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Effects of atomic number Z on the energy distribution of hot electrons generated by femtosecond laser interaction with metallic targets*

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The effects of atomic number Z on the energy distribution of hot electrons generated by the interaction of 60fs, 130mJ, 800nm, and 7×10^{17}W/cm^2 laser pulses with metallic targets have been studied experimentally. The results show that the number and the effective temperature of hot electrons increase with the atomic number Z of metallic targets, and the temperature of hot electrons are in the range of 190–230keV, which is consistent with a scaling law of hot electrons temperature.

Keywords: atomic number, effect, hot electron, energy distribution

PACC: 5250J

1. Introduction

The emission of hot electrons from short-pulse-laser-produced plasma has been studied intensively in the last few years. With shorter laser pulses and higher laser intensities, hot electrons, which have an anisotropic distribution[1] that depends not only on the laser intensity but also on the pulse duration,[2] dominated ion acceleration and x-ray production.[1,3−5] Therefore, the study of the energy distribution of hot electrons becomes important for various potential applications, among which is the 'fast igniter' scheme[6] where it is proposed that fast electrons generated by a short laser pulse could be used to heat rapidly the core of a compressed deuterium–tritium fuel pellet to ignition.

Usually, the hot electron energy distribution is characterized by a Maxwell-like distribution with an effective temperature following the simple scaling law[7]

$$T_{\rm h}({\rm keV}) = a(I\lambda^2/10^{17}{\rm W}\mu{\rm m}^2/{\rm cm}^2)^{\frac{1}{3}-\frac{1}{2}}. \quad (1)$$

For laser irradiance $I\lambda^2 > 10^{18}{\rm W}\mu{\rm m}^2/{\rm cm}^2$, the exponent is close to 1/2,[7] which reflects the change of the laser absorption mechanism. For a long laser pulse, the average energy of hot electrons is $\langle\varepsilon\rangle = 3T_{\rm h}/2$ with $a = 30$, while for a short laser pulse, the electrons mainly acquire energy in the direction perpendicular to the target surface, with $\langle\varepsilon\rangle = T_{\rm h}/2$ and $a = 100$.[8]

Obviously, the effective temperature of hot electrons only depends on the laser intensity according to Eq.(1). However, Wharton *et al* [9] demonstrated for the first time that the hot electron temperature depends on the materials of targets at intensities above 10^{19} Wcm^{-2}. Yu *et al* [10] reported that the x-ray yield and the hot electron temperature monotonically increase with increasing laser intensity, but even at higher intensity it still depends very little on the atomic number Z of the target. Chen *et al* [11] reported that the laser absorption in metallic targets is higher than that in dielectric targets, and thus results in higher hot electron temperature and more hot electrons. Recently, Badziak *et al* [12] reported that using double-layer foil targets containing high-Z front layer and low-Z hydrogen-rich back layer, instead of commonly used single-layer targets, a considerable increase in energies and flux of protons produced by an ultrashort-pulse laser is possible, in which proton energies and flux current increase with the number Z of

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the high-Z layer. This can be attributed to the increase of the number and/or the temperature of hot electrons produced by the high-Z layer. Wharton,[9] Yu,[10] Badziak,[12] obtained the hot electron temperature inferred from the slope of the continuum emission x-ray spectra; they did not obtain it directly from hot electron energy spectra, and did not give the increasing level of hot electron either.

In this paper, we study the effects of atomic number Z on the energy distribution of hot electrons in the interaction of 60fs, 130mJ, 800nm, and 7×10^{17}W/cm^2 laser pulses with metallic targets. We measure the energy spectra of hot electrons using the magnetic spectrometer and estimate the number and the effective temperatures of hot electrons from various materials of target.

2. Experiment setup

The experiments were carried out on a Table Top Terawatt laser system at Laser Fusion Research Center, China Academy of Engineering Physics. A 60fs, 800nm, and10 Hz repetition rate laser pulse with energies up to 300mJ was provided by a Ti: sapphire laser system based on the chirped pulse amplification (CPA) technique. The contrast ratio of the laser pulses is about 1:10^{-6} at 1–2ns before the main pulse, as measured with the auto-correlator.

In experiment a 40mm diameter (full width at half maximum, FWHM) laser beam was focused, by means of a $f/5$ off-axis parabolic mirror, on the metallic targets at 45° incident angle with P polarization, as illustrated schematically in Fig.1.

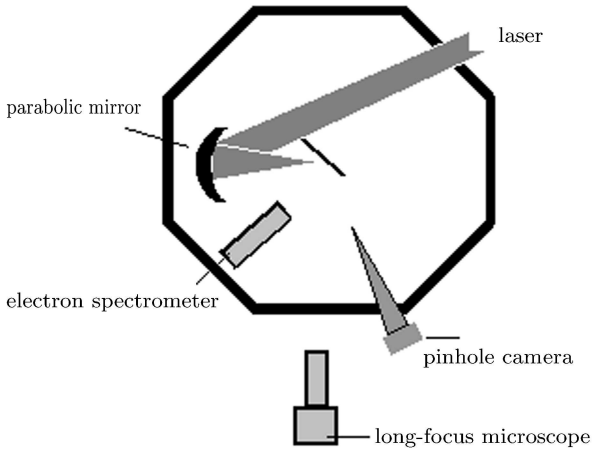


Fig.1. Schematic diagram of the experimental setup.

The energy irradiating on targets surface was about 130mJ. The focal spot diameter (FWHM) measured in vacuum was about 20 μm. As shown in Fig.2 a typical result was obtained for focal spot measured by pinhole fitted with an x-ray charge-coupled device (X-CCD) camera, giving a maximum intensity of 7×10^{17}W/cm^2 on the targets.

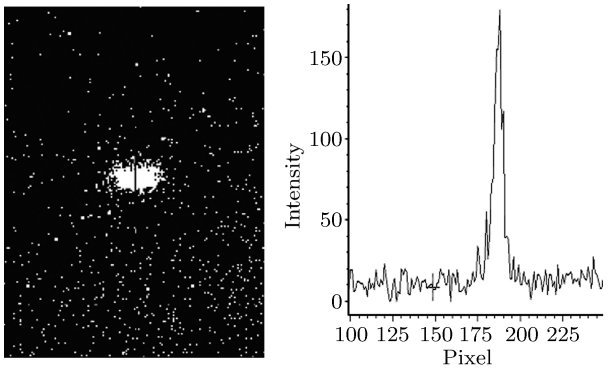


Fig.2. The image of the focus of the incident laser. The focal spot diameter (FWHM) measured in vacuum is about 20μm.

The targets were 20 μm thick, 1×1cm^2 Al, Cu, and Ta foils. The target mount was controlled by step-motors to ensure the laser pulses interacted with a fresh target surface at each shot. The parabolic mirror was controlled by other step-motors to focalize the laser pulses. A long-focus microscope outside the chamber was used to monitor the focal spot of the laser pulses.

The energy spectra of hot electrons was measured by the magnetic spectrometer, fitted with a permanent magnetic field of $B = 0.06$T. The energy range that the instrument covers was from 70 to 1250keV. The magnetic spectrometer was placed perpendicular to the target surface (see Fig.1), and the collection solid angle of the magnetic spectrometer was about 1.55×10^{-3}sr. An array of LiF thermoluminescent dosimeters (TLDs)[13] with a size of 3.2mm×3.2mm×0.38mm, which had been calibrated using Cs^{137} γ-ray sources,[14] was used in the spectrometer to detect hot electrons. Because the LiF TLDs are insensitive to visible light, it is not necessary to use Al foils in front of the LiF TLDs.

3. Results and discussion

All the experimental results presented here are obtained for laser incident on 20μm Al, Cu, and Ta targets at an angle of 45° with respect to the target normal without any prepulse.

In order to cut down the dose produced by the background which includes the x-ray emission and

the noise of TLD itself, a lead slab with a thickness of 3mm, which can eliminate electrons with energies below 5MeV (maximal energy of hot electrons is about 2MeV in our experiment), is placed in front of the magnetic spectrometer entrance. Figure 3 gives the background fluence produced in this case. It shows that the background fluence is less than $(6\pm0.42)\times10^3\text{keV}^{-1}\text{cm}^{-2}$ and is randomly distributed against the energy of hot electrons.

In order to compare the energy distribution of hot electrons from different materials of targets, the laser parameters and the experimental conditions are controlled carefully.

Figure 4 shows that the results of the energy spectra of hot electrons produced from the Al, Cu, and Ta targets after the background fluence is subtracted.

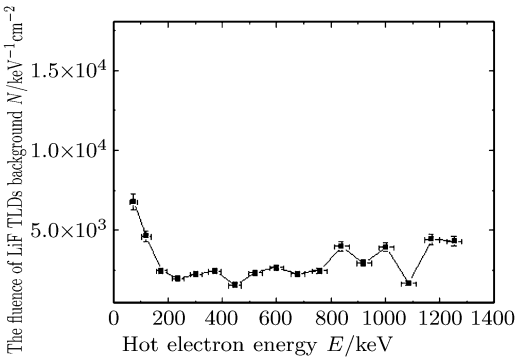


Fig.3. The fluence of LiF TLDs background by averaging 20 shots, when a lead slab of 3mm is placed in the front of the magnetic spectrometer entrance.

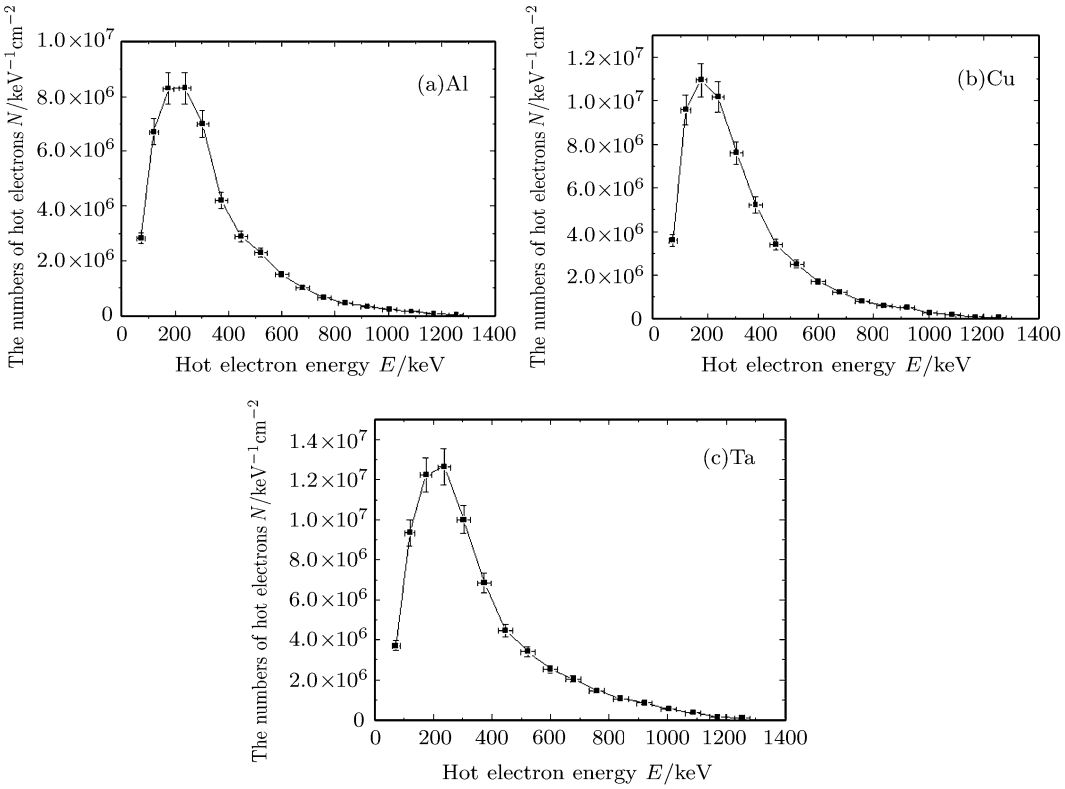


Fig.4. Energy spectra of hot electrons produced from Al target (a), Cu target (b), and Ta target (c) by averaging 20 shots after the background fluence is subtracted. Fitted with Maxwellian distribution, the effective temperatures are 192 ± 13keV, 197 ± 14keV, and 223 ± 16keV respectively. The numbers of hot electrons are about (9.76 ± 0.68) × 10^9/sr.shot, (1.20 ± 0.08) ×10^{10}/sr.shot, and (1.52 ± 0.11) ×10^{10}/sr.shot, respectively.

The fluence produced by hot electrons is about 1–4 orders larger than that of the background. It is not necessary to take into consideration the effect of the background radiation. These energy spectra are in Maxwell-like distribution and the peaks of hot electrons spectra are about 200keV. Fitted with Maxwell distribution, the effective temperatures are about 192±13keV, 197±14keV, and 223±16keV, respectively. The results show that the effective temperatures of hot electrons are only weakly dependent on the target materials, and there is no difference between Al and Cu targets as can be seen from the experimental error, which is consistent with Yu *et al*'s results.[10]

According to the scaling law of hot electrons temperature, under our experimental conditions, a short laser pulse (τ = 60fs), with a = 100, $I\lambda^2 = 4.48\times10^{17}\text{W}\mu\text{m}^2/\text{cm}^2 < 10^{18}\text{W}\mu\text{m}^2/\text{cm}^2$, the exponent is

close to 1/3, and then we have

$$T_{\rm h} = 100(I\lambda^2/10^{17}{\rm W}\mu{\rm m}^2/{\rm cm}^2)^{1/3}. \quad (2)$$

Equation (2) gives the hot electron temperature of 165keV, which is less than those inferred from the energy spectra. Perhaps the reason is that Brunel-type resonance absorption[15−17] could be excited at the optimum incident angle (45°).

In our experiment, the prepulse or pulse pedestal of $4\times10^{11}{\rm W/cm}^2$ is above the targets damage threshold. According to Zhidkov *et al*'s simulation[2] with a HYADES code, the prepulse or pulse pedestal can create a density gradient $L/\lambda \sim 1-2$ for the laser pulse with $I \sim 10^{17}{\rm W/cm}^2, \tau < 100fs, \lambda = 780{\rm nm}$ and the contrast ratio of $1{:}10^{-6}$, which are similar to ours. For an intermediate density gradient $L/\lambda \sim 1-2$, it is possible that the resonant absorption mechanism is excited and the Brunel-type resonance absorption plays a minor role. If the exponent is taken to be 1/2, then Eq.(2) gives the hot electron temperature of 212keV, which is more consistent with those inferred from the experimental energy spectra. As mentioned above, it reflects the change of the laser absorption mechanism.

In order to further compare the differences of the energy spectra of hot electrons produced from the Al, Cu, and Ta targets, by integrating the energy spectra of hot electrons from 70 to 1250keV, one can obtain the number of hot electrons with energy of 70–1250keV per solid angle averaged in a shot, which is about $(9.76\pm0.68)\times10^9$/sr.shot for Al target, $(1.20\pm0.08)\times10^{10}$/sr.shot for Cu target, and $(1.52\pm0.11)\times10^{10}$/sr.shot for Ta target. These results are consistent with that reported by Feurer *et at*,[18] where the total number of hot electrons is about $10^9{\rm sr}^{-1}$.

The conversion efficiency of laser energy to the energy of hot electrons can be deduced from the energy spectra of hot electrons. Assuming that the distribution function of hot electrons is

$$f(E_{\rm e}) = \frac{{\rm d}N}{N{\rm d}E_{\rm e}{\rm d}s}, \quad (3)$$

where $E_{\rm e}$ is the energy of hot electrons, ${\rm d}N$ the number of hot electrons with energy $E_{\rm e} \sim E_{\rm e} + {\rm d}E_{\rm e}$, N the total number of hot electrons, ${\rm d}s$ an differential area. Since $\Phi = ({\rm d}N/{\rm d}E_{\rm e}){\rm d}s$, which is the fluence of hot electrons, we have

$$f(E_{\rm e}) = \Phi(E_{\rm e})/N; \quad (4)$$

and the total energy of hot electrons is expressed as

$$E_{\rm e0} = N\bar{E}_{\rm e} = \int \Phi(E_{\rm e})E_{\rm e}{\rm d}E_{\rm e}, \quad (5)$$

According to the formula (5), integrating the energy spectra of hot electrons from 70 to 1250keV, one can conclude that the total energy of hot electrons from the target normal is about $(3.12 \pm 0.22) \times 10^{13}$keV/sr.shot, $(3.74 \pm 0.26) \times 10^{13}$keV/sr.shot, and $(5.19 \pm 0.36) \times 10^{13}$keV/sr.shot, for targets of Al, Cu, and Ta respectively.

Assuming that the laser energy is $E_{\rm L}$, the conversion efficiency of laser energy to energy of hot electrons from the target normal is

$$\eta = E_{\rm e0}/E_{\rm L}. \quad (6)$$

Under our experimental conditions, the conversion efficiencies of laser energy to the energy of hot electrons escaping from the targets with energy of 70–1250keV are approximately $(3.82 \pm 0.28)\%$/sr, $(4.54 \pm 0.32)\%$/sr, and $(6.37 \pm 0.45)\%$/sr, for targets of Al, Cu, and Ta respectively.

Zhidkov *et al*'s simulation[2] with a PIC code showed that the maximal absorption rate could exceed 60%, while the overall absorption efficiency was about 25%. Schnürer *et al*'s[19] experimental results measured in the direction of the Al target normal showed that the conversion efficiency of laser energy to the energy of hot electrons was 52%. Our results are well consistent with those of theirs when the isotropic hypothesis of the angular distribution of hot electrons[19] is used, but this hypothesis may bring on an over evaluation of the conversion efficiency.

The reason that the number and the effective temperature of hot electrons increase with the atomic number Z of metallic targets is attributed to the conductivity of target materials.[20,21] Bond *et al* [22] have pointed out that conductivity plays an important role in shielding the resistive electrostatic field via a return current. The return current also serves as the primary source of hot electrons in our experiment. Another difference among the target materials is the underdense plasma produced by the amplified spontaneous emission (ASE) and prepulse in front of the target. Wharton *et al*'s[9] 2D calculations with LASNEX showed a larger separation between the regions of critical density and solid density in CH (40μm), as compared to Al (22μm) and Cu (18μm). This difference is due to the variation in the number of Z of targets, and this will affect the intensity distribution of the laser

through filamentation instabilities and relativistic self-focusing.[23,24]

4. Conclusion

In summary, we have studied experimentally the effects of atomic number Z on the energy distribution of hot electrons generated by the interaction of 60fs, 130mJ, 800nm, and 7×10^{17}W/cm^2 laser pulses with metallic targets. The energy spectra of hot electrons are measured by a magnetic spectrometer. The number and the effective temperature of hot electrons from various materials of targets are deduced from the energy spectra of the hot electrons. It is shown that the number and the effective temperature of hot electrons increase with the atomic number Z of the metallic targets, and the temperature of hot electrons is in the range of about 190–230keV, which is better consistent with a scaling law of hot electron temperature.

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References

[1] Zhidkov A, Sasaki A and Tajima T 2000 *Phys. Rev.* E **61** R2224
[2] Zhidkov A, Sasaki A, Utsumi T, Fukumoto I, Tajima T, Saito F, Hironaka Y, Nakamura K G, Kondo K and Yoshida M 2000 *Phys. Rev.* E **62** 7232
[3] Zhidkov A G, Sasaki A, Tajima T, Auguste T, D'Olivera P, Hulin S, Monot P, Faenov A Ya, Pikuz T A and Skobelev I Yu 1999 *Phys. Rev.* E **60** 3273
[4] Hatchet S P, Brown C G, Cowan T E, Henry E A, Johnson J S, Key M H, Koch J A, Langdon A B, Lasinski B F, Lee R W, Mackinnon A J, Pennington D M, Perry M D, Phillips T W, Roth M, Sangster T C, Singh M S, Snavely R A, Stoyer M A, Wilks S C and Yasuike K 2000 *Phys. Plasmas* **7** 2076
[5] Clark E L, Krushenchik K, Zepf M, Beg F N, Tatarakis M, Machacek A, Santala M I K, Watts I, Norreys P A and Dangor A E 2000 *Phys. Rev. Lett.* **85** 1654
[6] Tabak M, Hammer J E, Glinsky M E, Kruer W L, Wilks S C, Woodworth J, Campbell E M, Perry M D and Mason R J 1994 *Phys. Plasmas* **1** 1626
[7] Beg F N, Bell A R, Dangor A E, Danson C N, Fews A P, Glinsky M E, Hammel B A, Lee P, Norreys P A and Tatarak M 1997 *Phys. Plasmas* **4** 447
[8] Zhidkov A G, Sasaki A, Fukumoto I, Tajima T, Auguste T, D'Oliveira P, Hulin S, Monot P, Faenov A Ya, Pikuz T A and Skobelev I Yu 2001 *Phys. Plasmas* **8** 3718
[9] Wharton K B, Hatchett S P, Wilks S C, Key M H, Moody J D, Yanovsky V, Offenberger A A, Hammel B A, Perry M D and Joshi C 1998 *Phys. Rev. Lett.* **81** 822
[10] Yu J, Jiang Z, Kieffer J C and Krol A 1999 *Phys. Plasmas* **6** 1318
[11] Chen L M, Zhang J, Teng H, Dong Q L, Chen Z L, Liang T J, Zhao L Z and Wei Z Y 2001 *Phys. Rev.* E **63** 036403-1
[12] Badziak J, Woryna E, Parys P, Platonov K Yu, Jabłoński S, Ryć L, Vankov A B and Wołowski J 2001 *Phys. Rev. Lett.* **87** 21500-1
[13] Bilski P, Budzanowski M, Olko P and Christensen P 1996 *Radiat. Prot. Dosim.* **66** (1-4) 101
[14] Cai D F, Gu Y Q, Zheng Z J, Cui G X, Wen T S and Yang X D 2003 *High Power Laser and Particle Beams* **15** 141 (in Chinese)
[15] Brunel F 1987 *Phys. Rev. Lett.* **59** 52
[16] Wilks S C and Kruer W L 1997 *IEEE J. Quantum Electron* **33** 1954
[17] Chen L M, Zhang J, Dong Q L, Teng H, Liang T J, Zhao L Z and Wei Z Y 2001 *Phys. Plasmas* **8** 2925
[18] Feurer T, Theobald W, Sauerbrey R, Uschmann I, Altenbernd D, Teubner U, Gibbon P, Főrster E, Malka G and Miquel J L 1997 *Phys. Rev.* E **56** 4068
[19] Schnürer M, Nolte R, Rousse A, Grillon G, Cheriaux G, Kalachnikov M P, Nickles P V and Sandner W 2000 *Phys. Rev.* E **61** 4394
[20] Bell A R, Davies J R, Guerin S and Ruhl H 1997 *Plasma Phys. Controlled Fusion* **39** 653
[21] Davies J R, Bell A R, Haines M G and Guérin S M 1997 *Phys. Rev.* E **56** 7193
[22] Bond D J, Hares J D and Kilkenny J D 1980 *Phys. Rev. Lett.* **45** 252
[23] Mori W B, Joshi C, Dawson J M, Forslund D W and Kindel J M 1988 *Phys. Rev. Lett.* **60** 1298
[24] Puhkov A and Meyer-ter-Vehn J 1996 *Phys. Rev. Lett.* **76** 3975