Threshold Phenomena in a Throbbing Dusty Plasma

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A dust cloud trapped in a plasma often contains a dust-free region ("void") near the plasma center. This void has important consequences [1, 2]: it induces a spatial inhomogeneity of the dust particle distribution and is at the origin of many intricate unstable phenomena. One of this behavior is the heartbeat instability consisting of successive contractions and expansions of the void [3]. This instability is characterized by a strong nonlinear dynamics [4] which can reveal the occurrence of incomplete sequences corresponding to failed contractions. These transitions have been recently identified as Mixed-Mode Oscillations (MMOs) [4]. In this paper we present for the first time an experimental characterization of these MMOs based on high-speed imaging. This analysis evidences a threshold phenomenon in both the dust cloud motion and the evolution of the plasma light emission [5].

Experiments are performed in the PKE-Nefedov reactor where a capacitively coupled radiofrequency (13.56 MHz) discharge is created in argon ($\sim$ 1.6 mbar, $\sim$ 2.8 W). Dust particles are grown by sputtering a polymer layer deposited on the electrodes. A few tens of seconds after plasma ignition, a visible three-dimensional dense cloud of grown dust particles (size of a few hundreds of nanometers) is formed. This cloud usually exhibits a void region in its center. The heartbeat instability can start spontaneously or can be triggered by reducing the pressure and/or increasing the power. As this instability is self-excited and very sensitive, the conditions triggering the instability can vary from one experiment to another. The instabilities are analyzed thanks to a high-speed camera at 1789 frames per second. We analyzed either the plasma glow or the dust cloud.

The evolution of the plasma glow during the instability is shown in Fig.1(a). First, we can see a strong enhancement of the central plasma emission which is related to a real void contraction (image 122) [3]. The void expansion follows and is characterized by a strongly reduced central glow in comparison with the surrounding plasma. Then, the central emission is expected to accelerate its increase (184) and to reach a value inducing the next contraction. On the contrary, the enhancement suddenly stops and the plasma emission evolves as for a classical void expansion (192) but with less marked changes. A new strong emission enhancement starts in 225 and

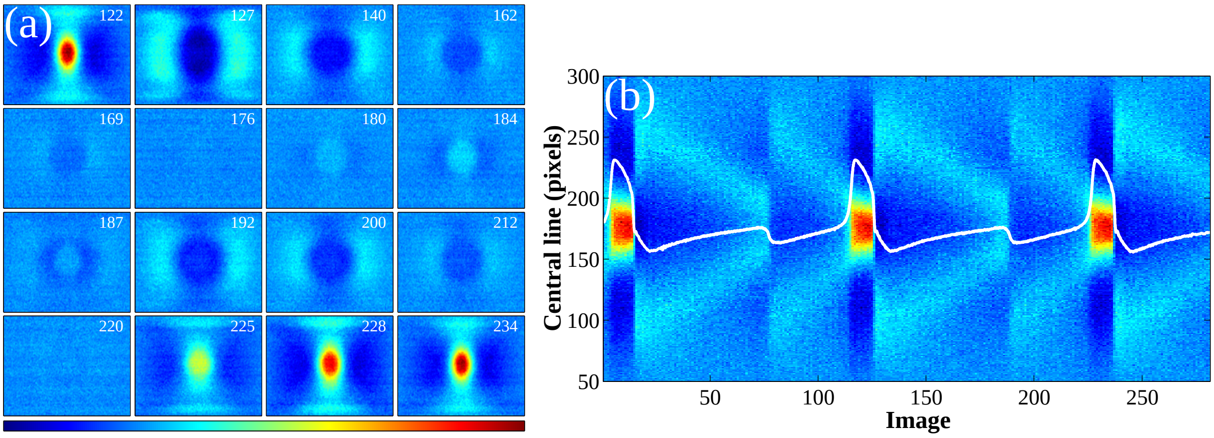

Figure 1: (a) Evolution of the plasma emission in the reactor (after image processing and with false colors) during a contraction-expansion-contraction sequence containing 1 failed contraction (image 184). (b) Spatiotemporal evolution constructed from all images by extracting their central line (discharge current is superimposed for comparison).

the maximum intensity is reached in 234 where the real contraction occurs.

In order to simplify the analysis of this complex spatiotemporal behavior, we represent the whole plasma dynamics by building one single image. On each image, the horizontal line passing through the void center is extracted [3]. By rotating these lines and putting them side by side, we obtain Fig. 1(b). Failed contractions clearly appear around image 75 and 184. After a real contraction (for example in 122), the regions of enhanced emission converge towards the center, as for a typical sequence, but once in the center (in 184) the enhancement stops and the normal contraction cannot be triggered. The system goes back to a situation close to a normal void expansion and the convergence starts again. Then, the enhancement becomes really strong and the normal contraction occurs. The failed events correspond to failed peaks in electrical or optical measurements [4] as observed by superimposing the amplitude of the discharge current in Fig. 1(b). From this analysis, it appears that failed contractions behave like usual ones, except that the emission enhancement is less marked.

Same kind of analysis has been performed for the dust cloud motion. Figure 2(a) shows the dust cloud during a sequence with two failed contractions. The series begins during a real contraction (image 130) and the void minimum size is reached around image 150. Then, the evolution of the completely empty central part of the void is little marked: main changes occur close to the bright plasma regions surrounding the void (as in image 127 of Fig. 1, see also [3]) which are out of the actual figure field of view. Figure 2 provides information when the symmetrical bright regions converge towards plasma center. Dust particle motions are thus visible from image 170. The two failed contractions occur at images 170 and 208 and the real one at

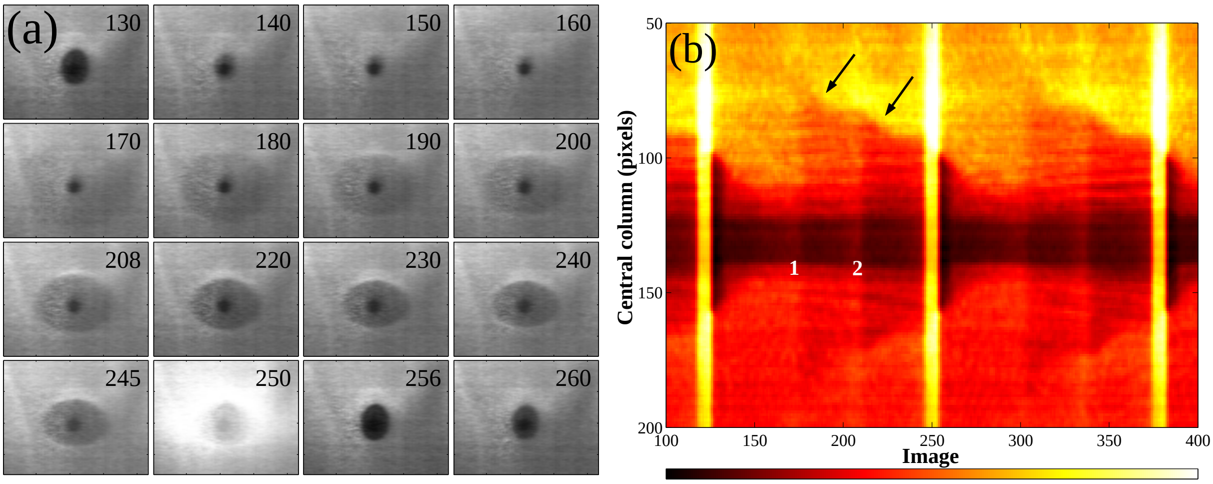

Figure 2: (a) Motion of the dust cloud during a sequence with 2 failed contractions (at images 170 and 208). (b) Spatiotemporal evolution constructed from all images by extracting their central column (failed contractions 1 and 2 indicated by numbers and arrows).

image 250 where the strong plasma light enhancement is also observed despite the presence of the interference filter on the camera. We used the same method than for Fig. 1(b) to extract the global dust cloud dynamics (Fig. 2(b)) (here the central columns are extracted instead of lines [3]). In Fig. 2(b), failed events are marked with numbers 1 and 2 close to the central dark region representing the totally empty void. Two arrows mark detectable changes induced by these failed contractions. They seem to correspond to an accelerated motion towards the center of the identifiable interface delimiting two regions of different dust particle densities. These regions are better observed in Fig. 2(a) (for example in image 180) where three regions can be described: the totally empty void, a gray region with a low density of slow dust particles and a high density region. The interface discussed above delineates the last two regions. For each failed contraction this interface accelerates its motion towards the center as seen in Fig. 2(a) between 170 and 180, or 208 and 220. Figure 2(b) confirms that the main contractions occur when a strong enhancement of the plasma emission takes place inside the void. By looking at marks 1 and 2 it proves that failed contractions also correspond to a slight enhancement of the plasma emission in the void region but below a critical threshold and thus unable to trigger a real contraction.

In this presentation, we evidenced for the first time a threshold phenomenon during the heartbeat instability. This effect can be observed on the evolution of both the global plasma emission and the dust cloud. On the plasma emission, failed events are almost similar to normal ones but are clearly characterized by variations with weaker amplitudes. The time required to reach a real contraction is shorter after a failed contraction than after a real one as shown in Fig. 1. It indicates that the system has been less perturbed and needs less time to reach the conditions for a real contraction. Concerning the dust motion, failed contractions appear as real contractions (motion towards the center), but they are weaker which is consistent with weaker changes in the plasma emission. Thus, an enhanced ionization rate (assumed to correspond to an enhanced plasma emission) in the void region corresponds to a decrease in the void size. It is the opposite situation to what is observed when the ionization rate is enhanced by, for example, increasing the power. This usually leads to an increase in the void size [6, 7, 8]. But, by increasing the power (through the electrodes) we certainly change the plasma in a global way. During the heartbeat instability the changes are self-induced and more localized in the center and thus it can lead to a different situation. Here, an enhanced ionization rate induces the void contraction by decreasing the ratio between the outward ion drag force and the inward electric force. It has been shown to be possible in the collisionless case in [9]. Nevertheless, in our case we are certainly in a collisional case as most of the time the void size is greater than the ion-neutral mean free path. In [10] it has been shown that for a collisional case, an enhanced ionization rate can induce a decrease in the void size by taking into account the ion diffusion. Very recently, a fluid simulation taking into account the variations of the ionization [11] shows that above a certain threshold of the ionization rate, the void contracts.

The results of the present paper will certainly support the approaches relating an enhanced ionization and a void contraction. It shows that it can only happen if a certain threshold for the ionization rate is reached. These new results can provide useful information on the physical mechanisms (especially the forces) involved in the void existence which is a still open challenging topic.

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