Ion Emission from Laser-Produced Plasmas with Two Electron Temperatures

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(Received 12 May 1978)

An analytic theory for the expansion of a laser-produced plasma with two electron temperatures is presented. It is shown that from the ion-emission velocity spectrum such relevant parameters as the hot- to cold-electron density ratio, the absolute hot- and cold-electron temperatures, and a sensitive measure of the hot- to cold-electron temperature ratio can be deduced. A comparison with experimental results is presented.

Recent experiments with laser-produced plasmas have shown that high-energy ions are emitted and can carry away a large fraction of the absorbed laser energy.[1,2] In an attempt to understand the processes that cause the emission of these fast ions, experimental ion-velocity spectra have been compared with predictions of theories[3] for the free expansion of a plasma with a single electron temperature. Some experimental data, however, have structure which cannot be accounted for by this approach.

X-ray–emission measurements at laser intensities in the range 10^{18}–10^{20} W/m^2 have shown that the absorption processes give rise to a non-Maxwellian electron velocity distribution with a high-velocity tail.[4,5] This velocity distribution can be represented as the superposition of a hot Maxwellian velocity distribution with a colder Maxwellian velocity distribution and is well characterized by two electron temperatures.[4] It is thought that it is the electrons in this tail which accelerate the fast ions.[5,6]

The limited theoretical work on this aspect of laser-produced plasmas to date consists mainly of computer codes designed to take as many of the laser-plasma interaction effects into account as is possible. While this approach is an essential aspect of laser-produced–plasma theoretical studies, much of the underlying physical insight that results from analytic work is lost. To isolate the effects of a two-temperature electron-velocity distribution function on the plasma ablation we have developed an analytic theory using similarity-transformation methods.

Recently the assumption has been made that the hot-electron temperature can be determined from the slope of experimental ion-emission velocity spectra.[1,2] The theory confirms this supposition and also shows that such relevant parameters as the hot- to cold-electron density ratio, the absolute hot- and cold-electron temperatures, and a sensitive measure of the hot- to cold-electron temperature ratio can be obtained. A comparison of the theory with experimental results is presented.

The boundary conditions assumed at time $t=0$ are a quasineutral plasma slab composed of ions with charge Ze and density n_0 for $x<0$ and vacuum for $x>0$, where x is the distance measured from a planar target. The electrons are of two species, belonging to hot and cold Maxwellian velocity distributions with temperatures T_h and T_c, respectively. Since the subsequent plasma expansion takes place on a time scale long compared with an electron plasma period, it is also assumed that each electron species is in equilibrium with the electrostatic potential and follows the appropriate Boltzmann density distribution $n_h = n_{h_0}\exp(e\varphi/kT_h)$ or $n_c = n_{c_0}\exp(e\varphi/kT_c)$. Here n_h and n_c are the hot- and cold-electron number densities, φ is the electrostatic potential, e is the magnitude of the electronic charge, k is Boltzmann's constant, and n_{h_0} and n_{c_0} are the hot- and cold-electron densities in the source plasma such that $Zn_0 = n_{h_0} + n_{c_0}$. The characteristic scale length for plasma-density variations is generally large compared with a Debye length, so that the plasma remains quasineutral during the expansion and $Zn = n_h + n_c$ holds, where n is the ion number density. The cold-ion collision-free fluid equations of continuity and momentum are used, and the temperatures of the hot and cold electrons are assumed to remain constant during the self-similar phase of the plasma expansion. The approximations of a collision-free cold-ion plasma become more accurate as the rarefaction expansion progresses.

Transforming the fluid equations so that the similarity parameter $\xi = x/t$ becomes the independent variable, we find that

$$(v-\xi)dn/d\xi + n dv/d\xi = 0,$$

$$(v-\xi)dv/d\xi + (S^2/n)dn/d\xi = 0,$$

and $v - \xi = S$, where v is the ionic velocity, M is the ion mass, and

$$S = [Z(n_h + n_c)/(n_h/kT_h + n_c/kT_c)M]^{1/2}$$

is the local ion sound speed. From the above we have

$$dv/d\xi = -(Ze/SM)d\varphi/d\xi. \tag{1}$$

Integration of Eq. (1), using the boundary conditions that $\varphi = 0$, $v = 0$, and $S = S_0$ in the undisturbed plasma, then gives

$$v = \left(\frac{1}{T_c} - \frac{1}{T_h}\right)^{-1}\left[\frac{C_c}{T_c}\ln\left(\frac{S - C_c}{S + C_c}\frac{S_0 + C_c}{S_0 - C_c}\right) + \frac{C_h}{T_h}\ln\left(\frac{C_h + S}{C_h - S}\frac{C_h - S_0}{C_h + S_0}\right)\right], \tag{2}$$

where $C_h = (ZkT_h/M)^{1/2}$, $C_c = (ZkT_c/M)^{1/2}$, and $S_0 = (Z[n_{h_0} + n_{c_0}]/[n_{h_0}/kt_h + n_{c_0}/kT_c]M)^{1/2}$ is the sound speed in the source plasma. From (2) and the relation $v - \xi = S$, the ion velocity as a function of distance from the source plasma at time t can be obtained. Note that, since the ions are not in equilibrium with the electrostatic potential, $\frac{1}{2}Mv^2 \neq |e\varphi|$.

To compare the above theory with experiments on laser-produced microballoon plasmas it is assumed that the self-similar solution holds till a time t_0, after which no further ion acceleration occurs. The ions then freely drift to the walls with the velocities that they have acquired from the self-similar potential. The ion velocity spectrum observed by a probe remote from the target is then the same as the ion velocity spectrum in the self-similar flow at time t_0. Since no source plasma is produced after the laser pulse ends, it seems reasonable to identity t_0 with the laser pulse duration and, since the ions move a distance of the order of the microballoon diameter during the laser pulse, we can approximate the self-similar phase of the microballoon ablation as planar. The plasma surface area A is then approximately the surface area of the microballoon.

Let $(\partial N/\partial v)_{t=t_0} dv$ be the number of ions in the velocity range dv at a time t_0; then $(\partial N/\partial v)_{t=t_0} = At_0 n d\xi/dv$, and using the relation $v - \xi = S$ and Eq. (1) we find that

$$\frac{1}{An_0t_0}\left(\frac{\partial N}{\partial v}\right)_{t=t_0} = \frac{n}{n_0}\left[1 - \frac{1}{2}\frac{n_h n_c}{[n_h/T_h + n_c/T_c]^2}\left(\frac{1}{T_c} - \frac{1}{T_h}\right)^2\right]. \tag{3}$$

Figure 1 shows plots of the ion-emission velocity spectrum obtained from Eqs. (2) and (3) for a variety of initial conditions. The most notable feature of these curves is the pronounced dip in the distribution. This dip develops in a region of the self-similar flow where the ions are rapidly accelerated and its depth is particularly sensitive to the hot- to cold-electron temperature ratio, T_h/T_c. A change in T_h/T_c from 8 to 9 dramatically increases its depth, while it is only just visible when $T_h/T_c = 6$. The depth of the dip is therefore a sensitive measure of the ratio T_h/T_c while its position provides an estimate of the hot- to cold-electron density ratio in the source plasma.

In a laser-produced plasma it is often the case that $n_{h_0} \ll n_{c_0}$. From Eqs. (2) and (3) we then have that, for small ion velocities, $(\partial N/\partial v)_{t=t_0} \simeq At_0 n_{c_0} \exp(-v/C_c)$; and for large ion velocities, $(\partial N/\partial v)_{t=t_0} \simeq At_0 n_{h_0} \exp(-v/C_h + B)$, where B is constant for specific initial conditions. Thus, in Fig. 1, the slopes of the upper and lower asymptotes are $-(M/ZkT_c)^{1/2}$ and $-(M/ZkT_h)^{1/2}$, and from these slopes the absolute hot- and cold-electron temperatures can be determined. It is particularly interesting to note that if the ratio $T_h/T_c > 5 + \sqrt{24} \approx 9.9$, then Eq. (2) becomes singular in the vicinity of the dip, signifying the breakdown of the quasineutrality assumption in this region. Further details of the theory will be presented elsewhere.[7]

Experiments have been carried out using Faraday-cup ion detectors to determine the ion-emission velocity spectra produced from small (70 μm diam) microballoon-type targets when irradiated with a high-power (0.3 TW, 100 ps) Nd-glass–laser system.[8] Target irradiation was achieved using two opposing $f/1$ lenses to give intensities on the poles of the target up to 5×10^{19}

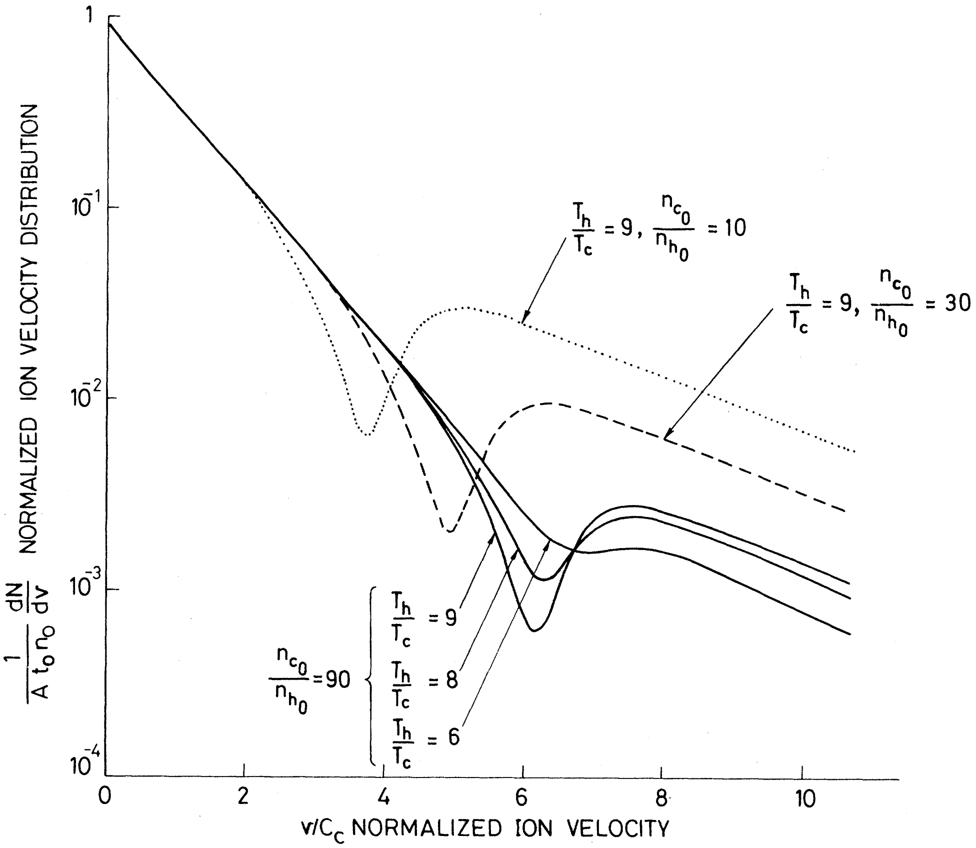

FIG. 1. Theoretical normalized ion-velocity distributions obtained from Eqs. (2) and (3) for various values of the hot- to cold-electron temperature ratio (T_h/T_c) and target-plasma cold- to hot-electron density ratio (n_{c_0}/n_{h_0}).

W m^{-2}. Several detectors were situated around the target at a distance of 0.38 m and their construction was such that secondary-electron emission and hot-electron collection were suppressed and only ion current recorded. The currents received by each probe were converted into ion velocity distribution assuming the ions to originate from the glass microballoon and to have an average atomic weight of 20 and $Z=10$.

Figures 2(a) and 2(b) show experimental ion distributions obtained from a detector situated in the target equatorial plane (plane perpendicular to the laser beams) on two consecutive laser shots. As can be seen, these curves exhibit closely the features predicted theoretically. The two shots shown represent the extremes of distributions observed in terms of the depth of the dip. It should be noted that distributions similar to those shown in Fig. 2(b), where the dip is a small feature, have been observed by others.[1]

Theoretical ion distributions derived from Eqs. (2) and (3) have been fitted to the two experimental curves, giving reasonable agreement at low ion velocities, as can be seen in the figures. The poorer agreement at high ion velocities may be caused by errors in the average ion-charge to -mass ratio, due to the presence of fast protons.[8]

Comparison of the theoretical curves with these and many other experimental results allows the following statements to be made about the properties of the glass-shell plasma near critical density. The hot- to cold-electron temperature ratio (T_h/T_c) varies between 5 and 8 both from shot to shot and also between different observation directions on the same shot. The cold- to hot-electron density ratio (n_{c_0}/n_{h_0}) remains reasonably constant with a value of about 30. Values of T_c and T_h observed cover the ranges 0.6–1.4 and 9.0–11.0 keV, respectively.

These temperatures and temperature ratios deduced from the ion velocity distributions can be compared with temperature measurements made by observation of the x-ray–emission spectrum using filtered diode arrays. Such measurements

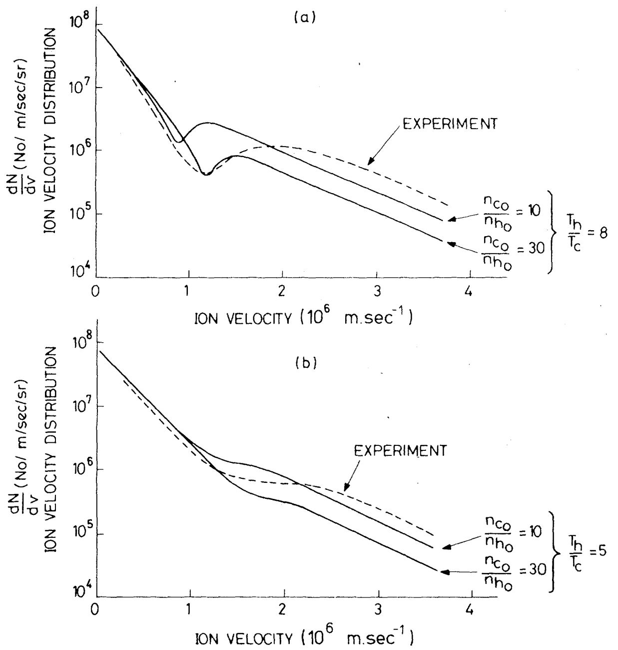

FIG. 2. (a), (b) Comparison of experimental ion-velocity spectra with theoretical distributions. The two experimental curves were derived from the currents to a detector situated in the target equatorial plane for two consecutive shots on microballoon targets at intensities of 5×10^{19} W m^{-2}.

indicate values of T_h/T_c varying between 6 and 10 with values of T_c and T_h in the ranges 0.7–1.0 and 5–8 keV, respectively. These values are in remarkably good agreement with the ion results if we bear in mind that the x-ray data give information about a region of plasma of density considerably higher than critical and that averaging over the whole target takes place.

Finally we note that the magnitudes of the observed and predicted ion currents are of the same order. This can be seen by comparing the theoretical value of $(\partial N/\partial v)_{v=0} \simeq n_0 A t_0$ with that obtained by extrapolating the experimental curves back to $v=0$. Taking $n_0 = n_c/Z = 10^{26}$ m^{-3}, $t_0 = 100$ ps, and A to be the microballoon surface area divided by 4π gives $(\partial N/\partial v)_{v=0} \simeq 1.2\times10^7$ ms^{-1} sr^{-1}, which is to be compared with a value of about 8×10^7 ms^{-1} sr^{-1} obtained experimentally.

In conclusion, we have shown that the application of the theory presented to experimental ion-velocity spectra allows such important target-plasma parameters as the hot- to cold-electron density and temperature ratios and the absolute hot- and cold-electron temperatures to be determined.

We wish to thank Dr. M. H. Key for his interest and helpful discussions. This work has been supported by the Science Research Council, United Kingdom.

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