Time resolved air-wedge-shearing interferometry and spectroscopy on a picosecond plasma∗

E.J. Iglesias
Universidad Simón Bolívar, Departamento de Física, Caracas, Venezuela

R.C. Elton and H.R. Griem
University of Maryland, Institute for Electronics and Applied Physics, College Park, MD 20742

H.A. Scott
Lawrence Livermore National Laboratory, Livermore, CA 94551

Recibido el 25 de abril de 2002; aceptado el 2 de septiembre de 2002

We present the results of an air-wedge shearing interferometer applied to a KrF, ≤ 20 ps, laser-xproduced plasma on a boron-carbide target. We produced synthetic interferograms in order to match the experimental ones by solving the differential equation of light rays in a plasma. The plasma was represented by an axisymmetric function with a variable dependence along the plasma axis. Inferred electron densities were compared to results obtained from the atomic postprocessor CRETIN running on fits to Lasnex hydro data, and from spectroscopically measured Stark widths in the XUV.

Keywords: Laser-produced-plasma; shearing interferometer; picosecond; Stark width.

1. The experiment and analysis

The knowledge of the electron density ($N_e$) spatial distribution in a laser-produced plasma (LPP) is a fundamental quantity to be measured, since it provides considerable information on the basic dimensions and gradients of the system. $N_e$ also controls the rates of the atomic physics processes available at the temperatures established in the plasma.

As part of an ongoing investigation on measuring the plasma parameters of a picosecond LPP, we set up an experiment using the so-called air-wedge shearing interferometry technique (as opposed to using a plate, which is not suitable for short-lived plasmas) [1]. Using this technique we were able to measure the 2D distribution of $N_e$ in an axisymmetric, ≤ 0.3 mm long plasma, with a resolution of about 10 µm. Time resolution was limited to the duration of the probing beam, which is ≈ 10 ps.

For the probing beam we divert a ≈ 15 mm² section of the main KrF beam before the final amplification stage ($F \geq 2 \times 10^{-4}J/(cm^2)$). The main KrF beam had an energy of about 60 mJ, ≥ 10 ps pulse for a power density on target of ≈ 2.5 \times 10^{14}W/att/(cm²). We sent the probing beam at 90° to the plasma axis. We collected the beam with a quartz lens (f#5.5) in a x2 magnification mode. The beam is further magnified by a factor of 5, using an UV achromatic quartz-fluoride condenser (see Fig. 1).

The principle of the technique is to combine the two reflections produced on the quartz-air interfaces that bound an air-wedge between two quartz plates (air-gap angle 2° degrees). The plates are at 45° to the probing beam. The two sheared copies of the original beam generated at the air-wedge continue to an image intensifier detector whose fluorescent image is focussed, and x2 magnified, onto a polaroid film pack (see Fig. 1). The total magnification of the system is about x22. In this way we produced a rear-referenced interferogram (see Fig. 2) [2].

We modeled the interferogram (see Fig. 3) by solving the ray equation in 3 dimensions [3]

$$\frac{d}{ds} \left( n \frac{dr}{ds} \right) = \nabla n$$
for a cylindrically symmetric plasma, allowing for any functional form along the Z direction, where $n$ is the refractive index, and $\vec{s}$ is a vector tangent to the trajectory. To estimate the phase difference between the probing (refracted) beam and an optically equivalent vacuum (reference) beam at the screen (see Fig. 3), we extended to 3D the equations in Ref. 4. For the calculations we used an analytical 3D function for $N_e(r, z)$ to fit the observed experimental interferograms:

$$N_e(r, z) \propto \exp \left( -\frac{r}{V_r} \right) \times \frac{1}{1 + \rho_o^2},$$

(2)

where

$$\rho_o = \left( \left( \frac{r}{V_r} \right)^2 + \left( \frac{z}{V_z} \right)^2 \right)^{1/2},$$

(3)

and the $V_r(r, z)$ and $V_z(r, z)$ could be chosen appropriately. The parameters as such provide enough flexibility to match the experimental profiles and possess a simple interpretation. The log($N_e$) contours of such function, in Fig. 4, correspond to the interferogram in Fig. 2.

**FIGURE 2.** 1-Main beam; 2-plasma; 3-spherical front after plasma (both reference and refracted beamlets belong to this front; therefore, they end at the same point on the screen); 4-refracted beamlet; 5-reference beamlet.

**FIGURE 3.** Interferogram taken at $\approx$ 140 ps. White mark = 50 $\mu$m.

**FIGURE 4.** Model interferogram, contours correspond to log($N_e$) = 18.6, 18.8, 19.0, 19.2, 19.4, 19.6, 19.8, 20.0

# 2. Results and Conclusions

It is well known that, although very effective, simple Abel inversion algorithms have limitations when the medium is strongly refracting or moves away from cylindrical symmetry. Our method of analysis, i.e., producing a synthetic interferogram starting off with a known function, takes these effects into account consideration. The synthetic interferogram is then compared to that obtained experimentally, providing an analytical function that could supply all the necessary information about the $N_e$ distribution of the plasma for any post-analysis. Accuracies better than 20% of the values of $N_e$ could be achieved at distances beyond 50 $\mu$m. However, for the particular interferogram (140 ps) on Fig. 2, gradients are already too low for plasma to be detected beyond 200 $\mu$m from the target, where we still have $N_e \approx 10^{18}$ cm$^{-3}$. Closer than 50 $\mu$m, the method fails to reproduce the trend of $N_e$ in the dark areas around the laser focus. Those areas are due to probe beam radiation going out of the collection optics. This is a limitation of the experimental technique in spite of the short wavelength that is used. Such an effect is taken into account in the calculations, using the experimental collection solid angle value as a cut-off limit for the maximum beam deviation. It should be mentioned that model estimates for LPP infer scale lengths of the order of a fraction of the focal spot size, hence it is expected, considering that the critical electron density is $N_c \sim 1.8 \times 10^{22}$ cm$^{-3}$, that $N_e$ could change more than an order of magnitude within that distance.

Preliminary modeling with density and temperature profiles provided by analytic fits to 2D Lasnex simulations [5] show a considerable discrepancy with our interferogram results. The fits were used for convenience, both to avoid repetitive costly simulations and to extend the simulations to later
times and larger distances. They capture the gross features of the plasma evolution over a fairly wide range of spatial scales, but do not capture some important high-density features close to the target surface. In particular, the fits assume a uniform target surface with a density falling off monotonically away from the surface. The simulations show that the laser actually excavates a pit in the target surface, leaving a non-uniform region of high electron density partially hidden by undisturbed target material. In addition, the density structure exhibits a peak close to the initial surface, corresponding to the initial shock structure. Spectra constructed using the simulation data appear closer to the experimental observations than those constructed from the fits. However, the simulations only extend out to 400 ps and are quite limited in radial extent. In the future, we plan to extend the simulations and use the simulation data directly for the analysis.

Figure 5 summarizes the electron density profiles obtained by different methods. For the spectroscopically inferred $N_e$ from the FWHM of different lines, we have a consistent picture with respect to $N_e$ vs Z. We again find a discrepancy with interferometer and model results. Part of the discrepancy is likely due to spatial resolution and optical depth effects - a large optical depth is evident for the $L_{\gamma \beta}$ of CVI (the results shown in Fig. 5 do not account for this). Care should be taken in the interpretation of Fig. 5, as the different sets of data represent different aspects of the time history. While the interferograms have a time resolution of the order of the probe beam lifetime, line width measurements are inferred from time-integrated spectra over the lifetime of the plasma \( \leq 1 \) ns. The model is an actual snapshot of the predicted $N_e$ vs Z at 400 ps with a resolution of 1 ps. For times earlier than \( \approx 100 \) ps the model represents a plasma closer to the target, with $N_e$ off the scale of Fig. 5. There is one further consideration in determining the observation times of our interferograms. Although our setup has the advantage that the probe beam is completely anchored to the main pulse, we cannot rule out a jitter of the order of the pulse width. We have recorded interferograms that show evidence of plasma present in a range of \( \approx 150 \) ps, and used the fading of the plasma as a criterion for setting the zero time. However, given the preliminary qualitative observations of the model - where the laser could be excavating a pit - it will take some time for the plasma to evolve to a large enough extent to be probed. Our 40 ps observation time would then be a lower limit to the actual time, and a relevant issue for future analysis.

**FIGURE 5.** Presents the comparison of $N_e \times 10^{20} \text{ cm}^{-3}$ vs Z in microns obtained using a) shearing interferometry at 400 \( \pm 20 \) ps, b) the values obtained from FWHM of $He_{\beta}$ of Boron and Carbon and $He_{\gamma}$ of Boron c) model results from fits to hydrodynamic plasma parameters from a Lasnex 2D run at 400 ps.
* Supported by the National Science Foundation of the USA


