Maximum Expansion Velocities of Laser-Produced Plasmas

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Comparisons of observed ion velocity maxima with predictions of theoretical models suggest that departures from ideal isothermal expansion behavior are caused by nonequilibrium critical-surface electron distributions.

In the designing of ablatively driven, laser-fusion targets, the character of the electron distribution at the critical surface as it affects energy transport and momentum transfer in the expanding plasma is a critical factor. We present experimental evidence of a truncated, non-Maxwellian electron velocity distribution at the critical surface. A sharp velocity maximum in the ion expansion has been observed. In this Letter, two theories are presented which can explain this phenomenon: first, the effect of charge separation and second, the impact of a truncated Maxwellian electron distribution.

The latter mechanism gives better correlation with the experimental data. The data were obtained by measuring the ion expansion from planar targets irradiated with short (50 psec) Nd-laser pulses. The plasma is approximately planar during the laser pulse because the expansion dimensions are on the order of, or less than, the focal-spot radius (100 μm). The electron thermal conductivity in the hot expanding plasma is sufficiently large and the electron-ion cross relaxation sufficiently low that the plasma region tends to be isothermal with $T_i/T_e \simeq 0$ during the laser pulse.[1]

Figure 1(a) is a sketch of a typical profile along a line through the middle of the focal spot and normal to the target surface, for the laser power levels considered here, for which, as the data indicate, flux limiting near the critical surface is not significant.

The distribution of the faster plasma ion velocities at the time of the end of pulse arrival is approximately retained in subsequent expansion because the flow is quite supersonic and the internal energy is, therefore, much less than the kinetic energy, and thus incapable of having a significant effect on the final expansion velocities.

It should, therefore, be expected that observations of the faster part of the expansion, which comes from the higher-temperature region, would approximately obey the well-known self-similar solution for isothermal planar expansion of a semi-infinite medium,[1]

$$N_i = \exp(-\xi), \tag{1}$$

$$U = \xi + 1, \tag{2}$$

shown in Fig. 1(b) in solid lines. From (1) and (2) the velocity distribution at a remote detector would be

$$dN_i/dU \sim \exp(-U). \tag{3}$$

Here $N_i \equiv n_i/n_{i0}$, $N_e \equiv n_e/n_{e0}$, $\xi \equiv x/C_I t \equiv x/x_I$ (the similarity variable), $C_I \equiv (ZkT_e/m_i)^{1/2}$, $U \equiv v_{ix}/C_I$, and $\psi \equiv e\varphi/kT_e$, where T_e is electron temperature, Z and m_i are ion charge and mass, respectively, and x is the distance from the initial target surface; E_x, φ, and v_{ix} are the electric field, electric potential, and ion flow velocity, respectively. Here n_e, n_i, n_{e0}, and n_{i0} are electron and ion densities and their values at the sonic point, $x=0$. Finally Δt, assumed to be on the order of the pulse length, is the period during which T_e in the isothermal region remains near its peak value.

In deriving Eqs. (1) and (2), charge neutrality and a Maxwellian electron distribution are assumed, i.e.,

$$N_e = ZN_i, \tag{4}$$

$$N_e = \exp(\psi). \tag{5}$$

The self-consistent electrostatic field through which electron pressure gradients accelerate the ions is

$$\mathcal{E} = -\frac{\partial\psi}{\partial\xi} = -\frac{\partial\psi}{\partial N_e}\frac{\partial N_e}{\partial\xi}, \quad \mathcal{E} = \frac{E_x}{m_i C_I/Ze\Delta t}. \tag{6}$$

Equations (1), (4), (5), and (6) give $\mathcal{E} = 1$ [see Fig. 1(b)] for this pure Maxwellian case.

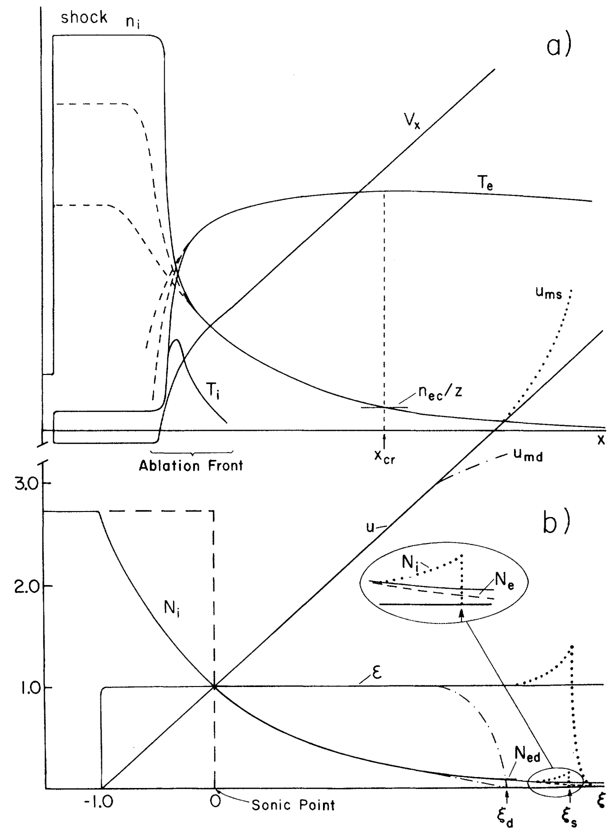

FIG. 1. (a) Form of typical profiles normal to the target surface. (b) Ideal isothermal Maxwellian expansion profiles (solid lines) of an initally homogeneous semi-infinite plasma (long-dashed line) modified by a charge separation sheath at ξ_s (dotted lines) or modified at ξ_d by a non-Maxwellian electron distribution (broken lines).

Average parameters from a considerable number of shots on flat CH_2 targets are given in Table I. Figure 2 shows velocity distributions obtained from Faraday-cup traces taken on two shots with different peak power. Both clearly show the exponential form [Eq. (3)] of isothermal expansion. Values of dN_i/dV above the dashed line on the left come from the higher-density, nonisothermal side of the ablation front [Fig. 1(a)]. The absolute magnitude of dN_i/dV depends on the sonic point density, n_{i0} [Fig. 1(b)], which occurs on the lower-density side of the ablation front approximately where the isothermal region begins. The ratio of n_{i0} to the peak density on the dense side of the front varies with absorbed power and ranges from 10^{-1} to 10^{-3} in cases of interest.[2] C_I and T_e in Fig. 2 are obtained from the dashed-line slopes and Eq. (3).

TABLE I. Average experimental parameters and comparisons with theory.

Power	10^{14} W/cm^2
Pulse length	50 ps
Isothermal T_e	2.5 keV
Isothermal sound speed, C_I	4.9×10^7 cm/sec (H^+)
	3.5×10^7 cm/sec (C^{6+})
Maxwellian ion velocity, V_{im}	27×10^7 cm/sec (H^+)
U_m ($\equiv V_{im}/C_i$)	5.5 (H^+)
	7.8 (C^{6+})
U_{ms} [$\equiv$ (sheath velocity)/C_I]	21.9 [a]
	19.6 [b]
	17.3 [c]
$n_{ed} = N_{ed} n_{eo}$ (distribution cutoff density)	10^{20} cm^{-3} [a]
	4.1×10^{19} cm^{-3} [b]
	10^{18} cm^{-3} [c]
V_{ecd}/V_{eth} (cutoff velocity) at critical surface)	0.94 [a]
	1.79 [b]
	2.34 [c]

[a] For $n_{e0} = 10^{23}$ cm^{-3}.
[b] For $n_{e0} = 10^{22}$ cm^{-3}.
[c] For $n_{e0} = 10^{21}$ cm^{-3}.

Equation (3) implies a smoothly decreasing number of ions up to arbitrarily large (nonrelativistic) velocities. By contrast, a Thomson-parabola analyzer and a photomultiplier/fluorescer combination both show a clearly defined ion velocity maximum on each shot (see Table I).

Two mechanisms could modify the ideal isothermal behavior described above in a way that would limit ion velocities to observable maxima: (I) charge separation resulting in breakdown of

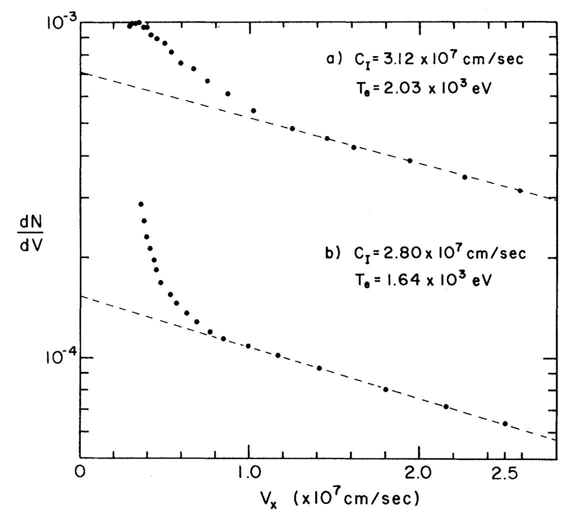

FIG. 2. Faraday-cup currents, dN/dV, as a function of ion velocity, V, for two shots with different laser pulse energies.

Eq. (4) at low densities; and (II) absence of the high-temperature Maxwellian tails of the electron velocity distribution, resulting in modification of Eq. (5), at low densities.

Mechanism I, charge separation, limits the ion velocities by forming a nonneutral electrostatic sheath which truncates the exponential density profile at a point, ξ_s, near where the Debye length, λ_D [$\equiv(4\pi n_e e^2/m_e)^{1/2}$], equals the density scale length, $C_I\Delta t$. Charge neutrality and, therefore, coupling of electron pressure to the ions should be expected to fail at this and lower densities. Self-consistency requires this truncation if the vacuum E_x field is very different (usually much less) from E_x [Eq. (6)] in the expanding plasma. This effect was first seen in numerical simulations.[3] An analytic theory derived by the authors gives modified profiles,

$$N_i=[4\epsilon^2+\epsilon^{-1}\exp(-\epsilon^2/2)],\quad \xi<\xi_s,\qquad N_i=0,\quad \xi>\xi_s, \tag{7}$$

$$U=1+\xi+\epsilon,\quad \epsilon\equiv\exp(\xi-\xi_s), \tag{8}$$

which closely resemble the simulation solutions,[3] and a maximum ion-sheath velocity at ξ_s of

$$U_{ms}=2[1+\ln(\sqrt{2}\,\omega_{pi0}\Delta t)],\qquad \omega_{pi0}=(4\pi n_{i0}Z^2e^2/m_i)^{1/2}. \tag{9}$$

These modifications of isothermal expansion which violate self-similarity are sketched as dotted lines in Fig. 1(b).

Mechanism II, absence of the Maxwellian tails of the electron velocity distribution, also limits ion velocities by truncating the exponential density profiles of an isothermal expansion, but does so by effectively modifying the electron pressure equation of state. Under those quasistatic conditions the electron velocity distribution can be written as $f_e(\epsilon_e)$, where $\mathcal{E}_e\equiv\frac{1}{2}m_eV_e^2-e\varphi$ is the electron energy. If the tials of the otherwise Maxwellian $f_e\sim\exp(-\epsilon_e/kT_e)$ of this almost collisionless plasma are cut off at $\epsilon_e=\epsilon_{ed}$, the velocities will be cut off at V_{ed}:

$$V_{ed}=V_{e\text{th}}[(\epsilon_{ed}+e\varphi)/kT_e]^{1/2},\qquad V_{e\text{th}}\equiv(2kT_e/m_e)^{1/2}, \tag{10}$$

with $V_{e\text{th}}$ the thermal velocity. Wherever $\epsilon_{ed}\gg-e\varphi$, f_e is essentially Maxwellian with temperature T_e. However, as $-e\varphi$ approaches ϵ_{ed}, which occurs near the point $\xi=\xi_d$ where the density is truncated [see Fig. 1(b)], $V_{ed}/V_{e\text{th}}$ approaches zero, which is equivalent to having the effective temperature, i.e., the mean thermal energy, decrease to zero. Thus, the electron pressure at a given density is decreased relative to the Maxwellian pressure at temperature T_e. In this modified isothermal system it is, therefore, $f_e(\epsilon_e)$ which is independent of position while near ξ_d the effective temperature decreases from T_e to zero.

A generalization of the procedure that led to Eqs. (1) and (2) gives

$$\frac{dN_i}{d\xi}=-\left[\frac{d}{dN_i}\left(N_i\frac{d\psi}{dN_i}\right)^{1/2}+\frac{1}{N_i}\left(N_i\frac{d\psi}{dN_i}\right)^{1/2}\right]^{-1}, \tag{11}$$

$$U=\xi+(N_i d\psi/dN_i)^{1/2}. \tag{12}$$

Equations (11) and (12) are solved, together with Eq. (6) relating ψ and ξ, by assuming charge neutrality, $N_e=N_i$, because when Mechanism II is operative it will occur at higher densities than those involved in Mechanism I. The resulting modified density and field profiles, $N_i(\xi)$ and $\epsilon(\xi)$, go to zero at some finite $\xi=\xi_d$, and $U(\xi)$ is also modified, as sketched in broken lines in Fig. 1(b). For ξ near ξ_d, i.e., for $0<\psi-\psi_d\ll1$, the step in f_e gives $N_e(\psi)\sim(\psi-\psi_d)^{1/2}$ and Eqs. (6), (11), and (12) give $(U_{md}-U),\mathcal{E},N_i\sim(\xi_d-\xi)$. Here $\psi_d\equiv-\epsilon_{ed}/kT_e$ and U_{md} is the maximum ion velocity determined by the distribution cutoff at ϵ_{ed} (recall $\psi<0$). For less abrupt cutoffs $N_e\sim(\psi-\psi_d)^\mu$, $\mu>\frac{1}{2}$, and $N_i\sim(\xi_d-\xi)^{2\mu}$. These modified isothermal expansions retain self-similarity. Consequently, U_{md} is independent of pulse length, Δt. From the above forms of N_i and N_e near ϵ_d, the second term in Eq. (12) is zero at ξ_d and

$$U_{md}=\xi_d. \tag{13}$$

The density at which truncation of the expanding plasma occurs, i.e., the density that would be found at ξ_d if the truncation did not occur, can now be obtained from Eqs. (14) and (1) and from the charge neutrality:

$$N_{ed}=N_{id}=\exp(-U_{md}). \tag{14}$$

The T_e in Table I is obtained from C_I of the predominant plasma species, C^{6+}, but values of C_I and U_m for this T_e in H^+ are also shown and are used in calculating N_{ed} because the fastest ions are H^+. The uncertainty introduced by this complication is not large enough to affect qualitative conclusions. Values of U_{ms} from Eq. (9) are shown for different values of the sonic electron density, n_{e0}, within the plausable range [see discussion above Eq. (8)]. The logarithm in Eq. (9) makes U_{ms} so insensitive to experimental parameters and the observed scatter in values of U_m is sufficiently small that the ratio of 3 or 4 between values of U_{ms} and U_m appears significant and makes it difficult to believe that mechanism I is responsible for the observed ion-velocity maxima.

Considering mechanism II, the Table I values of the cutoff density n_{ed} are obtained from Eq. (14) for N_{ed}, the average measured U_m, and the range of n_{e0}. These values of n_{ed} range from just below the critical density, $n_{ec} = 10^{21}$ cm^{-3}, to much less. The velocity at the critical surface, V_{ecd}, of the electrons with the cutoff energy ϵ_{ed}, is particularly interesting and can be calculated by using the fact that these electrons have zero kinetic energy at the tip of the truncated density profile, $\xi = \xi_d$. Using the uniform field of the pure Maxwellian solution, i.e., $\mathcal{E} = 1$ or $E_x = m_i C_I / Ze\Delta t$ [see below Eq. (6); see also Eq. (10)], to calculate the potential energy between the critical surface and $\xi = \xi_d$ (a good approximation if $N_{ed} \ll N_{ec}$) gives

$$V_{ecd} \simeq V_{e\mathrm{th}} [\ln(N_{ec}/N_{ed})]^{1/2}. \tag{15}$$

Values of $V_{ecd}/V_{e\mathrm{th}}$ in Table I for the range of n_{e0} values indicate that the electron velocity distributions produced at the critical surface are truncated at between about 1 and 2 times the thermal velocity. Such truncation suggests the wave-breaking mechanism that is believed to accompany resonant absorption.[4] No velocities are produced above the crest of the wave in phase space.[4]

The assumptions and implications of mechanism II are consistent with theory and recent experimental results. Thus, truncation of the Maxwellian electron distribution is the more likely explanation of the definitive maximum ion velocity in the plasma expansion from laser-irradiated planar targets.

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[1]For discussion of expanding plasmas see T. P. Hughes, *Plasmas and Laser Light* (Wiley, New York, 1975), p. 317 and following, and extensive references contained therein. For discussion of isothermal expansion, see L. D. Landau and E. M. Lifshitz, *Fluid Mechanics* (Addison-Wesley, Reading, Mass., 1959), p. 359; and J. S. Pearlman and R. L. Morse, "Isothermal Expansion of Laser Produced Plasmas" (to be published).

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