Ion-Wake-Mediated Particle Interaction in a Magnetized-Plasma Flow

Jan Carstensen, Franko Greiner, and Alexander Piel
IEAP, Christian-Albrechts-Universität, D-24098 Kiel, Germany

(Received 11 July 2012; published 27 September 2012)

The interaction forces between dust grains in a flowing plasma are strongly modified by the formation of ion wakes. Here, we study the interparticle forces mediated by ion wakes in the presence of a strong magnetic field parallel to the ion flow. For increasing magnetic flux densities a continuous decay of the interaction force is observed. This transition occurs at parameters, where the ion cyclotron frequency starts to exceed the ion plasma frequency, which is in agreement with theoretical predictions. The modification of the interparticle forces is important for the understanding of the structure and dynamics of magnetized dusty plasmas.

DOI: 10.1103/PhysRevLett.109.135001 PACS numbers: 52.30.−q, 52.25.Xz, 52.27.Lw, 52.40.Kh

Wake fields occur in numerous plasma environments, when macroscopic objects interact with flowing plasmas. In space, the solar wind creates extended wake structures behind moons [1,2] and planets affecting the charging of asteroids and satellites passing through it [3]. Further, wake charging can be a real concern for space-craft docking operations, since large potential differences may lead to arc discharges [4]. In the context of dusty plasmas [5], where particles are typically small (and light), forces mediated by the positively charged ion wakes become important and are of fundamental interest for the understanding of the structure and dynamics of strongly coupled particle ensembles. Attractive forces between like-charged particles can trigger the spontaneous formation of particle chains [6–8]. The upstream propagation of any disturbance is inhibited by the supersonic ion flow, which results in a strongly asymmetric (nonreciprocal) particle interaction parallel to the flow. This provides an effective mechanism to transfer energy from the flowing ions to the particles [9] resulting in different types of instabilities [6,10,11].

In dusty plasmas, these ion-wake-related phenomena have been studied extensively for unmagnetized plasma flows. For magnetized plasma flows, as they appear, e.g., in fusion devices or space plasmas, there is a lack of experimental observations and only a few theoretical predictions [12,13] and computer simulations [14,15] exist. In this parameter regime, the trajectories of ions scattered in the Coulomb field of highly charged dust particles can be strongly modified by a magnetic field parallel to the ion flow (see Fig. 1). Even in this simplified model (neglecting collisions and collective phenomena), it becomes apparent that a magnetic field severely modifies the ion distribution downstream to the dust particle. Without a magnetic field [Fig. 1(a)], the focusing effect and therefore an enhanced ion density on the axis is clearly visible. In the magnetized case [Fig. 1(b)], the scattering process transfers energy from the parallel to the perpendicular motion, which triggers a helical ion motion and creates an extended ion-depleted shadow.

In the limit of linear response theory, Nambu *et al.* [12] have predicted a damping of the wake oscillations by the presence of the magnetic field. Particle-in-cell simulations by Patacchini *et al.* [14] showed an additional ion cyclotron wake further away from the dust particle (probe) at parameters, where the cyclotron damping is not too strong. Thus, for particle ensembles, where the interaction forces are mediated by ion wakes, we expect a strong influence of the magnetic field on the particle interaction. It is the intention of this Letter to analyze this situation experimentally. The focus hereby lies on a quantitative determination of the nonreciprocal interaction forces and the charging of the particles.

In a magnetized plasma the ions are subject to the Lorentz force. Based on Refs. [12,13], we use the dimensionless parameter $\beta_i = \omega_{ci}/\omega_{pi}$ to describe the magnetization of the ions. ω_{ci} is the ion cyclotron frequency and ω_{pi} the ion plasma frequency. For our particular situation of dust grains in the plasma sheath, this definition can be interpreted in the following way: For ions flowing at Bohm speed $v_B = \sqrt{k_B T_e/m_i}$ the screening length provided by

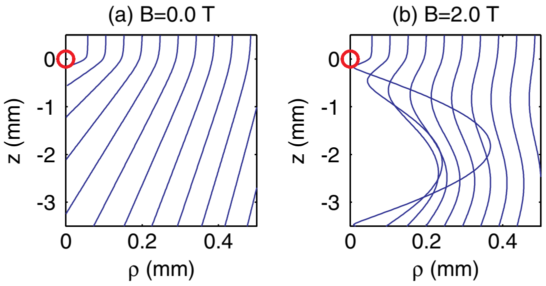

FIG. 1 (color online). Trajectories of Argon ions scattered in the pure Coulomb field of a single charged dust grain with $Q_d = -20\,000e$ (a) without magnetic field ($B = 0$ T) and (b) with magnetic field ($B = 2$ T) in cylindric coordinates. The magnetic field is aligned parallel to the ion flow in the z direction. ρ is the distance from the z axis. Cold Argon ions with an initial velocity equal to the Bohm speed are assumed.

the ions can be approximated by $\lambda_D = \sqrt{\epsilon_0 k_B T_e/(n_i e^2)}$ [16,17], T_e is the electron temperature and m_i the ion mass. The deflection of the ions passing by a charged dust particle happens mainly within the Debye sphere of the particle. The Lorentz force must be taken into account, when the transit time of the ions $\tau_t = \lambda_D/v_B$ is comparable to the time scale of the cyclotron motion $\tau_{ci} = 1/\omega_{ci}$, e.g., $\beta_i = \tau_t/\tau_{ci} = \omega_{ci}/\omega_{pi}$. However, ion-neutral collisions can suppress the magnetization of the ions, when the ion-neutral collision frequency ν_{in} exceeds ω_{ci}. For the present measurements the Hall parameter $H_i = \omega_{ci}/\nu_{in}$ is comparable to the magnetization β_i. Although collisions affect the wake fields, $\beta_i \geq 1$ is a reasonable criterion to separate unmagnetized and magnetized wakes, because $H_i \geq 1$ holds in this parameter regime.

The sheath of a plasma is ideally suited to study wake effects. The sheath electric field sustains a strong ion flow and, in addition, it can be used to levitate the negatively charged particles against the force of gravity. A sketch of the experimental situation is shown in Fig. 2. Two melamine particles with 11.66 μm in diameter are confined in the sheath of a capacitively coupled radio frequency (rf) discharge. A small recession of 2 mm in depth ensures the horizontal confinement of the particles. At sufficient low gas pressures, $p = 8$ Pa (Argon), and moderate rf voltages ($U_{\mathrm{rf}} = 100\,V_{pp}$) the particles align vertically due to the formation of ion wakes [8,18]. Under these conditions the ion flow velocity is of the order of the Bohm speed with a Mach number $M \approx 1$, the ion density is $n_i \approx 10^{14}$ m^{-3}, and the electron temperature is typically $T_e = 3$ eV [19]. The whole plasma chamber is mounted in a superconducting solenoid, which provides a homogeneous magnetic field of up to 4 T at its center. The direction of the magnetic field is parallel to the ion flow.

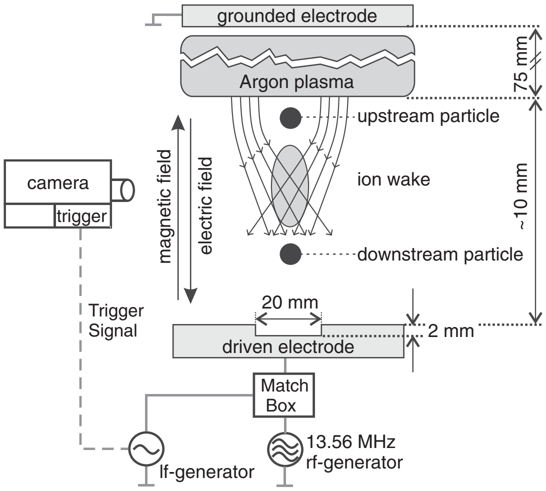

FIG. 2. Sketch of the experimental setup (not true to scale): Two particles are confined in the plasma sheath above the driven electrode. A magnetic field parallel to the ion flow up to $B = 4$ T can be applied. The vertical resonances of the particle ensemble are measured by the phase resolved resonance method [21].

To probe the ion-wake-mediated interaction forces between the particles, we evaluated the vertical resonances of the particle pair [20]. For this purpose, the particles are set into vertical oscillation by a sinusoidal modulation of the electrode bias. For small oscillation amplitudes the particles can be treated as asymmetrically coupled driven harmonic oscillators [21]. The corresponding equation of motion reads

$$\ddot{\xi}_1 + 2\gamma_1\dot{\xi}_1 + \omega_1^2\xi_1 + D_{12}(\xi_1 - \xi_2) = K_1 \exp(i\omega t), \quad (1)$$

$$\ddot{\xi}_2 + 2\gamma_2\dot{\xi}_2 + \omega_2^2\xi_2 + D_{21}(\xi_2 - \xi_1) = K_2 \exp(i\omega t). \quad (2)$$

ξ_j is the excursion from the equilibrium positions of the upstream ($j = 1$) and downstream ($j = 2$) particle, γ_j is the friction coefficient accounting for friction induced by the ambient neutral gas, ω_j is the confinement frequency of the particles, and K_j the amplitude of the excitation force normalized by the particle mass m_j. The D_{ij} can be considered as effective spring constants describing the strength of the interaction force. Here, we allow $D_{12} \neq D_{21}$ to account for the nonreciprocity of the particle interaction [6]. In order to determine the dynamical properties (ω_j, D_{ij}, γ_j) of this system, the phase resolved resonance method [20] is applied. Resonance curves are obtained by varying the excitation frequency ω and measuring the particle positions ξ_j at a certain phase φ with respect to the excitation. For comparison, the resonance curves for $B = 0.2$ T and $B = 1.2$ T magnetic induction are shown in Fig. 3. The fits of model Eq. (1) (full lines) are in good

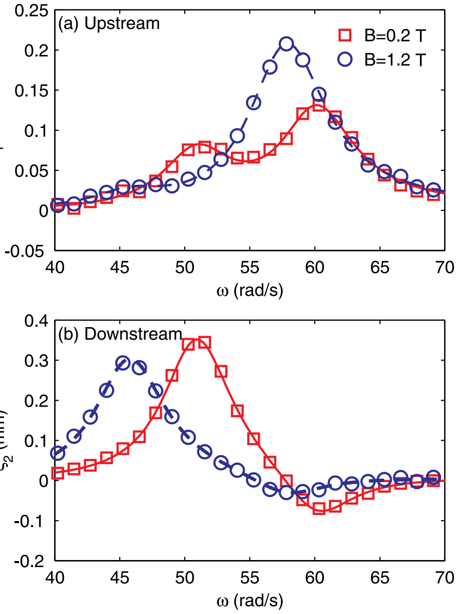

FIG. 3 (color online). Resonance curves of the (a) upstream and (b) downstream particle for magnetic inductions of $B = 0.2$ T (squares) and $B = 1.2$ T (circles). ξ_j is the excursion from the equilibrium position at a phase of $\varphi = 0°$ with respect to the excitation signal. The full and dashed lines are fits of the model Eq. (1).

agreement with the measurement allowing an accurate determination of ω_j, D_{ij}, γ_j.

We analyzed the resonances of the particles for a range of magnetic inductions from $B = 0.2$ T to $B = 2.5$ T. At $B = 0.2$ T the electrons are strongly magnetized, e.g., the Hall parameter of the electrons is $H_e \gg 1$ and a further increase of the magnetic induction does not alter the electron dynamics. For $B > 2.5$ T the particle ensemble becomes unstable due to the filamentation of the plasma [22]. In this parameter regime, we find only a weak dependence of the plasma parameters and the particle charges on the magnetic induction. This is shown in Figs. 4 and 5(a). Figure 4 shows the plasma glow intensity I_p above the lower electrode ($z = 0$) versus the magnetic induction B. The plasma glow is an indicator for the electron density and the electron temperature. Thus, for magnetic inductions of 0.2 T $< B < 2.0$ T the plasma glow (parameters) can be considered constant. In Fig. 5(a) the confinement frequencies of the upstream and downstream particle are plotted versus B. Since ω_j depends on the charge-to-mass ratio of the particles ($\omega_j^2 \propto Q_j/m_j$), Fig. 5(a) shows that the particle charges remain approximately constant over the entire range of magnetic induction. Further, we have verified that the levitation heights of the particles are nearly unaffected in this range of magnetic inductions, which supports the finding that the particle charges remain constant. The measurements were started at $B = 1.8$ T, then B was decreased to $B = 0.2$ T and increased again to $B = 2.5$ T (dashed line in Fig. 5). There is a small drift in ω_0 indicating a change of the plasma parameters or particle properties [21,23] over the measurement time of a few hours, which will be neglected in the following.

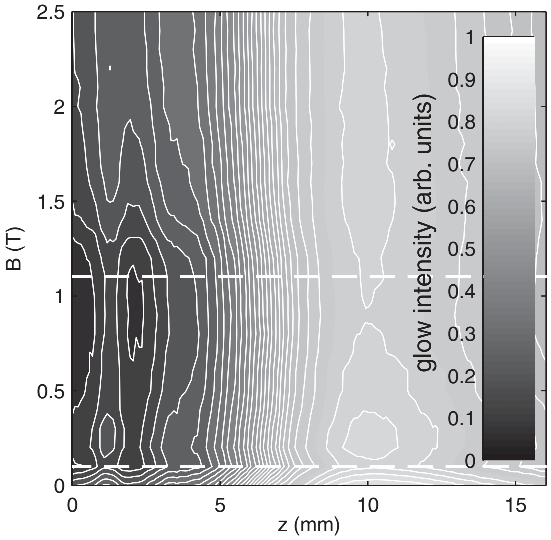

FIG. 4. Plasma glow intensity I_p versus magnetic induction B and vertical position z. I_p is averaged in the horizontal direction. The driven electrode is at $z = 0$. The dashed lines correspond to $B = 0.2$ T and $B = 1.2$ T, as chosen for the sample curves in Fig. 3.

In contrast to the plasma glow and the particle charges, the interparticle forces are strongly affected by the magnetic field [see Fig. 5(b)]. For $B = 0.2$ T, the ions are partially magnetized ($\beta_i < 1$) and the coupling constants are comparable to those found in an unmagnetized plasma [20] under similar conditions. However, for $B = 1.5$ T the ions are magnetized ($\beta_i > 1$) and D_{12} and D_{21} are reduced by a factor of three. For small and large values of B, the degree of asymmetry D_{21}/D_{12} is between 5 and 6 with a minimum at $B \approx 1$ T in the transition region. This gradual change of the particle interaction occurs at magnetic inductions of the order of 1 T. As stated above, this is the parameter regime where the ion cyclotron frequency ω_{ci} becomes comparable to the ion plasma frequency ω_{pi}, e.g., the magnetization is $\beta_i \approx 1$. Because the particle charges Q_j and the plasma parameters are to a good approximation independent of the magnetic induction B, this reduction of the coupling forces can be attributed to a modification of the ion wake structure around the particles.

For the presented parameter regime the particle charges show only a weak dependence on the magnetic induction. The charging of the upstream particle is only weakly influenced by the downstream particle, e.g., the charging is comparable to that of an isolated dust grain. This is in agreement with particle-in-cell simulations by Patacchini *et al.* [24] addressing the problem of a (single) spherical

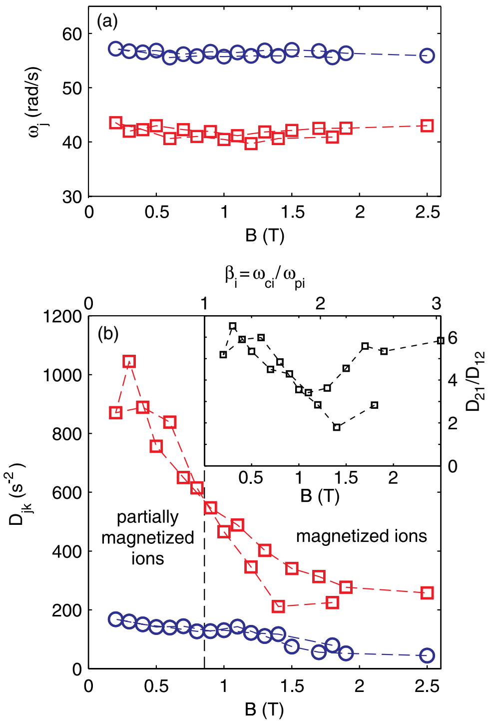

FIG. 5 (color online). (a) Eigenfrequency ω_j of the upstream (circles) and downstream (squares) particle versus magnetic induction B. The dashed line indicates the measurement sequence. (b) The coupling constants of the upstream particle D_{12} (circles) and of the downstream particle D_{21} (squares) versus magnetic induction B.

probe or dust particle in a collisionless streaming magneto plasma. There the particle charge does not depend on the magnetic induction for particles which are small compared to the Debye length and the averaged Larmor radius of the ions, which is the case for the present experiments. For the downstream particle the situation is more complex. As we had shown for unmagnetized plasmas in Ref. [20], the charging of particles in the wake of another can be quite different compared to isolated particles, which is in agreement with simulations [25]. Here, the charging of the downstream particle is not significantly altered when the ion wake becomes magnetized. To our knowledge there are no theories or simulations available addressing the question of particle charging in a magnetized ion wake. This issue should be addressed in the future and is beyond the scope of this Letter.

The interparticle forces D_{ij} decrease for increasing magnetic inductions B. This result is in agreement with linear response theory [13], which predicts a damping of the wake oscillations by the magnetic field. Further this damping occurs at parameters where the ion cyclotron frequency ω_{ci} starts to exceed the ion plasma frequency ω_{pi}, which is also in agreement with Ref. [13]. We like to mention that it is difficult to determine the local plasma density n_i. Since $\omega_{pi} \propto \sqrt{n_i}$, the systematic error of the magnetization scale β_i in Fig. 5(b) can be of the order of 30%, but this does not change the conclusions.

For small magnetic inductions ($B < 0.2$ T), the magnetization of the electrons changes the discharge properties, which is accompanied by a change in the plasma glow and a lowering of the confinement frequencies ω_j and a change of the levitation heights of the dust particles. For this reason we restricted the measurements to the high B regime ($B > 0.2$ T), where the plasma glow, the particle charges, and the levitation heights of the particles show only a weak dependence on the magnetic field. Thus, the sudden drop of the D_{ij} at $B \approx 0.8$ T must be a result of the magnetization of the ion wake and cannot be attributed to modified plasma parameters.

To conclude, at parameters typical for dusty plasmas we demonstrated for the first time that strong magnetic fields of the order of 1–2 Tesla substantially alter the interparticle forces parallel to the ion flow. This effect occurs at parameters, where the magnetization of the ions β_i is of the order of unity. Here, a reduction of the interparticle forces is observed. Since the nonreciprocal interaction forces are important for the structure and stability of particle ensembles, this result implies that the dynamics of strongly coupled particles in magnetized plasma flows is substantially different from unmagnetized plasmas. A detailed understanding into this mechanism can be expected from self-consistent simulations. Further, the experiments indicate that the magnetization of the ions does not alter the charge of the upstream and downstream particle. In the future, it might be promising to check whether this result persists for larger particles with diameters larger than the Debye length, as is the situation for small objects (satellites, asteroids) in the solar wind.

This work was supported by the Deutsche Forschungsgemeinschaft DFG in the framework of the SFB-TR24 Greifswald Kiel, Project A2.

[1] J. S. Halekas, V. Angelopoulos, D. G. Sibeck, K. K. Khurana, C. T. Russell, G. T. Delory, W. M. Farrell, J. P. McFadden, J. W. Bonnell, and D. Larson, Space Sci. Rev. **165**, 93 (2011).
[2] I. H. Hutchinson, J. Geophys. Res. **117** (2012).
[3] V. V. Yaroshenko, W. J. Miloch, S. Vladimirov, H. M. Thomas, and G. E. Morfill, J. Geophys. Res. **116**, A12218 (2011).
[4] J. Wang, P. Leung, H. Garrett, and G. Murphy, J. Spacecr. Rockets **31**, 889 (1994).
[5] G. E. Morfill and A. V. Ivlev, Rev. Mod. Phys. **81**, 1353 (2009).
[6] V. A. Schweigert, I. V. Schweigert, A. Melzer, A. Homann, and A. Piel, Phys. Rev. E **54**, 4155 (1996).
[7] K. Takahashi, T. Oishi, K.-i. Shimomai, Y. Hayashi, and S. Nishino, Phys. Rev. E **58**, 7805 (1998).
[8] A. Melzer, V. A. Schweigert, and A. Piel, Phys. Rev. Lett. **83**, 3194 (1999).
[9] A. V. Ivlev, M. H. Thoma, C. Räth, G. Joyce, and G. E. Morfill, Phys. Rev. Lett. **106**, 155001 (2011).
[10] R. Kompaneets, S. V. Vladimirov, A. V. Ivlev, V. Tsytovich, and G. Morfill, Phys. Plasmas **13**, 072104 (2006).
[11] L. Couëdel, V. Nosenko, A. V. Ivlev, S. K. Zhdanov, H. M. Thomas, and G. E. Morfill, Phys. Rev. Lett. **104**, 195001 (2010).
[12] M. Nambu, M. Salimullah, and R. Bingham, Phys. Rev. E **63**, 056403 (2001).
[13] M. Salimullah, M. Torney, P. K. Shukla, and A. K. Banerjee, Phys. Scr. **67**, 534 (2003).
[14] L. Patacchini and I. H. Hutchinson, Plasma Phys. Controlled Fusion **49**, 1719 (2007).
[15] L. Patacchini and I. H. Hutchinson, Plasma Phys. Controlled Fusion **53**, 065023 (2011).
[16] A. Piel and A. Melzer, Plasma Phys. Controlled Fusion **44**, R1 (2002).
[17] T. E. Sheridan, J. Appl. Phys. **106**, 033303 (2009).
[18] V. Steinberg, R. Sütterlin, A. V. Ivlev, and G. Morfill, Phys. Rev. Lett. **86**, 4540 (2001).
[19] M. Klindworth, O. Arp, and A. Piel, J. Phys. D **39**, 1095 (2006).
[20] J. Carstensen, F. Greiner, D. Block, J. Schablinski, W. J. Miloch, and A. Piel, Phys. Plasmas **19**, 033702 (2012).
[21] J. Carstensen, H. Jung, F. Greiner, and A. Piel, Phys. Plasmas **18**, 033701 (2011).
[22] M. Schwabe, U. Konopka, P. Bandyopadhyay, and G. E. Morfill, Phys. Rev. Lett. **106**, 215004 (2011).
[23] J. Pavlů, A. Velyhan, I. Richterová, Z. Němeček, J. Šafránková, I. Čermák, and P. Žilavý, IEEE Trans. Plasma Sci. **32**, 704 (2004).
[24] L. Patacchini and I. H. Hutchinson, Plasma Phys. Controlled Fusion **53**, 025005 (2011).
[25] W. J. Miloch, M. Kroll, and D. Block, Phys. Plasmas **17**, 103703 (2010).