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Energy Partition in CO_2-Laser-Irradiated Microballoons

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A self-consistent study of the partition of energy absorbed in nanosecond single-CO_2-laser-beam irradiation of glass microballoons is reported. Through interferometric inference of shell heating, and quantitative fast-ion spectrometry, it is shown that a major fraction of the absorbed energy is converted to fast-ion expansion and only 25% contributes to thermal heating of the target.

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Studies of nanosecond CO_2-laser irradiation of plasmas at intensities of $>10^{13}$ W cm^{-2} have shown that absorption primarily occurs through collisionless processes, particularly resonance absorption,[1] which generate superthermal electrons[2] that are confined by the ambipolar field they establish with the ions to form a hot low-density corona. These collisionless electrons will in general follow nonradial paths[3] in this coronal plasma and drive its expansion. On each encounter with the plasma sheath, an electron loses a small fraction $\sim(Zm_e/m_i)^{1/2}$ of its energy to fast-ion expansion[4] and thus many reflections are required to convert a sizable fraction of the absorbed energy to fast-ion expansion.

In nanosecond irradiation of spherical targets, the sheath will expand with a characteristic speed $c_h \sim (ZkT_h/m_i)^{1/2}$, where T_h is the hot-electron temperature. Consequently, for long laser pulses, it can expand to dimensions such that the geometric cross section of the target is small.[5] Only those electrons whose orbits do intersect the dense cool plasma may contribute to heating of the target. Thus, the fraction of energy converted to fast-ion expansion depends upon a number of factors including the value of T_h, the laser pulse duration, and target geometry. Various estimates of this loss ranging from 9% to 90% have been inferred through indirect means.[6]

The experiments reported here are the first self-consistent measurements of the energy partition in a CO_2-laser-produced plasma. Independent estimates were obtained for the total energy absorbed, the energy lost to fast ions, and the energy deposited into the dense target. The targets used were of three types: empty glass microballoons of 150 and 220 μm diameter with a wall thickness 1.5 μm; empty glass microballoons of 200 μm diameter, coated with 20-μm-thick $(CH_2)_n$; and solid glass spheres of 220 μm diameter. These targets were irradiated by single 20-J, 1.4-ns [full width at half maximum (FWHM)] pulses from the COCO-II laser system. The $f/2.5$ center-focused beam had a half-energy diameter of 110 μm.

An estimate of the total thermal energy deposited in the target was inferred from interferograms taken at various times during and following irradiation of the target with the aid of a synchronized 0.53-μm, 70-ps probe pulse and a folded wave front interferometer. The plasma in the focal region shows strong density-profile steepening, indicative of ponderomotive and superthermal pressure effects at the critical density.[7] However, away from the focal region the electron density resembles that expected for a simple isothermal expansion, Fig. 1(a), from which a characteristic scale length, L, may be obtained.

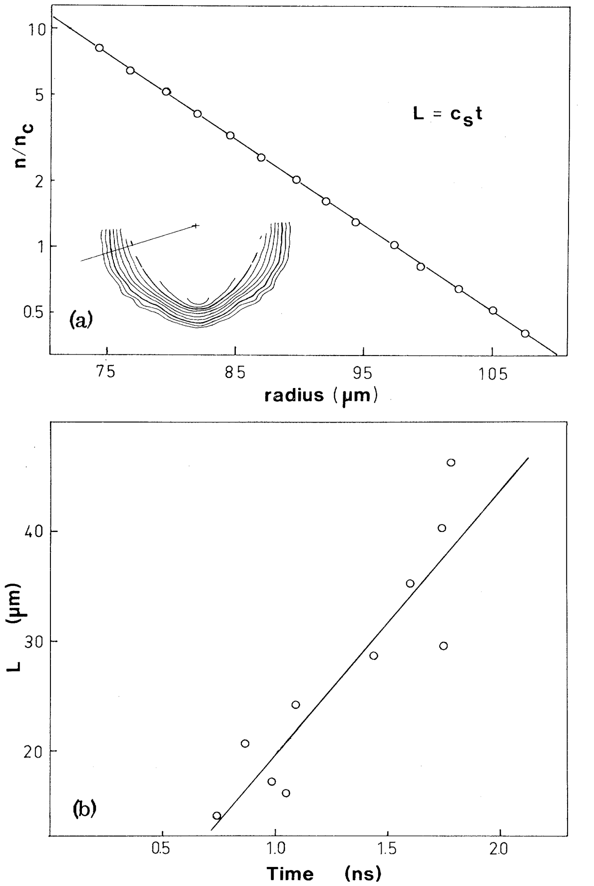

FIG. 1. Deduction of the electron temperature from the density profile in regions remote from the interaction zone. (a) The deduced scale length of the plasma along the radial line identified in the inset at a time $t = 0.87$ ns. (b) The variation of this scale length with time provides an estimate of the thermal plasma velocity, c_s.

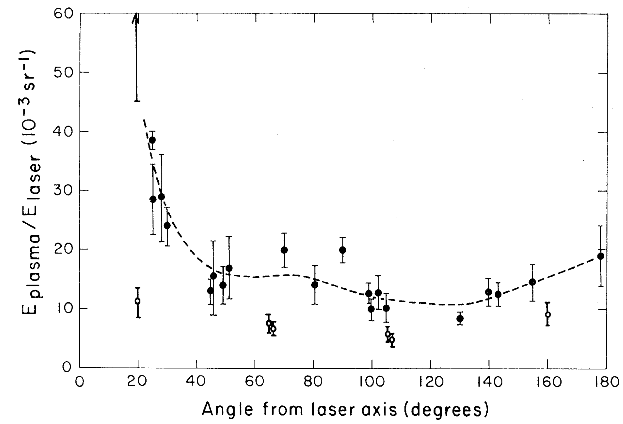

FIG. 2. Normalized total absorbed energy distribution as measured by plasma calorimeters (solid circles). The open circles represent the measured fast-ion energy fluxes, deduced from ion spectrometry. The error bars shown are due only to the extrapolation process. The lower bar represents the energy directly measured, while the upper bar includes the full extrapolation.

Figure 1(b) shows the variation of L with time, from which, by equating $c_s = dL/dt = (ZkT_e/m_i)^{1/2}$, a characteristic temperature of the rarefaction may be deduced. A temperature of 30 ± 10 eV was inferred in all regions except the focal zone. X-ray pinhole photographs[8] of the target showed a bright emitting region confined to the focal cone, consistent with a thermal electron temperature of ~300 eV inferred from the x-ray continuum emission spectrum,[8] and a weaker emitting region on the opposite side of the balloon. Very weak emission originated from the rest of the shell, most probably due to hot-electron–induced fluorescence. The absence of any emission from the expanding plasma in this region is consistent with $T_e < 100$ eV.

If the entire 150-μm-diam shell were heated to the maximum inferred temperature $T_e \sim 30$ eV, only 0.2 J of electron thermal energy would be required. Due to the small depth of the heated layer[9] little energy is contained in the focal zone. Ionization energy would account for another 0.2 J, and kinetic energy of ion expansion at the end of the laser pulse, a further 0.6 J.[10] The total energy emitted through bremsstrahlung and blackbody radiation is less than 0.1 J. Thus at most ~1.1 J of the absorbed laser energy is deposited into the microballoon shell. Additional thermal energy must have been expended in heating that part of the supporting glass stalk enveloped by the expanding corona. This surface area exceeds that of the target itself.

Measurements of the total plasma blowoff energy from 150-μm-diam microballoons were made by means of an array of twenty plasma calorimeters.[11] Figure 2 shows the resultant distribution, averaged over five shots and normalized to the incident laser energy, plotted against the angle from the incident laser axis. No asymmetries related to the beam polarization were apparent. Spherical integration of the plasma blowoff energy yields a total absorption of 0.21 ± 0.02. This integration was performed on the individual calorimeter signals for each of six shots, with use of the method of representative areas.[11] The estimate of uncertainty of the absorption was derived from a detailed error analysis of the expression used in this method, but the uncertainty quoted also corresponds closely to the actual shot-to-shot variation in the total absorption.

The quantitative measurement of the partition of absorbed energy to fast-ion acceleration was made with the aid of three Thomson parabola ion spectrographs, utilizing CR-39 nuclear-track detector material, deployed at 65° and 160° from the laser axis in the plane of polarization, and at 106°, up 45° from the plane of polarization. We analyzed 107 spectra via direct particle-track counting, and typical spectra are shown in Fig. 3. The presence of Si^{+4} to Si^{+12} on some shots, and the predominance of O^{+6} and C^{+5} on most, are consistent with the interferometrically inferred temperature T_e.

Integration of the individual ion spectra permits the total energy deposited in each species to be determined. The sum of these integrations normalized to the incident laser energy are represented by the open circles in Fig. 2, which shows data from the three ion spectrographs for two shots. Two additional shots yielded data at 20°, which exhibited considerable shot-to-shot variation; however, the total contribution of the forward-ion blowoff to the integrated fast-ion energy is relatively small. The spectrum below 200 keV was not recorded due to the fall-off in the instrument and detector sensitivity. An estimate for the energy in the spectrum below this limit was made by extrapolating the individual ion spectra to lower energy.

Clearly the fast-ion data can account for ~50% of the plasma blowoff energy. Recombination, particularly of the protons, may reduce the measured flux, although at a chamber pressure of 4 $\times 10^{-6}$ Torr this should be negligible, as should the energy remaining in the electric field after 1 μs.[12]

Figure 3 clearly shows that the fast-ion spectrum is a strong function of angle of observation, implying that for nonsymmetric irradiation the total fast-ion contribution can only be deduced from a knowledge of the full angular distribution. Moreover, the fast-ion spatial distribution was not distinctly dependent on target wall thickness, with one exception. Whereas the total plasma distribution increased at $\theta = 180°$ for thin-walled and $(CH_2)_n$-coated microballoons, no such increase was observed for solid targets. This is suggestive of heating by superthermal electrons which have penetrated the target from the irradiation region, and is consistent with x-ray pinhole photographs of microballoons[8] and recent interferometric observations on thin-walled cylinders showing regions of enhanced heating on the wall opposite the irradiation zone.[13] Although this energy represents only a small fraction of the absorbed energy, it would be a serious source of preheat to a DT-filled target. It should also be recognized that during the irradiation of the target, the plasma sheath expands with a speed c_h $\sim 10^8$ cm s^{-1} to a radius ~1 mm.[5] Thus most of the thermal heating of the shell occurs early in the laser pulse and therefore would be sensitive to pulse rise time.

Thus in these experiments, at least 50% of the

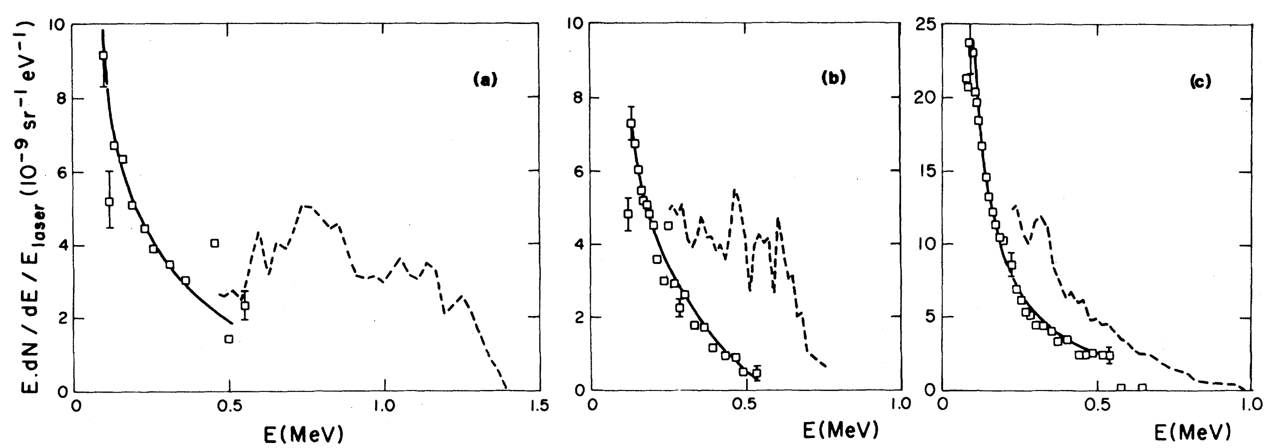

FIG. 3. Normalized energy spectra obtained from irradiation of a 220-μm-diam microballoon of wall thickness 1.5 μm. The continuous line represents the proton spectrum whereas the dotted line represents the sum of all other species. The data at (a) 65°, (b) 106°, and (c) 160° to the laser axis were all obtained on the same shot.

absorbed energy was removed from the target in the form of fast-ion kinetic expansion. At most, ~25% of the absorbed energy could be accounted for in direct thermal heating of the microballoon shell, thus implying that no more than 6% of the laser energy would have contributed to compression of the target. Hydrodynamic energy efficiencies of ~0.5% have recently been estimated for similar targets, which is less than one-tenth of the usefully absorbed energy. This hydrodynamic efficiency is therefore not inconsistent with the results quoted here.[14]

Hence, improving the efficiency of the direct-drive approach for CO_2 laser implies the use of shorter pulses, higher intensities, and the consequential generation of higher values of T_h, or the utilization of larger targets with higher aspect ratio which are consequently more sensitive to hydrodynamic instabilities. Fast-electron preheat is not constrained by either approach, and presents a serious limitation to CO_2-laser fusion.

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