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Thomson parabola spectrometry of laser generated plasma at PALS laboratory

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Abstract. Laser generated Plasma has been obtained at PALS laboratory in Prague irradiating thin films by Target Normal Sheath Acceleration (TNSA) regime. The irradiated targets were polymers and metals with embedded nanostructures and different thicknesses. In the present work, plasma has been characterized by using Thomson Parabola Spectrometer placed in forward direction. The regime of laser intensity was of the order of 10^{16}W/cm^2 at 1.3 μm wavelength. Simulations performed by TOSCA code have been employed to compare theoretical prevision with experimental data. This approach permitted the recognition of parabolas and the evaluations of ion charge, energy and mass-to-charge ratio. Results revealed that the maximum ion acceleration is obtained n metallic foils for optimal thickness of the order of 10 μm and for target containing nanostructures responsible for the increase of the plasma electron density and resonant absorption effect, as will be presented and discussed.

1. Introduction

In the last years many improvements occurred in the field of laser-matter interaction and in many laboratories of the world have been achieved accelerated ion beams of multi-MeV energy [1]. Much kind of detectors have been employed to analyse the ions beams plasma generated, such as ion collectors, semiconductor and track detectors.

A useful instrument able to detect energy spectra of all ions species in a single laser shot, in a well defined solid angle, is the Thomson Parabola Spectrometer (TPS) [2]. This detector can be available for high laser power density and sub-nanosecond laser pulses irradiating solid matter and producing hot plasmas expanding in vacuum at supersonic velocity. The non-equilibrium charge distribution of the plasma generates high electric fields driving ion acceleration at energies exceeding 1 MeV per charge state [3]. The laser-accelerated ion streams can be characterized in term of energy and charge distributions, maximum ion energy, angular divergence and emission yield, as well as shot-to-shot reproducibility. The Thomson Parabola Spectrometer deflecting a little sampling of ion emission is fast and shows high sensitivity in mass-to-charge ratio. However comparative techniques of ion analysis are need to avoid possible errors of interpretation in parabola recognition, energy measurements and yield emission. To this TPS spectra generally are compared with time-of-flight (TOF) spectra obtained using semiconductor or ion collector detectors, track detectors and scintillators.

2. Experimental setup

At PALS laboratory in Prague an Iodine laser system with 10^{16} W/cm^2 laser intensity, 1.315 μm fundamental wavelengths, 300 ps pulse duration and a beam focus diameter of 70 μm, operating in single shot mode, was employed [4]. Laser irradiates solid thin films in Target Normal Sheath Acceleration (TNSA) regime in order to generate non-equilibrium plasma in forward direction i.e. in the rear side of the target. The irradiation produces a high electric field driving the ion acceleration. Irradiated targets were thin polymers, such as polyethylene (PE) and mylar and metallic foils of Al and Au.

Ion acceleration emitted from plasma was monitored employing different detectors based on time-of-flight (TOF) configuration, such as ion collectors (IC) and SiC semiconductor detectors, track detectors (CR39) and TPS. Generally SiC detectors were placed at different angles and at 60 cm from the target.

SiC semiconductor detectors were employed efficiently because of their fast response, not sensitivity to the visible light (energy gap 3.26 eV) and proportionality to the energy of detected ions. Their current density signals, J_{SiC} depends on [5]:

$$J_{SiC} = e\,(n_i\,E_i/\varepsilon)\,\mu_{eff}\,(U_d/d) \qquad (1)$$

where e is the electron charge, n_i is the ion density, E_i is the ion energy, ε is the energy necessary for electron-hole pair creation, μ_{eff} is the electron mobility in SiC, U_d is the bias applied to the semiconductor detector (~ 600 V) and d is the thickness of the semiconductor sensitive layer (~ 100 μm).

A Thomson Parabola Spectrometer has been placed along the normal to the target surface in a forward direction at about 1 m from the target. A sketch of TPS structure is reported in figure 1.

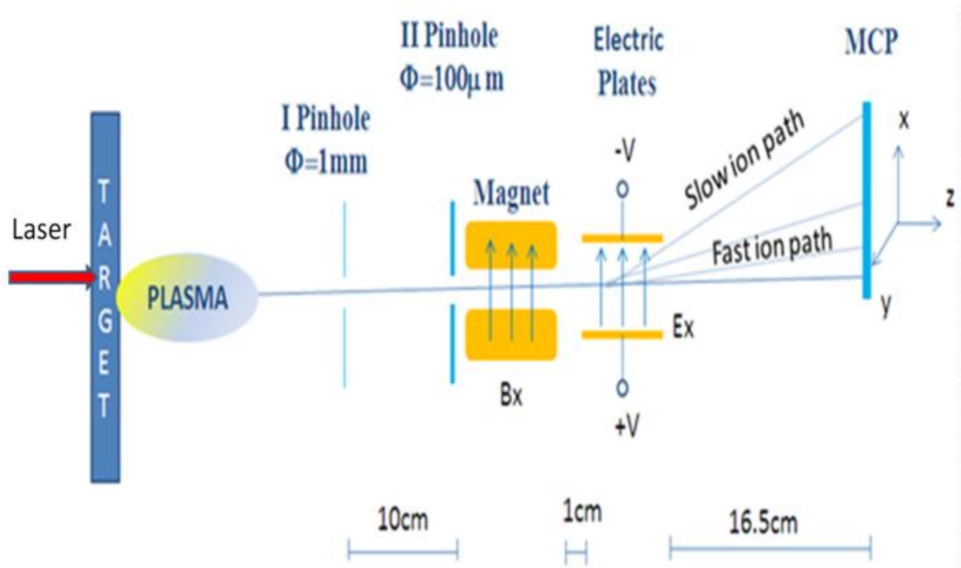

Figure 1. Sketch of Thomson Parabola utilized at the PALS laboratory in Prague.

Two pinholes collimate the ions species accelerated along the normal to the target surface; the first has 1 mm diameter and the second, laced at 10 cm distance from the first, has 100 μm diameter. This second pinhole is located at a distance of 5mm with respect to the magnet. A magnetic field of 0.06-0.12 T and a parallel electric field at 0.5-1.4 kV/cm have been applied orthogonally to the direction of the incident ions. Charged particles are deflected by electrostatic and magnetic fields towards the multi-channel plate (MCP) fixed at a distance of 16.5 cm from the electrostatic plates. The deflection of ions produces a good mass/charge and charge state separation by the image parabolas on a MCP

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coupled to a phosphorus screen and a fast CCD Camera [6, 7]. By the comparison between the experimental parabola images and the simulation parabolas achieved by Opera 3D/ TOSCA code and Mat-LAB software [8] it is possible to measure the mass per charge state, the charge state and the energies of the detected ions. Moreover, assuming the MCP/phosphorus light signal to be proportional to the number of detected ions, it is possible to have preliminary information about the ion energy and charge state distributions. The Simulations permit the parabola recognition using the real geometry of the used TPS and the real values and shapes of the used magnetic and electric fields.

3. Results

Measurements performed at 10^{16} W/cm^2 laser intensities, irradiating thin foils in TNSA configuration, permitted to evidence that ions are emitted at energies up to about 4 MeV per charge state. Fig. 2a reports a typical TPS spectrum obtained by irradiating 6 μm thin PE target with 590 J pulse energy. The spectrum shows a circular zone where photons and neutral particles arrive on MCP and a lot of parabolas outgoing from this circle. Fig. 2b shows the conversion of the experimental spectrum in gray scale levels and the simulation data (lines) overlapped to the experimental one, as obtained by Opera 3D/ TOSCA code and Mat-LAB software.

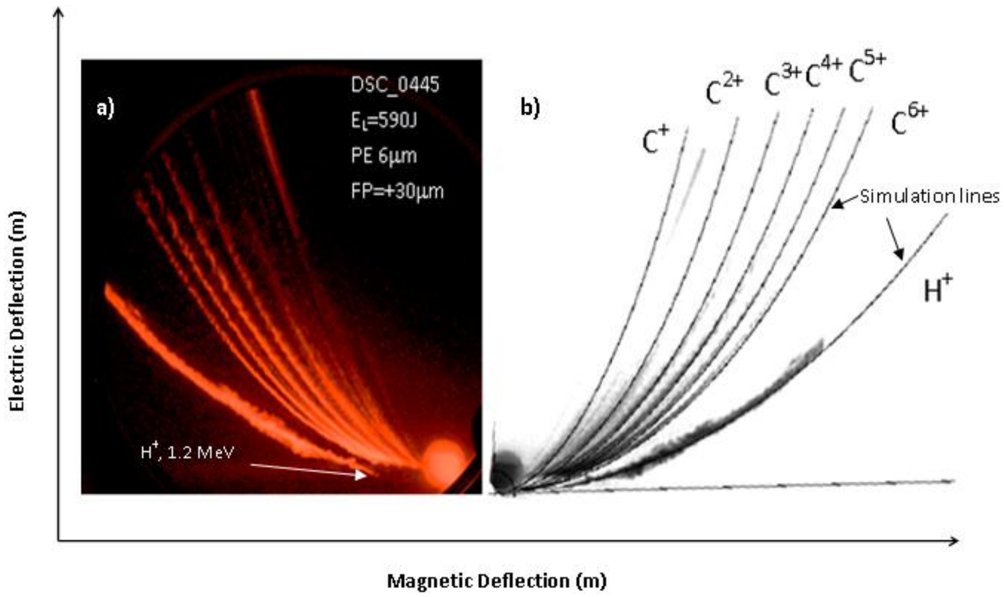

Figure 2. Experimental parabolas from a 6 μm PE irradiation at 590 J (a), and spectra transformation in gray scale with identification of the different parabolas (b).

The lower parabola is due to proton deflections and the others to C ions with all the six charge states. The parabola points nearest to the circular zone are due to the detection of highest energy ions. The distance between the protons parabola and the centre circle is compatible with a proton maximum energy of 1.2 MeV.

In order to confirm the agreement with experimental TPS results and TOSCA simulations, measurements were compared with those obtained using SiC detector spectra.

Figure 3 shows a typical spectrum of a SiC detector obtained during the same laser irradiation of 6 μm PE giving the spectrum of Fig. 2. SiC is placed in forward direction at 30° and 60 cm flight distance. Spectrum shows a photopeak, which represents the start of the TOF measurements, a background due to electron and/or electron Bremsstrahlung detection and a large peak due to the ion detection. The faster ions are due to protons located at 35 ns and corresponding to a kinetic energy of 1.5 MeV, in good agreement with TPS spectrum.

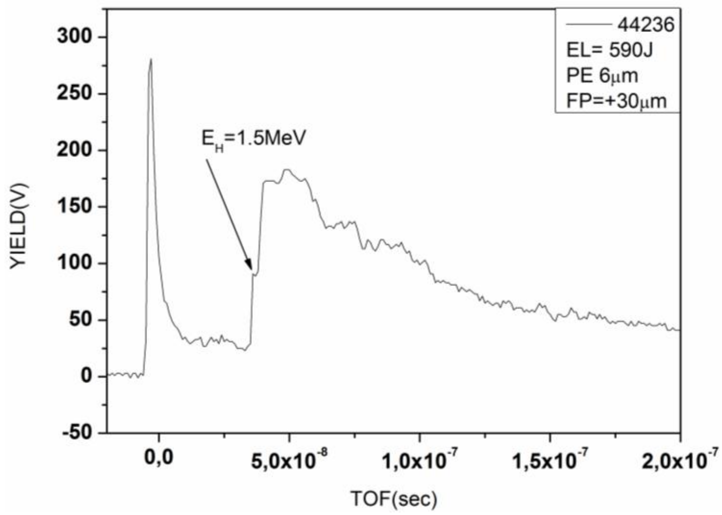

Figure 3. SiC spectrum achieved irradiating PE-TNSA target 6 μm thick.

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The relative light intensity of the TPS parabolas permits to elaborate the ion energy and charge state distributions. For the 6 μm PE TNSA irradiation hydrogen and carbon atoms are all ionized.

Figure 4a shows the ion energy distributions with, as a first approximation, Boltzmann-like shapes. Protons reach the energy of 1.5 MeV while carbon ions reach the energies of 900 eV, 1.8 MeV, 2.7 MeV, 3.6 MeV, 5 MeV and 6 MeV for the charge states C^{1+}, C^{2+}, C^{3+}, C^{4+}, C^{5+} and C^{6+}, respectively. Thus in average an acceleration of about 1 MeV/charge sate is obtained. Fig. 4b shows the charge distribution indicating that proton charge is higher with respect to the carbon one, due to the higher hydrogen content for stoichiometry and for absorbed gas in the target.

Irradiating polymer in which metallic nanostructures are embedded, resonant absorption effects have been observed due to plasmon resonances induced by the laser light. Irradiating thin metallic foils with the optimal thickness of 10 μm the plasma electron energy increases. Using advanced targets in which reflection coefficient is reduced, due to peculiar surface treatments, the absorption coefficient of the laser light increases. In these three cases the electric field driving ion acceleration generated in the rear side of the TNSA target increases and, with the used laser intensity, protons with a kinetic energy above 4 MeV have been measured.

4. Discussion and conclusions

Measurements performed with a Thomson Parabola Spectrometer give information about ion species, energy distribution and charge states distribution (that can be given by the intensity light of the CCD images) in a single laser shot.

An interesting obtained result is that the proton energy achieved by using TPS is lower than the value obtained by SiC detector. This behaviour is explained considering the higher sensitivity of the semiconductor device, with respect the TPS one’s. The plasma temperature, evaluated as a first approximation from the maximum charge states measured through TPS, increases with the electron density of the target. This means that high plasma temperatures and high acceleration of ions can be obtained in heavy metallic targets with respect light metals or polymeric ones.

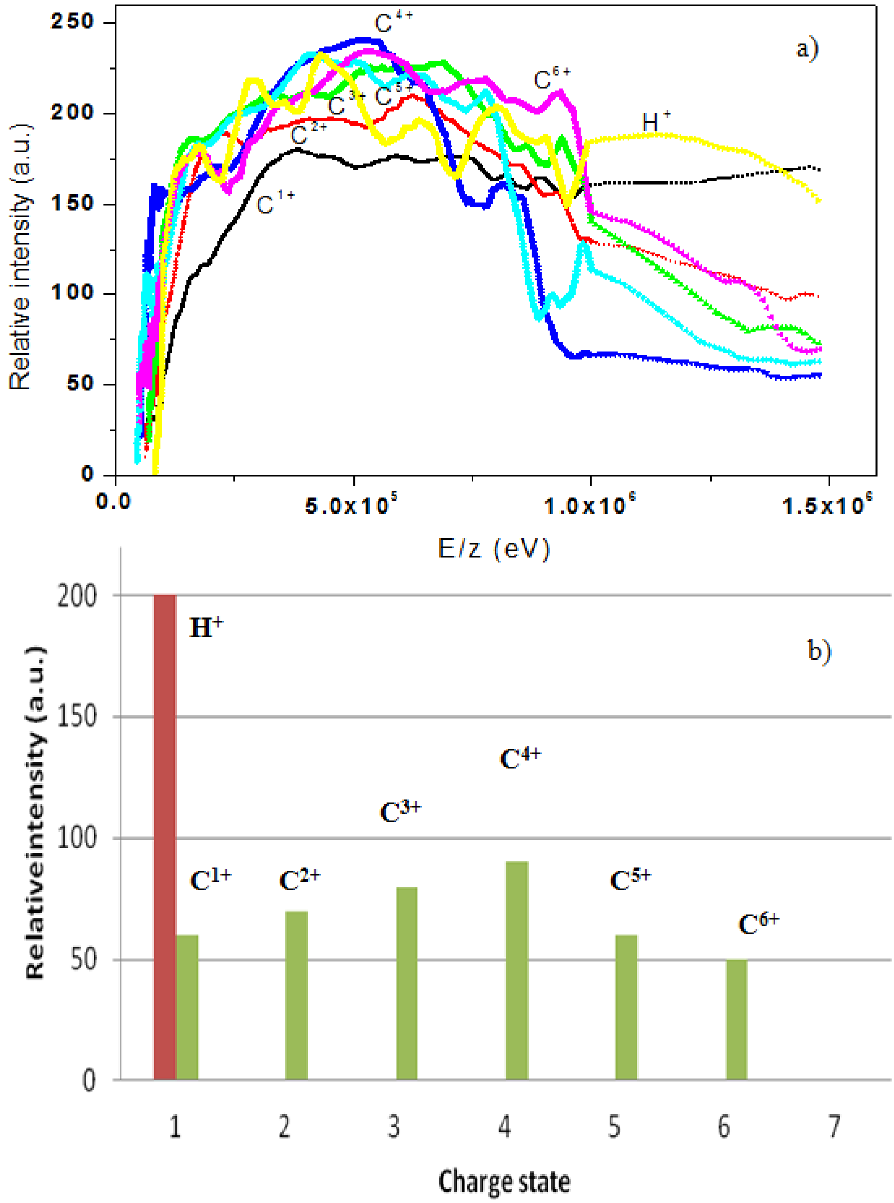

Figure 4. distributions (a) and charge state distributions (b) for 0.6 µm polyethylene target irradiated at 590 J.

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