Diagnostics of fast plasmas produced by intense laser pulses

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Abstract

Plasma has been generated in high vacuum by high intensity laser roughly 10^{16} W/cm^2 irradiating polymeric and metallic targets with micrometric thickness. Plasma generated in forward directions, with Target Normal Sheath Acceleration (TNSA) approach, produces non equilibrium phenomena with photons, electrons and ions emission. The involved dynamics, developing charge state separation, have been investigated by using a Thomson Parabola Spectrometer coupled to multi-channel plates (MCP). Measurements, employed in time of flight configuration, have been compared with others detectors, such as SiC semiconductors, that have been fixed in forward and in backward directions with respect to the normal to the target surface. Radiation detection has been employed in order to investigate on the dynamic behaviour, composition and distribution of the non equilibrium plasma. The results, demonstrated that high electric fields, generated along the normal to the target surface, drive the ion acceleration. Protons are accelerated above 3 MeV and ions above 500 keV/charge state. The experiments have been performed at PALS laboratory in Prague with the ASTERIX IV laser system.

Introduction Plasma is generated during the laser-matter interaction and its properties are function of the intensity and the wavelength and of the target composition and geometry. The TNSA approach has been investigated for plasma production mainly in forward direction, i.e. from the rear part of the target. In a laser field the electron will be driven with an oscillatory motion a maximum quiver velocity [1] $v_0 = -eE_0/m_e\omega$, where e is the electron charge, E_0 is the maximum electric field of the coherent wave, m_e is the electron mass and ω is the laser frequency. For laser intensities of order 10^{18} Wcm^{-2} the quiver motion becomes relativistic, modifying the refractive index of the plasma, according to literature [1]. A laser with a transverse intensity profile which is peaked on axis will be self-focused by the gradient in the refractive index profile. The quiver motion of electrons is responsible of changing of plasma density and consequently, the refractive index of the plasma. The ponderomotive force is responsible of the electron emission and of their energy acquired during the oscillations. Ions are dragged with the electrons via the Coulomb force and a double layer is produced in the rear side of the target. The electric field developed in the double layer is very high and of the order of tens GV/m [2]. It is responsible of the ion acceleration along the normal direction to the target surface. In this context SiC detectors, ion collectors (IC) (Faraday cups) and Thomson Parabola Spectrometer (TPS) have been employed to characterize the hot laser-generated plasmas. SiC detectors are not sensitive to the visible, soft UV, and infrared light. Optical photons are not able to produce electron-hole pairs owing to their energies are below the 3.2 eV of the 4H-SiC gap energy [3]. The energies of the emitted ions are monitored in Time Of Flight (TOF) configuration. TPS permits a fast diagnostic of the plasma using an ions deflection due to a magnetic and electric fields; it measures the ion mass, ion energy and charge state from a single laser shot. SiC spectra have been compared with those of IC and TPS.

Experimental set-up The high-power iodine laser system was employed at PALS laboratory in Prague [4]. It operated at 1.315μm of wavelength, 10^{16} W/cm^2 of intensity, 350 ps pulse duration, with a spot dimension of 70μm and a laser energy ranging between 50 J and 600 J. Polyethylene, Mylar, Al and Au foils within 1μm ÷ 10μm in thickness were used in this experiment to be irradiated and produce plasmas. Generally laser beam hits the target surface at 0° incidence angle. Accelerated ions have been detected by using ion collectors and SiC detectors placed at 30° with respect to the target normal direction, both in forward and in backward space. The ionized species were analyzed by a Thomson Parabola Spectrometer placed along the normal direction to the target surface in forward. Among the devices employed, a KENTECH X-ray streak camera fixed in a side view having 2 ns exposition time. Plasma emitted ions pass through a first pinhole with a diameter of 1mm and the second one 100 μm in diameter. The second pinhole is fixed at a distance of 5 mm from the magnetic plates. A magnetic field ranged between 0.05 and 0.2 T and electric field acting on two plates at 1÷3 kV have been applied orthogonally with respect to the direction of the charged particles.

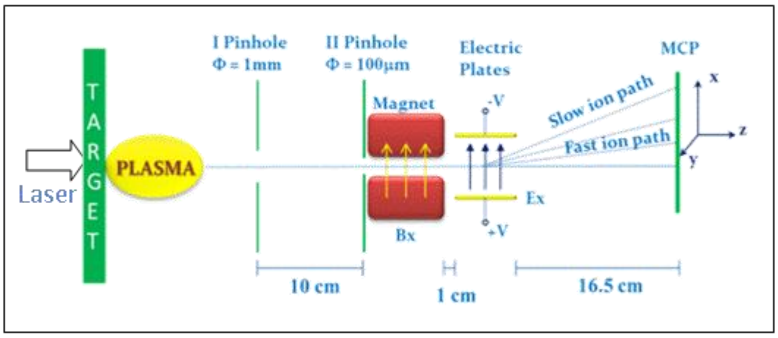

Fig. 1. Scheme of the used Thomson Parabola Spectrometer

The emitted ions are deflected by electrostatic and magnetic fields towards the MCP positioned at a distance of 16.5 cm from the electrostatic plates and arranged with a phosphor screen with a diameter of 2 cm and coupled to a CCD camera. By the comparison between experimental images and simulations, determined with Opera 3D/TOSCA code and Mat-LAB software [5], have been measured the mass per charge state, the charge state and the energies of the detected ions. Fig. 1 shows a scheme of the used TPS.

Results and Conclusions In thick targets irradiated at low intensities ($\sim 10^{10}$ W/cm^2) the ion produced in backward direction generally have maximum energies of the order of 200 eV per charge state of 10^+ and a maximum kinetic energy of about 2 keV. The ion energy distributions follow the "Coulomb-Boltzmann-shifted" function [6] and the charge state distribution indicates an inversely proportionality to the ionization potentials of the atomic species, as expected. Measurements performed at high power laser-plasma interaction ($\geq 10^{15}$ W/cm^2), in thin targets with TNSA approach, permitted accurate investigations of the maximum energy of ions emitted in forward direction with energies above 1 MeV per charge state. TPS's spectra allowed the identification of ion species, providing for Au the maximum charge state of the order of 70^+ with a maximum ion kinetic energy is of about 150 MeV. The image shown in Fig. 2a regards a typical TPS spectrum obtained by irradiating 10 μm thin Al target.

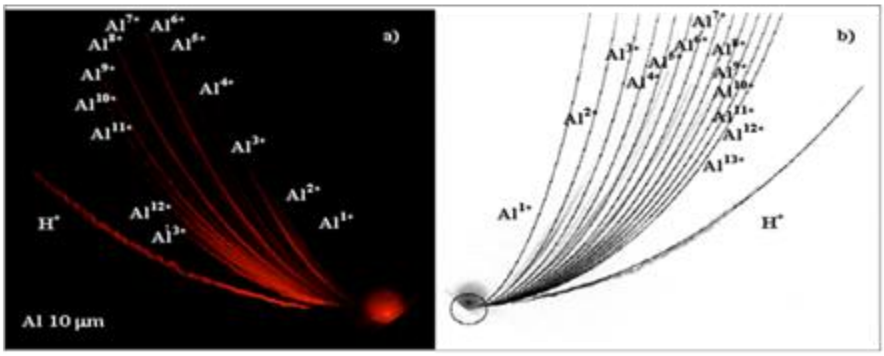

Fig. 2. Typical TPS spectrum of Al plasma (a) and comparison with simulation recognition spectrum (b)

The spectrum reports the Thomson spectrometer zero for the zone of undeflected photons and neutral particles arriving on MCP and a lot of parabolas. Fig. 2b shows the conversion of the experimental spectrum in gray scale colours and the simulation data overlapped to the experimental one, obtained by Opera 3D/ TOSCA code and Mat-LAB software. The lower parabola is a consequence of proton deflections and the others to Al ions with high 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 2.5 MeV. The Al maximum ion energy increases with the charge state. A value of 5 MeV, 25 MeV and 32.5 MeV has been evaluated for the charge states Al^{2+}, Al^{10+} and Al^{13+}, respectively. Samples of polyethylene and gold with different thickness have been irradiated. Fig.3 features a comparison of two experimental TPS spectra obtained irradiating polyethylene (a) and gold (b) at 10 μm and 2.5 μm, respectively. Maximum proton energies in forward direction of 2.2 MeV and 3.0 MeV have been obtained in the two cases. Results demonstrated that the higher proton kinetic energies, above 3 MeV, can be obtained by gold targets using the high pulse intensities at the fundamental frequency, using a focal position of -100 μm and target thickness of 10 microns, according to literature [7]. Plasma diagnostics using SiC permitted to evaluate with high sensitivity proton energy and the maximum energy of the accelerated ions. Using a spectra deconvolution with shifted Boltzmann distributions it is possible to have information on the different ion contributions to the SiC-TOF spectra. Fig. 3c shows a typical example of SiC spectrum and Au ion deconvolution; the different spectra shift is of about 2 MeV, indicating an ion acceleration of about 2 MeV per charge state. In conclusions the diagnostics of fast plasmas produced by intense laser pulses can be performed though IC, SiC and TPS placed at different angles with respect to the target normal direction in order to have information of the plasma properties.

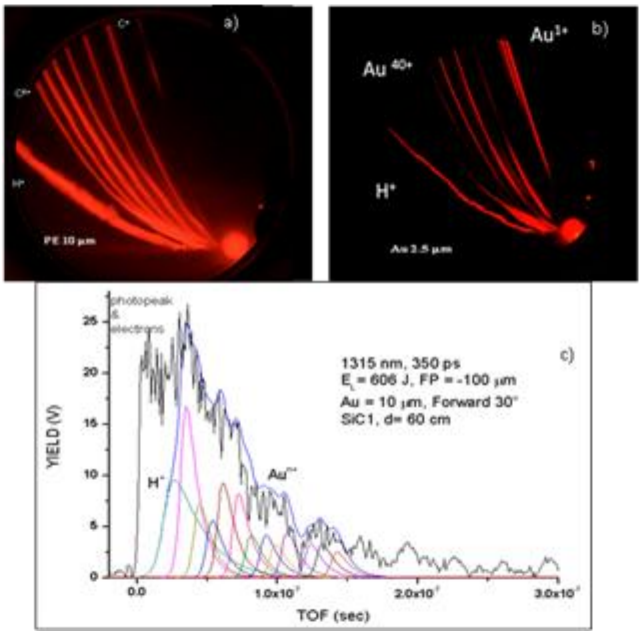

Fig. 3. Typical TPS spectra in polyethylene (a) and gold (b) targets and SiC-TOF spectrum (c) relative to the ion detection from a gold plasma obtained in TNSA conditions.

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