Different void regimes and the heartbeat instability in complex plasmas

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Complex or dusty plasma is a medium containing ionized gas and micron-sized solid particles. The particles are negatively charged and form strongly coupled suspensions, which are used in basic research as a model system for particle-resolved studies of generic condensed matter. A void, i. e. a microparticle-free area, disturbs the homogeneity of the suspension. The void formation and growth also determine the nanoparticle generation cycle in plasma reactors. We have found out that the void can exist in two qualitatively different regimes: “dim” and “bright” [1].

Under certain conditions, the void can periodically contract. This phenomenon is called “heartbeat instability” [2–4]. Despite two decades of investigation, the instability mechanism is still unclear. In [4], it was revealed that the heartbeat instability can be stimulated by a laser tuned in resonance with one of the spectral lines of working gas. Observations of the heartbeat instability and its optogalvanic control let us suggest that the instability occurs due to an abrupt transition between the dim and bright void regimes.

The experiments were conducted in the ground-based PK-3 Plus chamber (see Fig. 1). The plasma was produced by means of a capacitively-coupled rf discharge in argon, the pressure was 35-37 Pa. We used two types of melamine formaldehyde spheres with the diameters of 1.95 μm and 2.15 μm as microparticles. The gravity was compensated by means of thermophoresis.

The microparticles were illuminated by a laser sheet with the wavelength of 532 nm. Three Ximea MQ042RG-CM video cameras with interference bandpass filters captured the microparticle motion and the plasma emission at the same discharge area. The filters had the central wavelengths of 532, 750 and 810 nm respectively, and the transmission band width of the filters was 10 nm.

We investigated the effect of the resonant laser light on the void stability using a Toptica DL Pro laser. The width of the laser spectral line was less than 1 MHz. The power of the unattenuated laser beam was about 50 mW. The laser scanned the wavelength range of 220 MHz around the center of the 772.38 nm argon spectral line. A mechanical chopper was used to modulate the laser beam. The laser light induced the fluorescence in the 810.4 nm spectral line.

The self-excited heartbeat instability (see Fig. 2) existed within a certain range of discharge power and gas pressure and required high density of the microparticle suspension. We illustrate

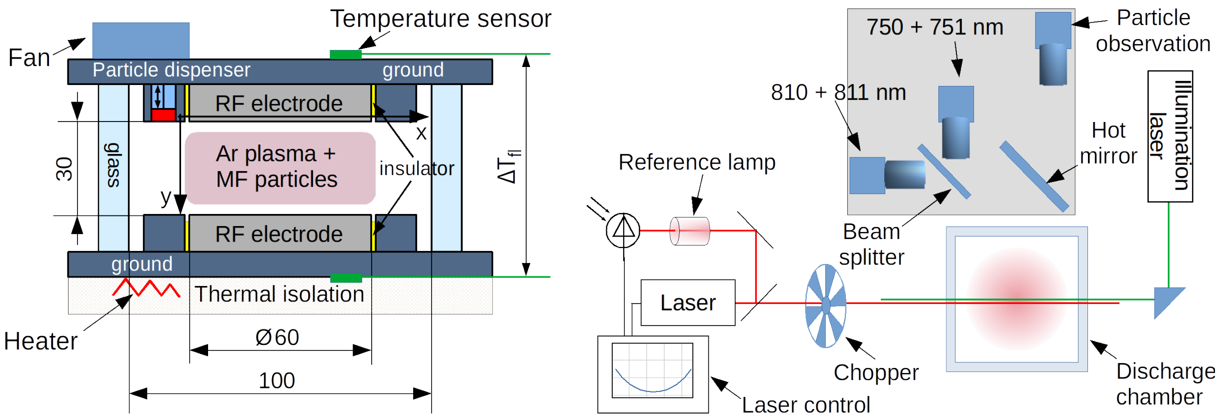

Figure 1: *Scheme of the experimental setup, (a) — side view, (b) — top view. The heart of the experiment is the PK-3 Plus chamber [5]. The bottom flange of the chamber can be heated to control the temperature gradient between the electrodes. The cameras observe the microparticle motion and plasma emission. The reference Ar lamp is used to control the wavelength of the tunable laser.*

the instability using spatiotemporal patterns (periodograms) for the velocities of the microparticles (calculated using OpenPIV code [6]) and plasma emission. For every frame, we averaged the data along the vertical (horizontal) direction in a narrow horizontal (vertical) stripe and stacked the profiles into a spatiotemporal pattern. The horizontal stripe was chosen at the height of the void, and the vertical stripe was at the center of the discharge image. Just before the void contraction, the plasma glow shortly flashed in the void, at the same time, the discharge side regions became darker. After that, the emission from the contracted void became weaker, and from the sides — brighter, than it was before the flash. Small oscillations of the microparticle motion and the plasma emission are visible in the spatiotemporal patterns between the large void collapses, similar to [2]. In the velocity patterns, a small slope of the oscillations can be seen, which suggests that the oscillations propagated from the discharge edge to the center.

Passing through the void, the continuous laser beam stabilized the microparticle suspension. The modulated laser beam stimulated the heartbeat instability, even if the microparticle suspension was stable without the laser. If the laser beam passed through the void, the void collapsed just after the beam closing. If the discharge power is not too low in comparison with the lower self-excitation boundary, and the beam power is high enough, no resonant effects were mentioned (see Fig. 3). In the case of low chopper frequency, every closing of the beam caused the void collapse. Also, some minor oscillations are visible after opening the beam. For higher chopper frequencies, the void collapses occurred once for a certain number of the laser pulses. It seems, the void must expand enough after the collapse to be ready for a new stimulated contraction. If the laser beam was shifted horizontally from the void center to the distance of 1

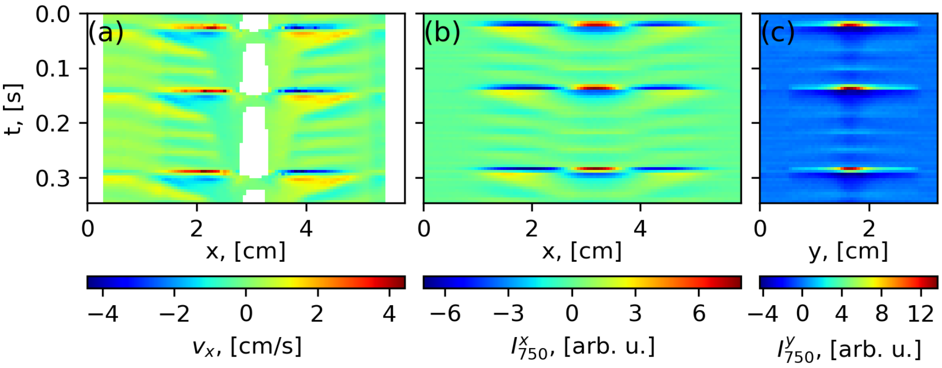

Figure 2: *Spatiotemporal distributions of (a) the velocity and (b, c) the plasma emission variations in (a, b) horizontal and (c) vertical stripes during the self-excited heartbeat instability. White color in the* v_x *plot depicts the areas in which no microparticles are present. The temporal average value of the emission is subtracted.*

cm, the void collapsed after the laser opening. If the discharge power was much lower than the heartbeat self-excitation boundary, or the laser beam was strongly attenuated, the optogalvanic heartbeat excitation had resonance character as reported in [4]. The heartbeat appeared, when the chopper frequency was close to the frequency of small oscillations which were observed without the laser.

Earlier, we found out that the stable void has two regimes: “dim” and “bright” [1]. The dim void forms at relatively low discharge powers and exhibits no emission feature associated with it. With the increase of the discharge power, the bright emission from the void appears, i.e. the void experiences a transition from the dim to the bright regime. The transition has a discontinuous character.

A simplified time-averaged 1D fluid model [1] could reproduce the bright void. The bright emission in the void was caused by the strong time-averaged electric field at the void boundary and elevated electron density inside the void. The bright void was closing without the dim void phase with the decrease of the ionization rate as soon as the ion drag force was unable to balance the electrostatic force. The dim void could be, however, obtained by artificially including a radial diffusion term into the ion flux continuity equation in a certain range of axial positions around the discharge midplane. In the microparticle suspension the radial diffusion was neglected because the microparticles are obstacles for the ion flow. Electric field at the void boundary was in this case two orders of magnitude lower than that in the bright void regime, and electron density distribution was flat. It was, therefore, demonstrated that the void in the dim and bright regimes forms due to two different mechanisms.

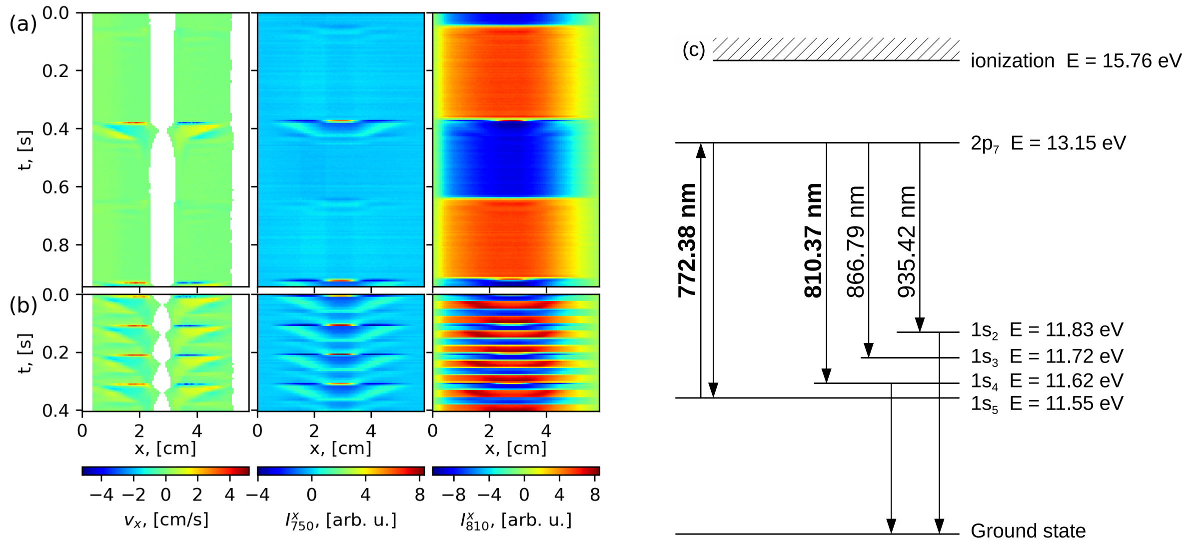

Figure 3: *(a–b) Transient optogalvanic excitation of the heartbeat instability. From the left to the right: velocities of the microparticles, the plasma emission variation captured through the filter with the central wavelength of 750 nm and 810 nm. The chopper frequency was (a) 1.7 Hz, (b) 19.6 Hz. (c) The atomic transitions induced by the laser.*

Before the contraction, the void was dim. Since the heartbeat instability is accompanied by the flash inside the void, we suggest that an abrupt transition between the dim and bright void regimes is a critical step of the instability. An increase of the ionization rate may switch the void from the dim to the bright regime. The ionization rate can be modified by the laser which explains the optogalvanic control of the instability. The laser excites the metastables to a higher excited state, then they can stepwise relax to the ground state (see Fig. 3(c)). Therefore, the laser causes a decrease of the ionization rate. In the case of self-excited heartbeat instability, transition from the dim to the bright void regime is evidently mediated by the breathing oscillations, which are precursors of the heartbeat instability.

The details of the experiment are available in [7].

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