COMPLEX PLASMOID BEHAVIORS IN DUSTY PLASMA EXPERIMENTS

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ABSTRACT

In this paper, we report on a particularly impressive feature of dusty plasma instabilities where moving bright plasma spots (plasmoids) appear in between the electrodes of a low-pressure capacitively-coupled rf discharge (ccrf). These plasmoids show complex behaviors like mutual interactions consisting in their merging or splitting. The interest of this study is beyond the field of dusty plasmas as well-delimited regions of enhanced emission are observed in many different kinds of plasmas (for example at atmospheric pressure in dielectric barrier discharges (DBDs).

1. INTRODUCTION

The presence of dust particles in a plasma is a relatively common situation. Dusty plasmas can be encountered in many different environments such as in astrophysics, fusion devices or industrial processes. The origin of these dust particles is usually the presence of reactive gases or material sputtering. As dust particles are growing and get charged in contact with the plasma, they can strongly disturb the plasma equilibrium when their number density is not negligible. In low pressure capacitively coupled rf discharge, low frequency instabilities can be triggered by dust particle growth [1, 2]. These unstable phenomena can be easily detected on the plasma glow emission and their complexity can be revealed thanks to high speed imaging at a few thousands frames per second (fps). A particularity of these instabilities is that they can be characterized by the appearance of well-delimited bright plasma spots in the plasma [3, 4]. These plasmoids can move through the plasma and interact with each other. Very impressive phenomena like the splitting of a single plasmoid into two parts or the merging of two separated plasmoids are also observed [4].

2. OCCURRENCE OF PLASMOIDS IN PLASMAS

Plasmoids are localized structures with an enhanced emission that are encountered in many different types of plasmas. For example, they are well known in magnetized plasmas for fusion where they are called "blobs". In this field, they are involved in transport phenomena [5, 6]. In atmospheric pressure plasmas, and especially in DBDs, these regions appear as filaments. Interactions between these structures have been observed with impressive phenomena like self-organization and merging or splitting of these regions [7, 8, 9]. These phenomena are also observed in plasma jets where plasma streams with a comet-like shape (sometimes called plasma bullet) are able to split into two parts, or to merge giving rise to a single structure [10, 11, 12, 13]. In experimental conditions closer to the present study (ccrf), we can report on relatively similar observations where moving "plasmoids" are observed in the plasma bulk [14] or in grid orifices [15]. All these different observations corresponding to localized regions of enhanced emission are certainly related to slightly different physical mechanisms driving their creation and dynamics. Nevertheless, an electrical effect is the obvious common point between all these phenomena and any further investigation on these plasmoids can provide useful information for different fields.

3. EXPERIMENTAL CONDITIONS

The plasma is created by a typical capacitively-coupled radio-frequency (13.56 MHz, ~ 3 W) discharge at low pressure ($\sim$ 1.5 mbar). One particularity is that the rf power is applied in push-pull mode, giving a more homogeneous plasma for dust particles only affected by very low frequency evolutions (from a few to a few thousands of Hz).

In this reactor [16], the two electrodes are separated by 3 cm and have a diameter of 4 cm. When the plasma is switched on, the plasma ions sputter previously injected micrometer size particles made of polymer (melamine formaldehyde) and lying on the electrodes. It leads to the injection in the gas phase of molecular precursors that can give birth to the growth of carbon based dust particles [17]. The buffer gas can be argon or krypton but in the present study, the more surprising results have been obtained with krypton. Dust particle growth induces the appearance of low frequency instabilities in the plasma. These unstable phenomena are recorded thanks to a high-speed camera with typical speeds in between 8000 and 20000 fps.

4. PLASMOIDS IN DUSTY PLASMAS

Using a standard 24 fps camera, the instabilities related to dust particle growth usually appear as striations of the plasma glow as shown in Fig. 1. These striations are mainly in the vertical direction in between the two electrodes. The unstable nature of the plasma is stronger in Kr than in Ar. It seems that it is related to slight differences in the grown dust particle population. Indeed, qualitatively, a Kr plasma produces, by sputtering, a higher amount of smaller dust particles than an Ar plasma. This higher dust density strongly disturbs the plasma equilibrium and gives rise to much more developed instabilities.

Fig. 1: Instabilities appearing during dust particle growth in a capacitively coupled rf discharge shown with a standard 24 fps CCD camera. They appear as striations in the emission of the Kr plasma.

The exact nature of the striations can only be revealed using high-speed imaging. Figure 2 taken at 8000 fps clearly shows the existence of well-localized regions of enhanced emission with typical sizes of about a few mm. They have a comet-like shape and seem to originate from the electrode vicinity. These plasmoids propagate through the plasma where they can interact with each other. These interactions can lead to changes in the plasmoid trajectories or to more drastic interactions with the merging of two colliding plasmoids. In this last case, plasmoids come progressively closer to each other and merge giving birth to a single plasmoid. The opposite situation has also been observed with the splitting of a unique spheroid into two parts. The size of the two new plasmoids is more or less the same than the one of the parent plasmoid.

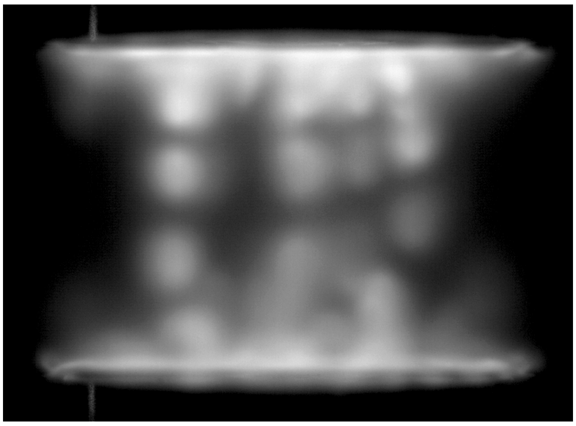

Fig. 2: Plasmoids appearing during dust particle growth and revealed thanks to high-speed imaging during the instabilities.

The changes in the plasmoid trajectory and a case of splitting are well described in Fig. 3. Each image represents the inter-electrode space in false color (from dark blue to red). In each image, the two bright regions at the top and bottom are the pre-sheath regions. The interesting events are encircled and the direction of the central plasmoid is indicated by arrows. A clear plasmoid is observed in image 7 and go towards the bottom electrode. At image 17 the appearance of a new plasmoid close to the top electrode changes the central plasmoid direction. Now, it goes up, towards the new plasmoid. At image 21 the central plasmoid splits into two parts. The lower plasmoid goes up, up to image 35 where again, the appearance of a new plasmoid (this time close to the bottom electrode) changes its direction towards the bottom.

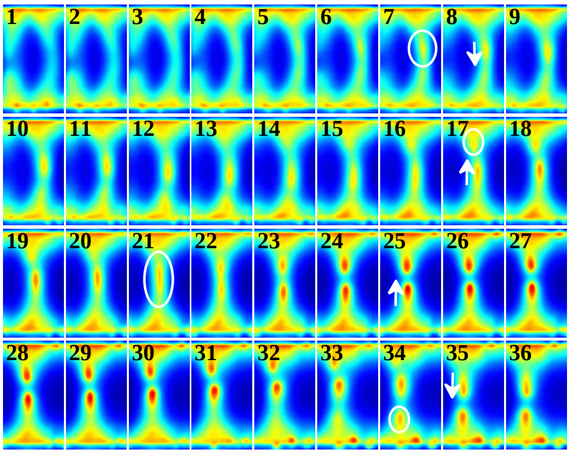

Fig. 3: *Appearance, up and down motions and splitting of spheroids in the center of the discharge. The frames are extracted from a movie at* 16000 *fps.*

The dynamics of the plasmoid can be better estimate by summarizing the whole sequence information in one single image shown in Fig. 4. To construct this image, the columns covering the region of interest have been summed up for each image. It produces a column per image and the juxtaposition of the columns gives the Fig. 4. The contrast is enhanced by subtracting a mean value calculated on each line of Fig. 4. It allows to take into account the global plasma glow structure and to enhance the central plasma regions with respect to the presheaths. The events described in Fig. 3 are encircled again in Fig. 4. The appearance of the central plasmoid is clearly evidenced and its motion towards the bottom electrode is observed until a new plasmoid appears close to the top electrode. While this new plasmoid goes towards the center, the central plasmoid clearly changes its direction towards the new plasmoid, revealing the existence of an interaction between them. The splitting of the central plasmoid is also very clearly evidenced with the connections between the new plasmoids and the parent one.

5. CONCLUSIONS

In this paper we evidenced the existence of well-delimited plasma regions characterized by an enhanced emission. These plasmoids originate from the sheath vicinity and are able to move through the whole plasma volume. Interactions between plasmoids have been shown to exist, revealing a possible electrostatic attraction between these regions. A more impressive behavior has been analyzed consisting in the splitting of a plasmoid into two parts with sizes comparable to the parent plasmoid. These experimental observations are particularly interesting as they can open new perspectives in the understanding of delimited plasma regions encountered in many different types of plasmas.

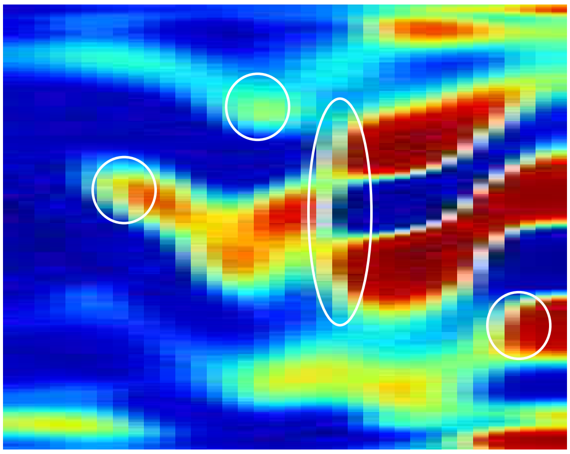

Fig. 4: *Column profile (averaged over the region of interest) constructed from Fig. 3 evidencing the plasmoid dynamics: up and down motions, attraction, splitting. Appearances of new plasmoids are encircled.*

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