Fast electron transport in high-intensity laser-plasma interactions diagnosed by optical and ion emission

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Abstract. Light and proton emission from rear surface of sandwich-like targets, which are irradiated by intense femtosecond laser pulses, have been measured. It is found that both of them depend on the transport material and density inside the targets. For metal transport layers the patterns of the optical images and the proton beams are uniform. While for the transport layers of dielectric, low-density foam and vacuum gap, the patterns are broken up. This indicates that the fast electron beams are also broken up probably due to instabilities.

1. Introduction
Transport of forward fast electrons in the interaction of a high intensity relativistic laser pulse with plasma is of significance for fast ignition in inertial confined fusion [1], high-energy ion generation [2], x-ray emission [3], etc. The huge fast electron current will induce strong electrostatic fields and magnetic fields in the plasma or target bulk. The bulk fields, in turn, will affect the fast electron transport. The feedback processes between the fast electrons and the bulk fields can lead to a self-organized propagation of fast electrons. Firstly, the electrostatic fields will lead to an effective energy loss of the fast electrons and inhibit the electron penetration [4,5]. Secondly the fast electron beam will be pinched by the static magnetic fields [6,7,8,9]. Finally, the fast electron beam may be broken up into filaments due to the instabilities [10,11], resulting in a self-organized state in which the net current of each filament is less than the Alfvén limit [12]. Since fast electron current has to be compensated by the return current of background cold electrons, the target resistivity and the density are very important for the transport.

Strong electric fields will also be induced at the target rear surface when the fast electrons reach there. The fields can accelerate ions (preferably protons) by the normal sheath acceleration (TNSA) mechanism [2]. Therefore the characteristics of the proton beam will correlate with the fast electron
transport. When the fast electrons pass the rear target surface-vacuum boundary, transition radiation (TR) occurs. Such optical light can also be used to diagnose fast electron transport [13].

In this paper the TR light and proton emission from the back surface of sandwich-like targets irradiated by intense laser pulses are measured. It is found that both the $2\omega$ optical light and the proton beam profile closely depend on the transport materials inside the targets.

2. Experiment

The experiments were performed using the SILEX-I laser facility at China Academy of Engineering Physics. The laser facility can deliver up to 6J of energy in 50fs pulse every. The $p$-polarized pulse was focused with an $f/3$ off-axis parabolic mirror on sandwich-like targets at an incident angle of 24°. The diameter of the focal spot was about 60µm. The sandwiched targets consisted of interaction layer, transport layer and emission layer. The laser pulses were incident on the interaction layer to produce fast electrons. Then the electrons propagated in the transport layer in which materials could be changed. In the experiments copper, plastic solid, plastic foam and vacuum gap were used as transport layer, respectively. To keep the condition of the rear target surface consistent for all shots, the targets were coated by an Al or Ta layer after the transport materials as the target-vacuum boundary where optical light and protons were emitted from.

The spatial distributions of the accelerated protons were recorded with 5cmx5cm CR-39 nuclear track detectors. The detectors were placed behind the foil target and parallel to the target foil. The central part of the CR-39 was covered by a polyimide film with a thickness of 3.6µm and a width of 3mm ~ 5mm to estimate the proton energy. An f/2 lens in the target normal direction was used to collect the TR light and image the target rear surface to a 16 bit CCD with a magnification factor 14.5. Narrow filters were used to choose the $2\omega$ light.

3. Experimental results and discussions

First, we compared the effect of the metal transport layer with the dielectric plastic foam transport layer on fast electron transport. Figures 1(a) and 1(b) show the typical TR images of a 10µm Ta+10µmCu+5µm Ta sandwiched target and a 10µm Ta+500µm foam (160mg/cm²)+5µm Ta target, respectively. The image for the copper transport layer is more uniform than that for the plastic foam target. The peak intensity of the copper is 8509, which is larger than that of the foam, 331. These features are expected since the fast electrons propagate much smoothly in the high conductivity copper, in which the return current of the background cold electrons can be provided easily.

![Figure 1. TR images for the sandwiched targets, 10µm Ta+10µm Cu+ 5µm Ta (a); 10µm Ta+500µm foam+5µm Ta (b), respectively.](image)

Figures 2(a) - 2(e) show the optical emission images obtained using Ta solid target and various sandwiched targets with plastic, foam, and vacuum gap as transport layers. Note the images are not shown with the same intensity scale in order to see the beam structures clearly. The peak and integrated count of TR signals are shown in Table 1. The profile of the electron beam for 100 µm Ta target is homogenous while it becomes larger and inhomogeneous for the target of a 60 µm plastic transport layer. The TR light signals become weaker accordingly. Figure 2(c) show density effect. When the a 500 µm thick, 160 mg/cm³ foam is used as transport layer the signal intensity is further reduced by about two orders, and the beam is much distorted and broken up. For the target with the vacuum gap, the TR image caused by the fast electrons escaping from the rear surface of the first Ta layer is also broke up into two parts clearly.

![Figure 1. TR images for the sandwiched targets, 10µm Ta+10µm Cu+ 5µm Ta (a); 10µm Ta+500µm foam+5µm Ta (b), respectively.](image)
Figure 2(e) shows the optical emission image measured under the same conditions as Fig. 2(d). The two images show the similar signal intensity. However the orientation and the fine structures of the breakup are different. This indicates to some extent that such breakup of the fast electron beam is induced by instabilities.

![Figure 2](image)

**Figure 2.** TR images for the targets with different transport layers. (a) 100µm Ta, (b) 20 µm Ta+60 µm CH +20 µm Al , (c) 10 µm Ta+500 µm Foam (160 mg/cm²) +5 µm Al, (d) 20 µm Ta+75 µm vacuum gap (pressure~2.0x10⁻² Pa)+20 µm Al , and (e) the same target as (d), respectively.

**Table 1.** Laser intensity, peak count, and integrated count for the four kinds of targets shown in Fig. 2.

| Laser intensity (10¹⁸W/cm²) | Peak count (arb. units) | Integrated count (arb. units) |
|---------------------------|------------------------|------------------------------|
| 100µmTa Fig. 2(a)         | 2.44                    | 1.2x10¹⁰                     | 75880                         |
| 20µmTa+60µmCH +20µmAl Fig. 2 (b) | 2.67                  | 4.3 x10⁹                  | 18597                         |
| 10µmTa+500µmFoam +5µmAl Fig. 2 (c) | 1.34                  | 1.7 x10⁷                  | 331                           |
| 20µmTa+75µm vacuum+20µmAl Fig. 2 (d) | 2.12                 | 9.7 x10⁸                  | 3841                          |

Figures 3(a)-(c) show the angular distributions of the proton beam behind the targets. In Fig. 3(b) and (c) the CR-39 detectors were placed at a distance of 4 cm from the target, and centered in the target normal direction. While in Fig. 3(a), the distance was changed to 6 cm and the center of the detector was not in line with the target normal direction. The horizontal dark strip on the images corresponds to the regions covered by the 3.6µm thick polyimide film. For the 20 µm Ta only a few proton tracks can be observed in the dark region under optical microscope. This indicates that the maximum energy of the protons generated at the rear surface of the first Ta layer is only about 350keV, which can not pass through the transport layer and the last 20 µm Al layer. Therefore the protons measured in Fig. 2(b) and (c) should come from the last rear target surface.

The mean proton numbers for the single 20 µm Ta, 60 µm CH and 75 µm vacuum gap transport targets are ~8x10⁹, 4x10⁷ and 5x10⁶/sr, respectively. Figure 3(c) shows that there are still some electrons escaped into vacuum after the first Ta layer and propagate to the second Al layer even though the electrostatic filed at the rear surface of the first Ta layer can effectively inhibit fast electrons. The proton beam behind the single Ta foil does not present many fine structures. While the proton beam for the target with CH layer is very inhomogeneous with ripples and spots. This is much obvious for the vacuum gap target where the proton beam is broken up seriously.

From Fig. 2 and Fig. 3, one can see that the intensities of the TR signals and the proton beams are decreased and the patterns are broken up for the sandwiched targets with the dielectric, low foam and vacuum transport layers. This indicates that effective inhibition and breakup occur for the fast electron beam during their transport in the targets.
Figure 3. Angular distributions of the proton beam measured behind the targets of 20 µm Ta (a), 20 µm Ta+60µm CH +20µm Al (b) and 20µm Ta+75µm vacuum gap +20µm Al (c).

In summary, the optical light and proton emission from the rear surface of the sandwiched targets have been used to diagnose fast electron transport inside targets. The results for the targets with different transport layers show that the fast electron beam are inhibited effectively, accompanied with beam breakup probably due to instabilities.

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