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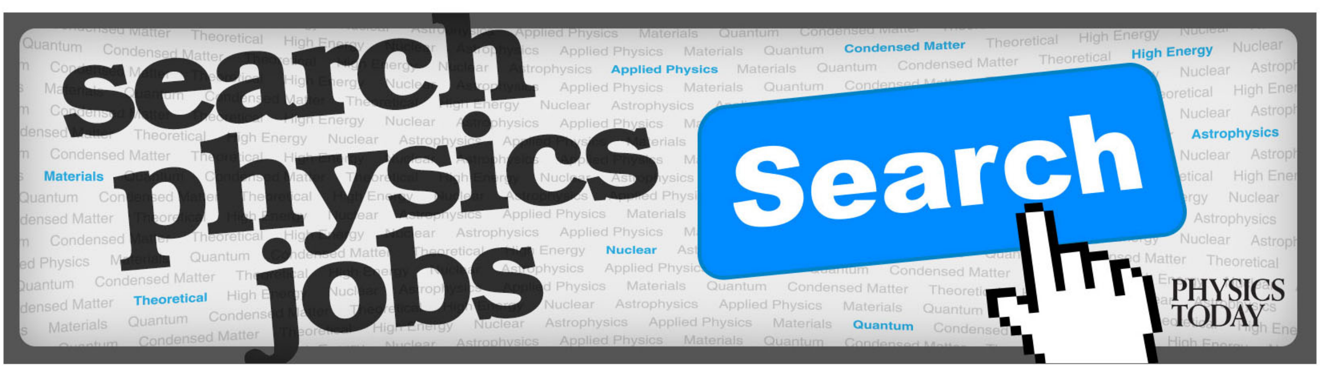

PHYSICS OF PLASMAS **17**, 074501 (2010)

Modeling of laser induced plasma expansion in the presence of non-Maxwellian electrons

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The one-dimensional expansion into vacuum of ion-electron plasma produced by laser ablation is investigated. The ions considered as an ideal fluid are governed by a fluid model where charge quasineutrality is assumed to prevail, while electron density follows a non-Maxwellian distribution. Showing that the expansion can be described by a self-similar solution, the resulting nonlinear Euler equations are solved numerically. It is found that the deviation of the electrons from Maxwellian distribution gives rise to new asymptotic solutions of physical interest affecting the density and velocity of plasma expansion. © *2010 American Institute of Physics*. [doi:10.1063/1.3458671]

Plasma expansion into vacuum is a basic physical problem with a variety of applications, ranging from space to laboratory scales.[1–4] Caused generally by electron pressure, it serves as an energy transfer mechanism from electrons to ions. The expansion process is often described under the assumption of Maxwellian electrons with velocities in local thermal equilibrium (LTE), known to be isotropically distributed around the average velocity. This assumption easily fails with a lack of collisions. Indeed, in many cases of astrophysical and laboratory plasmas expansion, the electron distribution functions (EDFs) are non-Maxwellian and exhibit more complex shapes showing high-energy tails, as in the weakly collisional corona and solar wind acceleration region.[5] The fundamental reason is that fast electrons collide much less frequently than slow ones. Indeed their free path is very large since proportional to v_e^4, where v_e is the electron velocity, and cannot relax to a Maxwellian. The energetic electrons could have a significant effect on ionization and expansion of the plasma. As reported by many authors,[6–8] in an expanding plasma produced by laser ablation experiments, the high mobility light electrons escape faster into vacuum compared to heavier particles, thus generating a self-consistent ambipolar electric field that accelerates the ions and slows electrons.

Another phenomenon observed in plasma expansion is that the heat exchange between electrons and heavy particles such as ions is inefficient as only a fraction of the thermal energy of the order of m_e/m_i is transferred per collision, where m_e and m_i are the electron and ion mass, respectively. This causes the electron temperature T_e to differ from the ion temperature T_i. T_e in non-LTE plasmas is higher than T_i because of insufficient electron-electron collisions which provide the essential mechanism to reach thermal equilibrium.[9] This phenomenon is also crucial in pulsed laser deposition (PLD) experiments, where the efficiency of the deposited films depends on the parameters of the laser induced plasma that expands into vacuum or in an ambient environment. A very simple view of the PLD divides the process into two main stages: first, the incident laser rapidly heats the target, then a dense, warm plasma is created near the target surface, leading the plume to expand adiabatically. Finally, the plume deposits onto a substrate with nonequilibrated structure due to the presence of high energy particles.[10] The fast expansion causes physical parameters to change in a time scale that is too small to allow the establishment of elementary process balances, thus leading to nonequilibrium excitation and chemical processes.[11–13]

Initially, the nonthermal electrons were modeled by the Cairns distribution which was first introduced by Cairns *et al.*[14] to study the effect of nonthermal electrons on the nature of ion sound solitary structures observed in the upper ionosphere. Later, Mamun[15] and Tang and Xue[16] also considered the nonthermal electrons and warm ion effects on ion acoustic waves. In fact it has been shown here that for given values of the nonthermal parameter, cylindrical and spherical Korteweg–de Vries (KdV) equations can be invalid and one has to consider the modified KdV equation. Recently, Mora and Grismayer[17] investigated the collisionless expansion into vacuum of a thin plasma foil using a non-Maxwellian EDF in the framework of laser fusion experiments. The deviation from a Maxwellian distribution inherent to the expansion leads to the acceleration of the ion-acoustic velocity.

In the present brief communication, we investigated the impact of the EDF on the expanding profiles of a laser induced plasma into vacuum involved in PLD applications or in fusion experiments. For this purpose, we used the Cairns nonthermal distribution which can be seen as a composition of Maxwell distribution functions to find the velocity and the density profiles of an ejected plasma far from the target.

A two-component plasma consisting of electrons and ions is considered where electrons are assumed to follow a non-Maxwellian velocity distribution function, modeled by the Cairns nonthermal electron distribution[14]

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$$f_e(v_e) = \frac{n_{e0}}{\sqrt{2\pi v_{eth}^2}} \frac{(1+\alpha v_e^4/v_{eth}^4)}{(3\alpha+1)} \exp(-v_e^2/2v_{eth}^2), \quad (1)$$

where n_{e0} is the unperturbed electron density, $v_{eth}=\sqrt{T_e/m_e}$ is the average thermal velocity of the electrons, T_e is the electron temperature in the absence of nonthermal effects, and α is a parameter that measures the deviation from thermal equilibrium.

It is clear that Eq. (1) expresses the isothermally distributed electrons when $\alpha=0$. The nonthermal electron distribution in the presence of nonzero potential can be derived by replacing v_e^2/v_{eth}^2 with $(v_e^2/v_{eth}^2-2\phi)$. Consequently, the electron number density is

$$n_e = \int f_e(v_e) dv_e = n_{e_0} \exp(\Phi)(\beta\Phi^2 - \beta\Phi + 1), \quad (2)$$

where $\beta=4\alpha/(3\alpha+1)$ and $\Phi=e\phi/T_e$ is the normalized electrostatic potential. To have physical solution, β must be smaller than 1.

It is known that plasma expansion process includes two important stages: the initial stage is one-dimensional and the final stage consists of two- or three-dimensional expansion. The initial one-dimensional stage which is strictly directed perpendicularly to the target occurs during laser energy deposition and early times of expansion into vacuum. The validity of this approximation is demonstrated in literature and is justified only up to a distance from the target of the order of the laser spot size.[13,18] This forward peaking phenomenon for deposition is now generally accepted as arising from collisions between plume species.[13] At a later stage, away from the target surface, expansion in the radial direction will become important, and the model has to be extended to two dimensions (radial symmetry) or three dimensions.[19,20] Then, a possible solution to this problem is to employ more than one model, each suitable for a particular stage, and match them at an intermediate time. In this work, for the sake of simplicity, we use a one-dimensional description of the laser ablation process, such as it applies at early times after the end of the laser pulse, i.e., as long as lateral heat conduction can be neglected. Consequently, the ions with density n_i and velocity v_i are described by the following fluid equations:

$$\frac{\partial n_i}{\partial t} + \frac{\partial(n_i v_i)}{\partial x} = 0, \quad (3)$$

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial x} + \frac{1}{m_i n_i}\frac{\partial P_i}{\partial x} + \frac{e}{m_i}\frac{\partial \phi}{\partial x} = 0, \quad (4)$$

where x is the distance from the center of the planar target.

Assuming the plasma as an ideal gas, the pressure is given by $P_i=n_iT_i$. The electron thermal conductivity in the hot expanding plasma is considered sufficiently high for the plasma to be isothermal, which means that T_e and T_i are assumed to remain constant during plasma expansion.[21,22] The characteristic length scale for plasma density variations is generally large compared with the Debye length, so that the plasma remains quasineutral during the expansion: $n_e=n_i$.

In the presence of free boundary associated to plasma expansion, it is a hard task to solve the problem numerically. Under certain assumptions, the partial differential equations describing the expansion can be reduced to ordinary differential ones which greatly simplifies the problem. This transformation is based on the assumption that a self-similar solution exists, i.e., every physical parameter preserves its shape during the expansion.[22] Self-similar solutions usually describe the asymptotic behavior of an unbounded or a far-field problem; the time t and the space coordinate x appear only in the combination of (x/t). It means that the existence of self-similar variables implies the lack of characteristic lengths and times. These solutions are usually not unique and do not take into account the initial stage of the physical expansion process.

The one-dimensional self-similar solution of Eqs. (1)–(4) with the quasineutrality assumption can be constructed by using the ansatz defined as

$$\tilde{n}_i = n_i/n_{i_0}, \quad \tilde{v}_i = v_i/c_s,$$

where c_s is the ion sound velocity given by $c_s=\sqrt{T_e/m_i}$ and n_{i_0} is the initial density of the plasma. Using the dimensionless self-similar variable $\xi=x/c_st$ and Eqs. (3) and (4), we obtain the following set of normalized ordinary equations:

$$(-\xi+\tilde{v}_i)\frac{d\tilde{n}_i}{d\xi} + \tilde{n}_i\frac{d\tilde{v}_i}{d\xi} = 0, \quad (5)$$

$$(-\xi+\tilde{v}_i)\frac{d\tilde{v}_i}{d\xi} + \delta\frac{1}{\tilde{n}_i}\frac{d\tilde{n}_i}{d\xi} + \frac{d\Phi}{d\xi} = 0, \quad (6)$$

where $\delta=T_i/T_e$. Differentiating Eq. (2) and using quasineutrality assumption, we obtain

$$\frac{d\Phi}{d\xi} = \frac{F(\Phi,\beta)}{\tilde{n}_i}\frac{d\tilde{n}_i}{d\xi}, \quad (7)$$

where $F(\Phi,\beta)=(\beta\Phi^2-\beta\Phi+1)/(\beta\Phi^2+\beta\Phi-\beta+1)$ is a positive function whatever the value of β.

From Eqs. (6) and (7), one obtains

$$(\delta+F(\Phi,\beta))\frac{d\tilde{n}_i}{d\xi} + \tilde{n}_i(-\xi+\tilde{v}_i)\frac{d\tilde{v}_i}{d\xi} = 0. \quad (8)$$

If we treat all the derivative terms as independent variables and the resulting set of equations as algebraic ones, then the nontrivial solution to the system of Eqs. (5) and (8) requires that the determinant of their coefficients must vanish,[23] i.e.,

$$-\xi+\tilde{v}_i = \pm\sqrt{\delta+F(\Phi,\beta)}. \quad (9)$$

In this work, the positive root has been chosen to correspond to an expansion in the $+x$ direction and a velocity increasing with increasing x. Initially, the metal target surface is located at $x=0$, and the target is in the $x<0$ region. Laser radiation is switched on in the $-x$ direction and the plasma starts expanding. Due to the expansion, the plasma density will decrease and hence a rarefaction wave will propagate in the $-x$ direction.[24]

The velocity is then given analytically by

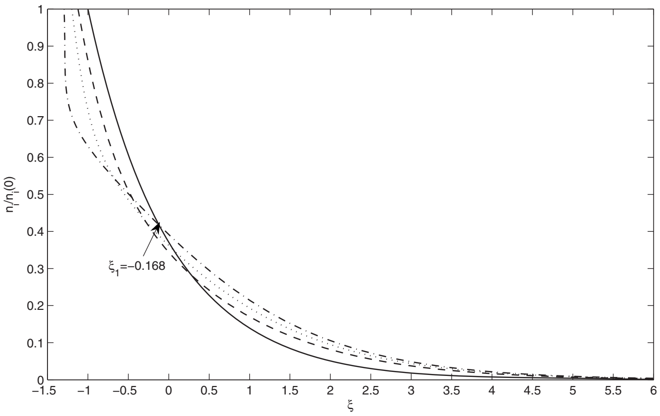

FIG. 1. Densities normalized to their initial values as function of the similarity variable for different values of β. Solid curve corresponds to $\beta=0$, dashed curve to $\beta=0.2$, dotted curve to $\beta=0.3$, and dash-dotted curve to $\beta=0.4$. $T_i/T_e=0.01$.

$$\tilde{v}_i=\xi+\sqrt{\delta+F(\Phi,\beta)}. \tag{10}$$

Differentiating Eq. (10) gives

$$\frac{d\tilde{v}_i}{d\xi}=1+\frac{1}{2}G(\Phi,\beta)\frac{d\Phi}{d\xi}\frac{1}{\sqrt{\delta+F(\Phi,\beta)}}, \tag{11}$$

where $G(\Phi,\beta)=\beta(2\beta\Phi^2-2\beta\Phi+\beta-2)/(\beta\Phi^2+\beta\Phi-\beta+1)^2$.

Using Eqs. (5), (10), and (11) in Eq. (7), we obtain a system of differential equations relatively to the ion density and electrostatic potential

$$\frac{d\tilde{n}_i}{d\xi}=-n_i\frac{\sqrt{\delta+F(\Phi,\beta)}}{0.5F(\Phi,\beta)G(\Phi,\beta)+\delta+F(\Phi,\beta)}, \tag{12}$$

$$\frac{d\Phi}{d\xi}=-\frac{F(\Phi,\beta)\sqrt{\delta+F(\Phi,\beta)}}{0.5F(\Phi)G(\Phi)+\delta+F(\Phi,\beta)}. \tag{13}$$

The plasma under consideration is expanding into vacuum at $t>0$. The initial time $t=0$ in our case corresponds to an unperturbed plasma with initial parameters $n_0=1$ and $v_0=0$.[25] As a consequence, we require that there should exist a point ξ_0 at $t\leq 0$ for which the plasma is unperturbed and at rest, such that $v(\tilde{\xi}_0)=0$, $n(\tilde{\xi}_0)=1$, and $\Phi(\xi_0)=0$.

From Eq. (10), it follows that

$$\xi_0=-\sqrt{\delta+\frac{1}{(1-\beta)}}. \tag{14}$$

In the case of Boltzmann distributed electrons ($\beta=0$), the solution is analytic and is given by

$$\widetilde{v_i(\xi)}=\xi+\sqrt{\delta+1},$$

$$\widetilde{n_i(\xi)}=\exp\left(-\frac{\xi}{\sqrt{\delta+1}}-1\right),$$

$$\Phi(\xi)=-\frac{1}{\sqrt{\delta+1}}(\xi+\sqrt{\delta+1}).$$

Setting $\delta=0$, for cold ions, we retrieve the well-known analytic self-similar solution for an isothermal expansion in a semi-infinite medium.[22] For $\beta\neq 0$, to find the density and the potential, Eqs. (11) and (12) have been solved numerically using Runge–Kutta method with appropriate initial conditions. The limit of β is taken to be 4/7 to overcome physical instabilities that could appear in the electronic distribution.[26]

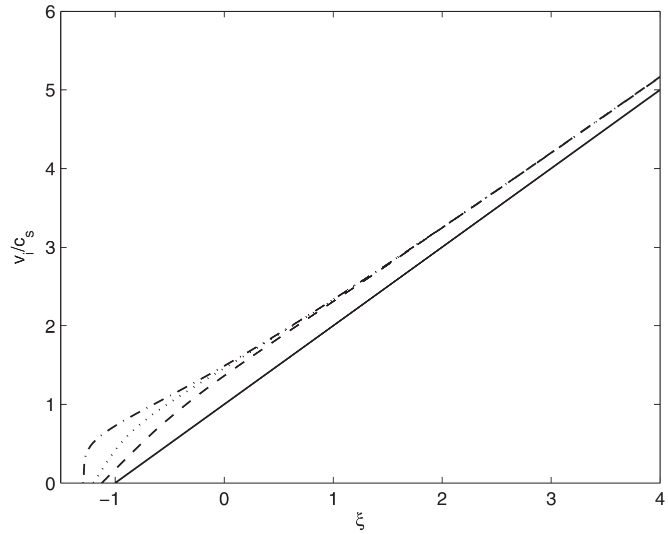

FIG. 2. Velocities normalized to the sound velocity as function of the similarity variable for different values of β. Solid curve corresponds to $\beta=0$, dashed curve to $\beta=0.2$, dotted curve to $\beta=0.3$, and dash-dotted curve to $\beta=0.4$. $T_i/T_e=0.01$.

To investigate the self-similar expansion into vacuum, in Figs. 1 and 2, we plot ion densities normalized to their initial values and ion velocities normalized to sound velocity, versus the self-similarity variable for different values of the nonthermal parameter. δ, the ratio of temperatures, is taken to be equal to 0.01.

It is important to know that the curves are plotted using conditions at ξ_0 instead of $\xi=0$, showing that initial conditions depend on physical parameters such as temperatures and nonthermal effects.

Regarding the profile given by a Maxwellian EDF, Fig. 1 shows that the behavior of ion density for $\beta\neq 0$ can be split into two parts, relatively to the intersection point ξ_1. For example, for $\beta=0.4$ and $\xi<\xi_1=-0.168$, the density profile lies under the thermal one while for $\xi>\xi_1$, it is above the thermal case. Under the intersection point, as β value increases, the amount of fast electrons is increasing but the ion density depletion is reduced. It is seen from Fig. 1 for example at $\beta=0.4$, $n_i/n_i(0)=0.63$ and for $\beta=0.3$, $n_i/n_i(0)=0.73$. Near the source, the main cause of expansion is due to thermal pressure that pushes the ions ahead following the fast electrons to ensure quasineutrality. Beyond the intersection point, on the other hand, we obtained for any ξ, the increase of ion density with β; for example at $\xi=1$, $n_i/n_i(0)=0.17$ for $\beta=0.2$ and $n_i/n_i(0)=0.194$ for $\beta=0.3$. Indeed, far away from the source, the mean cause of the expansion can be attributed to the electrostatic potential enhanced by fast electrons moving ahead leading ions to ensure quasineutrality and reducing the ion depletion.

In Fig. 2, we noticed that the ions are more accelerated with the self-similar variable when β is increasing. In fact,

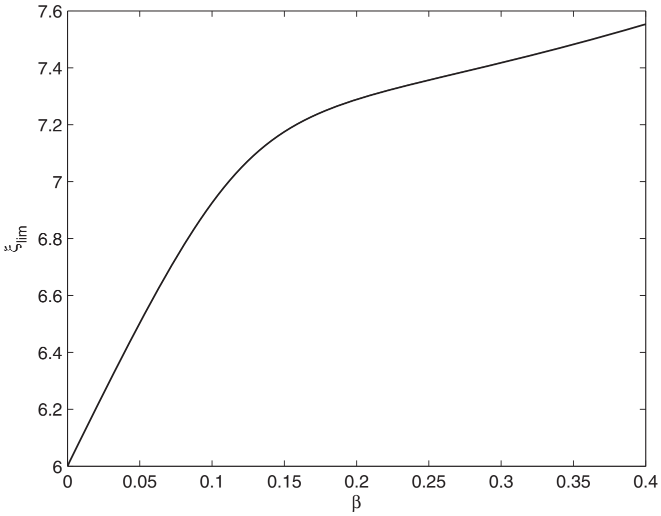

FIG. 3. Limit of the self-similarity variable vs β for $T_i/T_e=0.01$.

nonthermal electrons generate fast ion expansion via the ambipolar potential that is set up to keep the electrons from leaving the target. The ion acceleration is most effective at the beginning of the plasma expansion where the plasma density is so low that the ions can be accelerated by thermal pressure essentially without losing the acquired energy in collisions. From $\xi \approx 3.5$, the ions tend to reach the same final velocity independently from the value of β. The maximum velocity is also increasing with β from the value of $7c_s$ for $\beta=0$ to a value of $8.6c_s$ for $\beta=0.4$. With non-Maxwellian distributions having suprathermal electrons, the ambipolar electric field, which ensures plasma quasineutrality and zero electric current, is greater and a higher electrostatic potential is needed to be accelerate ions and produce larger final speeds.[27] Moreover, it is also pointed out that the end of the expansion corresponds to vanishing density. It is represented by a limit of the self-similar parameter which is increasing with β. From Fig. 3, it is seen that ξ_{lim} is increasing from the value of 6 for $\beta=0$ to reach approximately the value of 7.553 for $\beta=0.4$. The self-similar solution of the expansion is more extended with the deviation of electrons from thermal equilibrium. We also note that for small β value ($\beta<0.15$), ξ_{lim} increases more rapidly. In the presence of high population of fast electrons ($\beta>0.15$), all the ions are pulled ahead more rapidly and therefore the end of the expansion is reached independently of β.

All the used data have been selected in order to have nonvanishing values of the denominator in Eqs. (12) and (13), in order to have finite derivatives.[28] This is why the value of β is limited to 0.4 in Figs. 1 and 2.

The expansion of a plasma created by pulsed laser ablation is studied in the presence of fast electrons modeled by the nonthermal distribution. The self-similar solution, obtained using initial self-similar value depending on the nonthermal parameter, shows that the density and velocity profiles depend not only on the nonthermal parameter but also on the limiting self-similar parameter. Depending on the self-similar range, the ion depletion is related to the decrease or increase of the nonthermal parameter. It is found that the presence of fast electrons enhances the ion expansion.

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