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THOMSON PARABOLA SPECTROMETER FOR ENERGETIC IONS EMITTED FROM SUB-NS LASER GENERATED PLASMAS

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Abstract. Laser-generated plasmas were obtained in high vacuum by irradiating micrometric thin films (Au, Au/Mylar, Mylar) with the Asterix laser at the PALS Research Infrastructure in Prague. Irradiations at the fundamental wavelength, 300 ps pulse duration, at intensities up to about 10^{16} W/cm^2, enabled ions to be accelerated in forward direction with kinetic energies of the order of 2 MeV/charge state. Protons above 2 MeV were obtained in the direction orthogonal to the target surface in self-focusing conditions. Gold ions up to about 120 MeV and 60^+ charge state were detected. Ion collectors and semiconductor SiC detectors were employed in time-of-flight arrangement in order to measure the ion velocities as a function of the angle around the normal direction to the target surface. A Thomson parabola spectrometer (TPS) with a multi-channel-plate detector was used to separate the different ion contributions to the charge emission in single laser shots, and to get information on the ion charge states, energy and proton acceleration. TPS experimental spectra were compared with accurate TOSCA simulations of TPS parabolas.

Keywords: Thomson parabola spectrometer, high intensity laser, focal position, Opera 3D Tosca code, simulation.

1. Introduction

Ion acceleration driven by laser-generated plasma is a major topic in various scientific fields, from ion sources to ion implantation, nuclear physics and biomedicine.

In investigations of the macroscopic and microscopic effects occurringwhen a laser interacts with matter, one of the most important parameterd is the product $I\lambda^2$, where I is the laser intensity and λ is the laser wavelength. It is well known that increasing the $I\lambda^2$ parameter increases the ponderomotive energy transferred to plasma electrons and, consequently, the ion acceleration [10]. The formation of laser plasma and its dynamics are different in cases of low or high laser power densities. In the case of low power densities, the plasma in a high vacuum chamber expands along the normal direction to the irradiated target surface with a non-relativistic velocity, and the energy of the ion beam produced is of the order of 200 eV per charge state [9]. In the case of high densities, the ion beam expands with a relativistic velocity, the typical ion energy values being about 2 MeV per charge state [1]. The investigated ion beam must be characterized in terms of the maximum ion energy, charge states, energy distribution, etc., as well as shot-to-shot reproducibility.

Various detector systems were exploited to investigate of the ion acceleration in the laser-produced plasma, one of the most useful being the Thomson parabola spectrometer (TPS). In TPS, the ions are deflected with a combined magnetic and electric field producing a mass/charge and charge state separation. Much information on the physics of ion acceleration can be obtained by analyzing the parabolas imaged on a micro-channel plate (MCP) based detector coupled to a phosphorus screen [12].

2. Material and Methods

At the National Laboratories in Catania, several kinds of specimens were irradiated by IR laser light from an Nd:YAG laser operating at $1 \div 10$ Hz, with an intensity of 5×10^{10} W cm^{-2}, 9 ns pulse duration and a beam diameter of 500 µm. It was possible to detect the plasma produced in backward direction as a consequence of thick target irradiation [6].

Several experiments have been carried out recently at the PALS laboratory, Prague, where an Iodine laser with $7 \times 10^{16}\,\mathrm{W\,cm^{-2}}$ of laser intensity, 1315 nm (1ω) and 438 nm (3ω) wavelengths, 300 ps pulse duration and a beam diameter of 70 µm in single shot mode [8] has been employed for irradiating both thick and thin targets. The *hottest* were the forward expanding plasmas generated in interaction of the laser with thin targets. Much effort was focused on the choice of target materials, such as thick and thin polymers (polyethylene and mylar), metals (Cu and Au) and targets with synthesized nanoparticles.

Various tools have been used for ion detection, based on time-of-flight (TOF) techniques and on magnetic and electric ion deflections, including the Thomson parabola spectrometer.

Ion collectors (IC) were fixed at a known distance and angle from the target, and their outputs were connected to a fast storage oscilloscope. The IC current density signal depends on the ion charge, and is given by [3]

$$J_{\mathrm{IC}} = e\, z_{\mathrm{i}}\, n_{\mathrm{i}}\, v_{\mathrm{i}}\,, \tag{1}$$

where e is the electron charge, z_{i} is the ion charge state, n_{i} is the ion density and v_{i} is the ion velocity.

At low laser intensity, the use of an ion energy analyzer (IEA) permits us to evaluate the amount of energy per charge state (E/z) of the ions emitted from plasma. IEA is constituted by two coaxial metallic plates that deflect electrostatically to 90° the ions arriving at a windowless electron multiplier (WEM) detector that selects them in terms of E/z. The ratio E/z is given by the relation

$$\frac{E}{z} = 2\,k\,V\,, \tag{2}$$

where k is the gain parameter ($k = 10$) depending on the WEM and V is the voltage applied to both deflection plates [7]. By varying the bias voltagei, it was possible to select different E/z and finally to plot the ion energy and the charge state distributions.

SiC semiconductor detectors were adopted due to their fast response, their insensitivity to visible light (energy gap 3.2 eV) and the energy proportionality of the detected ions. Their current density signals are given by [3]

$$J_{\mathrm{SiC}} = e\left(n_{\mathrm{i}}\frac{E_{\mathrm{i}}}{\epsilon}\right)\mu_{\mathrm{eff}}\left(\frac{U_{\mathrm{d}}}{d}\right)\,, \tag{3}$$

where E_{i} is the ion energy, ϵ is the energy necessary for electron-hole pair creation, μ_{eff} is the quantum efficiencyi, which takes into account the energy loss in the detector, U_{d} is the bias applied to the semiconductor detector, and d is the thickness of the semiconductor sensitive layer.

At high laser intensity, a Thomson parabola spectrometer was placed along the normal to the target surface in forward direction. The model of TPS employed at the PALS laboratory in Prague is shown in Fig. 1a.

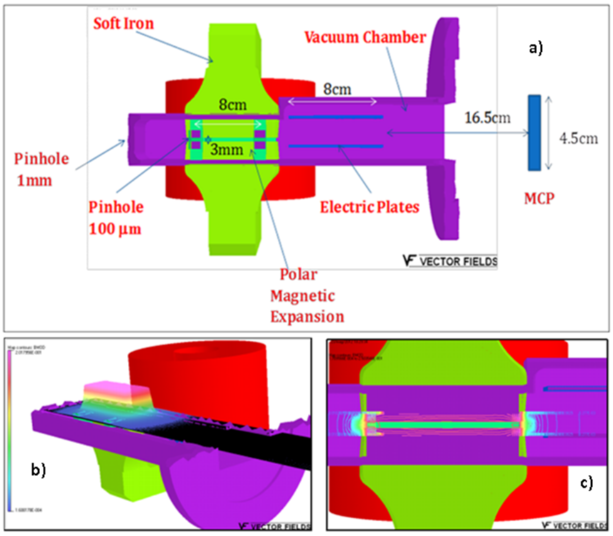

FIGURE 1. Model of the Thomson Parabola Spectrometer (a) Profiles of magnetic fields (b) and electric fields (c) provided by OPERA 3D/TOSCA.

Two pinholes collimate the input ions; the nearest is 1 mm in diameter and the other, 10 cm distant, is 100 µm in diameter. The latter is placed at a distance of 5 mm with respect to the magnetic plates. The applied magnetic fields ranged between $0.05 \div 0.2$ T, and an electric voltage of $1.0 \div 3.0$ kV was applied across two deflecting plates, producing an electric field orthogonal to the direction of the incident ions.

Charged particles were deflected by electrostatic and magnetic fields towards the MCP fixed at a distance of 16.5 cm from the electrostatic plates. The MCP was made up with a phosphor screen 2 cm in diameter coupled with a CCD camera [5].

A comparison between the experimental images and the simulations carried out using Opera 3D/TOSCA code and MATLAB software [4] enabled us to evaluate the mass per charge state, the charge state and the energies of the detected ions. Figures 1b, c show the profiles of the magnetic and electric fields calculated using TOSCA, in order to evaluate the effects of the edge and field gradient on the ion trajectories.

3. RESULTS

The measurements carried out at low laser intensities, with thick targets, provided evidence that ions are emitted from plasma in backward direction with energies of the order of 200 eV per charge state. For Au, the maximum charge state is of the order of 10^{+}, thus the maximum kinetic energy is of about 2 keV. The ion energy distributions follow the Coulomb–Boltzmann shifted functions, and the charge state distributions are inversely proportional to the ionization potentials of the atomic species. Investigations performed at high laser intensities, with thin targets, showed that ions emitted from plasma in the forward direction can have much higher energies, of the order of 2 MeV per charge state. For Au, the maximum charge state

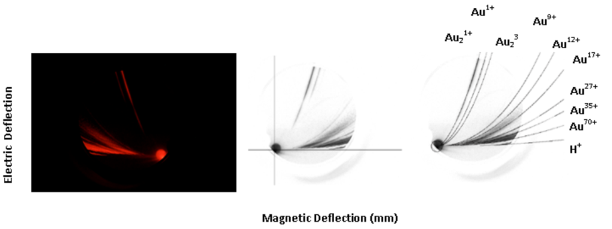

Figure 2. Experimental parabolas for a target of Au 0.6 µm in thickness (a), transformation in gray scale (b) and identification of the parabolas (c).

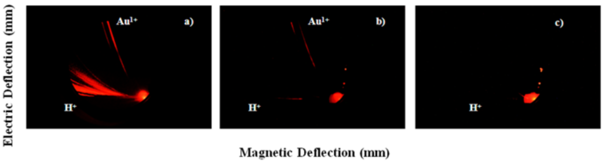

Figure 3. Experimental parabolas obtained for targets of Au at three different thicknesses irradiated by an Iodine laser.

is of the order of 70+, thus the maximum kinetic energy is of about 150 MeV, as seen from the TPS spectra.

The image shown in Fig. 2a represents a typical TPS spectrum obtained by irradiating a 0.6 µm thin Au target. The spectrum contains a bright circular zone caused by undeflected photons and neutral particles arriving on MCP, and a lot of parabolas outgoing from this circle. Figure 2b shows conversion of the experimental spectrum in gray scale colors. Figure 2c shows the simulation data overlapped with the experimental data, as obtained by Opera 3D/TOSCA code and MATLAB software. The lowermost parabola corresponds to the deflected protons, while the other parabolas corresponds to Au ions with high charge states.

The closer the parabola points are to the circular zone, the higher is the energy of the ions. The maximum proton energy determined from the proton parabolas was as high as 2.5 MeV. The maximum energies of Au ions increase with the charge state. Values of 160 keV, 20 MeV, 60 MeV and 130 MeV have been evaluated for the charge states Au^{2+}, Au^{20+}, Au^{40+} and Au^{60+}, respectively. Several homogeneous Au samples ranging in thickness from 0.6 to 50 microns were irradiated at the same experimental and geometrical conditions for laser energy, focal position and magnetic-electric deflections.

Figure 3 features a comparison of three experimental TPS spectra obtained for different Au sample thicknesses, from 0.6 up to 50 µm. This experiment showed that the maximum kinetic energy of the protons emitted from laser-produced plasma in the forward direction is proportional to the target thickness. Proton energies from 2.5 MeV (Au 0.6 µm) up to 3.5 MeV (Au 50 µm) were observed.

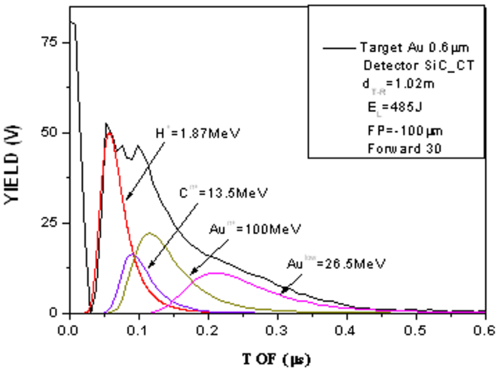

Figure 4. SiC-TOF spectrum relative to 0.6 mm Au target irradiation.

These results can be explained on the basis of plasma electron density that increases with the thickness of the target producing enhancement of the electric field driving the ion acceleration. Of course, for thicker Au targets above 100 µm the transmitted charge particles in the rear side of the target decrease so low due to the high energy loss, and practically no plasma is therefore obtainable in forward direction. A large number of forward-accelerated protons with very high kinetic energies, above 2 MeV, can be generated in high electron density plasmas produced when high-intensity laser pulses interact with thin targets made of a heavy material, such as gold.

With the aim of comparing the experimental results and the simulations, we treated the data obtained by using SiC detectors fixed in forward direction in a TOF approach. They agree well with TPS measurements, as seen from the SiC spectrum in Fig. 4. In this case, the corresponding proton peak energy is about 1.9 MeV. The proton, carbon and gold peaks can be interpreted as a convolution of the Coulomb–Boltzmann shifted distributions, according to the literature [2].

4. Conclusions

Thomson parabola spectrometry can provide useful detailed information on physical processes, ion species and charge states generated in single-shot laser experiments.

A combination of measurements and simulations helps to recognize well the ion species, the charge states, the maximum value of the ion energies, and the intensity distributions.

The reported results show that the energy of protons accelerated in forward direction is higher than the energy of protons accelerated in backward direction, with increasing thickness of the specimen (for micrometric thicknesses). In addition, we observed an increase in plasma temperature, with the electron density of the sample. This effect was evaluated as a first approximation from the maximum charge states measured through TPS. In shots with heavy metallic targets, the observed plasma temperatures and ion driving acceleration potentials were higher than those observed when using light metals or polymeric targets. The same behavior was observed for all the irradiated targets at the different laser intensities and wavelengths that were used. The results of the experiments at PALS also demonstrated well that plasma temperature, maximum kinetic ion energy and maximum charge state depend on parameter $I\lambda^2$, as expected [10, 11].

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