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Velocity Distribution of Ions and Anisotropy of Kinetic Ion-Temperatures in Laser Plasma Experiments

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Abstract

Using a 200 mJ, 5ns Nd: YAG laser the velocity distribution of ions in the plane of incidence, at angles ranging from −17.5° to 60° with reference to the normal to the target plane was investigated at a laser intensity of approximately 7×10^{10}W/cm^2. The time of flight spectra of the ions of each ionization state for the elements carbon, aluminum, nickel and tantalum were obtained. The kinetic temperatures of ions of each ionization state and each element were estimated, on the plane of incidence, and the results are presented. From the experimental results and their analysis it was observed that the velocity distribution function of the ions departed significantly from a Maxwellian one and the ion-temperatures of the expanding plasma were found to be highly anisotropic.

Keywords:

Ion-temperature, distribution function, laser-plasma interaction

1. Introduction

Although, in laser-plasma experiments, a Maxwellian or a near Maxwellian velocity distribution for particles has been assumed, recently, Schnurer *et al.* [1], in their experiments on the energy distribution of hot electrons produced by the interaction of short-pulse (0.7ps–1.05μm) and high intensity (5–10^{17}W/cm^2) laser beams with solid targets reported that the hot-electron distribution deviates "significantly from a Maxwell-Boltzmann shape with a single electron temperature parameter". With recent interest in the deposition of semiconducting and high-Tc superconducting thin films from bulk targets and, on the analysis of the experimental results obtained so far, one is inclined to have a critical insight into the velocity distribution of particles and specially the ions of different ionization states. Singh and Narayan [2], in this context, have reported that the velocity distribution of the plasma is partially "much broader" than an indeal Maxwellian distribution and their observation has also drawn conviction from reported works of the earlier investigators [3-5]. In the present work our motivation is to determine whether the velocity distribution of ions under consideration (carbon, aluminum, nickel and tantalum) is truly Maxwellian or has a departure from it as well as the ion-temperatures are fully thermalized and isotropic. We have determined the time of flight spectra of the ions of each ionization state and their kinetic temperatures for different angles in the plane of incidence. From the experimental results and their analysis it is observed that the particle distribution function departs significantly from a Maxwellian and the ion-temperatures of the expanding plasma were found to be anisotropic leading to a conclusion that the energy equipartition between electrons and ions has not taken place. The other supplementary conclusions are presented and the results are discussed.

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2. Theoretical and Experimental Consideration

Using the criteria for the validity of local thermodynamic equilibrium (L.T.E.) as given by Griem [6] and taking into account the electron temperature of 30eV in the present experiments, with the electron density varying between 10^{18}–10^{20}particles/cm^3 we have checked that the plasma has a complete local thermodynamic equilibrium. The plasma electron temperature was estimated from the works of Sinha et al [7], using the two-foil ratio technique, from soft x-ray emissions, which reasonably agrees with the scaling law reported in the works of Sakabe *et al.* [8]. Using the LTE criterion given by Griem [6] the inequality relation for an aluminum plasma for the validity of LTE, at temperature Te = 30eV, was calculated and was found that the electron density n_e must be greater or equal to 4.3×10^{16}cm^{-3} . Similar figures were obtained for the other three cases. Since the plasma has a density varying from 10^{18}–10^{20} or even 10^{21}cm^{-3} depending upon the time, the criterion is fully satisfied. Following the formulation given by Spitzer [9] the electron-ion-equipartition times for carbon, aluminum, nickel and tantalum, at an ion-density of 10^{18}cm^{-3} and and electron temperature of 30eV, have been estimated to be 11.6, 20.4, 83.4 and 507.2 nanoseconds respectively. That is to say, for a 5 ns pulsewidth laser, the plasma particles do not have sufficient time to equilibrate during the period of heating by laser beam, although, this requirement is very much relaxed at higher densities of 10^{19} and 10^{20}cm^{-3}. As the electron temperatures Te varies as t^{-2} and r^{-2} approximately with respect to time (t) and space (r) as analytically deduced and reported by Rumsby and Paul [10], the conditions for equipartition of energy between electrons and ions are not fully satisfied. In fact, it was noted that the electrons equilibrate with the ions only in a short region of the plasma near the critical density and, more favourably, for low mass number elements like carbon and alumimum. To estimate the ion-temperature Ti from the time of flight spectra of ions we have followed the technique used by Stritzker *et al.* [5] such that $Ti = (1/2k\ln 2).\ m_i\, u_o^2.(\Delta t^-/t_o)^2 = (1/2k\ln 2).\ m_i\, u_o^2.(\Delta t^+/t_o)^2$.

Where m_i k, u_o and t_o are the ion mass (m_i), the Boltzmann constant (k), the ion-velocity (u_o) and time (t_o) corresponding to the peak of the distribution function respectively. The terms Δt^- and Δt^+ represent half temporal width at half maximum of the distribution function towards higher and lower velocity of the particles respectively. If the ion distribution function $f(t)$ is truly Maxwellian, the function $f(t)$ will be symmetrical and $\Delta t^- = \Delta t^+$. The degree of departure of the ratio ($\Delta t^+/\Delta t^-$) from unity will be a measure of departure of the function from a truly Maxwellian one. The plasma was produced by a Nd:YAG Q-switch pulse (τ = 5ns, λ = 1.06μm) incident at a fixed angle of 45° on to flat, rotating targets. The investigated materials were carbon, aluminum, nickel and tantalum. The laser energy varied from about 20 mJ to 180 mJ and had a flux density variation from approximately 10^{10} to 10^{11} W/cm^2. The freely expanding ions of the plasma were investigated in the angular range from $\theta = -17.5°$ to 60° relative to the target normal and at a distance of 37.5 cm from the target. Analysis of the ion velocity distribution and charge was obtained by means of a time of flight-retarding potential detector whose transmission function was controlled carefully. Complete details of the experimental arrangement and the measurement technique have been earlier reported by Mann and Rohr [11].

3. Results and Discussion

In Figs.(1-4) we have displayed the variation of kinetic temperatures of ions of different ionization stages for C, Al, Ni and Ta as a function of the angles of emission. In all the figures we observe that the higher the ionization state, the more is the value of the kinetic temperature. Thus, the ions of the ionization state unity show the lowest values for the temperature at any given angle and those of states four and three show higher values. The variation of ion-temperatures is quite anisotropic and the angles corresponding to the peaks of temperature variation are different for different ionization states and mass numbers. In other words, one can say that the equipartition of energy between electrons and ions has not taken place. Were it so, the temperature variation would have been isotropic.

We have further observed that the velocity distribution of ions is no longer Maxwellian and is not symmetric. Secondly, time of flight spectra of ions from high mass number elements like nickel and tantalum are smoother and show less departure from Maxwellian than those of ions from low mass number like carbon and aluminum. The asymmetry of the distribution was estimated by measuring the departure of the ratio ($\Delta t^+/\Delta t^-$) from unity. From measurements of Δt^+ and Δt^- it was observed that, for higher mass number elements like Ni and Ta, the departure from Maxwellian profile is around or less than 60% but for low mass ions like carbon and aluminum, in some of the cases, the

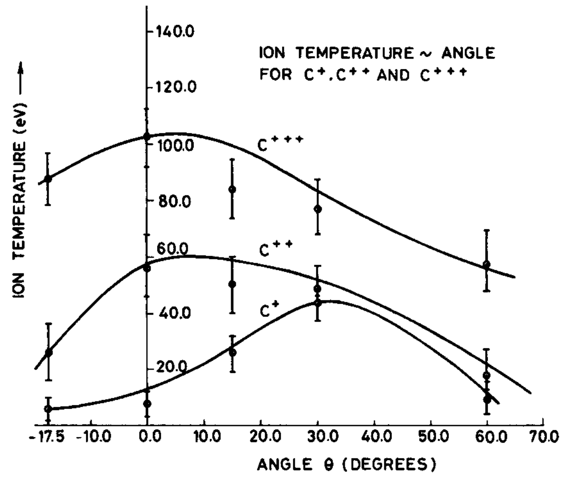

Fig. 1 Angular variation of the temperature C^{+1}, C^{+2} and C^{+3} ions.

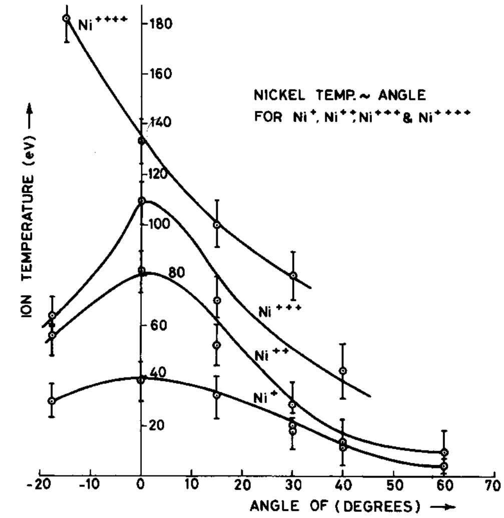

Fig. 3 Angular variation of the temperature N^{+1}, N^{+2} and N^{+3} ions.

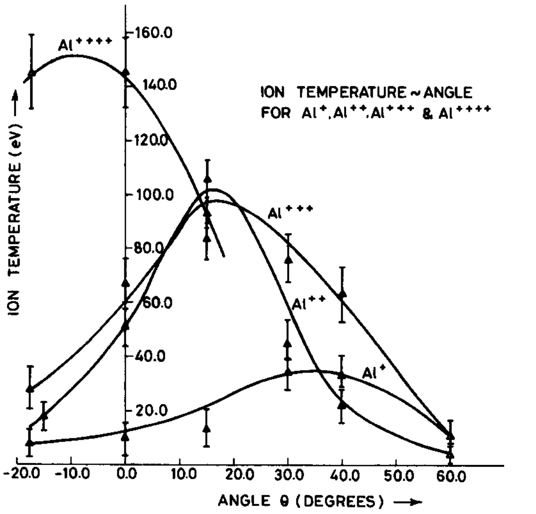

Fig. 2 Angular variation of the temperature Al^{+1}, Al^{+2} and Al^{+3} ions.

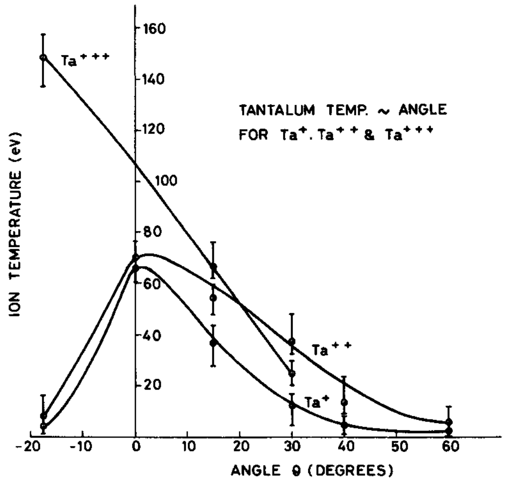

Fig. 4 Angular variation of the temperature Ta^{+1}, Ta^{+2} and Ta^{+3} ions.

variation may be even of the order of 200% or more.

At this stage it is necessary to dwell upon the estimates of the plasma electron temperature and the ion-temperatures as estimated from the time of flight spectra of the ions of each ionization state. An electron temperature of 30eV represents the average temperature of the plasma which, at best, can be estimated within an accuracy of ±25% for laser-produced plasmas. This further depends on the techniques of measurement and, usually, there is a wide scatter in the estimates of this temperature as reported by Sakabe et al [8] as well as Kieffer *et al.* [12]. In our estimates of the ion-temperature, the ions with higher charge number show higher temperatures and preferentially in a narrow cone around $\theta = 0°$. If we consider all the ions at all the angles and consider the inaccuracy of ±25% in measurement, the average ion temperature may be reasonably taken in the vicinity of 50 eV. Comparatively higher ion-temperatures for higher *Z*-elements are because of higher absorption due to inverse bremsstrahlung and generally higher temperatures in a narrow cone around $\theta = 0°$ come because of preferential conversion of plasma energy into hydrodynamic energy along this narrow cone. The experimental results clearly establish the anisotropic nature of the ion-temperatures.

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