Science in China Series G: Physics, Mechanics & Astronomy

© 2008 SCIENCE IN CHINA PRESS

www.scichina.com
phys.scichina.com

Study of hot electrons generated from intense laser-plasma interaction employing Image Plate

LIANG WenXi[1], LI YuTong[1], XU MiaoHua[1], YUAN XiaoHui[1,2], ZHENG ZhiYuan[1], ZHANG Yi[1], LIU Feng[1], WANG ZhaoHua[1], LI HanMing[1,3], JIN Zhan[1], WEI ZhiYi[1], ZHAO Wei[2], LI YingJun[1,3] & ZHANG Jie[1†]

[1] Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China;
[2] State Key Laboratory of Transient Optics Technology, Chinese Academy of Sciences, Xi'an 710068, China;
[3] School of Sciences, China University of Mining and Technology, Beijing 100083, China

Image Plate (IP) is convenient to be used and very suitable for radiation detection because of its advantages such as wide dynamic range, high detective quantum efficiency, ultrahigh sensitivity and superior linearity. The function mechanism and characteristics of IP are introduced in this paper. IP was employed in the study of hot electrons generated from intense laser-plasma interaction. The angular distribution and energy spectrum of hot electrons were measured with IP in the experiments. The results demonstrate that IP is an effective radiation detector for the study of laser-plasma interaction.

IP, laser-plasma interaction, hot electrons

A mass of high energy particles and radiation such as hot electrons, ions and X-ray are generated in the procedure of intense laser-plasma interaction. Measurements of these products are of importance for understanding the mechanisms of hot electrons generation and transportation and the processes of energy absorption and transition during laser-plasma interaction, which are critical for the study on laser inertial confinement for fusion (laser ICF). Radiation measurement is such an important means that many instruments have been developed, including gas counter, scintillation counter, semiconductor detector and thermoluminescent detector[1,2], and photo-film, two-dimensional proportional counter tube, X-ray image intensifier and X-ray TV for two-dimensional radiation image[3]. But there are only a few ways suitable for experimental study on laser-plasma interaction due to the restricted conditions such as vacuum, complex scheme for multi-detectors,

Received November 13, 2007; accepted January 16, 2008; published online August 5, 2008
doi: 10.1007/s11433-008-0146-y
†Corresponding author (email: jzhang@aphy.iphy.ac.cn)
Supported by the National Natural Science Foundation of China (Grant Nos. 10675164, 60621063, 10334110, 10575129, 10510490, and 10390161), the Funds of the Chinese Academy of Sciences for Key Topics in Innovation Engineering (Grant No. KJCX2-YW-T01) and the National High-Tech ICF Program

multi-detectors, and electromagnetic pulse environment (EMP). In recent years, the mostly used in direct measurement of hot electrons from intense laser-plasma interaction are films (i.e. X-ray film or Radiochromic film, RCF[4,5]) and the thermoluminescent detector (i.e. LiF:(Mg, Cu, P) arranged spherically to measure the angular distribution of hot electrons[6]); the former have limited sensitivity, dynamic range and linearity (to be discussed), while the latter needs to do much work in the preparation and readout processes due to the limitation of its structure and size. Better ways for laser-plasma detection are being developed.

Image Plate (IP) is a phosphors image sensor developed by Fuji Film Corporation, which was designed to replace the X-ray film for digital X-ray photography[7]. IP has wide applications in X-ray detection, especially in digital medical image for its wider dynamic range, higher detective quantum efficiency (DQE), better linearity and sensitivity compared with other films, and reusable ability after the residual latent image is erased[8−10]. Practical applications show that IP is suitable for replacing some solid and gas detectors besides films[8]. Some physical applications with IP have been reported in recent years. In 2000, IP was applied to positron detection by Yu et al.[11] and the study on intense laser-plasma interaction by Tanaka et al.[12]. The IP's response to electrons with different energy was measured by Tanaka et al.[13] in 2005, so IP has been proved capable of quantificational electrons measurement. In 2006, IP was employed to measure the spatial distribution of hot electrons from intense laser-plasma interaction. With this clear image result, Li et al. demonstrated the mechanism of hot electrons guided by the target surface in the Cone focus geometry for Fast Ignition for laser ICF[14]. In the same year, Izumi et al., invited by *Rev. Sci. Instrum.*, introduced in details the experimental laser-plasma study with IP in LLNL and Rutherford Appleton Laboratory[15].

IP was employed to measure the hot electrons generated by ultra intense laser-plasma interaction in this work, and the spatial distribution and energy spectrum of hot electrons from a planar foil target were detected. The results from IP explain the mechanism of hot electrons generation and transportation from the foil target and show good consistency with those from theoretical simulation. It is shown that IP is an efficient two-dimensional radiography imager and a convenient means for hot electrons measurement. The study of laser-plasma interaction will be improved with IP.

1 Elements of IP

A set of IP device includes an IP to record radiation and a reader to extract data. IP is exposed to the radiation to be detected, and the recorded data are read out by the reader and transferred to a computer where the data are processed and analyzed directly.

1.1 How IP works

IP is composed of a protective layer, a photo-stimulable phosphor layer and a support[3]. The plastic protective layer with 0−10 μm in thickness can reduce the intensity of radiation, so various thickness of different IP is suitable for applications, and naked IP is used for low intensity radiation. The photo-stimulable phosphor layer with 50−180 μm in thickness is the effective component of IP, composed of cubical ion crystal $BaFX{:}Eu^{2+}$ (X = Cl, Br or I, typically $X = Br_{0.85}I_{0.5}$)[3]. Some types of the photo-stimulable phosphor layer with blue dye absorb the 632.8 nm read-out laser to avoid spatial resolution reduction caused by read-out laser diffusing. The polyester support of IP is flexible for the experimental setup.

IP is capable of storing radiation because of photo-stimulated luminescence (PSL). PSL is formed by duplicate stimulations. Ba in crystalline photo-stimulable phosphor is replaced by Eu^{2+} to create a solid solution while stimulated by radiation such as hot electrons. A metastable color center is formed to store the first excitation. X-ray experiments for the crystal X = Br reveal that some Eu^{2+} ions are turned to Eu^{3+} under the first stimulation, then some electrons are released to the conduction band. Empty lattice is formed due to the absence of halogen atoms which belongs to the intrinsic faults in crystal, and the released electrons will be trapped to form the color center. The photo-stimulable phosphor crystal is excited again while data are read out. The color center absorbs the energy from the read-out laser, and the trapped electrons are released into the conduction band or recombined with Eu^{3+}. The energy from electron-hole recombination is transferred to Eu^{2+} ion, the illumination center, which forms the excitation state of Eu^{2+} ion. Then PSL is generated and the stored radiation information is released[16]. The mechanism of PSL is schematically shown in Figure 1[3].

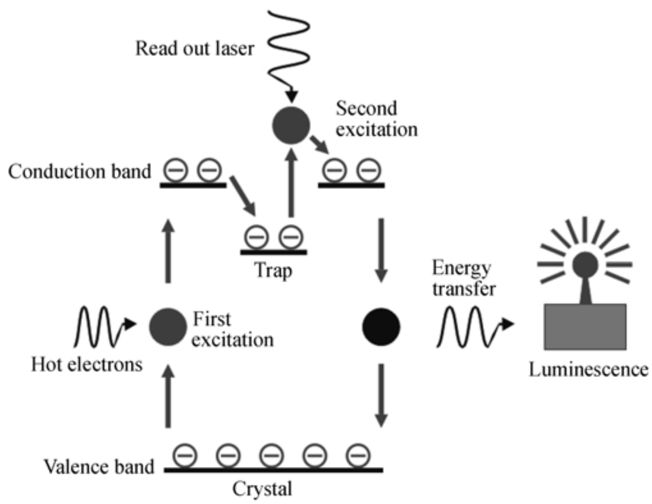

Figure 1 Process of PSL.

A part of electrons trapped in the metastable color center will automatically recombine with Eu^{3+} ions until they are read out, thus the recorded image is weakened. This procedure is called fading[3]. The effect of fading and how to handle it are to be discussed in the coming section.

1.2 Data readout

Data recorded on IP need to be read out by IP reader. Exposed IP is scanned by the focused He-Ne laser in the reader and 390 nm PSL is stimulated from photo-stimulable phosphor. PSL is gathered and amplified, and then converted to 8—16 bit digital signal to form two-dimensional digital image, which can be processed and analyzed by computer directly. 60%—90% of data on IP will be erased by the reader, and the residual latent image can be wiped off with the erasing device so that IP is reusable. The characteristic of multi-types of IP is stable after 1000 usage cycles, tested by Fuji Film Corporation[3].

1.3 Comparison of IP and films

X-ray film is mostly used in two-dimensional radiation photography. The wide dynamic range and the rigid linearity are the best features of IP compared with X-ray film, provided by Fuji Film Corp., shown in Figure 2[3]. The measurement was carried out with 1.7 MeV β-ray from ^{32}P. Figure 2 shows that IP has much better dynamic range, sensitivity and linearity than films. Consistent results are shown in measurements carried out with different energy electrons, X-ray and γ-ray[3]. Multiple characteristics between IP and X-ray film were compared via experiments by Gales et al. at British Atomic Weapons Establishmen (AWE), including DQE, dynamic, spatial resolution, sensitivity, linearity and so on[17]. Modulation transfer functions (MTF) of different IP were measured by Izumi et al. with a standard test pattern, and the spectrum response of IP with various thickness to different energy X-ray was also calculated[15]. The advantages of IP method compared with films are summarized as follows[3]: 1) Ultrahigh sensitivity. The sensitivity of IP is several ten times or several magnitudes higher than that of films, depending on different samples. 2) Wider dynamic range. IP has a range of 10^4 to 10^5 over the 10^2 range of photography. 3) Better linearity. PSL emission is proportional to the dose in the entire range. 4) Higher DQE. 5) Digital output can be processed by computer directly. The spatial resolution of IP is limited due to the diffusion during exposure and readout periods, though the grain size of photo-stimulable phosphor is minimized to 5 μm. So the resolution provided by the film is better than that by IP[15,17].

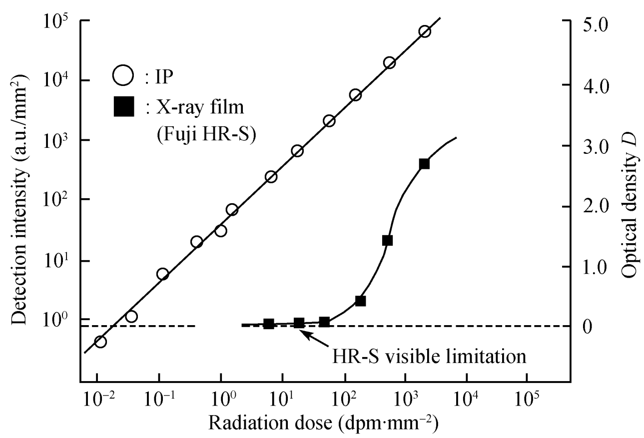

Figure 2 The comparison of characteristics of IP and film (ref. [3]).

2 Data processing of IP

2.1 Calculation of PSL

Many parameters can be set on the reader, so there is difference among outputs from different readers. PSL value should be converted to compare the results. Many types of readers are manufactured by several companies. The commonly used model interiorly is from Fuji Film Corp., and the PSL of the reader is calculated as

$$PSL = \left(\frac{pix}{100}\right)^2 \times \frac{4000}{S} \times 10^{L\left(\frac{QL}{G}-0.5\right)}, \tag{1}$$

where *pix* is the set size of pixel (in um) while IP is read out, *S* is the set value of sensitivity, *L* is the set value of the exposure range, *QL* is the gray scale value of the pixel of interest, and *G* is the maximum of the set gray scale.

2.2 Calibration of IP

Readout is carried out after exposure, while IP will fade due to the escape of electrons trapped by the color center. So the result must be analyzed with consideration of fading. Fading varies with the types of IP and the temperature of environment. The fading of BAS-SR IP was measured by Tanaka et al. with β-ray from ^{47}Pm at room temperature, and the result shows that the fading of this type of IP tends to be stable at 60 min after exposure. The fading is calculated by[13]

$$f(t) = 0.16 \times \exp\left(-\ln 2 \times \frac{t}{0.56}\right) + 0.21 \times \exp\left(-\ln 2 \times \frac{t}{11}\right) + 0.63 \times \exp\left(-\ln 2 \times \frac{t}{1991}\right), \qquad (2)$$

where t is the time in minute.

The irradiation dose is computed by the PSL value from the read-out image after the PSL is calibrated by radiation. The absolute value of PSL from BAS-SR IP was calibrated by Tanaka et al. with ^{147}Pm, 11.3 MeV, 30 MeV and 100 MeV β-ray from LINAC, based on the relative sensitivity from ref. [18]. The response curve of IP to electrons with energy up to 10 MeV is shown in Figure 3. Hot electrons can be conveniently quantified based on the curve in Figure 3. The experiments by Tanaka et al. reveal that the response curve of IP to electrons with energy higher than 1 MeV is very stable, which matches the results from the simulation for response of photo-stimulable phosphor to electrons with energy from 1 to 100 MeV[13].

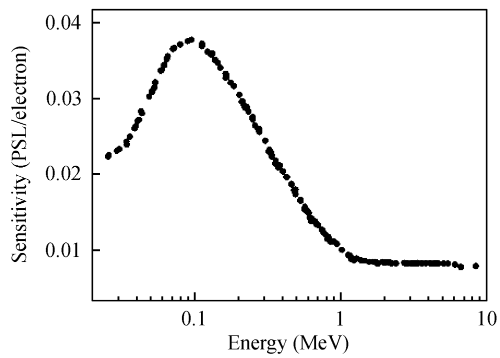

Figure 3 The response curve to electrons up to 10 MeV (ref. [13]).

The angular sensitivity of IP was measured by Tanaka et al. The result is a 1/cosθ function depending on the incidence angle θ, which keeps consistence with the linearity of IP.

3 Employing IP in study on hot electrons

Measurement of hot electrons is an important detecting method for studies on ultra intense laser-plasma interaction. There is intense EMP in the environment of experiments for hot electrons measurement. IP is totally immune to EMP and needs separate operations for radiation recording and data readout, thus IP can be easily set up in experiments despite irradiation damage. Considering all these features IP was applied in our hot electrons experiments to replace the solid detector. Spatial distribution and energy spectrum of hot electrons from the planar foil target were measured with IP, and the results demonstrate the mechanism of hot electrons generation and transportation[14,19,20]. The model of the reader in our experiment was BAS1800I from Fuji Film Corp.

3.1 Spatial distribution of hot electrons

The direction of hot electrons emission is a key feature of Fast Ignition for laser ICF. The generation and transportation of hot electrons are restricted by multiple mechanisms of particles acceleration and energy absorption, which can be illustrated by the spatial distribution of hot electrons. The main detector we have ever used in our experiments is the thermoluminescent detector. A half spherical metal support was designed to mount a lot of pieces of LiF, which was placed around the target to collect the hot electrons. The spatial distribution of hot electrons was reconstructed according to the gathered signal based on the LiF arrangement[6]. But the shortages of LiF were obvious, the spatial resolution was limited by the size of LiF, and furthermore, setting up and reading out the thermoluminescent detectors consumed much of time. Both the spatial resolution and the efficiency of the experiment were improved when IP was employed in our study on hot electrons.

BAS-MS2025 IP was applied in our spatial distribution measurement experiment. The schematic setup for the measurement is shown in Figure 4. The angle between the incident laser and the normal of the thin Al target surface was 70°, while 0° was defined as the direction of the incident laser. Several pieces of multi IP layers were set on the plane of the incident laser, at 20°—326° around the target. Al filters with various thickness were inserted between two IP layers to block electrons with different energy.

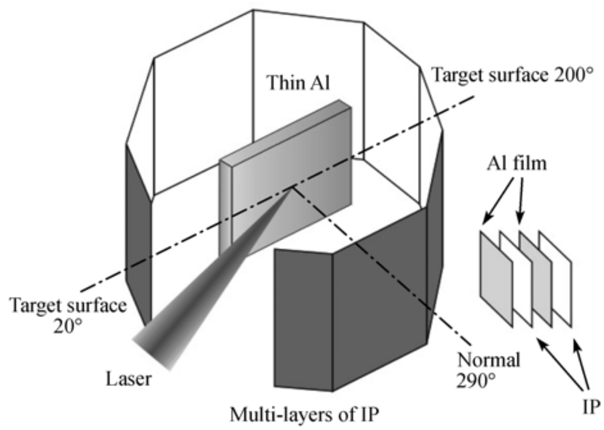

Figure 4 The setup for measuring spatial distribution.

Figure 5 shows one of the results. The gray scale value is proportional to the amount of the stored electrons, and the bright pattern illustrates dense electrons. The image shows that there is an evident emission peak located between the reflection direction and the target surface under the large incident angle condition. More results with different incident angles sum up how the distribution of hot electrons depends on the incident angle of laser, which agrees with the results from theoretical simulation. The guiding effect caused by the target was illustrated clearly[14,19].

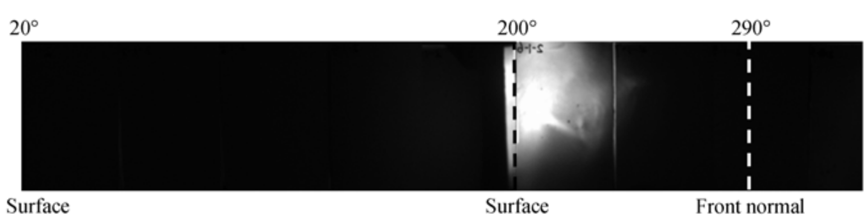

Figure 5 Spatial distribution of hot electrons.

3.2 Energy spectrum

The measurement of electron energy spectrum plays a key role in the experimental study on hot electrons. Many characteristics of hot electrons such as different emission for different materials or various laser situations can be studied by the measurement of the energy spectrum. LiF was also applied as the detector in the spectrometer in our previous designs. As discussed before, the size of LiF limited the energy resolution of the spectrometer. When IP was induced into the spectrometer, the energy resolution was greatly improved due to the excellent spatial resolution of the IP.

The spectrometer based on IP is shown as Figure 6. A slice of IP was mounted on a detachable board to record electrons. Blue BAS-SR2025 IP was chosen to enhance the spatial resolution for better spectral resolution. The experimental setup for the measurement of hot electron spectrum is shown as Figure 7. The spectrometer with a range of 2 MeV to 2.4×10^{-4} sr was set on the incident plane.

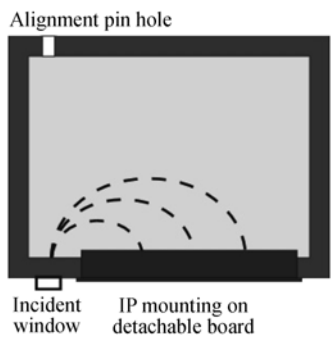

Figure 6 The spectrometer based on IP.

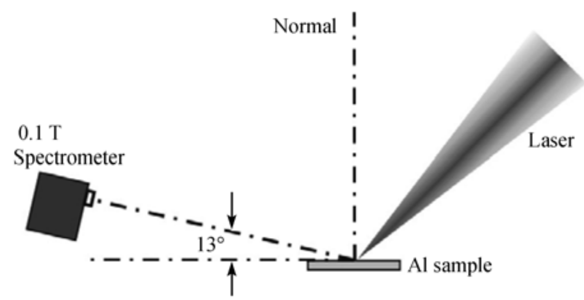

Figure 7 The setup for spectrum measurement.

Figure 8 shows a spectrum measured at 13° with respect to the front target surface. The result was converted to an absolute value of exposure dose based on the calibrated curve from ref. [13], then the temperature of hot electrons was logarithmically fitted. More spectral results sum up that the energy of emitted electrons is proportional to the energy density of incident laser, which demonstrates the energy transfer during the laser-plasma interaction[14,20].

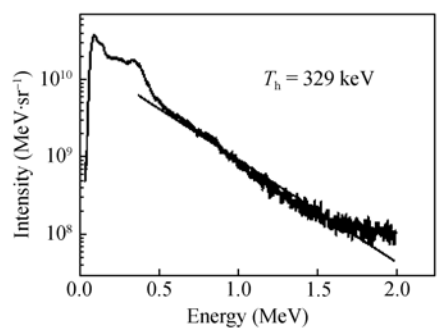

Figure 8 Spectrum of hot electrons emitted at 13° from the surface.

4 Conclusions

IP has many advantages for radiation image, including a wide dynamic range, high DQE, rigid linearity and high sensitivity. Data extracted from IP is convenient to be processed and analyzed with computer because IP provides digital output. IP is easy to be applied in laser-plasma interaction environment for its feature immune to EMP, and IP is more suitable than films for detection in study on laser-plasma interaction, though X-ray film cannot be totally replaced by IP because the spatial resolution of IP is lower than that of the film. With flexible support, IP is very easy to be set up compared with solid detectors. The period of experiments shortens with IP due to the scanning read-out method. IP was employed in our research on laser-plasma, and the results illustrate that IP both images electron spot precisely and measures the amount of electrons quantificationally. The study on laser-plasma will be boosted by applying IP in experiments.

By so far most of the applications of IP in physics have been launched in X-ray detection and electron measurement, but IP can also be employed to detect other particles with high energy such as neutrons or ions. Expanding the applications of IP can benefit study on physics.

1 Ouseph P J. Introduction to Nuclear Radiation Detectors (in Chinese). Beijing: Science Press, 1980. 44－157

2 Chen C M. Development of Radiation Detectors in Physics and Biology (in Chinese). Beijing: Atomic Energy Press, 1978. 50－97

3 http://www.fujifilm.com/products/life_science/si_imgplate/img_plate.html, 2008-07

4 Kolodner P, Yablonovitch E. Proof of the resonant acceleration mechanism for fast electrons in gaseous laser targets. Phys Rev Lett, 1976, 37: 1754－1757

5 Moore C I, Ting A, McNaught S J, et al. A laser-accelerator injector based on laser ionization and ponderomotive acceleration of electrons. Phys Rev Lett, 1999, 82: 1688－1691

6 Li Y T, Zhang J, Sheng Z M, et al. Spatial distribution of high-energy electron emission from water plasmas produced by femtosecond laser pulses. Phys Rev Lett, 2003, 90: 165002

7 Miyahara J, Takahashi K. A new type of X-ray area detector utilizing laser stimulated luminescence. Nucl Instrum Methods Phys Res A, 1986, 246: 572－578

8 Amemiya Y, Miyahara J. Imaging plate illuminates many fields. Nature, 1988, 336: 89－90

9 Rowlands J A. The physics of computed radiography. Phys Med Biol, 2002, 47: 123－166

10 Qi J. Digital X-ray photography: From now to future. J China Clin Med Imag (in Chinese), 1999, 10: 4－5

11 Yu R S, Wang B Y, Wei L, et al. Application of image plate as a sensitive detector of positrons. Nucl Tech (in Chinese), 2000, 23: 401－404

12 Tanaka K A, Kodama R, Fujita H, et al. Studies of ultra-intense laser plasma interactions for fast ignition. Phys Plasmas, 2000, 7: 2014－2022

13 Tanaka K A, Toshinori Y, Takashi S, et al. Calibration of imaging plate for high energy electron spectrometer. Rev Sci Instrum, 2005, 76: 013507

14 Li Y T, Yuan X H, Xu M H, et al. Observation of a fast electron beam emitted along the surface of a target irradiated by intense femtosecond laser pulses. Phys Rev Lett, 2006, 96: 165003

15 Izumi N, Snavely R, Gregori G, et al. Application of imaging plates to X-ray imaging and spectroscopy in laser plasma experiments. Rev Sci Instrum, 2006, 77: 10E325

16 Iwabuchi Y, Mori N, Takahashi K, et al. Mechanism of photostimulated luminescence process in $BaFBr:Eu^{2+}$ phosphors. Jpn J Appl Phys, 1994, 33: 178－185

17 Gales S G, Bentley C D. Image plates as X-ray detectors in plasma physics experiments. Rev Sci Instrum, 2004, 75: 4001

18 Taniyama A, Shindo D, Oikawa T, et al. Detective quantum efficiency of the 25 um pixel size Imaging Plate for transmission electron microscopes. J Electron Microsc, 1997, 46: 303－310

19 Yuan X H, Li Y T, Xu M H, et al. Influence of laser incidence angle on hot electrons generated in the interaction of ultrashort intense laser pulses with foil target. Acta Phys Sin (in Chinese), 2006, 55: 5899－5904

20 Xu M H, Li Y T, Yuan X H, et al. Generation of surface electrons in femtosecond laser-solid interactions. Sci China Ser G-Phys Mech Astron, 2006, 49(3): 335－340