TOF-based diagnosis of high-energy laser-accelerated protons using diamond detectors

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Introduction

The Time of Flight (TOF) technique has been so far extensively used for the diagnosis of laser-accelerated proton and ion beams at low energy (up to tens of MeV) and single shot laser systems [1,2]. Coupling the technique with detectors as Faraday Cups, ion collectors or semiconductor-like detectors as diamond and silicon carbide ones, such diagnostic technique allows real-time measurement of beam characteristics such as the energy cut-off and distribution, current as well as allowing to monitor shot-to-shot reproducibility.

Detection of high energy ions in high power laser experiments is mostly based on well-established detectors, e.g. Radiochromic films (RCF), Image Plate or Nuclear Tracks detectors (CR-39), which require some form of processing after the exposure, and are typically used on a single-shot basis [3].

Thanks to ongoing advances in laser technologies, the acceleration of high-energy ions at high repetition rate is becoming possible, opening new opportunities for the use of laser-accelerated ion beams in multidisciplinary applications. For this purpose, real-time measurements of laser-generated particles, possible with TOF techniques, become a crucial requirement for obtaining a controlled and stable beam [4].

However, the detection of ion/proton beams up to the ~100 MeV level with TOF methods requires the use of fast detectors with high temporal resolution, in order to disentangle the high-energy component of the beam [5]. Diamond and silicon carbide detectors, displaying interesting advantages as radiation hardness, fast time response and high signal-to-noise ratio, are particularly attractive for time-of-flight measurements of highly pulsed, high-energy ion beams [6,7].

The experiment reported here, carried out in the VULCAN Target Area Petawatt was aimed at testing diamond detectors in a TOF arrangement with high-energy laser-accelerated protons, and demonstrate the suitability of such method for high energy proton detection. A novel analysis method was developed to convert TOF signal into energy distribution for a specific ion species, i.e. protons and was validated comparing the results with well-established diagnostics, namely RCF and CR-39 stacks and Thomson Parabola spectrometer.

Experimental Setup

The experiment was conducted at the PW VULCAN target area Petawatt with the setup shown in Fig. 1.

The laser of wavelength of 1.054 µm and pulse duration of about 700 fs FWHM delivered up to 600 J of energy on target in a single shot. The laser was focused onto a 25 um Aluminium foil target by a f/3 off axis parabolic mirror with an incidence angle of 20° with respect to the target normal.

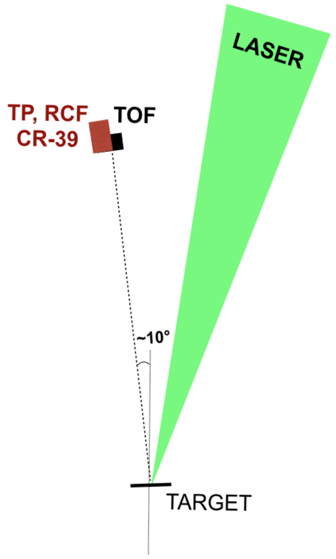

Fig 1. Experimental set-up used during the irradiation with PW VULCAN laser.

A single crystal diamond detector (sDD), 3x3 mm^2 and 500 μm thick, and a polycrystalline diamond detector (pDD), 2x2 mm^2 and 100 μm thick, both supplied by the CIVIDEC company [8] were placed at different flight paths, ranging from 1 m up to 4 m, in the backward direction at about 10° with respect to the target normal direction.
Due to the high particle flux of laser-accelerated proton beams, such detectors are used in current mode, i.e. the single particle signal cannot be distinguished and a total average current is detected. Moreover, no amplification is needed to acquire a sufficient signal amplitude to exceed the background noise (mainly due to the electromagnetic pulse, EMP, typical of a high-power laser interaction environment). For such reason, the detectors were directly connected to a 2.5 GHz 40 Gs/s Tektronik digital oscilloscope with a 50 Ω load impedance for the signal acquisition.

A Thomson Parabola Spectrometer (TPS) was facing the front

side of the target at a pinhole-target distance of 127 cm and at an angle of about 10° from the target normal, to provide ion species identification and ion energy spectra. Radiochromic films stacks (EBT3 model) and CR-39s were also used to provide a reference proton energy spectrum in the backward as well as in the forward direction.

Images of the DD and TP detectors placed downstream a pipe and within the target chamber are shown in figure 2.

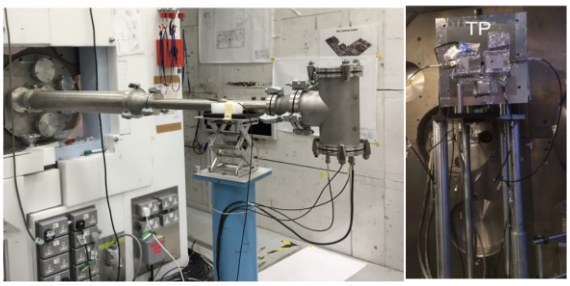

Fig 2. Snapshot of the DD detectors and the TP mounted in TAP.

Methods and results

Figure 3 shows a typical TOF signal acquired with the pDD detector placed at 2.35 m from the target in the backward direction.

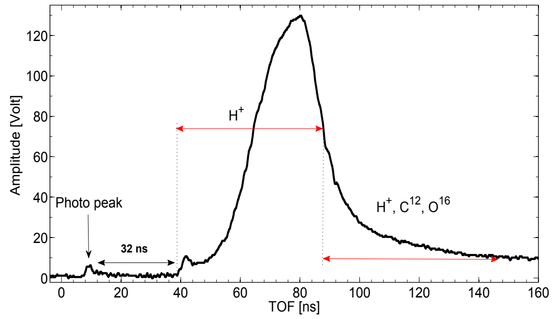

Fig. 3. TOF signal acquired with the pDD @ 2.35 m downstream the target.

The first tiny peak appearing at the beginning of the time axis (7-12 ns) corresponds to the so-called photo-peak, arising from UV, X-rays and fast electrons emitted from the target, and fixes the starting point for the acquisition, i.e. the trigger signal.

The low sensitivity of thin diamond detector to light is reflected in a narrower photo-peak with respect to detectors such as Faraday cups and ion collectors, enabling to deconvolve the high-energy proton component, even for short flight paths and short TOF (~ 30 ns) as in the case shown in Fig. 3.

In spite of the short flight path (2.35 m), two time-separated large peaks can be easily distinguished in the TOF signal, arising from the different ion species accelerated from the target. When different ion species are accelerated together with protons, as in the case of figure 3, the TOF signal results from the convolution of the signals generated from the single ion species reaching the detector at a specific TOF.

Following the approach shown in [9,10,11], the total TOF signal is typically described using the Maxwell-Boltzmann shifted functions (MB), defined for each ion species and depending on two parameters: the ion shift velocity and the temperature.

In the experiment described here, the use of the TPS placed along side the diamond detectors provided the identification of the ion species accelerated and the measurement of the corresponding energy cut-offs. Carbon and Oxygen ions with charge states, respectively, from 4+ to 6+ and from 6+ to 8+ were identified with maximum energies per nucleon not exceeding 4 MeV/u and a flux near the cut-off of about few 10^9 MeV^{-1} sr^{-1} .

Thanks to the simultaneous TPS measurements of the maximum ion energy, the corresponding minimum TOF (at a specific flight path) expected in the TOF signals for carbon and oxygen ions can be calculated for each shot. This allows selecting a TOF interval in which the signal is solely generated from protons and can therefore be easily converted in an energy distribution.

In particular two different regions in the TOF signal shown in Fig.3 are identified: in the range 40-85 ns the signal is originated exclusively from protons in the energy range between 4 MeV and 18 MeV; at 85-150 ns the signal results as the sum of H+, C^{12} and O^{16} signals. In this latter region, it is not possible to directly disentangle single species contributions from the total TOF signal to reconstruct the energy spectrum for each ion species.

On the contrary, in the first time interval (40-85 ns), the incident kinetic energy of protons can be calculated from the measured TOF values, given the flight path and considering the distance travelled from the source to the detector by the UV and X-rays as it is reported in [7].

The signal amplitude, according to the detector characteristics, gives information on the energy distribution and the absolute number of particles.

In contrast to detectors as faraday cup and ion collector, where the response is proportional to the flux of particles impinging onto the detector, for semiconductor-like detectors, such as silicon carbide and diamond detectors, the signal amplitude depends on the energy released in the detector's active layer and the electron-hole pair energy creation of the given detector material. This, together with the high temporal resolution characterizing such detectors, is extremely advantageous for diagnosing laser-driven ion experiments.

Thus, knowing the detector response and the energy of particles reaching the detectors, the energy distribution for a given ion species can be reconstructed from the TOF signals.

Such technique was used so far to reconstruct the energy spectrum for low-energy laser-accelerated protons (few MeV) having a range less or equal than the detector's active thickness. In such case, the particles impinging onto the detector release their total kinetic energy, directly calculated from the TOF measurement, and the energy distribution can be easily extracted.

On the other hand, for particles having higher incident kinetic energy, so that they release only a fraction of the incident energy within the detector thickness, the energy loss corresponding to the kinetic energy given by the TOF measurement has to be estimated to extract the correct energy distribution and the absolute number of particles.

For this purpose, a procedure has been recently developed for the energy spectrum reconstruction from TOF signals, specifically optimized for protons up to 100 MeV energy level. The approach is based on the use of Monte Carlo simulations reproducing the experimental conditions to calculate the energy loss in the detector. As an example the proton energy distribution in the energy interval within 4.5 MeV and 18 MeV related to the TOF signal of Fig. 3, is shown in Fig.4.

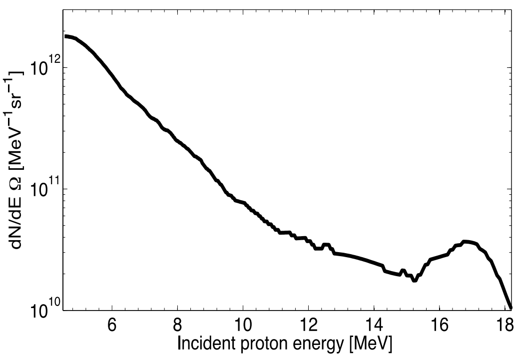

Fig.4 Proton energy spectrum reconstructed for the shot shown in Fig.3

As it is shown in Fig. 4, a decreasing exponential energy distribution, typical of the TNSA acceleration regime, can be clearly observed with a cut-off energy of about 18 MeV.

Moreover, performing an integration in energy is then possible to extract the absolute number of particles per sr in such energy interval, resulting of $3.6\ 10^{12} \pm 2.7\ 10^{11}$.

The procedure was also validated by comparing the results, in terms of proton maximum energy and flux, with data obtained with the TPS, the RCF stacks (EBT3 model) and the CR-39s placed at the same distance and close to the diamond detector.

The comparisons show a rather good agreement confirming the reliability of the TOF technique, coupled with the use of diamond detectors and the proposed analysis method, for high-energy laser-accelerated proton diagnosis.

Finally, the pDD was also placed on the rear side of the target direction (forward direction) at about 2.5 m from the target, where, according in the TNSA regime, protons are expected to be accelerated to a higher energy cut-off than in the backward direction. A proton energy cut-off of 31 MeV, corresponding to a TOF of 33 ns, was measured in this case. Such result was also consistent with measurements obtained with a RCF stack placed in the forward direction.

Conclusions

The results discussed in this contribution confirm that TOF technique represents suitable tool for the measurement of the energy distribution and the flux of protons in a laser-plasma experiment. In particular, diamond detectors, characterized by a low sensitivity to X-rays, a fast signal and a high signal-to-noise ratio, are particularly suitable for the detection of high-energy laser accelerated protons as demonstrated with the experiment conducted with the PW Vulcan laser system. The new analysis procedure, for energy spectrum reconstruction, which has been developed to convert TOF signals in energy distribution in the energy range from tens of MeV up to 100 MeV, was also validated against well-established diagnostics, as TPS, RCF and CR-39s and the complete analysis will be discussed elsewhere.

TOF measurements up to a proton energy cut-off around 30 MeV were performed for the first time, with a limited flight path. Such results together with the possibility to measuring the beam characteristics in real time, demonstrate how such technique coupled with the use of diamond as well as SiC detectors, represents a promising instrumentation for on-line measurement of higher (100 MeV) energy protons accelerated from high-repetition rate laser systems. This diagnostic approach is particularly attractive for the characterization of single species ion beams, e.g. as emerging from cryogenic hydrogen targets [12].

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