Energy Transport through High-Z Metal Foil in a Laser-Produced Plasma

J. Mizui and N. Yamaguchi
Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan

and

T. Yamanaka and C. Yamanaka
Institute of Laser Engineering, Osaka University, Suita, Osaka 565, Japan

(Received 18 March 1977)

Double-layer thin films of high-Z metal and low-Z polyethylene and each single-layer film were irradiated with a 1.06-μm, 200-psec laser pulse at intensities from 10^{14} to 7×10^{14} W/cm^2. From the measurements of the transmittance of the laser through these films, the spatial distributions of the transmitted light, expanding ion currents, and x rays, the energy transport is found to be due not only to superthermal electrons but also to x-ray radiation in a high-Z material.

In order to find the optimum condition of laser-driven implosion, it is of prime importance to clarify the mechanism of the energy transport through the plasmas of pellet materials: low-Z ablator, high-Z tampers, and D-T fuel.[1] In low-Z material the flux limitations of electron thermal conduction have been determined by measuring the transmittance of laser light through thin plastic foils.[2,3] Preheat effects in the interior of targets by fast electrons have been reported through the measurement of $K\alpha$ radiation[4] from neon-filled glass balloons. This Letter reports on the energy transport in a laser-produced high-Z plasma as compared with that in a low-Z plasma.

The double-layer target used in this experiment consists of a 4-μm-thick film of polyethylene chemically coated with a thin layer of nickel. The maximum energy of the mode-locked laser was 10 J in 0.2 nsec. The pulse had a full width at half-maximum of 160 ± 10 psec, but it had a long prepulse region and tail (70 ± 10 and 100 ± 20 psec at a quarter of the maximum intensity, respectively). The effective pulse duration was estimated to be about 0.2 nsec. The laser beam was focused on the target at an angle of 45° to the normal by an $f/1.33$ aspheric lens. The focal-spot diameter was about 80 μm [as shown in Fig. 3(b)]. The experimental setup is indicated in Fig. 1. The energies of the incident, transmitted, specularly reflected, and backscattered light are measured all together by the use of a single biplanar phototube with a filter, IR-80, which is calibrated with a power meter. The time resolution of the tube is less than 1 nsec and is enough to separate these lights.

The transmittance through five kinds of targets are shown in Fig. 2 as a function of incident laser intensity. When the laser beam irradiates the polyethylene layer of the double-layer film, the transmittance is almost constant and less than 2%. But when the beam irradiates the nickel layer of the double-layer film, the transmittance reaches a maximum value of 50% in the 2.3-μm-thick nickel case, and of 15% in the 1.0-μm-thick nickel case. The enhanced transmittance is also seen in single high-Z metal foils of a few microns in thickness, such as Al, Ni, and Au, as compared with that in a low-Z polyethylene film. In the case of a 4-μm-thick polyethlene film, the transmittance is the same as that in the polyethylene layer of the double-layer film. But in the case of Ni foils of 2.5 and 1.25 μm thickness, the transmittance increases to 50% and 20%, respectively, and then maintains this level at the higher intensities without decreasing to a lower level as for the Ni-polyethylene target. With the use of a 6-μm-thick Al foil, the transmittance is about 5% at a laser intensity of

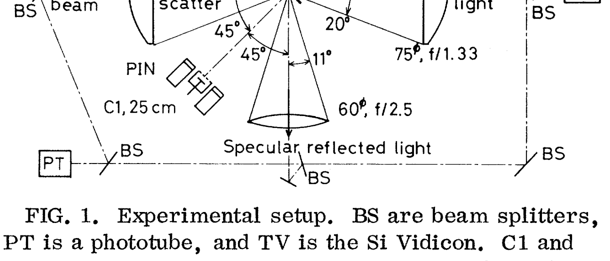

FIG. 1. Experimental setup. BS are beam splitters, PT is a phototube, and TV is the Si Vidicon. C1 and C2 are Faraday cups. PIN is p-i-n diodes for soft-x-ray measurements.

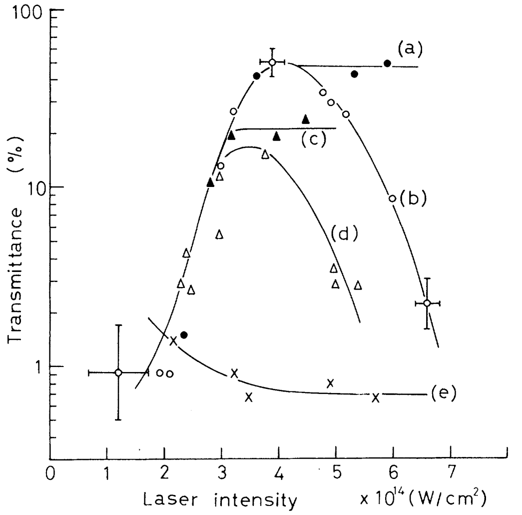

FIG. 2. Transmittances of laser light as a function of the incident intensity. Laser beam is focused on, curve *a*, 2.5-μm Ni foil; curve *b*, 2.3-μm Ni foil plated on 4.0-μm polyethylene film; curve *c*, 1.25-μm Ni foil; curve *d*, 1.0-μm Ni foil plated on 4.0-μm polyethylene film; and curve *e*, 4.0-μm polyethylene film.

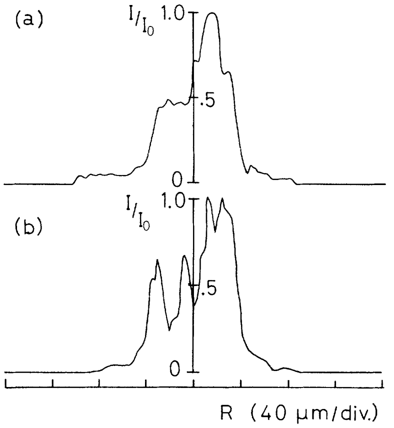

FIG. 3. Spatial profiles of beam intensity at the focused surface: (a) transmitted laser light; (b) incident laser light.

4.8×10^{14} W/cm^2. A 3-μm-thick Au foil shows a transmittance of 30% at 5.5×10^{14} W/cm^2. The possibility of a parasitic laser oscillation that develops between the mirrorlike metal target and some component in the laser system is eliminated from our measurement because the laser beam has been focused on the target with a 45° incident angle and the transmittances are determined by the time-resolved measurement. This is also confirmed by the experimental results as follows. The backscattered light for a metal target had a smaller intensity than that for polyethylene. In the x-ray signal of the *p-i-n* diode, no second pulse was observed at least during about 400 nsec from the first pulse.

For the enhanced transmission of laser light through a high-*Z* foil, four models can be considered: (1) Filamentation of laser light makes underdense tunnels through the thin plasma by a ponderomotive force, or the plasma thermally expands to be transparent as the interior of the foil is heated by (2) electron thermal conduction, by (3) superthermal electrons or by (4) x-ray radiations, emitted from the laser-irradiated region. The spatial distribution of the time-integrated laser intensity was measured as shown in Fig. 3 using an infrared Si Vidicon with a filter, IR-80, and video recorder. As shown in Fig. 3, the incident laser light has many local peaks (b), but the distribution of the transmitted light is converted into a smooth profile (a). This result indicates that no filamentation takes place. The transmittance through a high-*Z* nickel foil becomes large as the thickness of the foil doubles. This result cannot be explained by electron thermal conduction, contrary to the results obtained elsewhere.[2,3] The ion current of an expanding plasma was observed with a Faraday cup located at the rear side of the target [*C*2 in Fig. 1] when the laser irradiated the metal surface of double- and single-layer films. As shown in Fig. 4, the ion current has generally two components[5]: The first component is the spike due to the fast ions and the second hump is due to a thermally expanding plasma. These two components overlap at a laser intensity of about 4 $\times10^{14}$ W/cm^2, where the light transmission has its maximum value. The arrival time of the second hump is delayed in the double-layer case at higher intensities of the laser, where the transmittance decreases. On the other hand, the ar-

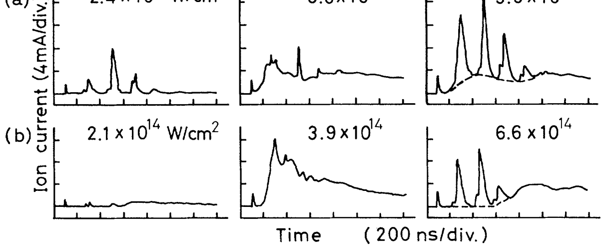

FIG. 4. Faraday-cup traces measured at the rear side of targets at each intensity of the incident laser. Laser beam is focused on (a) 2.5-μm Ni foil and (b) 2.3-μm Ni foil plated on 4.0-μm polyethylene film. The dashed lines show the signal of an expanding plasma.

rival time is not delayed in the single-layer case at the higher intensities, where the transmittance maintains the level. At lower intensities, the arrival time of the second hump is delayed and current of the hump becomes very small, where the transmittance decreases very much. To explain these experimental results, we consider that a laser-irradiated high-Z plasma is the source of fast electrons or x-ray radiation for heating the interior of the target. The intensity of the source changes when the laser-irradiated plasma expands. The heating of the interior depends on the thickness of the target, and on the intensity of the source. As the temperature of the interior is raised, the foil target expands rapidly to both sides enough to become transparent during the laser irradiation. This model explains that the earlier arrival of the thermally expanding plasma is related to the large transmittance. X-ray emission in the energy range from 2 to 20 keV was measured by p-i-n diodes. The ratio of the p-i-n diode current in the Ni case to that in the polyethylene case increased with the incident laser intensity from 1 ± 0.3 at 10^{14} W/cm^2, to 2.4 ± 0.2 at 5×10^{14} W/cm^2. These results indicate that the laser-produced high-Z plasma is a strong x-ray source at least in this energy range and the heating effect by the absorption of x rays should be taken into account.

Using the experimental results on the electron temperature of a laser-heated plasma and the reflectivity of an incident laser light, we can theoretically estimate the heating effect by the fast electrons and x-ray radiations. The electron temperature was derived from the filter-absorber technique using p-i-n diodes. At an incident laser intensity of 5×10^{14} W/cm^2, the electron temperature was about 500 eV in the polyethylene case and 200 eV in the Ni case. In the Ni case the effect of line radiation was included. These temperatures may be used for a qualitative discussion of the heating effect, because the temperature in the Ni case does not rise more than in the polyethylene case. The backscattered reflectivity through an $f/1.33$ lens was about 6% in the polyethylene case and 2% in the Ni case at an incident laser intensity, Φ_L, of 5×10^{14} W/cm^2. The specular reflectivities through an $f/2.5$ lens were 4% and 2%, respectively, at the same incident laser. If the sum of these two reflectivities is assumed to be the total reflectivity, Φ_S,[6] the absorbed laser intensity is equal to $\Phi_L - \Phi_S$. The reabsorption of fast electrons is calculated as follows. The average ion charges, $\bar{Z}$, are 2.5 (CH$_2$) and 13 (Ni), respectively, assuming a simple coronal model. From these values and the scale length of density gradient, $L = C_T \Delta t$, where C_T is an isothermal sound velocity and Δt is a half-duration of the incident laser pulse, the ratios of the intensity absorbed through inverse bremsstrahlung to the incident laser intensity, $\Phi_{\mathrm{CA}}/\Phi_L$,[7,8] are calculated to be 50% (CH$_2$) and 86% (Ni). If the residue of incident laser intensity ($\Phi_L - \Phi_S - \Phi_{\mathrm{CA}}$) is assumed to be taken up as resonance absorption Φ_{RA}, then the average energies of the fast electrons[9] are 45 keV (CH$_2$) and 15 keV (Ni). By the use of the mean free path of fast electrons, λ_e,[10] and the thickness of the foil, l, the ratio of the reabsorbed energy flux of the fast electrons to the incident laser intensity, $A_e = \frac{1}{2}[1 - \exp(-l/\lambda_e)]\Phi_{\mathrm{RA}}/\Phi_L$, is 0.5% for the 4-$\mu$m-thick polyethylene, 2% for the 1.25-μm-thick nickel, and 4% for the 2.5-μm-thick nickel. X radiation can be simply estimated by use of a theory of blackbody radiation.[11] If the laser-irradiated region is assumed to be an isothermally expanding plasma[7] and the source of x-ray radiation is in the region from the cutoff density, n_c, to solid density, n_s, then the size of the source, x_p, is equal to $L \ln(\bar{z} n_s/n_c)$ and the average square density, $\langle n^2 \rangle$, is equal to $n_s^2 L/2x_p$. From these assumption, we find $x_p \ll l_{lx} < l_x$ for polyethylene and $l_{lx} < x_p < l_x$ for nickel, where l_{lx} is the mean free path in an optically thin medium and l_x is the Rosseland mean free path for bremsstrahlung. The nickel case satisfies the blackbody condition[12] and the ratio of the x-ray intensity to the incident laser intensity, Φ_X/Φ_L, is calculated to be 35%. If the mean free path for the absorption of x rays in the interior of a target, l_{ls}, is calculated from the solid density and the temperature of laser-irradiated region, then the ratio of the absorbed x-ray intensity to the laser intensity, $A_x = \frac{1}{2}[1 - \exp(-l/l_{ls})]\Phi_X/\Phi_L$, is 9% for 1.25-$\mu$m-thick nickel and 13% for 2.5-μm nickel, which are underestimations because the higher temperature is assumed. In the case of polyethylene, the medium is optically thinner for the radiation of free-free transitions than for that of bound-free transitions. The ratio Φ_X/Φ_L is calculated to be several percent, using the mean free path for the radiation of bound-free transitions, and the value of reabsorption is found to be negligibly small. These calculations qualitatively agree with the experimental results. The absorbed energy flux through a high-Z plasma is larger than that through a low-Z plasma and the flux is proportional to the thickness of the target.

In summary, the transmittance of the laser through a laser-produced high-Z thin plasma is larger than that through a low-Z plasma, and the maximum transmittance through the Ni foil of 2.5 μm thickness is larger than that through the 1.25-μm foil. The transmittance is related to energy transport through the rate of a plasma expansion. These experimental results indicate that the energy transport is due not only to superthermal electrons but also to x-ray radiation in a high-Z material. The simple theoretical calculations, based on the measurements of the electron temperature and reflectivity, qualitatively agree with the experimental conclusion.

---

[1] G. S. Fraley, W. P. Gula, D. B. Henderson, R. L. McCrory, R. C. Malone, R. J. Mason, and R. L. Morse, in *Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, 1974* (International Atomic Energy Agency, Vienna, 1975), Vol. 2, p. 543.

[2] R. C. Malone, R. L. McCrory, and R. L. Morse, Phys. Rev. Lett. 34, 721 (1975).

[3] J. S. Pearlman and J. P. Anthes, Appl. Phys. Lett. 27, 581 (1975).

[4] B. Yaakobi, I. Pelah, and J. Hoose, Phys. Rev. Lett. 37, 836 (1976).

[5] A. W. Ehler, J. Appl. Phys. 46, 2464 (1975).

[6] The measurement of the angular distribution of scattered light has been reported by R. Sigel, K. Eidmann, H. C. Pant, and P. Sachsenmaier, Phys. Rev. Lett. 36, 1369 (1976); B. H. Ripin, Appl. Phys. Lett. 30, 134 (1977); R. A. Hass, W. C. Mead, W. L. Kruer, D. W. Phillion, H. N. Kornblum, J. D. Lindl, K. MacQuigg, V. C. Rupert, and K. G. Trisell, Phys. Fluids 20, 322 (1977). Because $l < \lambda_e$ and $\lambda_e \propto \Phi_{RA}$, the heating ratio, A_e, has no strong dependence on Φ_{RA}. Then the estimate of Φ_S does not affect the qualitative features. Assuming the total reflectivity, Φ_S is twice as much as the value of our experiment, the ratio A_e becomes 0.5% (4-μm CH_2), 2% (1.25-μm Ni), and 3% (2.5-μm Ni), and is close to the value in the text.

[7] See Haas, Ref. 6.

[8] K. A. Brueckner, Nucl. Fusion 16, 387 (1976).

[9] J. P. Freidberg, R. W. Mitchell, R. L. Morse, and L. I. Rudsinski, Phys. Rev. Lett. 28, 795 (1972).

[10] K. A. Brueckner and S. Jorna, Rev. Mod. Phys. 46, 325 (1974).

[11] Y. B. Zel'dovich and Y. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Academic, New York, 1966), pp. 167, 260, and 279.

[12] M. C. Marsh and P. C. Thompson, J. Phys. D 8, 383 (1975).

Studies of Doublet Plasmas in Doublet IIA

R. K. Fisher, S. J. Adcock, J. F. Baur, N. H. Brooks, J. C. DeBoo, R. L. Freeman, W. C. Guss,
F. J. Helton, C. L. Hsieh, T. H. Jensen, A. F. Lietzke, J. M. Lohr, M. A. Mahdavi,
K. Matsuda, C. P. Moeller, T. Ohkawa, N. Ohyabu, S. C. Prager, J. M. Rawls,
T. Tamano, V. Vanek,[a] and T. S. Wang
General Atomic Company, San Diego, California 92138

(Received 3 January 1977)

Doublet plasmas have been produced in Doublet IIA using an active field-shaping coil system. Significant increases in the electron density and energy confinement time have been observed for the doublet configuration relative to elliptic and circular plasmas in Doublet IIA.

Doublet IIA[1,2] is a noncircular-cross-section tokamak which allows direct comparison of various plasma configurations in the same device. The ability to compare plasmas of different cross sections in the same device and within a few shots insures the same vacuum and wall conditions which are critical in tokamak operation. Detailed diagnostic measurements of the plasma properties of doublet, elliptic, and circular cross-section discharges have been performed. The measured plasma properties of the circular discharges are characteristic of those obtained in contemporary circular-cross-section tokamaks of similar size and toroidal field strength. The measured energy confinement time and electron density for the circular discharge are in agreement with the scaling found by Daughney[3] and Murakami,[4] respectively. A comparison of elliptic and circular plasmas produced in Doublet IIA was reported earlier.[5] This Letter reports successful control of a doublet configuration by use of an active field-shaping coil system. Measurements on doublet discharges are presented which show a significant increase in the electron density n_e and