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Note	

Study of Hot Electrons by Measurement of Optical Emission from the Rear Surface of a Metallic Foil Irradiated with Ultraintense Laser Pulse

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Hot electrons and optical emission are measured from the rear surface of a metallic foil. The spectra of the optical emission in the near infrared region have a sharp spike around the wavelength of the incident laser pulse. The optical emission is ascribed to coherent transition radiation due to microbunching in the hot electron beam. It is found that the optical emission closely correlates with the hot electrons accelerated in resonance absorption.

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There has been an increasing interest in energetic electrons generated in ultraintense laser plasma interactions because of their many applications, one of which is the fast igniter (FI) scheme of inertial fusion energy [1–3]. In the FI scheme, fuel is compressed with long laser pulses and then ignited with ultraintense laser pulses. Fuel heating and ignition are realized by energetic electrons generated in the ultraintense laser plasma interaction. Energetic electrons, which are usually generated around the critical density, have to propagate in overdense plasmas before reaching and heating the compressed core. Obviously, the propagation of relativistic electrons in an overdense plasma is a key issue in the FI scheme. Such energetic electrons have been extensively measured with various methods, either direct or indirect [4–7]. Important properties of hot electrons such as hot electron fraction and temperature have been obtained. However, some details of hot electrons in overdense plasmas are still vague, such as bunch form and spatial profile of the electron beams. Since heating processes and beam instabilities can affect the beam properties, these processes can be inferred from the detailed knowledge of the hot electron beam. Recently, it was suggested that a radiation phenomenon, i.e., transition radiation can be measured to study hot electron beams in more detail [8–10].

Transition radiation occurs when a charge crosses the interface between two layers of materials with different dielectric constants [11]. Transition radiation, especially coherent transition radiation, has been extensively measured to study relativistic electron beams in a free-electron laser [12]. By detecting the spectrum of coherent transition radiation, some subtle properties of electron beams like microbunching are inferred, which cannot usually be measured with other methods. Since the spectrum of coherent transition radiation depends on the form of the electron beam, which can be affected by the generation of hot electrons, heating mechanisms of hot electrons can be studied by this means. In this Letter, we report our experimental measurement of the optical emission from the rear surface of a metallic foil target. Unlike Santos's [9] *et al.* and Baton's *et al.* [10] research, in which they observed broad-band optical emission in the spectral range between 370 and 880 nm, we concentrate our measurement on narrow-band optical emission around 1.053 μm and correlate the optical emission with direct electron measurement with an electron spectrometer. We identify that the narrow-band optical emission is coherent transition radiation due to the hot electrons generated in resonance absorption. To our best knowledge, this Letter is the first report on coherent transition radiation in the experiment of ultraintense laser plasma interaction, indicating that electrons are generated in resonance absorption.

The experiment was performed with the GMII laser facility at the Institute of Laser Engineering, Osaka University. This facility is operated at a wavelength centered at 1.053 μm with the spectral width of 3 nm. The pulse duration after compression is about 0.6 ps, and the maximum output energy is about 20 J. The GMII has a prepulse, whose level is about 6×10^{-4} at 700 ps before the main pulse. With a $f/3.8$ off-axis parabola mirror, 25% of the laser energy can be focused within an ellipse with 20 μm long and 16 μm short axes. The layout of our experimental setup is shown in Fig. 1. Optical emission from the rear surface of foil collected with a lens passes through an aperture and then is relayed with another lens. The target is finally imaged onto the entrance slit of an optical spectrometer equipped with a 150 grooves/mm grating blazed at 1 μm. A glass filter is inserted in the light path so that only infrared light with a wavelength longer than 850 nm can reach our detectors. The spectrum of the optical emission is measured with a Hamamatsu S-1 streak camera and recorded with a charge-coupled device. Hot electrons escaping from targets are measured with an electron spectrometer (ESM) [13], which is set at 34° to the laser axis in the vertical plane. The ESM is equipped with a pair of magnets with a field strength of 4.5 kG. Hot electrons are dispersed in the static magnetic field and recorded with an imaging plate. The distance between the target and the ESM is 1.3 m, and the solid angle of the ESM is 10^{-5} sr. In the experiment, the laser pulse can be focused onto the target

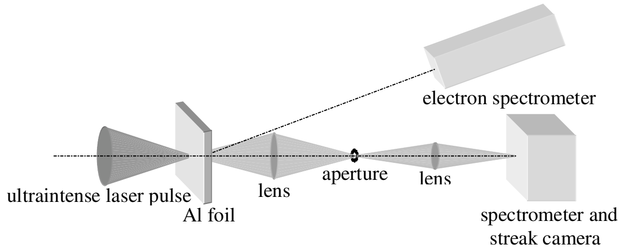

FIG. 1. Layout of the experimental setup.

surface either in p polarization or in s polarization. In both cases, the angle between the laser axis and the target normal is 20°. The target material is aluminum. In this Letter, if not specified, experimental data are obtained in the p-polarization case.

The spectrum of optical emission from the rear surface of an Al foil is rather narrow. A typical spectrum is shown in Fig. 2(a). The spectral width of the optical emission is only about 2 nm, which is close to that of the incident laser. No significant broad-band optical emission is observed in the wavelength range in which we make the measurement. Presented in Fig. 2(b) is the energy spectrum of hot electrons in the same shot. The energy spectrum of energetic electrons exhibits the characteristics of two temperatures. In the energy range between 2 and 7 MeV, the energy spectrum can be well fitted with a Boltzmann distribution function with the temperature of 1.0 MeV, as shown in Fig. 2(b). However, the hot electrons have a superhot tail. The tail can also be fitted with a Boltzmann distribution function, but with the temperature of about 3 MeV. This two-temperature characteristic of hot electrons is always observed in our experiment. While the temperature of bulk hot electrons ranges from 0.7 to 1.2 MeV, the temperature of superhot electrons scattered between 2 to 4 MeV.

We ascribe the spikelike spectral line shown in Fig. 2(a) to coherent transition radiation. We know from theoretical calculations that the spectrum of transition radiation could be greatly enhanced due to the coherent effect around some particular frequencies if there are periodic fluctuations along an electron beam [14]. If there is no coherent effect, the spectrum of transition radiation should be broad band and nearly flat in the near infrared region [14]. We consider that there should be some periodic fluctuations along the hot electron beam, whose period is about that of the incident laser, i.e., $\tau = \lambda_0/c$, where $\lambda_0 = 1.053\ \mu$m is the wavelength of the incident laser, and c is the light speed. As is well known, electrons can be accelerated in many processes. In some processes, e.g., resonance absorption [15] and vacuum heating [16], electrons are accelerated once per the laser cycle. It is obvious that the energetic electron beam generated in these processes consists of a chain of electron micropulses. The time interval τ between two adjacent micropulses should be equal to the period of the driving force, i.e., the period of the laser, $\tau = \lambda_0/c$. As a consequence, the hot electron beam acquires periodic fluctuations along its propagation due to the heating processes. If these fluctuations can survive till the beam propagates through the rear surface, transition radiation becomes coherent at the bunching frequency $1/\tau$ and is greatly enhanced at this frequency. The spectrum then presents a narrow spectral line around λ_0. Therefore, the spectrum shown in Fig. 2(a) is a direct evidence that at least a fraction of the hot electrons is generated once per the laser cycle.

We integrate the spectra of the optical emissions around 1.053 μm and then obtain the relative energy of the radiation. When we increase laser intensity while fixing the foil thickness of 50 μm, we find that the energy of the optical emission rises nonlinearly with the laser intensity, as shown in Fig. 3(a). The error bar shown in Fig. 3(a) is due to the uncertainty when we integrate the optical spectrum. In the experiment, we vary laser intensity by changing laser energy while keeping the size of the focusing spot. Fitting the scaling law I^α to the experimental data, we obtain the index α of the scaling law,

$$\alpha = 3.5 \pm 1, \qquad (1)$$

i.e., $\varepsilon_{TR} \propto I^{3.5\pm1}$, where ε_{TR} is the energy of the optical emission, and I is the laser intensity. The increase of optical emission with the laser intensity is a function of temperature and the number of hot electrons. Since the hot electrons approximately have a Boltzmann energy distribution, their velocities distribute from 0 to c. The

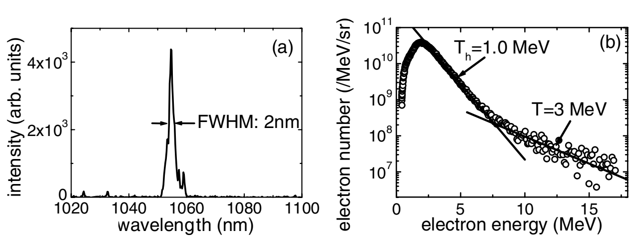

FIG. 2. Typical spectrum of (a) optical emission from the rear surface of Al foil, and (b) hot electron energy, where the target thickness is 50 μm, and the laser intensity is 1.7×10^{18} W/cm^2.

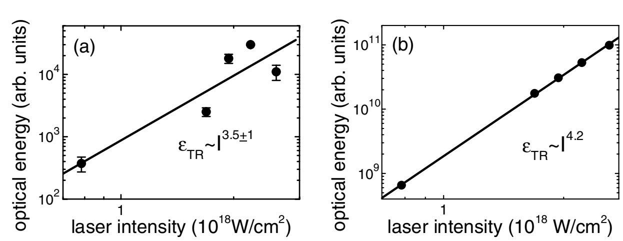

FIG. 3. Dependence of the energy of optical emission around 1.053 μm on the laser intensity: (a) experimental results, and (b) calculated results, where foil thickness is 50 μm.

amplitude of any periodic fluctuations in the electron beam then decreases with the propagation distance due to the velocity dispersion [14]. In the case of $T \gtrsim m_e c^2$ (where m_e is the electron mass), the electron velocity dispersion becomes smaller when electron temperature is higher, because more electrons have velocities close to c. Therefore, when the temperature is higher, the amplitude of fluctuations along the beam is larger if the beam propagates the same distance. An electron beam with higher amplitude of periodic fluctuations emits more intense transition radiation at the bunching frequencies. On the other hand, since the energy of coherent transition radiation is proportional to the square of the hot electron number, more electrons means higher energy of coherent radiation.

We can calculate the dependence of optical emission on laser intensity based on our experimental data of hot electrons obtained with the ESM. If the optical emission is really coherent transition radiation due to the hot electrons, calculation should give a scaling law with the index α in agreement with the experimental one, i.e., 3.5 ± 1. The ESM results are shown in Fig. 4. The electron temperature can be determined within a relative uncertainty of 5%, given by fitting the slope of the energy spectrum of the bulk hot electron, as presented in Fig. 2(b). The temperature of bulk hot electrons scales with the laser intensity according to

$$T_{\mathrm{MeV}} = 0.82 I_{18}^{1/3}, \tag{2}$$

where I_{18} is in the unit of 10^{18} W/cm^2. The electron number estimated with the ESM scales with the laser intensity as

$$N_e \propto I_{18}. \tag{3}$$

When we calculate the relation of the radiation energy versus the laser intensity, we do not need the knowledge of the absolute number of the hot electrons but just the relation (3), because the radiation energy is dependent on the square of the hot electron number. Using Eqs. (2) and (3), we calculate the dependence of the optical intensity on the laser intensity. The dots are the calculated results in Fig. 3(b). We fit the scaling law I^α to the calculated results. The resultant index is ~4.2. This number is in reasonable agreement with 3.5 ± 1, which is inferred from experimental data. The consistency between the experimental and theoretical results is another evidence that the signal should be coherent transition radiation.

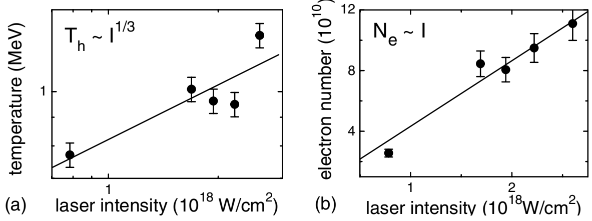

FIG. 4. Scaling law of (a) hot electron temperature, and (b) electron number versus laser intensity, where target thickness is 50 μm.

The spectrum of the optical emission indicates that the hot electrons are accelerated at the frequency of the incident laser. Resonance absorption and vacuum heating are the two candidates of such heating mechanisms. In our experiment, we believe that resonance absorption is the dominant process. The reasons are given as follows: We note that the temperature of bulk hot electrons scales with the laser intensity as $I^{1/3}$ [seeing Eq. (2)], which is consistent with both simulations [17] and experiments [4,18] for resonance absorption. The bulk hot electrons measured with the ESM should be generated in resonance absorption. Vacuum heating becomes dominant only when the plasma have a very small scale length [16]. However, independent experiment shows that a preplasma with the scale length of about 40 μm is readily produced at the arrival of the main pulse, which is measured with an optical interferometer [19]. This rather large scale length makes vacuum heating negligible [16]. The large-scale-length preplasma could also explain why the hot electron temperature in our experiment is significantly higher than previous studies. It is well known that a laser channel could be formed when an ultraintense laser pulse interacts with a preformed plasma. The effective laser intensity could be enhanced by 1 order or more due to self-focusing in the laser channel [20]. In our experiment, the laser power ranging from 4 to 12 TW is much higher than the threshold power for relativistic self-focusing even at a very underdense region. For instance, at a density of $0.05 n_c$, the threshold for relativistic self-focusing is just ~0.4 TW. Thus relativistic self-focusing may occur in our experiment. Therefore, the high temperature in our experiment could be ascribed to enhanced laser intensity in laser channel in preplasma.

As mentioned above, the amplitude of periodic fluctuations along an electron beam decreases with the propagation distance because of the velocity dispersion. Hence, energy of optical emission should decrease with the foil thickness. In the experiment, we shoot foil targets with thickness of 50, 100, and 150 μm, while we fix the laser energy at 15 J. The experimental results are shown in Fig. 5. The energy of coherent transition radiation decreases about 10 times when the target thickness increases from 50 to 150 μm. Our theoretical calculations show that the descending rate of the signal intensity versus foil thickness sensitively depends on hot electron temperatures [14]. The higher the temperature, the smaller the descending rate because of smaller velocity dispersion. Therefore, we can infer the hot electron temperature from the experimental data presented in Fig. 5. We fit well the two points at 50 and 100 μm except the point at 150 μm. On the other hand, the points at 100 and 150 μm are well fitted except the point at 50 μm. This fact is similar to the

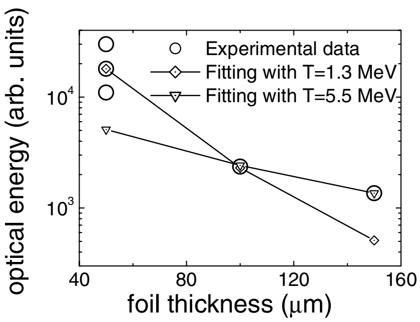

FIG. 5. Dependence of signal intensity on the target thickness, where the laser intensity is 2.5×10^{18} W/cm^2.

observation made by Santos *et al.* [9]. From the two points at 50 and 100 μm, we infer that the hot electron temperature is about 1.3 MeV. This inferred temperature is in good agreement with the result estimated by the scaling law of Eq. (2), which gives $T \sim 1.1$ MeV. The temperature inferred from the two points at 100 and 150 μm is much higher, 5.5 MeV. However, our ESM data show that electrons have a superhot tail, with temperature ranging from 2 to 4 MeV, as shown in Fig. 2(b). The inferred temperature is in fair agreement with the ones measured by the ESM. Although we do not identify the mechanisms of the superhot tail in this experiment, we suggest that these superhot electrons are still generated in a process in which electrons are accelerated once per the laser cycle because of the narrow-band optical emission similar to that shown in Fig. 2(a).

It should be pointed out that we also observe spectral lines similar to that shown in Fig. 2(a) even in the case of *s*-polarization incidence. But the intensity of the emission varies irregularly with the increasing of the laser intensity. A detailed discussion on *s*-polarization results will go beyond the scope of this paper. Here we do not present them but just give a brief explanation. As well known, $\mathbf{j} \times \mathbf{B}$ heating could become dominant in the case of *s*-polarization incidence [21,22]. In this case, the period of fluctuations in the hot electron beam should be half of that of the incident laser because electrons are accelerated twice per the laser cycle in this process. The resultant spectrum of transition radiation should have a spike around 0.526 μm [10] but not at 1.053 μm in the case of *s*-polarization incidence. A possible explanation to this fact is that a hole may be formed due to the extreme light pressure and the electric field of the laser can directly accelerate the plasma electrons on the sides of the hole [22]. Resonance absorption and/or vacuum heating can still occur in this case.

In summary, we studied optical emission from the rear surface of aluminum foil irradiated with an ultraintense laser pulse. The spectrum of the emission presents a sharp spike around the wavelength of the incident laser, indicating that the hot electron beam holds some microbunching. This optical emission is ascribed to the coherent transition radiation and closely correlates with the energetic electrons generated in resonance absorption. Hot electron temperature inferred from this optical emission compares well with that obtained by our electron spectrometer. Coherent transition can provide distinctive information on the generation of energetic electrons and thus has been proven to be a valuable tool for the study of hot electrons.

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