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To cite this article: D Batani et al 2008 J. Phys.: Conf. Ser. 112 022048

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Recent experiment on fast electron transport in ultra-high intensity laser interaction

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Abstract. We performed an experiment with cone targets in planar geometry devoted to the study of fast electron generation, propagation, and target heating. This was done at LULI with the 100 TW laser at intensities up to 10¹⁹ W/cm². Fast electrons penetration, with and without cones, was studied with different diagnostics (Kα imaging, Kα spectroscopy, visible emission) for ω or 2ω irradiation. At ω, the pre-plasma generated by the laser pedestal fills the cone and prevents the beam from reaching the tip.

1. Introduction

One of the main issues of the fast ignitor scheme is the transport of fast electrons to the compressed thermonuclear fuel. Recently, a new target scheme [1], based on the use of cones to guide the PW ignition laser has been proposed as an alternative approach to fast ignition. The ultra-high-intensity short-pulse laser is focused directly through the cone, so to be guided as close as possible to the core. Indeed, integrated fusion experiments [2] showed an increase in neutron yield in presence of the cone. However, according to 3D PIC simulations, cones should also enhance fast electron production (conversion efficiency) and electron energy, in comparison with planar targets [3]. In particular, part of the electrons should be accelerated and confined along the inner cone surfaces due to self-generated electric and magnetic fields. Enhanced collimation should result from their convergence at the tip [4].
Despite the clear interest of such results, still many points remain obscure. Therefore, we performed an experiment in a simpler geometry, devoted to the study of fast electron generation, propagation, and target heating in presence of the cone. The experiment was performed at LULI with the 100 TW laser facility. The penetration of fast electrons, with and without cones, was diagnosed with several techniques (X-ray K-shell imaging and spectroscopy, optical and proton emission) for a large set of interaction conditions. Laser wavelength, focalization, cone geometry, pulse duration have been systematically varied. Our best results were obtained with frequency-doubling, corresponding to ASE-free interaction conditions. Our data pinpoint the detrimental influence of the pre-plasma generated by the laser pedestal at $1\omega$ (as suggested also by a recent study on the Vulcan laser [5]), which fill the cone, preventing the laser beam from reaching the cone tip. Nevertheless, even in best conditions, no positive effects, such as enhanced electron production or heating was observed.

2. Experimental set-up

The 100 TW laser at LULI was focused by an f/3 off-axis parabola at normal incidence onto three-layer targets (Al-Cu-Al) with and without cone. The minimum focal spot was 15 $\mu$m FWHM with the target in the best focus position. We used two laser configurations: at the fundamental frequency $1\omega$ (1.057 $\mu$m) and frequency doubled $2\omega$ (0.53 $\mu$m) so to test the influence of the laser pedestal. The maximum available laser intensity is $10^{19}$ W/cm$^2$ at $1\omega$, in the best focus position and $5 \times 10^{17}$ W/cm$^2$ when the laser is defocused (corresponding to a large focal spot in order to minimize ASE intensity).

The cones were manufactured by the target group of ILE, Osaka: made with 10 $\mu$m thickness gold and opened at the tip. They were fixed on planar targets with glue at the external side of the cone tip. Three kinds of cone have been used: 30° and 60° total angle with 20 $\mu$m tip diameter and 30° angle with 40 $\mu$m tip. The planar targets consisted of 3 layers: a first Al layer (on laser side) varied from 0 to 70 $\mu$m thickness ($\Delta x$), a second 20 $\mu$m Cu fluor layer, and a third 20 $\mu$m Al (at the rear side). This last Cu/Al bi-layer was molecularly bonded. FIG. 1 shows two examples of cones used in the experiment.

FIG. 1: Cones used in the experiment, 60° (left) and 30° (right) total angle, tip hole diameter of 20 $\mu$m, and cone length of 900 $\mu$m. Targets of typically 300 $\times$ 300 $\mu$m$^2$ at cone tip.

The ASE, the focus position of the laser with respect to the target plane, the laser pulse duration, and the characteristics of cone have been varied in order to systematically study their influence on electron transport. Several diagnostics were implemented: X-ray K\(\alpha\) image [6] and spectroscopy [7] of buried layers, and protons emission using radiochromic films (RCF) [8]. Also, gated optical imager (GOI) and the HISAC [9] diagnostics were used to image the target rear side in the visible region so to record either optical transition radiation (OTR [10]) or thermal emission depending on the time delay. Concerning the X-ray diagnostics, we used a spherical Bragg crystal producing a monochromatic 2D image of the Cu-K\(\alpha\) emission (8.04 keV) from the rear side of the target on an Andor CCD while a conical Bragg crystal spectrometer [11] recorded Cu-K\(\alpha\) and Al-K\(\alpha\) emission on a DEF film (Kodak).

The X-ray K\(\alpha\) imaging system detected the signal from the buried Cu layer (8.048 keV) while the X-ray K\(\alpha\) spectrometer detected the cold K\(\alpha\) lines from the Al layer, its hot lines (i.e. the shifted K\(\alpha\) lines emitted from ionized Al), and the Cu K\(\alpha\) line at the 5th order.
3. Results

In this report, we mainly focus on the results obtained by X-ray and proton diagnostics, because in presence of the cone, the visible signal from target rear side detected by the GOI and the HISAC diagnostics was systematically too weak to be exploited quantitively. Concerning Kα imaging, when we shoot at 1ω, in all cases the signal measured with the cone was much weaker than the signal measured without the cone. We tried several configurations: the ASE pedestal duration was changed from 2 ns to 0.5 ns; the beam was focused directly on the target or defocused, the laser pulse duration was varied from 0.4 to 1.5 ps, and of course we tested different cone tip diameters and total angles.

![FIG. 2: The first two Cu Kα images were obtained at 1ω with a 0.4 ps laser pulse (2ns ASE pedestal). Al(20 µm)/Cu(20 µm)/Al(20 µm) 3-layer target without cone [left], and with cone (30° angle / 40 µm tip) [centre left]. The laser was defocused giving an intensity of $5 \times 10^{17}$ W/cm². The last Cu Kα images were at 2ω with a 0.4 ps laser-pulse (ASE-free). Cu(20 µm)/Al(20 µm) 2-layer target without cone [centre right], and Al(10)/Cu(20)/Al(20) 3-layer target with cone (30° angle/20 µm tip) [right]. The laser was focused directly on the target plane. Same color scale.](image)

Our best results at 1ω are shown in Fig. 2 for what concerns 2D Kα images. Images in Fig. 2 (left and centre left) were obtained by shooting with a 0.4 ps laser pulse (2ns ASE pedestal), and by defocusing the laser by 300 µm yielding an intensity of $\sim 5 \times 10^{17}$ W/cm². These are very close to results obtained at 1ω with a 1.5 ps pulse (0.5 ns ASE pedestal), and by focusing the laser directly on the target, which corresponds to an intensity of $2 \times 10^{18}$ W/cm². In all other cases, we practically got no significant signal with the cone. In particular, let’s notice that the laser intensity on target was of $\sim 2 \times 10^{18}$ W/cm² or less due either to the longer pulse or the increased spot diameter. The shots at $10^{19}$ W/cm² (short pulse, best focusing on target) produced a much weaker signal in presence of the cone.

Quantitatively, the reduction in Kα signal in the spot with the cone is a $\sim 3.5$ for both conditions (obtained either by defocusing the beam or increasing its duration). As for the Kα source size, it practically was the same with and without cones. The decrease of the signal with the cone is also observed in spectra. For planar targets, we see the cold Kα lines from both Al and Cu. With the cone, only a faint Al line was recorded while Cu emission was practically always absent (at the noise level).

Qualitatively, the same situation was observed by looking at proton emission. In this case we shoot on simple Al foil (15 µm thick) in order to maximize proton emission, with or without the cones. Proton emission was diagnosed by stacks of radiochromic films (RCF), protected by 30 µm Al, ~25 mm behind target rear side. 1ω shots without cone yielded signal up to the 12th RCF evidencing proton energies up to 16 MeV. By contrast, shooting into a cone, no signal was recorded beyond the 3rd RCF, implying maximum proton energy of 3 MeV. At the same time, the number of energetic protons decreased by a factor $\sim 2.5$. From these values, we may infer the cone-induced changes in fast electron distribution. Since proton acceleration occurs inside the Debye sheath set up by the fast electron through an electric field of amplitude $E \sim (n_e T_e)^{1/2}$, where $n_e$ and $T_e$ are the hot electron density and temperature. Finally, since charge neutrality requires equal proton and fast electron densities, we may conclude that cones cause a reduction in $n_e$ and $T_e$ by factors of 2-3 and 10-11, respectively.

The situation was quite different when we shoot the laser at 2ω: the results in presence of the cone were noticeably better, as it is evident by looking at the images in Fig. 2 (right and centre right). Here,
both Kα images, and the signal levels, appear similar with and without the cone (note that the slightly lower Kα signal in Fig. 2, right, is due the additional 10 µm Al layer). Let’s notice that at 2ω the maximum laser intensity is reduced by at least 20%, and the factor (Iλ2) suffers an additional 75% decrease. On the other hand, all 2ω shots were performed under best focusing conditions. As a result, the factor (Iλ2), and therefore the fast electron mean properties, are expected to differ a little between the cases of Fig. 2 at ω (left and centre left)[12].

4. Discussion and conclusions

Summarizing our experimental results, for 1ω at 10¹⁹ W/cm², the presence of the cone implied that the signals measured with all diagnostics almost completely disappeared. A better situation is obtained for reduced intensity (obtained either by defocusing the beam) or for reduced (0.5 ns) pedestal duration. Finally for 2ω irradiation, Kα signals with and without the cone were comparable.

The obvious interpretation of our experimental data points out the role of the pre-plasma created by the laser pedestal. For 1ω irradiation at 10¹⁹ W/cm², and a contrast ratio of about 10⁻⁷, we get a pedestal intensity of 10¹² W/cm², enough to create a long plasma. Cone geometry indeed acts to increase plasma filling as compared to a planar situation. When the laser intensity is reduced by defocusing the beam, we do not expect the creation of such long plasma. With increased pulse duration (1.5 ps, obtained by changing the compressor grating distance) we do not expect the ASE intensity to change appreciably but in this case we reduced ASE duration to 0.5 ns. Finally, with 2ω conversion, the pedestal is suppressed and we approximately observe the same Kα signals with and without cone.

Our experiment shows that the coupling of the laser beam to the cone-target assembly is a very critical problem. “Filling” of the cone by the preplasma may completely prevent the laser beam to reach the higher-density regions of the target. However we must stress that, even in our best cases, we observed no beneficial effect from the cone, i.e. there is no evidence from our experimental data, that the cone plays a positive role in guiding either the laser or the produced fast electrons. Mechanisms proposed in [3] do no seem to play any role, at least in our experimental conditions. These simulation results have been obtained in the case of prepulse-free laser beams, which is not the case of our 1ω experiment, but should be close enough to our 2ω irradiation conditions (except for the reduced laser intensity). In conclusion, the main role of the cone is preventing the interaction of the laser with the large corona around the pellet, creating a preferential access channel for the laser.

Acknowledgements

This work has been supported by the Access to Research Infrastructures activity in the Sixth Framework Programme of the EU (contract RII3-CT-2003-506350, Laserlab Europe).

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