Development of dust particle manipulation method in capacitively coupled plasmas via the Electrical Asymmetry Effect

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Transport of micrometer size dust particles in a capacitively coupled radio frequency plasma is realized experimentally and understood by a kinetic particle simulation combined with a model. Applying a voltage waveform consisting of two consecutive harmonics with a variable phase angle, θ, to one electrode, control of the spatial ion density and potential profile is obtained by tuning θ at low pressure. In this way, the forces exerted on dust particles are controlled. By changing θ abruptly, dust particles are transported between both sheaths through the plasma bulk.

We demonstrate a novel method to realize transport control of dust particles in capacitively coupled radio frequency (CCRF) discharges via the Electrical Asymmetry Effect (EAE) [1, 2]. The EAE allows to generate and control a dc self bias, V_{dc}, electrically even in geometrically symmetric discharges. It is based on driving one electrode with a particular voltage waveform, $\phi(t)$, which is the sum of two consecutive harmonics with an adjustable phase shift, θ, between both driving frequencies: $\phi(t) = \phi_0[\cos(2\pi ft+\theta)+\cos(4\pi ft)]$, where ϕ_0 is the identical amplitude of both harmonics. In such discharges, V_{dc} is an almost linear function of θ. At low pressures of a few Pa, the EAE additionally allows to control the maximum sheath voltage and sheath width at each electrode by adjusting θ [1]. Therefore, the spatial plasma potential and the ion density distribution are shifted in a well controllable way. Consequently also the forces acting on the dust particles, namely the electrostatic and the ion drag forces, are controlled.

The experiments are carried out using a CCRF discharge in argon gas at p = 2-9 Pa, excited by applying $\phi(t)$ with f = 13.56 MHz and ϕ_0 = 50-200 V to one electrode. The lower (powered) and upper (grounded) electrodes of 100 mm diameter are placed at a distance of 22 mm. The upper electrode has a 20 mm diameter hole sealed with a fine sieve in the center for injecting SiO_2 dust particles of 1.5 μm size from

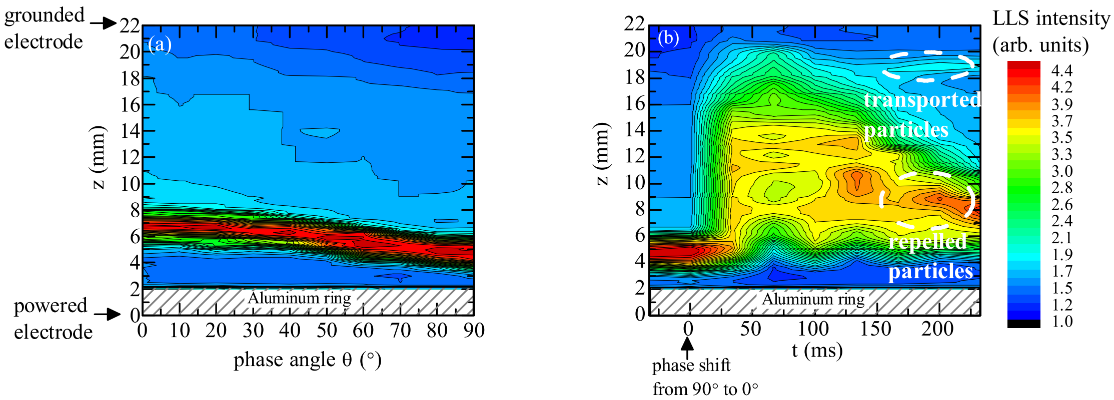

Fig. 1: (a) Spatiotemporal profile of the laser light scattering (LLS) intensity from the dust particles obtained by the (a) adiabatic or (b) sudden phase shift from 90° to 0° for ϕ_0 = 100 V and p = 2Pa.

a dispenser located above the upper electrode. An aluminum ring (100 mm outer diameter, 60 mm inner diameter, 2 mm height) is set on the lower electrode to confine the dust particles radially. In this study, the motions of dust particles corresponding to either adiabatic (slow) or sudden change of the phase were observed using two-dimensional laser light scattering. Dust particles injected into the discharge are initially located at the sheath edge adjacent to the lower electrode. The adiabatic change of the phase leaves the particles at an equilibrium position close to the lower sheath edge as shown in Fig. 1(a). If the phase is changed very quickly from 90° to 0°, all particles undergo rapid oscillations between the sheaths which is damped by friction. In the end most particles return to the initial equilibrium position at the lower electrode but a smaller group resides at a new equilibrium at the upper electrode. In this way, sheath-to-sheath transport is realized (see Fig. 1(b)) [3]. A certain threshold value of the rapid change of the self-bias is required to achieve sheath-to-sheath transport. This threshold increases with pressure, due to increasing collisionality as shown in Fig. 2(a). Figure 2(b) shows the spatial profiles of the potential energy calculated from PIC simulation data [4,5] for θ = 0° and 90° [3]. The sudden phase shift leads to a correspondingly abrupt change of the sheath width, and this introduces the particles instantaneously to a high potential that accelerates them to high kinetic energies. The mean free path of the dust particles is found to be several times as large as the bulk length [3]. Therefore the dust particles bounce between both sheaths several times while their velocity is reduced. Finally, dust particles with kinetic energy is lower than the central maximum of the potential in the plasma bulk are trapped inside either the local minimum around the upper or the lower electrode. The probability of the sheath-to-sheath transport is estimated to be $L_1/(L_1+L_2) < 0.5$, where L_1 and L_2 are the widths of the upper and lower potential wells for θ = 0°, respectively. The asymmetry of the potential profile is caused by the gravity.

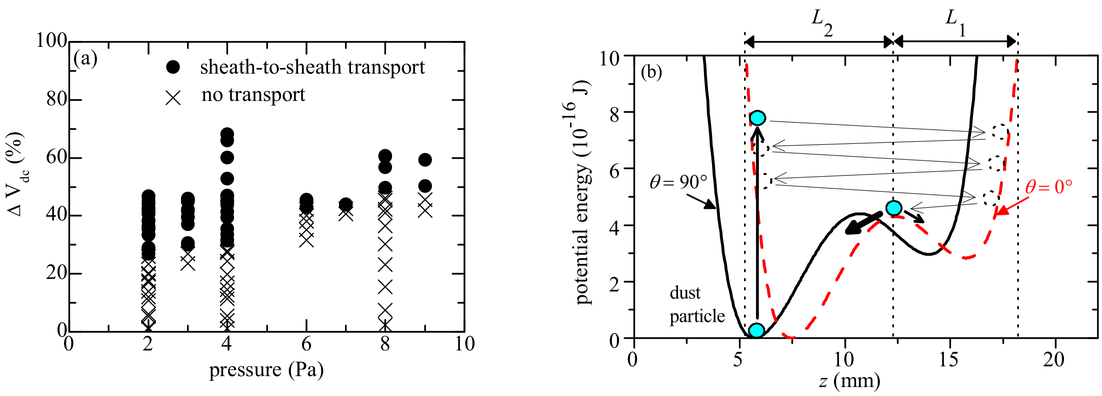

Fig. 2: (a) Classification of the sheath-to-sheath transport as parameters of pressure and change of self bias ΔV_{dc}. (b) Spatial profiles of the potential energy calculated from PIC simulation data for $\theta = 0°$ and 90°.

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