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Measurement of the Force on Microparticles in an Energetic Ion Beam

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Introduction

The coexistence of microparticles and streaming ions is a common situation in natural environments in space, in laboratory experiments and in technological applications. Several "dusty plasma" experiments were performed, where in an electric field drifting plasma ions [1, 2, 3] or additionally injected energetic ions [4, 5] exerted an ion wind or ion drag force on the particles via impact and deflection in the electric field of the charged microparticle. Comprehensive theoretical work has been dedicated to the ion drag force in different parameter regimes [6]. However, the ion energies theoretically and experimentally considered so far were mostly in the order of room temperature thermal energies ($\ll 1$ eV), and the ion velocities were rather isotropically distributed than directed (subthermal ion drift). Hirt *et al.* were the only ones who published an ion drag measurement for ion energies up to 40 eV. In previous studies an ion beam of several hundreds of eV was applied to modify the equilibrium position of microparticles trapped in the sheath of an rf discharge, but there the ion drag was overshadowed by strong friction in streaming gas [5]. This article focuses on the two mechanisms of the drag force due to an energetic ion beam when ion-atom collisions are significant: not only ions but also fast neutral atoms hit the microparticle and contribute to the momentum transfer.

Experiment

The ion beam is produced by a broad beam ion source, which was designed for industrial use [1]. The performance of this source has been investigated earlier and can be found in [7]. The source uses electron cyclotron resonance (ECR) in a microwave field for ionization of argon gas. Two plane molybdenum grids with a diameter of 125 mm and 751 circular 3.2 mm holes respectively are used for extraction and acceleration of the ions.

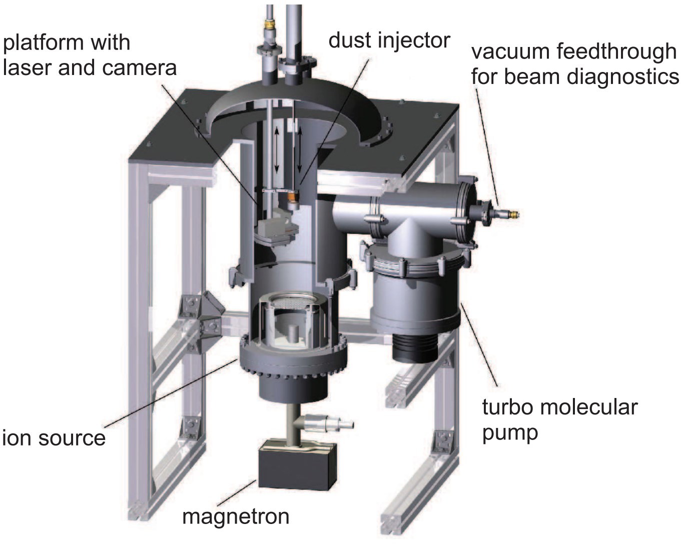

Figure 1: The <u>V</u>ertical <u>I</u>on <u>B</u>eam <u>EX</u>periment (VIBEX).

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[1] Ion-Tech MW/A 125 from Ion-Tech GmbH, Germany

The ion energy is chosen by means of the voltage of an anode ring in the ceramic ion source chamber, which allows to shift the plasma potential to corresponding positive potentials. The ion source produces beam currents up to 120 mA. The vacuum chamber is basically a vertical stainless steel cylinder with an inner diameter of 30 cm and a height of 40 cm, and the pressure in the vacuum chamber (outside the source) is 5×10^{-2} Pa.

The model particles are spherical hollow glass microspheres with narrow size distribution of $r_\mathrm{p} = (100 \pm 15)\ \mu$m, wall thicknesses of $d_\mathrm{p} = (0.74 \pm 0.28)\ \mu$m and masses of $m_\mathrm{p} = (5.0 \pm 2.3) \times 10^{-11}$ kg. The particles are injected downwards into the beam, where they are stroboscopically illuminated with a 5 mW horizontally oriented laser diode (655 nm) which is vertically expanded to a thin fan. A charge-coupled device (CCD) camera records their trajectories. Laser and camera are mounted on a platform in the vacuum chamber at a distance of $z = 30$ cm above the ion source.

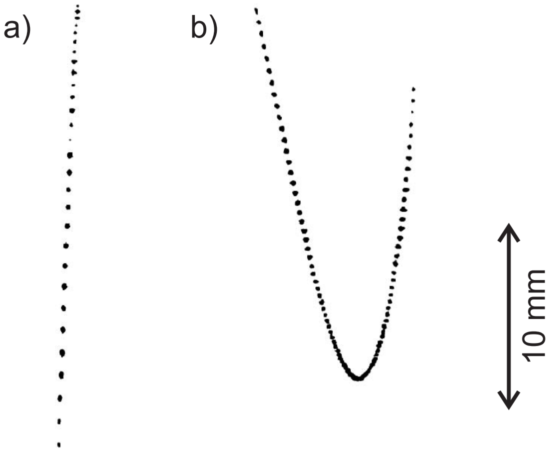

Figure 2: Particle trajectories (a) without beam and (b) with a 410 eV beam. The stroboscopic frequency is 500 s^{-1} in both cases.

The trajectory shown in Fig. 2(a) appears as dotted line due to the stroboscopic illumination with 500 Hz, so that each spot serves as timestamp. In this case the beam was switched off, so that the particle was freely falling only under the influence of gravity (gas friction can be neglected at this low pressure). The increasing velocity can clearly be seen from the downwards increasing distance between the dots. Figure 2(b) shows a particle trajectory under the additional influence of an ion beam. The microsphere is injected into the field of view with an initial, essentially downward directed velocity, decelerates, reaches a turning point and is accelerated upwards. The trajectories are well described by parabola equations, which indicates that the movement has a constant horizontal velocity and a uniform vertical acceleration.

Results and Discussion

Figure 3 displays the measured force (from which the gravitational force has been subtracted). Two sets of measurements have been performed for different particle injector heights. As one expects, the starting height of the particles does not affect their acceleration, and therefore both measurements are in good agreement. The forces are derived from the observed accelerations using their mean mass.

In a first attempt the measured forces are compared to the ion drag force in its conventional form. Due to the high kinetic energy of an ion in comparison to its potential energy at the particle surface, the effective cross section is nearly identical with the geometrical cross section, and the ion drag can be written as

$$F_\mathrm{i} = \pi r_\mathrm{p}^2 m_\mathrm{i} \left(\frac{2W_\mathrm{i}}{m_\mathrm{i}} \right)^{\frac{1}{2}} \frac{j_\mathrm{i}}{e} \qquad , \tag{1}$$

where W_i is the preset ion energy and j_i is the ion current density, which is measured with a Faraday cup. The argon ion mass is m_i, and e is the elementary charge. The resulting ion drag forces are shown in Fig. 3.

The calculated ion drag force is smaller by a factor of two to four in comparison with the force measurement, which cannot be explained alone with the high statistical errors of the force measurements. For that reason we consider now the contribution of fast neutral atoms, which are created by collisions of argon ions with argon atoms from the background gas in the target chamber.

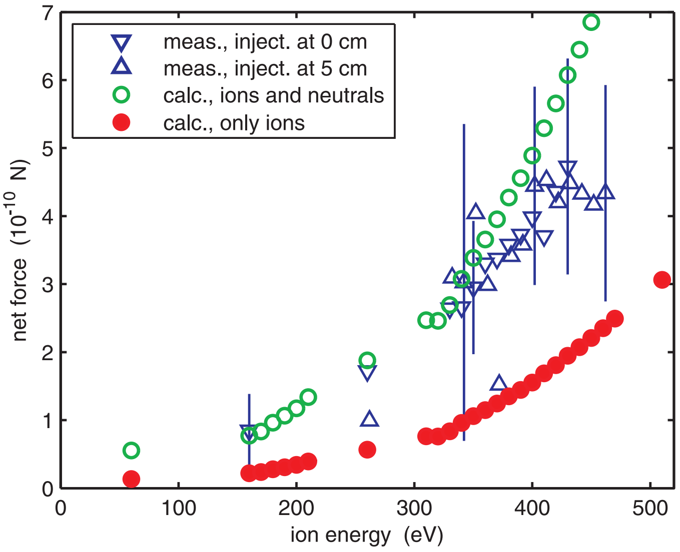

Figure 3: Comparison of the measured beam drag force with the calculated forces exerted by ions alone and by ions and fast neutral atoms together.

For a simple model we use the analytic approximations given by Phelps for experimental data of energy dependent cross sections [8]. It turns out that charge-exchange collisions are the dominating effect at such high kinetic ion energies. In a charge-exchange collision, ion and atom change their identities, and in particular the momentum of the former ion is essentially conserved (see Aberth and Lorents [9]). When such an energetic atom collides with the microparticle, momentum is transferred in the same way as if the atom were an ion. The fit formula given by Phelps show, that the mean free paths $\lambda_\mathrm{cx} \approx 25$ cm are somewhat smaller than the trajectory length from the ion source to the microparticle which is $z \approx 30$ cm. The total force, including energetic ions and neutral atoms, is

$$F_\mathrm{i+n} = F_\mathrm{i} \exp\left(\frac{z}{\lambda_\mathrm{cx}} \right) \qquad . \tag{2}$$

The exponential factor in this equation is then in the range of three to four. Figure 3 shows also the total force $F_\mathrm{i+n}$, which finally is in good agreement with the measurement.

Conclusion

In this contribution we have studied the force exerted on a microparticle in an energetic ion beam. The measured particle accelerations were in the order of magnitude of the gravitational acceleration. A simple model for the quantitative understanding of the ion beam force was presented, which takes charge-exchange collisions of beam ions with background gas atoms into account. The energetic neutral atoms are found to be responsible for more than half of the total force due to the mean free paths somewhat smaller than the distance between ion source and microparticle. For calculation of the ion part of the force, the geometrical cross section has been used, which differs only negligibly from the momentum transfer cross section for charged particles.

A further improvement of the experiment could be the use of model dust with well known and narrow size and mass distribution, in order to reduce the errors in the force and the statistical error in the acceleration measurements. This would be an important step toward the application of the presented technique as a novel beam diagnostic supplemental to electrostatic methods, and could become a useful tool in the development both of terrestrial ion beam sources and of ion thrusters for space flights. Some future scientific space missions demand for highly precise micronewton thrusters for attitude and position control. A novel indirect thrust measurement technique using microparticles would be especially useful in the development of ion engines in the very low thrust range [10].

References

[1] C. Zafiu, A. Melzer, and A. Piel, Phys. Plasmas **10**, 1278 (2003)

[2] V. V. Yaroshenko, S. Ratynskaia, S. A. Khrapak, M. H. Thoma, M. Kretschmer, and G. E. Morfill, Contrib. Plasma Phys. **45**, 223 (2005)

[3] T. Trottenberg, D. Block, and A. Piel, Phys. Plasmas **13**, 042105 (2006)

[4] M. Hirt, D. Block, and A. Piel, Phys. Plasmas **11**, 5690 (2004)

[5] H. Kersten, R. Wiese, H. Neumann, and R. Hippler, Plasma Phys. Control. Fusion **48**, B105 (2006)

[6] V. Fortov, A. Ivlev, S. Khrapak, A. Khrapak, and G. Morfill, Phys. Rep. **421**, 1 (2005)

[7] M. Zeuner, F. Scholze, H. Neumann, T. Chassé, G. Otto, D. Roth, A. Hellmich, and B. Ocker, Surf. Coat. Technol. **142–144**, 11 (2001)

[8] A. V. Phelps, J. Appl. Phys. **76**, 747 (1994)

[9] W. Aberth and D. C. Lorents, Phys. Rev. **144**, 109 (1966)

[10] D. Feili, D. M. Di Cara, H. J. Leiter, J. G. Del Amo, H. W. Loeb, St. Weis, D. Kirmse, P. E. Frigot, M. Orlandi, H. Müller, and B. K. Meyer, in *Proceedings of the 30th International Electric Propulsion Conference, Florence, Italy*, IEPC-2007-218 (2007)