Hot-Electron Characterization from $K\alpha$ Measurements in High-Contrast, p-Polarized, Picosecond Laser-Plasma Interactions

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Strong $K\alpha$ emission is observed in picosecond laser-plasma interactions with high-intensity-contrast, p-polarized, picosecond laser pulses. $K\alpha$ emission from Si substrates overlaid with various thicknesses of Al is compared with a Monte Carlo simulation. The results show that the hot electrons which deposit their energy in the solid material have a 3-keV temperature and carry 10% of the incident laser energy. The shifted $K\alpha$ emission indicates that the solid is heated to a temperature of 35 eV up to 5000 Å from the target surface, which is consistent with the preheat of the hot electrons.

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Short-pulse (≤ 1 ps) laser-plasma interactions have aroused special interest because of the possibilities of producing ultrashort x-ray pulses [1–3] and near-solid-density plasmas [4,5]. Recently, it has been shown that, for a high-intensity-contrast, picosecond, p-polarized laser pulse incident at a large oblique angle, the absorption can be as high as 60% [6]. Simulations predict that a large fraction of the absorbed laser energy can be carried by hot electrons in high-intensity, short-pulse laser-plasma interactions [7,8]. Experimentally, the generation of hot electrons from the short-pulse laser plasma has been reported using an 80-fs pulse with a 3-ns pedestal (amplified spontaneous emission) at normal incidence [9]. In this Letter, we report for the first time a quantitative measurement of the hot electrons generated in short-scale-length laser-plasma interactions by high-intensity-contrast (contrast of main pulse to the pedestal is greater than 10^5) picosecond laser pulses. This high contrast enables the main laser pulse to interact with a very short-scale-length (much less than the laser wavelength) plasma instead of interacting with a long-scale-length preformed plasma created by the prepulse. The results are significantly changed when a prepulse is present. The hot-electron energy was deduced from the $K\alpha$ spectra of multilayered targets, a technique which has been successfully demonstrated for long-pulse laser plasmas [10,11]. The temperature of the hot electrons is measured to be 3 keV by fitting the experimental data by the Monte Carlo calculations and the total $K\alpha$ yield shows that the hot electrons which deposit their energy in the solid target carry $\sim 10\%$ of total laser energy assuming an isotropic Maxwellian distribution function. These hot electrons can preheat the target up to 100 eV producing a relatively cold solid-density plasma behind the hot surface plasma. This is consistent with the observed shifted $K\alpha$ emission. A strong dependence of the $K\alpha$ emission on the polarization of the laser pulse at 60° incidence angle is observed, consistent with resonance absorption in short-scale-length laser-plasma interactions [7,12].

In the experiment, a 1.3-ps (FWHM), 1.05-μm pulse with an average energy of 10 mJ is provided by a Nd:glass laser system based on the chirped pulse amplification and compression (CPAC) technique [13,14]. With a saturable absorber (Kodak 9860 dye) after the compression gratings [13], a 5×10^{-6} contrast of prepulse with respect to the main pulse is achieved. This is sufficient to keep the prepulse below the breakdown threshold of typical solids [15]. The laser is incident at 60° from the target normal with peak intensity 3×10^{15} W/cm^2 in a 12×24-μm elliptical focal spot ($1/e$ intensity). The target has a double-layered structure: a 0.05- to 1.0-μm optical-quality Al layer coated on a polished 100-μm-thick Si wafer. The Si layer is used as the $K\alpha$ emitter because its K-shell electron binding energy is lower than the expected hot-electron energy but higher than the photon energy of the strong He-like α line of Al plasma. Thus, Si $K\alpha$ can be efficiently pumped by the hot electrons but not by the line emission from the plasma. The target was moved after each shot to ensure that the laser pulse interacts with a fresh target surface. A Von Hamos crystal spectrograph [16] consisting of a PET crystal ($2d=8.742$ Å) with a 2-in. radius of curvature is used and the spectrum is recorded on a Kodak DEF film under a 25-μm Be filter. The spectrum was converted to source brightness by using the crystal reflectivity [17], filter transmission, and the film D-log$I$ curves [18]. The total yield of x rays detected from the Von Hamos spectrograph was found to agree with the measurement of filtered x-ray p-i-n diodes within 20% if a mosaic crystal reflectivity was assumed [17]. This is reasonable because of the age and large curvatures of the PET crystal. An average of 300 shots was accumulated for each spectrum. The standard deviation of laser intensity (including energy, pulse duration, and focal-spot fluctuations) was $\pm 20\%$.

Figure 1 shows time-integrated x-ray spectra from an Al/Si target (2000 Å Al) taken with high-intensity-contrast, p-polarized, picosecond pulses at a 60° angle of incidence. The He-like α line of Al^{11+} ion [He$_\alpha$, $1s2p(^1P)$-$1s^2(^1S)$] is at 7.757 Å and the Al $K\alpha$ line from low ionization states of Al (Al^{1+}-Al^{4+}) is at 8.34 Å. Between these two are so-called "shifted" Al $K\alpha$ lines

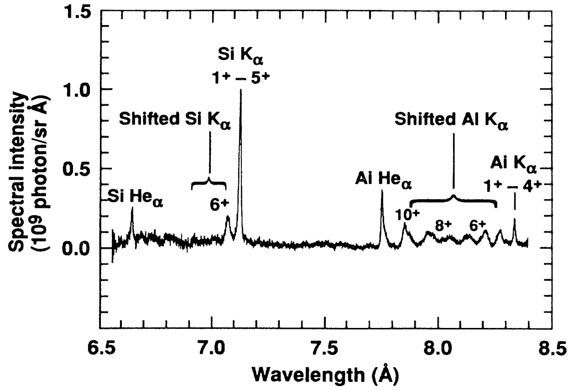

FIG. 1. Time-integrated x-ray spectra of Al/Si target (2000 Å Al on 100 μm Si) taken with high-contrast, p-polarized, $I=3\times10^{15}$ W/cm^2 laser pulses. Al and Si He-like α lines [He$_\alpha$, $1s2p(^1P)$-$1s^2(^1S)$] are emitted from hot plasma in Al and Si layers and $K\alpha$ lines (inner shell transition of Al^{1+}-Al^{10+} and Si^{1+}-Si^{7+}) are emitted from relative cold inner region of Al and Si.

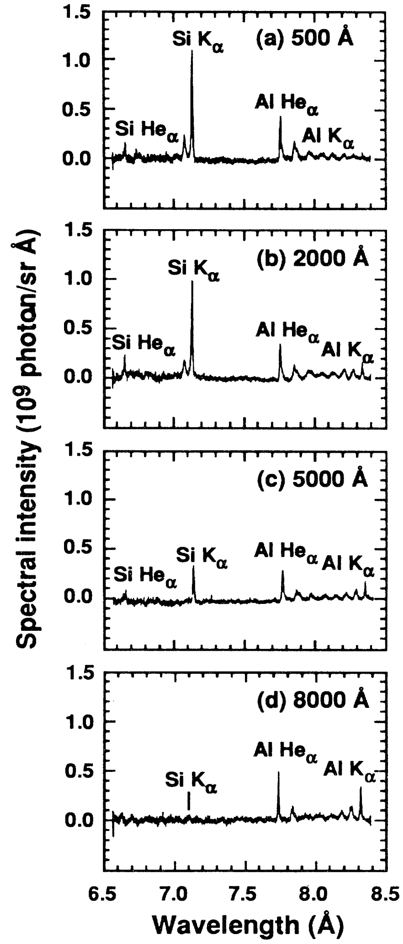

FIG. 2. A series of spectra taken under the same laser condition as in Fig. 1 for the following Al thickness: (a) 500 Å, (b) 2000 Å, (c) 5000 Å, and (d) 8000 Å. Si He$_\alpha$ line is the signature of the heat front penetration which has a depth of about 5000 Å. The intensity of Si $K\alpha$ as a function of Al thickness is used to determine the hot-electron temperature.

from Al^{5+}-Al^{10+} ions [19]. These originate from $K\alpha$ emission of partially ionized Al ions. The $K\alpha$ line of Al^{10+}, which is also called dielectronic satellites, originates not only from the inner-shell ionization by hot electrons like other $K\alpha$ lines, but also from the thermal inner-shell excitation of Al^{10+} and the dielectronic recombination of Al^{11+} in the hot surface-plasma region. In the range of 6.64 Å to 7.13 Å, similar to the Al lines, there is a band of lines from the Si layer: unshifted and shifted Si $K\alpha$ lines, as well as the Si He$_\alpha$ line. In general, He-like Al and Si lines are emitted in the hot surface region (T_e is expected to be ≥ 300 eV for He-like Al ions) created by the thermal heat front. The $K\alpha$ lines are emitted from the colder region beyond the thermal heat front where there is only hot-electron preheat.

The observed Si $K\alpha$ yield is too high to be induced by the keV radiation from the plasma; therefore, hot electrons are expected to be the dominant source for the $K\alpha$ emission. A series of spectra were taken with different Al coating thicknesses to study the hot-electron characteristics. Figure 2 shows four such spectra with 500, 2000, 5000, and 8000 Å Al thicknesses, respectively. The intensity of Si $K\alpha$ drops as the Al-layer thickness increases because the Al layer attenuates the hot electrons streaming inward and also absorbs the Si $K\alpha$ photons. On the other hand, the intensity of the Al $K\alpha$ emission increases with the Al-layer thickness. The Al He$_\alpha$ line remains at the same intensity for all Al thicknesses because only a very thin surface layer ($\sim$7 Å for solid-density Al) contributes to its observed intensity due to the large opacity on this line [20].

The Si $K\alpha$ intensity as a function of Al thickness is used to deduce the hot-electron energy and total number of hot electrons. By comparing the theoretical $K\alpha$ yield obtained from a Monte Carlo code [10,21] to the experimental results, the hot-electron kinetic energy is determined from the slope of the $K\alpha$ yield versus the Al thickness and the total number of hot electrons is determined by matching the calculated single-electron $K\alpha$ yield to the total $K\alpha$ yield observed. In the code, the electron source is assumed to be plane isotropic [22] and have a Maxwellian energy distribution. The hot-electron energy deposition is assumed to be the same for neutral and ionized material. Figure 3 shows a comparison of the experimental data (dots) and the Monte Carlo calculations (curves). The experimental Si $K\alpha$ yield includes the contribution of shifted $K\alpha$ components. The curves are the code calculations of the single-electron-induced Si $K\alpha$ yield multiplied by various scaling factors (i.e., total number of electrons) for hot electrons of $T_H=1$, 3, and 10 keV. Here, we have scaled the curves to the experimental data with 1000 Å Al. The experimental data are

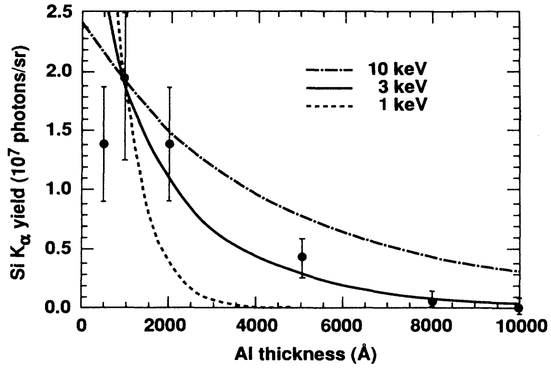

FIG. 3. Comparison of the experimentally observed Si $K\alpha$ yield (dots) to the theoretical results (curves) calculated from a Monte Carlo code. The initial energy of hot electrons is assumed to be a Maxwellian distribution with $T_H = 1$, 3, and 10 keV. The slope of the $K\alpha$ yield as a function of Al thickness shows that the hot-electron temperature is 3 keV and the absolute amplitude of the $K\alpha$ yield is used to determine the total energy of the hot electrons which penetrate into the solid, i.e., 10% of incident laser energy.

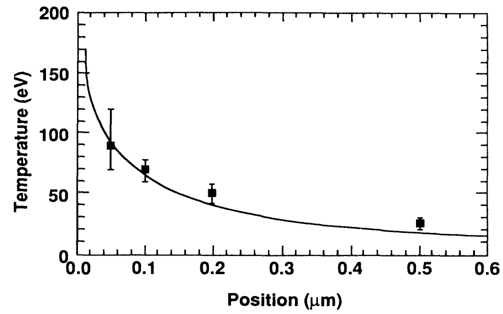

FIG. 4. Comparison of calculated temperature profile due to the hot-electron preheating (curve) and the observed target temperature (data points) from the highest order of the shifted Si $K\alpha$ line in the spectra.

well fitted by a hot-electron temperature of 3 keV. By multiplying the total number of hot electrons and the average electron energy ($\frac{3}{2} k_B T_H$), the total energy carried by the hot electrons directed towards the solid is then determined to be 10% of the incident laser energy. Monoenergetic, beamlike electrons with 10-keV kinetic energy result as well in a good fit to the experimental data. Within the experimental error bar, we cannot tell the exact distribution of the hot electrons from this technique. However, the Maxwellian distribution appears more consistent with the fast-ion measurements [12]. A strong dependence of the x-ray emission (both line emission and $K\alpha$ emission) on the laser polarization was also found in the experiments. The keV x-ray emission is reduced by at least a factor of 20 by changing from p polarization to s polarization. The hot-electron temperature and the polarization dependence are consistent with the resonance absorption predicted for our laser-plasma conditions ($L/\lambda \sim 0.1$, $I \sim 3\times10^{15}$ W/cm^2) [7,12].

The hot electrons can preheat the target as they penetrate. The preheat temperature T (in eV) can be calculated by the use of the equation of state [22] $E = aT^b$. Here a and b are 4.4 and 1.5, respectively, for solid Si [23], and E is the hot-electron energy deposition density in kJ/g computed from the Monte Carlo code. For 3-keV hot electrons carrying 10% laser energy, incident in an area of the laser focal spot ($\sim 230\ \mu$m^2), the predicted preheat temperature is shown by the curve in Fig. 4. The target temperature can be estimated from the shifted Si $K\alpha$ lines. The highest temperature in the Si layer is estimated from the highest order of the shifted Si $K\alpha$ line since it represents the target temperature at the depth of that Al thickness. For example, in the case of 2000 Å Al, the highest-order shifted $K\alpha$ observed is from Si^{7+}, and an approximate temperature of 65 eV is obtained for this ionization stage using an atomic physics code POPION [24]. The temperatures observed from shifted $K\alpha$ for various Al thicknesses are shown by the dots in Fig. 4. In the region of 500 Å to 5000 Å from the original target surface, these temperatures estimated from the highest order of shifted Si $K\alpha$ lines are consistent with the calculated hot-electron preheat temperature.

The preheat by hot electrons is believed to occur in the initial picosecond during the hot-electron generation in the laser-plasma interaction. A 3-keV electron will penetrate several thousand angstroms in a few tens of femtoseconds and lose almost all of its energy heating the target and producing the $K\alpha$ emission. The heat front of the thermal plasma can propagate only a few hundred angstroms in 1 ps. Thus the $K\alpha$ emission from the Si layer will not be influenced by the heat front of the surface plasma if the Al layer is thicker than 1000 Å. The thermal heat front will reach the inner target region in a later time. This is reflected in the spectrum. In Fig. 1, the Al $K\alpha$ lines show a low-temperature (≤ 100 eV) region in the Al layer but the Si He$_\alpha$ line shows a high-temperature region in Si behind the Al layer. This is because the Al $K\alpha$ emission occurs before the heat front reaches the Si layer and produces Si He$_\alpha$ emission. The observation of the Si He$_\alpha$ line up to an Al thickness of 5000 Å indicates a penetration depth of the thermal heat front of about 5000 Å. This penetration depth is somewhat longer, but not inconsistent with the depths measured using shorter laser pulse durations and short wavelengths by Zigler *et al.* [25] (600 fs, 2500 Å) and by Audebert *et al.* [9] (80 fs, 1000 Å).

In conclusion, we have experimentally demonstrated significant hot-electron production from the high-intensity-contrast, picosecond laser-plasma interactions. The $K\alpha$ emission from Al/Si targets of various Al thicknesses agrees well with the Monte Carlo calculations assuming the incident hot electrons are isotropic Maxwellian distributed. The temperature of these hot electrons that penetrate into the target is measured to be 3 keV and the hot electrons carry 10% of the total incident laser energy. The hot-electron temperature and its strong dependence on laser polarization are consistent with the theoretical predictions [7,12]. In addition, the hot-electron flux preheats the target to a temperature of tens of eV and forms a large region of cooler, dense plasma behind the hot surface plasma. With specially designed $K\alpha$ emitter material, monochromatic, ultrashort, high-brightness $K\alpha$ x-ray pulses can be achieved [26].

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