Properties of rodlike particles levitating in the sheath of rf discharge plasma

A. G. Khrapak[1] and B. M. Annaratone[2]

[1]*Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia*
[2]*Max-Planck-Institut für extraterrestrische Physik, Garching, Germany*

The interaction of the electrostatic dipole/duadrupole and the plasma sheath electric field of the rf discharge has been studied for cylindrical particles. The equilibrium orientation of the micro-rods was recorded as a function of the plasma parameters. Experiments were performed in an rf parallel plate reactor in argon plasma. In this reactor the lower electrode, 40 mm in diameter, was rf driven at 13.56 MHz, the upper electrode and the chamber being grounded. The strong geometrical asymmetry of the reactor is confirmed by the building up of a high dc bias on the electrode, about 2/3 of the rf voltage amplitude. This rf enhanced sheath has proved to be essential for the levitation of our particle, nylon micro-rods, 5 μm in diameter and 300-600 μm long, that could not levitate above the grounded electrode. The particles were visualized by illuminating the chamber with a laser, knife oriented in a vertical plane, and recorded with a video camera from side. The plasma parameters were monitored by a Langmuir probe, $r = 87.5$ μm and $l = 2$ mm. In order to re-construct the voltage profile in the sheath we have fitted a parabolic potential profile which extends from the electrode to the plasma.

Different orientation of 600 μm micro-rod particles injected in plasma was observed at different pressures. For pressures lower than 60 Pa particles levitate vertically, furthermore for the pressures lower than 22 Pa they settle in two layers and even in three layers at the very lower pressure before falling (about 15 Pa). At 60 Pa there is co-existence of vertical and horizontal orientations, and for higher pressures the particles are normally oriented horizontally.

The equilibrium orientation of rod is determined by the competition between its dipole d and quadrupole D moments [1, 2]. The dipole torque turns the rod along the electric field E, whereas the quadrupole torque tends to make it horizontal. Only two equilibrium orientation, vertical and horizontal, are possible. The condition for the stable angle α one can get from the second derivative of the potential energy: $\partial^2 U/\partial\alpha^2 \sim (\mathrm{K}-1)\cos 2\alpha > 0$, where K is the "orientational parameter", $\mathrm{K} = 2d\ell_E/D$ ($\ell_E = |E/E'|$). Particles levitate horizontally, $\alpha = \pi/2$, when K < 1, and vertically, $\alpha = 0$, when K > 1. For comparison of the obtained experimental results with the theoretical model, it is necessary to estimate some parameters of particles and plasma. The mass of the particles $m = \pi a^2 L\rho = 1.34\cdot10^{-11}$ kg. The logarithm of the aspect ratio $\Lambda = 5.48$. The electron energy $T_e = 3$ eV. The particle charge is determined according to the measured values of the electric field strength, $Z \cong mg/eE$. Then, using experimental values of ℓ_E, the parameter K is determined. It is found, that, in full agreement with our theoretical model, the vertical orientation of the rodlike particles corresponds to K = 4.3 >> 1, the horizontal one to K = 0.1 << 1, and transition from one to another orientation takes place at K ~ 1.

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