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Non-equilibrium Ta plasmas produced by fast pulsed lasers

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Abstract

A Nd:YAG laser, 9 ns pulse width, 30 Hz repetition rate, a maximum pulse density of 10^{10} W/cm^2 and an iodine laser, 400 ps pulse, operating in single pulse width with a maximum power density of 10^{16} W/cm^2, are employed to produce pulsed plasmas in vacuum. A comparison of the results obtained for the ablation of tantalum targets is presented, including the ablation yields, the ion and neutral emissions and the angular distributions. A plasma plume is produced along the normal to the target surface; it expands adiabatically at supersonic velocity carrying neutral and charged particles and emits visible light, UV and X-rays as well. The plasma has been characterised in terms of an equivalent ion and electron temperature ($\sim 10^7$ K), density ($\sim 10^{17}$ cm^{-3}), and fractional ionisation, which is proportional to the laser intensity. A special attention is devoted to the ion production and to ion kinetic energy, which can reach values of the order of 1 MeV. Such an ion acceleration is due to high electric fields generated inside the non-equilibrium plasma, which can reach values of the order of GV/cm at high laser intensities.

Finally, some applications of the laser-produced plasma for the ion injection into ion sources and for the multi-energetic ion implantation plasma-laser are presented.

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Keywords: Plasma laser-generated; Plasma temperature; Electrical field; Debye length

1. Introduction

Starting from 1998, the Physics Department of Messina University and the INFN-LNS of Catania have been investigating the production of non-equilibrium plasmas by high energy pulsed lasers ablating metallic targets. The experience is based on the use of the pulsed 900 mJ Nd:YAG laser with 9 ns pulse width and a maximum repetition rate of 30 Hz and on the use of the European Laboratory facility of PALS (Prague Asterix Laser System) in Prague by using a 1 kJ iodine laser pulsed at 400 ps and operating in single pulse mode [1,2]. The maximum intensity of the laser pulses is 10^{10} W/cm^2 and 10^{16} W/cm^2 for the first and the second laser, respectively.

The laser–matter interaction is performed on metallic targets inside a vacuum chamber and the plasma is studied with "on-line" measurements using time-of-flight (TOF) techniques for particle detection and measurements of velocity and kinetic energies and with a mass quadrupole spectrometer in order to study the gas evolution following the ablation effects. Moreover, photon detection in the range of infra-red, visible, ultra-violet and X-ray is also possible. A special attention is given to the measurements of the energy of ions and electrons inside the plasma plume and of the density versus time and versus target distance; ion energy distribution, ion charge states, velocity of neutrals and electrons and yield of X-rays production are also measured to get information about the plasma [3,4].

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From the point of view of the applications of the laser-generated pulsed plasma, the primary interest was related to the study of a Laser Ion Source (LIS), which is operating in Catania for the ion injection into the ECR (Electron Cyclotron Resonance) ion source of the Cyclotron with improvement in the charge state and current production [5,6]. More recently the project of a new accelerator, which uses multi-energetic ion beams generated by pulsed plasmas with post-acceleration at energies ranging between about 5 keV and 500 keV was proposed for ion implantation [7].

In this work some interesting results obtained with the lasers of Catania and Prague are compared and the properties of the non-equilibrium plasma there obtained are presented and discussed.

2. Materials and methods

At INFN-LNS, Catania, a Nd:YAG laser operating at the fundamental wavelength 1064 nm and in the second harmonic at 532 nm with a pulse duration of 9 ns and a maximum pulse energy of 900 mJ may be used in single pulse mode or with 30 Hz repetition rate. It is focused on a target placed in vacuum through a focal lens in air. The spot size generally ranges between 0.1 and 1 mm^2. The maximum fluence is 900 J/cm^2. At PALS, Prague, a iodine mixing laser (Asterix) is operating at the fundamental wavelength 1315 nm and at the third harmonic at 438 nm with a pulse duration of 400 ps and a maximum pulse energy of 1 kJ in single pulse mode. The laser beam is focused on a target placed in vacuum through a focal lens in air. The spot size generally is about 0.1 mm^2 which corresponds to a laser fluence of about 1 MJ/cm^2 at the fundamental wavelength. Fig. 1 shows a photo of the experimental set-up of Catania (a) and Prague (b).

An ion energy analyser (IEA) is employed in order to measure the velocity of the ion emission and the ion charge states. It consists of a cylindrical electrostatic deflector which deflects the ions of 90°, thus filtering them with the bias of the energy-to-charge (E/z) ion ratio. By changing the bias of the deflection plates it is possible to change the E/z ratio and to measure the ion energy distribution as a function of the laser fluence. Deflected ions are detected with a windowless electron multiplier (WEM) placed 160 cm from the target. TOF measurements give the average ion velocities and kinetic energies as a function of their charge state [8].

Tantalum targets, 4 cm^2 surface and 4 mm thick, have been placed in vacuum and are irradiated at an incident angle of 30°. The target holder can be moved in order to change the incident angle θ. The IEA detector was placed along the normal to the target surface ($\phi = 0°$).

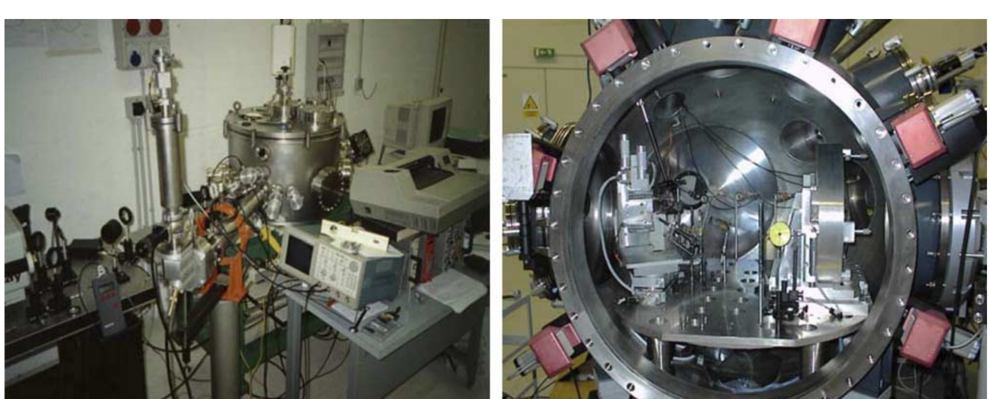
A CCD "Pixefly" VGA camera, 640×480 pixel, 10×10 μm/pxl, with a fast frame exposition variable from 1 μs up to 10 μs was employed to photograph the plasma plume expansion in the vacuum chamber. It was triggered with the laser pulse and it was mounted at $\phi = 90°$ angle with respect to the normal to the target surface.

A Balzers prisma MQS (Mass Quadrupole Spectrometer) 300 at high sensitivity and 1–300 amu range was employed to detect the residual gas in the vacuum chamber and the neutral atomic emission from the laser ablation.

A surface profiler, Tencor P10, with 1 nm depth resolution and 100 nm lateral resolution, was employed to measure the crater dimension and to evaluate the ablation yield as a function of the laser fluence.

3. Results

Fig. 2 shows two typical TOF spectra of tantalum target ablation performed with the Nd:Yag at 1064 nm (a) and with the Asterix laser at 438 nm (b) at 500 J and 700 J pulse energy, respectively. The first spectrum shows characteristic peaks due to the production of eight charge states at a laser fluence of 100 J/cm^2, while the second spectrum features the production of fifty charge states at a laser fluence of 180 kJ/cm^2. The ion energy strongly depends on the charge state z and on the emission angle ϕ with respect to the normal of the target surface. The ion energy increases with the charge state and it decreases with the angle



(a) (b)

Fig. 1. Experimental set-up at LNS of Catania (a) and PALS of Prague (b).