DOI: 10.1007/s11433-006-0335-5

Generation of surface electrons in femtosecond laser-solid interactions

XU Miaohua[1], LI Yutong[1], YUAN Xiaohui[1,2], ZHENG Zhiyuan[1], LIANG Wenxi[1], YU Quanzhi[1], ZHANG Yi[1], WANG Zhaohua[1], WEI Zhiyi[1] & ZHANG Jie[1]

1. Key Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China;
2. State Key Laboratory of Transient Optics Technology, Chinese Academy of Sciences, Xi'an 710068, China

Correspondence should be addressed to Zhang Jie (email: jzhang@aphy.iphy.ac.cn)

Received April 18, 2005; accepted January 9, 2006

Abstract The characteristics of hot electrons produced by p-polarized femtosecond laser-solid interactions are studied. The experimental results show that the outgoing electrons are mainly emitted in three directions: along the target surface, the normal direction and the laser backward direction. The electrons flowing along the target surface are due to the confinement of the electrostatic field and the surface magnetic field, while the electrons in the normal direction due to the resonant absorption.

Keywords: hot electrons, surface magnetic field, femtosecond laser pulses.

1 Introduction

Hot electrons produced by sub-picosecond laser-solid interactions have been widely investigated for their potential applications in science and industry. Collimated electron beams in the target normal direction and the laser specular direction have been observed under the non-relativistic laser conditions[1−4]. In the relativistic regime, hot electron bunches with maximum energy of tens of MeV are observed in the target normal direction and the laser propagation direction during the laser-solid interactions[5−8]. In the sub-relativistic regime, the production of the hot electrons is quite complex because of the competition between various acceleration mechanisms. Further investigations on the behaviors of the hot electrons in this regime are necessary to be done to clarify the underlying physics.

In this paper, we study the angular distributions and the energy spectra of hot electrons in the femtosecond laser-solid interactions in the sub-relativistic regime. It is found that the ejected electrons are mainly emitted in three directions: along the target surface direction, the normal direction and the laser backward direction. As far as we know, the observation of the fast electron jet along the target surface has not been published. The number and temperature of this electron bunch are comparable or even larger than the other two electron bunches. We believe that the electrons flowing along the target surface are formed by the confinement of the electrostatic field and the static magnetic field generated around the target surface, and the electrons in the normal direction are mainly due to the resonant absorption.

2 Experimental setup

The experiments were carried out on the home-made 20 TW Ti-sapphire laser system (XL-II) based on chirped pulse amplification technique. The laser system is capable of delivering up to 650 mJ energy in 30 fs, with a repetition rate of 10 Hz. The contrast ratio of the laser pulses was measured to be ~1:10^{-5} by a third-order auto-correlator. Fig. 1 shows the experimental setup.

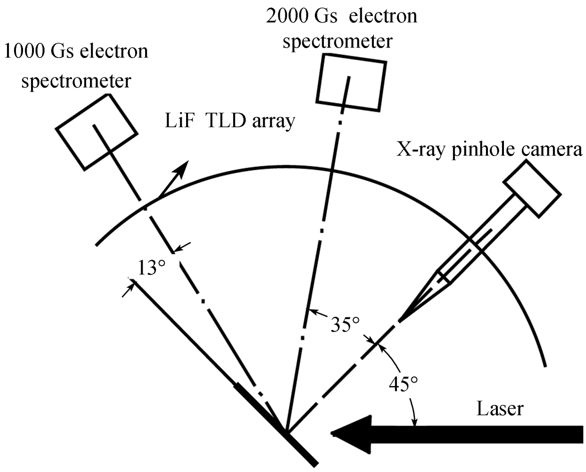

Fig. 1. Schematic experiment setup.

The p-polarized laser beam was focused with an *f*/3.6 off-axis parabolic mirror onto a 3-mm-thick aluminum target at an incident angle of 45°. The focal spot size was monitored with an X-ray pinhole camera right above the target normal direction. Fig. 2 shows an X-ray image and the intensity profile of the laser focus measured with a 10-μm-diameter pinhole. The FWHM of the focus was about 15 μm. In order to reduce the influence of the amplified spontaneous emission (ASE) pedestal on the laser-solid interactions, the laser intensity was controlled at $6\times10^{17}-8\times10^{17}$ W/cm^2.

The LiF (Mg, Cu, P) thermo-luminescence dosimeters (TLD) were used to measure the angular distributions of hot electrons. They were mounted on a 6-cm-radius aluminum loop covering 120° in the incident plane. The angular resolution was 4°. The LiF detectors were coated with a 22-μm-thick aluminum filter that blocked electrons with energy less than 50 keV. Two electron spectrometers were installed in the incident plane to measure the energy spectra of the hot electrons. The one with a magnetic field of 1000

Gauss was placed at 13° with respect to the front target surface. The collection solid angle of this spectrometer was 2.4×10^{-4} sr. The other spectrometer with 2000 Gs magnets was put 35° from the target normal. The solid angle was 3.6×10^{-4} sr. This spectrometer can measure electrons with energy less than 5 MeV. The absolutely calibrated image plates (IP)[9] coupled with the spectrometers were used as detectors .

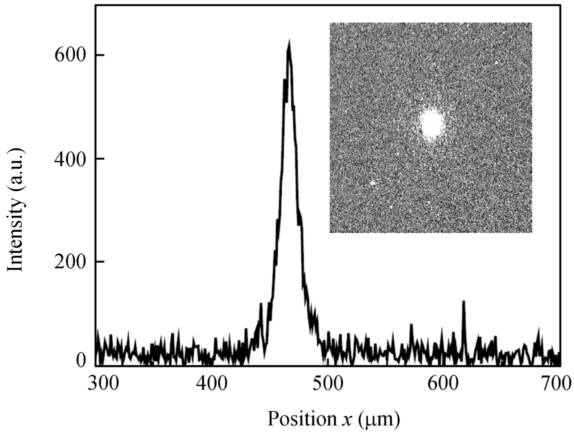

Fig. 2. An X-ray image and the intensity profile of the laser focus measured by the X-ray pinhole camera.

3 Results and discussions

Fig. 3 shows a typical angular distribution of fast electrons when the p-polarized laser was focused onto the aluminum solid target with an incident angle of 45°. The laser intensity was 6×10^{17} W/cm^2. One can see that the hot electrons are mainly emitted in three directions: along the target surface, the normal direction, and between the laser axis and the normal direction (hereafter referred to as laser backward direction). The intensity of the hot electrons flowing along the target surface is comparable or even larger than the other two bunches of electrons.

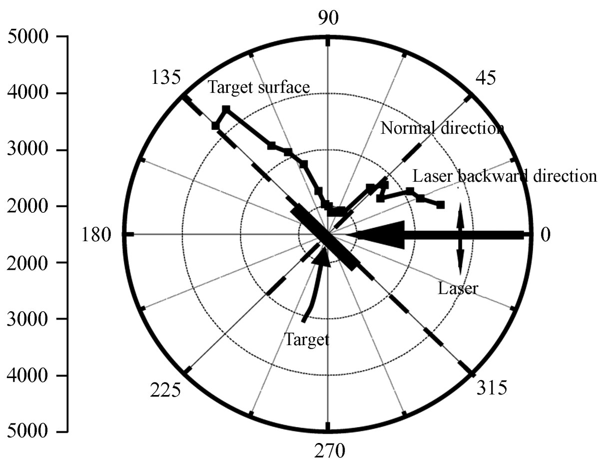

Fig. 3. Angular distribution of outgoing electrons with energy larger than 50 keV recorded by the TLD arrays.

The emission characteristics of the hot electrons in the laser plasma interactions depend on the laser intensity[10], polarization[1], the density scale length of the plasma[8,11], etc. In our experiments, the p-polarized laser was focused on the solid target with an intensity of 6×10^{17} W/cm^2. According to the contrast ratio of the laser beam ($1:10^5$), the intensity of the ASE can reach 10^{12} W/cm^2, which is sufficiently high enough to form a preplasma in front of the solid target before the main pulse arrives. According to the 1-D hydrodynamic simulations under the similar laser condition[11], the density scale length of the preplasma is about $L=1\text{–}2\lambda$. Under such plasma conditions, the mechanism of resonant absorption[12,13] becomes the dominant acceleration mechanism. The incident laser beam can excite large-amplitude electron plasma waves at the reflection plane, which accelerate the electrons in the density gradient direction. This may lead to the fast electron emission in the target normal direction.

Fig. 4 shows the energy distribution measured by the magnetic spectrometer in the direction 35° from the target normal. The energy spectrum shows a quasi-Maxwellian distribution. By fitting the curve with a Boltzmann distribution, we infer that the effective temperature of the hot electrons is about 300 keV.

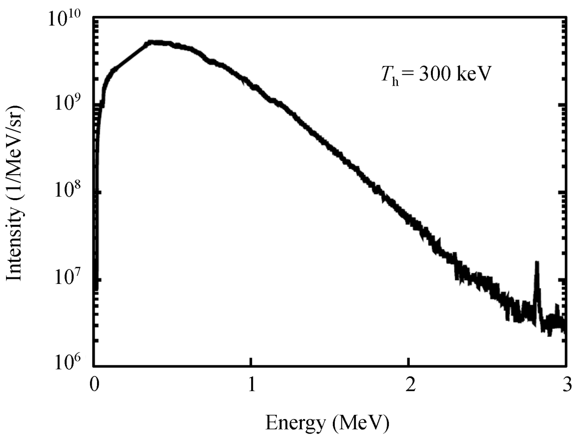

Fig. 4. Energy distribution of hot electrons in the direction 35° away from the normal direction.

The hot electron jet along the target surface may be caused by the confinement of the static magnetic field and the electrostatic field along the target surface. When an ultra-intense laser pulse irradiates obliquely on the solid target, on one hand, some electrons will be dragged into the vacuum by the laser electric field, resulting in a separated electric field in front of the target surface. Sentoku's simulations showed that the outgoing hot electrons can also induce megagauss magnetic field[14]. On the other hand, some electrons are accelerated into the target due to $\boldsymbol{J}\times\boldsymbol{B}$ heating[15], forming a current in the laser propagation direction. A background cold electron return current will be induced to maintain the charge neutrality in the target. Therefore the outgoing electron bunch and the return current form a surface magnetic field perpendicular to the incident plane. When the magnetic field component along the target surface is strong enough, it will reflect a significant fraction of fast electrons initially moving in the laser propagation direction into the vacuum. The reflected electrons and the initially outgoing electrons will be dragged back into the target again by the charge separation field. Thus the hot electrons are confined by the surface magnetic field and the sheath electric field and flow along the target surface. The surface current in turn enhances the surface magnetic field. In this way, the positive feedback is maintained and large quantities of electrons are directed to the target surface direction. This process has been analyzed by Nakamura in detail[16].

Fig. 5 shows the energy distribution of hot electrons measured at 13° relative to the front target surface in the incident plane. The effective temperature is about 400 keV after fitting the spectrum by a Boltzmann distribution.

An emission peak of hot electrons in the laser backward direction is also observed in our experiments. Similar electron peak has also been observed using an s-polarized laser pulse[17]. Andreev[18] suggests that a periodic electron density modulation will reflect the laser beam in the backward direction, which can accelerate the electrons in the backward direction. Further experimental and theoretical work is needed to find out the generation mechanisms of the backward hot electrons.

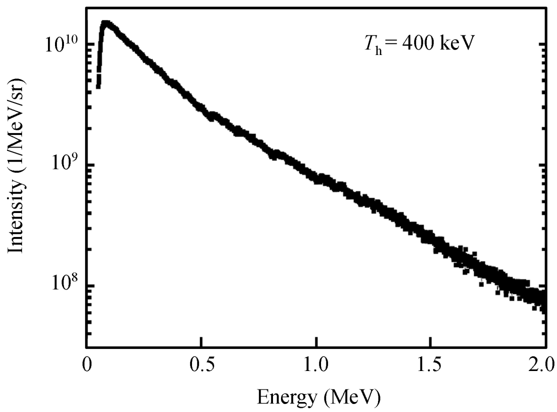

Fig. 5. Energy distribution of hot electrons in the direction about 13° from the target surface.

4 Conclusion

The characteristics of hot electrons produced by p-polarized femtosecond laser-solid interactions are studied in the sub-relativistic regime. The experimental results show that there are mainly three emission peaks of the hot electrons: along the target surface, the normal direction and the laser backward direction. We believe that the electrons emitted along the target surface are formed by the confinement of the electrostatic field and the surface magnetic field, which originates from the ingoing electrons accelerated by the laser ponderomotive force and the outgoing electrons ejected from the front surface. The electrons in the normal direction are mainly generated by the resonant absorption mechanism.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant Nos. 10374115, 10374116 and 10376160), the National High-Tech ICF Program of

China, and the National Key Laboratory of High Temperature and High Density Plasma. The authors would like to acknowledge the helpful discussions with Prof. Z. M. Sheng and Dr. M. Chen.

References

1 Chen L M, Zhang J, Li Y T, et al. Effects of laser polarization on jet emission of fast electrons in femtosecond-laser plasmas. Phys Rev Lett, 2001, 87(22): 225001

2 Bastiani S, Rousse A, Geindre J P, et al. Experimental study of the interaction of subpicosecond laser pulses with solid targets of varying initial scale lengths. Phys Rev E, 1997, 56(6): 7179—7185

3 Chen L M, Zhang J, Dong Q L, et al. Hot electron generation via vacuum heating process in femtosecond laser-solid interactions. Physics of Plasmas, 2001, 8(6): 2925—2929

4 Li Y T, Zhang J, Chen L M, et al. Hot electrons in the interaction of femtosecond laser pulses with foil targets at a moderate laser intensity. Phys Rev E, 2001, 64(4): 46407

5 Malka G, Miquel J L. Experimental confirmation of ponderomotive-force electrons produced by an ultrarelativistic laser pulse on a solid target. Phys Rev Lett, 1996, 77(1): 75—78

6 Cowan T E, Hunt A W, Phillips T W, et al. Photonuclear fission from high energy electrons from ultraintense laser-solid interactions. Phys Rev Lett, 2000, 84(5): 903—906

7 Li Y T, Zhang J, Sheng Z M, et al. High-energy electrons produced in subpicosecond laser-plasma interactions from subrelativistic laser intensities to relativistic intensities. Phys Rev E, 2004, 69(3): 036405

8 Santala M I K, Zepf M, Watts I, et al. Effect of the plasma density scale length on the direction of fast electrons in relativistic laser-solid interactions. Phys Rev Lett, 2000, 84(7): 1459—1462

9 Tanaka K A, Yabuuchi T, Sato T, et al. Calibration of imaging plate for high energy electron spectrometer. Review of Scientific Instruments, 2005, 76(1): 13507

10 Zhang J, Zhang J, Sheng Z M, Li Y T, et al. Emission direction of fast electrons in laser-solid interactions at intensities from the nonrelativistic to the relativistic. Phys Rev E, 2004, 69(4): 46408

11 Zhidkov A, Sasaki A, Utsumi T, et al. Prepulse effects on the interaction of intense femtosecond laser pulses with high-Z solids. Phys Rev E, 2000, 62(5): 7232—7240

12 Estabrook K, Kruer W L. Properties of resonantly heated electron distributions. Phys Rev Lett, 1978, 40(1): 42—45

13 Forslund D W, Kindel J M, Lee K. Theory of hot-electron spectra at high laser intensity. Phys Rev Lett, 1977, 39(5): 284—288

14 Sentoku Y, Ruhl H, Mima K, et al. Plasma jet formation and magnetic-field generation in the intense laser plasma under oblique incidence. Physics of Plasmas, 1999, 6(7): 2855—2861

15 Kruer W L, Estabrook K. $\boldsymbol{J}\times\boldsymbol{B}$ heating by very intense laser light. Phys Fluids, 1985, 28(1): 430—432

16 Nakamura T, Kato S, Nagatomo H, et al. Surface-magnetic-field and fast-electron current-layer formation by ultraintense laser irradiation. Phys Rev Lett, 2004, 93(26): 265002

17 Cai D F, Gu Y Q, Zheng Z J, et al. Experimental study for angular distribution of the hot electrons generated by femtosecond laser interaction with solid targets. Physics of Plasmas, 2003, 10(8): 3265—3269

18 Andreev A A, Platonov K Y, Salomaa R R E. Backscattering of ultrashort high intensity laser pulses from solid targets at oblique incidence. Physics of Plasmas, 2002, 9(2): 581—588