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Proton emission from resonant laser absorption and self-focusing effects from hydrogenated structures

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ABSTRACT

Effects of resonant absorption and self-focusing are investigated by using fast and intense laser pulses. The ion emission and acceleration in the non-equilibrium laser-generated plasma are investigated at low and high intensities, from 10^{10} up to about 10^{16} W/cm^2.

The properties of plasma are strongly dependent on the time and space, laser intensity and wavelength.

A special interest concerns the energetic and intense proton generation for the multiplicity use that proton beams have in different scientific fields (Nuclear Physics, Astrophysics, Bio-Medicine, Microelecronics, etc.).

Investigations have been performed at INFN-LNS of Catania and at PALS Laboratory of Prague, by using thick and thin targets and different technique of ion analysis.

The mechanisms of resonant absorption of the laser light, produced in special targets containing nanostructures with dimensions comparable with the laser wavelength, enhances the proton energy. The mechanisms of self-focusing, obtained by changing the laser focal distance from the target surface, increase the local intensity and consequently the high directional ion acceleration.

Real-time ion detections were performed through Thomson parabola spectrometer (TPS), ion collectors (IC), SiC detectors and ion energy analyzer (IEA) employed in time-of-flight configuration (TOF).

The energy and the amount of ions increase significantly when the two non-linear phenomena occurs, as will be described.

1. Introduction

The interaction of short laser pulses with solid targets has become an important field of study because of many applications, such as the fast ignition scheme of inertia confinement fusion, the plasma-based particle accelerator, coherent x/γ-ray sources, etc. For most of these applications, the nature of the absorption process must be determined.

The density scale length of the plasmas generated from the target surfaces can be estimated as:

$$L = c_s \tau_p \quad (1)$$

where c_s is the ion sound speed and τ_p is the laser pulse duration [1]. For high intensities (>10^{16} W/cm^2) and very short pulses (<1 ps) the scale length is too short to generate sufficient absorption effects and resonance absorption at the critical surface is suggested to be one of the major absorption mechanisms. Some experiments show that it plays an important role even for plasmas with a scale length considerably shorter than the laser wavelength λ_0. However many theoretical works on resonance absorption are only valid for the case in which $L > \lambda_0$ [2].

At higher laser intensity, say $L < v_{os}/\omega_0$, the electrons being pulled out and then returned to the plasma at the interface layer by the wave field can lead to a phenomenon like wave breaking. Thus, the electron plasma wave is hard to develop and vacuum heating tends to be dominant. Here, $v_{os} = eE_0/m_e\omega_0$ is the quiver velocity of the electron, E_0 is the electric field normal to the interface, and ω_0 is the laser frequency.

A simple model is used to calculate the energy absorption efficiency when a laser of short pulse length impinges on a dielectric slab that is doped with an impurity with a resonant line at the laser frequency. It is found that the energy absorption efficiency is maximized for a certain degree of doping concentration (at a given pulse length) and also for a certain pulse length (at a given doping concentration). Dimensionless parameters are constructed, allowing calculations with one set of parameters be used to infer the results expected for other sets of parameters.

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Absorption processes are generally dependent on the density scale length. For shorter scale length or higher laser intensity, vacuum heating tends to be dominant. Literature reports that the electrons being pulled out and then returned to the plasma at the interface layer by the wave field can lead to a phenomenon like wave breaking. This can lead to heating of the plasma at the expanse of the wave energy [3].

Interaction of the laser radiation above some threshold intensity with a plasma of defined properties may significantly increase the charge state and energy of the produced ions, due to a peculiar effect occurring in the plasma, which focalizes further the laser pulse (self-focusing effect) acting so as a small vapor lens placed in front of the target surface. Advances in laser technology have recently enabled the observation of self-focusing in the interaction of intense laser pulses with plasmas. Self-focusing in plasma can occur through thermal, relativistic, and ponderomotive effects [4].

Thermal self-focusing is due to collisional heating of plasma exposed to electromagnetic radiation: the rise in temperature induces a hydrodynamic expansion, which leads to an increase of the refraction index and further heating. Relativistic self-focusing is caused by the mass increase of electrons traveling at speed approaching the speed of light, which modifies the plasma refractive index, depending on the electromagnetic and plasma frequencies. Ponderomotive self-focusing is caused by the ponderomotive force, which pushes electrons away from the region where the laser beam is more intense, therefore increasing the refractive index and inducing a focusing effect.

Both effects of resonant absorption and self-focusing were investigated in order to produce high yield of energetic proton emission from laser irradiated targets, as will be presented and discussed.

2. Experimental set-up

The main experiments have been performed by using the Nd:Yag laser of INFN-LNS of Catania and the Iodine Asterix laser of PALS Laboratory of Prague. The first can be employed at 1064 nm, 532 nm and 355 nm, 9 ns pulse duration, 1 J maximum pulse energy, with intensities between 10^8 and 10^{11} W/cm^2. The second can be employed at 1315 nm (1ω) and 438 nm (3ω), 300 ps pulse duration, 800 J maximum pulse energy, with intensities between 10^{13} and 10^{16} W/cm^2.

At higher intensities the data were collected from literature and compared with our measurements in order to evaluate the generalized law of $I\lambda^2$ scale factor.

In order to generate protons, the irradiated targets were thick and thin hydrogenated films. Many of these were polyethylene based (CH_2-mnomer) with inclusions of nanostructures such as carbon-nanotubes (CNT) of different length and oxides (such as Fe_2O_3), other consisted of hydrogenated Si, thin films of mylar covered by Au or Al films, hydrates and metals. Generally thick films (1 mm thickness) were used at LNS for irradiation at low laser intensities to generate backward directed plasmas, while thin films (of the order of 1 μm in thickness) were employed at high laser intensity at PALS in order to generate forward directed plasmas.

Time-of-flight (TOF) measurements have been obtained with ion collectors (IC), semiconductor detectors based on SiC, and electrostatic deflector ion energy analyzer (IEA) that permits to measure the average ion energy, the ion energy and the charge state distributions, respectively. Details on IC, SiC and IEA detector are given in the literature [5,6].

The ion plasma temperature, T_i, was measured though the Coulomb–Boltzmann shifted (CBS) fit of the experimental ion energy distributions [7]; the electronic plasma temperature, n_e, was measured through the evaluation of the atoms removed from the laser crater and volume of the visible plasma observed by a fast CCD camera.

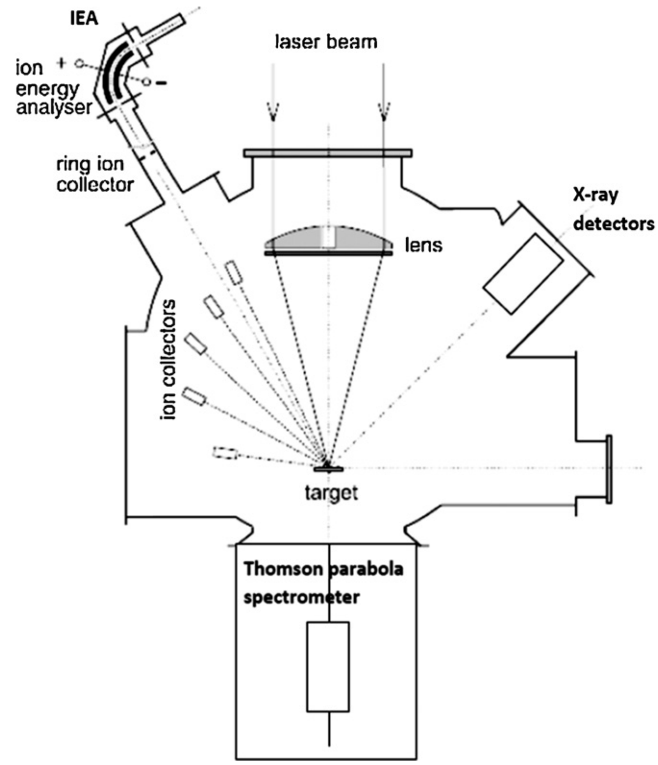

Fig. 1. Experimental set-up scheme at PALS Laboratory of Prague.

A Thomson parabola spectrometer (TPS) was also employed at PALS in forward direction along the normal to the target surface in order to measure the energy, charge states and ion species of ejected particles from plasma, thanks to their magnetic and electric deflection that use a magnetic field, of the order of 0.1 T, and an electric field, of about 3 kV/cm, to deflect the ions toward a multichannel-plate (MCP) detector placed orthogonally to the incident high collimated ion beams.

A streak camera was employed at PALS to measure the laser focal position (FP) distance with respect to the sample surface. Negative distances mean a focus in front of the surface while positive distances mean a focus inside the target.

Silicon photodiodes of different types were tested for the possibility of measurement of high-intensity X-ray pulses in the energetic range 0.7–23 keV. The main problems encountered were non-linearity and overloading of the detectors, especially for detectors assigned for soft radiation. These problems were overcome by operating the photodiodes in the integrating mode, which accomplishes a much greater dynamic range. Photodiodes BPYP03 were used for the measurement of the soft component (0.7–1.5 keV), while FLM photodiodes for the harder component (4–23 keV), both realized at the Institute of Electron Technology, Warsaw [8]. The photodiodes were placed at the distances from 100 to 200 cm from the target and at 30° detection angle from the normal to the target surface in backward direction. Different filters (Be, Al) of various thicknesses changed the range of detector sensitivity.

Fig. 1 shows a schematic experimental set-up employed at PALS Laboratory of Prague.

3. Results

At low intensities, of the order of 10^{10} W/cm^2, with 3–9 ns pulse duration and 1064 nm wavelength, a typical spectrum of ions