Dusty Plasma Dynamics During a Void Instability: Heartbeat Instability

Maxime Mikikian, Lénaïc Couëdel, Marjorie Cavarroc, Yves Tessier, Laïfa Boufendi

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M. Mikikian*, L. Couëdel, M. Cavarroc, Y. Tessier, L. Boufendi

GREMI, Groupe de Recherches sur l'Energétique des Milieux Ionisés, UMR6606,

CNRS/Université d'Orléans, 14 rue d'Issoudun, BP6744, 45067 Orléans Cedex 2, France

**maxime.mikikian@univ-orleans.fr*

Abstract

When a three-dimensional dust cloud is present in a plasma, a dust-free region, called void, is usually observed in the plasma centre. Forces involved in the void existence are an inward electrostatic force and an outward ion drag one. Under certain conditions, this force balance can be disturbed and this region exhibits a self-excited unstable behaviour consisting in successive contractions and expansions of its size. This low frequency instability (few Hz), called "heartbeat", is here characterised by various diagnostics: electrical and optical measurements, high-speed video imaging. The results brought to the fore the main features of this instability. Correlations between physical processes in the plasma volume and the dust cloud motion are investigated through experimental results.

1. Introduction

Experiments are performed in the PKE-Nefedov chamber [1, 2]. The plasma is produced by a capacitively coupled radio frequency (rf) discharge operating in push-pull mode at 13.56 MHz. The planar parallel electrodes are 4 cm in diameter and are separated by 3 cm. In this chamber, argon is introduced to a typical pressure of 1.6 mbar (static pressure) and the plasma is ignited with a rf power of typically 2.8 W. Dust particles are grown by sputtering a polymer layer deposited on the electrodes and constituted of previously injected melamine formaldehyde dust particles. They are observed by laser light scattering using a thin laser sheet produced by a laser diode at 685 nm. Time evolution of the amplitude of the discharge current fundamental harmonic is representative of global changes in plasma properties during the instability [3] and can be related to electron density variations. This measurement is correlated with spatially resolved optical measurements (optical fibers) and high-speed camera imaging (1789 fps $\equiv$ 560 μs) during the heartbeat instability.

2. Dust cloud motion

A high-speed camera movie containing both dust cloud and central plasma glow information has been recorded for a sequence where a stable open void [2, 4] suddenly enters in size oscillation. First contraction-expansion sequence is shown in figure 1(a). Image 135 clearly shows the stable open void marked with a drawn ellipse. In image 142, plasma glow starts increasing and at nearly the same time, the void starts shrinking. Plasma glow reaches its maximum value in 144 where it appears that the enhancement affects a region bigger than the void size (assuming

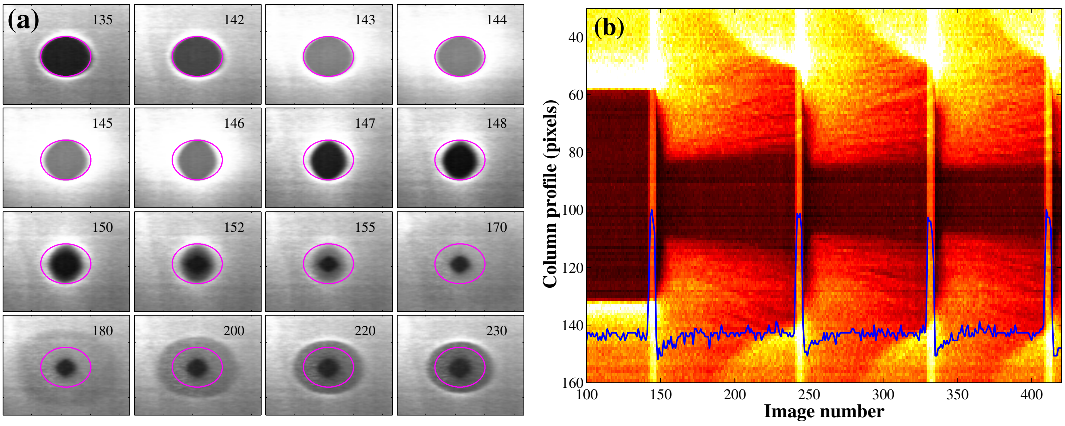

Figure 1: Simultaneous record of dust cloud and central plasma glow during the heartbeat instability: (a) direct images, (b) time evolution of central column profile (in false colors), the superimposed curve is the plasma glow in the void central pixel.

that the intensity increase in the surrounding dust cloud is entirely due to plasma glow changes and not to any dust density modifications). Then the central plasma glow starts decreasing and reaches its minimum value in image 148 before slowly increasing again. During this decrease the void continues to shrink towards its minimum size obtained in image 155. Then, void inner part slowly increases in size and a grey intermediate region, constituted of dust particles going back to their original position, becomes gradually visible from image 170. This corona region decreases in size and this motion looks like a "wave front" directed towards the void centre.

In order to better depict this contraction-expansion sequence, the time evolution of a column profile is shown in figure 1(b). To construct this false colour image, the vertical line passing through the void centre is extracted from each video image. Time is represented by image number in x-axis and column profile is given in the y-axis. This representation interest is that it gives in one single image a clear spatio-temporal characterisation of the instability. Low dust density regions appear in dark while high dust density ones appear in bright. For better understanding, temporal evolution of plasma glow in the central pixel of the void is superimposed in the image bottom. The stable open void is accurately defined with its constant size and its high dust density boundaries (between images 100 and 142). Main steps (described just above) of the contraction-expansion sequence are here clearly evidenced. Furthermore, it appears that the void didn't reach its original size when the new glow increase (contraction) occurs. This effect is traduced, first by the dark inner part which doesn't rejoin the position of the stable void and second by the intermediate corona region which is bigger than the original void size. This last point means that the wave front formed by returning dust particles is still moving towards original void boundaries, but its speed appears to slow down when approaching original conditions.

Furthermore, it is clearly visible that the instability is in a setting up phase. Indeed, starting from a stable open void, characteristics of first and second contraction-expansion sequences are slightly different in terms of minimum void size and re-opening time duration.

In some conditions the dust cloud shrinks horizontally before shrinking vertically [5, 6]. Thanks to the drawn ellipse shown in figure 1(a), it clearly appears that the void shrinks first in the horizontal direction (starting from image 143) and then in the vertical one (starting around image 147). Reasons why this effect appears in some cases are unclear due to a lack of statistics and spatiotemporal limitations of video acquisition. Nevertheless, one possible explanation is related to the reactor geometry, characterised by different confining conditions in horizontal and vertical directions. Indeed, electrodes imposed a strong electrostatic barrier and vertical modifications and motions are then drastically controlled by the sheaths.

3. Evolution of plasma glow

The whole plasma glow (not only the central part like in previous section) recorded by fast imaging during a contraction-expansion sequence is shown in figure 2(a). Presheath regions correspond approximately to upper and lower limits of the images. Before the contraction-expansion sequence (stable situation with an open void), the central plasma region is relatively uniform and not very bright (image 160). Then, the glow increases and concentrates in the discharge centre (image 200) before disappearing and leaving a darker region in the centre (image 215) as observed in previous section. Thus, contraction corresponds to a bright (i.e. higher ionisation) central region and dark (i.e. lower ionisation) edges. A reverse situation (dark centre and bright edges) starts just before the re-opening. Then, the glow becomes slowly anew uniform. The deduced line profile (figure 2(b)) is very significant and summarise the above description. Indeed, starting from a void expansion (dark inner part and bright plasma edges), slow concentration of the glow from plasma edge towards centre takes place. This motion can be correlated to the grey corona region observed in the dust cloud and presented in previous section. Furthermore, it clearly appears that the two brightest edge regions do not meet completely and no homogeneous plasma is restored. The central glow increases at the expense of plasma edges before the brightest glow regions fully converge towards plasma centre. This central enhancement is then followed by the strong and fast reversal. Electrical measurements are superimposed on line profile in figure 2(b). The bright region moving from plasma edge towards plasma centre corresponds to a continuous increase of the current. Then, it appears that the strong brightness reversal is related to the presence of a sharp peak in the current. Measurements without a clear peak are also observed and certainly correspond to cases where the brightness reversal between plasma centre and edges is not strongly marked. This sharp peak is an interesting feature al-

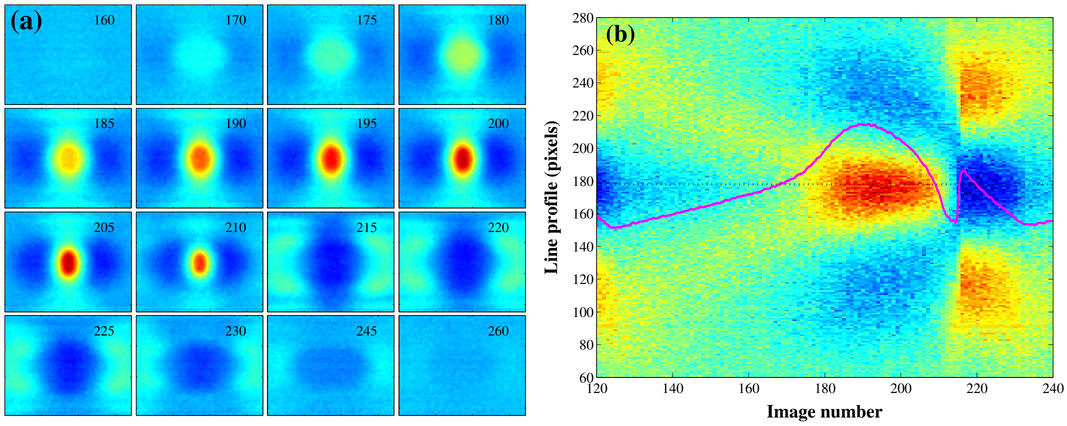

Figure 2: Plasma glow in the whole volume, (a) post-processed images in false colors, (b) time evolution of central line profile with electrical measurements superimposed.

ready observed but not fully explained. Indeed, in [3], preliminary results suggested that this peak could be correlated to a strong glow decrease in the centre and increase in the plasma edge. These measurements were performed thanks to a spatially resolved (four different positions) analysis of an argon line emission at 750.4 nm. Further results with five optical fibres (also used for characterisation of dust particle growth instabilities [7]) and integrating all plasma wavelengths gave similar results [5] but no complete description was available.

4. Conclusions

The void contraction corresponds to an increase of the central plasma glow. Thus, a sudden higher ionisation in the plasma centre enhances the ratio between the inward electrostatic force and the outward ion drag one. The void is never entirely filled by dust particles meaning that a force, supposed to be the ion drag, prevents further motion towards centre.

An asymmetry in void contraction has been evidenced in some cases. This behaviour can found its origin in the discharge geometry, confined by electrodes in the vertical direction and more free to diffuse in the horizontal one.

The sharp peak in electrical measurements can be associated with the glow reversal from bright centre and dark edges to bright edges and dark centre.

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