Dust Hour Glass in a Capacitive RF Discharge

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***Abstract*— Cyclic transport of dust particles (dust hour glass) in a capacitively coupled radio frequency discharge with horizontal electrodes is demonstrated. Dust transport toward the upper electrode is initiated by varying the electrical asymmetry of the discharge. A shaped upper electrode guides dust particles to move toward the center of the discharge. Subsequently, the dust drops through the plasma bulk spontaneously, this way returning to the starting location.**

***Index Terms*— Dusty plasmas, plasma sheaths, radio frequency.**

DUST particle behavior in plasmas has been the subject of numerous investigations, motivated by the wide variety of physical phenomena that can be observed and also by the presence of dust in processing plasmas [2]. In our earlier studies, we have proposed a control method for the dust position via utilizing the electrical asymmetry effect (EAE) [3] in a capacitively coupled radio frequency (CCRF) discharge [4], [5]. The EAE is present in discharges driven by asymmetric excitation waveforms, $\phi(t)$, e.g., $\phi(t) = \phi_0\ [\cos(2\pi ft + \theta) + \cos(4\pi ft)]$. Here, f and ϕ_0 are the fundamental frequency of the waveform and the identical amplitude of both harmonics, respectively. θ is the adjustable phase angle. The EAE allows one to control the maximum sheath voltage and width at each electrode by adjusting θ, resulting in the control of the forces exerted on dust particles.

In the experiments reported here, we observe a response of the spatial distribution of dust particles to their perturbation by the EAE, which can be repeated periodically. The experiments were carried out using a CCRF discharge operated in argon gas at 4 Pa, excited by applying $\phi(t)$ with $f = 13.56$ MHz and $\phi_0 = 100$ V. Details of the experimental setup have been described elsewhere [4], [5]. The voltage waveform is generated by a dual-channel frequency generator (1 harmonic per channel). Each harmonic is amplified and matched separately. Both harmonics are then combined and applied to the lower electrode. The phase, θ, is adjusted via the frequency generator. The upper grounded electrode has a 30-mm diameter hole at the center, sealed with a fine sieve for injecting SiO_2 dust particles of 1.5 μm in size, from a dispenser situated above the upper electrode. The sieve has a convex curvature to realize a shaped sheath structure as shown in Fig. 1. The injected dust particles are illuminated by a vertical laser sheet, and are observed through a side window using a CCD camera equipped with an interference filter (see details in [4] and [5]).

The dust particles injected into the discharge are initially located at the lower sheath edge adjacent to the inside wall edge of the Al ring ($t \leq 0$ ms). At $t = 0$ ms, the abrupt change of the phase, θ, from 90° to 0° within a few microseconds is applied. This is the only phase change performed during the time interval shown in Fig. 1. Consequently, the potential suddenly changes to a high value at the location of the dust particles that have a high inertia [4], [5]. Consequently, the dust particles are accelerated by the enhanced sheath electric field at the lower electrode and, hence, part of them are transported toward the upper sheath edge and reside there ($t = 0$–133 ms in Fig. 1, sheath-to-sheath transport [4], [5]). Afterward, these dust particles, guided by gravity, move along the potential minimum at the upper sheath edge (that closely follows the contour of the electrode) toward the center and gather there ($t = 133$–600 ms). As their density in the equilibrium position at the radial center close to the upper sheath edge increases (the potential well fills up), their interaction with the plasma might be similar to that of a collective particle or dust cloud. Thus, several effects may change the conditions and forces exerted on the dust particles locally: 1) the shape of the potential surface depends on the density distribution of particles. In particular, it may change, e.g., due to a decrease of the charging of the individual particles and/or of the ion drag force exerted on them [6]; 2) the repulsive force between the dust particles becomes nonnegligible; and 3) the local agglomeration of dust particles might lead to a local depletion of the electron density, which in turn can affect the charging of individual dust particles and the local electric field. Consequently, the dust particles

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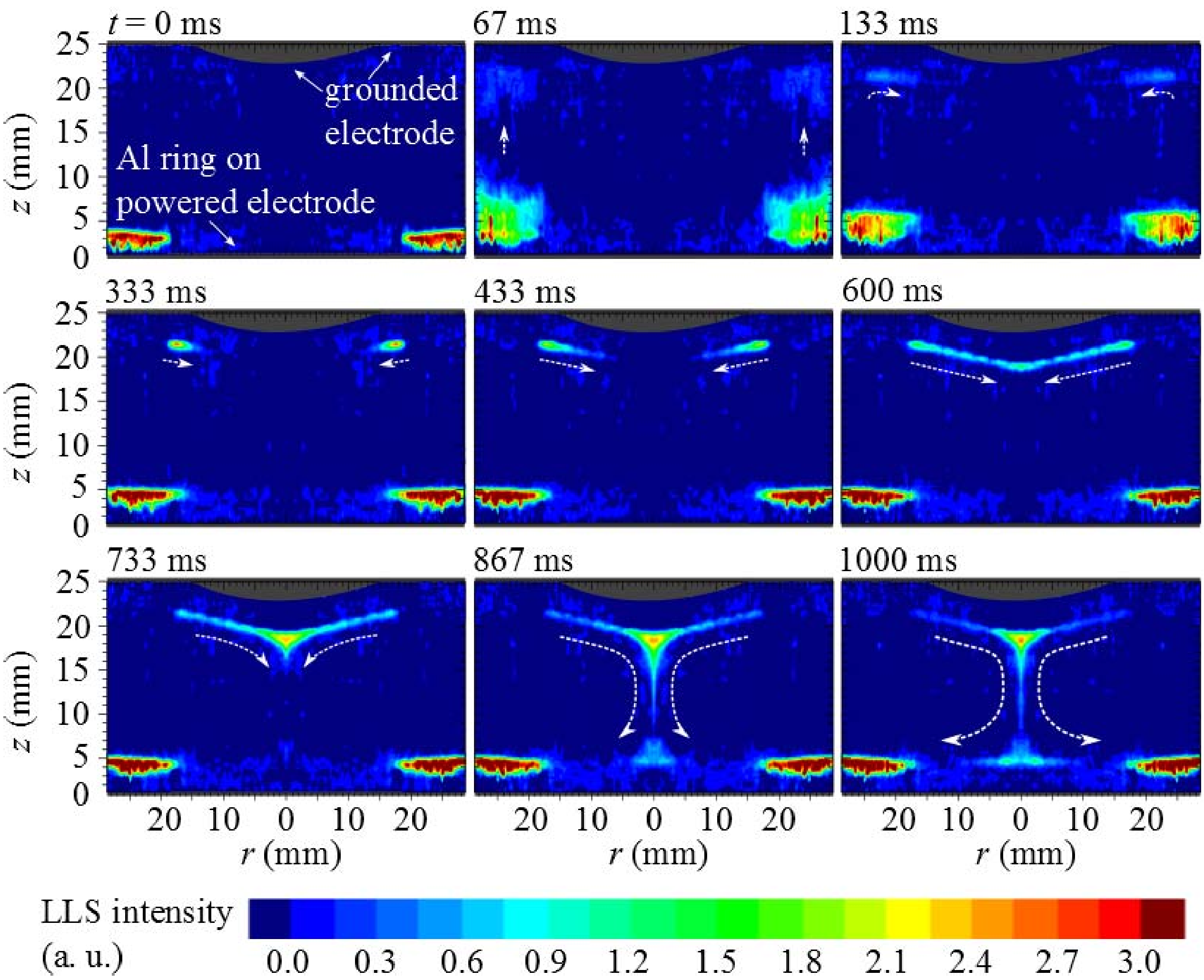

Fig. 1. Time evolution of the spatial profile of the laser light scattering intensity from the particles in the dust hour glass. An aluminum ring is set on the lower electrode to confine the dust particles radially. The discharge arrangement is cylindrically symmetrical around a vertical axis at $r = 0$. The scattering images have been mirrored for illustrative purposes. At $t = 0$ ms, the abrupt change of the phase, θ, from 90° to 0° within a few microseconds is applied, and the dust transport starts. This is the only phase change during the time interval from 0 to 1000 ms. The dust particles are transported toward the upper sheath edge due to an abrupt change of the driving voltage waveform, move to the center of the top electrode along the upper sheath edge, fall through the plasma bulk, and eventually move to the starting location of the sequence of their transport along the lower sheath edge. The complete video is accessible online [1].

begin to fall through the plasma bulk ($t \sim 733$ ms in Fig. 1), and then move back toward the starting location of their transport ($t \sim 867$–1000 ms). At $t = 1.5$ s (not shown here), except for a small population of the particles, which are trapped in the potential well at the upper sheath edge, most of them return to the starting position at the lower sheath edge adjacent to the inner wall of the Al ring. Note that when applying the abrupt change of θ from 90° to 0° repeatedly, the sequence described previously is cyclically observed keeping the total number of dust particles in the discharge volume almost constant. The cyclic transport of dust particles (dust hour glass) in CCRF discharges via the EAE might potentially be applicable to the surface processing of micro/nanoparticles.

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