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On temperature measurements in a non-equilibrium plasma

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ABSTRACT

We report temperature and drift velocity measurements on the ion component of a plasma produced by the interaction of a UV laser beam with a Cu solid target. A XeCl excimer laser (308 nm wavelength, 20 ns pulse duration, 70 mJ pulse energy) was used, achieving a power density on the target of about 0.3 GW/cm^2 after beam focusing. The diagnostics was performed by means of ion collector measurements. Suitable theoretical expressions were derived for fitting the recorded ion current, under the assumption of a "shifted" Maxwell-Boltzmann distribution for the ion velocity. Two specific Faraday cups were used, which sampled the plasma in two orthogonal directions. So, a longitudinal plume drift velocity value of 5300 m/s resulted. Surprisingly, two different temperature values were found: $5 \cdot 10^5$ K (~ 50 eV) and $5 \cdot 10^4$ K (~ 5 eV) for the "longitudinal" and "transverse" temperature, respectively.

INTRODUCTION

Plasmas generated by pulsed lasers are characterized by a high concentration of ionized matter which in turn can generate pulsed high current ion streams. For example, in the field of accelerators, Laser Ion Sources (LISs) [1] can supply ions to the electron cyclotron resonance machines to enhance the available charge state with respect to the standard methods. Moreover, ion implantation with or without an additional ion acceleration [2, 3] is a very useful technique for superficial modification of several materials, in order to improve the properties of resistance to corrosion and wear of metals and alloys.

Due to the high laser fluence necessary to get ablation, the target heats until the boiling temperature. The produced vapours are subsequently ionised and heated via inverse bremsstrahlung up to reach a plasma temperature much higher than the maximum target one. The resulting plasma expands adiabatically along the target normal.

The extreme speeds of the involved processes do not allow to get direct measurements of the plasma temperature. Although this drawback, the plasma parameters can be derived from plasma corpuscular diagnostics. In particular, time-of-flight (TOF) diagnostics is utilized in this work in order to record the signal of the ions carried by the drifting plasma. By fitting the ion signals by a modified Maxwell-Boltzmann distribution [4], it is possible to derive the "longitudinal" and "transverse" temperature of plasma. The knowledge of plasma parameters is useful to understand the physical processes involved in the laser plasma generation as well as to improve the applications of the ion streams.

THEORY

Usually the so-called "shifted" Maxwell-Boltzmann distribution is assumed for the velocity of ions in the laser-produced free expanding plasma [4]:

$$f\left(v_x, v_y, v_z;\, v_d, T\right) = A\,exp\left\{-\beta\left[\left(v_z - v_d\right)^2 + v_x^2 + v_y^2\right]\right\} \qquad (1.1)$$

$$A \equiv \left(\frac{M}{2\pi kT}\right)^{\frac{3}{2}} \; ; \quad \beta \equiv \frac{M}{2kT} \qquad (1.2)$$

where Cartesian coordinates (x, y, z) are used, taking the z direction perpendicular to the target surface; $f\left(v_x, v_y, v_z\right)dv_x dv_y dv_z$ is the number of particles having velocity values within $\left(v_x, v_x + dv_x\right)$, $\left(v_y, v_y + dv_y\right)$, $\left(v_z, v_z + dv_z\right)$; v_d is the plume drift velocity; T is the ion temperature; M is the ion mass; and k is the Boltzmann constant.

On the basis of such a simple picture, Faraday cup (FC) diagnostics of plasma temperature and drift velocity is straightforwardly applicable in the laser power density range 0.1 - 1 GW/cm^2 and for laser pulse duration of the order of 10 ns, provided that only the abundance of +1 ions is predominant in the plume [5, 6]. Assuming a free expansion from a point-like source, readjusting and generalizing the results of Utterback *et al.* [7], the following expression can be derived for the ion density, *i.e.*, the number of particles per unit volume, $\rho(\boldsymbol{r}, t)$, at the point $\boldsymbol{r}$ and time t from the laser pulse:

$$\rho(z, r, t) = A C t^{-3} \exp\left[-\beta (r/t)^2\right] \cdot \exp\left[-\beta \left(z/t - v_d\right)^2\right] \qquad (1.3)$$

where C is the overall number of ions and cylindrical coordinates $\boldsymbol{r} = (z, r, \varphi)$ have been introduced due to the symmetry of the plume with respect to the z axis. The particle current density, $\boldsymbol{j}(\boldsymbol{r}, t)$, *i.e.*, the number of particles per unit time per unit area, is given by

$$\boldsymbol{j}(\boldsymbol{r}, t) = \rho(\boldsymbol{r}, t)\boldsymbol{v} \qquad (1.4)$$

where $\boldsymbol{v} = \boldsymbol{r}/t$ due to the self-similar plume expansion.

For a FC with a small acceptance angle, like in this experiment, the recorded ion current can be considered as directly proportional to the current density at that point [8]. So, for a FC placed at a distance L from the target and centred on the z axis, the following expression for the ion current, $i_L(t)$, can be easily derived from the previous equations:

$$i_L(t) \propto Lt^{-4} \exp\left[-\beta(L/t - v_d)^2\right] \quad (1.5)$$

Instead, for a FC placed transversally to the z axis, at the position $(0, R, \varphi)$, the following expression for the current, $i_R(t)$, is obtained:

$$i_R(t) \propto Rt^{-4} \exp\left[-\beta(R/t)^2\right] \quad (1.6)$$

EXPERIMENTAL APPARATUS AND RESULTS

A XeCl excimer laser (λ = 308 nm, 20 ns pulse duration) was utilised. The beam power density on a Cu target was 0.3 GW/cm^2. Fig. 1 shows a sketch of the experimental chamber [5]. TOF measurements were performed by two FCs. The axial one was 8 cm in diameter and was placed along the plasma propagation direction at a distance L = 20 cm from the target, while the radial one was 3.3 cm in diameter and was placed transversally to the target at a distance R = 6 cm. In order to collect the positive ions, the FCs were negatively polarised at -200 V. The oscilloscope was decoupled from the bias voltage by means of a 5 μF capacitor and the cup signals were closed on a 50 Ω load resistor. Furthermore, the FCs were equipped with a suitably biased suppressor electrode for stopping the secondary electron current.

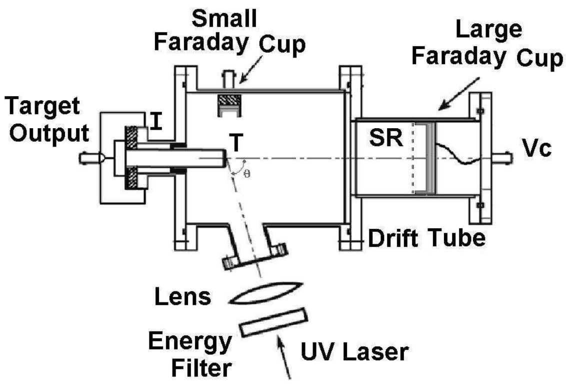

Fig. 1. Experimental apparatus. The laser beam axis was tilted of 70° with respect to the chamber axis.

Fig. 2a and Fig. 2b show the ion current signals of the axial and radial FCs, respectively. They were fitted with the distribution function defined in Eqs. (1.5) and (1.6), respectively, obtaining “longitudinal” and “transverse” temperatures of about $5{\cdot}10^5$ K and $5{\cdot}10^4$ K, respectively. A value of 5300 m/s resulted for v_d.

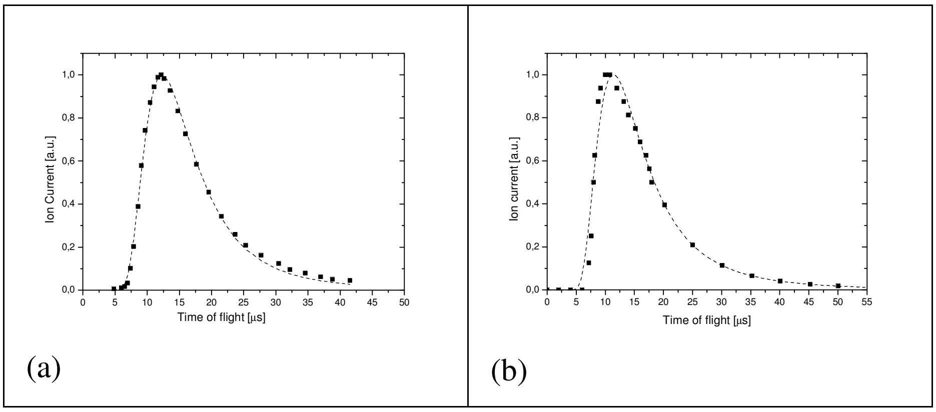

Fig. 2. a): Ion current waveform recorded by the axial FC. The dash line represents the best fit curve by Eq. (1.5). b): Ion current waveform recorded by the radial FC. The dash line represents the best fit curve by Eq. (1.6).

CONCLUSION

Our findings suggest at least two hypothesis: i) the plasma ions are not at all in thermal equilibrium and their expansion can not be described by an equilibrium distribution such as the shifted Maxwell-Boltzmann one; or ii) the plasma plume is composed of several ion groups (for example, one group for each charge state), each one with its own values for drift velocity and temperature, and occurring with a not negligible abundance. So, owing to the different angular distributions resulting for each group of particles, the axial FC would collect high energy ions in strongly forward-peaked expansion, while the side FC would collect low energy ions in quasi-spherical expansion.

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