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Electrostatic Fields and Ion Separation in Expanding Laser Produced Plasmas

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ABSTRACT

The separation of ions of different charges in a plasma produced by laser irradiation of a solid target is investigated theoretically. For this purpose the equations of motion are solved numerically for plane and spherical geometry including the influence of the electrostatic field in the plasma.

It is shown that the expansion velocities of ions of different charges are equal as soon as the friction between the species is included. Thus, contrary to the suggestions of several authors, the experimentally observed separation of ions cannot be explained by the different forces acting upon them in the electric field, but must be due to other effects, e.g. to inhomogeneities of the power density in the laser spot.

INTRODUCTION

It is well known that the plasma produced by irradiating solid targets with giant pulse lasers contains ions of different charge (OPOWER 1966, GREGG et al. 1966, BASOV et al. 1967, BRIAND et al. 1967, MATTIOLI et al. 1969) (Fig. 1). Such plasmas are of interest because they could be used, for example, as a source of heavy ions for accelerators (PEACOCK et al. 197o, IRONS et al. 197o). Optical and mass spectroscopical investigations of the expanding plasma cloud show that the more highly charged the ions are the higher is their kinetic energy (FENNER 1966, BOLAND et al. 1968, PATON et al. 1968, APOLLONOV et al. 197o, DEMTRÖDER et al. 197o, PEACOCK et al. 197o). Therefore the plasma breaks up into spatially more or less separated ion groups of different charge numbers. For the dependence of the ion energy on the charge number DEMTRÖDER et al. (197o) found a very exact, and PATON et al. (1968) and BOLAND et al. (1968) an approximate linear relation. These authors suggest the following explanation of their results: owing to their small mass the hot electrons have a much higher thermal velocity than the ions; they therefore escape from the plasma into the vacuum until a retarding voltage of the order kT_e builds up in the plasma cloud. This potential is maintained for the duration of the laser pulse and accelerates the ions proportional to their charge number.

For a currentless homogeneous plasma it is known that an electric field can only exist in a surface layer. The depth to which this field extends is of the order of the Debye length, the interior of the plasma being field-free. A laser plasma produced from a solid target, however, expands during the heating process, so that both density and temperature are very inhomogeneous. Therefore such a plasma may contain an electrostatic field of appreciable strength in its interior.

The aim of this paper is to calculate this internal electric field and investigate its influence on the ion separation. Although this electric potential proves to be in excess of 1 kT_e (typically 4 kT_e), the proposed explanation of the observed ion separation becomes untenable as soon as the friction between the ions of different charge is taken into account.

BASIC EQUATIONS

We consider a solid target exposed to a laser pulse of constant intensity and assume that electrons and two ion species with charge numbers Z_1 and Z_2 ($Z_2 > Z_1$) and equal masses are produced. Recombination and charge exchange processes are neglected. Heating and expansion are then described by the usual conservation laws of gas dynamics for particle number, momentum and energy. Allowance is made for the friction between the two ion species. Thermal conductivity and ionization energy can be neglected since typical laser powers in such experiments are in the region of 10^{10} - 10^{13} W/cm^2 (GREEN 197o, MULSER 197o). The temperature of the electron gas is T_e, for the two ion species a common temperature $T_i = T_1 = T_2$ can be assumed. The conservation equations are then as follows (BRAGINSKII 1965, MULSER 197o):

$$\frac{\partial n_1}{\partial t} + \nabla(n_1\vec{v}_1) = 0 \quad (1a), \quad \frac{\partial n_2}{\partial t} + \nabla(n_2\vec{v}_2) = 0 \quad (1b), \quad \frac{\partial n_e}{\partial t} + \nabla(n_e\vec{v}_e) = 0 \quad (1c')$$

$$n_1 m_i \frac{d\vec{v}_1}{dt} = -\nabla p_1 + n_1 n_2 R_{12}(\vec{v}_2 - \vec{v}_1) + n_1 Z_1 e\vec{E} \quad (2a)$$

$$n_2 m_i \frac{d\vec{v}_2}{dt} = -\nabla p_2 - n_1 n_2 R_{12}(\vec{v}_2 - \vec{v}_1) + n_2 Z_2 e\vec{E} \quad (2b)$$

$$n_e m_e \frac{d\vec{v}_e}{dt} = -\nabla p_e - n_e e\vec{E} \quad (2c')$$

$$\frac{3}{2} n_e k \frac{dT_e}{dt} = -p_e \nabla\vec{v}_e + \nabla\vec{\Phi} - \frac{3}{2} n_e k(n_1\alpha_{e1} + n_2\alpha_{e2})\cdot(T_e - T_i) \quad (3a)$$

$$\frac{3}{2} k\left(n_1 \frac{dT_i}{dt} + n_2 \frac{dT_i}{dt}\right) = -p_1\nabla\vec{v}_1 - p_2\nabla\vec{v}_2 + \frac{3}{2} n_e k(n_1\alpha_{e1} + n_2\alpha_{e2})\cdot(T_e - T_i) \quad (3b)$$

where $p_1 = n_1 kT_i$, the other components being expressed correspondingly;

n_e, n_1, n_2 and $\vec{v}_e, \vec{v}_1, \vec{v}_2$ and p_e, p_1, p_2 are the particle densities, velocities and pressures respectively, $\vec{E}$ the electrostatic field, $\vec{\Phi}$ the laser intensity, R_{12} the friction coefficient of the ions which is given as (BRAGINSKII 1965)

$$R_{12} = \frac{4\sqrt{m_i\pi}\, Z_1^2 Z_2^2 e^4}{3k^{3/2}} \cdot \frac{\ln\Lambda}{T_i^{3/2}}$$

Friction between electrons and ions R_{ei} can be ignored in eqs. (2) since $R_{ei}/R_{12} \lesssim \left(\frac{m_e}{m_i}\right)^{1/2}$. The laser energy is absorbed by the electrons due to electron-ion collisions. As a consequence of these collisions part of the heat is transferred to the ions according to the transfer coefficients α_{e1}, α_{e2}:

$$\alpha_{e1} = \frac{8\sqrt{2m_e\pi}\, Z_1^2 e^4}{3m_i k^{3/2}} \cdot \frac{\ln\Lambda}{T_e^{3/2}} \quad , \quad \alpha_{e2} = \left(\frac{Z_2}{Z_1}\right)^2 \alpha_{e1}$$

Any frictional heating of the plasma can be neglected in eqs. (3).

In the expected density and temperature regime the plasma can be treated as quasi-neutral, i.e. $|Z_1 n_1 + Z_2 n_2 - n_e|/n_e \ll 1$. We therefore use the relation

$$n_e = Z_1 n_1 + Z_2 n_2 \tag{1c}$$

instead of eq. (1c′). We can further simplify eq. (2c′). The R.H.S. contains terms that are at least of the same order as those in the momentum equations for the ions. However, the inertia term on the L.H.S. becomes significant only when $\vec{v}_e$ attains values of the order of $\frac{m_i}{m_e}\vec{v}_1$ or $\frac{m_i}{m_e}\vec{v}_2$. This can occur only if electron plasma oscillations are excited. But their frequency is $\omega_{pe} \gtrsim 10^{12}$ sec^{-1} and we are interested in motions of much larger time scale only. Therefore the inertia term of the L.H.S. in eq. (2c′) can be neglected and we get

$$\nabla p_e + n_e e \vec{E} = 0 \tag{2c}$$

That is, the $\vec{E}$ field is produced by the electron pressure and maintains the balance with it. Since, moreover, no appreciable current can flow in the isolated plasma cloud, the electron velocity results as

$$\vec{V}_e = \frac{1}{n_e}\left(Z_1 n_1 \vec{V}_1 + Z_2 n_2 \vec{V}_2\right) \tag{4}$$

this, in turn, being quite compatible with $n_e m_e \cdot \frac{dv_e}{dt} \approx 0$.

The influence of the electric field and the friction on the ion separation can be emphasized by rearranging eqs. (2a) and (2b). With the total ion number $n_i = n_1 + n_2$, subtracting eq. (2a) from (2b) yields

$$m_i\left(\frac{d\vec{v}_2}{dt} - \frac{d\vec{v}_1}{dt}\right) + n_i R_{12}(\vec{v}_2 - \vec{v}_1) = (Z_2 - Z_1)e\vec{E} + kT_i\left(\frac{\nabla n_1}{n_1} - \frac{\nabla n_2}{n_2}\right)$$

From qualitative considerations it follows that the term $kT_i\left(\frac{\nabla n_1}{n_1} - \frac{\nabla n_2}{n_2}\right)$ tends to reduce to zero, since the temperature T_i and the mass m_i are equal for both ion fluids. Therefore we can ignore it for the discussion of ion separation, and the above relation reduces to

$$m_i\left(\frac{d\vec{v}_2}{dt} - \frac{d\vec{v}_1}{dt}\right) + n_i R_{12}(\vec{v}_2 - \vec{v}_1) = (Z_2 - Z_1)e\vec{E} \tag{5}$$

This equation contains the separating force on the R.H.S. and depends explicitly only on the total density n_i of the ions. If there was no friction ($R_{12} = 0$) a pronounced ion separation would occur. However, estimates with realistic friction coefficients show that small velocity differences already lead to a friction term $n_i R_{12}(\vec{v}_2 - \vec{v}_1)$ which can compensate the separating force $(Z_2 - Z_1)e\vec{E}$. Therefore the system (1-4) can be solved in a first approximation using $\vec{v}_1 = \vec{v}_2 = \vec{v}$. The upper limit for the velocity difference can then be evaluated from eq. (5) omitting the inertia term.

NUMERICAL RESULTS

With the assumption of a common outflow velocity v for the two ion species numerical solution of the system (1-4) in a one-dimensional geometry is straightforward and yields T_i, T_e, n_i, v and E as functions of space and time. Neglecting the (positive) inertia term in eq. (5) one obtains the maximum velocity difference $\Delta v = v_2 - v_1$ for a known E field

$$\frac{\Delta v}{v} = \frac{(Z_2 - Z_1)eE}{n_i R_{12} v} \tag{6}$$

$\Delta v/v$ was calculated for a laser with $\lambda = 10^{-4}$ cm and constant power density $\Phi_0 = 10^{13}$ W/cm^2, first for the one-dimensional plane case where the solid occupies a half-space and then for a spherical particle with diameter $r_o = 10^{-2}$ cm upon which laser radiation is radially and uniformly incident from all sides. The initial density of the ions in both cases was set equal to $n_i^o = 5\cdot 10^{22}$ cm^{-3}, and it was assumed that $Z_1=1$, $Z_2=2$, $n_1/n_2=1$, and the ion mass $m_i = 7\cdot 10^{-24}$ g. The solid was treated as incompressible; this assumption speeds up the calculation without noticeably altering the results. Figures 2a and 2b plot n_i, T_e, T_i, v, and the relative velocity difference $\Delta v/v(x)$ or $\Delta v/v(r)$ in space at the time t = 8 nsec after the laser pulse is switched on. As can be seen, a relative velocity difference of $4\cdot 10^{-3}$ in the plane case and $9\cdot 10^{-3}$ in the spherical case is sufficient to balance the separating force of the electric field. These low values justify the assumption $v_1=v_2$, the resulting error in the other dynamic quantities being insignificant. At lower laser powers the relative velocity difference is even smaller.

With the results (2a) and (2b) the Poisson equation can be used to check the quasi-neutrality of the plasma. The maximum relative charge difference is then found to be $|Z_1 n_1 + Z_2 n_e - n_e|/n_e = 3\cdot 10^{-5}$. The influence of the thermal diffusion force on the ion separation can also be estimated as insignificant.

The potential U from eq. (2c) is

$$U(x) = -\int_{x_F}^{x} E\,dx = \frac{k}{e}\int_{x_F}^{x} \frac{1}{n_e}\frac{\partial(n_e T_e)}{\partial x}\,dx = \frac{k}{e}\left[T_e(x) - T_e(x_F)\right] + \frac{k}{e}\int_{n_e(x_F)}^{n_e(x)} T_e \frac{dn_e}{n_e} \qquad (7)$$

(x_F = plasma front). In a plasma of uniform density only the first term of the sum on the R.H.S. remains, i.e. $eU=kT_e$; if, on the other hand, T_e is constant everywhere, the first term vanishes and the second yields $eU=kT_e \ln \frac{n_e(x)}{n_e(x_F)}$. The contribution of the two terms to the total potential may vary widely from case to case. For an adiabatic rarefaction wave in a fully ionized plasma, for example, the ratio of the second to the first term is found to be $1/(\gamma-1)$, whereas in an isothermal rarefaction wave it can become arbitrarily large (γ = adiabatic exponent). In the case of laser produced plasmas the second term of eq. (7) also makes the main contribution to the potential. In Figs. 2a and 2b, $kT_{e,max}$ is 78o and 6oo eV respectively, while eU on the solid surface is $3.3\cdot 10^3$ and $2.7\cdot 10^3$ eV respectively, i.e. four times as large as $kT_{e,max}$.

The high electric potential is maintained due to plasma production by the laser. Once the light intensity has decayed, the potential drops quickly with decreasing density and temperature. As long as the expansion of the plasma can still be described hydrodynamically, the variation of the velocity difference after the laser is switched off can be roughly estimated assuming adiabatic expansion. If L or R is the size of the plasma, the mean values for the plane case are $n_i \sim L^{-1}$, $T \sim n_i^{2/3} \sim L^{-2/3}$, $R_{12} \sim T^{-3/2} \sim L$, $E \sim \nabla p_e/n_i \sim L^{-5/3}$ and for the spherical case $n_i \sim R^{-3}$, $T \sim R^{-2}$, $R_{12} \sim R^3$, $E \sim R^{-3}$, hence

$$\Delta v \sim \frac{E}{n_i R_{12}} \sim \frac{L^{-5/3}}{L^{-1} L} = L^{-5/3} \quad \text{or} \quad \Delta v \sim \frac{R^{-3}}{R^{-3} R^3} = R^{-3}$$

i.e. increasing expansion of the plasma hampers ion separation. In this context it is not possible to determine the effect of ion separation in the boundary layer where the hydrodynamic description breakes down. As long as the laser radiates, however, the boundary layer makes up only a small fraction of the whole plasma (MULSER 197o).

The above results which are calculated with the usual transport coefficients for plasmas justify the assumption that the electrostatic field cannot be responsible for the ion separation. This experimentally observed effect must have other reasons, e.g. the spatial and temporal inhomogeneity of the laser intensity. In the center of the focus the ions produced are hotter and more highly charged than on the outside (IRONS et al. 197o) (see Fig. 1) and, moreover, ionization degree and ion energy are higher at the maximum intensity than at the beginning and the end of the laser pulse. In addition, for the detailed explanation of the measured dependence of the ion energies on their charge number ionization and recombination effects during the expansion phase of the plasma cloud may be important.

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FIGURE CAPTIONS

Fig. 1 Laser produced plasma (schematically).

Fig. 2a Temperatures T_e, T_i, ion density n_i, velocity v, electrostatic potential U and relative velocity difference at t = 8 nsec. Plane geometry.

Fig. 2b Temperatures T_e, T_i, ion density n_i, velocity v, electrostatic potential U and relative velocity difference at t = 8 nsec. Spherical geometry.

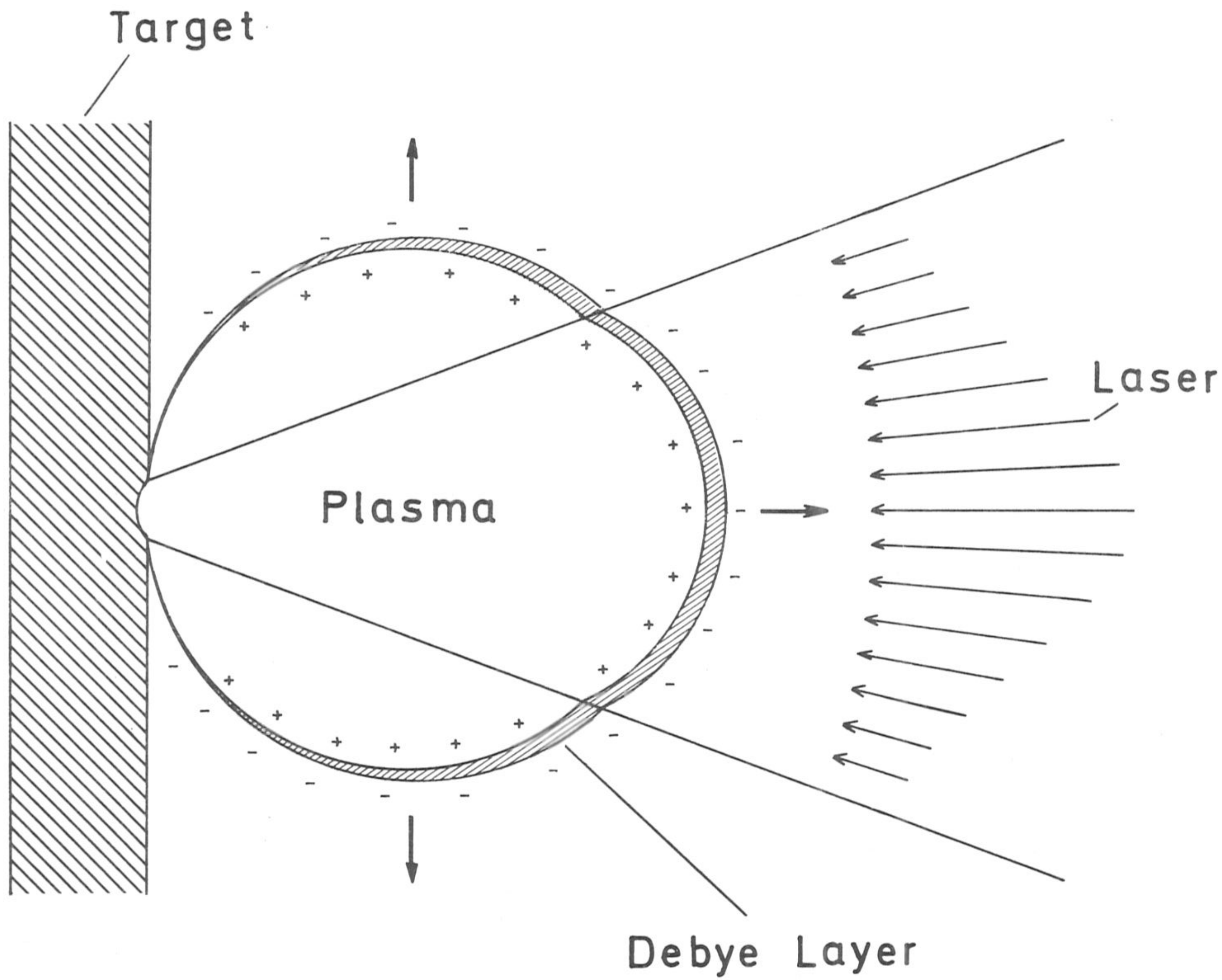


Fig. 1

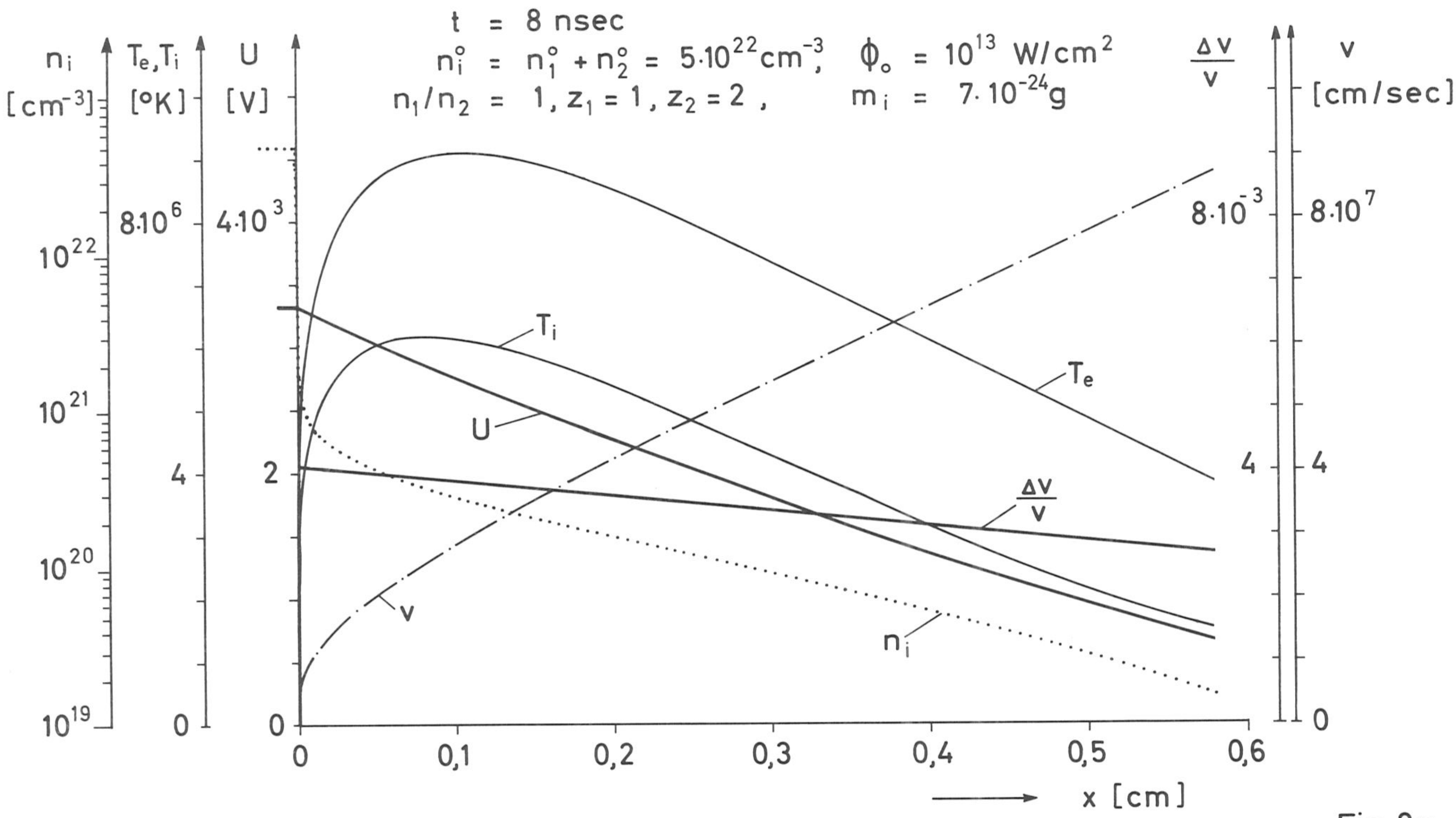
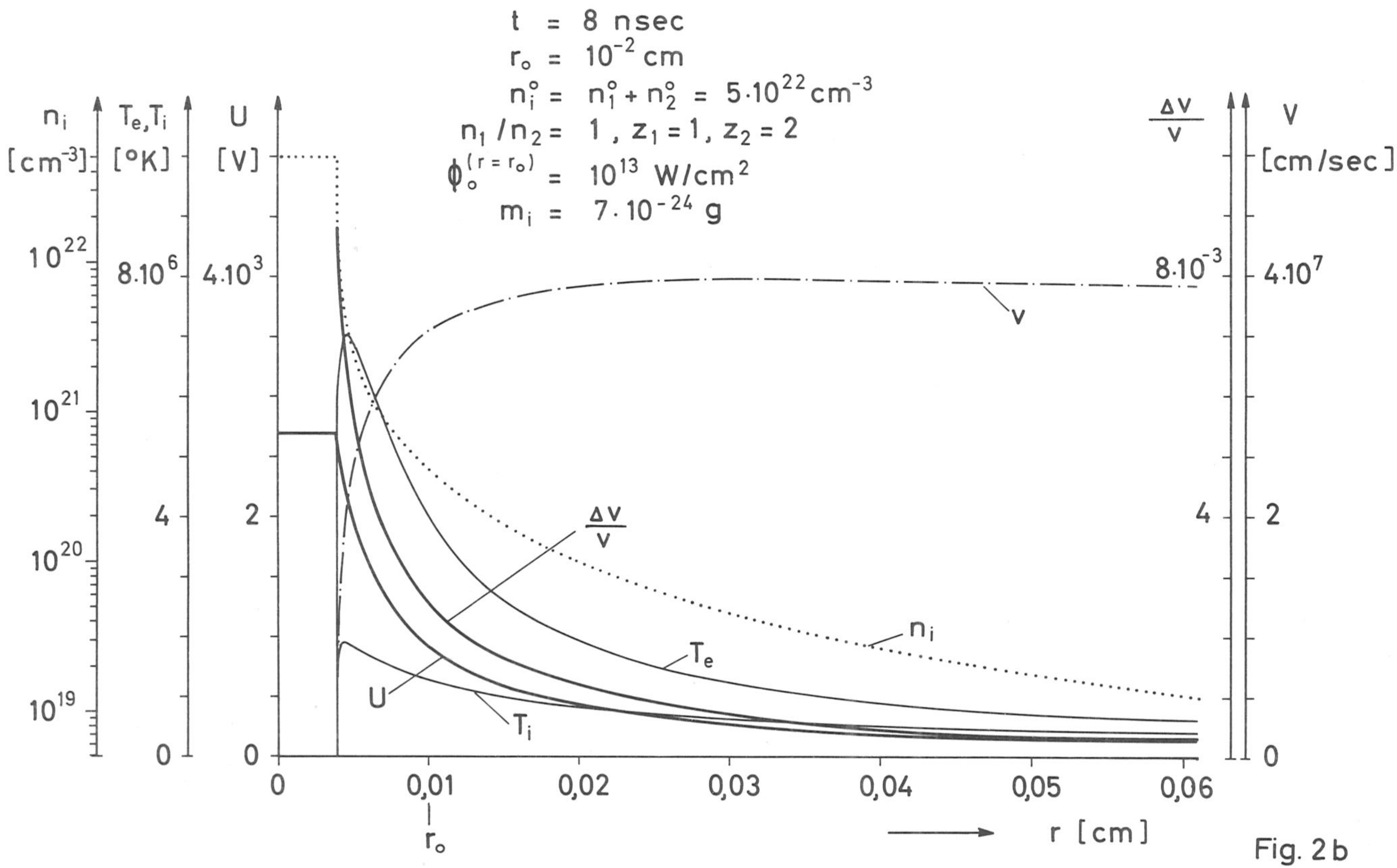

t = 8 nsec
n°i = n°1 + n°2 = 5·10^22 cm^-3, Φo = 10^13 W/cm^2
n1/n2 = 1, z1 = 1, z2 = 2, mi = 7·10^-24 g
ni [cm^-3]
Te, Ti [°K]
U [V]
Δv/v
v [cm/sec]
10^22
10^21
10^20
10^19
8·10^6
4
0
4·10^3
2
0
8·10^-3
4
8·10^7
4
0
Ti
Te
U
Δv/v
v
ni
0
0,1
0,2
0,3
0,4
0,5
0,6
x [cm]

Fig. 2a



t = 8 nsec
r₀ = 10⁻² cm
n_i° = n_1° + n_2° = 5·10²² cm⁻³
n_1 / n_2 = 1 , z_1 = 1, z_2 = 2
Φ_0^(r = r_0) = 10¹³ W/cm²
m_i = 7·10⁻²⁴ g
n_i
[cm⁻³]
10²²
10²¹
10²⁰
10¹⁹
T_e, T_i
[°K]
8.10⁶
4
0
U
[V]
4.10³
2
0
Δv/v
8.10⁻³
4
v
[cm/sec]
4.10⁷
2
0
0
0,01
0,02
0,03
0,04
0,05
0,06
r₀
r [cm]
v
n_i
T_e
U
T_i

Fig. 2b