Fast-Ion Emission from CO2 Laser-Produced Microballoon Plasmas

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Abstract—Quantitative measurements of fast ions from CO_2 laser-produced microballoon plasmas using a Thomson parabola ion spectrometer in conjunction with cellulose nitrate film are reported. The implications of fast-ion fluxes observed at a very large angle with respect to the laser beam axis are discussed.

ONE-SIDED irradiation studies of empty glass microballoons with intense ($I \sim 10^{14}$ W $\cdot$ cm^{-2}) CO_2 laser radiation can give valuable insight into the important processes of absorption and energy transport in spherical geometry. At these high intensities a steep density gradient is produced at the critical density [1]-[3] and the absorption of radiation occurs mainly by collective processes giving rise to a nonthermal electron distribution [4]. The properties of the distribution function of these stochastically heated electrons can be investigated by studying the hard X-ray spectra [5], energy spectra of the fast ions [6], or directly by interferometry as has been suggested by Bezzerides *et al.* [7]. It has recently been shown that the application of a two-temperature isothermal rarefaction wave model to the velocity spectrum of the ions can give information on T_H and T_C, the hot- and cold-electron temperatures, respectively, and n_H/n_C, the hot-to-cold electron density ratio [8]. Significant energy loss to fast-ion expansion may be indicative of inhibited thermal transport although considerable controversy remains regarding the fraction of energy carried off by the fast ions as observed both in experiments [9] and in numerical simulations employing flux-limited multigroup diffusion treatment of electron transport [10]. In this letter we present for the first time quantitative data on the fast-ion energy distributions from a microshell target irradiated on one side only using intense CO_2 laser radiation. In addition, the implications of significant fast-ion fluxes observed at a very large angle with respect to the laser beam axis are discussed. Similar experiments with 1.06-μm laser radiation using a Thomson parabola have been reported by Berger *et al.* [11].

Empty glass microballoons approximately 150 μm in diameter and 1-μm nominal wall thickness were irradiated by focusing the output of the COCO-II laser system (30-J 1.5-ns full width at half maximum (FWHM)) to a half energy diameter of 110 μm by using a $f/2.5$ off-axis parabolic mirror. The beam was focused at the center of the microballoon, the depth of focus being ±150 μm. A Thomson parabola mass spectrometer in conjunction with cellulose nitrate film (Kodak LR115 type II) [12] was used to record the energy distributions of fast ions at 22° and 112° with respect to the laser axis. Both the target chamber and the spectrometer were evacuated to a vacuum of 10^{-5} torr to minimize the charge exchange effects. In addition a flat PET ($2d = 8.73$ Å) crystal spectrograph with a 40-μm space resolving slit was used to record spatially resolved line and free-free and free-bound continuum emission from the laser irradiated microballoon.

The X-ray spectrum recorded with a PET crystal with 30 J on target showed no line emission from He-like Si XIII and H-like Si XIV ions. Only *F-B* and *F-F* continuum and the Si K_α line could be recorded. A thermal temperature of 330 ± 70 eV was deduced from the slope of the continuum emission between 1.6–2.5 keV after taking into account crystal and film sensitivities [13].

The asymptotic velocity distributions of the predominant fast-ion species from the microballoon plasma are shown in Fig. 1. A significant fraction of the fast ions were in fact found to be contaminant proton and carbon ions. In plane geometry a Maxwellian hot-electron distribution leads to an exponentially decaying ion velocity spectrum in the isothermal approximation, with the fast-ion acoustic speed C_s as the characteristic velocity. For long pulses such as those used here, isothermal fast expansion from even a planar target may not be purely one-dimensional since the scale length of the fast rarefaction $C_s\tau$ (τ is the FWHM laser pulse duration) is much greater than the focal spot size. The Si XI velocity spectrum, shown in Fig. 1, indicates that the velocity distribution may be characterized by $dN/dV = A \exp^{-V/V_a}$. Thus although the asymptotic velocity spectra are exponential even in spherical geometry, V_a cannot be directly related to C_s.

The slope of the high energy part of the X-ray continuum under similar irradiance conditions using 10-μm radiation has given "hot-electron temperatures" between 10–15 keV [14]. Thus a two-temperature electron distribution with the hot-to-cold electron temperature ratio $T_H/T_C \sim 30$ typically exists in these plasmas for $I\lambda^2 \sim 10^{16}$ W $\cdot \mu$m$^2 \cdot$ cm^{-2}. The formation of rarefaction shocks is predicted in an expanding two-temperature plasma for $T_H/T_C > 5 + \sqrt{24}$ giving rise to a density discontinuity where the hot-electron density becomes comparable to the cold-electron density, thus clearly separating the fast and the slow rarefactions [7]. However, considering the

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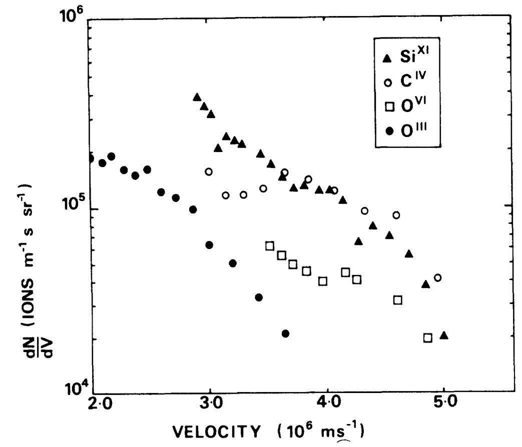

Fig. 1. Velocity distributions of the predominant fast-ion species. Si XI, C IV, and O VI distributions were obtained at 22° with respect to the laser beam axis, whereas O III distribution was obtained at 112°. The C IV ions are thought to originate from the target contamination.

number density of hot electrons generated during resonance absorption [4] in a density profile steepened initially by radiation pressure in the vicinity of n_C, and the hot-to-cold temperature ratios, typical of 10-μm experiments, one expects the hot-electron induced jump (or the rarefaction shock) to occur at this steepened surface thereby contributing to the total step height through n_C. The fast rarefaction thus extends from the lower shelf density to where the quasi-neutrality breaks down as the hot-electron Debye length exceeds the density scale length. Such a viewpoint is supported by recent interferometric measurements [1] under similar conditions, which have revealed step heights that imply a temperature as well as density step at n_C, separating the cold high density plasma from the hot low density blowoff.

Significant fast-ion flux was observed when the spectrometer was placed at 112° with respect to the laser axis. For example the O III distribution recorded at 112° is only about a factor 4 less intense than the Si XI distribution recorded at 22° from the laser beam. There are several possible mechanisms which can give rise to a broad angular distribution of fast ions in spherical geometry. Such mechanisms include: i) the lateral spreading of the quasi-neutral plasma sheath comprising the fast rarefaction; ii) acceleration of a thin surface layer by the electrostatic field surrounding the target [15]; iii) acceleration of ions by electrons that penetrate the shell and are isotropized by electron-ion scattering; and iv) large angle deflection of fast ions by self-generated magnetic fields [16]. Any of these processes can result in broadening of the angular distribution of the fast-ion component. A broad fast-ion angular distribution has been inferred from 1.06-μm laser-produced microballoon plasmas by using the pinhole imaging technique [17]. However, this apparent broadening of the emitting region has been explained in terms of plasma generated space-charge effects around the imaging pinhole by Gitomer and Brysk [18]. In the present study this complication does not arise since two identical Thomson parabolas were used to observe the ion emission simultaneously at 22° and 112° with respect to the laser axis.

Experiments on microdisk targets with thicknesses much greater than the mean free path of the hot electrons have shown that a three-dimensional electrostatic field, resulting from electrons making large amplitude orbits from the target but confined by the target potential [19], and electrons escaping completely from the target field, causes fast-ion emission from the rear side of such targets [15]. In spherical geometry the tendency of long mean free path electrons to orbit the target between reflections by the sheath potential has been investigated by Albritton *et al.* [20]. A significant fraction of these long mean free path electrons with large angular momentum may remain in the low density region and not couple to the high density region until a significant radial velocity component is acquired due to multiple scattering. Thus a larger fraction of their energy may be extended accelerating the ions than that if the electrons simply moved radially inwards at the end of their orbit as is assumed to be the case in the flux-limited multigroup diffusion treatment of electron transport [10].

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