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

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Abstract

Commonly, laser-induced plasma expansion is modeled by assuming local thermodynamic equilibrium conditions for all plasma components. In the present work, we investigate the case of plasma containing electrons obeying a non-Maxwellian distribution. To this purpose, a two-fluid model is considered with charge quasi-neutrality assumption. The deduced set of non-linear differential equations is solved numerically using a self-similar approach. It is found that the deviation of the electrons from Maxwellian distribution gives rise to an increasing of the electrostatic potential that accelerates ion motion.

Introduction

The present work deals with the problem of laser induced plasma expansion into vacuum in the regime where the expanding plasma consists of hot electrons and warm ions. The expansion is caused by electron pressure and serves as an energy transfer mechanism from electrons to ions. This process is often described under the assumption of Maxwellian electrons, which easily fails in the absence of collisions. Indeed, plasmas, both in the laboratory and in space, are often not in thermodynamic equilibrium, and the plasma electron distribution function (eedf) is accordingly non-Maxwellian. Then, caution must be taken during the temporal acquisition of data specially when one tries to develop a calibration free Laser Induced Breakdown Spectroscopy (LIBS) method [1] in pulsed laser deposition experiments, for instance.The classical approach of this technique and its validity are essentially based on the existence of local thermodynamic equilibrium (LTE) conditions and of optically thin plasma. But, in the conditions of the experiments, as a consequence of fast expansion, the plasma parameters can change in times shorter than those necessary for the establishment of elementary process balances, thus leading to non-equilibrium excitation and chemical processes [2]. Then, electron, ion and atom temperatures can essentially differ. The electron temperature in non-LTE plasmas is higher than that of ions because of insufficient collisions among like particles. So, the knowledge of the deviations from the LTE is really important to understand the limits of theory to be taken into account for practical applications [3]. In this work, we have investigated the impact of the electron deviation from Maxwellian distribution on the expanding profiles of a laser induced plasma into vacuum in a pulsed laser deposition experiment. Using a self-similar approach and assuming a quasi-neutrality of charge in the plasma, the expansion is investigated.

Basic equations

We consider a one-dimensional, two-component plasma consisting of electrons and ions. Electrons are assumed to follow a non-Maxwellian velocity distribution function and the ions are described by fluid equations. The plume expansion is considered in the x direction. The fundamental reason for the electrons to be non-Maxwellian is that fast electrons collide much less frequently than slow ones because of their greater free path, so that they cannot relax to a Maxwellian. Since the electrons are assumed to be nonthermally distributed, the electron velocity distribution function with a population of fast particles is given by the Cairns distribution function [4]

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

where $v_{eth} = \sqrt{k_B T_e/m_e}$ is the average thermal velocity of electrons, m_e, the mass of an electron and T_e is the electon temperature. Consequently, the electron number density is given by

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

where $\beta = \frac{4\alpha}{3\alpha+1}$ is a parameter that measures the deviation from thermal equilibrium and $\Phi = e\phi/T_e$ is the normalized electrostatic potential that fulfills the quasi-neutrality of charge in the plasma: $n_e = n_i$. For physical realization solution, $\beta < 1$. It is clear that Eq. (1) expresses the isothermally distributed electrons when $\beta = 0$, i.e. $\alpha = 0$.

The ions with density n_i and velocity v_i are described by the following fluid equations:

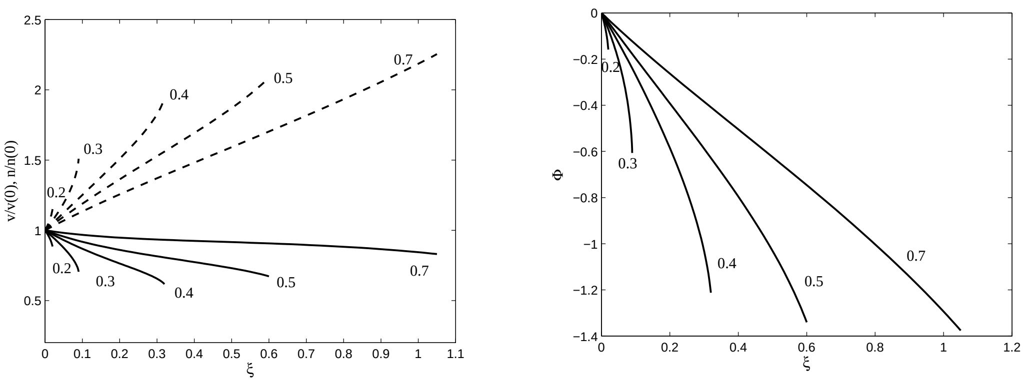
$$\frac{\partial n_i}{\partial t} + \frac{\partial (n_i v_i)}{\partial x} = 0, \tag{3}$$

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

Assuming that the plasma behaves as a perfect gas, we set $P_i = n_i T_i$, where T_i is the ion temperature.

Self-similar solutions and discussion

In general, hydrodynamic equations describing the expansion are difficult to solve numerically, but under certain assumptions, these partial differential equations can be reduced to ordinary



(a) (b)

Figure 1: Normalized Velocities (−−) and densities (—) (a) and normalized electrostatic potential (b) versus the similarity variable for different values of β for $T_i/T_e = 0.01$. Initial conditions are $\tilde{n(0)} = 1$, $\tilde{v(0)} = 1$ and $\Phi(0) = 0$.

differential equations which greatly simplifies the problem. This transformation is based on the assumption that we have a self-similar solution, i.e. every physical parameter distribution preserves its shape during expansion and there is no scaling parameter [5]. 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 (*x/t*). It means that the existence of self-similar variables implies the lack of characteristic lengths and times.

The one dimensional self-similar solution of Eqs. (1)-(4) with the quasi neutrality of charge can be constructed by using the ansatz defined as, $\tilde{n_{i0}} = \frac{n_i \omega t}{n_{i0}}$, $\tilde{v}_i = v_i/c_s$, where c_s is the ion sound velocity given by $c_s = \sqrt{T_e/m_i}$, T_e is the electron temperature and ω, the plasma frequency, $\omega = \sqrt{4\pi n_{i0} e^2/m_i}$, n_{i0} is the initial density of the plasma.

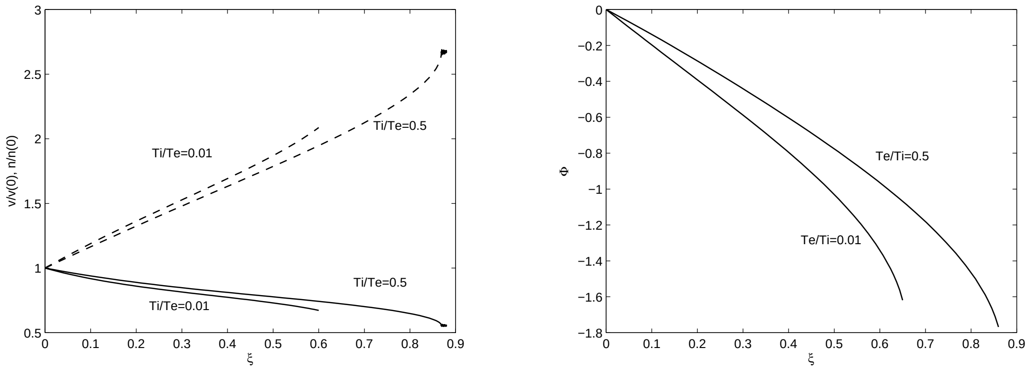
$$\frac{d\tilde{v}_i}{d\xi} = -\frac{T_i/T_e + F(\Phi)}{(-\xi + \tilde{v}_i)^2 - T_i/T_e - F(\Phi)} \tag{5}$$

$$\frac{d\tilde{n}_i}{d\xi} = \frac{\tilde{n}_i}{(-\xi + \tilde{v}_i)} - \frac{\tilde{n}_i}{(-\xi + \tilde{v}_i)} \frac{d\tilde{v}_i}{d\xi} \tag{6}$$

$$\frac{d\Phi}{d\xi} = \frac{d\tilde{n}_e}{d\xi} \frac{F(\Phi)}{\tilde{n}_e} \tag{7}$$

with $F(\Phi) = (\beta\Phi^2 - \beta\Phi + 1)/(\beta\Phi^2 + \beta\Phi - \beta + 1)$ In Fig. 1, we draw normalized density and velocity of the plasma (a) and the normalized electrostatic potential (b) versus the self-similarity variable in the case where $T_i/T_e = 0.01$ for different initial values of β.

The results of calculations show that the maximum self-similarity variable is increasing with the initial β parameter i.e. the self-similar solution of the expansion is more extended with



(a) (b)

Figure 2: Same as Fig. 1 for $\beta = 0.5$, for two temperature ratios, $T_i/T_e = 0.01$ and $T_i/T_e = 0.5$.

the deviation of electrons from thermal equilibrium. The maximum expansion velocity and electrostatic potential are also increasing and the density is decreasing more slowly with β, showing that the nonthermal electrons should be not neglected in the expansion since they accelerate the deposition process. In Fig. 2, we draw normalized density and velocity of the plasma (a) and the normalized electrostatic potential (b) versus the self-similarity variable for the same initial conditions than in Fig. 1, for $\beta = 0.5$ and for two temperature ratios, $T_i/T_e = 0.01$ and $T_i/T_e = 0.5$.

For all the profiles, it is shown that the expansion is more extended with growing T_i/T_e ratio.

References

[1] M. Capitelli, F. Capitelli and A. Eletskiid, Spectrochim. Acta Part B **55**, (2000) 559.

[2] A. De Giacomo, V.A. Shakhatov, O. De Pascale, Spectrochim. Acta Part B **56**,(2001) 753.

[3] M. Capitelli, A. Casavola, G. Colonna and A. De Giacomo, Spectrochim. Acta Part B **59**, (2004) 271.

[4] R.A. Cairns et al., Geophysical Research Letter **22**, (1995) 2709.

[5] Ch. Sack and H. Schamel, Phys. Reports **156**, (1987) 11.