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OPTICAL SPECTROSCOPY IN LASER-GENERATED PLASMA AT A PULSE INTENSITY OF 10^{10} W/cm^2

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Abstract - *A Nd:YAG laser operating at 1064 nm wavelength, 9 ns pulse width, 500 mJ maximum pulse energy is employed to irradiate different metallic targets (Al, Ti, Fe, Ag) in vacuum. Optical spectroscopy and ion energy analysis are employed to characterize the laser-plasma. The plasma temperatures and densities are measured through optical spectroscopy, ion energy distributions and fast CCD imaging. Results indicated that high temperature and density gradients occur. The temperature in the core zone is in the order of 100 eV while in the coronal zone it in the order of 1 eV. The maximum plasma density is in the order of* $5\cdot10^{16}$ cm^{-3} *in the coronal zone.*

Introduction - It is known that intense pulsed laser beams can be focused on a solid material in order to cause ablation and formation of hot non-equilibrium plasmas, which are used for several applications in these last years. The processes developed inside the laser-generated plasma are very complex and they depend on many parameters, such as the laser characteristics, lens focalization, target composition, irradiation conditions, etc.

Plasma characterization, in terms of temperature, density, energy and charge state distribution of ejected particles, is of special interest in different fields (Microelectronics, Engineering, Bio-medicine, Nuclear physics, etc.)

Our investigation concerns the ns-laser ablation of different metallic targets and the evaluation of the plasma temperature and density. To this aim, different on-line analytical techniques are employed [1].

Experimental section - The employed laser is a Q-switched Nd:Yag pulsed laser operating at 1064 nm wavelength, 9 ns pulse duration and 1–900 mJ pulse energy. The laser beam is focused through a convergent lens on metallic targets (Al, Ti, Fe, Ag,) placed inside a vacuum chamber at 10^{-7} mbar. The spot diameter is 1 mm and the incidence angle, $\phi_{inc,}$ is 45°. An optical spectrometer system (OSS) (Lynear- Horiba Jobin Yvon) detects the visible light plasma-emitted in the wavelength region from 300 nm up to 700 nm with a 2 nm resolution. It operates by analyzing the signal detected by a small convergent lens focusing the plasma light on an optical fiber which transports it to the spectrometer input. The plasma plume is observed at 45° angle with respect to its expansion axis and the laser operates at 30 Hz frequency repetition rate hitting the metallic target.

In order to measure accurately the ion energies and charge states a special Ion Energy Analyzer (IEA), based on the electrostatic ion deflection, was used. It measures the time-of-flight (TOF) of the ions traveling for a 1.55 m target-detector distance along the normal direction to the target surface. By varying the bias of the electrostatic deflection plates, it is possible to filter different energy-to-charge, E/z, ratio values. The ion velocities were estimated by the TOF technique applied on the ion spectra acquired by a fast storage oscilloscope operating in single laser shots.

In order to measure the visible plasma volume, a fast Pixelfly CCD camera with a high resolution (1392 x 1024 pixel), high efficiency and 5 μs acquisition time, externally triggered by the laser shot, was used. The CCD camera was mounted at 90° with respect to the normal direction to the target surface. More details about the used detectors are given in literature [2].

Results and Discussion - Spectroscopic measurements, in the visible emission range, have been carried out on laser generated metallic plasmas. The excitation electron plasma temperature can be obtained by calculating the relative intensity of the emitted lines of neutral atoms of the plasma. Boltzmann plot uses several emission lines providing an accurate estimation of the electron temperature [3]. As an example Fig. 1a reports a detail of the experimental spectrum obtained irradiating a Fe target with a laser pulse energy of 335 mJ and observing the emission spectrum between 330 and 400 nm wavelength; its comparison with the theoretical expected lines distribution (vertical bars) is also shown.

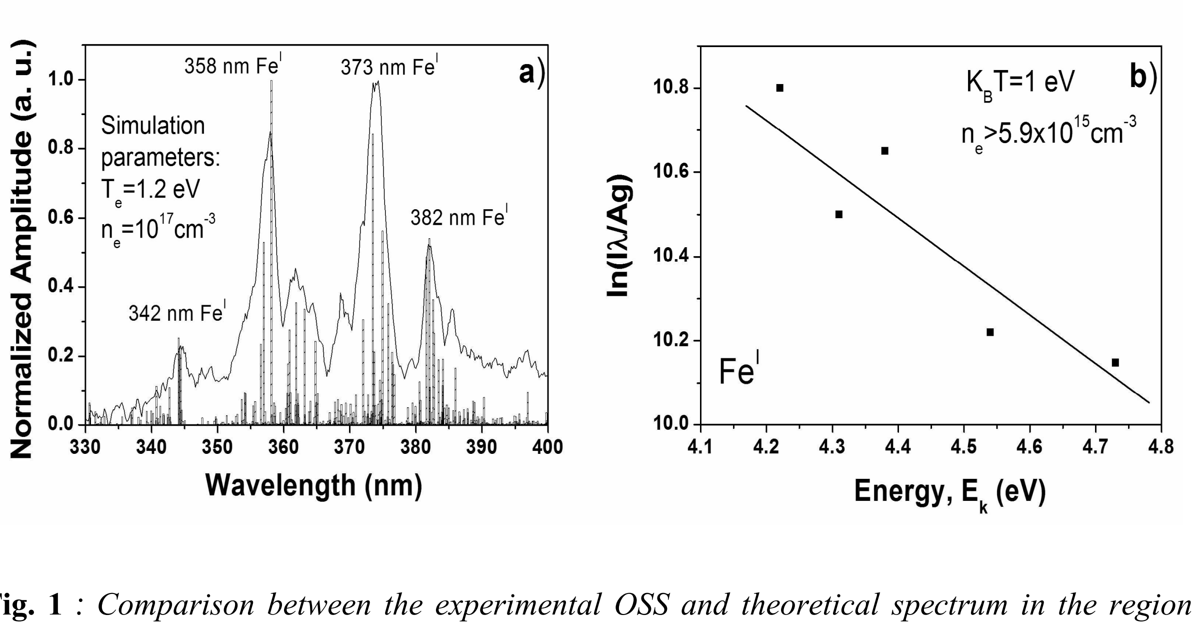

Fig. 1 : *Comparison between the experimental OSS and theoretical spectrum in the region 330-400nm wavelength (a) and Boltzmann plot of the optical spectroscopy analysis giving a coronal plasma temperature of 1 eV from* Fe^{I} *de-excitation lines.*

The differences between the experimental and theoretical spectra are due to the limited energy resolution of the used spectrometer, to the analysis of a plasma in non-equilibrium condition and to the presence of contaminant traces. Assuming the plasma to be in Local Thermal Equilibrium conditions, the best-fit experimental-theoretical comparison, obtained changing the input temperature and density parameters, shows that the best plasma temperature and density are 1.2 eV and $10^{17}/cm^3$, respectively. Fig. 1b shows the Boltzmann plot, obtained for the Fe ablation at 335 mJ, relative to the Fe^{I} de-excitation lines. It indicates a plasma temperature of 1 eV and the LTE assumptions impose that $n_e > 0.59 \times 10^{16}$ cm^{-3} [4]. Similar measurements carried out on, Ti, Ag and Al laser-produced plasmas indicate a plasma temperature of 0.66eV, 5eV and 15eV, respectively and an electron density, $n_e > 0.3 \times 10^{16} cm^{-3}$ for Ti plasma, $n_e > 1.7 \times 10^{16} cm^{-3}$ for Ag plasma and $n_e > 2 \times 10^{16} cm^{-3}$ for Al plasma.

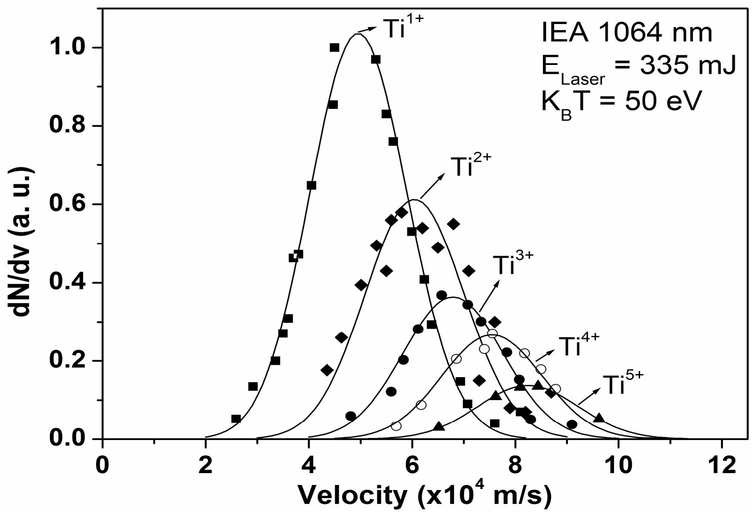

Fig. 2 *: Ion energy distribution as a function of the Ti charge state, giving a fit equivalent temperature of 50 eV.*

Fig. 2 shows a typical velocity distribution relative to the ions emitted by laser ablation of titanium irradiated in vacuum at laser pulse energy of 335 mJ. This distribution is obtained from several IEA measurements by changing deflection bias from 10V to 160 V and filtering different E/z ratio [E]. Experimental data (points) indicate that ions have Boltzmann distribution depending on their charge state. Increasing the charge state the mean ion energy shift towards higher energy. This result is in agreement with the Boltzmann-Coulomb-shifted distribution (BCSD) presented by L. Torrisi et al. in previous articles [5]. The ion velocity distributions can be fitted by a function of the temperature and of the Coulomb interaction occurring inside the plasma. The fitting parameters determine the plasma equivalent temperature and the different components of the ion velocity. The equivalent temperature obtained with a laser pulse energy of 335 mJ is 50 eV, 260 eV and 46 eV for Ti, Ag and Fe respectively.

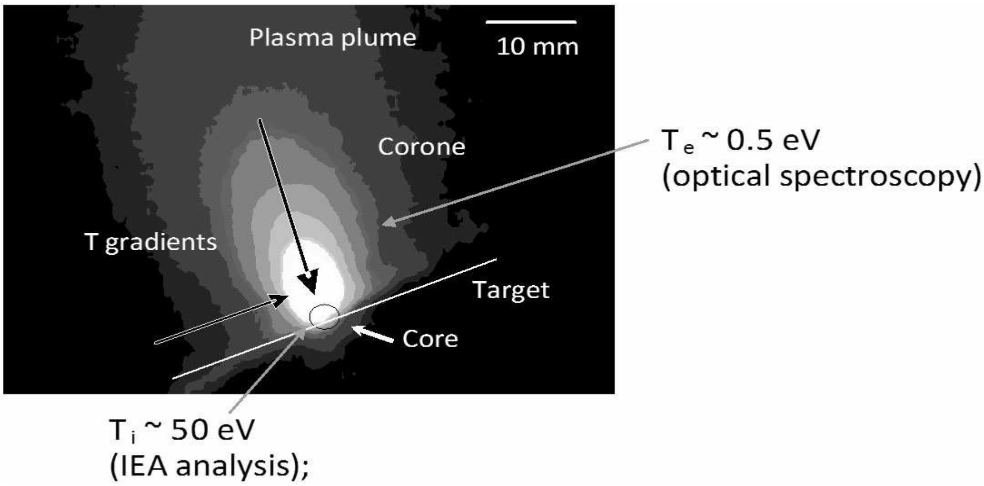

Fig. 3 : *CCD optical image of the Ti plasma plume expanding in vacuum.*

The data analysis above reported, indicate that, the ion plasma equivalent temperature is different in the core and in the coronal zone. The ion detection contains information about the plasma core zone, i.e. the inner plasma zone where thermal and Coulomb interactions take place (Kundsen layer). The visible light detection, instead, contains information about the plasma coronal zone, i.e. the colder zone of neutrals and ionized vapour. In fact, the visible light emitted from the inner plasma zone is absorbed by the external vapour and it is nearly not observed. For this reason a mean gradient of temperature of about 8.2 eV/mm, 12.8eV/mm and 51eV/mm for Ti, Fe and Ag respectively exist in the plasma plume along a direction orthogonal to the main axes of the plume. The geometrical dimension of the visible plasma plume obtained with the a CCD camera image (5 μs exposition time) and the measure of the crater profile, giving the number of atoms ejected per laser pulse (ablation yield), permitted to evaluate the temperature gradient and the atomic density of the produced plasma. Fig. 3 reports, as an example, a CCD image, obtained for a Ti-plasma, indicating the different zones of the plasma plume.

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