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Self-similar two-electron temperature plasma expansion into vacuum

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Abstract

A theoretical model is developed to describe self-similar plasma expansion into vacuum with two different electron temperature distribution functions. The cold electrons are modeled with a Maxwellian distribution while the hot ones are supposed to be non-thermal obeying a kappa distribution function. It is shown that ion density and velocity profiles depend only on cold electron distribution in early stage of expansion whereas ion acceleration is mainly governed by the hot electrons at the ion front and is strongly enhanced with the proportion of kappa distributed electrons. It is also found that when the kappa index is decreasing, the critical value of temperature ratio T_{eh}/T_{ec}, limiting the application of quasi-neutrality, becomes larger than the $5+\sqrt{24}\approx 9.9$ value obtained in the two-electron Maxwellian Bezzerides model [Bezzerides, B., Forslund, D. W. & Lindman, E. L. (1978). *Phys. Fluids* **21**, 2179–2185].

Keywords: Ion acceleration; Kappa distribution function; Laser produced plasma; Plasma expansion into vacuum; Two-electron temperature plasma

I. INTRODUCTION

The problem of plasma expansion into vacuum has been studied for many years since the paper of Gurevich *et al.* (1966). Interest in this problem is crucial for better understanding the physics of ion acceleration in the laser–plasma interaction and in particular, to give a quantitative description of this phenomenon. The study of ion acceleration is among the key problems in various applications of high-power lasers, such as laser fusion, injectors of fast particles, and radioactive sources used in medicine and nuclear physics (Kovalev *et al.*, 2001).

Most studies of plasma expansion into vacuum are based on a semi-bounded plasma model with isothermal electrons and cold ions (Wickens *et al.*, 1978; Gurevich *et al.*, 1979; Mora & Pellat, 1979; Gurevich & Meshcherkin, 1981). It is however proven from experiments (Bulgakova *et al.*, 2000) that the hypothesis of isothermal electrons is not appropriate for laser–plasma interactions. A more realistic model has to account for two-electron populations: Cold dominant and hot minority. It was shown in the literature, for example in (Breizman & Arefiev, 2007) that, in contrast to the two-component distribution, a single-temperature distribution of electrons is predestined to underestimate the energy of accelerated ions for a given absorbed laser power. In laser produced plasma, the deviation from Maxwell distribution, at the earlier stage, is attributed to the existence of an electron emission relaxation region. In this region the plasma interaction with matter can be modeled by assuming a partially ionized gas separated from the surface by an electrical sheath in which charged particles are accelerated. Thus, two groups of electrons exist; accelerated electrons emitted from the heated target and slow plasma electrons. This leads to a collisional dominated plasma heated by accelerated electrons (Beilis, 2007). With moderate laser energies (10^6-10^{10} W/cm^2), ion acceleration mechanism is explained by invoking the shifted Maxwellian ion energy distribution (Beilis, 2012). It is also assumed, as a consequence of these two groups of electrons, that increasing laser intensity as well as energy causes an increase in emission of both fast (hot) and thermal (cold) ions (Wolowski *et al.*, 2002; Krasa *et al.*, 2007). The fast electrons component escaping from the interaction region has been observed and interpreted as a signature of a two-electron temperature plasma formation (Mascali *et al.*, 2012). There, a relatively small number of hot electrons, accelerated by laser, enters into a cold target and induces the ion acceleration. The electron density could then be considered as a sum of two Boltzmann distributions with cold (T_{ec}) and hot (T_{eh})

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temperatures (Tikhonchuk *et al.*, 2005; Diaw & Mora, 2011) given by:

$$n_e = n_{ec} + n_{eh} = n_{ec0}\exp(e\varphi/T_{ec}) + n_{eh0}\exp(e\varphi/T_{eh}),$$

with $T_{ec} \ll T_{eh}$ and $n_{ec0} \gg n_{eh0}$. n_{ec0}, n_{eh0} are the cold and hot initial densities, respectively, and φ is the electric potential.

On the other hand, it was proven by many authors that fast electrons have non-Maxwellian distributions in the laboratory experiments, for example, during high-intensity laser–matter interactions, where the generated plasma fails to thermalize within the short observation time interval (Hellberg *et al.*, 2000; Yoon *et al.*, 2005; Goldman *et al.*, 2007; Sarri *et al.*, 2010). 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 (Bennaceur-Doumaz & Djebli, 2010). Moreover, measurements show that the electron distribution function in the laser-pellet experiments is a non-Maxwellian with an energetic tail. These energetic electrons could effectively have a significant effect on ionization and expansion processes (Gurevich *et al.*, 1979; Yoon *et al.*, 2005; Beilis, 2012). It was also found that the moving space-charge electric field accelerates ions to energies well above the energy of the fast electrons (Mora, 2003, 2005). A quantitative comparison with existing theories involving only Maxwellian plasmas is then not accurate since in the experiment the energetic electrons have a non-Maxwellian distribution (Hairapetian & Stenzel, 1988, 1991). Various models have been proposed to analyze the qualitative behavior of plasma expansion assuming, for instance, for the fast electrons, different non-Maxwellian distribution functions such as a truncated Maxwellian distribution (Lontano & Passoni, 2006), a super-Gaussian distribution (Kovalev *et al.*, 2001, 2002), Cairns distribution (Bennaceur-Doumaz & Djebli, 2010), a steplike electron energy distribution, (Kiefer *et al.*, 2013) or kappa distribution (Hellberg *et al.*, 2000).

In this paper, we proposed for the first time, in the framework of plasma expansion and ion acceleration, a theoretical model for the free expansion of semi-infinite plasma into vacuum combining cold Maxwellian electrons with hot ones assumed to be non-Maxwellian. For the latter, the electrons are supposed to follow kappa distribution function. This distribution function has a Maxwellian-like core and a high-energy component of power-law form, which reproduces smoothly the velocity dependence. In laser produced plasma, it has been already used to model ion acceleration and plasma expansion for one-electron temperature plasma in (Shokoohi & Abbasi, 2009; Mehdian *et al.*, 2014; Bennaceur-Doumaz *et al.*, 2015), where the authors showed numerically that by increasing the population of energetic electrons, the expansion took place faster, the resulting electric field was stronger, and the ions accelerated to higher energy.

2. BASIC EQUATIONS OF THE MODEL

2.1. Electron density

The present work concerns the study of one-dimensional (1D), non-relativistic, collisionless expansion into a vacuum of semi-infinite laser produced plasma. The approximation of a 1D description of the expansion is justified as long as lateral heat conduction can be neglected. In order to describe the realistic situation we have to include the cold electrons in the plasma, because not all of the target electrons are heated up by the laser, so the plasma is considered with two-electron populations, hot electrons and cold electrons with much lower temperature, but higher density.

The cold population follows Boltzmann distribution while the hot one, which can be considered as fast, is governed by the kappa distribution. The total electron density is then the sum of the cold and hot electron densities given by:

$$\begin{aligned} n_e &= n_{ec} + n_{eh} \\ &= n_{ec0}\exp(e\varphi/T_{ec}) + n_{eh0}\left(1 - \frac{e\varphi/T_{eh}}{(\kappa - 3/2)}\right)^{-\kappa+1/2} \end{aligned} \quad (1)$$

$n_{e0} = n_{ec0} + n_{eh0}$ is the total initial density, $\kappa \geq 3/2$ is the spectral index which measures the strength of the excess superthermality. When $\kappa \rightarrow \infty$, we retrieve the case of two-electron temperature Maxwellian plasma.

2.2 Ion motion modeling

The cold ion motion is modeled by fluid equations:

$$\frac{\partial n_i}{\partial t} + v_i\frac{\partial (n_i v_i)}{\partial x} = 0 \quad (2)$$

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

where n_i, v_i, and m_i are the ion density, ion velocity, and ion mass, respectively. We assume a plasma with single charged ions $Z = 1$.

Electron–electron collisions which would eventually equilibrate the hot and cold species are ignored; electron–ion collisions are also neglected (True *et al.*, 1981).

2.3. Quasi-neutrality of charge

During the expansion of hot plasma under vacuum, a sizable fraction of the beam energy is carried by the quasi-neutral region of the expanding plasma and the characteristic scale length for plasma density variations is generally large compared with the Debye length, so that the plasma remains quasi-neutral during all the expansion. The equation of quasi-neutrality is given by:

$$n_e = n_{ec} + n_{eh} = n_i \quad (4)$$

The quasi-neutrality condition guarantees the validity of self-similar solutions, motivating the interest of the present paper in these types of solutions.

3. SELF-SIMILAR SOLUTION

In the presence of free boundary associated with plasma expansion, under certain assumptions, the partial differential Eqs (2) and (3) can be reduced to ordinary differential equations. This transformation is based on the assumption that we have a self-similar solution, that is, every physical parameter distribution preserves its shape during expansion and there is no scaling parameter (Zel'dovich & Raizer, 1966; Sack & Schamel, 1987). Self-similar solutions usually describe the asymptotic behavior of an unbounded problem and the time t and the space coordinate x appear only in the combination of $\tau = x/t$. It means that the existence of self-similar variables implies the lack of characteristic lengths and times. Indeed, this is justified when we deal with the assumption of charge quasi-neutrality in the plasma. The Debye length then, loses its importance as a characteristic length in the plasma.

In the framework of self-similar theory, we obtain the following set of ordinary equations:

$$(v_i - \tau)\frac{dn_i}{d\tau} + n_i\frac{dv_i}{d\tau} = 0 \tag{5}$$

$$(v_i - \tau)\frac{dv_i}{d\tau} + \frac{e}{m_i}\frac{d\varphi}{d\tau} = 0 \tag{6}$$

Deriving (1) with respect to τ and using the equation of quasi-neutrality (4), we obtain,

$$\frac{dn_e}{d\tau} = \frac{dn_i}{d\tau} = Ae\frac{d\varphi}{d\tau} \tag{7}$$

$$\begin{aligned} A &= \frac{n_{ec0}}{T_{ec}}\exp(e\varphi/T_{ec}) \\ &+ \frac{n_{eh0}}{T_{eh}}\frac{(\kappa-0.5)}{(\kappa-1.5)}\left(1-\frac{e\varphi/T_{eh}}{(\kappa-1.5)}\right)^{(-\kappa-0.5)} \\ &= \frac{n_{ec}}{T_{ec}} + \frac{n_{eh0}}{T_{eh}}\frac{(\kappa-0.5)}{(\kappa-1.5)}\left(\frac{n_{eh}}{n_{eh0}}\right)^{(-\kappa-0.5)/(-\kappa+0.5)} \end{aligned} \tag{8}$$

Equation (6) becomes:

$$\frac{1}{Am_i}\frac{dn_i}{d\tau} + (v_i - \tau)\frac{dv_i}{d\tau} = 0 \tag{9}$$

If we treat all the derivative terms as independent variables and the resulting set of equations as algebraic ones, then the non-trivial solution to the system of Eqs (5) and (9) requires that the determinant of their coefficients must vanish, that is, while choosing the positive solution corresponding to an expansion in the $+x$ direction and a velocity increasing with increasing x (Yu & Luo, 1995):

$$\begin{aligned} v_i - \tau &= \sqrt{\frac{n_i}{m_i A}} \\ &= \sqrt{\frac{n_i}{m_i\left(\begin{array}{c} n_{ec}/T_{ec} + n_{eh0}/T_{eh}(\kappa-0.5)/ \\ (\kappa-1.5)(n_{eh}/n_{eh0})^{(-\kappa-0.5)/(-\kappa+0.5)} \end{array}\right)}} = c_s \end{aligned} \tag{10}$$

c_s is the ion sonic velocity of the plasma.

The metal target used in producing laser-plasma is supposed unlimited and is homogeneously filled negative half space. At time $t = 0$, the target surface involved in the experiments is located at $x = 0$, and the target is in $x < 0$ region. Laser radiation is switched on in $-x$ direction and the plasma starts expanding. Ions are cold and initially at rest with density, $n_i = n_{i0}$ for $x < 0$ and $n_i = 0$ for $x > 0$ with a sharp boundary. At $t > 0$, plasma begins to expand into vacuum. Due to the expansion, the plasma density will decrease and hence a rarefaction wave will propagate in the $-x$ direction (Cheng *et al.*, 2009) with the velocity c_s.

Differentiating (10) and using (8) gives:

$$\frac{dv_i}{d\tau} = 1 + 0.5\sqrt{\frac{1}{m_i}}\left(\frac{e\sqrt{A}}{\sqrt{n_i}} - \frac{\sqrt{n_i}}{A^{1.5}}B\right)\frac{d\varphi}{d\tau}, \tag{11}$$

where

$$\frac{dA}{d\tau} = Be\frac{d\varphi}{d\tau}$$

and

$$\begin{aligned} B &= \left(\frac{n_{ec0}}{T_{ec}^2}\right)\exp(e\varphi/T_{ec}) + \left(\frac{n_{eh0}}{T_{eh}^2}\right) \\ &\times \frac{(\kappa-0.5)(\kappa+0.5)}{(\kappa-1.5)^2}\left(1-\frac{e\varphi/T_{eh}}{(\kappa-1.5)}\right)^{(-\kappa-1.5)} \end{aligned}$$

Using Eqs (6), (10), and (11), we found the equation to solve for the electrostatic potential as:

$$e\frac{d\varphi}{d\tau} = -\frac{\sqrt{m_i}\sqrt{n_i}}{1.5\sqrt{A} - 0.5n_i B/A^{1.5}} \tag{12}$$

Potential, velocity, and density of the ions are given numerically by the solution of the system of Eqs (12), (7), and (11) under the assumption of quasi-neutrality using Runge–Kutta method.

The expansion profiles are deduced in normalized forms such as $\tilde{n}_i = n_i/n_{i0}$, $\tilde{v}_i = v_i/c_{sh}$ and $\Phi = e\varphi/T_{eh}$, according to the dimensionless self-similar variable $\xi = x/c_{sh}t = \tau/c_{sh}$, where $c_{sh} = \sqrt{T_{eh}/m_i}$ is the ion sound velocity in the hot electron species.

The initial time $t = 0$ in our case corresponds to an unperturbed plasma with initial parameters $\tilde{n}_i = 1$ and $\tilde{v}_i = 0$ (Ivlev & Fortov, 1999; Bara *et al.*, 2014). 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 $\tilde{v}_i(\xi_0) = 0$, $\tilde{n}_i(\xi_0) = 1$, and $\Phi(\xi_0) = 0$. From Eq. (10), its expression is given by:

$$\xi_0 = -\sqrt{\left(\frac{\alpha}{(1+y_u)} + \frac{y_u}{(1+y_u)}\frac{(\kappa - 0.5)}{(\kappa - 1.5)}\right)^{-1}}, \qquad (13)$$

where $y_u = n_{eh0}/n_{ec0}$ and $\alpha = T_{eh}/T_{ec}$.

4. DISCUSSION OF THE RESULTS

4.1. Case of two-electron Maxwellian populations

Bezzerides *et al.* (1978) have shown that for the case of two-electron Maxwellian distributions, a continuous self-similar solution for semi-infinite expanding plasma by assuming the quasi-neutrality is limited when the solution for the potential $\varphi(x/t)$ is multi-valued, that is, when temperature ratio α is higher than $5 + \sqrt{24} \approx 9.9$. In the point of view of fluid theory, it means that the solutions of these equations become double valued when $dc_s^2/d\varphi + 2 < 0$ where c_s is the ion sound velocity defined by (Diaw & Mora, 2011):

$$c_s^2 = \frac{(n_{ec} + n_{eh})}{m_i(n_{ec}/T_{ec} + n_{eh}/T_{eh})} = c_{sh}^2\left(\frac{1+y}{\alpha + y}\right) \qquad (14)$$

obtained from Eq. (10) when $\kappa \to \infty$ and $y = n_{eh}/n_{ec}$ is the density ratio.

Since double-valued solutions are unphysical, they become discontinuous under such conditions. For higher temperature ratios, they have deduced that a collisionless shock front in the rarefaction wave is formed, and it provides a spatial separation of the two-electron populations. Then, ions are accelerated at the shock front to the hot ion acoustic velocity.

To show the influence of two-electron temperatures on the plasma expansion, we present, in Figures 1 and 2, normalized ion densities and normalized ion velocities, respectively, as functions of the self-similar variable ξ for different values of the parameter α up to the α limit value for a given density ratio y_u.

In Figure 1, the self-similar solutions show two behaviors of ion density relatively to the intersection point $\xi = 0$, considered as the original position of the plasma surface. The different ion profiles are compared with the one-electron temperature plasma expansion represented by $\alpha = 1$, published for the first time by Gurevich *et al.* (1966).

Near the source, $\xi < 0$, first the hot electrons leave the plasma, pulling the ions behind. During the expansion of plasma, space-charge effects self-consistently produce an ambipolar electric field whose amplitude is controlled by the energy of the hot electrons. The ambipolar electric field accelerates a small number of ions to streaming energies. The thermal electrons follow, guiding the slower thermal ion group (Rohlena

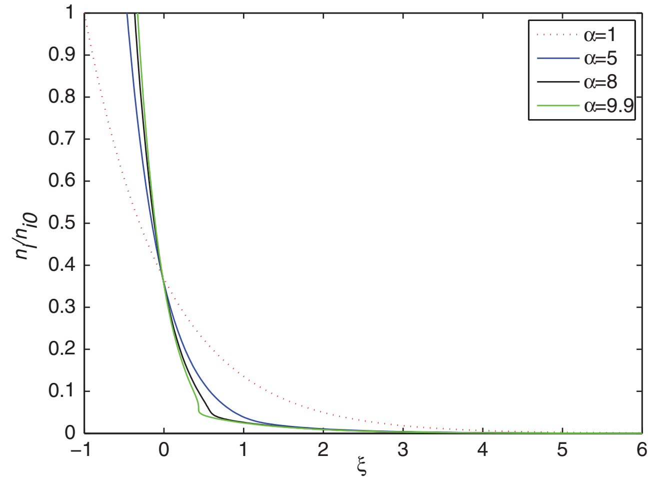

Fig. 1. Variation of the normalized ion density with ξ for different values of temperature ratios α, for initial density ratio $y_u = 0.1$.

et al., 1996). The ionic sound velocity in this region is given from Eq. (14) by $c_s \approx c_{sh}\sqrt{(1/\alpha)} = c_{sc} = \sqrt{T_{ec}/m_i}$, which is the ion sound velocity of the cold electrons species only, since there $y \ll 1$. Consequently, it is the cold electron population which governs the expansion; indeed, the expansion is slowing down relatively to the isothermal case $\alpha = 1$ and the ion depletion is less pronounced. The density is given for the cold electron plasma as $\tilde{n}_i \approx \exp(-\sqrt{\alpha}\xi - 1)$.

Far from the target, a visible drop of density is shown. The ion depletion is more pronounced with increasing temperature ratio, indicating that ion acceleration is more effective and driven by the hot electrons, whereas majority of cold electrons are retarded by the self-consistent electric field. As the expansion progresses, the potential becomes more negative and the hotter electrons can no longer be regarded as a low number density component. In fact, at sufficiently negative potentials they become the majority species, and

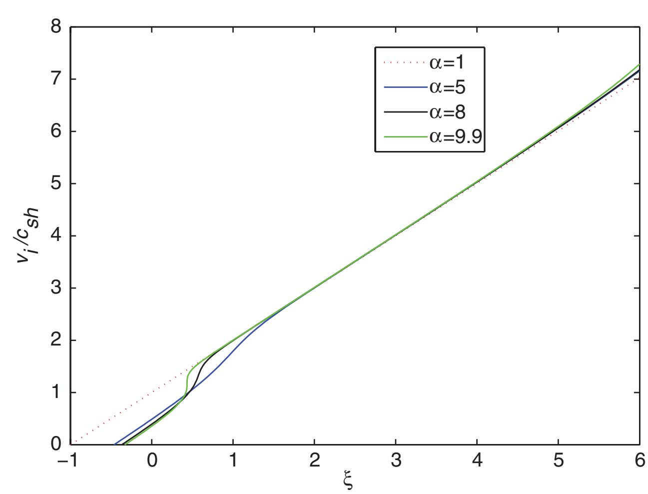

Fig. 2. Variation of the normalized ion velocity with ξ for different values of temperature ratios α, for initial density ratio $y_u = 0.1$.

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might then be expected to have the dominant effect on the ion acceleration. The ionic sound velocity is then given by $c_s \approx c_{sh}$ from Eq. (14) because there $y \gg 1$ and the density tends to the asymptote $\tilde{n}_i \approx \exp(-\xi - 1)$ at the ion front (Wickens & Allen, 1979). At $\alpha = 9.9$, a discontinuity begins to appear clealy indicating the separation of the two-electron populations and the onset of the shock front. Moreover, it is also pointed out that the end of the self-similar expansion corresponds to vanishing density.

In Figure 2, we have plotted the ion velocity profiles with different values of α. For $\alpha = 1$, as it is well-known, the self-similar ion velocity is linear for the one temperature case (Gurevich *et al.*, 1966). However, for $\alpha \neq 1$, the figures show an expansion with three phases:

- a zone of slow expansion dominated by cold electrons and due to charge quasi-neutrality, the ions follow the cold electrons and are also slowed with subsonic velocities. The ionic sound velocity is given by c_{sc} and ions move with a linear velocity depending on α parameter such as $\tilde{v}_i \approx \xi + (c_{sc}/c_{sh}) = \xi + \sqrt{1/\alpha}$. During the early stages of the expansion the ion acceleration is thus determined by the colder electron species.
- an intermediate zone where the two populations coexist and begin to separate. A double layer-like develops across the region where the separation occurs similar to the theoretically predicted rarefaction shock when α tends to its critical value.
- a zone where the expansion is held by the hot electrons ending at the ion front. There, ions are accelerated by strong electric fields to supersonic velocities and experience a strong increase in their energy. The ionic sound velocity tends to c_{sh} such that the ions move linearly with $\tilde{v}_i \approx \xi + 1$, as in the case of a one-electron temperature plasma (Gurevich & Meshcherkin, 1981; Mora, 2003, 2005).

The effect of the cold electrons is then restricted to the plasma surface, and a singularity occurs in the potential-profile for high temperature ratios when Eq. (12) vanishes (Bezzerides *et al.*, 1978). At the ion front, there is no big difference between the one- and two-temperature plasma expansion, the velocity is mostly defined by the hot electron parameters, showing that the presence of cold electrons increases very slightly the ion acceleration (e.g., at $\xi = 6$, for $\alpha = 9.9$, the increase of velocity is 3.73% relatively to the one temperature case) and the effect of the temperature is small.

To show the influence of density ratios y_u on the plasma expansion, we have drawn in Figures 3 and 4, the density and velocity profiles, for different values of y_u for a given temperature ratio α. For the densities as it is shown in Figure 3, there is practically no influence of density ratio on the profiles in early plasma expansion where the density tends to the asymptote $\tilde{n}_i \approx \exp(-\sqrt{\alpha}\xi - 1)$ but it is seen to have some significance in later expansion where the

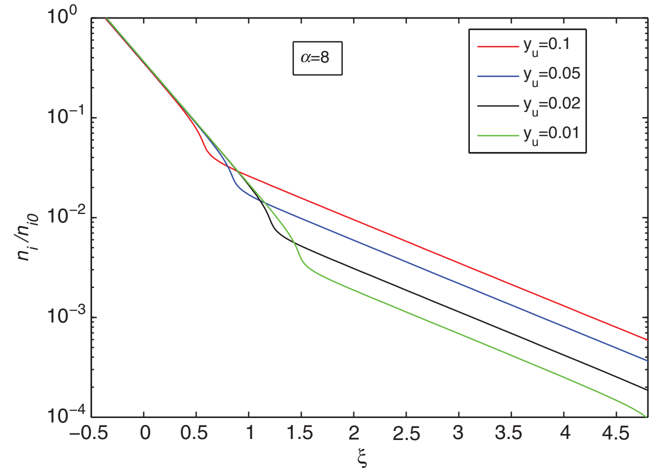

Fig. 3. Variation of the normalized ion density with ξ for different values of initial density ratios y_u for $\alpha = 8$.

density is given by $\tilde{n}_i \approx \exp(-\xi - 1 + B)$, where

$$B = \frac{1}{(\alpha - 1)}\left\{\alpha^{0.5} Ln\left(\frac{4y_u^{-1}}{[1+\alpha^{-0.5}]^2}\right) + Ln\left(\frac{4y_u}{[1+\alpha^{0.5}]^2}\right)\right\}$$

is a function of y_u, as calculated by Wickens and Allen (1979). Then for a given temperature ratio, the increasing of cold population relatively to the hot one has the role of enhancing the ion depletion and accelerating the expansion.

In Figure 4, for velocities, we observe the same phenomenon for early plasma expansion where again there is no influence of y_u on the profiles since their behavior tends to the asymptote $\tilde{v}_i \approx \xi + (c_{sc}/c_{sh}) = \xi + \sqrt{1/\alpha}$, but as the expansion proceeds, the influence of y_u is apparent at the ion front where the velocities tend to $\tilde{v}_i \approx \xi + B$ (Wickens & Allen,

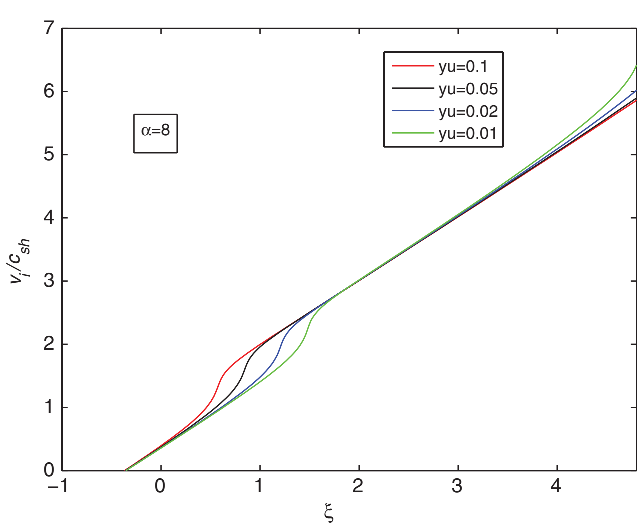

Fig. 4. Variation of the normalized ion velocity with ξ for different values of initial density ratios y_u for $\alpha = 8$.

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1979) and where ion acceleration is more effective with increasing electron cold population.

For example, the contribution of the density ratio to ion acceleration is about 8.13% at $\xi = 4.8$ when passing from $y_u = 0.1$ to $y_u = 0.01$.

4.2. Effect of non-Maxwellian electron population on the plasma expansion

In this part, we investigate the role of non-Maxwellian electrons on plasma expansion and ion acceleration. In Figure 5, the ion velocity profiles are drawn for different values of κ parameter for $\alpha = 9$ and $y_u = 0.1$ and compared with the case of two-electron Maxwellian plasma obtained when $\kappa \to \infty$ in Eq. (1).

In early stage of plasma expansion near the target, the ion acoustic velocity is given approximately by the ion acoustic velocity in the cold electrons species that is:

$$c_s = c_{sh}\sqrt{\frac{1+y}{\left(n_{eh0}/n_{ec}(\kappa-0.5)/(\kappa-1.5)(n_{eh}/n_{eh0})^{(-\kappa-0.5)/(-\kappa+0.5)}+\alpha\right)}} \approx c_{sh}\sqrt{\frac{1}{\alpha}} = c_{sc},$$

the part dependent of κ is negligible relatively to α so it appears that energetic electrons again have no effect on ion expansion and consequently, in this region, ions move with a linear velocity depending on α parameter such as $\tilde{v}_i \approx \xi + (c_{sc}/c_{sh}) = \xi + \sqrt{1/\alpha}$.

The role of non-Maxwellian electrons is more apparent beyond the trapping region of the cold electrons and is predominant in the expansion front where their velocity tends to the asymptote $\tilde{v}_i = (\kappa - 1/2)/(\kappa - 1)\xi + \sqrt{(\kappa - 1/2)(\kappa - 3/2)}/(\kappa - 1)$ already given in (Bennaceur-Doumaz *et al.*, 2015), where only one-component nonthermal electrons are involved in the expansion. When $\kappa \to \infty$, the velocity tends to Maxwellian case where $\tilde{v}_i \approx \xi + 1$.

We can deduce that the presence of energetic tail electrons whose population enhances with decreasing κ parameter, has the role to increase ion acceleration much more than the acceleration driven by the hot Maxwellian electrons obtained when $\kappa \to \infty$. Then, supposing two-electron Maxwellian populations induces an underestimation of ion acceleration in laser produced plasma expansion.

It is also worth to indicate that in the present study of ion acceleration, the continuous self-similar solution limit, assuming charge neutrality is increasing when κ is decreasing (increasing of population of non-thermal electrons), reaching the value of 15.9 for $\kappa = 2$. This is illustrated in Figure 6 where ion velocities are drawn for different α limits depending on κ parameter. These limit values are obtained numerically when handling the present electron distribution function [Eq. (7)], in contrast with the case of two-electron Maxwellian distributions where the limit $\alpha = 9.9$ is obtained analytically by Bezzerides *et al.* (1978).

5. CONCLUSION

The expansion of laser produced plasma is studied in the presence of two-electron temperature populations: A cold one modeled by Maxwellian distribution and a hot one which contains energetic non-Maxwellian electrons modeled by kappa distribution function.

The self-similar solution, obtained shows that the effect of cold electrons is restricted in a region confined in the early stage of expansion whereas the hot ones are responsible of ion acceleration at the ion front. It is found that in addition to thermal effects, the presence of non-Maxwellian electrons enhances the ion expansion and also extends the validity of the self-similar solution. This study could be useful in

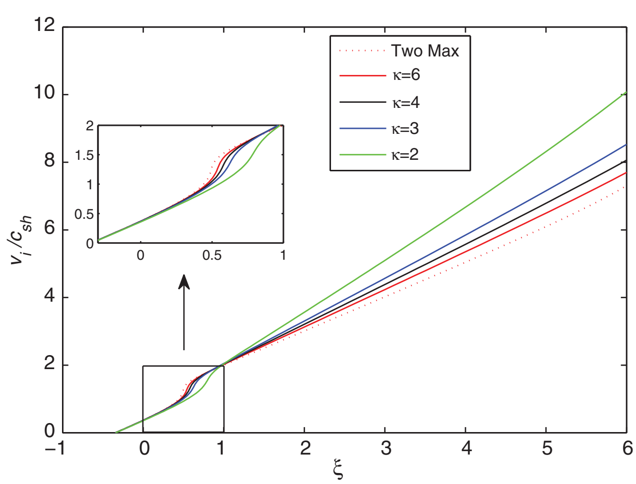

Fig. 5. Influence of non-Maxwellian electrons on ion velocity expansion for $\alpha = 9$ and $y_u = 0.1$.

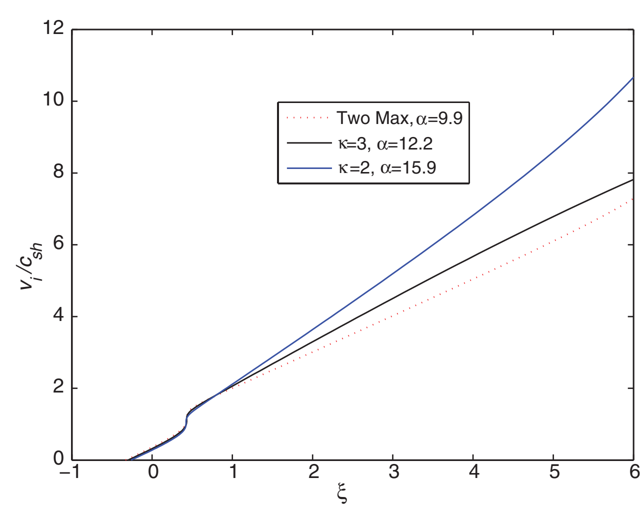

Fig. 6. Ion velocities in the α limit of self-similar solution for different values of κ, $y_u = 0.1$.

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modeling laser produced plasma expansion in laser ablation experiments for fusion purposes where the intensity of the laser does not exceed 10^{13} W/cm^2 and the α parameter is not too high in order to keep quasi-neutrality condition and self-similar solutions valid during expansion which is not the case when very large electric fields are built with very intense lasers (Tikhonchuk *et al*., 2005; Diaw & Mora, 2011; Bennaceur-Doumaz *et al*., 2015).

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