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Published in: Physical Review E

DOI: 10.1103/PhysRevE.88.055101

Published: 01/01/2013

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Download date: 24. Oct. 2018
Absolute measurement of the total ion-drag force on a single plasma-confined microparticle at the void edge under microgravity conditions

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(Received 30 August 2013; published 19 November 2013)

We present an absolute measurement of the total ion-drag force on one single microparticle at the edge of the void where usually the induced void would have its edge. In this Brief Report we present an absolute measurement of the ion-drag force on a single microparticle at the position of the border of the void, during parabolic flights. The results were obtained by performing measurements at a gas pressure which is chosen such that a single microparticle (particle 1 with mass $m_{p1}$ and radius $r_{p1}$) under normal gravity conditions ($g = 1g_0$, with $g_0 = 9.81 \, \text{m/s}^2$) is confined at the same positions $z_{eq}$ as a larger microparticle (particle 2 with mass $m_{p2}$ and radius $r_{p2}$) under microgravity conditions ($g = 0g_0$) during parabolic flights. The mentioned configurations are denoted with “Configuration 1” and “Configuration 2,” respectively in Fig. 1.

On the particle in equilibrium position $z_{eq}$ in configuration 1, the force balance consists of three dominant forces: the gravitational force $\vec{F}_{g1} = m_{p1} g_0$, the total ion-drag force $\vec{F}_{i1}(z_{eq})$, and the compensating electrostatic force $\vec{F}_{e1}(z_{eq})$. Here $m_{p1}$, $Q_{p1}(z_{eq})$, and $E_{1}(z_{eq})$ are the mass, the time-averaged local charge of particle 1, and the time-averaged local value of the shear electric field, respectively. The force balance for configuration 1 at position $z_{eq}$ yields

$$\vec{F}_{g1} + \vec{F}_{i1}(z_{eq}) = \vec{F}_{e1}(z_{eq}),$$  \hspace{1cm} (1)

For configuration 2, the gravitational force is absent and, hence, the force balance—also at $z = z_{eq}$—is given by

$$\vec{F}_{i2}(z_{eq}) = \vec{F}_{e2}(z_{eq}).$$  \hspace{1cm} (2)

In absence of gas flows (sealed vessel during experiments), the neutral drag force is zero. Furthermore, temperature gradients and laser intensity are sufficiently low that thermophoretic and laser-irradiation forces can safely be neglected (see also Ref. [21]).
radii and $\vec{F}_{g1}$ is easily derived:

$$\vec{F}_{i2}(zeq) = \left( \frac{r_{p1}}{r_{p2}} \right)^{-1} \vec{F}_{g1}.$$  

(3)

III. EXPERIMENT

The experiments were performed in a sealed 200 x 200 x 200 mm³ aluminum vacuum chamber filled with argon gas at a certain set (but variable) pressure. A ~5 W radio frequency (rf) driven (at 13.56 MHz) discharge was operated between two squared (70 x 70 mm²) parallel plate electrodes aligned within the horizontal plane and vertically separated 40 mm. Microparticles of either 2.45 or 4.90 μm in radius were injected one by one by a home-built particle injector, after which they fell through a hole in the upper (grounded) electrode. Once in the discharge region, these particles gained negative charge and became confined within the electric field in the plasma sheath just above the rf powered lower electrode. A 1 mm deep indent in this electrode prevented the particles from horizontal loss. The geometrical size of this indent was chosen such that in the center, and at least a few millimeters around, the equipotential surface was horizontally flat; this has been verified by monitoring the equilibrium position of one full layer of monodisperse microparticles. The singly confined microparticle was illuminated by an expanded 532 nm diode laser beam while its vertical equilibrium position was monitored by a CCD camera behind a 532 nm interference filter with 20 ms time resolution. The apparent gravitational acceleration was measured in three perpendicular directions by an accelerometer with 20 ms time resolution as well. The vacuum chamber, together with the vacuum pump, gas- and power supplies, optics, and readout electronics, was mounted on a base plate, which was—for the microgravity experiments—mounted in the Novespace Airbus A300 with which parabolic flights were carried out. During these parabolic flights, the airplane originally flying at fixed height pulls up for about 20 s, inducing hypergravity conditions (at about $1.8g_0$). After this hypergravity phase, the airplane lowers its engine power such that it is just sufficient to overcome air friction. Hence, the airplane and all experiments in it are subject to free fall. This induces microgravity conditions for about 20 s after which the airplane has to pull up in order to prevent crashing.

It should be noted that the changes in apparent gravitational acceleration were sufficiently slow to allow the particle to adapt its equilibrium position instantaneously.

IV. RESULTS AND INTERPRETATION

Figure 2 gives the vertical confinement position of the particle with $r_p = 4.90$ μm as a function of time for three different gas pressures. As can be observed, during the hypergravity phase, the particles are pulled closer to the electrode. When via the second transition phase $T$ the apparent gravitational acceleration is altered towards microgravity, the particle appears to be confined at positions closer to the plasma bulk, i.e., this is the position at which the ratio between the ion-drag and electrostatic forces $F_i/F_E$ equals
unity, i.e., the traditional position of the void edge. As can be observed, at and below 0.16 mbar the microparticle is lost from the discharge under microgravity conditions. Since the particle would be vertically confined in the upper part of the discharge as well, the particle is thought to be lost horizontally by small horizontal accelerations in the airplane; at these high equilibrium positions, the horizontal confinement induced by the indent in the lower electrode is not effective anymore.

The vertical confinement positions of the $r_p = 4.90 \, \mu m$ particle under microgravity conditions have been plotted as a function of the gas pressure in Fig. 3 together with the confinement position of the $r_p = 2.45 \, \mu m$ particle under normal gravitational conditions in the laboratory. Indeed, these two profiles show intersection at $0.18 \pm 0.01$ mbar. At this intersection point Eq. (3) applies. At the corresponding position ($z = z_{eq} = 6.3 \pm 0.1$ mm) above the powered RF electrode, we find for the total ion-drag force on the $r_p = 4.90 \, \mu m$ microparticle: $\vec{F}_{i2} = (3.6 \pm 0.3) \times 10^{-12}$ N. In this method, the error bar of $0.3 \times 10^{-12}$ N is induced by the uncertainty in the radii of the particles used, influencing the uncertainty of the values of $r_{p1}$, $r_{p2}$, and $\vec{F}_{g1}$ in Eq. (3).

Although not used to determine $F_{i2}(z_{eq})$ we sum up some plasma parameters for this configuration in order to support future modeling efforts to reveal solutions to the fundamental questions left regarding the ion-drag force. For that we use the values found in Ref. [21] for exactly the same configuration and plasma settings at a pressure (0.20 mbar) very close to the intersection pressure found in this work: sheath width, 7.0 \pm 0.5 mm; plasma potential, 32 \pm 6 V; electron bias potential, $-82 \pm 1$ V; plasma density, $(7 \pm 2) \times 10^{14}$ m$^{-3}$; and electron temperature, 2.0 \pm 0.5 eV.

Despite the fact that the found value for the total ion-drag force lays well within the range of ion-drag forces published in the literature [4,8], comparison of the results obtained here with that obtained in the literature is rather difficult. The reason for this is the fact that all measurements and numerical simulations published so far have the necessity to make assumptions about the available models (e.g., shielding length, influence of collisions) and/or the need to measure or “guess” other plasma parameters such as the local ion velocity, electrical field, and plasma density.

V. THE MODEL’S SENSITIVITY TO THE USED ASSUMPTIONS

In our analysis, the error bar in the value of $F_{i2}(z_{eq})$ is determined by the uncertainties in $r_{p1}$ and $r_{p2}$. Here we investigate the sensitivity of the obtained result against the two assumptions done. First, for the sensitivity with respect to the first assumption that the ion-drag force depends on $r_{p2}$, we have determined the upper limit of the influence of the $r_p$ dependence of the Coulomb logarithm taken into account in the orbital component of the ion-drag force [18,19]. Since the intersection point of the two curves in Fig. 3 is close to the transition from plasma sheath to plasma bulk [21], we have used for this estimate a directed ion velocity equal to the Bohm velocity and a Debye length as normally calculated in the plasma bulk. Assuming that 100% of the ion drag is delivered by the orbital-drag force (the collection component to the ion-drag force depends always on $r_p^2$), delivering the largest possible deviation from $r_p^2$ dependence of $F_{i2}(z_{eq})$, the influence is estimated at about 35% of the total value. Although at low ion velocities (close to the plasma bulk) the orbital component is large compared to the collection component, indeed, this deviation is an absolute overestimation. Second, we investigate the sensitivity of the result with respect to the second assumption that the particle charge depends linearly on $r_p$. Especially under conditions where collisions between streaming ions and neutrals become more important, these ions are caused to lose energy and may become trapped in the Debye cloud which electrostatically shields the negative charge on the particle. Once these ions are collected by the particle, this additional term in the ion current lowers the negative particle potential. From Ref. [23] we estimate that the maximum reduction in particle potential for the larger particle with respect to the smaller particle is about 10%. In turn, this effect may cause a deviation of the end result of less than 5%.

VI. CONCLUSION

In this Brief Report we have presented an absolute measurement of the total ion-drag force on one single microparticle at the traditional border of a void.

ACKNOWLEDGMENTS

This research was financially supported by ESA Grant No. 21045/07/NL/VJ and by the Netherlands Space Office, SRON. The authors are grateful to the ESA and Novespace for having us participating in their 54th parabolic flight campaign. Finally, Ab Schrader is especially acknowledged for his skilled support up front and during the measurement campaign.