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Laser-generated plasma by carbon nanoparticles embedded into polyethylene

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ABSTRACT

Carbon nanoparticles have been embedded into polyethylene at different concentrations by using chemical–physical processes. The synthesized material was characterized in terms of physical modifications concerning the mechanical, compositional and optical properties. Obtained flat targets have been irradiated by Nd:YAG laser at intensities of the order of 10^{10} W/cm^2 in order to generate non-equilibrium plasma in vacuum. The laser–matter interaction produces charge separation effects with consequent acceleration of protons and carbon ions. Plasma was characterized using time-of-flight measurements of the accelerated ions. Applications of the produced targets in order to generate carbon ion beams from laser-generated plasma are presented and discussed.

1. Introduction

The use of composite materials enriched of particular elements permits to modify their chemical and physical surface and bulk properties. In the field of plasma laser-generated in vacuum a special interest is devoted to the use of materials with advanced mechanical, optical and electrical properties. Plasmas obtained by nano and sub-nanosecond pulsed lasers at high intensity permit to produce charge separation effects with high directive ion acceleration, which characteristics depend strongly on the chemical and physical properties of the target [1]. The optical and electrical properties of the target, for example, influence the penetration depth of the laser and the electron density of the plasma produced [2]. The target thickness and mechanical strength influence the electron and ion accelerations from the non-equilibrium plasma, both in terms of kinetic energy and angular distribution, as well as the directionality of the emitted ions and the possible deformation of irradiated thin foils [3,4]. The target composition, density and microscopic structure influence the plasma components, temperature density and fluid dynamics [5].

In particular the use of nanoparticles acting as doping species alters the target properties, for example, enhancing the absorption coefficient at particular wavelength regions, modifying the plasma composition, density and temperature, inducing resonant absorption effects in thin foils and enhancing the processes of ion acceleration in plasma [6].

In this context targets based on ultra-high-molecular-weight-poly-ethylene (UHMWPE) have been investigated as pure and as enriched by carbon nanoparticles (CNP) in order to study the effects produced by laser irradiation and the consequent non-equilibrium generated plasma in vacuum. The interest in this material comes from in the possibility of using it as a source of high concentration of energetic proton and carbon ion beams. Such accelerated ion species, in fact, play an important role in different scientific fields, from the hadrontherapy to microelectronics, and from biology to chemistry [7]. To this aim the composite polymers containing CNP were prepared at different doping concentrations and some physical properties were investigated to pay attention on their effects under infrared pulsed laser light irradiating, at high intensity, placing thick and thin foils in high vacuum. Mechanical strength, for example, was measured in order to consider the high radiation pressure acting on the thin foils during experiments of target-normal-sheath-acceleration (TNSA) regimes occurring at laser intensities of the order of 10^{18} W/cm^2 at which pressures higher than 10 GPa can be produced [8]. Measurements performed at low laser intensity, of the order of 10^{10} W/cm^2 have high interest because permit to investigate on the effects of prepulses of main *fs* giant pulses. Prepulses play an important role on the laser transmission in undercritical plasma, on the laser interaction with the plasma gradients and on the laser reflection at the critical plasma density. Prepulse may induce self-focusing effects, generation of hot electrons and production of filamentations and may be

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employed to control some plasma properties [9–11]. The prepulse effect is not negligible on the plasma properties, X-ray production and electron and ion acceleration because the main laser pulse before the target hits the pre plasma generated in front of it. However it is not entirely demonstrated that prepulse has only advantages on the mechanisms of TNSA ion acceleration, although it appears that the control of the pedestal could greatly improve the acceleration of particles in energy and yield by high-intensity lasers.

2. Experimental set-up

Ultra high molecular weight poly ethylene (UHMWPE GUR 1020, $\rho = 0.930$ g/cm^3, Mw $\approx 3 \times 10^6$ g/mol, average size 150 μm), supplied by Ticona was employed in this experiment. The filler material in order to make the UHMWPE laser light absorbent was a powder of carbon nanoparticles (CNP), supplied by Goodfellow; the mean particle size of the powder was of about 100 nm. CNP were embedded into UHMWPE at different weight percentages (0.2%, 0.5% and 1.0%) using pure ethanol as dispersing medium. The mixture was kept in ultrasound bath at room temperature for two hours. Then, the solvent was separated under stirring in a heated plate. Both the pure UHMWPE powder and the CNP were molded in a hot press at 200 °C for 20 min and at a pressure of 20 MPa, obtaining sheets 60 mm × 60 mm surface and 1 mm thickness, very flat, by using releasing thin Teflon films (100 μm thickness). The pure UHMWPE sheets in visible light appeared translucent while the UHMWPE+CNP composite was black in color.

Optical characterizations of the prepared polymer sheets have been carried out by absorption coefficient measurements in visible and near IR regions as a function of the doping CNP concentration (0.2%, 0.5%, 1%). The investigations were performed using the characteristic peaks emitted from an Hg (Ar) lamp monitored with a high-sensitivity optical spectrometer (Hobira Jobin) operating at the wavelength region 220–1100 nm. A software spectroscopy Lynear code acquires 100 spectra per second and the average spectra is then stored in a PC. The absorption coefficient μ of the sample was evaluated by using the Lambert–Beer law:

$$\mu = \left(\frac{1}{\Delta x}\right) \ln\left(\frac{I_0}{I_t}\right), \quad (1)$$

where Δx is the foil thickness, I_0 the intensity of the incident light and I_t the intensity of the transmitted light.

Raman spectroscopy was performed in the prepared targets in air and at room temperature by using a Horiba XploRA spectrometer equipped with a confocal microscope and a Peltier-cooled charge-coupled detector (CCD). Spectra were excited using the 638 nm line from a solid state laser and integrated for 120 s, using a ×50 long working distance microscope objective. In order to prevent laser induced damage or heating, measurements were carried out using a low laser power (2.5 mW on the illuminated area of 2.0 μm^2). Spectra from several random positions on each specimen were collected taking into account of the possible spatial non-homogeneity of the samples.

The mechanical resistance to tensile test was investigated at 25 °C by means of a LLOYD LR 10 K universal testing machine with a crosshead speed of 5 mm/min.

Morphological investigation of the prepared targets was performed using the optical and the electronic (SEM) microscopies.

A Nd:YAG laser, operating at 1064 nm, 3 ns pulse duration, single pulse or 1 ÷ 10 Hz repetition rate, intensity of 10^{10} W/cm^2, max pulse energy of 300 mJ and focalized laser spot of 0.5 mm^2 was employed to interact with the polymer surface in a vacuum chamber at 10^{-6} mbar pressure. The laser incident angle was 45° and the focusing lens was external to the vacuum chamber. Along the normal to the target surface an ion collector (IC) was placed at 118 cm distance in order to monitor the plasma properties using time-of-flight (TOF) measurements. A fast storage oscilloscope was employed to record the IC spectra.

Mass quadrupole spectrometry (MQS) was employed coupled to the laser ablation in order to evince the ablated atomic and molecular species removed during the laser–matter interaction. MQS has a mass range 1–200 amu and a sensitivity lower than 1 ppm (part per million).

Fig. 1a shows a scheme of the experimental apparatus used to irradiate in vacuum the prepared targets, while Fig. 1b shows a photo of one pristine pure UHMWPE and of one 1% wt UHMWPE +CNP compound sheets employed in this experiment.

3. Results

Results about the absorption coefficient measurements as a function of the wavelength for different CNP concentrations in the prepared targets are reported in Fig. 2a. The plots show that the absorbance is low in the pristine polyethylene and increases with the CNP concentration especially in the wavelength region 400–600 nm, in a narrow band at about 750 nm and in the near IR region at the laser wavelength of 1064 nm. Due to different C—C and C—H groups the absorption coefficient doesn't vary proportionally to the wavelength unless we use 1064 nm of at which the absorption growth linearly with the CNP concentration. The coefficient of absorption generally doesn't growth linearly with the concentrations, showing a saturation region at the concentration higher than 0.2%, as reported in Fig. 2b. The high absorption at 1064 nm permits to foresee that high laser energy can be

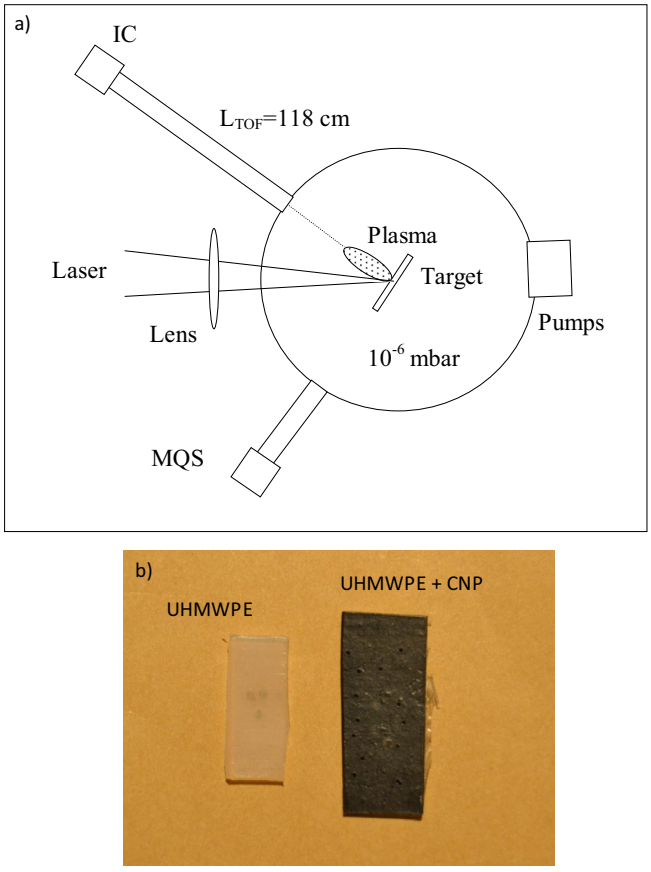

Fig. 1. Scheme of the used experimental set-up (a) and photo of the pure UHMWPE (white) and of the polyethylene containing 1% CNP (black) (b).