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High performance compact magnetic spectrometers for energetic ion and electron measurement in ultra intense short pulse laser solid interactions

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Ultra intense short pulse lasers incident on solid targets can generate relativistic electrons that then accelerate energetic protons and ions. These fast electrons and ions can effectively heat the solid target, beyond the region of direct laser interaction, and are vital to realizing the fast ignition concept. To study these energetic ions and electrons produced from the laser-target interactions, we have developed a range of spectrometers that can cover a large energy range (from less than 0.1 MeV to above 100 MeV). They are physically compact and feature high performance and low cost. We will present the basic design of these spectrometers and their test results from recent laser experiments.

I. Introduction

MeV electrons and protons are commonly produced from intense ($I\lambda^2 > 10^{19} W cm^{-2} \mu m^2$) short pulse laser-solid interactions. It is believed that the relativistic electrons are driven by direct laser electric fields and by the ponderomotive force associated with the gradient of the field [1, 2]. These electrons can then generate energetic protons through the target-normal sheath acceleration mechanism [3, 4]. These fast electrons and protons can effectively heat the solid target beyond the region of direct laser interaction and are important aspects of the fast ignition concept [5].

Due to the importance of understanding the generation and transport of these short pulse laser produced hot electrons and ions, extensive experimental effort has been made in the past decades to measure them quantitatively, through approaches such as inferring the hot electrons by measuring characteristic line radiation or bremsstrahlung [2, 6, 7]. This method relies on the accuracy of the collisional atomic data and the understanding of electron transport in the target. Another often-used approach is to measure directly the escaping electrons and ions in vacuum [2], and this method relies on the understanding or assumption of target space charge conditions [2, 8].

In the past few years, we have been pursuing direct measurements of the vacuum electrons. We employed several versions of electron spectrometers as illustrated in Fig. 1. The earlier version used a scintillating fiber array coupled with fiber front CCD (Fig. 1 (a)) [9], and later versions use image plates (Fig. 1 (b) and (c)). These new spectrometers are significantly more cost effective, physically compact, and easier to use. The

spectrometer response to energetic electrons has been absolutely calibrated. Proton spectrometers constructed using a similar design principle enable measurements of energetic protons with greatly improved energy resolution over that was achieved by the conventional radiochromic film packs. These improved hardware capabilities have been demonstrated in short pulse laser experiments studying the hot electron generation and transport.

II. Spectrometer design and calibration

The principle of our electron and proton spectrometers is simple. We used the magnetic field generated from permanent magnets to disperse charged particles according to their kinetic energy. In contrast to electromagnets, permanent magnets do not need an external power supply that could be affected by the often-intense electro-magnetic pulses in the short pulse laser environment. The magnetic field strength (typically with variations of less than 10% across the dispersion plane) was adjusted to obtain the desired energy coverage. For example, using a field of 0.8 Tesla, we can disperse electrons with energies from 0.1 to 100 MeV, and protons from 0.01 to 100 MeV using the design geometry illustrated in Fig. 2, with the image plate detectors set along the two curved dispersion surfaces for electrons and protons, respectively.

The detectors we used for these new spectrometers are image plates [10]. Although using scintillating fiber array coupled to CCD [9] has the advantage of taking data remotely without breaking the detector vacuum, using image plates have multiple advantages: higher resolution, EMP insensitivity, reusability and compactness. Image plates allow

much higher electron energy resolution than that of a scintillator array due to their smaller pixel size. Secondly, image plates are not sensitive to the electro-magnetic pulses from the ultra-intense laser-solid interactions, which present a harsh environment for CCD usage. Thirdly, image plates are reusable and significantly more cost-effective. Lastly, using image plate eliminates the complex mechanical requirements, such as vacuum electrical feedthroughs and a cooling system needed for a CCD. Due to these compelling reasons, image plates play an increase role as detectors in many short pulse laser physics experiments [11].

The physical sizes of the new spectrometers are all compact as shown in Fig. 1. Without additional shielding, the smaller (low-field, Fig. 1. (c)) spectrometers are about 0.5 inch wide, 3 inches tall and 5 inches long, and the larger (high-field, Fig. 1 (b)) spectrometers are about 2.5 inches wide, 3 inches tall and 5 inches long. The compact sizes enable these spectrometers to use little floor space in target chambers that are often crowded with many other diagnostics.

Additional considerations in the spectrometer design include radiation shielding and signal filtration. Proper shielding is important to reduce the background contamination caused by high-energy x-rays and gamma rays inside the laser chamber. Depending on the laser and target condition, a single layer of high-Z material such as tantalum or lead may be enough for laser intensities up to 10^{19} W/cm^2, while for higher laser intensities, we need a combination of high-Z material (tantalum or lead) with medium-Z copper and aluminum to block the MeV photons and ions. We found that an increase up to 100 in

signal-to-noise ratio can be achieved by varying the shielding for high intensity laser-solid interactions. Filtration in front of the image plates can provide particle discrimination and energy calibration (via stopping edges). For example, by adding a thin (3 μm) layer of polypropylene, a pure proton spectrum at energy range between 0.1 to 4 MeV can be separated from energetic ion contamination.

The calibration of the image plate response to hot electrons in these new spectrometers was initially done by cross calibrating to the old electron spectrometer based on the scintillating fibers, which was in turn absolutely calibrated using a pulsed electron gun: the total number of electrons collected by the spectrometer was referenced to the absolute value measured using a faraday cup. The cross-calibration was realized by placing the two spectrometers adjacent to each other in the laser chamber. However, this method had large uncertainties due to the electron source variation caused by the electron directionality from the targets. A more reliable calibration was performed using a set of absolutely calibrated ultra-thin thermoluminescence dosimeters (TLD), by exposing both the image plate and the TLDs to the same electron source within the same spectrometer. The details of this calibration were reported elsewhere [12]. Briefly, we calibrated the photostimulated luminescence of the image plate (Fuji BAS SR2040) for electrons at energy between 0.1 to 4.5 MeV. Together with the previous published data from Tanaka et al. [11] and with our simulation using the Monte Carlo radiation transport code MCNPX, this calibration data can be easily extracted for use on other spectrometer designs.

IV. Experiments and results

We used these compact magnetic spectrometers on the Callisto and Titan short pulse lasers at Lawrence Livermore National Laboratory as well as the Vulcan petawatt laser at Rutherford Appleton Laser laboratory. Here we only present some sample electron and proton data from the measurements on the Callisto laser.

Multiple electron and proton spectrometers were setup on Callisto laser shown in Fig. 3. The Callisto short pulse laser is a Ti:sapphire laser. It has a pulse length of 130 fs and delivers up to 10 J laser energy at 800 nm. The laser is focused with an f/3 parabola to a focus spot size of about 5 μm, and the laser intensity ranges from 10^{17} - 10^{20} Wcm^{-2}. The laser is incident on aluminum foil target at 45 degrees off normal. Arranged around the target in the horizontal plane, the electron spectrometers recorded the angular variation of the escaping electrons from the target, as shown in Fig. 4. Although the electron directionality has been previously studied by many[13], the physics of the electron angular distribution is still not well understood due to its complexity. The large variation in electron distribution is also the reason why the cross-calibration of two spectrometers did not work as desired.

At the same experiment described above, we fielded two high-field magnetic spectrometers (as shown in Fig. 3) to record the proton energy distributions. The proton spectrometers have a much higher energy resolution relative to that which can be achieved by commonly used radiochromic film. As comparison, in Fig. 5 the two proton energy data points that can be recorded by radiochromic film (HD-810) packs (with 20

μm Al foil in front) are marked on the top of the proton spectra. There are marked differences in the proton spectra, shown in Fig. 5, from the front and back of the target. Physically, this difference arises from the fact that the front and back of the target have very different plasma scale lengths at the instant the short pulse laser hits the target. The rapid creation of a hot electron component (before the ions get a chance to move) creates a large electric field that quickly accelerates the ions. The strength of this field is inversely proportional to plasma scale length on each surface [4]. Since the front of the target has a large plasma scale length due to the laser pre-pulse, the protons off the front can gain only so much energy. The rear surface of the target on the other hand (which was shielded from the pre-pulse) has an exceptionally sharp scale length, and therefore a much larger accelerating field, compared to the front: hence, higher energy protons relative to the front [14].

In summary, we have described the design of compact, cost effective and high performance particle spectrometers for fast electrons and proton measurements in short pulse laser plasma interaction. These spectrometers use images plates as detectors, whose response has been calibrated for fast electrons. We expect the data taken from these spectrometers will contribute to the study of fast electron and proton generation and transport physics.

Acknowledgments

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Figure Caption

Fig. 1. Pictures of three particle spectrometers. (a): the old version which uses scintillating fiber array coupled to a fiber front CCD; (b): the new high-field spectrometer that uses image plate; and (c): the new low-field spectrometer.

Fig. 2. New design of dispersion planes for electron and proton and their respective dispersion energies.

Fig. 3. Experimental setup in the Callisto laser chamber.

Fig. 4. Electron spectra for two laser intensities of 5×10^{18} (dots) and 5×10^{19} Wcm^{-2} (lines) from two spectrometers fielded at target front (Spectrometer #3, upper figure) and target back (Spectrometer #5, lower figure).

Fig. 5. Proton spectra from the same shots from two spectrometers. The energy steps from the RCF packs are marked in the figure as comparison.

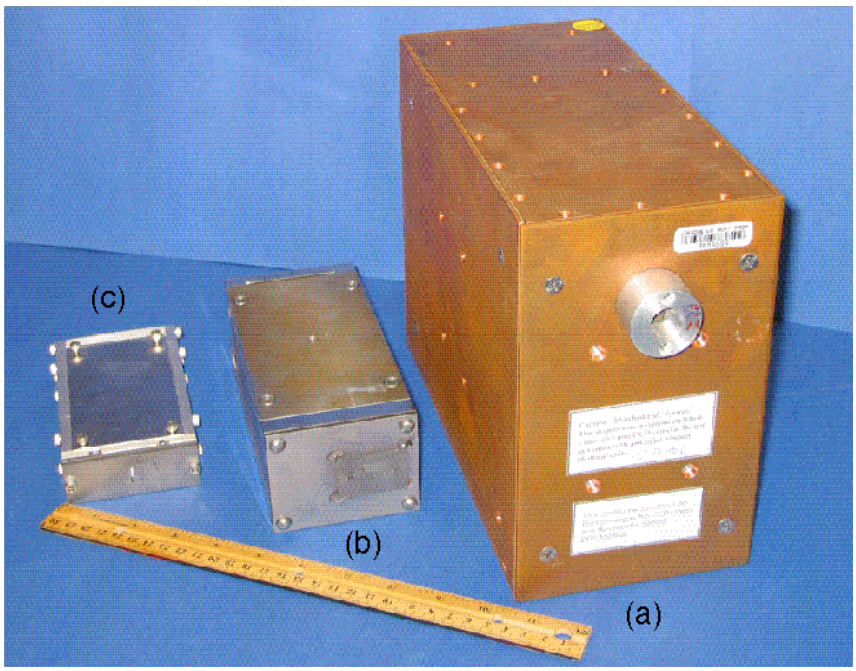
(c)
(b)
(a)

Fig. 1

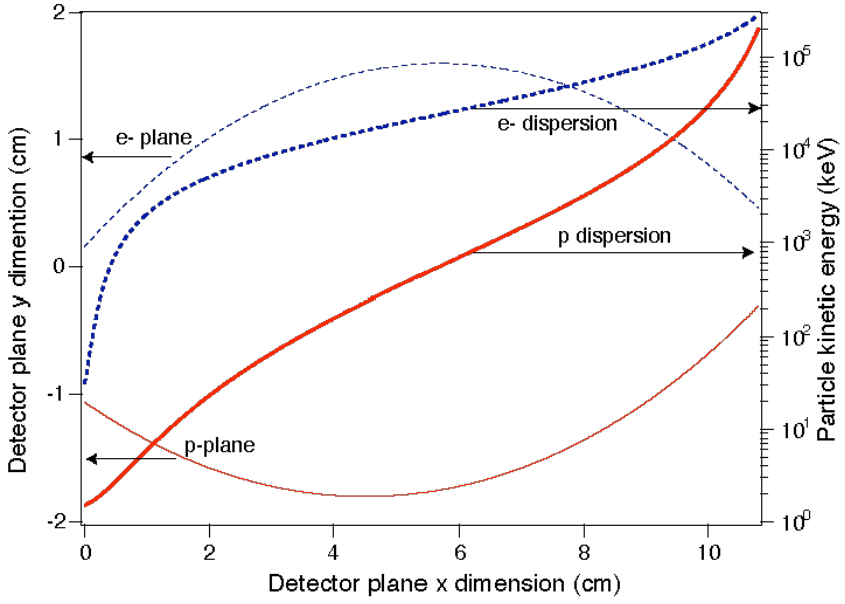
e- plane
e- dispersion
p dispersion
p-plane
Detector plane y dimention (cm)
Detector plane x dimension (cm)
Particle kinetic energy (keV)
2
1
0
-1
-2
0
2
4
6
8
10
10^5
10^4
10^3
10^2
10^1
10^0

Fig. 2

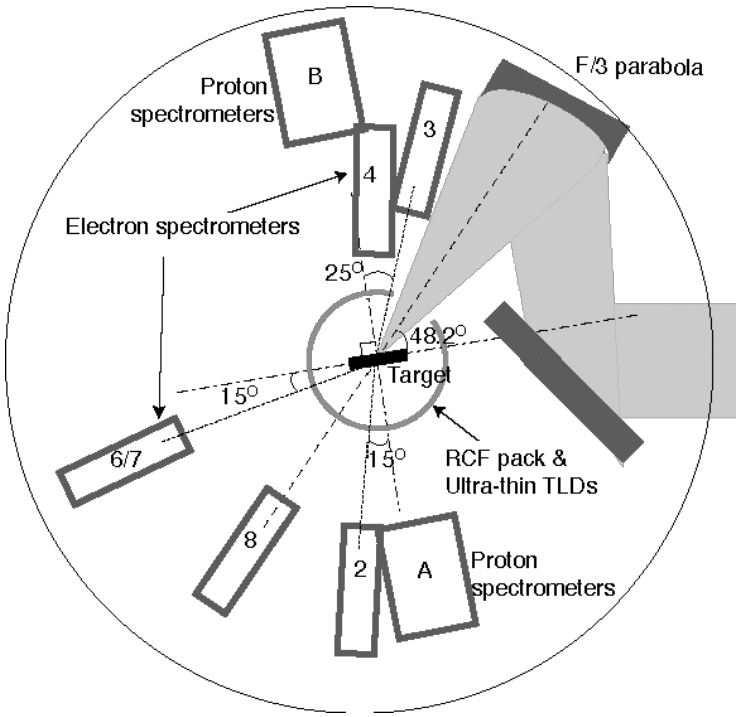
Proton
spectrometers
B
3
4
F/3 parabola
Electron spectrometers
25°
48.2°
Target
15°
6/7
15°
RCF pack &
Ultra-thin TLDs
8
2
A
Proton
spectrometers

Fig. 3

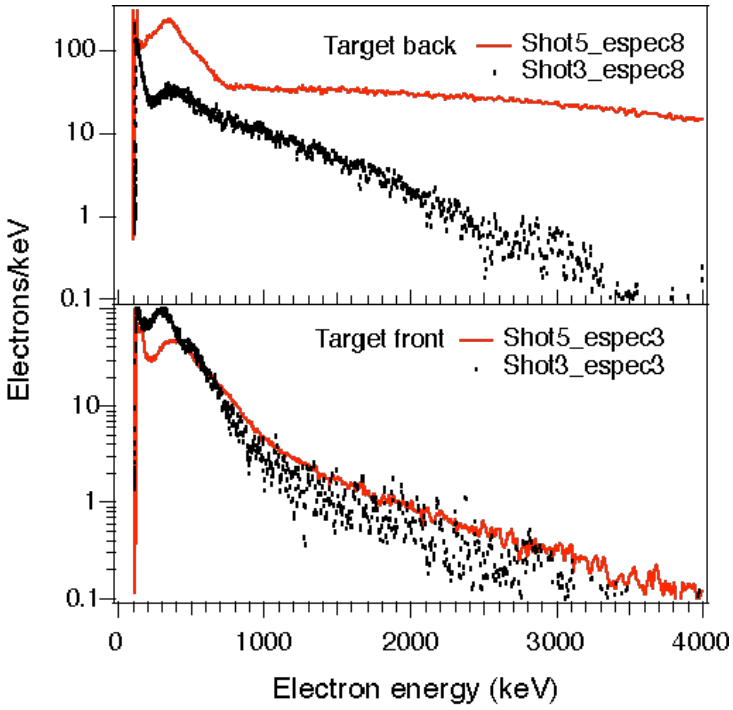
Target back
Shot5_espec8
Shot3_espec8
Target front
Shot5_espec3
Shot3_espec3
Electrons/keV
100
10
1
0.1
0
1000
2000
3000
4000
Electron energy (keV)

Fig. 4

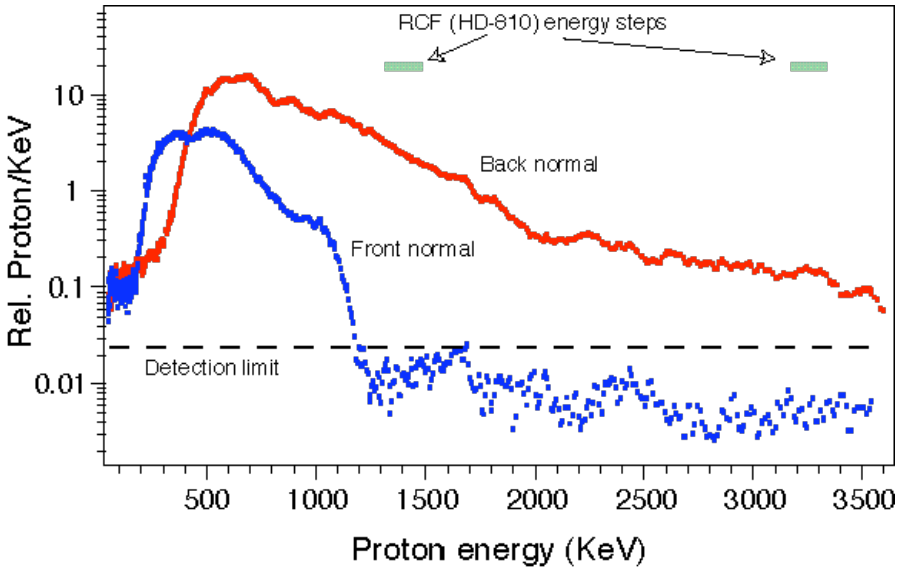
RCF (HD-810) energy steps
Back normal
Front normal
Detection limit
Rel. Proton/KeV
10
1
0.1
0.01
500
1000
1500
2000
2500
3000
3500
Proton energy (KeV)

Fig. 5