Generation of a Shock Wave by Soft-X-Ray–Driven Ablation

T. Endo, H. Shiraga, K. Shihoyama,[a] and Y. Kato
Institute of Laser Engineering, Osaka University, Suita, Osaka 565, Japan

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Experimental observation of a shock wave generated by soft-x-ray–driven ablation is reported. An aluminum foil was irradiated by soft x rays emitted from a gold plasma. At the soft x-ray intensity of 1.9×10^{12} W/cm^2, the shock velocity is measured to be 1.1×10^6 cm/sec. The ablation pressure driving the shock wave is estimated to be 1.3 Mbar. This ablation pressure is in good agreement with the value determined independently from an x-ray burn-through measurement.

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Recently, the generation of x rays in laser-produced plasmas has been extensively studied.[1] However, there have been only a limited number of works on the transport of intense x-ray radiation through high-density matter. Several experimental results indicate that when solid-density materials are irradiated by high-intensity laser light, x-ray radiation plays an important role in energy transport.[2,3] Theoretically, when treated as a diffusion process, radiation energy is transported as a radiation heat wave in optically thick matter.[4,5] According to a more detailed radiation hydrodynamic code,[6] radiation energy transport is based on ionization burn-through (propagation of an ionization front) which arises from a large change in opacity due to an absorption-edge shift when the matter is heated by x-ray absorption. This theoretical prediction was supported by an experiment of Mochizuki *et al.*[7] and also by more refined experiments that we have performed recently.[8] In the latter work we have determined the propagation velocity of the ionization front. From the result of this measurement, we infer that a shock wave is generated by radiation-driven ablation and it should propagate through the matter ahead of the ionization front.

In this paper, we report on the experimental observation of the shock wave generated by soft-x-ray–driven ablation. We show that the ablation pressure estimated from the measured velocity of the shock wave is consistent with the value determined independently from the ionization burn-through measurement.

In the present experiment, the matter that we studied was an aluminum (Al) foil of 5–25 μm in thickness. It was irradiated by soft x rays from a separate x-ray emitter, a laser-produced gold (Au) plasma. The experimental arrangement is shown in Fig. 1. The Au plasma was produced by 351-nm-laser irradiation of the inside wall of an Au hemisphere of 400-μm radius. The third harmonic of the 1.052-μm output from the GEKKO MII glass laser[9] with energy of 35 J and pulse width of 0.73 nsec FWHM was focused with an $f/3.1$ aspheric lens onto the target at the entrance of the hemisphere. This experimental arrangement, where the Al foil was irradiated only by x-ray radiation, was chosen in order to avoid the complications encountered when the matter was irradiated directly by laser light.[2,3] Optical luminescence generated at the rear surface of the Al foil was observed with an optical streak camera and also with a biplanar photodiode. The rear surface was imaged with a magnification of 3 on the slit of the streak camera of 50-psec time resolution. Optical filters which transmit luminescence at 390 nm with a bandwidth of 59 nm and reject other background radiations were used to attain good signal-to-noise ratio. The biplanar photodiode, whose absolute sensitivity is known, was used in order to determine the absolute luminosity.

In order to determine the soft x-ray intensity on the Al foil, the x-ray emission from the Au hemisphere was observed through the collimator of the target with no Al foil. Figure 2 shows a time-integrated x-ray spectrum measured with a transmission grating spectrometer and recorded on Kodak 101-07 film. The absolute value of the spectral irradiance was determined with use of the measured diffraction efficiency of the transmission grating used in this experiment[10] and the absolute sensitivity of the 101-07 film.[11] We note that one-third of the x-ray energy is concentrated in the spectral region of <400 eV which is effective for ionization burn-through in Al.

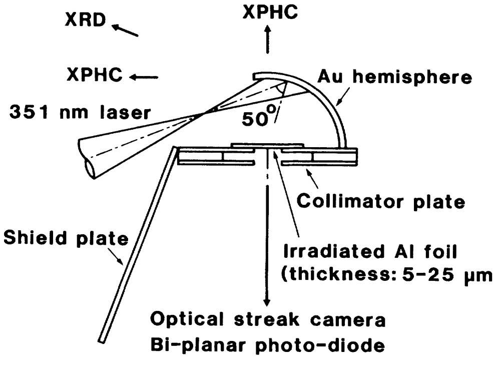

FIG. 1. Schematic diagram of the experimental arrangement. A shield plate (30-μm-thick Al) was used to prevent 1- and 0.5-μm laser light from irradiating the rear side of the target.

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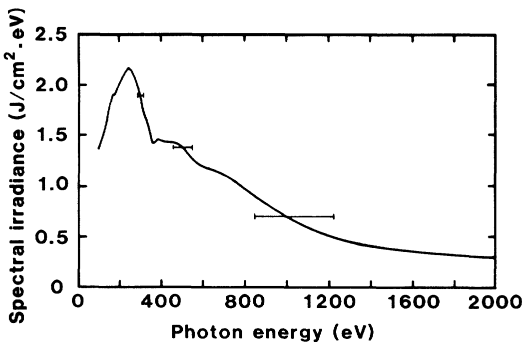

FIG. 2. Time-integrated absolute spectrum of the x-ray irradiance on the Al foil. Spectral resolution is indicated by the horizontal lines at different photon energies.

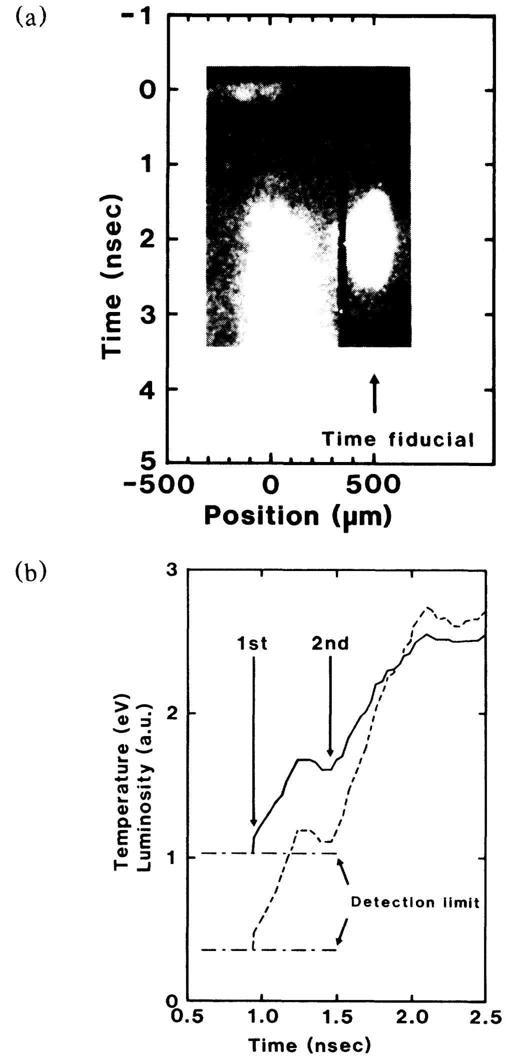

FIG. 3. Time history of the optical luminescence from the rear surface of a 15-μm-thick Al foil: (a) A streak image and (b) the luminosity (dashed line) and the temperature (solid line) of the rear surface of the Al foil, respectively.

Also, we measured the temporal shape of the x-ray pulse using an x-ray streak camera coupled with a transmission grating spectrometer. The observed x-ray pulse duration was 850 psec FWHM. With use of these data and with the geometrical configuration of the target taken into account, the soft x-ray intensity on the Al foil integrated over the spectral range of 100 eV to 2 keV was determined to be 1.9×10^{12} W/cm^2. The x-ray emission from the Au hemisphere, monitored by means of two x-ray pinhole cameras (XPHC) and four x-ray diodes (XRD), was very reproducible in all the target shots.

Optical luminescence with a short rise time was observed for Al foils of 15 to 25 μm in thickness. An example of the steak image of the luminescence at the rear side of the target obtained for a 15-μm-thick Al foil is shown in Fig. 3(a). The abscissa shows the position at the rear side of the target, with the origin at the center of the collimator, and the ordinate shows the time, with the origin at the laser peak. The signal at $t=0$ is due to stray laser light. The time-resolved luminosity determined from this streak image is shown by the dashed line in Fig. 3(b). The absolute value of the luminosity was determined by our comparing the signal of the streak camera to that of the biplanar photodiode. The brightness temperature of the rear surface determined from the absolute luminosity is shown by the solid line in Fig. 3(b). The luminescence has two sharp temporal rises, which we call the first and second luminescences hereafter. We can identify these two luminescences from the differences in the luminosities and the onset times. These two luminescences were observed also for a 20-μm-thick Al foil, whereas only the second luminescence was observable for a 25-μm-thick Al foil.

The dependence of the onset times of the first and the second luminescences on the Al-foil thickness is shown by the filled and the open circles, respectively, in Fig. 4. The pulse shape of the x ray at $h\nu=260$ eV is also shown as a reference. Since the first and the second luminescences have sharp temporal rises, the onset times of these luminescences should correspond to the times when two different energy flows reach the rear surface. The propagation velocities of these energy flows, obtained from the dependence of the onset times on the Al thickness, are 1.1×10^6 cm/sec and 3.7×10^6 cm/sec, for the first and the second luminescences, respectively. Also the onset times of these luminescences extrapolated to zero thickness are -0.46 and 1.06 nsec, respectively.

In order to confirm that the first luminescence is due to soft x-ray irradiation on Al, we made test shots using two modified types of targets. In the first type (type I), the Au hemisphere had an additional hole on the opposite side of the entrance so that the reflected laser light and the expanding Au plasma could escape from the cavity. In the second type (type II), the inside wall of the Au hemisphere of the type-I target was coated with 15-

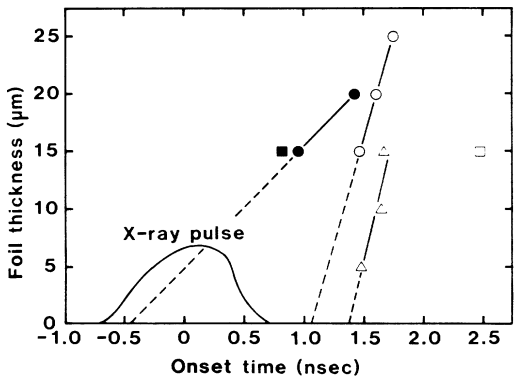

FIG. 4. Observed onset times of the first and the second luminescences for the standard target (filled and open circles), for the type-I target (filled and open squares), and for the type-II target (triangles, second luminescence only), respectively, for different thickness of the Al foils.

μm-thick CH so that the x-ray emission intensity was reduced. The results are shown in Fig. 4. In the type-I target, the first luminescence was observed at approximately the same time as in the standard target, but the second luminescence was observed at about 1 nsec later. In the type-II target, we observed only the second luminescence, with the propagation velocity of 4.4×10^6 cm/sec. On the basis of these observations, we conclude that the first luminescence is due to soft x-ray irradiation and not due to irradiation by scattered laser light. On the other hand, the second luminescence is ascribed to collisions with the plasma from the hemisphere. We note that for foils of 5 and 10 μm in thickness, luminescence of sharp temporal rise was not observed for the standard and the type-I targets whereas it was observed with the type-II target. An evaluation of the preheating of the Al foil due to the high-energy component ($h\nu > 500$ eV) of the x-ray spectrum shown in Fig. 2 suggests that the rear surface of the foil is vaporized before the arrival of the energy flow corresponding to the first luminescence when the foil thickness is approximately less than 10 μm. In this case luminescence of sharp temporal rise at 390 nm is not observable because of absorption in the Al vapor.

In the following we concentrate our discussion on the first luminescence. Since the temperature of the rear surface has a sharp temporal rise and the peak temperatures are the same for the 15- and 20-μm-thick Al foils (both of them are 1.7 eV), the energy flow generating the first luminescence is a shock wave in a steady state.[12-14] From the observed shock velocity of 1.1×10^6 cm/sec and the shock Hugoniot data of Al,[15] the pressure driving the shock wave is estimated to be 1.3 Mbar.

We now examine the relationship between the present experiment and the burn-through experiment.[8] In the latter experiment, we measured the propagation velocity of the ionization front in an experimental arrangement similar to that shown in Fig. 1 but using thinner Al foils (0–1 μm in thickness). Time-resolved spectra of the x rays transmitted through Al foils of different thicknesses were recorded with use of a transmission grating spectrometer coupled with an x-ray steak camera. In this experiment the ionization front velocity was measured to be 1.1×10^5 cm/sec for the same x-ray irradiation conditions as in the present experiment. Also, the average ionic charge of the heated Al plasma was determined to be approximately 8 from this burn-through experiment. With the assumption of steady-state ablation, the ablation front velocity should be equal to the ionization front velocity. From the measured ionization front velocity, the mass ablation rate $\dot{m}$ is determined to be 3.0×10^5 g/cm$^2\cdot$sec. For an Al plasma of an average ionic charge of 8, the temperature is estimated to be 50 eV with use of the coronal model, and 100 eV with use of the local thermodynamic equilibrium model.[16] Therefore, the sonic velocity C_s is evaluated to be in the range of 4.0×10^6–5.7×10^6 cm/sec. Thus the ablation pressure P_a is evaluated to be 1.2–1.7 Mbar with use of the relationship $P_a = \dot{m}C_s$. This value agrees with the ablation pressure of 1.3 Mbar evaluated from the shock velocity. In order to make a more accurate evaluation, we should take account of the bound-bound absorption and the detailed atomic physics such as the lowering of the ionization potential and Stark broadening in a hot, dense plasma.[17,18] But small errors in the estimations of the average ionic charge and the temperature do not make significant contributions to the error in the estimation of the ablation pressure since the sonic velocity is proportional to the square root of the average ionic charge or the temperature. On the other hand, we have used the measured value of the mass ablation rate which contributes linearly to the estimation of the ablation pressure. Therefore, this agreement is regarded to be quite significant.

In conclusion, we have observed the time history of the real-surface temperature of Al foils irradiated by soft x-ray radiation from Au plasma. The velocity of the shock wave propagating in cold Al and generated by x-ray-driven ablation has been measured. The ablation pressure driving the shock wave is estimated to be 1.3 Mbar at the irradiating x-ray intensity of 1.9×10^{12} W/cm^2. This ablation pressure is in good agreement with the value determined from an x-ray burn-through measurement.

Since we have experimentally verified the relationship between the ionization burn-through and the shock-wave generation, this research can be extended to more general situations, such as the dependence on the target material and the scaling to higher radiation intensity.

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(a)Permanent address: Laser Laboratory, HOYA Corporation, Akishima, Tokyo, Japan.

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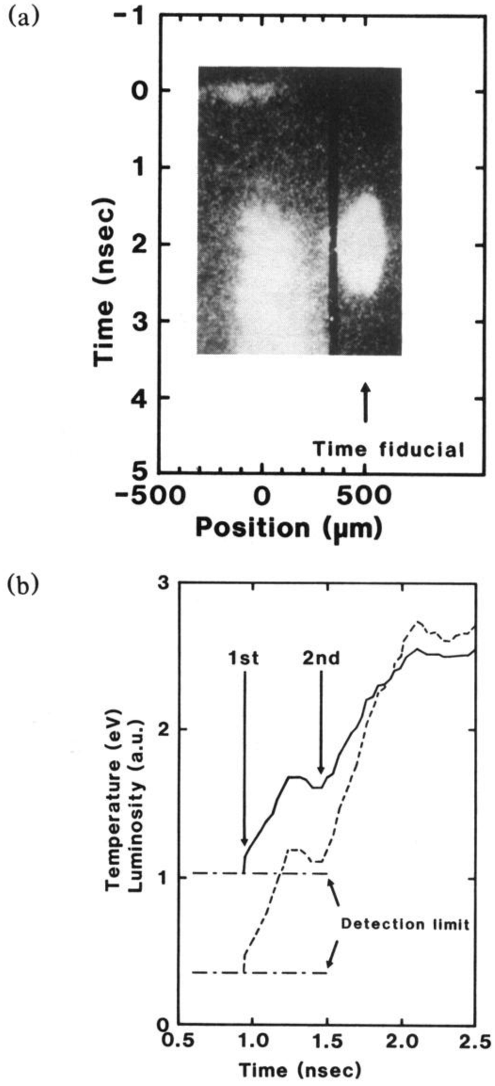

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