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2011 Chinese Phys. Lett. 28 095203

(http://iopscience.iop.org/0256-307X/28/9/095203)

CHIN. PHYS. LETT. Vol. 28, No. 9 (2011) 095203

Development of a Real-Time Ion Spectrometer with a Scintillator for Laser-Driven Ion Acceleration Experiments *

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(Received 15 June 2011)

A real-time ion spectrometer mainly based on a high-resolution Thomson parabola and a plastic scintillator is designed and developed. The spectrometer is calibrated by protons from an electrostatic accelerator. The feasibility and reliability of the diagnostics are demonstrated in laser-driven ion acceleration experiments performed on the XL-II laser facility. The proton spectrum extrapolated from the scintillator data is in excellent agreement with the CR39 spectrum in terms of beam temperature and the cutoff energy. This real-time spectrometer allows an online measurement of the ion spectra in single shot, which enables efficient and statistical studies and applications in high-repetition-rate laser acceleration experiments.

PACS: 52.38.Kd, 52.50.Jm DOI:10.1088/0256-307X/28/9/095203

The acceleration of ions to high energies within a short distance in laser plasma interactions has been widely investigated in the past decade, due to a variety of potential applications.[1−3] Usually the energy spectra of the ion beam accelerated in high power laser-plasma interactions can extend over a very broad range of energies.[4,5] In recent years, the production of quasi-monoenergetic proton beams or modulated energy spectra by the radiation pressure acceleration (RPA) mechanism, or by using complex targets and plasma devices, have also been reported.[6−10] Thus diagnosing the broad-range ion spectra with high resolution is indispensable and essential in laser-driven ion acceleration experiments.

The Thomson parabola (TP) spectrometer is a well-known frequently utilized diagnostic to characterize the energy spectra and the charge states of the accelerated ions. The ions enter a pinhole and get deflected by a magnetic and an electric field, and then incident on a detection medium in parabolic-like patterns. Usually, a traditional nuclear track detector CR-39 is utilized as the detection media at the back of the spectrometer. The advantage of CR39 over any other detector is that each pit on the detector corresponds to a single ion, thus it can deliver unequivocal and accurate information about the particle number and the ion flux. However, processing one piece of a CR39 detector demands several hours on average, including etching, scanning and particle counting even with automated systems. In some experiments, Fujifilm image plates (IPs) are used for ion detection.[11] However, in order to renew the image plates in multi-shot-experiments, the vacuum chamber has to be vented frequently, which is also time-consuming. Thus those traditional detectors are not adapted to high-repetition-rate (e.g. 10 Hz) laser systems.

In the case of high-repetition-rate laser plasma interactions, a single shot realtime measurement which can operate at a high repetition rate is highly essential. A real-time energy spectrometer based on microchannel plates (MCP) has recently been utilized in some laboratories to improve the experimental efficiency significantly.[12,13] However, a number of disadvantages have to be considered as well. Since the MCP is a very sensitive component and can only work under a high vacuum of the order of 10^{-6}–10^{-7} mbar, the utilization of such a system is limited, for example, in the laser-gas or laser-droplet experiments. In addition, once exposed to air, the MCP system takes several hours to be reactivated to apply the voltage.

In this Letter, we introduce a novel real-time de-

*Supported by the National Natural Science Foundation of China under Grant Nos 10905092 (Young Scientists Fund), 10925421, 10974250, and 10935002, the National Basic Research Program of China under Grant No 2007CB815102, and the Fundamental Research Funds for the Central Universities.
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tection medium-plastic scintillator for ion detection in the dispersion plane of a Thomson parabola spectrometer. The scintillator is a flexible, stable, large area detector, which can be cut to the required size and mounted like film. Coupling it to a Thomson parabola ion spectrometer enables single-shot online measurements. This can instantly provides specific information of the accelerated ion species, charge state and the energy spectra.

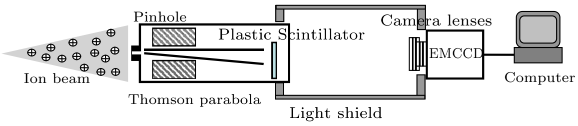

Fig. 1. Schematic of the real-time ion spectrometer.

A schematic of the real-time ion spectrometer is shown in Fig. 1. It is mainly composed of a compact Thomson parabola,[14,15] a sheet of polyvinyltoluene scintillator and an optical imaging system.

The magnetic field of the Thomson parabola given by two permanent magnets is measured with a Hall probe with peak strength of 0.225 T and the potential difference across the electric plates is 1250 V. The size of the pinhole applied in the experiment is 425 μm in diameter. The minimum energy of the protons which can be detected is 170 keV under this condition.

The plastic scintillator applied in the experiment is a 300-μm-thick sheet (BC430) from Saint–Gobain crystals. When the ion particles get deflected by the electric and magnetic field and then they hit on the scintillator, the scintillator emits photons centered at wavelength 580 nm. The resulting scintillation light is collected by a high-quality low-F-number camera lenses (Nikkor 35 mm,f/2D) to maximize the collection and the resolution and then imaged onto an Andor electron multiplying CCD (EMCCD), model IXON885. A protective layer of 100-nm-thick aluminum is coated on the front side of the scintillator to prevent the laser light and the stray light from reaching the CCD camera. The high sensitivity of the EMCCD camera which records the signal from the scintillator provides a reliable spatially distributed proton spectrum for each laser shot. The controllable EM gain of the camera enables the weak scintillation signal to be amplified and detected well above the noise level.

The main part of the real-time spectrometer is compact and can fit into the target chamber. The optical imaging system is positioned outside the chamber, gathering the scintillation light from the scintillator through a vacuum window. The stray light inside and outside the interaction chamber are strictly avoided to improve the signal-to-noise ratio of the system.

The optical image captured by the CCD camera delivers only the spatially distributed intensity of the scintillation light excited by the ions. In order to obtain the energy spectra of ion beams, a sensitivity calibration of the scintillator response to the ions is necessary. Since most of the ions accelerated in laser-plasma experiments are protons, we mainly calibrate the scintillator for protons. The dynamic range and the spatial resolution of the scintillators and the energy resolution of the real-time spectrometer have also been investigated.

The calibration experiment of the scintillator-based system was performed on a 4.5 MV Van de Graaff electrostatic proton accelerator at Peking University. The accelerator can deliver a dc beam current varying from nA to μA scale. A Faraday cup coupled with a sensitive galvanometer was used to measure the current of the proton beam. At the output of the accelerator, an electronic shutter was installed in the beam path before the protons reached the scintillator. The charge of the protons can then be calculated by multiplying the current and the shutter period. The scintillation signal was imaged onto the EMCCD camera outside the chamber.

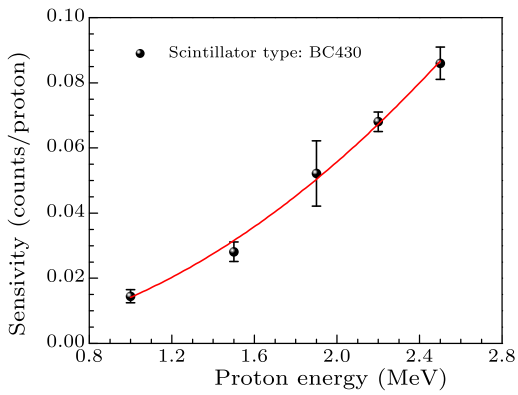

Fig. 2. The sensitivity of the scintillator to the protons as a function of the incident proton energy.

Unlike inorganic scintillators, the scintillation efficiency for organic scintillators is dependent on the incident particle energy, leading to the light output being unproportional to the deposited energy. Therefore, the sensitivity calibration was carried out at five proton energies: 1, 1.5, 1.9, 2.2 and 2.5 MeV. Figure 2 shows the sensitivity of the scintillator varying with the incident proton energy. The displayed data are averaged over several shots in order to reduce the shot-to-shot fluctuation error. The response of organic scintillators to the protons is observed to be a non-linear function of the energy. This result is consistent with the former investigations.[16]

The EM gain of the camera is applied in the laser-driven ion acceleration experiments to amplify the weak signal and to improve the signal-to-noise level. It has an important effect on the sensitivity of the real-time spectrometer. Therefore, the investigation of the gain factor of the camera is also necessary. An experiment was conducted utilizing a stable light source to measure the gain of the EMCCD. It was found that the actual gain factor of camera is linear with the gain setting in the software. After the calibrated gain factor is divided in the data extracting process to obtain the original intensity, all the data obtained with different gain settings can be normalized to original data without EM gain. The normalized data can be compared directly with high consistence, which has been further confirmed on the dc accelerator experiments. The details and the results will be described elsewhere.

The energy resolution of the real-time spectrometer was also investigated. Protons with slightly different energies (for example, E_n and $E_n - \Delta E_n$, as can be obtained flexibly from the dc accelerator), after deflected by the B and E fields, will produce two closely-spaced optical spots on the scintillator. When the two spots can just be resolved by the imaging system according to the Rayleigh criterion, the energy separation ΔE_n is the resolvable energy around E_n (the minimum energy separation that can be resolved). In this way, the energy resolution (defined as $E_n/\Delta E_n$) can be obtained over the whole energy range. The resolvable energy around 1 MeV is characterized to be 50 keV, giving a resolution of 20. The resolution at 2.5 MeV is measured to be 12.5.

The experimental results indicate that when plastic scintillator is utilized as the detection medium rather than CR39, the effect on the performance of resolving power is small. The reason is that among all the factors that affect the resolving power, the pinhole size of the TP dominates over all the other factors (include the spatial resolution of the detection media, the divergence of the beam and the spatial resolution of the optical imaging system behind, etc.) under the current conditions. To further improve the energy resolution, the pinhole size can be reduced, provided that the scintillation light is strong enough to obtain a measurable signal.

The novel real-time ion spectrometer was tested in a series of laser-driven ion acceleration experiments performed on the 20 TW Ti-sapphire laser system (XL-II) at the Institute of Physics, Chinese Academy of Sciences. The laser system is based on the CPA technique and is capable of delivering up to 600 mJ energy in 30 fs, with a repetition rate of 10 Hz. The ASE pedestal is of the order of 2×10^5 as measured by a third-order correlation system. The p-polarized laser pulse was focused with an $f/3.5$ off-axis parabolic mirror on aluminum foils at an incidence angle of 45°.

Ions emitted from the rear side of the foil were collected and collimated by the pinhole and deflected through the TP and then recorded by the real-time ion detector which has been mentioned above. The corresponding solid angle is 2.16×10^{-5} sr. For some shots, the ion spectra were recorded using CR-39 detectors instead of scintillator. In this way, the energy spectra obtained by these two detection methods can be compared directly.

Figure 3(a) shows a raw image of the scintillator captured by the EMCCD in laser-foil interaction. The data were taken at a laser intensity is 4.1×10^{18} W/cm^2. The target was a 2.5-μm-thick aluminum foil. The EM gain of the camera was set to be 300. The horizontal axis on the image gives the electric deflection, whereas the vertical axis gives the magnetic deflection. The ion tracks distributed on CR39 under the same experimental conditions is illustrated in Fig. 3(b). The ion pits were automatically scanned and readout by the TASLIMAGE system manufactured by Track Analysis Systems Ltd.

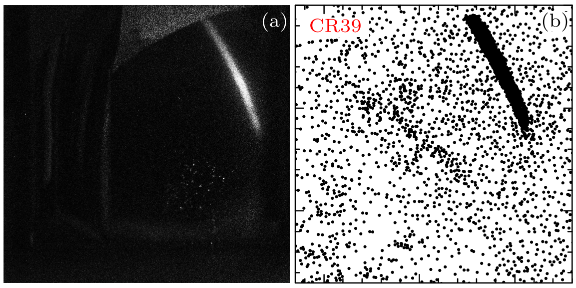

Fig. 3. (a) Raw image of ion spectrum on the scintillator. (b) Image of ion tracks distributed on the CR39.

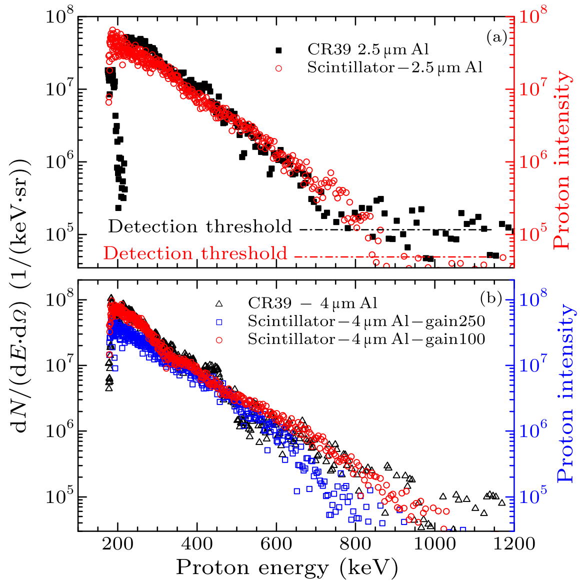

Fig. 4. Comparison of the proton energy spectra measured by the scintillator and the CR39 detector: (a) proton spectra accelerated from 2.5 μm Al measured by the CR39 (square) and by the scintillator (circle), (b) proton spectra accelerated from 4 μm Al measured by the CR39 (triangle), by the scintillator when the EM gain is 100 (circle) and 250 (square).

The calibration data obtained from the electrostatic dc accelerator as mentioned above were extrapolated to our experimental conditions and applied during the deconvolution process. It should be noted that the typical current density of the ultrashort (ns scale) proton bunches accelerated from the laser-plasma interactions is estimated to be $10^{-4}\sim10^{-3}$ A/cm^2, while in the dc accelerator it is about 10^{-10}–10^{-8} A/cm^2. The scintillation efficiency of the plastic scintillator in the two experiments might differ due to the significant difference in the current density. Therefore, the absolute value of the sensitivity was not directly used in the data extracting process. Instead, the energy-dependent relative response curve of the scintillator was applied to obtain the energy distribution function of the ion beam, as illustrated in Fig. 4(a). The ion spectrum deduced from the CR39 data is also presented in the graph as reference (black squares). The absolute intensity of the ion beam is inferred from the CR39 data, since the CR39 gives the most accurate information about the ion numbers. The result gives a total number of 1.3×10^5 protons entering the pinhole of the TP spectrometer.

The spectra in Fig. 4(b) were obtained when the thickness of the foil was changed to 4 µm. The EM gain of the camera is changed from 100 to 250 in order to check the influence of the gain setting on the final proton spectra. The calibrated gain factor of the camera mentioned above was taken into account in the data extracting process.

As can be seen from the graphs, the extrapolated proton spectrum from the scintillator shows an exponential energy distribution. It exhibits an excellent agreement with the CR39 spectrum when the temperature (slope of the curve) and the cutoff energy are considered. For the 2.5-µm foil, the cutoff energy inferred from the scintillator spectrum is around 800 keV, which is consistent with the CR39 spectrum. For the 4 µm foil, the spectra from the two diagnostics both indicate a cutoff energy around 1 MeV.

The dashed lines in Fig. 4(a) show the detection threshold of the two diagnostics, which are mainly decided by the background level of the detection media. For the CR39, the background is mainly caused by the "fake" ion pits distributed all over the piece, as illustrated in Fig. 3(b). While for the scintillator-based system, the background is mainly caused by the stray light. For protons with energy larger than 800 keV, the flux incident on the detector is too low,and then distinguishing the signal from background is difficult and statistical fluctuations are observable on the spectrum.

From Fig. 4(b) one can see that the modification of the EM gain setting of the camera has a negligible influence on the final proton spectrum. This is a crucial issue needed to be confirmed when an EMCCD is used in the diagnostics. The deviation of the two spectra under EM gains 100 and 250 is mainly due to the shot-to-shot fluctuation in the experiments.

It should also be noted that another parabolic track of carbon ions is appeared on the CR39 detector. However, this parabola track is not observable on the scintillator. This phenomenon indicates that the intensity of the carbon ions accelerated under the current experimental conditions is below the detection threshold of the real-time diagnostics. Thus the sensitivity of the real-time spectrometer needs further improvement.

In conclusion, we have designed and developed a novel real-time ion spectrometer mainly based on a high-resolution Thomson parabola and a plastic scintillator. The sensitivity and energy resolution of the diagnostics is calibrated using an electrostatic dc proton accelerator. The feasibility and reliability of the system have been confirmed in laser-driven ion acceleration experiments performed on the XL-Ⅱ laser system. The proton spectrum extrapolated from the scintillator data shows an excellent agreement with the CR39 spectrum, with respect to the temperature and the cutoff energy.

The striking advantage of using the scintillator-based real-time diagnostics is the possibility of online observation since the CCD images can be evaluated with a computer immediately. The average data-extracting time is thus reduced from several hours to a few minutes, which allows for very flexible experiments. Furthermore, large amounts of data can be acquired using this system, which enable a statistical interpretation of the acceleration experiments. It provides us a reliable and efficient tool for further laser-driven ion acceleration experimental studies.

We should also pay attention to the drawbacks of the scintillator-based diagnostics. The most important drawback compared to CR39 is that it is not sensitive to individual ions like CR39 and therefore requires a higher ion flux to produce a measurable signal. The sensitivity of the real-time spectrometer should be further improved. In addition, extra efforts must be made to strictly avoid the stray light in order to reduce the noise level of the scintillator-based system, while the CR39-base system does not need.

We thank Prof Jian-Yong Wang and Ling-Hua Gong from the Institute of Heavy Ion Physics of Peking University for their support and operation of the 4.5 MV electrostatic accelerator experiments.

References

[1] Key M H et al 2006 *Fusion Sci. Technol.* **49** 440
[2] Romagnani L et al 2005 *Phys. Rev. Lett.* **95** 195001
[3] Borghesi M et al 2006 *Fusion Sci. Technol.* **49** 412
[4] Fuchs J et al 2007 *Phys. Rev. Lett.* **99** 015002
[5] Lee K et al 2008 *Phys. Rev.* E **78** 056403
[6] Henig A et al 2009 *Phys. Rev. Lett.* **103** 245003
[7] Palmer C A J et al 2011 *Phys. Rev. Lett.* **106** 14801
[8] Hegelich B M et al 2006 *Nature* **439** 441
[9] Toncian T et al 2006 *Science* **312** 410
[10] Chen M et al 2009 *Phys. Rev. Lett.* **103** 24801
[11] Mančić A et al 2008 *Rev. Sci. Instrum.* **79** 073301
[12] Schowoerer H et al 2006 *Nature* **439** 445
[13] Harres K et al 2008 *Rev. Sci. Instrum.* **79** 093306
[14] Carroll D C, Brummitt P A, Neely D et al 2010 *Nucl. Instrum. Methods Phys. Res.* A **620** 23
[15] Carroll D C, Jones K, Robson L et al 2005/2006 *Central Laser Facility Annual Report* 16–20
[16] O'Rielly G V, Kolb N R and Pywell R E 1996 *Nucl. Instrum. Methods Phys. Res.* A **368** 745
[17] Saraf S K, Brient C E, Egun P M, Grimes S M, Mishra V and Pedroni R S 1988 *Nucl. Instrum. Methods Phys. Res.* A **268** 200