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ORIGINAL PAPER

Real-time diagnostics of fast light ion beams accelerated by a sub-nanosecond laser

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Abstract. Multi-MeV proton and light ion beams had been produced using the 300 ps, kJ-class iodine laser, operating at Prague Asterix Laser System (PALS) Centre in Prague. The target material had been chosen in such a way so as to increase the proton beam current density (approaching 0.1 A/cm^2 at the distance of 1 m from the source). The real-time ion detection was performed by means of a standard flat and ring ion collectors (IC) in the time-of-flight (TOF) configuration. The ICs had been shielded with aluminum foils of various thickness, in order to cut the long photo-peak contribution that is usually overlapping with the ultrafast particle signal, and to analyze mainly the laser-accelerated proton beam. The processing of the obtained experimental IC data is described in some detail, including the deconvolution of TOF signals, evaluation of the UV/soft-X-ray photo-peak absorption, and ion transmission calculations for different metallic filters.

Key words: laser-driven acceleration • ion beams • real-time diagnostics

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Introduction

Particle acceleration via the laser-plasma interaction at relativistic laser intensities is a novel technique which has the potential to revolutionize the methods used to generate streams of light ions for various practical purposes [1]. A spectacular increase in the brightness and a reduction in the pulse duration of particle beams would change the way the particle beams are used to investigate the properties of matter, with direct applications in biology, chemistry, solid-state physics, etc. Moreover, due to the compactness of the source, this new technique is considered to be a candidate for replacing conventional large accelerator systems that are used nowadays in nuclear experiments or in hadrontherapy centers for tumor treatments [12].

In the near future, in order to demonstrate that laser-plasma accelerators may indeed replace expensive conventional systems, not only the achieved maximum ion energy should be increased, but also the quality of the beam should be improved in terms of luminosity, divergence, energy spectrum and reproducibility. This in turn means that real-time diagnostic systems must be developed, which would allow experimenters to monitor and "tune" the laser-accelerated particle beams to meet the desired specifications.

Although in the upcoming years a dramatic rise in the attainable laser intensity is expected, that would make it possible to obtain values exceeding 10^{23} W/cm^2, e.g. in the future extreme light infrastructure (ELI) femtosecond-laser facility in Czech Republic [5], it is nevertheless important to study in detail the relativistic laser-matter interactions also at lower laser intensities. In fact, laser parameters (the prepulse and the peak laser intensity, the quality of the laser focal spot, the location of the focus, the contrast, the degree of polarization, and the shot-to-shot reproducibility) as well as the target properties (its structure, mass, density, shape, and thickness) are of fundamental importance for optimization of the generated beam. Therefore, investigations carried out using a relatively long-pulse laser systems ($0.1 \div 1$ ns) may still provide up-to-date results on the generation of very high gradients and currents for ion acceleration [9, 13].

Materials and methods

The basic parameters of the laser-driven ion beams, such as the mean and the maximum energy, the angular distribution and the total beam charge of very fast ion streams have been estimated by means of a variety of devices and techniques [2, 3, 15]. Nevertheless, it is important to develop diagnostic methods that allow to characterize the ion beam in a single measurement, mainly because of the shot-to-shot fluctuations, which are not negligible. The main goal of our work is to set up a real-time diagnostics framework that could be used to evaluate the kinetic energy of fast proton/ion beam accelerated by high power lasers and also give an absolute particle number estimate by means of relatively simple and cheap devices.

The TOF technique employed in electrostatic IC is widely used for plasma ion characterization at different laser intensity regimes [9, 11, 13, 16, 18]. The TOF spectra are usually composed of a broad ion peak signal (several microseconds at few meters detection distances) and a narrow photo-peak (few hundred nanoseconds) generated by the secondary electron emission on the collector due to the X-ray ultraviolet (XUV) plasma component [10]. For ion energies of several MeV, especially for proton or light ion beams, the difference in TOF between the photo-peak and the ion peak drastically decreases, to the extent that it becomes difficult to distinguish between these contributions.

In order to filter out the XUV component a simple novel method based on the application of thin metal foils has been developed at PALS. The crucial parameters of the foils – such as the material choice and the thickness – had been selected by means of an analysis which was aimed at an optimisation of the radiation transmission (a filter transmission database was used [6]) and the particle stopping range (the SRIM Monte Carlo (MC) code was used [4]).

In the experiment reported here three different configurations had been used: i) a flat IC divided into two or more sections (a multi-shielded IC), one of them unshielded and the others shielded with foils of different thickness, in order to get the information on different ion energy ranges; (ii) a shielded flat IC, placed at the rear side of an unshielded ring ion collector (ICR); (iii) a multi-shielded ring ion collector, employed to perform contemporary spectrometry measurements by means of an ion energy analyzer (IEA) [18]. As a filter we used Al foils with thickness in the range of $2 \div 10$ μm, together with and all the IC configurations described above. The different filter thicknesses used in the course of the experiment also helped us to confirm the validity of the technique used to filter out the photo-peak contribution (depending on the plasma vacuum ultraviolet VUV/X-ray spectrum and on the quantum efficiency of the detector), and gave us the possibility to vary the cut-off for the slowest ions in order to check experimental results against theoretical expectations.

Experiments had been performed at PALS facility [7] by using the first harmonics (1315 nm) of the 300 ps pulsed laser at a maximum energy of about 600 J (the beam spot had the focused diameter of approximately 100 μm). Various flat, bulk samples (graphite, silicon, hydrogen-enriched silicon) had been used as targets in order to accelerate protons and light ions in the vacuum ($\sim 10^{-6}$ mbar) to high kinetic energies. A picture of the interaction chamber at PALS is presented in Fig. 1a, along with the drawings of the three developed by us IC

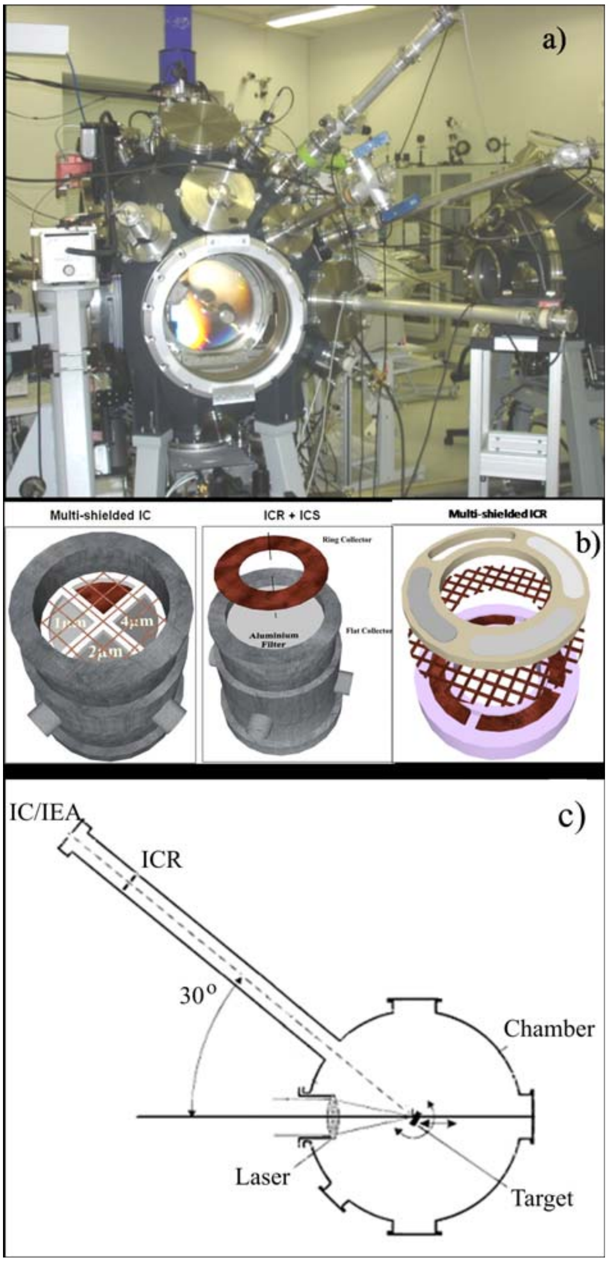

Fig. 1. (a) Photo of the interaction chamber at PALS; (b) the three different IC configurations; (c) a sketch of the experimental setup.

detection systems (Fig. 1b) and a simple sketch of the experimental setup, which are presented in (Fig. 1c).

Results and discussions

In Fig. 2 we show two typical examples of the experimental results, obtained by irradiating the graphite target (Fig. 2a) and the hydrogenated annealed silicon target at the maximum laser energy (Fig. 2b). The TOF spectra (shown on a semi-logarithmic scale) from the ICR the higher signal and the flat IC the central signal evidently show the long photo-peak (0÷100 ns), the fast ions (100÷200 ns) and the slow ions (> 200 ns); however, in both spectra the end of the photo-peak overlaps with the beginning of the fast ion signal, which makes the calculation of the maximum ion energy questionable. The TOF spectrum of the flat ion collector shielded (ICS) with 2 μm Al foil (the lower signal) has however a completely different shape: the long photo-peak is no longer clearly visible (as predicted by the filter X-ray transmission calculations), and the same is true for the slow ions (in perfect agreement with the ion stopping power of the Al filter); evidently only the fast ions (70÷250 ns) are detected. There is a possibility to sensibly compare the TOF and the current density of all the reported spectra, since they had been normalized at the same TOF-distance of 1 m, taking into account the effective active area of each detector.

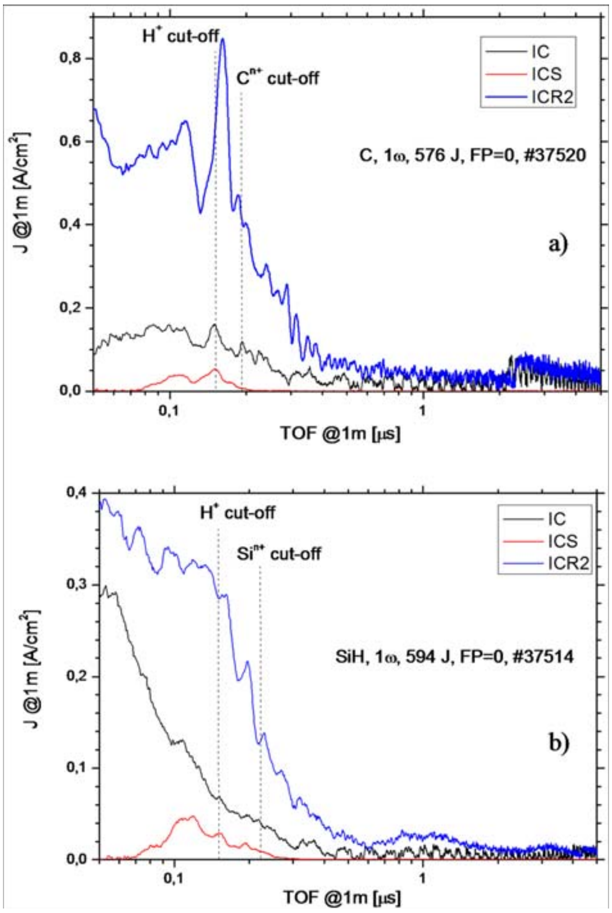

Fig. 2. Typical TOF spectra registered on different IC's for (a) the graphite target, and (b) for the hydrogenated annealed silicon target.

A zoom of the ICS spectrum (linear scale) for the H-enriched target is shown in Fig. 3a. The TOF spectrum consists of different contributions originating from the plasma-accelerated H^+ and Si^{n+} ions, which produce a characteristic multi-hump shape. Assuming that the main peak was centered at about 180 ns, the corresponding Si^{n+} current and the energy are about 40 mA and 10 MeV, respectively. The presence of proton and different silicon charge states in the accelerated bunch is confirmed by the IEA analysis, as may be seen on a typical spectrum displayed in Fig. 3b. The high charge state Si ions (up to 14^+) had been produced, as well as a large number of protons.

Finally, by means of a deconvolution method it is possible to extract the H^+ signal that is naturally superimposed on the Si^{n+} signal. In this way it becomes possible to give a quantitative estimate of the maximum proton/ion energy and total charge. To this end the following Boltzmann-like fit distribution had been proposed [8]:

$$j_{\mathrm{TOF}}(t) = A\frac{L}{t^5}\exp\left[-\frac{m_i}{2kT}\left(\frac{L}{t}-v_i\right)^2\right] \tag{1}$$

where: j is the TOF current; A is a normalization constant; L is the distance between the target and the detector; m_i is the ion mass; k is the Boltzmann constant; T is the plasma temperature; t is the TOF; v_i is the ion drift velocity, i.e. an additional component due to the movement of the plasma center-of-mass and to the quasi-electrostatic field acceleration.

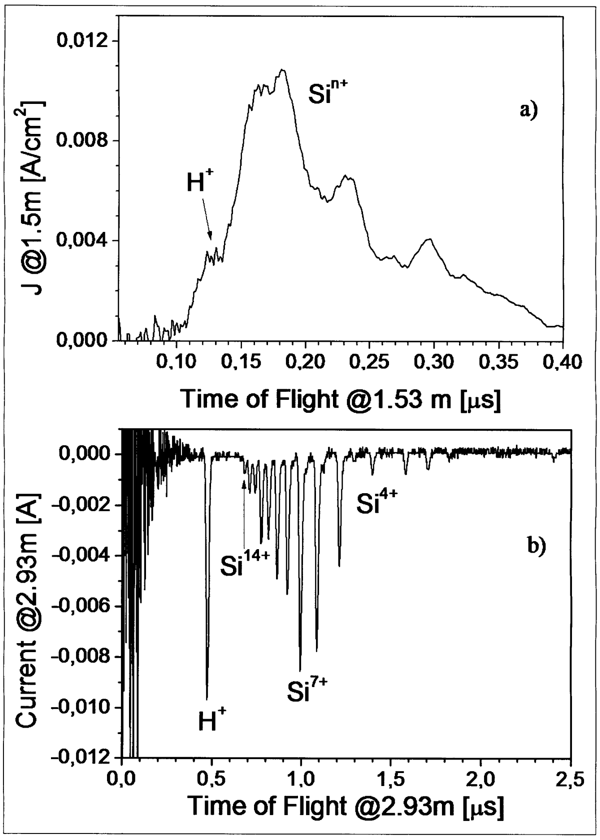

Fig. 3. (a) The shielded ion collector (ICS) TOF spectrum; (b) the IEA spectrum for a hydrogenated annealed silicon target.

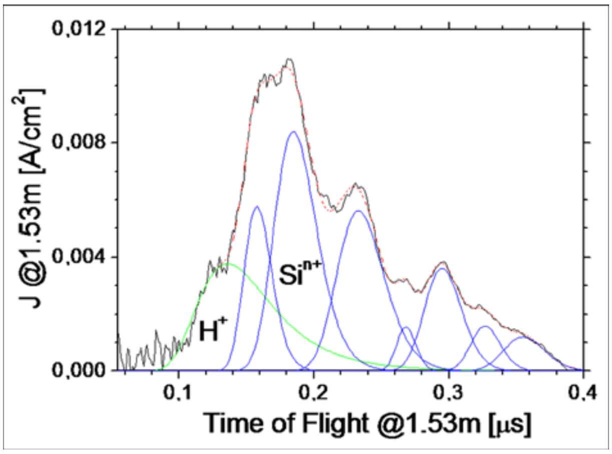

Fig. 4. The deconvolution of the ICS-TOF spectrum.

Figure 4 shows the result of the deconvolution procedure applied to the TOF spectrum previously reported in Fig. 3a. The fitting procedure, performed by means of a numerical code (Peak Fit 4.11) using the standard least-squares minimization ($r^2 = 0.99$), not only identified several silicon ion peaks for each recorded spectrum, but also clearly showed proton peaks. The first peak (from the left) corresponds to the proton component, while the others correspond to Si^{n+} (the calculated total signal is indicated by a dashed line). The maximum measured proton current is about 13.5 mA; moreover, by integrating in time the H^+ peak, it is possible to calculate the proton total charge and, as a consequence, the total number of accelerated fast protons per laser pulse, which is gives approximately $2 \times 10^{10}/cm^2$ at the distance of 1.5 m from the plasma source. The maximum kinetic energy of the proton signal, calculated at a level of 10% of the TOF peak, is approximately 2.2 MeV. In the deconvolution procedure described above the transmission and the energy loss of ions propagating through the filter were not taken into account; however, present authors estimated these effects in previous papers [13], showing that only the yield of the slowest ions (the tail at long TOF close to the energy cut-off) is underestimated, without any significant error in the evaluation of the maximum proton/ion energy and current.

Conclusions

The use of the real-time diagnostic technique by means of various ICs shielded by thin metal foils for multi-MeV laser-accelerated plasma proton and light ion detection had been investigated, with encouraging results. This technique can clearly separate the relatively long photo-peak and the fast ion signal, providing a direct estimate of the maximum ion energy and total ion charge.

The reported setup is inexpensive, simple and operates in real time, which is a considerable advantage if the shot-to-shot stability of the laser-accelerated beam has to be studied. This diagnostics may be considered complementary to the ion energy analyzer spectrometers, which are used for the ion charge state and species recognition, and of the Thomson parabola spectrometers, which are used for the determination of the ion energy distribution.

Recently the large-band-gap semiconductor detectors (single-crystal diamond and SiC) had also been preliminary tested in the TOF configuration and found to be promising, because they are not sensitive to the visible and near-UV radiation, which constitutes the long plasma photo-peak, although they require an accurate calibration [14, 17].

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