Self-consistent charged-particle motion in negative-ion plasmas

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The self-consistent one-dimensional kinetic theory of relaxation of a low pressure quasineutral negative-ion plasma destroyed in a limited region by a powerful laser light pulse is developed. Using the self-similar method, well known in hydrodynamics, we examine the counterflow of the negative plasma species and show the important role of the self-consistent electric field. The negative-ion temperature determined from the ballistic model is valid when the ratio of negative-ion to positive-ion densities is lower than 0.1. The overshoot of electron density that was observed experimentally is described by this method. We show that the overshoot can disappear when the positive-ion mass or temperature goes up. The self-similar solutions are also supported by numerous experimental results.

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I. INTRODUCTION

The negative-ion plasma is technologically important in the production of energetic neutral beams for heating, current drive, and diagnostics in fusion plasmas [1,2]. Therefore, the search for diagnostic techniques for these plasmas is a very important problem.

A generally applicable experimental technique suitable for studying negative-ion plasmas has been developed by Bacal *et al.* [3–7]. This diagnostic technique is based on laser photodetachment. Intense laser light rapidly dissociates the negative ions into atoms and free electrons. The measurement of the electron perturbation by a Langmuir probe gives important information about the negative-ion plasma parameters. The technique involving two laser pulses delayed in time was used for analyzing the dynamics of plasma in the laser channel [4,5]. Using this technique, Stern *et al.* [5] found experimentally and described theoretically a basic transport process, the "monopolar" drift, in which particles with the same charge preserve local neutrality by counterflowing (in contrast with the well-known ambipolar drift, which involves oppositely charged species flowing in the same direction). Stern *et al.* [5] treat the problem of the return of the negative-ion density to its steady state value by using a simple ballistic kinetic theory. This approach was very successful in studying the negative-ion evolution for times of order R/v_{th}^{-}, where R and v_{th}^{-} are the radius of the cylindrical region in the plasma affected by the laser beam and the thermal velocity of the negative ions. Friedland, Ciubotariu, and Bacal [7] first included the effects of self-consistent electric field. They modeled this plasma via a hybrid fluid-kinetic approach in which the electrons and positive ions are described by the fluid theory, while the negative ions are treated within the ballistic kinetic theory which was verified experimentally [6]. Therefore, it is of current interest to develop a complete self-consistent description of such negative-ion plasma.

Let us consider the relaxation process of plasma in the laser beam channel in more detail. After applying the laser pulse, the electron density inside the laser channel is higher than outside it, since the negative ions are destroyed. The additional electrons are monoenergetic with energy near 0.45 eV. As the average electron velocity is markedly in excess of the positive ion velocity, the electrons inside and outside the channel mix to an equilibrium state with a density inhomogeneity across the channel. As a result, an electric field appears and keeps the excess electrons inside the channel. It is well known (see Sec. II) that the potential of this field is related to the electron density by the Boltzmann relation. Furthermore, the plasma dynamics will be related to the ion motion. In the case of low electron temperature, when the electric field is weak, the ion velocity will be close to the ion thermal velocity; however, when the electric field is strong (for hot electrons) the ion velocity can exceed it. In the latter case, one should take into account the self-consistent electric field when determining the negative-ion temperature.

Thus we came to two conclusions. First, one needs to solve the self-consistent problem to determine the limit of the ballistic model and to find the negative-ion temperature. Second, the self-consistent plasma dynamics is of interest near the surface separating the two plasma regions. The ion dynamics is similar in the planar and cylindrical geometries until the negative ions travel a distance of the order of the laser radius; from there on, differences related to the geometry will become important. Friedland, Ciubotariu, and Bacal [7] have shown that in the ballistic approximation the overshoot is simi-

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lar in the planar and cylindrical geometries. Furthermore, the charged particles going to the axis of the cylinder are lost on the Langmuir probe and do not play any role in the relaxation process. Thus the cylindrical geometry is of secondary importance and we can examine the one-dimensional problem in self-consistent treatment in the Cartesian system. The solution of this self-consistent problem both has an independent meaning and represents the initial approximation for future negative-ion plasma research.

We will consider collisionless negative-ion plasmas. This obviously imposes a restriction on the time considered, which should be shorter than the elastic and inelastic collision times. Here, the considered time is the channel plasma relaxation time $t_r = R_L / v_i$, where R_L is the laser beam radius, v_i is the average negative-ion velocity, which has the same order of magnitude as the ion thermal speed. The rough upper estimate for the relaxation time is 1 μs for $R_L \sim 0.01$ m and $v_i \sim 10^4$ m/sec. Since the frequency of Coulomb collisions of particles of charge e and mass M with particles of the same charge, of density n, is $\nu = ne^4 L / [(16\pi\varepsilon_0)^2 M^2 v^3]$, where the Coulomb logarithm $L \sim 10$, and v—the relative average velocity of the colliding particles. Substituting the relevant parameters of the experiment (Ref. [5]) $n \sim 10^{17}$ m^{-3}, $v \sim v_{Ti} \sim 7.5 \times 10^3$ m/sec (for $Ti \sim 0.2$ eV), we find the collision time $\tau = 1/\nu \sim 7$ μs, which is longer than the characteristic relaxation time of this problem. It can be noted that for faster particles the collision frequency goes down. The collision time $(N\sigma v)^{-1}$ for the collision of negative ions with particles of the residual gas is at least 5 μs for the gas pressure used in the experiment (with $\sigma \sim 3 \times 10^{-19}$ m^2 and $N \sim 9 \times 10^{19}$ m^{-3}, see also Ref. [5]). Therefore, the collisionless approximation is appropriate for our investigation.

To solve this problem, we can apply the method of self-similar solutions, well known in hydrodynamics. We take the approach of Gurevich, Pariiskaya, and Pitaevskii [8]. They used the self-similar method to solve the self-consistent problem of the plasma expansion into vacuum or plasma. They generalized the method of the self-similar variables and solved the kinetic equations for plasmas, consisting of different species [9–11]. Ivanov *et al.* [12–14] showed that the propagation of a space-localized group of hot electrons into plasma is also self-similar. It should be noted that these nonlinear problems cannot be completely solved in analytical form but the knowledge of the characteristic peculiarity of the physical problems can lead to the simplification of the model and to a fundamental understanding of the physical processes.

For this problem the self-similar approach is supported by extensive experimental data [4–7]. In Ref. [5], for example, these data showed that a self-similar motion takes place outside the laser channel, i.e., that the motion is a function of r/t only. It was also shown that the Langmuir probe, located on the axis of the channel exhibits a signal which is a function of r/t [see Fig. 4(a) in Ref. [6]].

The distribution function of detached electrons can differ from a Maxwellian one, but in the experiments of Refs. [5] and [6] their mean energy is close to that of background electrons [4]. Thermalization of photodetached electrons for densities present in the experiments [5,6] we refer to occurs rapidly and so we can consider the electrons to be Maxwellian. In the general case, a different electron distribution should be considered.

One of the interesting phenomena connected with the laser detachment and described in Ref. [4] is the dip in the electron density time evolution which was denoted as "overshoot." A probe located on the axis of the system showed that the electron density can decrease below the background electron density, before retuning to the steady state.

In this paper we present a self-similar one-dimensional theory of low pressure hydrogen plasmas containing negative as well as positive ions and electrons.

In Sec. II the mathematical treatment and the assumptions and restrictions are discussed. Section III presents the self-similar solution obtained when the positive ions are at rest. Thus we demonstrate the role of electric field on the negative-ion motion. In Sec. IV the positive-ion motion is considered and we present the self-similar motion of both positive and negative ions. The discussion of the results obtained and of future research is made in Sec. V.

II. THE MODEL AND THE BASIC EQUATIONS

Let us consider two plasma regions separated by the plane $x = 0$. The first region $(x < 0)$ consists of electrons and negative as well as positive ions. The second plasma region $(x > 0)$ consists of electrons and positive ions only. Thus, the fast laser destruction of negative ions into atoms and electrons takes place in the second region for $x > 0$. As stated earlier, we study the one-dimensional problem only. The distribution functions of the negative ions $F_i^-(x,v,t)$ and that of the positive ions $F_i^+(x,v,t)$ satisfy the kinetic equations

$$\frac{\partial F_i^-}{\partial t} + V \frac{\partial F_i^-}{\partial X} + \frac{e}{M_-} \frac{\partial \Phi}{\partial X} \frac{\partial F_i^-}{\partial V} = 0 , \quad (1)$$

$$\frac{\partial F_i^+}{\partial t} + V \frac{\partial F_i^+}{\partial X} + \frac{Ze}{M_+} \frac{\partial \Phi}{\partial X} \frac{\partial F_i^+}{\partial V} = 0 , \quad (2)$$

where M_- and M_+ are the negative and positive ion mass, respectively. Z is the ion charge number, Φ is the electrostatic potential. We can write a few equations as (2) for all the plasma species, but in this paper, for simplification, we are dealing with one-plasma positive species only. As in the classical theory, the assumption of quasineutrality is used for the description of slow plasma streams

$$N_e + N_i^- = N_i^+ , \quad (3)$$

where N_e, $N_i^- = \int_{-\infty}^{\infty} F_i^- dV$, and $N_i^+ = \int_{-\infty}^{\infty} F_i^+ dV$ are the densities of electrons, negative ions, and positive ions, respectively.

From the first moment after photodetachment the quasineutrality Eq. (3) is valid. Electrons, being very fast compared to negative ions, penetrate into the negative-ion plasma region on a few Debye lengths. The rising electric field acts on the negative ions and after some time the width of the electron–negative-ion front will be much larger than the Debye length.

To complete this set of equations, we have to relate the electron density N_e and the electrostatic potential Φ. Strictly speaking, we can write the kinetic equation for electrons. But for this problem the small-scale motion is of no interest; thus we can write the well-known Boltzmann relation

$$N_e(\Phi)=n_{e0}\exp(e\Phi/T_e)\ , \tag{4}$$

where T_e is the electron temperature and n_{e0} is the electron density before photodetachment. The dependence of the electron density versus the adiabatic electric potential for a Maxwellian electron distribution is given, for example, in Ref. [15] where it is shown that with the assumption $\tau \gg L/V_e$ (τ and L are the typical time and length of the process, respectively; V_e is the typical velocity of the electrons) the electron density has the Boltzmann form (4). This equation was also examined by Mora and Pellat [16] for the problem of plasma expansion into vacuum. They showed that Eq. (4) was true for physically interesting electron parameters. It was shown by Gurevich and Pitaevskii [11] that if the electron distribution function is non-Maxwellian and the potential does not represent a well for electrons, the electron density has the form

$$N_e(\Phi)=\int_{V_1}^{\infty}\left[F_e dV\Big/\left[1+\frac{2e\Phi}{mV^2}\right]^{1/2}\right]+\int_{-\infty}^{-V_1}\left[F_e dV\Big/\left[1+\frac{2e\Phi}{mV^2}\right]^{1/2}\right]\ , \tag{5}$$

where $V_1=\sqrt{-2e\Phi/m}$, F_e is the electron distribution function for $\Phi=0$. The densities of (5) are shown in Fig. 1 for several distribution functions. It can be seen that the curves are close for small values of the potential and diverge for larger values.

We see that the system of Eqs. (1), (2), (3), and (4) or (5) can depend on X and t in the combination X/t. In this

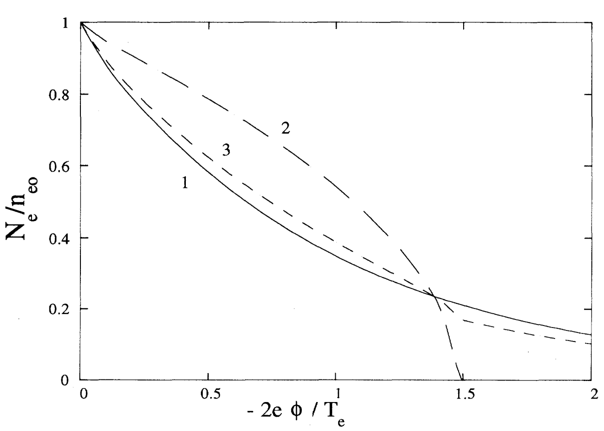

FIG. 1. The dependence of electron density vs potential for distribution function. 1: $f_1=(1/\sqrt{\pi})\exp(-v^2)$, 2: $f_2=\{^{0,\ v>v_{\rm eff}}_{(1/2)v_{\rm eff}\ v<v_{\rm eff}}$, 3: $f_0=0.8f_1+0.2f_2$.

case the system has a solution depending on X/t if the initial conditions depend on X/t only. Thus we can find the solution as in hydrodynamics using the self-similar variables. The equations become

$$(v-\xi)\frac{\partial f_i^-}{\partial\xi}+\frac{\partial\varphi}{\partial\xi}\frac{\partial f_1^-}{\partial v}=0\ , \tag{6}$$

$$(v-\xi)\frac{\partial f_1^+}{\partial\xi}-\frac{ZM_-}{M_+}\frac{\partial\varphi}{\partial\xi}\frac{\partial f_1^+}{\partial v}=0\ , \tag{7}$$

where we used normalized values $\varphi=2e\Phi/T_e$, $v=V/V_s$, $\xi=x/tV_s$, $f=F/n_0V_s$, where $V_s=(2T_e/M_-)^{1/2}$, which we denote as the negative-ion acoustic velocity, and n_0 is the background plasma density. The Boltzmann relation (4) is now

$$n_e(\varphi)=n_{e0}/n_0\exp(\varphi/2)\ . \tag{8}$$

III. THE SOLUTION WHEN POSITIVE IONS ARE AT REST

In order to study the motion of negative ions in plasmas, we first consider this motion under the condition $M_+=\infty$. This is consistent with a physical situation where the positive-ion mass is larger than the negative-ion mass (negative ion H^- and positive ion $H_3{}^+$, or Cs^+, or another heavy positive species). In this case, the positive ions are considered to be at rest and we can use this condition at least at the early stage of the relaxation of the illuminated plasma cylinder. The effect of positive-ion motion will be discussed in Sec. IV.

Thus we have to solve the nonlinear Eqs. (3), (6), and (8). An obvious transformation reduces this set to the nonlinear equation

$$(v-\xi)\frac{\partial f_i^-}{\partial\xi}+2\frac{\partial}{\partial\xi}\ln\left[1-\int_{-\infty}^{\infty}f_i^- dv\right]\frac{\partial f_i^-}{\partial v}=0\ . \tag{9}$$

For $\xi\to-\infty$ the plasma is unperturbed and the distribution function is Maxwellian,

$$f_{i0}^-(v)=n_{i0}^-\exp[-(v/v_i)^2]/(v_i\sqrt{\pi})\ , \tag{10}$$

with $v_i^2=T_i^-/T_e$. It is clear that Eq. (9) with the initial condition Eq. (10) has two parameters: n_{i0}^- (initial negative-ion density) and v_i (thermal velocity). This equation was solved numerically by the method of characteristics. The equation for the curves along which the value of the negative-ion distribution function is constant [these curves are the characteristics of Eq. (9)] has the form

$$(v-\xi)\frac{\partial v}{\partial\xi}=F(\xi)=2\frac{\partial}{\partial\xi}\ln\left[1-\int_{-\infty}^{\infty}f_i^- dv\right]\ . \tag{11}$$

Solving the characteristic equation (11) for the values of initial velocities $v_{i0}=v_{\min}+(i-1)\delta v$, where $i=1,2,\ldots,N_v$, we find the new velocity values for the new point $\xi=\xi_0+\Delta\xi$.

Now, at point ξ we find the negative-ion density

$$n_i^- = \int_{-\infty}^{\infty} f_i(v)dv = \frac{1}{2}\sum_{k=2}^{N_v}\{f_{i0}^-(v_{0k})+f_{i0}^-(v_{0k-1})\}\times[v_k(\xi)-v_{k-1}(\xi)]$$

and, further, the new value of F. In the next step, the calculation will be repeated for the new value of ξ. Figures 2, 3, and 4(a) show the results of a numerical simulation of the self-similar motion of the plasmas components for the initial parameters

$$v_i=0.2\ ,\ \text{i.e.,}\ T_i^-/T_e=4\times10^{-2}\ ,$$

$$n_{i0}^-=0.2\ ,\ \text{i.e.,}\ N_{i0}^-=0.2n_0\ .$$

For the initial value of $\xi_0=-2$ the negative ions have the Maxwellian distribution function that is cut off for $|v|>1$.

One can easily interpret the curve in Fig. 4(a). This curve shows either the dependence versus the actual length x at some time, or the uniform expansion around the point $\xi=0$ with time, the given density n_i^- moving with its own velocity. The convergence of all the characteristics toward the line $\xi=v$ (Fig. 2) is accompanied by the acceleration of ions (Fig. 3) and, respectively, by the decrease of ion density [Fig. 4(a)]. For comparison, the field-free ion expansion that was described by the equation

$$n_g(\xi)=\int_{\xi}^{\infty} f_{i0}^-(v,\xi)dv$$

is shown in Fig. 4(a) by the dotted line. One can note that the electric field accelerates the negative ions.

The time dependence of the negative-ion density can be reconstructed using Fig. 4(a). It corresponds to a motion of point ξ from $+\infty$ to 0.

One can see large-scale oscillations on the curves of Figs. 2 and 4(a). They show that the expansion of negative ions is not monotonous. These oscillations are smoothing down with the increase of negative ion temperature. The variation of the electron density in time and space can also be inferred from Fig. 4(a), since, due to the quasineutrality, Eq. (3), $n_e=1-n_i^-$.

The self-similar solution has no length or time parameter. In order to present the results in a more informative way, let us introduce a length scale L equal to the radius of the laser channel. We can thus conveniently illustrate the dependence of negative-ion density on time, measured in units L/V_s [see Fig. 4(b)]. In terms of planar geometry, L is the distance between the probe and the plane boundary of negative-ion plasma at initial time. It

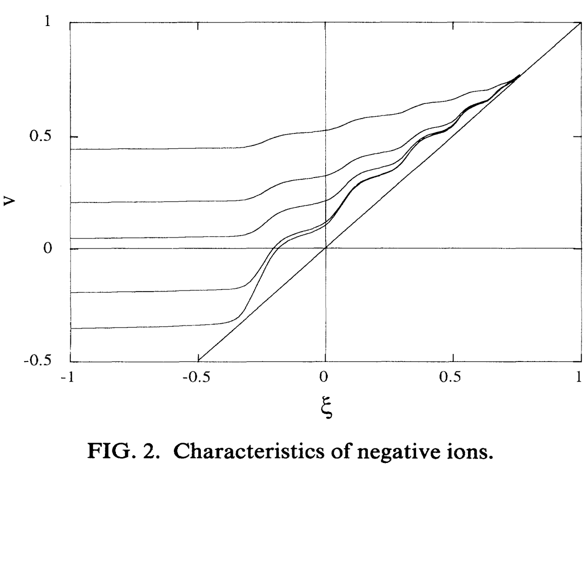

FIG. 2. Characteristics of negative ions.

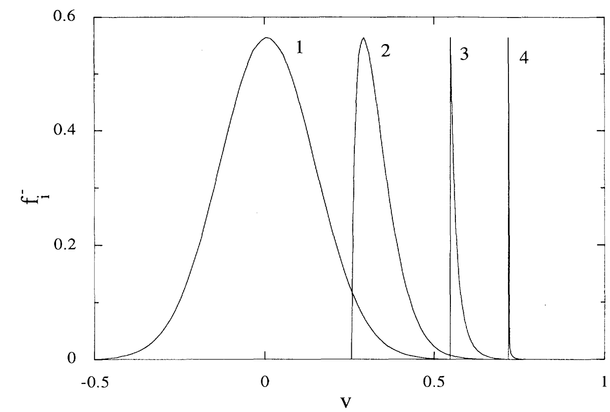

FIG. 3. Negative-ion distribution function for 1: $\xi=-1$; 2: $\xi=0.1$; 3: $\xi=0.5$; 4: $\xi=0.9$.

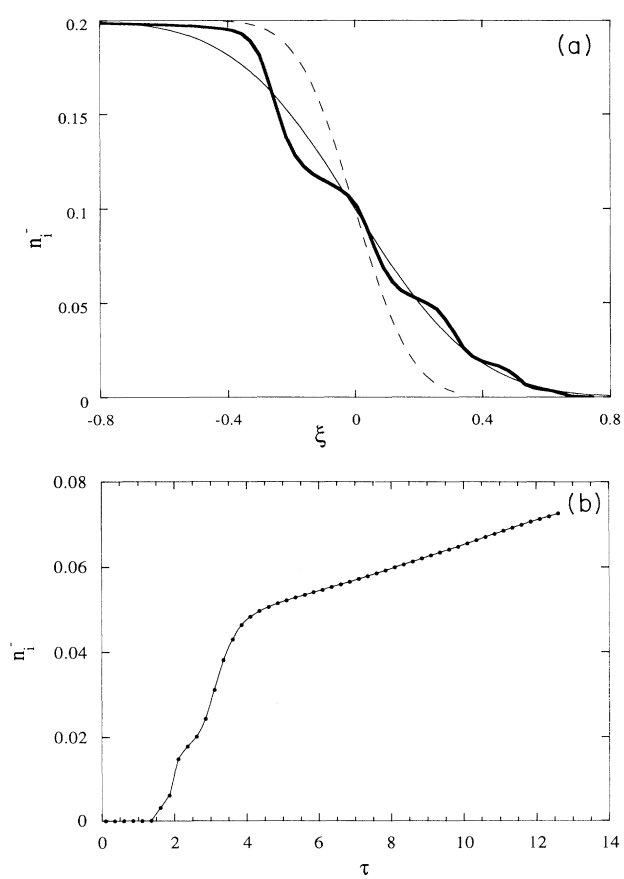

FIG. 4. (a) Dependence of negative-ion density on ξ for $T_i/T_e=0.04$. Thick full line curve—with self-consistent electric field; dotted line—ballistic theory with the same temperature; thin full line—ballistic theory with $T_i/T_e=0.18$. (b) Dependence of negative-ion density on time $\tau=tV_s/L$ at $x=L$ for $T_i/T_e=0.04$.

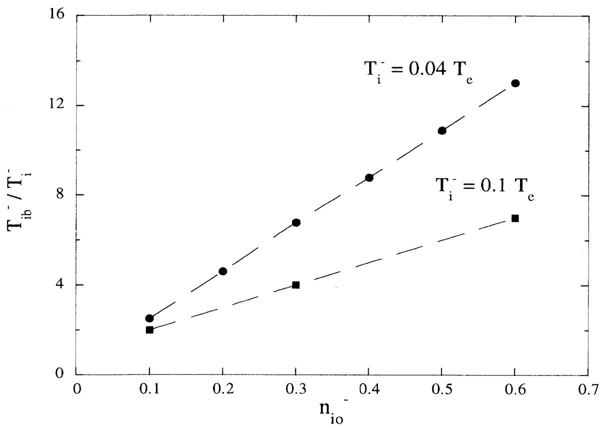

FIG. 5. Ratio of negative-ion temperature calculated with use of ballistic model T_{ib} to one calculated with use of self-consistent electric field vs negative-ion n_{i0}/n_{p0}. n_{p0} is the plasma density.

should be pointed out that the asymptotical value of the negative-ion density is lower by a factor of two than the initial one due to planar geometry, i.e,. at initial time the negative-ion plasma occupies the half space $x<0$ and extends from $x=-\infty$ up to $x=+\infty$ at t tending to infinity.

For comparing the ballistic model and the self-consistent one we used the following method. In Ref. [6] the ion temperature was found by fitting the theoretical curve to the experimental data. Using a similar method, we find first the theoretical curve with electric field. We consider this as an "experimental" curve and fit to it another theoretical curve, obtained in the ballistic approximation which gives the "ballistic" negative-ion temperature T_{ib}^-. Figure 5 shows the variation of the ratio T_{ib}^-/T_i^- as a function of the ratio n_{i0}^- of the negative-ion and positive-ion densities. Figure 5 shows that the ballistic model is valid when the ratio of negative-ion to positive-ion densities is lower than 0.1, which was the case in the work described in Refs. [4–6]. The present results describe possible effects if such studies were effected at a high ratio of negative-ion to positive-ion densities. Figure 6 shows the dependence of negative-ion density upon ξ for different electron distribution function.

The ballistic theory applies when the negative-ion density evolution coincides with that for field-free expansion (Fig. 4, dotted line). Figure 5 has shown how the validity of this theory is limited to low negative-ion fractions. The ratio of temperatures of various plasma species also affects the range of validity. Both experiment and calculation can prove this validity.

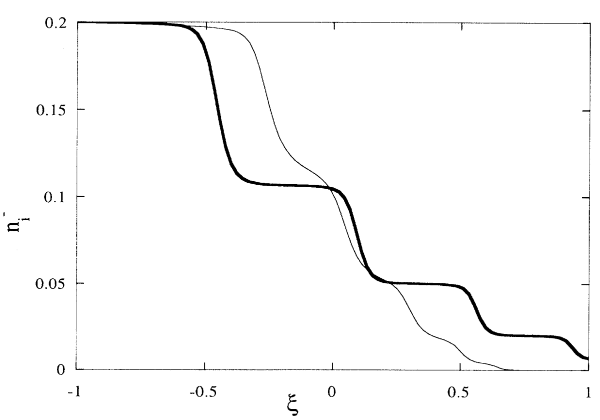

FIG. 6. Dependence of negative-ion density upon ξ for a distribution function f_2 (see Fig. 1) with $v_{\text{eff}}/v_{Te}=1.22$ (full curve) and for Maxwellian distribution function with v_{Te} (thin curve).

IV. THE ROLE OF POSITIVE-ION MOTION

We have already seen that when $n_-/n_+>0.1$ the negative ions are accelerated by the electric field and the ion velocity can be larger than the ion thermal velocity. An effect that could change our result is the finite positive-ion mass. Therefore, we have to consider now the set of equations (3), (6), and (8) and the additional Eq. (7). Let us consider a single positive-ion species. The equation of characteristics for Eq. (7) is

$$(v-\xi)\frac{\partial v}{\partial \xi}=-\varepsilon F(\xi)\ , \tag{12}$$

where $\varepsilon=ZM_-/M_+$.

Next we consider the case $\varepsilon<1$ and examine the movement of positive ions in the field that was created by the counterflow of negative ions and electrons (monopolar drift). Since the positive ions exist over all the space in the initial plasma, we use the normalized Maxwellian distribution function for positive ions at $\xi\to\xi_0$ and at $\xi\to-\xi_0$ in Maxwellian form:

$$f_{i0}^+(v)=\frac{1}{v_i^+\sqrt{\pi}}\exp(-(v/v_i^+)^2)\ ,\quad \text{with}(v_i^+)^2=T_i^+/T_e\ . \tag{13}$$

The method of numerical calculation of Eq. (12) was similar to that for Eq. (11) and was described above.

Figure 7 shows the characteristics of positive ions. It is seen that far from the line $v=\xi$ the characteristics are

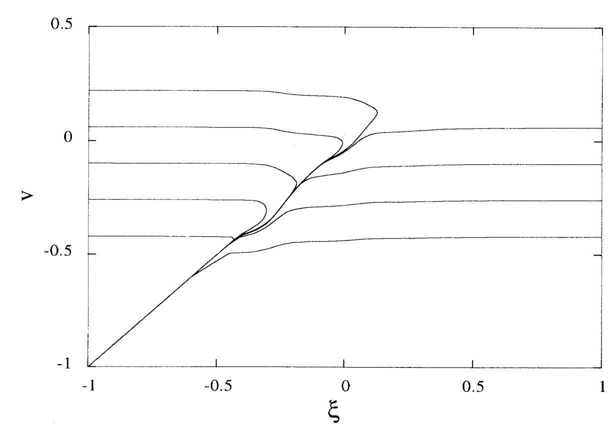

FIG. 7. Characteristics of positive ions with $T_i^+/T_e=0.01$ and $M_+/M_-=5$.

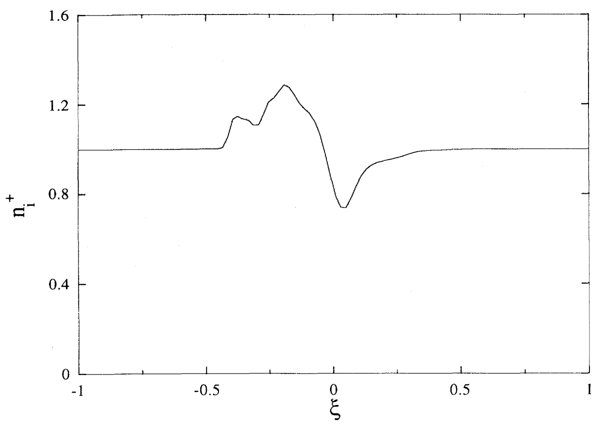

FIG. 8. Dependence of positive-ion density upon ξ.

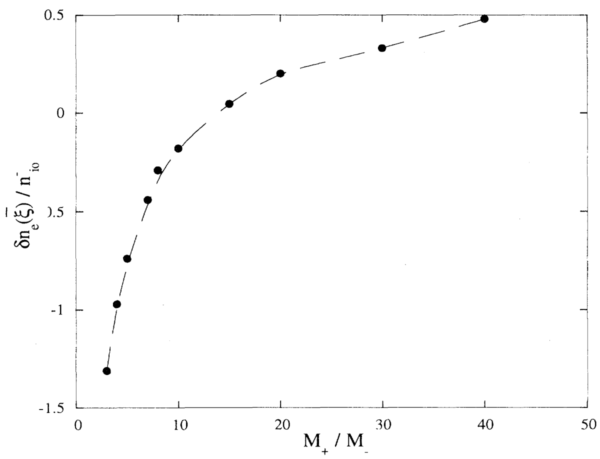

FIG. 9. Minimum value of electron-density perturbation in the overshoot region as a function of positive-ion mass. $n_{i0}^- / n_0 = 0.2$; $T_i^- / T_e = 0.04$; $T_i^+ / T_e = 0.01$.

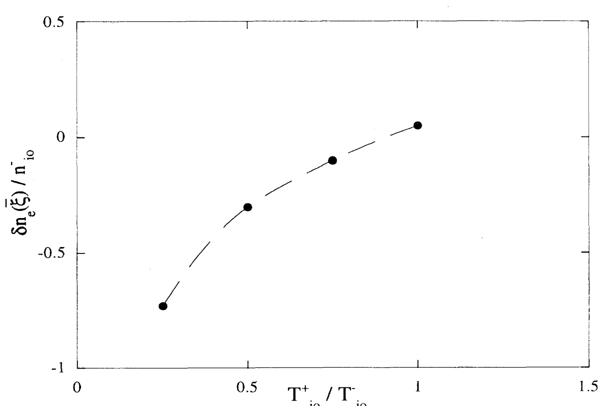

FIG. 10. Minimum value of electron-density perturbation in overshoot region as a function of positive ion temperature. $n_{i0}^- / n_0 = 0.2$; $T_i^- / T_e = 0.04$; $M_+ / M_- = 5$.

parallel to the ξ axis. In the vicinity of the line $v = \xi$ the characteristics coming from $\xi = -\infty$ first deviate and then tend to the line $v = \xi$. The characteristics from $\xi = +\infty$ monotonically decline, tending to the line $v = \xi$ as well. The larger M_+, the narrower the region adjacent to the line $v = \xi$, where the characteristics are not straight lines. This region vanishes in the limit $M_+ \to \infty$ when there is no positive-ion perturbation due to negative-ion motion.

Figure 8 shows that the positive ions are pushed out from the counterflow region, a depression in the positive-ion density being formed for a certain value $\xi > 0$. A depression occurs in the the electron density as well. This depression (the overshoot) was observed and interpreted [4] as the result of the joint depletion of positive-ion and electron densities after photodetachment. Friedland, Ciubotariu, and Bacal [7] showed theoretically that the amplitude of the overshoot depends on the ratio T_e / T_+. Note on Fig. 8 that the depression in the positive-ion density producing the observed overshoot arises near the boundary of two plasma regions and propagates to the detached right plasma region. On the other hand, a maximum of the ion density occurs in the left plasmas region ($\xi < 0$).

The amplitude of the overshoot is a function of mass and temperature of positive ions (see Figs. 9 and 10). We see that the growth of both the positive ion mass and positive-ion temperature causes the reduction of the overshoot amplitude.

V. DISCUSSION

We have shown that the self-consistent electric field can influence the relaxation of the plasma in the laser photodetachment channel and affect the recovery of the negative-ion density after photodetachment. For higher ratio n_- / n_+ and low $T_- / T_e \ll 1$ this could modify the value of the ion temperature determined from this recovery. The actual negative-ion temperature could then be lower than that determined from the ballistic model.

We have considered the role of the electric field in one-dimensional treatment in plane geometry. In the context of the quasineutrality assumption, we showed that these problems have self-similar solutions. It is possible to solve the problems with two boundaries and in a different geometry. For these problems, new variables can appear but the self-similar character of the solutions remains. We have examined the simple self-similar variable x/t. From our viewpoint this variable suits to the experimental data most closely. Generally speaking, the solutions depend on a self-similar variable in general form $\Omega(x,t)$. This variable allows one to describe the expansion of the boundary, the Riemann simple, waves, and the formation of shock waves.

It follows from our study that oscillations of negative ion and electron densities take place for relatively cold negative ions ($T_- / T_e \ll 1$), the oscillation vanishing as the negative-ion temperature increases. Similar oscillations were described in Ref. [17] for the expansion of the plasma with two ion species.

We have examined theoretically the overshoot and confirmed the statement made in Ref. [4] that the positive ions were pushed out from the boundary region ($\xi \approx 0$) to the external region ($\xi < 0$). The experimental investigations using different negative-ion plasmas will allow us to study these phenomena in more detail.

We studied the effect of the self-consistent electric field on the dynamics of positive ions and showed that this field could produce the overshoot in the electron density, which was observed in the experiments. In order to effect a quantitative comparison with experiment, we intend to solve this problem for the case of the cylindrical geometry. The finite size of the laser beam channel can lead to sound waves but these are not observed in actual experiments.

Thus the present theory is in qualitative agreement with the experimental data. We can say with reasonable confidence that there will also be quantitative agreement and the diagnostic method can be developed. To sum up, we note that this method has broader applications than we claim in this paper and we will apply these results to the actual geometry used in experiments.

The present work is relevant to collective charged particle acceleration. Future calculations using this approach could be a useful tool in studying different aspects of collective acceleration.

ACKNOWLEDGMENT

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