

"Experiments with Microrods in an RF Plasma Sheath"

L.R. Johnson,¹ B.M. Annaratone,¹ A.G. Khrapak,² H.M. Thomas,¹ G.E. Morfill¹

¹Max-Planck-Institut für Extraterrestrische Physik, D-85741 Garching, Germany

²Institute for High Energy Densities RAS, 125412 Moscow, Russia

The field of complex plasmas has made many advances in the past few years. It is important to extend this knowledge to the interaction of particles in the plasma sheath. In an rf-enhanced sheath, the rf voltage greatly alters the charging and levitation of particles. For elongated cylindrical particles, gravity and ion drag forces must be taken into account, and the local levitation force must be integrated over the length.

This poster presents an experimental analysis of the behavior of elongated particles suspended in an rf-enhanced plasma sheath and subjected to different forces. Two different experiments shall be presented here, both involving the neutral drag force on the microrods as they circulated through the sheath. This force allowed the particles to maintain a constant velocity as they circulated, and was counteracted either by the electrostatic or the Lorentz force exerted on the microrods. In both experiments, the sheath electric field, charging of the particles, floating potential, as well as many other factors, were used to find the forces exerted on the particles.

An argon plasma was generated in the vacuum chamber pictured below, by a radiofrequency excitation at 13.56 MHz and a peak-to-peak voltage ranging from 300 to 400 V. The upper electrode was grounded and the lower electrode driven. The diameter of the lower electrode was 30 mm, and the electrode was surrounded by a thin ring which confined the particles electrostatically. Nylon particles ($\rho = 1.14 \cdot 10^3 \text{ kg/m}^3$) of radius 5 μm and length 300 μm were injected into the plasma from a dispenser above the confining ring. The particles were illuminated by a vertical laser sheet and filmed at a 90° angle by a video camera. A Langmuir probe was used to

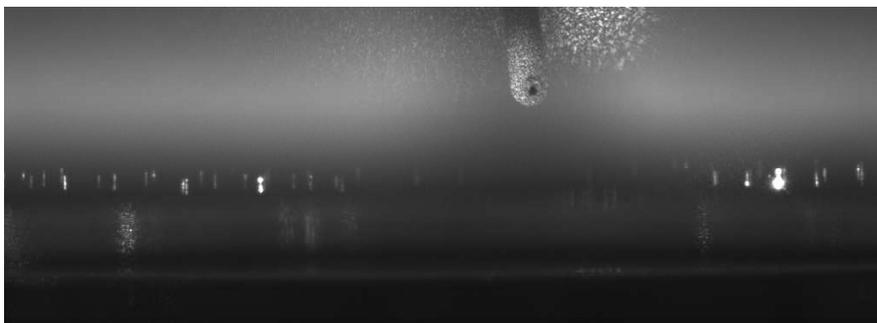


Fig 1: Particle repulsion by -60 V bias (6.5 x 8 mm frame)

measure various plasma parameters. The probe was also negatively dc biased in the electrostatic experiment. In the Langmuir probe analysis, the electrons are assumed

to have a Maxwellian

distribution, and for the pressures involved, the probe sheath is moderately collisional. The ABR theory was employed, which applies to the case of cold ions and neglects orbiting.

In both experiments, the particles levitated very near the plasma edge. The neutral drag force was compared in one case to the electrostatic force provided by a Langmuir probe immersed in the plasma and driven at a negative steady-state dc voltage. In the second variation, a magnet was placed under the vacuum vessel with the magnetic field horizontal and oriented along the video axis, and the resultant Lorentz force ($J_z \times B_x$) deflected the ion current J . Using the flux of these ions and their velocity, the force of the deflected ions was compared to the neutral drag force.

The neutral drag force was found from the classical theory of Epstein. Accomodation had to be made for the cylindrical geometry of the microrods. In Epstein's theory, there are two components of the drag force. The first component is the force of resistance of the impinging neutral particles on the microrod surface, D_i :

$$D_i = \int \int -(1/2)NmcV(\cos^2\theta + (1/2)\sin^2\theta)rdLd\theta = -(3/4)\pi rNmcVL$$

where N , m , and c are the number density, mass, and mean velocity of the neutrals respectively; V , L , and r are the velocity, length, and radius of the microrod respectively, and the integral is calculated for cylindrical geometry.

The second component involves the force of the emerging neutral particles. This component is a combination of the force of specular reflection and the force of diffuse reflection with conservation of velocity. The latter makes up 90% of the force of the emerging neutral particles. Thus, the total neutral drag force is a combination of all of these. The force of specular reflection is:

$$D_{sr} = \int \int (1/2)NmcV(\cos^2\theta - (1/2)\sin^2\theta)rdLd\theta = (\pi/4)rNmcVL$$

and the force of diffuse reflection with conservation of velocity is:

$$D_{cv} = (2/3)\int \int -(2/3)NmcV(\cos^2\theta)rdLd\theta = -(4/9)\pi rNmcVL$$

$$D_{tot} = D_i + (0.1)D_{sr} + (0.9)D_{cv}$$

For the experiments involving the Lorentz force, a bar magnet was held underneath the vacuum chamber parallel to the camera. The ion drag force was found from the Lorentz force:

$$qV_{vi}B = m_iV_{hi} / \tau$$

where B is the magnetic field in Gauss, V_{hi} is the horizontal ion velocity, $V_{vi} = (2E\lambda_{mfp}q / m_i)^{1/2}$ is the vertical ion velocity, and $\tau = \lambda_{mfp}/V_{vi}$ is the collision time. The same collision time is used for both the horizontal and vertical components. In the V_{vi} expression, E is the electric field at the

particle position and q is the charge of the ion. The mean free path is $\lambda_{\text{mfp}} = 1 / n\sigma$, where n is the neutral density, and σ is the scattering cross-section dependent on the ion energy.

The electric field E in V_{vi} is derived from the sheath potential profile using the parabolic approximation of Tomme *et al* (2000). The length of the sheath is approximated at 4 mm from the video images, and the drop in DC voltage from the plasma to the electrode is known from the Langmuir probe and dc bias. At a levitation height of 1 mm below the plasma, the electric field is $E=13850$ V/m.

From the equations mentioned above, V_{hi} can be found. For a microrod at floating potential, the ion and electron fluxes balance: $I_i = I_e$. Combining V_{hi} with the ion mass and the ion flux (I_i) to acquire the horizontal force on the microrod, a theoretical value for the microrod velocity can be determined.

$$F_{\text{hr}} = m_i I_i V_{\text{hi}} = (D_{\text{tot}} / V_{\text{exp}}) V_{\text{th}}$$

where V_{th} is the theoretical microrod velocity, V_{exp} is the experimental velocity measured from video images, and I_i is equal to:

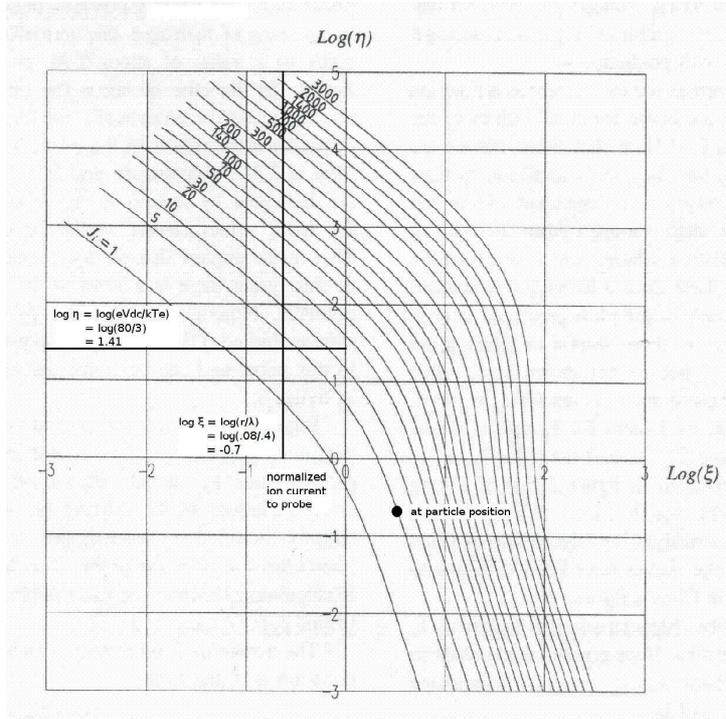
$$I_e = 2\pi r L (kT_e / 2\pi m_e)^{1/2} n_e e^{-eV_0 / kT_e} J(eV_0 / kT_e)$$

$J(eV_0 / kT_e)$ is the Bessel function of the normalized potential, which accounts for the rf-enhanced electron density in the sheath. The theoretical value is $V_{\text{th}} = 5.8 * 10^{-3}$ m/s. Comparing this to our experimental velocity, $V_{\text{exp}} = 1.64 * 10^{-3}$ m/s, we see a relatively accurate correlation.

For the experiment involving a negative dc bias on a probe immersed in the plasma, the ion drag force is vertical and negligible. The dominant horizontal force is the repulsive electrostatic force from the probe on the negatively charged microrods. Finding the experimental value for the horizontal electrostatic force is relatively simple: $QE_h = D_{\text{tot}}$, where E_h is the horizontal electric field due to the probe. The charge on the microrod, Q , is most easily and accurately derived from the equilibrium of the vertical forces: $Q = mg / E_{\text{el}}$, where E_{el} is the electric field between the plasma and electrode derived from the potential profile above, and mg is the gravitational force of a microrod. Once Q is found, it can be substituted into the former equation to find E_h .

In order to derive a theoretical value for the horizontal electrostatic force exerted by the biased probe on the particles, an electric field profile must be developed. For particle positions along the axis of the probe, the probe can be approximated to the tip, and spherical geometry is used. In the experiment described, the probe was driven at -60 V. At this potential, the effect of the electrons is negligible, and so the ion contribution is primary. Employing the theory given in

Nairn *et al* (1997), the normalized ion current (J) to the probe can be found using the normalized potential on the probe, $\eta = eV / kTe$, where V is the dc driven voltage plus the dc voltage across the plasma, and the normalized distance, $\xi = r / \lambda_D$, where r is the probe radius and λ_D is the Debye length. The normalized ion current is found at the intersection of the $\log \eta$ and $\log \xi$ graph. In our case, J was found to be approximately 5. The potential function at various distances from the probe in the plasma approximation is given as:



$$\xi / (J)^{1/2} = (e^\eta / (\eta)^{1/2})^{1/2}$$

Taking the new normalized distance at the particle position to be $\xi = d/\lambda_D$ (d \approx 1.3 mm is the distance from the particles to the probe), and following the J=5 curve at $\log(\xi)=-0.51$, $\log(\eta)$ is found to be -0.75, and η is 0.178. With the normalized potential at the particle distance and the new normalized distance known, the electric field at the particle can be found by:

$$E_h = (d\eta / d\xi)(ekTe / \lambda_D)$$

Fig 2: $\log \eta$ vs. $\log \xi$ graph for ion current to probe

$$d\eta / d\xi = (2\xi\eta / J)[e^\eta(\eta)^{1/2} - e^\eta / 2(\eta)^{1/2}]$$

In our case, this theoretical electric field is found to be 1891 V/m. This value is estimated for the plasma, and thus not totally accurate for the sheath. In comparison, the experimental value found was 1667.2 V/m. The approximated distance from the particles to the probe, the sheath approximation, as well as estimating the probe to spherical geometry, are reasonable explanations for this small discrepancy.

References

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