Langmuir probe measurements of laser-produced plasma at low pressures

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Abstract: *The behaviour of laser-produced plasma has been studied by Langmuir probe at different ambient gas low pressures. The plasma was generated by focusing a Nd:YAG laser beam (characterized by a 30 ns pulse duration, a 1064 nm wavelength, and 110 mJ energy) on a metal target. A single cylindrical probe with a 0.35 mm diameter was used for registering the I-V curve characteristics. By performing a time-resolved analysis of Langmuir probe signals, at different pressures, values of the electron temperature* T_e *and the ion density* n_e *were calculated. The maximum observed value of* T_e *is 29 eV determined at a pressure of about* 10^{-4} *mbar and a 1 mm distance from the target. By raising the pressure up to 10 mbar, the value of* T_e *diminishes approximately linearly to a value of 2 eV. The value of* n_e *decreases when the pressure is increased – the average value of* n_e *is estimated to be* 10^{13} cm^{-3}.

1. **Introduction :** The interaction of pulsed laser with metals has been studied extensively, because of its importance in applications, such as micromachining, thin film deposition and lithography [1]. Several diagnostics techniques have been used in order to characterize plasma. Electron temperature and plasma density can be measured by shadowgraphy and interferometry [2, 3]. Also, it is possible to determine some local information about plasma parameters by Langmuir probe. Langmuir probes are used for measuring ion density, plasma temperature, electrons and ions velocity [4 -9]. In principle, Langmuir probe is a simple tool and low cost but powerful for analysis local plasma parameters [4, 10]. In some experiments, applying optical method will not be effective. For instance in low pressure the shadowgraphy would not be a precise method. In this report, using laser produced plasma, the results of Langmuir probe for electrons and ions current in the nanosecond regime of laser field are presented and analyzed.

2. Experimental setup

The experimental setup is shown schematically in Fig. 1. A Q-switch Nd: YAG laser provided pulse irradiation with 1064 nm, pulse length of 30 ns and pulse energy of about 110 mJ. Laser beam was focused with 7.5 cm focal length lens placed inside a vacuum chamber on a steel target with 3.66 mm thickness. The laser fluency was kept at 5×10^{10} W/cm^2.

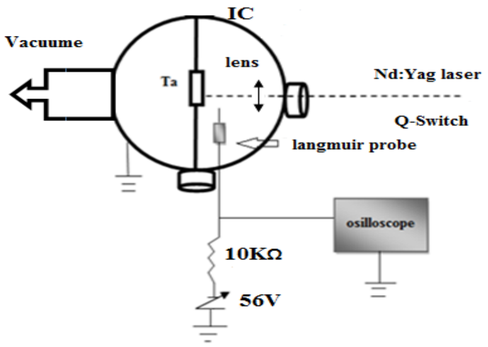

Fig.1. Schematic of experimental arrangement of interaction chamber and Langmuir probe.

The Langmuir probe used in the experiment is a stainless needle with 0.35 mm diameter and placed at different normal distance from the target. To attend the I-V characteristic, the probe was biased with a variable voltage in the range of -57 to +57 volt while the target and vacuum chamber were kept grounded. Electron and ion currents were determined from the voltage drop across a 10 kΩ using a fast digital oscilloscope. A fast photodiode was used for observing laser pulse signal.

3. Results and Discussion

Fig. 2 shows the typical time response of the positive and negative currents collected by the probe positioned 1 mm from the target and biased on -56 V and +56V at pressures of 1 bar and 10 mbar. Considering the Maxwellian distribution where the plasma is nearly to be assumed in quasi-equilibrium state, the measured electron current is given by:

$$I = I_e(sat)\exp\left(\frac{V-V_p}{kT_e}\right) \quad (1)$$

$$\frac{d\ln(I_p)}{dV} = \frac{1}{T_e} \quad (2)$$

$$I_i(sat) = qvAn_i \quad (3)$$

, where we have *I(sat)*=the saturation current, T_e =the electron temperature, V_p =plasma potential, *q*=the ion charge, *v*=the plasma flow velocity, and A the probe surface area [the electron temperature is given by relation (2) in eV unit]. Apparently, as it is revealed through preliminary inspection of the signal noise at the triggering time, the noise of high voltage is mixed with signal. Nevertheless, inspection of the data at a higher time resolution reveals that the rise-time and the peak-current of the real currents can be distinguished. In this experiment, the minimum electron temperature at a pressure of 10 mbar was 2 eV and the maximum was 29 eV at a pressure of 5×10^{-4} mbar (both at a distance 1mm). As it can be seen in Fig. 2, the magnitude of the electron current is larger than that of the ion current. The peak of the positive signals and the negative signals correspond to the time-arrival of the maximum ions and electrons respectively. Being the same, while the rise-time of electrons and ions signals are 1-1.7 μs at a pressure of 1 bar, they are reduced to a value of *ca*. 0.75 μs at a 10 mbar. This behaviour is also observed at much lower pressures up to 10^{-4} mbar. Also by probing the signal far away from the target, the smaller rise-time of electrons become more apparent. The general behaviour of electron temperature versus pressure and probe distance has been shown in Fig. 4, left and centre. As can be seen, when, in the range of 1 mm to 10 mm distances from the target, the pressure is raised, while T_e decreases slowly and shows a nearly linear dependency, T_e has fast reduction behaviour at a centimetre distance scale.

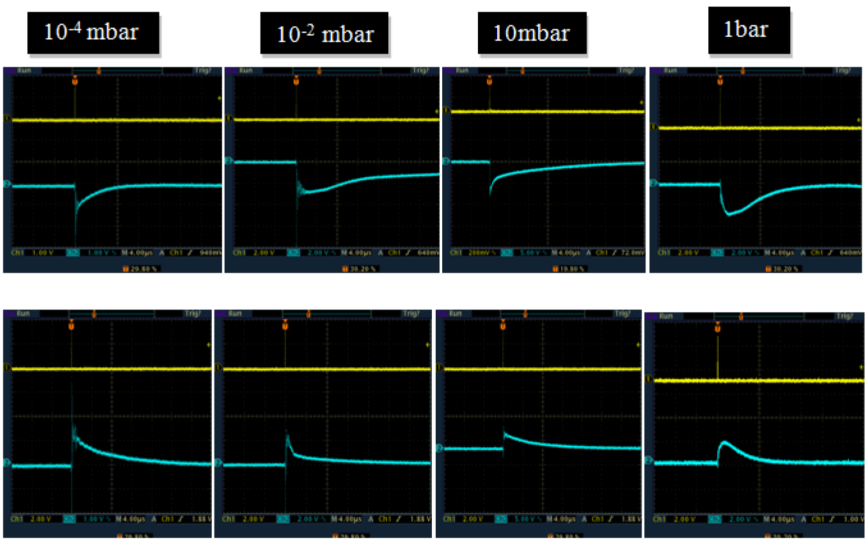

Figure2. Electron (up) and ion signal (down) of the probe as a function of time at a 1 mm distance from the target.

At pressures close to the atmospheric one, the collision rate of electrons with ambient gas molecules or atomic grows. Thus, since the rate of collision depends linearly on the gas density, such a decreasing for electron temperature is expected. At a constant pressure, by going far away from the target at centimetres of distance, the kinetic energy of electrons decreases fast.

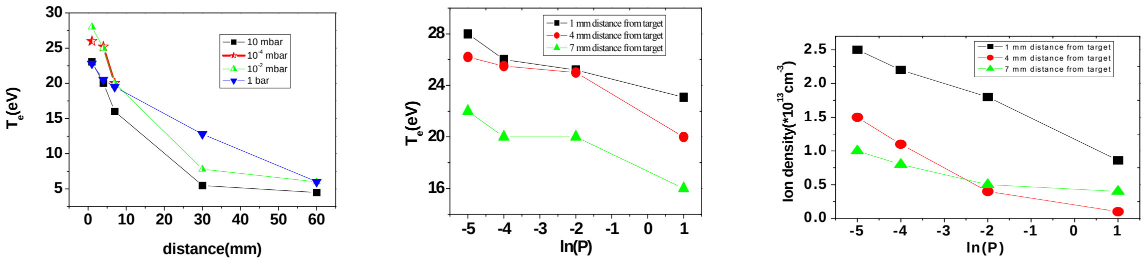

Fig. 4. (Left) Electron temperature as a function of probe distance, (centre) electron temperature verses pressure, (right) ion density verses pressure

This can be interpreted in the following manner. While, in a millimetre scale range, the number of particles with a high degree of kinetic energy is high, in a centimetre scale range the plasma becomes cold and the electrons interchange their energy with the ions, thus resulting in a fast decrease in the temperature. In Fig. 4, right, the variation of ion density as a function of pressure is shown. The average of ion density is estimated to be about 10^{13} cm^{-3} at pressures of 10^{-4} -10^{-2} mbar. This result shows that in a low range of pressure, plasma density is nearly constant at a fixed position of probe.

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