*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-1.144 (2005)*

MEASUREMENTS OF "EQUIVALENT ION TEMPERATURE" IN PLASMA PULSE LASER-GENERATED AT INFN-LNS AND PALS

L. Torrisi[1,2], S. Gammino[1], A. Picciotto[2], L. Andò [1], L. Laska[3], J. Krasa[3], K. Rohlena[3] and J. Wolowski[4]
[1]*INFN-Laboratori Nazionali del Sud, Catania, Italy*
[2]*Dipartimento di Fisica, Università di Messina, Italy*
[3]*Institute of Physics, ASCR, Prague, Czech Republic*
4 Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland

Abstract

Equivalent ion temperatures of pulsed laser-generated plasma have been measured at INFN-LNS of Catania and PALS of Prague. In the first case the laser intensity was of the order of 10^{10} W/cm^2 while in the second case it reaches about 10^{15} W/cm^2. Experimental data show Boltzmann-like ion energy distributions, which are shifted towards high energy when increasing the ion charge state. This function was employed to fit the experimental data and to calculate the "equivalent ion temperatures" and the components of the ion velocity due to thermal effects, expansion effects and Coulomb interactions.

1. Introduction

The main parameters of a laser-generated plasma are represented by the equivalent ion and electron temperature, plasma density, fractional ionization, average charge state and energy and ablation yield [1, 2]. The interaction of a high-intensity laser beam with solid targets generates a plasma, in which the absorbed energy is not completely transferred through collisional (thermal) processes. For high power density, the plasma physical properties are influenced by non linear effects (filamentation, self focusing, ponderomotive force) occurring at the target surface during the first microseconds of plasma plume generation [3]. In particular the concept of plasma temperature is important to determine the properties of Local Thermal Equilibrium (LTE) and non-LTE conditions [4].

2. Experimental set-up

A Nd:YAG laser at INFN-LNS operating at 532 nm with 9 ns pulse duration and 900 mJ maximum pulse energy, 30 Hz rate, was used to irradiate a Ta target in vacuum. The laser spot was 0.5 mm in diameter and the incidence angle 45°. The ablation occurs in vacuum at 10^{-7} mbar. A photo dissociation iodine laser system at PALS laboratory operating at 438 nm (third harmonic) with 400 ps pulse duration and 250 J maximum pulse energy, single pulse, has been used to irradiate a Ta target in vacuum. The laser sot was 70 micron (30° incidence angle). A mass quadrupole spectrometer (HIDEN EQP 300) was used to detect atoms and neutrals generated during the laser ablation and to extract the neutrals temperature.

An ion energy analyzer (IEA) [5] was placed at 160 cm apart at LNS and at 275 cm apart at PALS. It gives the energy-to-charge (E/z) ratio through time-of-flight (TOF) measurements and the ion energy distributions. A fast CCD photo camera (1024×1024 pixels) was used to catch up photos of the plasma plume evolution.

3. Results

The experimental data obtained from IEA and elaborated in terms of ion energy distributions, were fitted with the following "Boltzmann-Coulomb-shifted" function (complete description is given in [6]):

$$F(V_z, V_k, V_c) = A_0 \left(\frac{m}{2\pi K_B T} \right)^{3/2} V_z^3 \exp\left[-\left(\frac{m}{2K_B T} \right) (V_z + V_k + V_c)^2 \right] \quad (1)$$

in which V_z is the thermal velocity, V_k is the expansion velocity and V_c is the Coulomb velocity of plasma ions. From the equation (1), by fitting the experimental measurements of ion energy distribution, it is possible to evaluate the average "equivalent temperature" of the ions. Results give 400 eV for LNS experiment and 80 keV for PALS one. The correlation between plasma equivalent ion temperature and the available maximum charge state gives a picture of the energetic state of the plasma. The average charge state <Z> increases with the plasma temperature. For high plasma temperatures, the production of different groups of energetic ions were measured [7]. By using the PALS measurements on Ta ablation at the intensity of 10^{15}/cm^2, the calculated equivalent ion temperature, obtained though the experimental ion energy distribution data at LNS and PALS have been compared with theoretical approaches of Chen [8], Zakharenkov [9] and Morse [10], with a good agreement, as reported in Fig. 1.

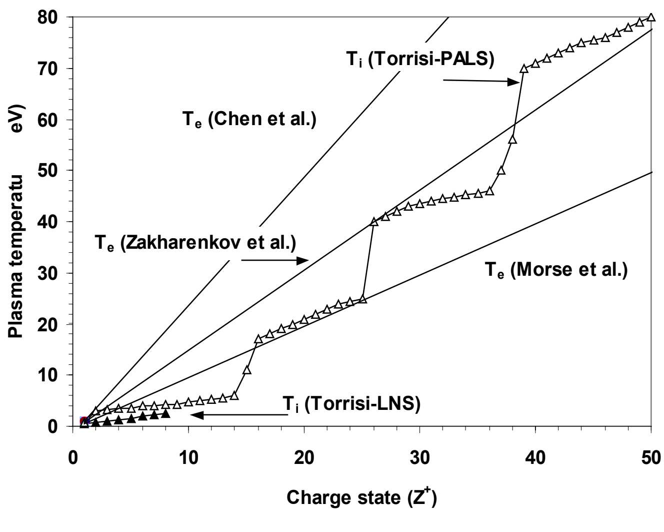

Fig. 1: Equivalent ion temperatures vs. charge state comparison for INFN-LNS and PALS and comparison with theoretical approaches.

As a first approximation the thermal motions of ions inside the plasma can be described by thermodynamic model, which gives, for mono-atomic species, the following ion temperature:

$$KT_i = \frac{m_i v_i^2}{3} \tag{2}$$

where m_i is the ion mass and v_i the ions velocity. The v_i was measured by the IEA detector. The comparison of Fig. 1 indicates that as a line of trend the temperature increases linearly with the charge state. The plot indicates that the thermal approach described in equation (2) can be considered acceptable for low charge states. The "equivalent ion temperature" with eq. (1) is in good agreement with the theoretical predictions of other Authors [8, 9, 10]. By fitting the time-of-flight spectra with the use of the Boltzmann-Coulomb-shifted distribution and by evaluating the deconvolution contribute peaks as a function of the time, it is also possible to correlate the equivalent ion temperature with the time. In this way it is also possible to observe the plasma plume cooling during the expansion in vacuum. Fig. 2 shows that PALS plasma is very hot in comparison with the LNS one, featuring a life time of about 5-6 μs, while for LNS it is about 30-40 μs. Thus the equivalent ion temperature depends on the time elapsed from the laser pulse through an exponential decay law.

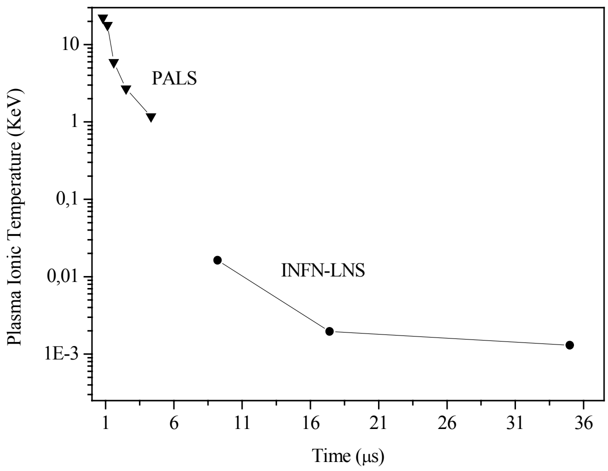

Fig. 2: Equivalent ion temperature vs. time evolution for INFN-LNS and PALS lasers.

Measurement of the grey gradient level of luminosity of CCD images taken in 1 μs exposition time, produced by the plasma expansion in vacuum, permitted to evaluate the temperature gradient vs. distance from the target surface. The experimental data were obtained assuming a constant temperature inside the plasma core (labelled d_1 distance in the photo inserted in Fig.3) and a temperature decay in the gradient zone developed within the distance d_2. The grey gradient in the d_2 distance, of about 500 μm, suggests that the plasma temperature decreases with the distance following an about linear decay, as reported in Fig. 3. This decay is not in agreement with a simple inverse law with the distance or the distance square, as it should be for a black body irradiating in equilibrium conditions. The high particle collision rate inside the "hot core" adds information on the plasma evolution; the momentum exchange between the "hot" internal core and the "cold" external plasma sheath, expanding with different velocity, produces a temperature decay with the distance less sharp.

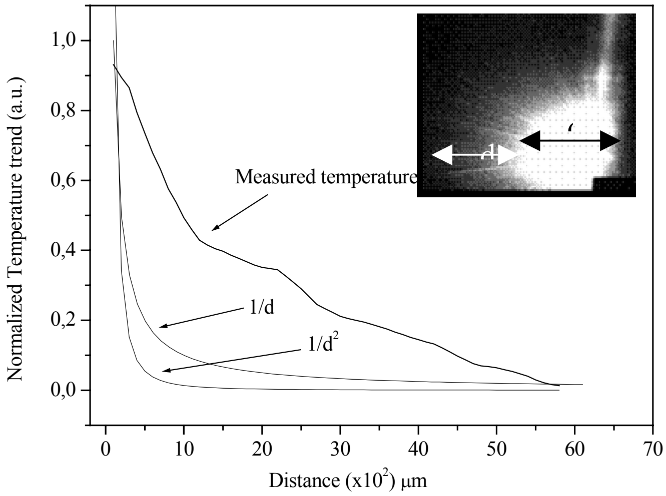

Fig. 3: Plasma temperature trend vs. distance (b) for INFN data.

4. Conclusions

At LNS the maximum charge state, using tantalum target, was 8^+ while at PALS the maximum reached the 50^+ and the equivalent ion temperature reached a high value of more than 80 keV as extrapolated by the fits of the IEA energy distribution data.

The empirical models described above, from equation (2) to (5), for the charge state 50+ give an electron plasma temperature of 125 keV, 82 keV, and 52 keV respectively.

The values of ions and electrons temperatures (comparing the Chen and the Torrisi fit for PALS data) are still about the same for high charge state, between about 25^+ up to 50^+, while they have a significant difference for charge state below 25^+.

References

[1] S. Gammino et Al., Nuclear Instruments and Methods B 209 , (2003) 345-350
[2] L. Torrisi et Al., Applied Surface Science 210 (2003) 262-273
[3] J. Wolowski et Al., Plasma Sources Sci . Technol. 11 (2002) A173-A177
[4] A. Picciotto et Al., PPLA 2003 Proceedings, World Scientific,191 (2004)
[5] E. Woryna et Al., Laser and Particle Beams (1996), vol 14, no.3, 293-321.
[6] L. Torrisi et Al., J. Appl. Phys. 91 (5), 18 2002
[7] A. Picciotto et Al., Proc. Fourth International Workshop and School "Towards Fusion Energy - Plasma Physics, Diagnostics, Applications", Kudowa Zdrój 2004, 659-663.
[8] F. Chen , Introduction to Plasma Physics and Controlled Fusion, Los Angeles, 1974.
[9] Y.A. Zakharenkov et Al., Proc. P.N. Lebedev Phys. Inst. **133,** 146 (1983).
[10] R.L. Morse et Al., 1973 Phys. Fluids 20, 909.