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CHARACTERIZATION OF LASER-GENERATED PLASMA BY ELECTROSTATIC MASS QUADRUPOLE ANALYZER

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Abstract

A study of laser ablation in vacuum of different targets (Al, Ni and Ta) by using 3 ns Nd:YAG laser radiation, at 532 nm wavelength and 10^9 W/cm^2 intensity, is reported. Laser pulse generates a plasma at the target surface and produces high non-isotropic emission of neutral and ion species, which are mainly emitted along the normal to the target surface. Mass quadrupole spectrometry, associated to the electrostatic ion deflection, allows an estimation of the energy distributions and of the emitted charge states, within the plasma plume, as a function of the incident laser energy. Neutrals show typical Boltzmann distributions while ions show Coulomb-Boltzmann-shifted distributions. The plasma is characterized in terms of velocity, kinetic energy, ion charge state and temperature of the ejected particles. A special regard is given to the parameters which influence the plasma properties, such as the free electron density of the ablated elements. The ion acceleration processes occurring inside the plasma, due to the high electrical field generated in the charge non-equilibrium conditions, is also discussed.

Introduction – Due to the multitude of photons and particles emission, laser-generated plasma can be characterized by different techniques, such as optical spectroscopy, mass spectrometry, Langmuir probe, charge collectors, etc.

The laser pulse hits a solid target and produces, in vacuum, a fast mass sublimation with emission of a dense vapour, which expands at supersonic velocity along the normal to the irradiated target surface [1].

At high laser intensities, the vapour absorbs the laser photons increasing the plasma temperature, the ion energy and charge state. Plasma characterization, in terms of temperature, density, energy of ejected particles and charge state distribution, is of special interest in different fields (Microelectronics, Engineering, Bio-medicine, Nuclear physics, Astrophysics, etc.). In this article a visible Nd:Yag laser is employed to irradiate different metallic targets and to characterize the produced plasma from the point of view of the ion emission.

Experimental section – A 3 ns Nd:YAG laser, operating at 532 nm (second harmonic) in single pulse or at 10 Hz repetition rate, with a maximum pulse energy of 150 mJ, was employed to irradiate in vacuum (10^{-6} mbar) different metallic targets (Al, Ni and Ta). The incident angle of the laser beam is 45° and the laser spot size at this angle is about 1 mm^2. An electrostatic mass quadrupole spectrometer (Electrostatic Quadrupole Plasma - EQP 300), was employed to monitor the particles ejected from the plasma with a mass range between 1 and 300 amu. The instrument detects neutrals and charged particles, in the energy range 1 eV - 1 keV, depending on the filament state. With filament "on" neutrals and ions are both detected while with filament "off" only ions are detected. The instrument contains four main sections: the ionisation source; the electrostatic energy filter; the mass filter; the SEM detector. More details on the EQP instrument are reported in literature [2]. EQP spectra were analysed to separate the neutrals from the ions and they were plotted as a function of the particle velocity, in order to fit them with the Coulomb-Boltzmann-shifted functions through the "Peakfit" numerical code.

A surface profiler (Tencor P-10) was employed in order to measure the craters depth and shape and to calculate the ablated mass per pulse vs. the laser fluence.

Results and Discussion - The ablation yield of the investigated elements was measured as removed mass per pulse vs. laser fluence, for an incident angle of 0°, as reported in Fig. 1a. Above the ablation threshold, typical of each element, the ablation yield increases linearly with the laser fluence. The experimental ablation thresholds are 1.0 J/cm^2, 0.60 J/cm^2 and 1.2 J/cm^2, while the theoretical values are 0.64 J/cm^2, 0.50 J/cm^2 and 0.76 J/cm^2, for Al, Ni and Ta, respectively.

The thresholds are proportional to the energy needed to sublimate, in vacuum, the irradiated mass of the element [3]. The ablation yields increase with the free electron density of the ablated elements, as reported in Fig. 1b.

Some typical EQP spectra, obtained ablating Al and Ni at 150 mJ laser pulse energy, are reported in the comparison of Fig. 2. The spectra show the velocity distributions for the various detected ion charge states. The neutrals spectra are obtained as a deconvolution from the single ionized ions plus neutrals detection (filament "on") and from the only ions, single ionized, detection (filament "off").

At 150 mJ the mean energy of the single ionized specie is 363 eV, 350 eV and 488 eV for the Ni, Al and Ta, respectively. The neutral mean energy, $\bar{E}_n$ is 290 eV, 265 eV and 360 eV for Ni, Al and Ta ablation, respectively. The fit of the experimental results indicated an equivalent plasma temperature of 12.1 eV, 11.2 eV and 14.9 eV, for Ni, Al and Ta, respectively.

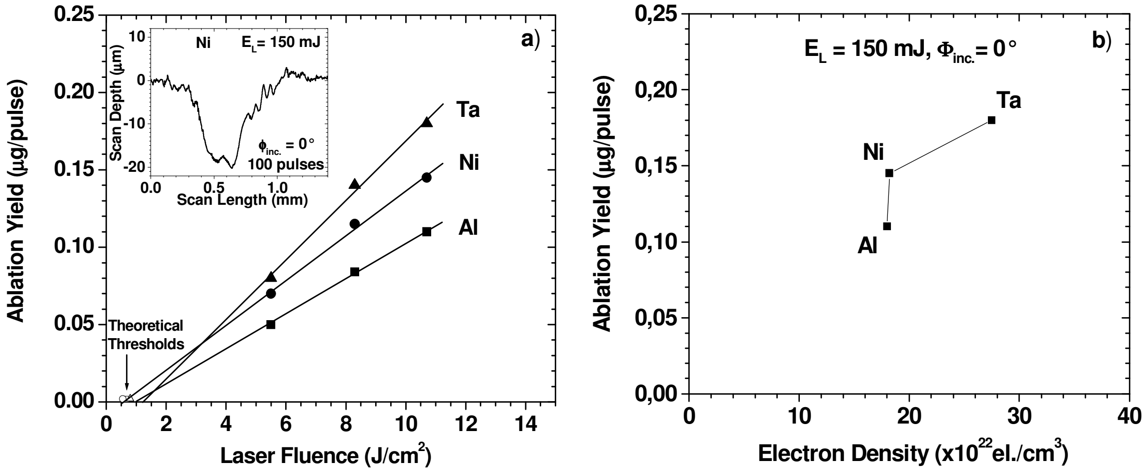

Fig. 1: Ablation yield vs laser fluence (a) and vs. free electron density of elements (b).

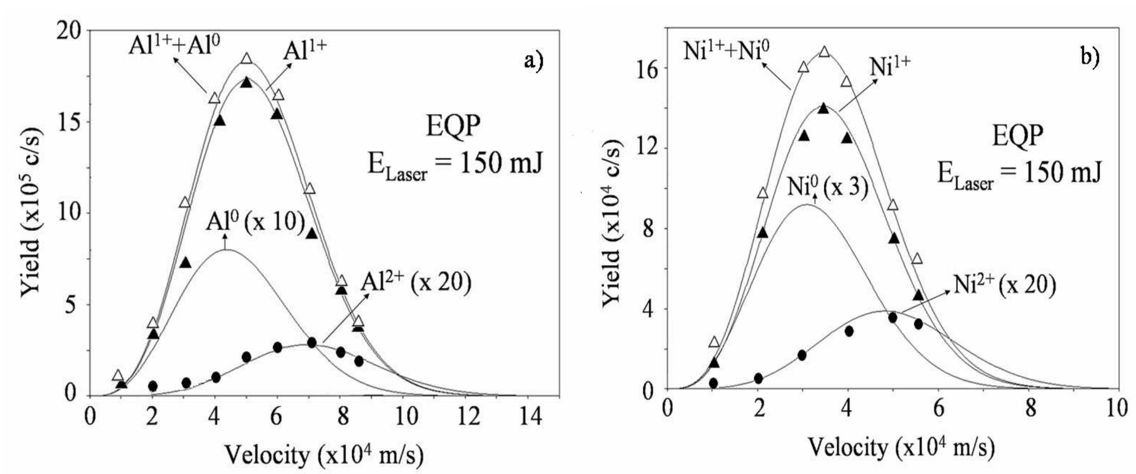

Fig. 2: Typical EQP ion and neutral spectra of Al (a) and Ni (b) laser ablation.

Ions are characterised by an energy value higher with respect to the neutrals' one, due not only to the thermal interactions between the plasma particles and to the adiabatic gas expansion in vacuum but also to their Coulomb interactions. The EQP measurements show an energy shift between the various ions charge states, according to previous results [4]. The regularity of the shift was confirmed by IC measurements for more energetic ions and it is due to the existence of an equivalent voltage developed in the plasma, which accelerates the ions towards the target normal direction. The maximum energy shift is 335 eV, 326 eV and 476 eV for Ni, Al and Ta, respectively.

Elements with high free electron density, such as tantalum (ρ_e= 27 x10^{22} el./cm^3), induce high equivalent voltage, V_o, and consequently high kinetic energy of the ionized species. Fig. 3 reports the dependence of the first ionized peak energy and of V_o vs. the free electron density of the irradiated elements.

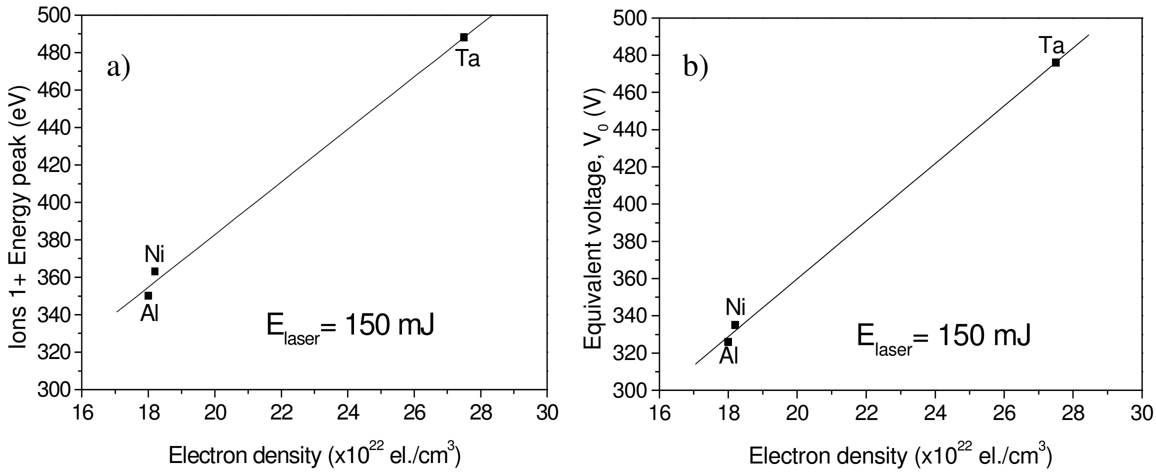

Fig. 3: First ionized peak energy (a) and equivalent acceleration voltage (b) vs. electron density.

Assuming the plasma to be in near local thermal equilibrium with an electron density of about 10^{16}/cm^3, the calculable Debye length in the plasma is about 0.26 μm for the three investigated elements. Thus, assuming the equivalent voltage to be applied on the Debye distance, the electric field transient can reach values of the order of 15 MV/cm, for the three different elements, in agreement with literature [5].

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