temperature $T_h = 6$ keV in agreement with the hard-x-ray observation, the density profile is strongly modified only at very low densities. For $\eta \leq 0.2$, the effect is negligible in the measured density range. For $\eta = 0.5$, it is negligible for $n_e \simeq 10^{20}$ cm$^{-3}$, and still within the error bar for $n_e = 2\times10^{19}$ cm$^{-3}$. It is concluded that the fraction of laser energy in fast electrons is not larger than 50%.

In conclusion, we have shown that the coronal density profile of a laser-heated target may yield information about heat transport. We find a flattening of the density profile in the outer zones of the corona which—within the limits of present modeling of the physics of such plasmas—is consistent with a strong flux inhibition ($f \lesssim 0.05$).

Technical asssitance is gratefully acknowledged from the technicians of the GRECO Interaction Laser Matière and of the Laser Plasma Group of Laboratoire de Physique des Milieux Ionisés. The x-ray measurements were taken by F. Amiranoff. We particularly appreciated support from and fruitful discussions with E. Fabre. This work was supported in part by a grant from Centre National de la Recherche Scientifique.

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# Ion Acceleration in an Expanding Rarefied Plasma with Non-Maxwellian Electrons

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(Received 25 December 1978)

Scaling laws are derived for the energy spectrum of accelerated ions of different masses and charges. The results are compared with existing experiments.

In experiments with laser-produced expanding plasmas high-energy ions have been detected and found to carry a large fraction of the absorbed laser energy.[1,2] Measurements of x-ray emission have shown that the electrons have a non-Maxwellian velocity distribution with a marked high-velocity tail.[3] Since the ions are accelerated by the fast electrons, measurements of the ion spectra for different charges, $Z_k$, and masses, $M_k$, may serve as an important diagnostic tool for laser-produced plasmas.

The possibility of ion acceleration in a rarefied expanding plasma was indicated by Gurevich, Pariiskaya, and Pitaevskii[4] and later theoretically investigated for the case of a Maxwellian electron distribution.[5,6] Recently, the possibility of two-temperature electron distributions has been analyzed.[7-9] In the present work the problem is solved for an arbitrary non-Maxwellian electron distribution. The results are compared with experiments[2] and it is shown that measurements of the ion spectra may be used to determine the electron distribution function.

The complete system of equations describing the fast ions in a one-dimensional plasma expansion is[4-9]

$$(v_k - \tau)\frac{dn_k}{d\tau} + n_k\frac{dv_k}{d\tau} = 0,$$
$$(v_k - \tau)\frac{dv_k}{d\tau} + \frac{eZ_k}{M_k}\frac{d\varphi}{d\tau} = 0, \quad n_e(\varphi) = \sum_k Z_k n_k. \tag{1}$$

Here $n_k$ and $v_k$ are the density and hydrodynamic flow velocity of ions with charge $Z_k$ and mass $M_k$. The self-similar variable is $\tau = x/t$, where $x$ is the distance from the original plasma boundary. The electron density $n_e(\varphi)$ is determined by the one-dimensional electron distribution $f_e(v,x,t)$. For large electron velocities, as compared to the plasma flow, $f_e(v,x,t)$ is related to the electron velocity distribution in the unperturbed plasma $f_{e0}(v)$ by $f_e(v,x,t) = f_e(-v,x,t) = f_{e0}([v^2 - 2e\varphi/m]^{1/2})dv$. This implies that

$$n_e = 2\int_0^\infty f_{e0}([v^2 - 2e\varphi/m]^{1/2})dv. \tag{2}$$

In the case of one type of ions the general solution of Eqs. (1) and (2) can be written (cf. Refs. 7, 8, and 10)

$$-\tau = S + (eZ/M)\int_0^\varphi d\varphi/S(\varphi), \quad v = \tau + S(\varphi), \tag{3}$$

where $n_e(\varphi) = Zn$ and $S^2(\varphi) = (eZ/M)n_e(\varphi)(dn_e/d\varphi)^{-1}$. The variables $v$, $n$, and $\tau$ depend essentially on the form of the function $n_e(\varphi)$, i.e., ultimately on the electron distribution function $f_{e0}$. It is easy to see that for a function $f_{e0}$ with an enhanced tail (compared to a Maxwellian) $S$ must be a decreasing function of $\varphi$. From Eq. (3) it follows that if (cf. Ref. 8)

$$\frac{d}{d\varphi}\left(\frac{n_e}{dn_e/d\varphi}\right) = \frac{M}{eZ}\frac{dS^2}{d\varphi} > -2, \tag{4}$$

then $\tau$ is a monotonic function of $n$. When condition (4) is invalid the curve $n(\tau)$ contains singular points. For example, for a power-law tail $f_{e0} \sim v^{-\alpha}$, condition (4) becomes invalid when $\alpha > 5$. According to Ref. 10 these points are of a hydrodynamic type. Close to the singular points quasineutrality (3) breaks down and a region is formed filled with oscillations of ion sound type. An analytic solution in this region near the singular points,[10] as well as numerical calculations,[9,11] demonstrates that the oscillations will not change the qualitative behavior of the expanding plasma and the accelerated ions. In Ref. 8, with use of conservation laws and associated jump conditions, monotonic rarefaction shock structures are obtained in the singular domain. However, this approach neglects the dynamic features and therefore gives only the gross characteristics of the potential variation.

When different ion components are present in the expanding plasma the acceleration depends essentially on the ratio $Z/M$. For ions with the same ratio $Z_k/M_k$, Eqs. (1) are identical. This means that the relative densities $n_k/n_{k0}$ and velocities $v_k$ depend on $\tau$ in the same way and therefore that the velocity distributions $n_k(v_k)/n_{k0}$ are the same for these ions. Using energy as the variable, it is seen that the ratio $n_k/n_{k0}$ is a unique function of the variable $E/Z_k$ (since $E/Z_k = \frac{1}{2}M_k v_k^2/Z_k$).

If the plasma contains a main ion component $(Z, M)$ and ion impurities $(Z_k, M_k)$ of low concentration ($nZ \gg \sum n_k Z_k$), the potential $\varphi$ is determined by the main component. The energy spectrum of the impurities, expressed in the variable $E/Z_k$, will then depend only on one parameter $P_k = MZ_k/M_k Z$ according to Eq. (1). A particular situation occurs for a Maxwellian electron distribution. In this case $d\varphi/d\tau = \text{const}$ and Eq. (1) for the different ion impurities will reduce to a single equation after a renormalization. The energy spectra for different ions should then be identical (or similar—shifted by a constant) in the variables $E/Z_k P_k$ (cf. Ref. 5).

We now analyze the results of the experiments performed by DeCoste and Ripin,[2] which gives very detailed measurements of the energy spectrum of ions with different $Z$ and $M$. A neodymium laser pulse (75 ps, $10^{20}$ W/m$^2$) irradiated $CD_2$ and $CH_2$ targets, the ionization was practically complete, and the ions $D^+$, $H^+$, and $C^{6+}$ were observed. We first consider the $CD_2$ target. The ions $C^{6+}$ and $D^+$ have the same $Z/M$ ratio. Consequently their relative energy spectra should be identical, expressed in the variables $E/Z$. As a matter of fact in these variables the experimental curves for the components $C^{6+}$ and $D^+$ coincide completely. This confirms that in a laser plasma ion acceleration takes place according to the mechanism considered in this paper. The experimental curve is given in Fig. 1(a). It is relatively complicated. The straight line shows the averaged experimental values. In the chosen variables, the straight line corresponds to a Maxwellian electron distribution. The slope, $k$, determined the electron temperature $T_e = 2/k^2$. In our case $T_e = 18$ keV. This is in general agree-

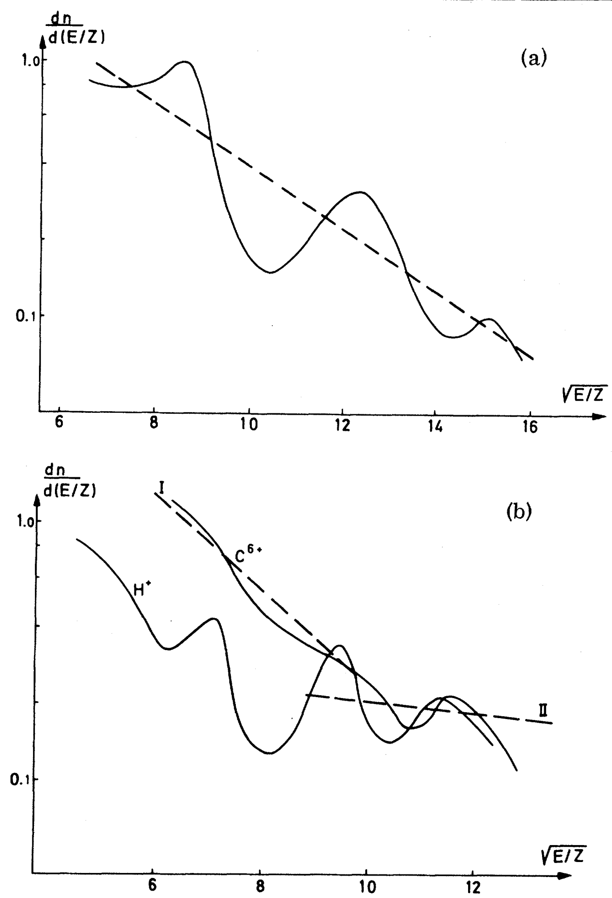


FIG. 1. (a) Ion spectrum ($D^+$) taken from Ref. 2 but reformulated in new variables ($E$ in keV). The straight-line fit indicates an electron temperature of 18 keV. (b) Ion spectra ($H^+$ and $C^{6+}$) from Ref. 2 in the same variables as in (a). The straight-line fit (curve I) for low energies indicates an electron temperature of 6 keV.

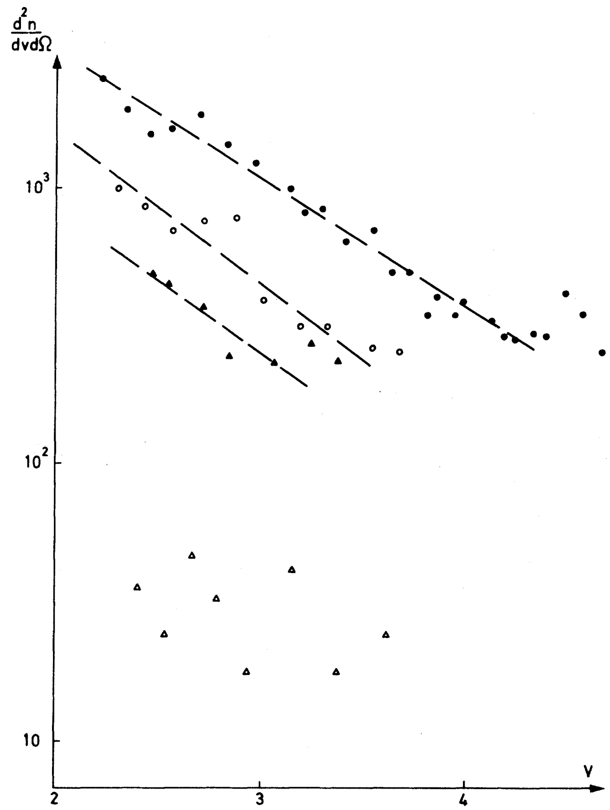


FIG. 2. Ion spectra taken from Ref. 11 (solid circles, $O^{8+}$ and $C^{6+}$; open circles, $C^{5+}$; solid triangles, $O^{7+}$; and open triangles, $Si^{13+}$). The ratio of the slopes of the straight-line fits is in very good agreement with the predicted 1:1.20:1.14. The $Si^{13+}$ data are too dispersed to allow a meaningful straight-line approximation.

ment with the results in Refs. 3 and 7, although the temperature of the hot electrons in our case is 1.5–2 times higher. We notice that the oscillations in the energy spectra [Figs. 2(a) and 2(b)] may be connected with the excitation of a special type of self-similar waves in expanding plasmas. That such waves should be excited during the expansion of a multicomponent plasma was shown theoretically in Ref. 5. In the case of $CH_2$ targets the ratio $Z/M$ is twice as large for $H^+$ as for $C^{6+}$. This means that hydrogen ions are more effectively accelerated and that their concentration consequently is decreasing more slowly with increasing $\tau$. For large $\tau$, i.e., for high energies $E/Z$, the hydrogen component should dominate. The carbon ion may in this region be considered as an impurity ion with the parameter $P_C = M_H Z_C / M_C Z_H = \frac{1}{2}$ (for hydrogen $P_H = 1$). The relation between $\ln[n_0^{-1} dn/d(E/Z)]$ and $(E/ZP)^{1/2}$ according to experiment is shown in Fig. 1(b). It can be seen that for high energies ($E/ZP > 100$ keV) the experimental curves for $C^{6+}$ and $H^+$ are similar (shifted by a constant).

This indicates that the electrons have a Maxwellian distribution function. In the low-energy region ($E/ZP > 40$ keV) the carbon ions dominate, $N_{H^+} \ll 6N_{C^{6+}}$. Here the experimental curves for $C^{6+}$ and $H^+$ are also similar which again confirms that the electron distribution is Maxwellian. The electron temperature as determined from the slope of line I is $T_e = 1/k^2 \simeq 6$ keV. One can see from Fig. 1(b) that the hydrogen ions are more effectively accelerated than the carbon ions (it must be remembered that the curves for $C^{6+}$ and $H^+$ are drawn in different scales). In the region 50 keV $\lesssim E/ZP \lesssim$ 120 keV the hydrogen spectrum changes very slowly with $E/Z$ (line II) which also agrees with the theoretical calculations for this "plateau" region.[5]

More detailed information on impurity ion spectra is provided by Ref. 12 (power 0.5 TW; target diameter 55–80 m). In order to compare with theoretical predictions we note that the velocity of an impurity ion is determined by $(v_k - \tau)dv_k/d\tau = (Z_k/M_k)(M/Z)S \equiv P_k S$ assuming a Boltzmann distribution for the electrons. If $P_k < 1$ we obtain approximately[5,6] $v_k - \tau \simeq P_k$ and from the density equation we then derive the spectrum of the ion impurity as $n_k(v_k)/n_k(0) = \exp[-v_k/(P_k S)]$. Thus the slopes, $\alpha_k$, of the different ion spectra in a logarithmic plot should be related to the slope of the main ion species, $\alpha$, by $\alpha_k/\alpha = 1/P_k$. This yields $\alpha(C^{5+})/\alpha(C^{6+}) = \frac{6}{5} = 1.20$ and $\alpha(O^{7+})/\alpha(C^{6+}) = \frac{8}{7} = 1.14$ in very good agreement with the experimental slopes as indicated in Fig. 2. The original slope of the main ion spectrum $(O^{8+}, C^{6+})$ yields an electron temperature of 18 keV, again a factor 1.5–2 larger than stated. Finally, we point out that, as in the previous experiment, a "plateau" region[5] seems to be present in Fig. 2.

We want to thank Dr. L. Falk for comments and support in preparing the manuscript.

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# Experimental Stabilization of Interchange Mode by Surface Line Tying

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(Received 26 December 1978)

Experiments are performed in an attempt to stabilize the magnetic-curvature–driven interchange instability (mirror flute mode) using a Q-machine plasma. The stabilization method consists of applying a tenuous plasma blanket, which is line tied to the end wall, around a flute-susceptible higher-density core plasma which has no electrical contact to the wall. By controlling the degree of line tying between the blanket and the wall, the stabilizing effect of surface line tying is demonstrated.

It is well known that a simple mirror with circular coils is susceptible to interchange instabilities (flutes) in which axially trapped plasma escapes by moving sideways across magnetic field lines.[1] When it was demonstrated that minimum-$|B|$-field configurations are stable against fluting,[2]