X-ray and charged particle emission from metal targets in femtosecond laser field of $10^{17}$ W/cm²

Yasuaki Okano, Yoichiro Hironaka, Kazutaka G. Nakamura, and Ken-ichi Kondo

Materials and Structures Laboratory, Tokyo Institute of Technology
4259 Nagatsuta, Midori, Yokohama 226-8503, Japan

Abstract. We investigated x-ray and charged particle emissions from metal target (mainly iron target) irradiated by a femtosecond laser-pulse (52 fs, 790 nm) at power density up to $10^{17}$ W/cm². Using a time-of-flight method, kinetic energy of positive ions measured by means of a charge collector. Ion velocity distribution showed two features, which were ion-velocity cutoff and a low-velocity peak. The ion-velocity cutoff showed a strongly dependence on the incident laser energy, and the cutoff energy was comparable with ponderomotive potential in the energy of several keV. The low-velocity ion component was corresponding to ions ablated from a deep-hole (20-mm depth), and the ion energies were estimated to be a few hundred eV.

INTRODUCTION

High-energy x-rays, ions and electrons are generated via laser-matter interactions in an intense optical field above $10^{15}$ W/cm² [1]. For x-rays produced by femtosecond laser irradiation on metal targets, temporal profiles and energy distributions in keV ranges have been measured at power density of $10^{17}$ W/cm² [2,3]. These x-rays have high fluxes and extremely short pulse duration (less than tens of ps), and they have been used for time-resolved studies of molecular and crystalline dynamics [4,5]. On the other hand, there are few investigations of ions or electrons in this laser-power regime. In previous studies at relatively lower laser-power region (under $10^{15}$ W/cm²), ion energy distributions of femtosecond laser plasma have been investigated [6,7]. For metal targets (Au, Cu and Al), two different ion components, consisting of high-energy (several keV) nonthermal ions and low-energy (tens of eV) ions occurring as a consequence of a thermal process following electron-lattice relaxation, have been observed at power density up to $10^{13}$ W/cm² [6].

Figure 1 shows typical energy spectra of x-rays emitted from several metal-targets by 50-fs laser irradiation at power density above $10^{16}$ W/cm². They are obtained using a direct-detection x-ray CCD camera, and characteristic x-ray emission is observed. In this work, we have studied ion and electron emission from an iron target produced by femtosecond laser irradiation (52 fs, 790 nm) where characteristic x-ray emission takes place, and surface morphology of the laser-irradiated target at power densities between $10^{16}$ and $10^{17}$ W/cm².
FIGURE 1. X-ray energy spectra emitted from metal-targets by 50-fs laser irradiation at power density above \(10^{16}\) W/cm\(^2\).

EXPERIMENTAL

The laser used in the present experiments is a tabletop terawatt laser system (B.M.industries, α10) consisting of a Ti:sapphire oscillator and amplifiers based on a chirped pulse amplification technique [2]. The amplified laser beam has a pulse duration of 52 fs (FWHM), a maximum energy of 200 mJ/pulse at a fundamental wavelength of 790 nm, and a repetition rate of 10 Hz. The pulse duration is measured by means of a single-shot autocorrelator. The contrast ratio of the main pulse to the prepulse that precedes it by 8 ns is greater than \(10^6\). In a vacuum chamber (\(10^{-6}\) Torr), the femtosecond pulse is focused on an iron target by an off-axis parabola at an incident angle of 60° with respect to the surface normal in p-polarization. A diameter of focal spot is approximately 44 μm [2]. The shape of the target is a disk of 70-mm diameter and 5-mm thick. In order to expose a fresh surface, the target is rotated and translated for each laser shot.

Charged particles from laser-produced plasma are detected by means of a charge collector consisted of an electrostatic probe in the shape of a Faraday cup. This collector is one of the simplest diagnostic tools for ions of laser plasma. The kinetic energy of positive ions is measured using a time-of-flight (TOF) method. The collector is located at a distance of 415 mm from the focal spot on the target surface at an angle of approximately 10° with respect to the surface normal. The entrance aperture in front of the collector is a hole of 3.2-mm diameter, with a resulting solid angle of \(5.2 \times 10^{-5}\) sr. To provide the zero-time, laser light reflected from the target surface is detected by a fast photodiode. Ion signal is amplified up to 30 dB with a high-bandwidth (350 MHz) DC voltage amplifier (Analog Modules, 353A), and is recorded by a digital-storage-oscilloscope (Tektronix, TDS684B).
The energy spectrum of electrons is measured with a magnetic spectrometer. The spectrometer is located at specular direction for incident laser pulse. In addition, hard x-rays up to 30 keV including Kα emission are also monitored using x-ray silicon photodiodes (International Radiation Detectors, AXUV-20HE1).

RESULTS AND DISCUSSION

Figure 2 shows typical velocity distributions for different laser energies between 4 and 123 mJ/pulse (laser power densities between 10^{16} and 10^{17} W/cm²). Each plot is an average for 500 laser shots. They are obtained from TOF spectra of ions by the relation of

\[ \frac{dQ}{dv} \approx \frac{t^2}{l} \frac{dQ}{dt}, \]  

where \( dQ/dv \) is velocity distribution of ion charge, \( t \) and \( l \) are flight time and drift distance, and \( dQ/dt \) is the time distribution of ion charge, respectively. The velocity distribution of ions shows two features, which are ion-velocity cutoff and a low-velocity peak. The velocity of the cutoff is strongly dependent on the incident laser energy and they increase in the velocity range between \( 6 \times 10^4 \) and \( 2 \times 10^5 \) m/s, which corresponds to the energy range between 1 and 10 keV of iron ions. As the laser energy increase, the ion charge yield of the low-velocity peak around \( 10^4 \) m/s is rapidly increase above laser energy of 44 mJ/pulse. Although the hydrogen ions emitted from adsorbates contribute to higher velocity part, these yields are negligible small compared to the total ion yield. X-ray intensity, which measured simultaneously with ion detection, increases with increasing laser energy in the present power density,
and an average x-ray intensity at laser energy of 123 mJ/pulse is about three times higher than that of 44 mJ/pulse. Electron energy distribution is also measured at the laser energy of 170 mJ/pulse (power density of approximately $2 \times 10^{17}$ W/cm$^2$), and the effective electron temperature is obtained more than 20 keV but the data cannot be expressed by single Boltzmann-distribution.

In intense laser field, pre-plasma can be formed due to the prepulse or the envelope of the Gaussian profile of the laser beam. The laser energy is also absorbed by the electrons not only in skin-depth region on a target surface but also in this plasma. In optical fields of the order of $10^{15}$ W/cm$^2$ or greater, both ion and free electrons are fundamentally affected by ponderomotive force inherent in the strong laser light [11]. Electrons are oscillated strongly in the field of the light wave and accelerated by ponderomotive potential [12]. Ion acceleration occurs by energy transfer from the electron to ion subsystem, which occurs due to the locally induced space-charge separation fields and electron-ion collisions [8]. Ion acceleration is considered to be due to electric fields, which is caused by energetic electrons ejected from the target surface or the pre-plasma. The ponderomotive potential is described by $2\pi e^2I(m,e\omega)^i$, where $\omega$ is the frequency and $I$ is the laser-power density. The calculated ponderomotive potential is increasing linearly for incident laser power density and comparable with the ion-cutoff energy of several keV.

We have also investigated the target surface by measuring profiles of ablated holes with a laser displacement meter (KEYENCE, VF-7500). Figure 3 shows typical cross-section profiles of the ablated hole at different power densities. At incident laser energy above 44 mJ/pulse, a deep hole of the order of $\mu$m is observed and the ion charge yield of the low-velocity peak is also increasing rapidly. Therefore, low-velocity ions are corresponding to ablation, which makes these deep holes, and high-velocity ions correspond to ablation on the top surface within optical skin-depth.

**FIGURE 3.** Cross-section profiles of laser-irradiated surface of an iron target at laser energies between 4 and 123 mJ/pulse.
These deep holes are considered to be produced as a result of indirect interactions of an intense laser pulse with a metal target, because absorption length of metal target for infrared light is limited by optical skin depth (ordinary several nm). For higher intensities enough energy is located below 1/e value extending more to the bulk. However, the laser energy at 0.1 μm is negligible small (1/e)^10 and the depth is much smaller than the hole. These deep holes have been observed in 200 fs-laser ablation of a steel plate at power density up to 5 × 10^16 W/cm^2 [8]. In an interaction of an intense laser pulse with a metal target [9], the laser energy is first absorbed by free electrons through inverse bremsstrahlung. The absorption is then followed by fast electron relaxation within the electron subsystem, electron thermal diffusion, and finally, energy transfer to the lattice through electron-phonon coupling. At laser intensity of close to the ablation threshold of 10^13 W/cm^2, two different ablation regimes in femtosecond laser ablation of metal targets have been reported by Furusawa et al. [10] and Amoruso et al. [6]. Figure 4 shows typical hole images for 44-mJ laser-pulse irradiation, and they are obtained by a field-emission scanning electron microscope (FE-SEM: Hitachi, S-4500). Melting of the target is inferred from the structure in Fig. 4 (b) and this indicates that the energy relaxation process, which mentioned above, occurred after laser irradiation. In addition, characteristic structures are observed in

FIGURE 4. SEM images of an ablated hole on an iron target irradiated by 75-mJ-laser pulse.
Fig. 4 (c) and (d), however they are not suggested yet. The difference between the two regimes is attributed to the thermal-diffusion-dominant process and the skin-depth-dominant process. In addition to these processes, photon pressure [12] and ablation pressure [13] (up to several TPa), which cause shock waves into target, can be generated at the present power density region. The low-energy ion emission is considered to occur as a result of both the energy relaxation process and these mechanical processes.

ACKNOWLEDGMENTS

The authors are grateful to M. Hasegawa for constructing the experimental setup, and K. Nemoto, Y. Oishi, and T. Nayuki for valuable discussions.

REFERENCES