About the temporal evolution of plasmas, produced by high-power laser

A.Aliverdiev[2,5], <u>D.Batani</u>[1], A.Benuzzi-Mounaix[4], R. Dezulian[2],

M.Koenig[4], V. Malka[3], and T.Vinci[1,4]

[1] *Dipart. di Fisica "G. Occhialini", Un. degli Studi di Milano - Bicocca, Milano, Italia*

[2] *Institute of Physics of DSC Russian Academy of the Science, Makhachkala, Russia*

[3] *Lab. d'Optique Appliquee, UMR CNRS - ENSTA - Ecole Polytechnique, Paris, France*

[4] *LULI, UMR CNRS CEA - Université Paris VI - Ecole Polytechnique, Paris, France*

[5] *International Humanitarian and Technical Academy, Makhachkala, Russia*

The investigation of hydrodynamics of laser-produced plasmas (in the intensity range $I_L \approx 10^{14}$ W/cm^3) is fundamental for several physics areas, first of all inertial confinement fusion. Although several theoretical models of plasma expansion were developed already in the 70's and in the 80's [1-3] and many experiments have studied this aspect, still there are not many clean experimental results. Indeed most previous experiments were influenced by 2D effects in the hydro expansion of the plasma. In recent years, several techniques have been introduced which allow the production of flat-top intensity profiles. Hence one fundamental experimental parameter, the laser intensity on target, is clearly defined, which is not the case with the usual Gaussian-like intensity distribution or, even worse, with typical focal spots affected by hot spots. This allows a well-characterized study of plasma expansion. Also, 2D effects in plasma expansion are strongly reduced, getting much closer to that described by 1D theoretical model. One of such technique is that of Phase Zone Plates (PZP [4]) which appeared in recent years, and which was also used in our experiment. Recently we reported a preliminary study of experimental results mainly concentrating on image analysis [5]. Now we present preliminary physical results.

Our experimental set up included a Nd:glass high power laser system with typical intensity of 10^{14} W/cm^3 (the temporal profile is approximately trapezoidal with rise and fall time of 150 ps and a flat top duration of 600 ps), a probe beam (Nd laser converted to 2ω) coupled to an interferometer and to a streak-camera with ps resolution. The diagnostic system allowed the evolution of the plasma density profile to be measured as a function of time. Different targets (CH$_2$, Al, Au) with different radiative properties were used. In particular plasma expansion with Au targets should be strongly influenced by radiation (XUV) transport [6,7], while, in the case of CH$_2$ targets, energy transport should be

determined by electrons only. Such phenomena are a key problem in the physics of Inertial Confinement Fusion (ICF) driven by lasers.
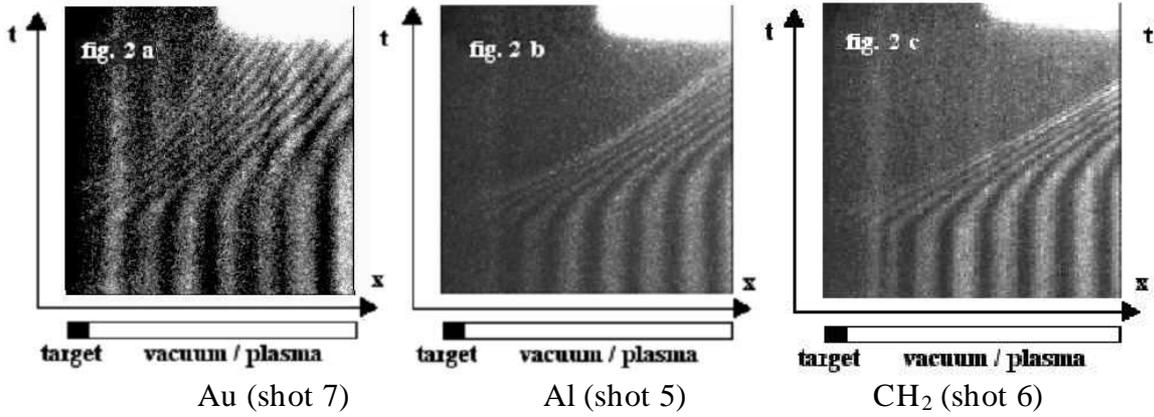

Au (shot 7)   Al (shot 5) CH_2 (shot 6)

Fig. 1. The interferograms recorded with the streak camera. The total image dimensions are 375 μm (horizontal scale) and 1.065 ns (vertical scale).

The phase shift in a point x of the interferometric picture (fig. 1) from classical optics is $\Delta\Phi_a(x) = 2\pi\alpha x/\lambda$, where α is the angle between the probe and reference beams the in interferometer; and λ the wavelength of the laser beam. The plasma-induced phase shift is $\Delta\phi_{plasma}(x,t) = \dfrac{2\pi L}{\lambda}\left(1 - \sqrt{1 - \dfrac{n_e(x,t)}{n_c}}\right)$, where $n_c = \dfrac{4\pi^2 c^2 \varepsilon_0 m_e}{\lambda^2 e^2}$ is the critical density; n_e is the free electrons density; λ is the laser wavelength; L is the transversal dimension of the plasma (along probe beam, i.e. perpendicularly to x; in this preliminary analysis, we have taken $L = 400$ μm, corresponding to the spot created by the PZPs). So,

$n_e = n_c\left(1 - \left(1 - \dfrac{\Delta\phi_{plasma}\lambda}{2\pi L}\right)^2\right)$, or, for $n_e << n_c$, $n_e = \dfrac{n_c \lambda}{L}N$, where N is the number of a π-phase shift in the interferometric streak-camera images. (Of course, this relation is correct only for uniform plasmas, that is $L \neq f(x,t)$. In other case it is completely impossible to find a one-digit 3D $n_e(x,y,t)$ from 2D $N(x,t) = \dfrac{1}{n_c\lambda}\displaystyle\int_0^L n_e(x,y,t)dy$.)

In the following step of the analysis we consider the points on the x-axis (spatial dimension), which before plasma production, correspond to maxima and minima of the interferograms, and then we follow the time evolution of N, taking it like a number of extremes, i.e. the number of a π-phase shift, from $t=t_0$ (where t_0 is a shot time). Then data
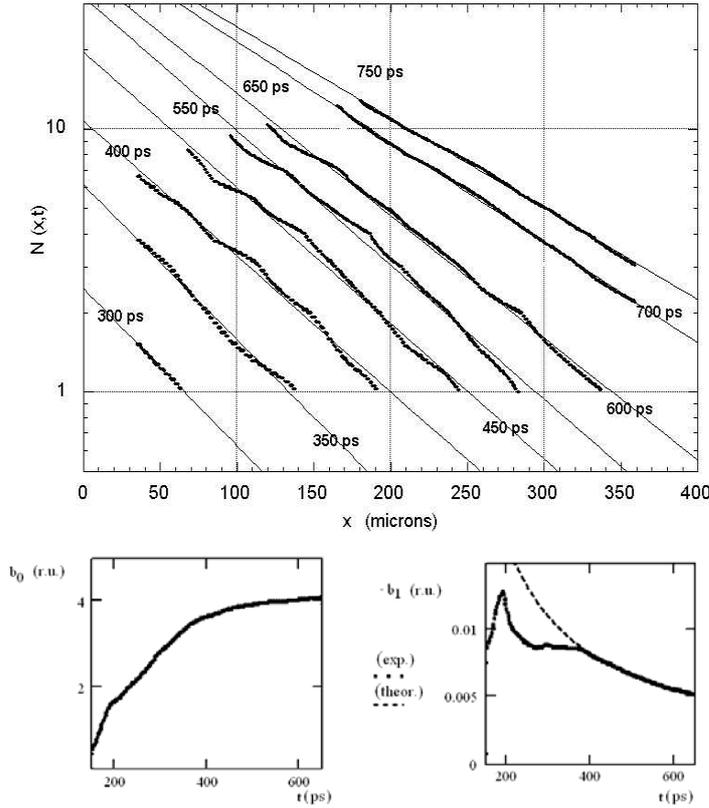
Fig. 2. Experimental dependences $\ln N(x,t)$ and calculated coefficients $b_0(t)$ and $b_1(t)$ (Au, shot 7).

was interpolated for all (x,t) square. For the precise analysis of experimental interferograms with a large noise, we also applied a technique of averaging with time shifts, which is similar to the application of a direct Radon transform [8], which was discussed in [5].

Let us see to the experimental dependences of $\ln N(x)$ vs. x at various fixed times t (for Au (shot 7) it's present in fig. 2). We can see that the lines are closed to straight ones. This is in good agreement with the theoretical model according to which

$$n_e(x,t) \propto \exp\left(\frac{-(x-x_0)}{c_s \cdot (t-t_0)}\right).$$ In this case $\ln N(x,t) \approx b_0 - b_1 \cdot x$, where $b_1 = \left(\frac{1}{c_s \cdot (t-t_0)}\right)$. We found b_0 and b_1 from the experimentally determined $N(x,t)$ by the least square method. The comparison of experimental interferograms (presented in fig. 1) with synthesized ones calculated from the experimental b_0 and b_1 is presented in the fig. 3.
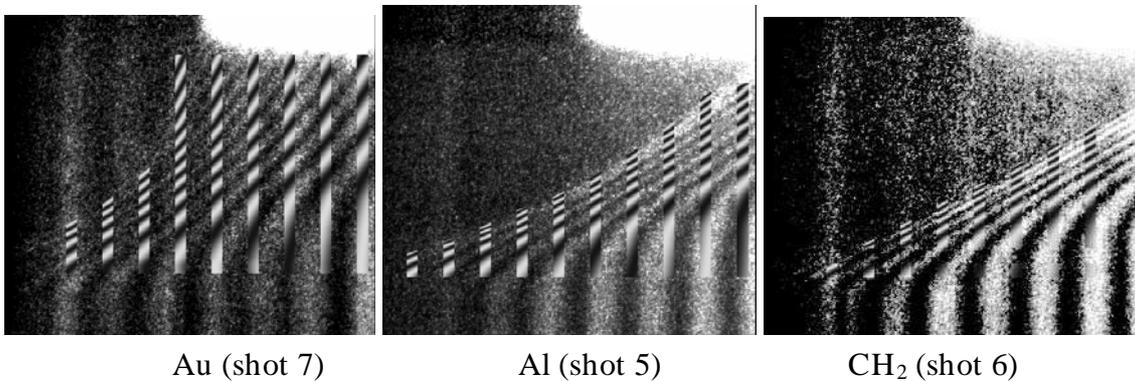

Au (shot 7)   Al (shot 5)   CH$_2$ (shot 6)

Fig. 3. The comparison of experimental interferograms with synthesized ones, calculated from the experimental b_0 and b_1.

Shot N^o	Target	Z^*	Energy of pulse, J	I_L (10^{13} W/cm^2)	T_e (eV)	$c_s = 9,79 \cdot 10^5 \sqrt{\dfrac{\gamma Z^* T_e}{\mu}}$ (10^7 cm/sec)	c_s^{exp} (10^7 cm/sec)
2	Al	13	42.66	4.	547	1.72	1.94
5	Al	13	49,60	5.3	605	1.81	2.039
6	CH$_2$	6.7	51.26	5.5	576	1.84	1.80
7	Au	36	54.43	5.7	665	1.96	2.23
10	Au	36	51.5	5.5	621	1.88	2.16

The table reports the expected plasma parameters like the electron temperature (calculated like $T_e(eV) = 10^{-6} \cdot \left(I_L \lambda^2\right)^{2/3}$, where I_L (W/cm^2), laser beam intensity; λ, wavelength in μm), the ionization degree Z* (calculated with the formula by Colombant & Tonon [9] which is valid in collisional-radiative equilibrium conditions), and the sound velocity with the comparison of a sound velocity, calculated from the experimental b_1 coefficient. We have found how the theoretical predictions (b_1 inversely dependent on time) are well verified t>400 ps. Moreover the value of sound velocity which is obtained for t>400 ps is in excellent agreement with the theoretical prediction obtained from model.

[1] C.E. Max, et al., *Phys. Fluids*, 23, 1620 (1980).

[2] W.M.Manheimer, D.G.Colombant, J.H.Gardner, *Phys. Fluids* 25, 1644 (1982)

[3] P.Mora, *Phys. Fluids* 25 (6) (1982)

[4] M. Koenig, et al., *Phys. Rev. E* 50, R3314 (1994)

[5] A. Aliverdiev, D.Batani, V. Malka, et al, *Book of Proc. of RGD04 (Bari, Italy, 2004), AIP Conf. Proc.*, New York, Melville, 762, 419-424 (2005)

[6] R. Sigel, et al., *Phys. Rev. Let.* 65, 587 (1990)

[7] N.Kaiser, J. Meyer-ter-Vehn, R. Sigel, *Physics of Fluids* B, 1, 1747 (1989)

[8] A. A. Aliverdiev and N. A. Ashurbekov, *Russian Phys. J.*, 47, 331-332 (2004)

[9] G.F.Tonon & D.Colombant, *J.Appl.Phys.* 44, 3524-3537, (1973)