6 May 2002

PHYSICS LETTERS A

ELSEVIER

Physics Letters A 297 (2002) 92–99

www.elsevier.com/locate/pla

Ion dynamics in a two-ion-species plasma

N. Chakrabarti [a,1], A. Fruchtman [b,*], R. Arad [a], Y. Maron [a]

[a] *Faculty of Physics, Weizmann Institute of Science, 76100 Rehovot, Israel*

[b] *Holon Academic Institute of Technology, 58102 Holon, Israel*

Received 24 December 2001; received in revised form 15 February 2002; accepted 13 March 2002

Communicated by F. Porcelli

Abstract

The ion dynamics in a two-ion-species plasma pushed by a magnetic field pressure is examined. It is shown that the behavior of such a plasma may significantly differ from the behavior of a single-ion-species plasma, in which the current is carried by the electrons and the ions move in the direction of the magnetic field force. Cases are demonstrated in which the current is carried by the ions, the ions acquire a velocity with a large component perpendicular to the magnetic field force, and one of the two ion species does not move in the direction of the magnetic field force exerted on the plasma. Experimental evidence for such an ion motion perpendicular to the magnetic field force is described. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 52.27.Cm; 52.30.Cv; 52.75.Kq

1. Introduction

Plasmas in space and laboratory are often pushed by a magnetic field pressure. This pushing is the dominant process in plasma devices such as pinches [1], plasma thrusters [2], and plasma opening switches [3]. The understanding of the process as it occurs in space and the design of devices in the laboratory are based on the notion that the current is carried by the plasma electrons and that the plasma ions are pushed in the direction of the force exerted by the magnetic field pressure. However, observations in experiments carried out in a plasma opening switch configuration [4–7] indicate that, apart from an ion motion in the direction of the force exerted by the magnetic field pressure, there is a significant ion motion in a direction perpendicular to that force. In this Letter we suggest an explanation to these observations by showing that the behavior of a plasma that is composed of more than one ion-species may significantly depart from the above mentioned notion. Indeed, we are able to theoretically demonstrate cases in which the current in the two-ion-species plasma is carried by the ions and in which ions acquire a velocity that has a large component perpendicular to the force exerted by the magnetic field pressure.

An additional effect is the difference in the motion of the two ion species in the direction of the magnetic field force. It is shown that it may happen that one of the two ion species is not being pushed at all

* Corresponding author.

E-mail address: amnon.fruchtman@weizmann.ac.il (A. Fruchtman).

[1] Present address: Plasma Physics Division, Saha Institute of Nuclear Physics, 1/AF, Bidhannagar, Calcutta 700 064, India.

0375-9601/02/$ – see front matter
PII: S0375-9601(02)00390-0

in that direction. This additional effect, the different ion motions in the direction of the magnetic field force, is related to a novel experimental finding of a special kind of ion separation in a two-ion-species plasma [6], as well as to other cases of ion separation [8–13]. In all these cases of ion separation studied previously the various ions move in the direction of the force (although with different velocities), in contrast to the above-mentioned ion motion perpendicular to the magnetic field force demonstrated in the present Letter.

The presence of two ion species is inherent to dusty plasmas [14–19]. Dusty plasmas, in which, in addition to the main ion, a second, heavy micron-size, ion is present, exhibit a rich behavior that is characterized by the appearance of additional wave modes [19]. The special features of such a two-ion-species plasma that will be shown in this Letter, the current conduction by the ions and the ion dynamics that include a perpendicular motion, bear relevance to dusty plasmas as well.

The Letter is organized as follows. In Section 2 we describe experimental measurements that indicate that ions in the plasma move in a direction that is perpendicular to the direction of the force exerted by the magnetic field pressure. In Section 3 a simple physical model for a two-ion-species plasma is presented. For the clarity of the demonstration the analysis is performed through examination of the linear eigenmodes of a uniform magnetized two-ion-species plasma. We focus on oscillations of a period between the ion and electron cyclotron periods. This is the time scale that is relevant, for example, to most plasma-opening-switch experiments. In Section 4, the linearized equations are solved for the normal modes and the dispersion relation, and the velocity amplitudes are presented. The theoretical results are shown to provide an explanation to the experimental measurements. We conclude in Section 5.

2. Experimental observation

Before describing the experimental observation, we discuss the role of the force exerted by the magnetic field pressure in a quasi-neutral plasma. The equations of motion for the various collisionless particle fluids in the plasma are written as

$$\frac{\partial}{\partial t}\left(m_\alpha n_\alpha \vec{V}_\alpha\right) + \vec{\nabla}\cdot\left(m_\alpha n_\alpha \vec{V}_\alpha \vec{V}_\alpha + \vec{\vec{P}}_\alpha\right) = q_\alpha n_\alpha\left(\vec{E} + \frac{1}{c}\vec{V}_\alpha \times \vec{B}\right), \quad (1)$$

where m_α, q_α, n_α, V_α, and $\vec{\vec{P}}_\alpha$ are the mass, charge, density, velocity and pressure tensor of the particle of species α. Also, $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields, and c is the speed of light in vacuum. Summing the equations for the various fluids, we obtain the momentum balance equation:

$$\frac{\partial}{\partial t}\left(\sum_\alpha m_\alpha n_\alpha \vec{V}_\alpha\right) + \vec{\nabla}\cdot\left[\sum_\alpha\left(m_\alpha n_\alpha \vec{V}_\alpha \vec{V}_\alpha + \vec{\vec{P}}_\alpha\right)\right] = \frac{1}{c}\vec{J}\times\vec{B}. \quad (2)$$

Although the electric field exerts a force on the individual fluids, the net force that it exerts on a quasi-neutral plasma is zero, since

$$\sum_\alpha q_\alpha n_\alpha = 0. \quad (3)$$

The only external force exerted on the plasma is the $\vec{J}\times\vec{B}$ force (which can generally be cast in the form of a gradient of the magnetic field pressure), where $\vec{J} = \sum_\alpha q_\alpha n_\alpha \vec{V}_\alpha$ is the current. Therefore, the total momentum gained by the plasma is zero in directions perpendicular to the $\vec{J}\times\vec{B}$ force. Since the momentum that the electrons acquire is negligible, due to their small mass, the total momentum gained by the plasma in a one-ion-species plasma is the momentum of the these single-species ions. Therefore, these ions cannot acquire a net momentum perpendicular to the magnetic field force. Also, since the total momentum in the direction of the current is zero, the ion velocity in that direction must be much smaller than the electron velocity, and therefore the electrons carry the current. These arguments support the notion that ions in a plasma acquire a velocity in the direction of the $\vec{J}\times\vec{B}$ force only, while electrons carry the current.

We have been performing experiments on the interaction between a pulsed magnetic field and a plasma in a plasma opening switch configuration [4–7]. Fig. 1 shows the measured time dependence of the electron density and of the intensity of the magnetic field (generated by a 150 kA current pulse driven through the

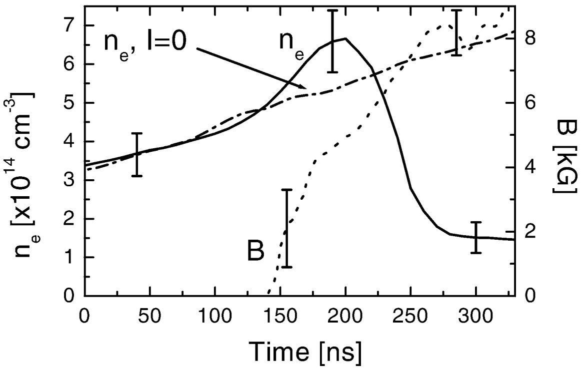

Fig. 1. The evolution-in-time of the electron density with (solid line) and without (dashed–dotted line) the application of the current pulse and of the magnetic field intensity (dotted line) at a location near the center of the plasma volume. The time $t = 0$ refers to the initiation of the current pulse.

plasma) at a certain location inside our plasma. A comprehensive description of the experimental system and measurements is included in a more detailed paper [7] that follows this Letter. As seen in Fig. 1, the electron density (deduced from the time-dependent emission from the low lying B III 2p level) drops significantly during the rise of the magnetic field intensity (deduced from the Zeeman splitting of the He I 6678 Å line). The same drop of the electron density during the rise of the magnetic field intensity occurs at other locations in the plasma as well. The drop in the electron density inside the quasi-neutral plasma must be followed by a drop in the ion density. The ions in the plasma are protons and (mostly triply charged) carbon ions. The density drop is too large to be accounted for only by the motion of the protons, indicating that the carbon ions have also been displaced. The current conducted between the anode and the cathode is perpendicular and the generated magnetic field is parallel to the electrodes. The direction of the $\vec{J} \times \vec{B}$ force is therefore predominantly parallel to the electrodes [4]. The velocity of the carbon ions in the direction of the $\vec{J} \times \vec{B}$ force, parallel to the electrodes, was deduced from Doppler-shift measurements and found to peak at $1.2 \times 10^7\ \mathrm{cm\,s^{-1}}$ [4]. The ion displacement associated with such a velocity is too small to explain the drop of the carbon ion density. Also, such a motion along the electrodes may cause a drop of the carbon ion density at certain locations but would not lead to a decrease of the total number of carbon ions inside the plasma, a decrease that, according to our measurements [7], does occur. An ion velocity towards the electrodes, however (a velocity that is difficult to measure reliably by our spectroscopic methods) *does* explain the measured decrease in plasma density. Hence, we conclude that the carbon ions also acquire a significant velocity *towards* the electrodes, in a direction that is *perpendicular* to the direction of the $\vec{J} \times \vec{B}$ force.

The experimental observation of an ion motion perpendicular to the direction of the force exerted by the magnetic field pressure contradicts the notion mentioned above, that ions in a plasma acquire a velocity in the direction of the $\vec{J} \times \vec{B}$ force only. However, this notion is not necessarily valid when the plasma is composed of more than one ion species, as it is in our plasma. In a multi-ion-species plasma each ion species can acquire a velocity perpendicular to the direction of the magnetic field force, say in the direction of the current. The total momentum in that direction is still zero, since the motion of one-ion-species along the direction of the current is balanced by an opposite motion of the other ion-species (in our experiment this would mean that the carbon ions and the protons move towards the electrodes in opposite directions). This is why it is possible in the multi-species plasma that the ions move in a direction perpendicular to the direction of the magnetic field force, and also that the ions carry most and even all the current.

3. The model

Motivated by the experimental observation described above, we perform an analysis that clearly demonstrates ion motion perpendicular to the magnetic field force in a multi-ion-species plasma. The features of the model problem we solve are similar to those of the experiment. The experimental magnetic field approximately points in one direction parallel to the electrodes. We, therefore, assume that the magnetic field has one component only, in a direction we denote by y. The current flows mostly in the direction perpendicular to the electrodes, a direction we denote by x. Thus, we consider an approximated one-dimensional problem, in which all variables depend on z only, the direction of the resulting $\vec{J} \times \vec{B}$ force. For simplicity, we describe the plasma by a linearized form of the above multi-fluid equations. We expect, however, that the behavior in the nonlinear regime be qualitatively similar. We consider, therefore, small perturbations in a uniform magnetized plasma consisting of electrons and several ion-species with different charges and masses. The magnetic field is written as $\vec{B} = \hat{e}_y[B_0 + B(z,t)]$ where $B(z,t) \ll B_0$. We also assume that the fluids are cold and neglect the pressure. The cold plasma approximation is justified for our case, in which the plasma pressure is much smaller than the magnetic field pressure.

In the cold-fluid description modes that are supported by a finite temperature (such as Bernstein waves) are excluded. The frequency of the fluctuations is assumed smaller than both the electron plasma frequency and the electron–ion lower hybrid frequencies. This justifies the assumption of quasi-neutrality and the related neglect of the displacement current. Employing the continuity equations we write the linearized equations of motion for the various particle fluids as:

$$m_\alpha \frac{\partial}{\partial t} V_{\alpha z} = q_\alpha\left(E_z + \frac{1}{c} V_{\alpha x} B_0\right), \tag{4}$$

$$m_\alpha \frac{\partial}{\partial t} V_{\alpha x} = q_\alpha\left(E_x - \frac{1}{c} V_{\alpha z} B_0\right). \tag{5}$$

To the equations of motion we add Maxwell's equations. These are Faraday's law

$$\frac{\partial E_x}{\partial z} = -\frac{1}{c}\frac{\partial B}{\partial t}, \tag{6}$$

and Ampere's law, in which we neglect the displacement current:

$$\frac{\partial B}{\partial z} = -\frac{4\pi}{c}\sum n_\alpha q_\alpha V_{\alpha x}. \tag{7}$$

The densities here n_α are the equilibrium densities. The current flows in the x direction. Another relation is needed. Since we neglect the displacement current in Ampere's law, which is equivalent to assuming quasi-neutrality, we should not employ Poisson's equation, but rather the resulting relation $\vec{\nabla}\cdot\vec{J} = 0$. This becomes

$$\sum_\alpha q_\alpha n_\alpha V_{\alpha z} = 0. \tag{8}$$

Eqs. (4)–(8) comprise a complete set of equations for $V_{\alpha z}$, $V_{\alpha x}$, E_z, E_x, and B, where given are B_0, and the mass, charge and density of the various particles.

We now restrict the discussion, for simplicity, to a two-ion-species plasma. The plasma is composed of electrons and two ion species of masses $m_\alpha \equiv m_e, m_1, m_2$, charges $q_\alpha \equiv -e$, q_1 $(= Z_1 e)$, and q_2 $(= Z_2 e)$, densities $n_\alpha \equiv n_e$, n_1 and n_2, and velocities $\vec{V}_\alpha = \vec{V}_e$, $\vec{V}_1$ and $\vec{V}_2$. Quasi-neutrality of the plasma becomes

$$n_e = Z_1 n_1 + Z_2 n_2 \equiv N_1 + N_2, \tag{9}$$

where $N_1 \equiv Z_1 n_1$ and $N_2 \equiv Z_2 n_2$.

Since we are looking for modes whose frequency is below the electron–ion lower hybrid frequency, we also neglect the electron inertia in the electron equation of motion. This allows us to write a useful relation between the electric field and the velocity of the electrons:

$$E_x = \frac{B_0 V_{ez}}{c}, \qquad E_z = -\frac{B_0 V_{ex}}{c}. \tag{10}$$

Employing the last equation, we now rewrite the equations for B and the six velocities only. These are

$$\frac{\partial V_{jz}}{\partial t} = -\Omega_j(V_{ex} - V_{jx}), \tag{11}$$

$$\frac{\partial V_{jx}}{\partial t} = \Omega_j(V_{ez} - V_{jz}), \tag{12}$$

$$B_0\frac{\partial V_{ez}}{\partial z} = -\frac{\partial B}{\partial t}, \tag{13}$$

$$\frac{\partial B}{\partial z} = -\frac{4\pi e}{c}(N_1 V_{1x} + N_2 V_{2x} - n_e V_{ex}), \tag{14}$$

and

$$n_e V_{ez} - N_1 V_{1z} - N_2 V_{2z} = 0, \tag{15}$$

where $j = 1, 2$ and $\Omega_j \equiv Z_j e B_0/m_j c$ is the cyclotron frequency of the jth ion.

Before performing the normal mode analysis, it is instructive to show how the relative motion of ions appears as a force term in the equations of motion. For this purpose we eliminate V_{ez} and V_{ex} from Eqs. (14) and (15), so that Eqs. (11) and (12) become

$$\frac{\partial}{\partial t}(m_j n_j V_{jz}) = -\left[\frac{B_0}{4\pi}\frac{n_j}{n_e}\frac{\partial B}{\partial z} + \left(\frac{eB_0}{n_e c}\right)N_1 N_2(V_{3-j,x} - V_{jx})\right], \tag{16}$$

and

$$\frac{\partial}{\partial t}(m_j n_j V_{jx}) = \left(\frac{eB_0}{n_e c}\right)N_1 N_2(V_{3-j,z} - V_{jz}), \tag{17}$$

for $j = 1, 2$. We see that an additional force that is proportional to the relative velocity between the two-ion-species exists. This force has a component also in the x direction, that allows each ion species to acquire a velocity in the direction perpendicular to the magnetic field force. The additional force, which exists only when more than one ion species is present, has been coined "collisionless resistivity" and has been related to a departure of the ions from the frozen-in-field approximation [15].

4. The ion dynamics

Let us write the solutions for the homogeneous Eqs. (11)–(15). We can then employ Eq. (10) in order to calculate the electric field. We write the unknown variables as

$$B = B_p \cos(\omega t - kz),$$
$$V_{\alpha z} = V_{\alpha z0} \cos(\omega t - kz),$$
$$V_{\alpha x} = V_{\alpha x0} \sin(\omega t - kz), \tag{18}$$

for $\alpha = 1, 2$, or e. Upon substituting this form of variables into the differential equations, they turn into a set of homogeneous algebraic equations for the seven unknowns B_p, $V_{\alpha z0}$ and $V_{\alpha x0}$. The solvability condition, the condition for the existence of a nontrivial solution, is the vanishing of the determinant of the equations. The result is the dispersion relation:

$$\omega^2\left(\omega^2 - \omega_c^2\right) = k^2 V_A^2\left(\omega^2 - \omega_r^2\right), \tag{19}$$

where $V_A^2 \equiv B_0^2/4\pi(n_1 m_1 + n_2 m_2)$ is the square of the Alfven velocity,

$$\omega_r \equiv \left[\Omega_1\Omega_2\left(\frac{f_1\Omega_2 + f_2\Omega_1}{f_1\Omega_1 + f_2\Omega_2}\right)\right]^{1/2}, \tag{20}$$

$$\omega_c \equiv f_1\Omega_2 + f_2\Omega_1, \tag{21}$$

and

$$f_j \equiv \frac{N_j}{N_1 + N_2}. \tag{22}$$

The solutions of the equations then satisfy the relations:

$$V_{ez0} = \frac{\omega}{k}\varepsilon, \quad \varepsilon \equiv \frac{B_p}{B_0} \ll 1, \tag{23}$$

$$V_{ex0} = -\frac{V_{ez0}\,\omega(\omega^2 - \omega_{ex}^2)}{(f_1\Omega_1 + f_2\Omega_2)(\omega^2 - \omega_r^2)}, \tag{24}$$

$$V_{jx0} = \frac{V_{ez0}\,\omega f_{3-j}\Omega_j(\Omega_j - \Omega_{3-j})}{(f_1\Omega_1 + f_2\Omega_2)(\omega^2 - \omega_r^2)}, \tag{25}$$

and

$$V_{jz0} = \frac{V_{ez0}\Omega_j(\omega^2 - \Omega_{3-j}\omega_c)}{(f_1\Omega_1 + f_2\Omega_2)(\omega^2 - \omega_r^2)}, \tag{26}$$

where

$$\omega_{ex}^2 \equiv f_1\Omega_2^2 + f_2\Omega_1^2. \tag{27}$$

When one-ion-species only, say the jth species, is present, the dispersion relation given above reduces to $\omega^2 = k^2 V_{Aj}^2$, where $V_{Aj}^2 \equiv B_0^2/(4\pi m_j n_j)$, which is the usual dispersion relation for the fast magnetosonic wave in a cold plasma (the compressional Alfven wave). The presence of two-ion-species adds a resonance ($k \to \infty$) at

$$\omega = \omega_r, \tag{28}$$

the ion hybrid resonance frequency [20], and a cutoff ($k = 0$) at

$$\omega = \omega_c. \tag{29}$$

There is a forbidden gap between these two frequencies.

Fig. 2 shows the solution of the dispersion relation, ω/Ω_2 as a function of kV_A/Ω_2 for $m_2/m_1 = 12$, $Z_2/Z_1 = 3$, and $n_2/n_1 = 0.25$ ($f_2/f_1 = 0.75$). These parameters characterize the plasma at our experiment in a plasma opening switch configuration [4], a plasma

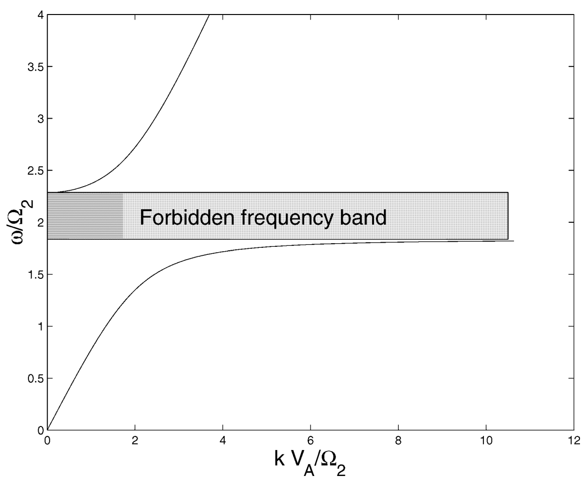

Fig. 2. Solutions of the dispersion relation Eq. (19): ω/Ω_2 as a function of kV_A/Ω_2 for $m_2/m_1 = 12$, $Z_2/Z_1 = 3$ and $n_2/n_1 = 0.25$.

that is composed of protons (the ion species denoted by 1) and carbon ions (the ion species denoted by 2). Apparent in Fig. 2 are the resonance and the cutoff, as well as the forbidden gap of frequencies. For our parameters $\omega_r/\Omega_2 = 1.8353$ and $\omega_c/\Omega_2 = 2.2857$.

The dispersion relation, Eq. (19), is equally valid for a dusty plasma, where the dust is usually considered to be a negatively charged massive particle. A special case is when $N_1 + N_2 = 0$, the solution of which describes waves in a two-ion-species plasma (one of them negative) with no electrons. Alternatively, this case is of waves in a usual single-ion-species plasma, where the electron inertia is not neglected. The resonance is then at the lower hybrid frequency $\omega_r = \omega_{lh} \equiv \sqrt{\Omega_e \Omega_i}$, where Ω_e is the electron cyclotron frequency and Ω_i is the cyclotron frequency of the single ion species. The cutoff frequency ω_c then moves to infinity.

The amplitudes of the velocities in a frequency regime that includes the resonance and the cutoff are shown in Figs. 3 and 4. We note that at the resonance, while the amplitude of the electron z velocity is zero (see Eq. (23)), the ion velocities, as well as the electron x velocity, are infinite (in the linear theory). Near the cutoff frequency all velocities are large, since the phase velocity ω/k is large. It is also clear from Eqs. (19) and (25) that when one of the two-ion-species is of a relatively low concentration, the resonance frequency approximately equals the cyclotron frequency of that ion, and its perpendicular velocity is large. This fact is utilized in fusion plasmas for heating minority ion species [21].

The infinite value of the velocities is a result of the cold plasma approximation. The use of kinetic theory would resolve the singularities. When we apply the theory to the experiment we do not rely on the actual values of the ion velocities at the cutoff and at the resonance. Furthermore, the cases that will be described in Figs. 5–7 occur for frequencies that are far from the resonance and cutoff frequencies.

We turn now to examine the motion of the ions perpendicular to the direction of the magnetic field force and the current conduction, the main issues of this Letter.

From Eq. (25) it is apparent that if there is one-ion-species only (f_1 or f_2 is zero), or if the ions have the same cyclotron frequency ($\Omega_1 = \Omega_2$), there is no motion of ions perpendicular to the magnetic

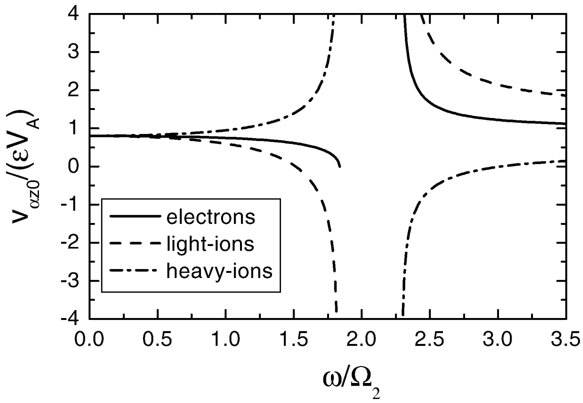

Fig. 3. Normalized velocity amplitudes (z component) of electrons, light-ion-species and heavy-ion-species as a function of the normalized frequency ω/Ω_2 for $m_2/m_1 = 12$, $Z_2/Z_1 = 3$ and $n_2/n_1 = 0.25$. The small parameter ε is defined in Eq. (23).

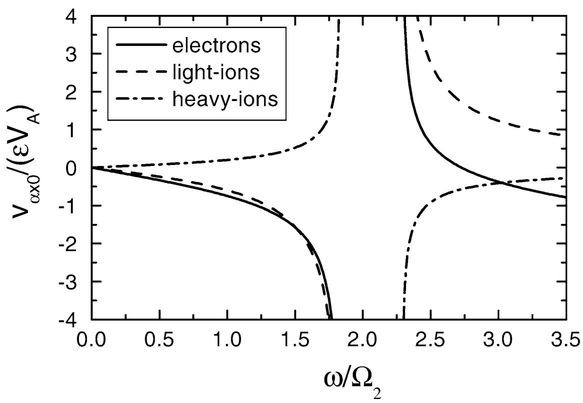

Fig. 4. Normalized velocity amplitudes (x component) of electrons, light-ion-species and heavy-ion-species as a function of the normalized frequency ω/Ω_2 for $m_2/m_1 = 12$, $Z_2/Z_1 = 3$ and $n_2/n_1 = 0.25$.

field force (in the x direction). Generally, however, the presence of two-ion-species results in a finite ion motion in that direction and the current is carried by both ions and electrons. In particular, at the frequency $\omega = \omega_{ex}$ ($= 2.7255\Omega_2$ here) the electron velocity in the x direction is zero, and the current is carried by the ions only. Fig. 5 shows the velocities of the electrons and the ions at this frequency in the $(V_{\alpha z}, V_{\alpha x})$ plane. Fig. 5 demonstrates the special features of ion dynamics in a two-ion-species plasma: a current conduction by ions and an ion motion perpendicular to the direction of the magnetic field force. The motions in the x direction of the two-ion-species are

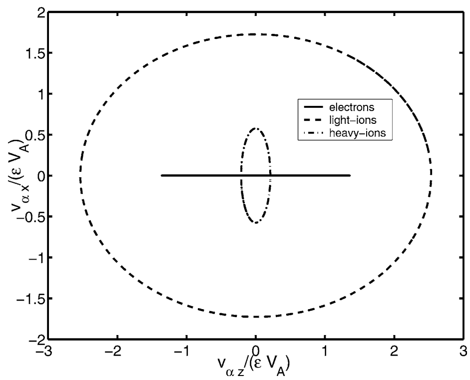

Fig. 5. Trajectories in the velocity space of electrons, light-ion-species and heavy-ion-species: $m_2/m_1 = 12$, $Z_2/Z_1 = 3$ and $n_2/n_1 = 0.25$, at $\omega = \omega_{ex} = 2.7255\Omega_2$. The electrons have no motion in the x direction, which implies that the current is carried by the ions only.

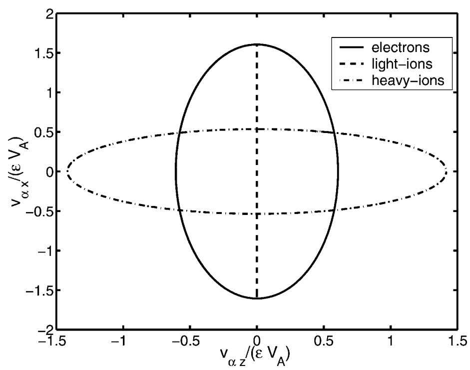

Fig. 6. Trajectories in the velocity space of electrons, light-ion-species and heavy-ion-species: $m_2/m_1 = 12$, $Z_2/Z_1 = 3$ and $n_2/n_1 = 0.25$, at $\omega = \sqrt{(\Omega_2\omega_c)} = 1.5119\Omega_2$. The light-ion-species is motionless in the z direction.

in opposite directions, so that the net ion momentum in that direction remains zero.

An additional feature, reminiscent of previously reported ion separations [6,8–13], is the different motions of the two-ion-species in the direction of the magnetic field force. There are frequencies at which the ions do not move in the axial direction along the direction of force. As seen in Eq. (26), these frequencies are $\sqrt{\Omega_2\omega_c}$ ($= 1.5119\Omega_2$ here) and $\sqrt{\Omega_1\omega_c}$ ($= 3.0237\Omega_2$ here), at which the first ion-species and the second ion-species, respectively, remain stationary, while the other ion-species carries the momentum imparted by the magnetic field force. The ion velocities in these two cases are shown in

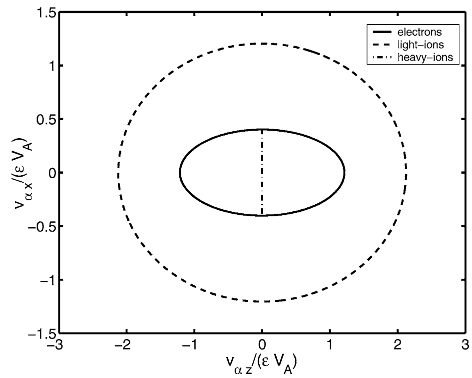

Fig. 7. Trajectories in the velocity space of electrons, light-ion-species and heavy-ion-species: $m_2/m_1 = 12$, $Z_2/Z_1 = 3$ and $n_2/n_1 = 0.25$, at $\omega = \sqrt{(\Omega_1\omega_c)} = 3.0237\Omega_2$. The heavy-ion-species is motionless in the z direction.

Figs. 6 and 7. The dynamics of ions in a multi-species plasma allows one, by a judicious choice of the density ratio, mass ratio, and charge ratio of the ion species, to control the ion motion.

In our experiment the rise-time of the magnetic field at each location is about 120 ns, so that the characteristic frequency ω is 1.3×10^7 s^{-1}, while Ω_2 is 2×10^7 s^{-1}, for a 8 kG magnetic field, the peak magnetic field intensity. Therefore, during the rise of the magnetic field the ratio ω/Ω_2 sweeps the values that are larger than 0.65. For these values of the ratio it is seen in Figs. 3 and 4 that the x components of the ion velocities, perpendicular to the force due to the magnetic field pressure, are comparable in magnitude to the z components of these velocities, in the direction of that force. Even though the velocities are calculated through a linear analysis, it is plausible that significant velocities in the direction of the electrodes are acquired by the ions in our experiment as well. If carbon ions indeed acquire a velocity in the direction of the electrodes that is comparable to the measured velocity parallel to the electrodes, a peak value of 1.2×10^7 cm s^{-1} [4], then their displacement towards the electrodes during the current pulse should be ≈ 1 cm, a displacement that is sufficient to cause the observed decrease in density.

5. Summary and conclusion

We have shown that the presence of second ion species can drastically alter the plasma behavior. In a two-ion-species plasma a significant part of the current may be carried by the ions, unlike the case of a single-ion-species plasma, in which the current is carried only by the electrons. Moreover, analyzing the ion and electron dynamics during the propagation of waves in a two-ion-species plasma, we have explicitly shown that at a certain frequency the electrons do not move at all in the direction of the current, and the current is then carried by the ions only. Each ion species can acquire a large momentum in the direction of the current, perpendicular to the direction of the magnetic field force, while the net momentum acquired in that direction is zero. We have also pointed out the difference in the dynamics of the two-ion-species in the axial direction (the direction of the force due to the magnetic field pressure), noting that each of the two ion species is motionless in the axial direction at a certain frequency. The ion motion perpendicular to the direction of the magnetic field force has been shown to explain the observed decrease of the plasma density during the current pulse in our experiment.

Recognition of these features of the plasma dynamics demonstrated here, current conduction by the ions and ion motion perpendicular to the direction of the magnetic field force, should broaden our notion of the behavior of plasmas in laboratory and space. The way these features are actually exhibited should be further explored in more detail for specific conditions, since here, for clarity and simplicity, they have been demonstrated for linear perturbations in a uniform plasma. The initial value problem, rather than eigenmode analysis, should be solved. Also, the ion dynamics in a plasma, that is initially not magnetized, upon interaction with the self magnetic field due to a large current that is driven in the plasma, as in the plasma opening switch, should be examined. The simple linear analysis given here, nevertheless, provides an insight into the way constraints imposed on the current conduction and the ion dynamics are removed in a multi-species plasma.

Acknowledgements

The authors are grateful to Dr. A. Weingarten, to Dr. R.J. Commisso and to Mr. K. Tsigutkin for useful discussions. This work is supported in part by the United States–Israel Binational Science Foundation and by Minerva Foundation, Munich, Germany.

References

[1] M.A. Liberman, J.S. De Groot, A. Toor, R.B. Spielman, High-Density Z-Pinch Plasmas, Springer, New York, 1998.
[2] R.G. Jahn, Physics of Electric Propulsion, McGraw-Hill, New York, 1968.
[3] C.W. Mendel Jr., S.A. Goldstein, J. Appl. Phys. 48 (1977) 1004;
G. Cooperstein, P.F. Ottinger, IEEE Trans. Plasma Sci. PS-15 (1987) 629, guest editorial.
[4] R. Arad, Ph.D. Thesis, Weizmann Institute of Science, 2001;
R. Arad, K. Tsigutkin, Yu.V. Ralchenko, A. Fruchtman, N. Chakrabarti, Y. Maron, in: Proceedings of the 12th International Conference on High Power Particle Beams, Haifa, Israel, 1998, Rafael, Haifa, 1998, p. 253, Vol. I.
[5] A. Weingarten, Ph.D. Thesis, Weizmann Institute of Science, 1998;
A. Weingarten, C. Grabowski, A. Fruchtman, Y. Maron, in: Proceedings of the 12th International Conference on High Power Particle Beams, Haifa, Israel, 1998, Rafael, Haifa, 1998, p. 346, Vol. I.
[6] A. Weingarten, R. Arad, Y. Maron, A. Fruchtman, Phys. Rev. Lett. 87 (2001) 115004.
[7] R. Arad, K. Tsigutkin, Yu. V. Ralchenko, J.D. Huba, A. Fruchtman, Y. Maron, Investigation of the ion dynamics in a multi-species plasma under pulsed magnetic fields, to be submitted to Physics of Plasmas.
[8] R.J. Commisso, H.J. Kunze, Phys. Fluids 18 (1975) 392.
[9] G. Barak, N. Rostoker, Appl. Phys. Lett. 41 (1982) 918.
[10] H.U. Rahman, P. Amendt, N. Rostoker, Phys. Fluids 28 (1985) 1528.
[11] C.W. Mendel Jr., Phys. Rev. A 27 (1983) 3258.
[12] L.I. Rudakov, Phys. Plasmas 2 (1995) 2940.
[13] A.V. Gordeev, Plasma Phys. Rep. 27 (2001) 659.
[14] N.N. Rao, P.K. Shukla, M.Y. Yu, Planet. Space Sci. 38 (1990) 543.
[15] N.N. Rao, Phys. Scripta 48 (1993) 363;
N.N. Rao, J. Plasma Phys. 53 (1995) 317.
[16] G. Mann, P. Hackenberg, E. Marsch, J. Plasma Phys. 58 (1997) 205.
[17] N.F. Cramer, L.K. Yeung, S.V. Vladimirov, Phys. Plasmas 5 (1998) 3126.
[18] P.K. Kaw, R. Singh, Phys. Rev. Lett. 79 (1997) 423.
[19] M. Salimullah, Phys. Lett. A 215 (1996) 296.
[20] S.J. Buchsbaum, Phys. Fluids 3 (1960) 418.
[21] C.N. Lashmore-Davies, V. Fuchs, G. Francis, A.K. Ram, A. Bers, L. Gauthier, Phys. Fluids 31 (1988) 1614.