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Large-scale studies of ion acceleration in laser-generated plasma at intensities from 10^{10} W/cm^2 to 10^{19} W/cm^2

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ABSTRACT

A large-scale study of ion acceleration in laser-generated plasma, extended to intensities from 10^{10} W/cm^2 up to 10^{19} W/cm^2, is presented. Aluminium thick and thin foils were irradiated in high vacuum using different infrared lasers and pulse durations from *ns* up to *fs* scale. Plasma was monitored mainly using SiC detectors employed in time-of-flight configuration. Protons and aluminium ions, at different energies and yields, were measured as a function of the laser intensity. The discontinuity region between particle acceleration from both the backward plasma (BPA) in thick targets and the forward plasma in thin foils in the target normal sheath acceleration (TNSA) regimes were investigated.

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1. Introduction

Laser irradiating solid materials in vacuum generates plasma with different properties depending on the laser characteristics, irradiation conditions and target composition and geometry. At low laser intensity plasma is generated in the backward direction from thick targets, it is typified by low ionization fraction, temperature and density. Particles exhibiting low kinetic energy and large angular distributions characterize the plasma produced in the backward particle acceleration (BPA) regime [1]. By high-intensity laser irradiation of thin foils, plasma with high ionization charge states, high temperature and density is developed both in the backward and forward directions. The high kinetic energy of particles and narrow angular distributions characterize the plasma generated in the forward direction in the target normal sheath acceleration (TNSA) regime [2–4].Considering a light wave propagating along the z-direction with the electric field E_y in the y-direction, electrons are subjected to transverse oscillations and the mean energy $\bar{\varepsilon}$ is approximately given by:

$$\bar{\varepsilon} = \frac{e^2 E_y^2}{2m\omega^2} \quad (1)$$

where e is the elementary charge, m the electron mass and ω the laser frequency [5]. The energy calculated by the Eq. (1) assumes a value of about 0.21 eV and 210 keV for laser intensity of 10^{10} W/cm^2 and 10^{18} W/cm^2, respectively. The average electron energy of the plasma after the passage of a short laser pulse of intensity I, wavelength λ and polarization p is given by Uf(p), where f(p) accounts for the polarization dependence and U, the oscillation or "quiver" energy of the electron in the laser field, is proportional to Iλ^2 factor. Thus it is possible to control the electron energy distribution simply by varying the polarization or the wavelength of the ionizing laser [6].

Once the light pulse is passed, the space charge separation produced by this displacement pulls the electrons back and a plasma oscillation occurs. Plasmon waves, induced by high intensity lasers, travel with phase velocity near to the c (light velocity in vacuum) and trap electrons that gain energy enhancing the acceleration in the forward direction. The electron energy acquired by this mechanism is above 1 MeV at laser intensity of the order of 10^{18} W/cm^2 [7].

In this way, electrons accelerated at the target front side play an important role cause at high laser intensity their mean free path is much larger than the thickness of the target, (generally it is few microns), thus electrons can cross the target and to be emitted from the rear side of the thin foils, where they generate high electric charge separation between the cloud of electrons and the positive found target. Conversely, at low laser intensity, electrons exhibit low mean free path, insufficient to be emitted from the rear surface but enough to be emitted in vacuum from the front surface generating electric charge separation in front (back-direction) of the irradiated face. The faster electrons that are electro-statically

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confined on the target front and rear surfaces set a charge separation field over a Debye length, typically of the order of a micron, generating strong electric fields of about 100 V/μm and 10 MV/μm at low and high laser intensity, respectively [8].

Such electric fields drive ion acceleration along the normal to the target surface in the backward direction from thick targets and in the forward direction from thin foils. Typical ion kinetic energy for charge state is of about 100 eV and 10 MeV for laser intensity of the order of 10^{10} W/cm^2 and 10^{18} W/cm^2, respectively, as reported in the literature [6,7,9].

At high laser intensity also other mechanisms produce ion acceleration such as the skin-layer ponderomotive acceleration model (SLPA) regime which is also called radiation pressure acceleration (RPA). In this case ponderomotive forces (nonlinear forces that a charged particle experiences in a high inhomogeneous oscillating electromagnetic field) induced by a short laser pulse near to the critical plasma surface drive dense plasma bunches. Due to the high charge density and to the high laser intensity, that reaches about 10^{19-20} W/cm^2 in RPA regime, in these cases it is possible to enhance the ion acceleration and modify their energy distribution up to near monochromatic energy [10].

In this paper the measurements of ion acceleration using both the BPA and TNSA regimes irradiating Al targets at different laser intensities under similar experimental conditions are presented and discussed.

2. Experimental set-ups

The presented study has been performed collecting and comparing our experimental results obtained characterizing Al plasmas obtained using different types of lasers with different characteristics.

The common diagnostics for the different produced plasmas consists in the time-of-flight (TOF) technique applied to ion collectors (IC) and SiC detectors for measurements of photons, electrons and ion energy. ICs are represented by Faraday cups with suppressor grids for measurements of current proportional to the charge arriving on the collector. The measured time of flight associated to the known flight length permits evaluating the ion kinetic energy. SiCs are represented by metal-semiconductor Schottky diodes with 200 nm Ni_2Si surface metallization, 80 micron active depth and 4 mm^2 active surface. SiC is transparent to the visible light due to its 3.1 eV gap energy, and absorbs UV and X-rays, electrons and ions. Their response is proportional to the radiation energy deposited in the active layer, thus their efficiency is 100% for radiations completely stopped in this zone and lower for radiation partially stopped inside it, according to the detection efficiency reported in Fig. 1. TOF measurements were performed using a digital fast storage oscilloscope (4 GHz and 8 GS/s), the detector photopeak due to the X-ray detection acts such as start signal and the particle detection as stop signal, as reported in the literature [11].

In particular the laser facilities here reported were employed:

(1) MIFT Department of Messina University, Italy: A Nd:YAG laser operating at 1064 nm wavelength, 3 *ns* pulse duration, 300 mJ single pulse energy, 0.5 mm^2 spot, 10^{10} W/cm^2 intensity. Al target, 1 mm in thickness, was irradiated at 45° incidence angle at 10^{-6} mbar pressure. Ion collector (IC) connected in time-of-flight (TOF) configuration was employed along the target normal direction using the laser pulse as start signal and the particle detection as stop signal. Spectra were acquired by a fast storage oscilloscope operating at 1 GHz and 4 GS/s, as reported in the literature [7].

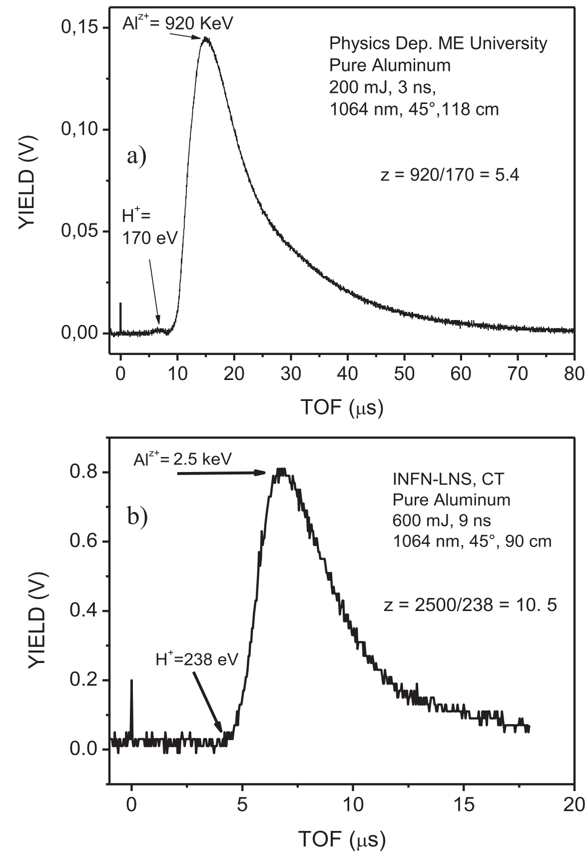

Fig. 1. IC-TOF spectra relative to the backward ions emitted from ns laser-generating plasmas obtained irradiating thick Al targets at Physics Department of Messina University (MIFT) at 10^{10} W/cm^2 intensity (a) and at INFN-LNS of Catania at 10^{12} W/cm^2 intensity (b).

(2) INFN-Laboratori Nazionali del Sud, Catania, Italy: Nd:YAG laser operating at 1064 nm wavelength, 9 *ns* pulse duration, 1 J single pulse energy, 0.1 mm^2 spot, 10^{12} W/cm^2 intensity. Al target, 1 mm in thickness, was irradiated at 45° incidence angle at 10^{-6} mbar pressure. Ion collector (IC) connected in time-of-flight (TOF) configuration was employed along the normal to the target surface using the laser pulse as start signal and the particle detection as stop signal. Spectra were acquired with a digital fast storage oscilloscope operating at 1 GHz and 4 GS/s, as reported in the literature [12].

(3) ENEA-ABC laser, Frascati, Rome, Italy: A Glass Neodymium Phosphate laser delivering a pulse energy of 35 J operating at 1.054 micron fundamental wavelength, 3 *ns* pulse duration, a focal spot of 40 μm diameter, was used in single mode. Laser intensity of 9×10^{14} W/cm^2 was employed. Al thin foils, 4 microns in thickness, were employed to be irradiated at 45°. SiC detectors were placed along the normal to the target surface in the backward and forward directions. Spectra were acquired in TOF approach using a digital fast storage oscilloscope [13].

(4) PALS facility of the ASCR, Prague, Czech Republic: A Terawatt iodine laser system operating at 1315 nm wavelength, 300 *ps* pulse duration, 700 J pulse energy and 70 μm spot diameter is employed in single pulse. Its intensity reaches 5×10^{16} W/cm^2. Both thick (1 mm) and thin (6 micron) of Al targets, were irradiated in high vacuum under the same conditions in the BPA and TNSA regimes. IC, SiC detectors and Thomson parabola spectrometer were employed to monitor the plasma [14].

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