results aims to be related with the previous measurements of an electron temperature peak at the beginning of the pulse and other recent time resolved measurements of ion energy distribution functions [13], [14].

V. Rotational Modes

Two plasma modes show a rotational behavior related with $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity. These kind of macroscopic collective rotational structures have been observed in other low temperature plasmas arousing deep interest in the plasma physics community [15]–[18]. Fig. 6 shows two sequences of four pictures, where the structures are changing its position in time. An eccentric rotational plasma lamina is observed in the proximity of the chamber wall covering approximately 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. The experimental settings are very critical to this rotational case where any small variation vanish the effect. However, the reproducibility is remarkable once the settings are reached. The magnetic field distributions for both the cases can be found in [19]. The second sequence shows the evolution of the structure previously denominated *Yin-Yang* under a narrow range of experimental parameters. The applied power and pressure dependencies of the plasma rotation frequency is in the range of 500–2300 W and 3–9 $\times$ 10^{-3} mbar, respectively. 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 8.7×10^{-3} mbar pressure). The reproducibility of this behavior is also remarkable under the above-mentioned conditions. The general magnetic

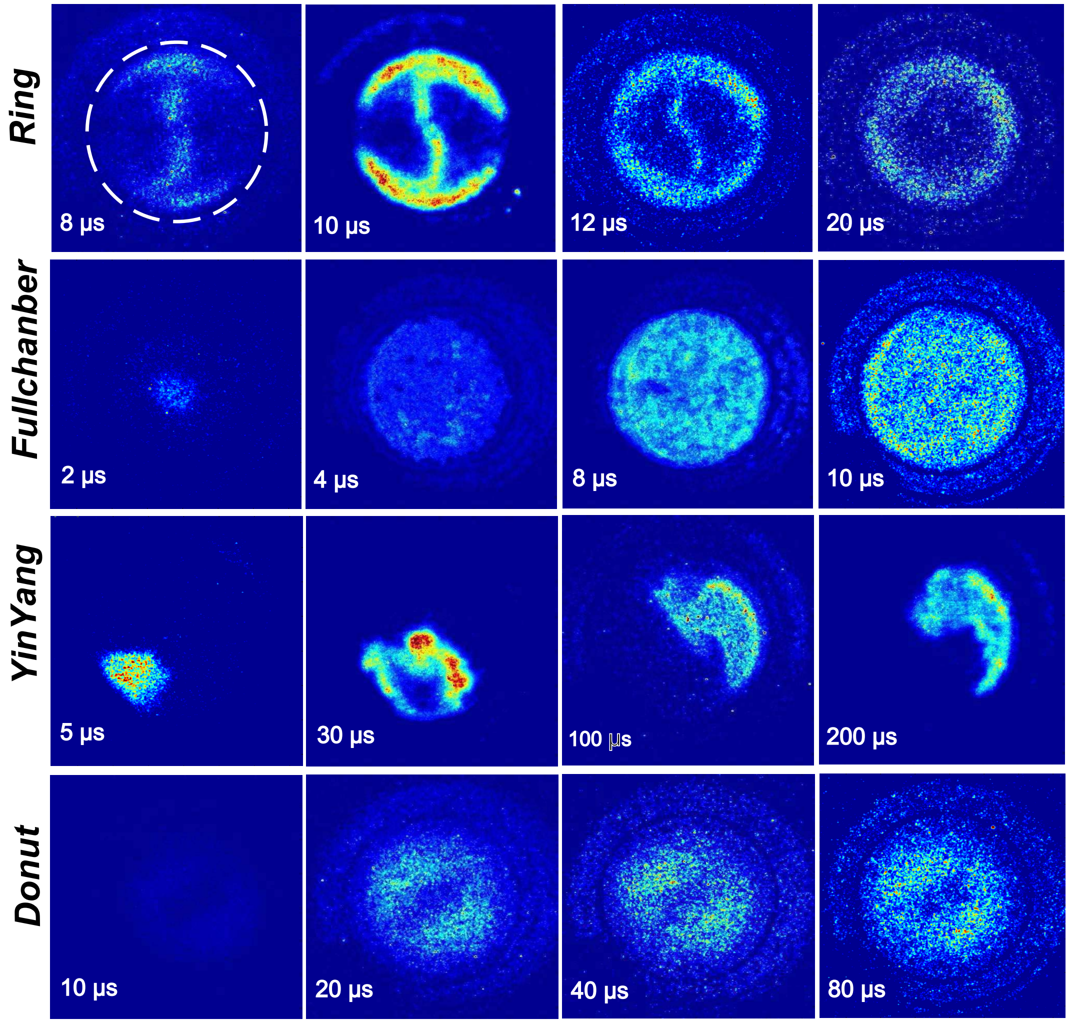

Fig. 5. Breakdown evolution pictures showing the typical evolution times for the *Ring, Fullchamber, Yin-Yang*, and *Donut* plasma modes. The first picture in top left corner shows the inner discharge chamber diameter in as a white dashed line.

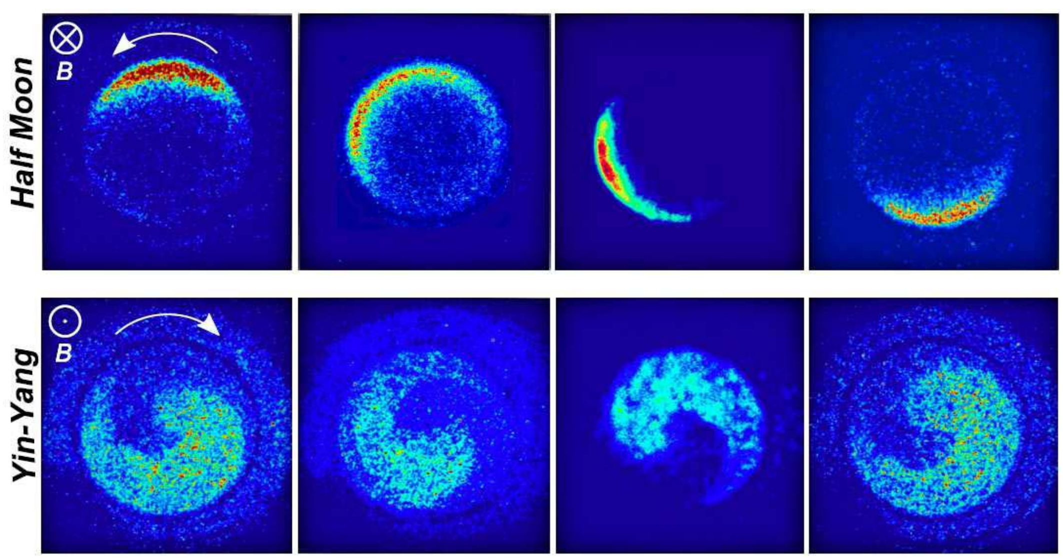

Fig. 6. Two plasma modes where a rotational behavior has been observed. Half Moon and Yin-Yang. The pictures have been obtained with 1 μs of exposure time and 30 μs each other.

field circulation is shown in the top left corner in the first picture of each sequence with the rotation way. The pictures are separated 30 μs each with an exposure time of 1 μs. Both the cases can be explained in terms of $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity [19], [20] produced by a quasi-neutrality breaking above ten times higher respect to a typical plasma sheath in this kind of devices.

VI. Conclusion

A review of the plasma structures recently found by us in a 2.45-GHz hydrogen ECR like discharge is presented. The plasma distribution modes show different kind of ionization spatial distributions and also a wide range of different formation dynamics. In spite of the big differences in terms of spatial distribution and evolution times all the plasma modes do have very similar behavior with respect to visible light emission of *Balmer-alfa* and *Fulcher-band*. Those emissions where related to the H^+, H_2^+, and H_3^+ ion populations in [12]. The external magnetic field, where the plasma is embedded, was proven to be the most important driver to produce changes between one mode to another with a remarkable reproducibility. Moreover, some structures also show a rotational behavior that can be explained in terms of $\boldsymbol{E} \times \boldsymbol{B}$ velocity drift and they could be responsible of some ion sources behaviors previously attributed to plasma instabilities.

In resume, the discovering of these distribution modes for this kind of plasmas opens an interesting new research field due to the physics involved and the different applications that could be developed. The possibilities of using these spatial plasma modes for different kinds of ion species production may be a future line of seeking.

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