Waves and wakes excited by a moving disturbance in a 2D magnetized dusty plasma

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Abstract. A hydrodynamic model is proposed to study a moving disturbance (for example a laser spot) excited waves and wakes in a two-dimensional (2D) magnetized dusty plasma, with particular attention being paid to the effect of magnetic field on structures of wake patterns. Numerical results show that in the weak magnetic field case the wakes exhibit typical V-shaped Mach cone structures similar to those observed in non-magnetized dusty plasmas. Whereas with increasing magnetic field, the wakes lose their symmetry gradually regarding the moving direction of the disturbance and the Mach cones become oscillatory wakes. In the case of extremely strong field, the wakes further turn into a non-oscillatory perturbation zone right behind the disturbance.

Contents

| Section                  | Page |
|--------------------------|------|
| 1. Introduction          | 2    |
| 2. Basic theory          | 3    |
| 3. Results and discussions | 6   |
| 4. Conclusions           | 9    |
| Acknowledgments          | 10   |
| References               | 10   |

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1. Introduction

A moving disturbance can create waves in a variety of media. Under certain circumstances, they can form wakes with stationary spatial patterns from the point of view of the moving frame. These patterns are caused by constructive interference of waves excited by the moving disturbance, and their structures are determined by the wave dispersion properties of the medium as well as the details of the disturbance–medium interaction [1].

Recently, wakes excited by a moving disturbance in a dusty plasma have attracted much attention [1]–[16]. Often these wakes are referred to as Mach cones, probably because most (if not all) of them are associated with waves having acoustical behaviour and exhibit typical cone structures (or V-shaped structures in the two-dimensional (2D) case).

Mach cones in dusty plasmas were first predicted in theory by Havnes et al [2] in 1995 and later observed in a 2D dust crystal experiment by Samsonov et al [3] in 1999. Inspired by above two studies, extensive research [1], [4]–[12] has been conducted on the formation of Mach cones and their structures in both experiment and theory. In particular, a well-controllable technique using a laser beam has been designed [5]–[7] to excite the Mach cone in a dusty plasma, and abundant structures as well as structure transitions [5]–[7], for example the compressional-wave Mach cones composed of multiple V-shaped structures [5], shear-wave Mach cones composed of single cones [6, 7] and their transitions [6, 7], have been observed in experiments. Various theoretical models [1], [8]–[12] have also been proposed to interpret these phenomena. However, magnetic field was commonly absent in these works.

More recently, theoretical work has been progressing on Mach cone phenomena in a magnetized dusty plasma. Mamun et al [13] first discussed the formation of Mach cones associated with long-wavelength dust Alfvén waves in Saturn’s ring dusty plasma and showed that this kind of Mach cone might be more prominent than any other longitudinal mode in that situation. Later, a theory of dust-acoustic Mach cones in a magnetized dusty plasma was proposed by Shukla et al [14] and generalized later by Shukla and Mamun [15] to discuss the role of magnetic field in the formation of a Mach cone on Saturn’s ring. More recently, Mamun et al [16] presented a theory to discuss the formation of Mach cones in a magnetized dusty plasma with strongly correlated dust particles, which could be realized in experiments. Additionally, they also discussed the possibility of observing this kind of Mach cone in experiments [16].

However, it should be pointed out that in the above studies of Mach cones in magnetized dusty plasmas [13]–[16], emphasis was mainly placed on the possibility of Mach cone formation in the presence of a strong magnetic field, whereas influences of magnetic field on the Mach cone structures (or more precisely, wake structures) are commonly ignored. Since the magnetic field will change the dispersive property of a dusty plasma dramatically and in addition, wake structures are largely determined by the dispersive property of a dusty plasma, these influences could be significant in some situations.

Another thing that should be noted here is that in most of the above work [14]–[16] the dust particles are not magnetized, while the magnetization of ions plays a very important role in determining the wave dispersion. Even though dust particles are very hard to magnetize in laboratory dusty plasmas currently [17, 18] (due to their large mass and high number density), it would be very interesting to see how the magnetization of dust particle changes the waves [18] and wakes in a dusty plasma.
It is the purpose of the present paper to show theoretically the influence of magnetic field on
the wake structures in a magnetized dusty plasma, with dust particles being magnetized in addition
to electrons and ions. In this study, we use a 2D hydrodynamic model [10]–[12] to describe
the dynamics of a 2D magnetized dust fluid under the perturbation of a moving disturbance.
The magnetic field is assumed to be constant, static and perpendicular to the fluid plane, while
the perturbation scans parallel to the plane with a constant speed. As an example, we will use a
moving laser beam as perturbation source in the numerical calculation, however, using of other
forms of perturbations, such as a test charge, is straightforward [11].

2. Basic theory

Here, we assume that a 2D dust fluid occupies the plane \( z = 0 \) in a Cartesian coordinate
system with \( \mathbf{R} = \{ x, y, z \} \), and that this fluid is immersed in a large volume of plasma with
a constant magnetic field \( \mathbf{B}_0 = \{ 0, 0, B \} \) and with the bulk values of the electron and ion number
densities given by \( n_{\text{exc}} \) and \( n_{\text{i,exc}} \). Bulk conditions are reached for such distances from the dust
layer that \( |z| \gg \lambda_D \) (Debye screening length), and we assume that the plasma is neutral there,
\( n_{\text{exc}} = n_{\text{i,exc}} = n_0 \). Let \( \sigma_d(\mathbf{r}, t) \) and \( \mathbf{u}_d(\mathbf{r}, t) \) be, respectively, the surface number density and the
velocity field (having only \( x \) and \( y \) components) of the dust fluid at the position \( \mathbf{r} = \{ x, y \} \) and
at time \( t \). The continuity equation and the momentum equation for the fluid are, respectively

\[
\frac{\partial \sigma_d(\mathbf{r}, t)}{\partial t} + \nabla \cdot [\sigma_d(\mathbf{r}, t)\mathbf{u}_d(\mathbf{r}, t)] = 0, \tag{1}
\]

\[
\frac{\partial \mathbf{u}_d(\mathbf{r}, t)}{\partial t} + \mathbf{u}_d(\mathbf{r}, t) \cdot \nabla \mathbf{u}_d(\mathbf{r}, t) = \frac{eZ_d}{m_d} \nabla \| \Phi(\mathbf{R}, t) \|_{z=0} + \frac{eZ_d}{m_d e} \mathbf{u}_d(\mathbf{r}, t) \mathbf{B}_0 + \frac{\mathbf{F}_{\text{ext}}}{m_d} - \gamma \mathbf{u}_d(\mathbf{r}, t), \tag{2}
\]

where \( m_d \) is mass of a dust particle, \( e > 0 \) is the elementary charge, \( Z_d \) is the average number of
excess electrons on each dust particle, and \( \gamma \) is the Epstein drag coefficient due to the collisions of
dust particles with neutral atoms/molecules in the plasma. The spatial differentiation in equations
(1) and (2) only includes tangential directions, vice versa, \( \nabla \| = \hat{x}(\partial/\partial x) + \hat{y}(\partial/\partial y) \). Note that \( \mathbf{F}_{\text{ext}}(\mathbf{r}, t) \) is the external perturbation force (having only \( x \) and \( y \) components) on each dust particle,
and will be specified to be the radiation force of a moving laser spot later, as an example.

The first term in the right-hand side of equation (2) indicates that, although the total
electrostatic potential \( \Phi(\mathbf{R}, t) \) depends on all three spatial coordinates \( \mathbf{R} \equiv \{ \mathbf{r}, z \} \), only the \( x \)
and \( y \) components of the electrostatic force, evaluated in the plane \( z = 0 \), affect the motion of
the dust fluid. The full spatial dependence of the electrostatic potential \( \Phi \) is determined by the
Poisson equation in 3D

\[
\nabla^2 \Phi(\mathbf{R}, t) = -4\pi e \left[ n_i(\mathbf{R}, t) - n_e(\mathbf{R}, t) - Z_d \sigma_d(\mathbf{r}, t) \delta(z) \right], \tag{3}
\]

where \( \nabla = \nabla_1 + \hat{z}(\partial/\partial z) \). The electron and ion volume densities are given by Boltzmann
relations, \( n_e = n_0 \exp\left( e\Phi/k_B T_e \right) \), and \( n_i = n_0 \exp\left( -e\Phi/k_B T_i \right) \) (with \( T_{i,e} \) being the ion (electron)
temperature and \( k_B \) the Boltzmann constant). It should be noted that this assumption is still valid
in the presence of a strong magnetic field, owing to the facts that firstly, even though electrons
and ions have been strongly magnetized and attached to the magnetic field line, both of them
can move freely along the magnetic field line and provide neutralizing as well as screening and, secondly, the movement of the laser spot and the dynamics of the massive dust particles are so slow that both electrons and ions are considered to have enough time to reach their respective local equilibria. This assumption is essentially analogous to the one used in deriving electrostatic ion cyclotron waves in usual electron–ion plasmas (see for example [19]) and has been adopted implicitly in studying wave dispersion relations of magnetized dusty plasmas [15, 18] recently.

In the unperturbed state of the system, we have \( \mathbf{F}_{ext} = 0 \), \( \partial / \partial t = 0 \), \( \sigma_d \equiv \sigma_{d0} = \text{constant} \), \( \mathbf{u}_d \equiv \mathbf{u}_{d0} = \mathbf{0} \), \( n_e \equiv n_{e0}(z) \approx n_0 + n_0(e/k_BT_e)\Phi_0(z) \), \( n_i \equiv n_{i0}(z) \approx n_0 - n_0(e/k_BT_i)\Phi_0(z) \), while the unperturbed value of the potential \( \Phi_0(z) \) is

\[
\Phi_0(z) = -2\pi e Z_d \lambda_D \sigma_{d0} \exp(-|z|/\lambda_D),
\]

after some algebra, with \( \lambda_D^{-2} = 4\pi n_0 e^2 ((1/k_BT_i) + (1/k_BT_e)) \).

In the perturbed situation, assuming a first-order perturbation in \( \mathbf{F}_{ext} \), we write \( \Phi(\mathbf{r}, t) = \Phi_0(z) + \Phi_1(\mathbf{r}, t) \), \( \sigma_d(\mathbf{r}, t) = \sigma_{d0} + \sigma_{d1}(\mathbf{r}, t) \), \( \mathbf{u}_d(\mathbf{r}, t) \equiv \mathbf{u}_{d1}(\mathbf{r}, t) \), \( n_e(\mathbf{r}, t) = n_{e0}(z) + n_0(e/k_BT_e)\Phi_1(\mathbf{r}, t) \), \( n_i(\mathbf{r}, t) = n_{i0}(z) - n_0(e/k_BT_i)\Phi_1(\mathbf{r}, t) \). Linearization of equations (1)–(3) gives, respectively

\[
\frac{\partial \sigma_{d1}(\mathbf{r}, t)}{\partial t} + \sigma_{d0} \nabla \cdot \mathbf{u}_{d1}(\mathbf{r}, t) = 0,
\]

\[
\frac{\partial \mathbf{u}_{d1}(\mathbf{r}, t)}{\partial t} = \frac{e Z_d}{m_d} \nabla \Phi_1(\mathbf{r}, t) \bigg|_{z=0} + \frac{e Z_d}{m_d} \mathbf{E}[\mathbf{u}_{d1}(\mathbf{r}, t) \times \mathbf{B}_0] + \frac{\mathbf{F}_{ext}}{m_d} - \gamma \mathbf{u}_{d1}(\mathbf{r}, t),
\]

and

\[
\nabla^2 \Phi_1(\mathbf{r}, t) = \lambda_D^{-2} \Phi_1(\mathbf{r}, t) + 4\pi e Z_d \sigma_{d1}(\mathbf{r}, t) \delta(z).
\]

Now by using a partial Fourier transform with respect to the \( \mathbf{r} \) and \( t \) dependences, we can write, e.g.

\[
\Phi_1(\mathbf{r}, t) \equiv \Phi_1(\mathbf{r}, z, \omega) = \int \frac{d^2 \mathbf{k}}{(2\pi)^2} e^{i \mathbf{k} \cdot \mathbf{r}} \int \frac{d\omega}{2\pi} \exp(i \mathbf{k} \cdot \mathbf{r}) \Phi_1(\mathbf{k}, z, \omega),
\]

where \( \mathbf{k} = \{k_x, k_y\} \). This allows us to reduce equation (7) to

\[
\frac{\partial^2}{\partial z^2} \Phi_1(\mathbf{k}, z, \omega) - (k^2 + 1) \lambda_D^{-2} \Phi_1(\mathbf{k}, z, \omega) = 4\pi e Z_d \sigma_{d1}(\mathbf{k}, \omega) \delta(z),
\]

where \( k^2 = k_x^2 + k_y^2 \), which can be easily solved as

\[
\Phi_1(\mathbf{k}, z, \omega) = -\frac{2\pi e Z_d \lambda_D}{\sqrt{k^2 + \lambda_D^2}} \sigma_{d1}(\mathbf{k}, \omega) \exp\left(-\sqrt{k^2 + \lambda_D^2} |z|/\lambda_D \right).
\]
the fluid velocity field, one can express the Fourier transform of the perturbed dust-fluid surface density in terms of the Fourier transform of the external force, as follows

$$\sigma_{d1}(k, \omega) = \frac{\sigma_{d0}}{m_d} \left[ \frac{k_x - i k_y \omega_c}{\omega(\omega + i \gamma)} \right] F_{\text{ext}}(k, \omega),$$

where

$$\epsilon(k, \omega) = 1 - \frac{\omega_c^2}{(\omega + i \gamma)^2} - \frac{\omega_0^2(k)}{\omega(\omega + i \gamma)}.$$  

is the dielectric function for acoustic waves in a magnetized 2D dust fluid, with

$$\omega_c = \frac{e Z_d B}{cm_d},$$

being the cyclotron frequency caused by the external magnetic fields, and

$$\omega_0^2(k) = \omega_{pd}^2 \frac{k^2 \lambda_D^2}{\sqrt{1 + k^2 \lambda_D^2}},$$

where

$$\omega_{pd} = \sqrt{\frac{2 \pi e^2 Z_d^2 \sigma_{d0}}{m_d \lambda_D}}$$

is the plasma frequency of a 2D dust fluid in the bulk plasma [1], [10]–[12]. Given the expression of the external force $F_{\text{ext}}(k, \omega)$, the static density perturbation in $r$ space: $\sigma_{d1}(r)$ can be obtained by substituting equation (11) into (8) (i.e. the reverse Fourier transform).

However, before moving on to the discussion of external force, let us have a closer look at the dielectric function of 2D magnetized dusty plasma equation (12). The dispersion relation of long-wavelength dust magneto-acoustic waves can be obtained by letting $\epsilon(k, \omega) = 0$, which can be solved analytically in the limit $\gamma \to 0$

$$\omega^2 = \omega_c^2 + \omega_0^2(k).$$

It is clear that the mode given in equation (16) is in the nature of a hybrid cyclotron–plasmon mode in 2D, resulting from superposing cyclotron oscillation due to magnetic field upon a 2D dust-acoustic wave. For convenience, here we introduce new parameters $\beta = \omega_c/\omega_{pd}$, $\bar{\omega} = \omega/\omega_{pd}$ and $\bar{k} = k \lambda_D$. Then equation (16) can be simplified as

$$\bar{\omega}^2 = \beta^2 + \frac{\bar{k}^2}{\sqrt{1 + \bar{k}^2}},$$

and further

$$\bar{\omega}^2 = \beta^2 + \bar{k}^2,$$

New Journal of Physics 9 (2007) 57 (http://www.njp.org/)
in the long-wavelength approximation ($\bar{k} \ll 1$). When the magnetic field is weak, i.e. $B \to 0$, $\beta \to 0$, so equation (17) turns into an ordinary 2D dust-acoustic wave [1], [10]–[12]: $\bar{\omega}^2 \approx \bar{k}^2 / \sqrt{1 + \bar{k}^2}$. However, with the increasing of the magnetic field, especially when $\beta \sim 1$, the cyclotron part (oscillation part) becomes dominant, while the wave part is depressed relatively. In particular, when $B \to \infty$, it becomes: $\bar{\omega}^2 \approx \beta^2$, a pure cyclotron oscillation. Physically, this implies that in this situation any perturbation to the system will not propagate any more but will stay locally.

Additionally, it is interesting to note that in the limit $\lambda_D \to \infty$, the system is reduced to a one-component-plasma (OCP) with pure Coulombic interaction, and equation (16) then becomes

$$\omega^2 = \omega_c^2 + \frac{2\pi e^2 Z_d^2 \sigma_{d0}}{m_d} \bar{k},$$

which is the dispersion relation of the local electrostatic magneto-plasmon mode for a 2D OCP [20, 21].

We now turn back to determine the form of external force $F_{\text{ext}}$. Note here that no explicit expression of $F_{\text{ext}}$ has been given up to this point, and the solutions obtained so far apply to a wide variety of external forces, such as, Coulomb force of a test charge and radiation force of a laser spot.

In the following calculation, we will use a laser spot as a perturbation, i.e. $F_{\text{ext}} = F_L$, with the profile of the laser force spot $F_L(r, t)$ being given by an elliptical Gaussian form [5]–[7]. Assuming that $F_L$ acts in the $x$-direction, and that the spot moves in the $x, y$ plane with velocity $v_L = \{v_x, v_y\}$, we can write

$$F_L(r, t) = f_0 \exp \left[ -\frac{(x - v_x t)^2}{a^2} - \frac{(y - v_y t)^2}{b^2} \right] \hat{x},$$

where $f_0$ is the intensity of the force and $a$ and $b$ are empirical parameters [5]–[7] defining the widths of the spot in the $x$- and $y$-directions, respectively. Therefore, the Fourier transform of the laser force profile in the $x, y$ plane is given by

$$F_L(k, \omega) = 2\pi^2 a b f_0 \delta(\omega - k \cdot v_L) \exp \left( -\frac{a^2}{4} k_x^2 - \frac{b^2}{4} k_y^2 \right) \hat{x}.$$  

However, for simplicity, we shall discuss only the case of the speed $v_L$ in the direction parallel to the radiation force, i.e. $v_x = v_L$ and $v_y = 0$ in the present paper.

3. Results and discussions

Now, we numerically analyse the perturbed density distribution of dust fluid in the wake region, for typical laboratory dusty plasma parameters [17]: $n_0 = 1 \times 10^8 \text{ cm}^{-3}$; $k_B T_i = 0.1 \text{ eV}$; $k_B T_e = 3 \text{ eV}$; the radius of dust particles $r_d = 0.1 \mu\text{m}$; $m_d = 1.0 \times 10^{-15} \text{ g}$; $Z_d = 100$ and $\sigma_{d0} = 100 \text{ cm}^{-2}$, which results in $\lambda_D \approx 231 \mu\text{m}$ and $\omega_{pd} \approx 250 \text{ s}^{-1}$. Additionally, the parameters in the expression of laser force are $a = b = 2.3 \lambda_D$, and $f_0 = 2.3 \times 10^{-13} \text{ dyne}$. The parameter $\beta$ (or equivalently the magnetic field $B$), is used as an adjustable parameter. More specifically, we use $\beta = 0, 0.1, 0.5$ and 1, corresponding to $B = 0, 1.5, 7.5$ and 15 tesla, respectively.
Figure 1. Perturbed density $\sigma_d$ in the wake region of $M = 0.8$ for: (a) $\beta = 0$, (b) $\beta = 0.1$, (c) $\beta = 0.5$ and (d) $\beta = 1$ with discharge pressure kept at $p = 0.2\text{ Pa}$ ($\gamma/\omega_{pd} = 0.1$).

These parameters are chosen by consulting a recent experiment [17] as well as some theoretical proposals [16, 18] of magnetized dusty plasmas.

Since the wake structures depend sensitively on the perturbation velocity $v_L$, given in terms of Mach number $M = v_L/v_s$ ($v_s = \lambda_D\omega_{pd}$ is the so-called dust-acoustic speed), as has been observed in both experiment and theory, we are going to discuss the influence of magnetic field on the wake structures for different $M$.

In addition, the damping effect due to the neutral gas friction is illustrated by adjusting the damping coefficient $\gamma/\omega_{pd}$ (or equivalently the discharge pressure $p$). In the following discussions, we use $\gamma/\omega_{pd} = 0.1$ and 1.0, which corresponds to $p = 0.2$ and 2 Pa, respectively. Also note that all the perturbed densities $\sigma_d$ are normalized by $\sigma_0 = \sigma_{d0}abf_0/(\pi m_d\lambda_D^3\omega_{pd}^2)$ in the following.

We first consider the wakes with weak damping, i.e. when $\gamma/\omega_{pd} = 0.1$. Figure 1 shows the wakes under subsonic perturbation, i.e. when the Mach number $M < 1$. It has been shown previously in non-magnetized 2D dusty plasmas that in the subsonic case wakes usually exhibit some transverse oscillatory structures [1, 7]. This is reproduced in our model when we let $\beta = 0$, and an example of $M = 0.8$ is shown in figure 1(a). In the presence of a magnetic field the wake (Mach cone) structures might change considerably, as is shown in the rest of the figures in figure 1. Firstly, when the magnetic field is weak, i.e. $\beta \ll 1$, one can see from figure 1(b) when $\beta = 0.1$ that the main structures of wakes, for example the transverse feature and the perturbation area, do not change much, while the symmetry of the density distribution along the $y$-direction (the direction perpendicular to perturbation velocity) is broken, due to the cyclotron motion of the dust particles. With increasing magnetic field strength, especially when $\beta$ approaches 1,
the symmetry is deteriorated further and some new features appear and become dominant. It can be seen clearly in figure 1(c) with $\beta = 0.5$ that the wake region in the $y$-direction shrinks significantly and the perturbation now turns into a zone behind the laser spot with some small oscillations along the $x$-direction. At the same time, the oscillation in the wake region is found to be seriously depressed. As we discussed in the last section, this is because the cyclotron motion of dust fluid becomes dominant now, while the perturbation is relatively weakened as it propagates outward. When the magnetic field becomes very strong, the wave turns into an oscillation and the perturbation just stays locally, as shown in figure 1(d) when $\beta = 1$, in which the wakes become featureless and the oscillations of the wakes almost disappear completely. In addition, a slight damping of perturbation magnitude along the $x$-direction can be observed.

Secondly, we study the influence of Mach number on the wake structures for $\beta = 1$ and $\gamma/\omega_{pd} = 0.1$. In figure 2, we show the wakes of $M = 0.8$, 1 and 2. By comparing figure 2(b) and (c) with figure 2(a), one might notice that the magnetic field seems to have stronger influence on wakes of low velocity excitation, as the wakes have been flattened in figure 2(a) but are still oscillatory in figure 2(b) and (c). This is true because in the low velocity case, only long-wavelength waves are excited and equation (18) applies there. Since the second term (wave part) on the right-hand-side (rhs) of equation (18) is very small, the cyclotron part ($\beta$) can easily become dominant. With increasing perturbation velocity, shorter waves are excited and one needs a stronger magnetic field to balance the effect due to the second term on the rhs of equation (17).

We next analyse wake structures with higher pressure or stronger damping effect. Figure 3 displays the perturbed density distribution in the wake region for $\gamma/\omega_{pd} = 1.0$ ($p = 2$ Pa), while...
the other parameters are kept the same as those in figure 1. As is expected, the wakes are sharply damped and oscillations in the wake region are soon smoothed out. The wakes without magnetic field ($\beta = 0$) or with a small magnetic field ($\beta = 0.1$) again reproduce our earlier results of Mach cones in non-magnetized dusty plasmas, whereas the influence of the magnetic field still remains, as can be seen in figures with $\beta = 0.5$ and 1 in figure 3, that the density distribution along the $y$-direction is asymmetric due to the cyclotron motion of the dust particles.

4. Conclusions

In summary, moving disturbance excited waves and wakes in magnetized dusty plasmas are studied by means of a 2D hydrodynamic model for a dust monolayer. Formulae of a wave dispersion relation of a 2D magnetized dust fluid (equations (16)–(20)) and expression of its density distribution (equation (11)) under external perturbations are obtained, and numerical results due to a laser beam excitation are given as examples to illustrate the structures of wakes for different magnetic field strengths and different excitation speeds. It is found that in the weak-(magnetic) field case, i.e. when $\beta \ll 1$, the wakes show typical V-shaped Mach cone structures similar to those observed in non-magnetized dusty plasmas [1], [3]–[12], as expected. However, with increasing magnetic field strength, the perturbation region (the wake region) in the $y$-axis direction (the direction perpendicular to the moving speed of the laser spot) shrinks continuously, and at the same time the symmetry of the wakes along the $y$-axis is deteriorated gradually, due to the depression of the propagation of waves. In the strong-field case, i.e. when $\beta \geq 1$, the original
oscillatory wake behind the laser spot becomes a featureless and non-oscillatory perturbation zone, because the wave mode turns now into a pure (cyclotron) oscillation and the perturbation cannot be propagated any more. With the increase of the discharge pressure, the wakes are sharply damped and oscillations in the wake region are soon smoothed out. However, the influence of the magnetic field can still be seen from the asymmetric density distribution along the $y$-direction.

Lastly, it should be pointed out that most of the above parameters are realizable in existing dusty plasma experiments, except the strength of magnetic field. The magnetic field has been chosen to be extremely strong in order to fully magnetize massive dust particles, whereas the strongest magnetic field used in previous dusty plasma experiments is $4$ tesla [17] (to our knowledge). Therefore such selection of the magnetic field is not directly related to existing experiments. However, since strong magnetic fields up to $20$ tesla have recently been easily achieved by using superconductor coils, experimental investigation of fully magnetized dusty plasmas should be possible [18].

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