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Effects of a prepulse on γ-ray radiation produced by a femtosecond laser with only 5-mJ energy

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Effects of a prepulse on γ-ray radiation have been investigated experimentally using 150-fs laser pulses at an irradiance of $I\lambda^2 \sim 5\times10^{15}\ \mathrm{W\,cm^{-2}}\,\mu\mathrm{m}^2$ focused on copper targets. The fraction of high energy photons (>100 keV) has been found to be greatly enhanced by introducing an 8% prepulse at 70 ps before the main pulse. Measurements have shown that a hot electron temperature as high as 83 keV has been produced at such a modest irradiance. [S1063-651X(98)50704-0]

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The interaction of very short laser pulses with matter has become an important field of study with the recent development of intense femtosecond (fs) lasers. Under fs laser irradiation at above $10^{14}\ \mathrm{W\,cm^{-2}}\,\mu\mathrm{m}^2$, hot electron generation becomes an important laser energy dissipation process [1–7]. Much effort has been devoted to the study of the hot electron generation [1–18]. In the absence of ultrafast diagnostics, time integrated hard x-ray and γ-ray spectroscopy can provide valuable information because hot electrons emit hard x-ray/γ-ray radiation via electron-ion impact excitation and electron-ion bremsstrahlung when they propagate in targets [8–15].

In earlier experiments with laser pulses from nanosecond (ns) to subpicosecond (ps), hot electron temperature measurements have been done at a number of laboratories [9–18]. A scaling for hot electron temperature $T_H\ (\mathrm{keV})=6\times10^{-5}(I\lambda^2)^{0.33}$ has been derived and generally is consistent with experiments [19–24]. At the relativistically strong (laser field strength $q=p_{\mathrm{osc}}/mc=8.53\times10^{-10}(I\lambda^2)^{1/2}>1$, where p_{osc} is the momentum of electrons oscillating in the laser field, m is the electron mass, c is the velocity of light, and I and λ are the laser intensity and wavelengths in units of $\mathrm{W\,cm^{-2}}$ and microns, respectively) laser irradiances, it has been demonstrated that the interaction of fs laser pulses with solid targets can produce hot electrons with energies up to MeV [6,13,24–26].

In this paper, we report on our experimental investigation with fs laser pulses at a much more modest irradiance of $I\lambda^2 \sim 5\times10^{15}\ \mathrm{W\,cm^{-2}}\,\mu\mathrm{m}^2$ (corresponding to a value for q of only 0.06). Strong effects of prepulses on γ-ray radiation have been observed. A hot electron temperature of 83 keV has been deduced from the γ-ray radiation spectra. This is significantly higher than those expected from the conventional scaling and also higher than those experimental results of other laboratories at similar irradiances using single or double nanosecond (ns) to picosecond (ps) pulses [7,14–17]. To our best knowledge, this is the first evidence that such a high value of hot electron temperature can be produced at such a modest irradiance.

A Ti:sapphire laser system delivered 150 fs pulses at 800 nm and was operated at a repetition rate of 10 Hz. The maximum output energy of this laser was about 5 mJ in a 10-mm-diam beam. The beam was focused on solid targets with a 10-cm focal length off-axis paraboloid. A microscope system with a second identical paraboloid as an objective was used to image the focal spot distribution on a charged coupled device (CCD). Thus, the focal condition could be directly monitored and optimized. The size and spatial distribution of x-ray emission was monitored by a pin-hole camera, which was filtered to see $h\upsilon>500$ eV and viewed the plasma at 45° from above.

P-polarized laser pulses were incident at 45° from the target normal. The targets used in the experiment were 2-mm-thick copper slabs. The target surface was polished to ensure the roughness of the surface to be less than 1 μm. The target was moved 50 μm after each shot so that a fresh surface interacts with laser pulses. The off-axis paraboloid and moving target were in a vacuum target chamber as shown in Fig. 1.

The use of a prepulse to create a preplasma before the arrival of the main laser pulse has been employed to improve absorption and x-ray emission [1,7,13]. Similarly a prepulse was introduced to be about 8% intensity of that of the main pulse and the time interval between them was set to be 70 ps using a dog-leg system [27]. The irradiance of the prepulse on target was high enough to generate a preplasma [5]. For some shots, a 10% prepulse at 200 ps before the main pulse was employed. Less marked, but similar tendency of prepulses in changing the spectral distribution of γ-ray radiation were observed. It seems that there exist an optimized combination of prepulse level and delay for the generation of high energy γ-ray radiation. Another detailed experiment has been scheduled to further investigate this issue.

The absorption of the laser beam was determined by measuring the scattered and specularly reflected light with a group of calorimeters in different angles. An absorption >10% was estimated by assuming an isotropic distribution of the scattering energy. A PET crystal ($2d=8.742$ Å) spec-

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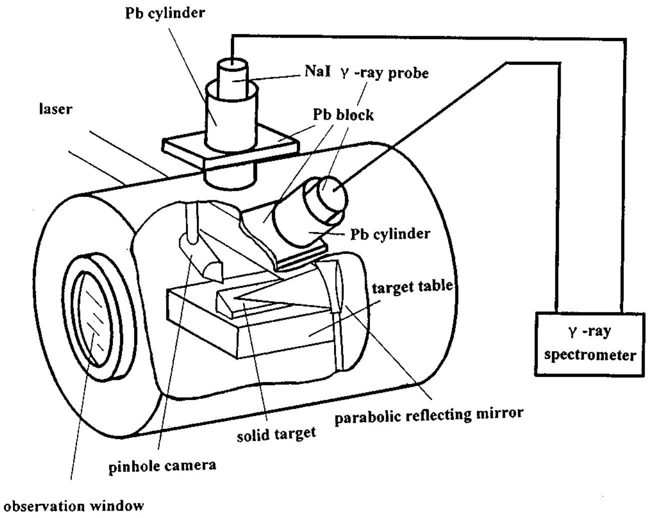

FIG. 1. Schematic experimental setup.

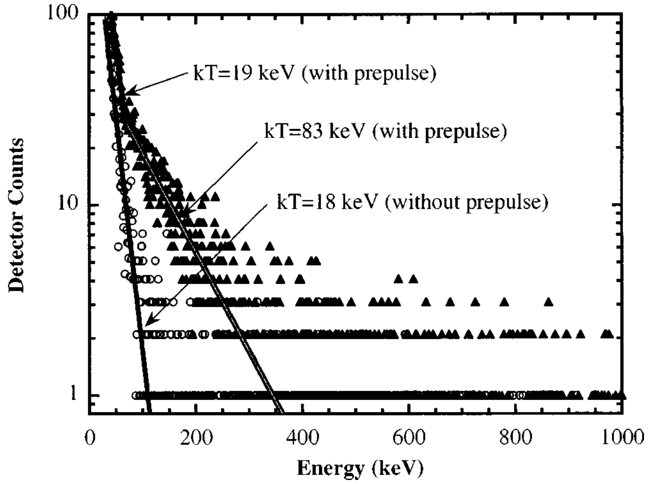

FIG. 3. γ-ray spectra of plasmas without prepulse (open circle) and with prepulse (solid triangle). Solid curves are exponential fits to determine the hot electron temperatures on the assumption of exponential spectral distribution of γ-ray radiation. The abscissa shows photon energy and the ordinate represents detector counts with a background (one count). The detector counts shown here were deconvolved by taking into account the detector response and the transmission of the detecting window.

trometer was used to measure the x-ray spectral distribution from the plasma emission in order to characterize the plasma. The spectrum was recorded on a Kodak DEF film under a 25-μm Be filter.

Figure 2 shows a typical x-ray image taken by a pin-hole camera. The source size was determined to be about 25 μm from this image. However, the diameter of the pin-hole was 25 μm. This measurement then gave an upper limit of the source size. The low bound of the average focal irradiance on targets is therefore 5×10^{15} W cm^{-2} μm^2.

A 20-mm-diam hole in a 50-mm-thick Pb block was used to collimate the γ-ray radiation and shield the detector. The detector aperture is located 360 mm from the plasma, hence collecting a solid angle of 7.7×10^{-4} sr from the source. The γ-ray radiation up to a few hundred keV was measured using a γ-ray spectrometer. This spectrometer consisted of a NaI detector, a photomultiplier, an amplifier and a multichannel energy analyzer. This assembly was fully enclosed by a Pb block and cylinder, as shown in Fig. 1, in order to eliminate the noise caused by the random γ-ray scattering. The spectrometer had been calibrated using a γ-ray source ^{22}Na (511 and 1270 keV [28]. An electronic gated shutter in front of the detector was synchronized with the main laser pulse to eliminate background noises and enhance the ratio of signal to noise. The NaI detector of the spectrometer is placed 360 mm directly above the target, also shown in Fig. 1. A second shielded NaI detector was used to monitor the stability of γ-ray photon yield for each shot and provided a cross calibration with the first one. The second NaI detector used a 4-mm-thick aluminum filter to remove γ rays below 30 keV. The γ-ray spectral distribution was determined using single-photon pulse height analysis. To avoid overlap of photons in detectors, the distances between the detectors and the plasma and the diameter of the hole in the lead block in front of the detectors were adjusted so that the probability of detecting a γ-ray photon by the detectors for each shot is less than 0.2. The detector response was checked with calibrated γ-ray sources.

Figure 3 shows the γ-ray spectra from a copper target for the cases with (solid triangle) and without prepulse (open circle). The spectra were deconvolved by taking into account the detector-filter response and the transmission of the detecting window. The spectra are continuous without distinctive line structure. This indicates that the γ-ray radiation is due to hot electron bremsstrahlung emission when hot electrons propagate in targets, as suggested in Ref. [13]. apparent effects were observed on the γ-ray spectra when an 8% prepulse was introduced 70 ps before the main pulse. It can be easily seen from Fig. 3 that the high energy γ-ray photon

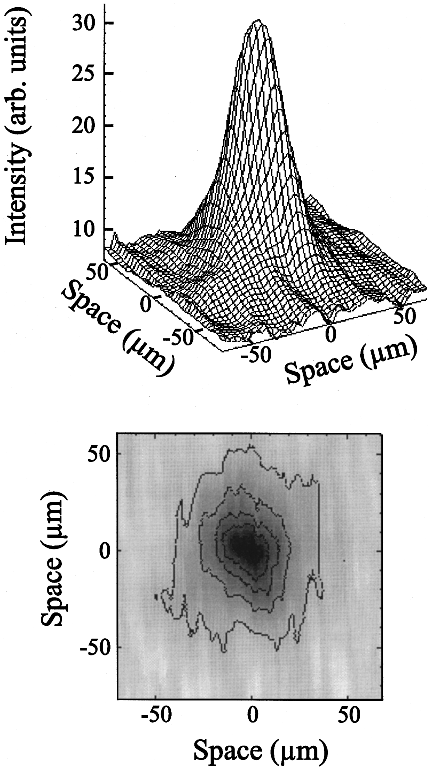

FIG. 2. Intensity distribution of an x-ray pin-hole image.

yield ($h\upsilon > 100$ keV) were greatly enhanced by introducing the prepulse, whereas the low energy γ-ray photon yield ($h\upsilon < 100$ keV) remained similar level to the case without prepulse. Especially, 400 keV photons could only be clearly seen above background while the prepulse was on. With the prepulse, the ratio of the photon number with energies higher than 60 keV to those below 60 keV is 0.92. Without the prepulse, this ratio drops down to 0.33. Hot electron temperatures for the cases of with and without prepulse can be deduced from the γ-ray spectra on an assumption of exponential spectral distribution of γ-ray radiation. For the case without prepulse, the hot electron temperature is about 18 keV. By introducing the prepulse, a group of electrons was accelerated to a much higher temperature ~83 keV as shown in Fig. 3. The maximum photon energy clearly above the background is about 400 keV. Each curve presented here represents over 10 000 laser shots.

We have investigated the effects of prepulse on γ-ray radiation generated by 5 mJ, 150 fs laser pulses focused on a copper target at an irradiance of $I\lambda^2 \sim 5 \times 10^{15}$ W cm^{-2} μm^2. We have found that fs laser pulses at a much more modest irradiance (corresponding to a value for q of only 0.06) can produce high energy γ rays equivalent to a 18 keV effective temperature of hot electrons. By introducing a small (8% at 70 ps in advance) prepulse to create some preplasma before the arrival of the main pulse, the γ-ray radiation has been found to extend beyond 400 keV. This is equivalent to a temperature of 83 keV, significantly higher than the temperature value expected from the conventional scaling: T_H (keV)$=6 \times 10^{-5}(I\lambda^2)^{0.33}$ [18–23] and also higher than those experimental results of other laboratories with similar values of q using single or double nanosecond to picosecond pulses [9,10,14,16]. To our best knowledge, this is the first experimental evidence that such a high value of the hot electron temperature can be produced at such a modest irradiance. It still remains unclear at present what the exact physics mechanism is responsible for such hot electron temperature. The experimental facts are, however, definite.

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