The influence of preformed plasma on a laser-driven shock produced in a planar target at the conditions relevant to Shock Ignition

J. Badziak[1], T. Chodukowski[1], Z. Kalinowska[1], P. Parys[1], T. Pisarczyk[1], P. Rączka[1], M. Rosiński[1], L. Ryć[1], J. Wołowski[1], A. Zaraś[1], L.A. Gizzi[2], F. Baffigi[2], G. Cristoforetti[2], P. Koester[2], L. Labate[2], L. Antonelli[3,4], M. Richetta[3], D. Batani[4], G. Folpini[4],G. Malka[4], Y. Maheut[4],E. Krousky[5], M. Pfeifer[5], O. Renner[5], M. Smid[5,7], J. Skala[5], J. Ullschmied[6], M. Kucharik[7], R. Liska[7], Y. J. Rhee[8], F.Consoli[9], R. De Angelis[9], C. Spindloe[10]

[1] *Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland*; [2] *Intense Laser Irradiation Laboratory, INO-CNR, Pisa, Italy;* [3] *University of Roma "Tor Vergata", Roma, Italy;* [4] *Centre Lasers Intenses et Applications, Universite Bordeaux 1, Talence, France;* [5] *Institute of Physics, Prague, Czech Republic;* [6] *Institute of Plasma Physics, Prague, Czech Republic;* [7] *Czech Technical University, FNSPE, Prague, Czech Republic;* [8] *Nuclear Data Center, KAERI, Korea;* [9]*ENEA,Centro Ricerche Frascati, Frascati, Italy,* [10]*Scitech Precision, Rutherford Appleton Laboratory, Didcot, UK*

Abstract

The effect of preformed plasma on a laser-driven shock produced in a planar target at the conditions relevant to the shock ignition scenario of ICF was investigated at the kilojoule PALS laser facility. Characteristics of the preformed plasma were controlled by the delay Δt between the auxiliary beam (1ω, 7×10^{13} W/cm^2) and the main 3ω, 250 ps laser pulse of intensity up to 10^{16} W/cm^2, and measured with the use of 3-frame interferometry, ion diagnostics, an X-ray spectrometer and K_α imaging. Parameters of the shock produced in a CH(Cl) target (25 μm or 40 μm thick) by the intense 3ω laser pulse with energy ranging between 50 J and 200 J were determined by measuring the craters produced by the shock in a massive Cu target behind the layer of plastic. The volume and the shape of these craters was found to depend rather weakly on the preplasma thickness, which implies the same is true for the total energy of shocks and pressure generated by them. From the comparison of the measured crater parameters with those obtained in 2D simulations using the PALE code, it was estimated that for $I_{3\omega} \approx 10^{16}$ W/cm^2 the pressure at the rear (non-irradiated) side of the 25-μm plastic layer reaches about 100 Mbar.

Introduction

Shock ignition (SI) is a novel concept of ICF [1, 2] which promises achieving a high energy gain with relatively simple targets and laser driver energy lower than for the conventional hot spot ignition scheme. Like in the fast ignition approach, the target compression is separated from the target ignition, however both these processes are driven in SI by a single, properly shaped laser pulse. A multi-ns low-intensity (~ 10^{14} – 10^{15} W/cm^2) part of the laser pulse drives the compression, while its short (~ 0.2 – 0.5 ns) high-intensity (~ 10^{16} W/cm^2) part (spike) generates a strong convergent shock which ignites the compressed fuel at the stagnation phase.

Recent hydrodynamic simulations show that SI is a relatively robust approach with regard to hydrodynamic instabilities and that a significant energy gain (~ 100) could be achieved with as little as ~ 300 kJ of UV laser energy [1, 3-5]. However, to produce the shock pressure needed for ignition, the laser spike intensity has to be sufficiently high, above the threshold for the nonlinear interaction of the laser pulse with large scale plasma produced by the multi-ns (compressing) part of the pulse. In this context, the most important nonlinear processes are: two plasmon decay (TPD), stimulated Raman (SRS) or Brillouin (SBS) scattering and filamentation instability (FI) [6,7]. They can lead to a significant increase in the total light reflectivity and to the transformation of a part of laser energy into fast electrons that can preheat the fuel as well as keep the laser absorption far away from the critical surface. Though the preheat of a precompressed fuel by fast electrons is here a less important issue than in the conventional central ignition (the igniting spike is applied when the areal density of the fuel is large enough to shield itself from fast electrons of energy below ~ 100 keV [8] and the production of fast electrons may actually raise the ignitor efficiency [9, 10]), the above phenomena can considerably decrease the igniting shock parameters and disturb the transport of energy to a hot spot.

The aim of the experiment performed at the PALS laser facility in Prague was to study the effect of large scale preformed plasma on the parameters (total energy and pressure) of a laser-driven shock wave produced in a planar target at the physical conditions relevant to SI. Parameters of the preformed plasma were controlled by the delay Δt between the auxiliary beam (1ω, 7×10^{13} W/cm^2) and the main 3ω, 250 ps laser pulse of intensity up to 10^{16} W/cm^2. Parameters of the shock produced in a CH(Cl) target (25 μm or 40 μm thick) by the intense 3ω laser pulse with the energy ranging between 50 J and 200 J were determined on the basis of volume of craters produced by the shock in the massive Cu target behind the layer of plastic. Characteristics of the plasma ablated from the plastic target were measured with the use of 3-frame interferometry, ion diagnostics, an X-ray spectrometer and K_α imaging. This allowed us to determine the preplasma thickness L_{pre} and temperature T_{pre} for the given delay Δt, together with characteristics of hot electrons and fast ions emitted from the ablated plasma.

Results

Fig.1. presents the thickness L_{pre} of CH(Cl) preplasma produced by the auxiliary 1ω beam and measured by optical interferometry at the electron density $n_e \approx 10^{19}$ cm^{-3}, as a function of

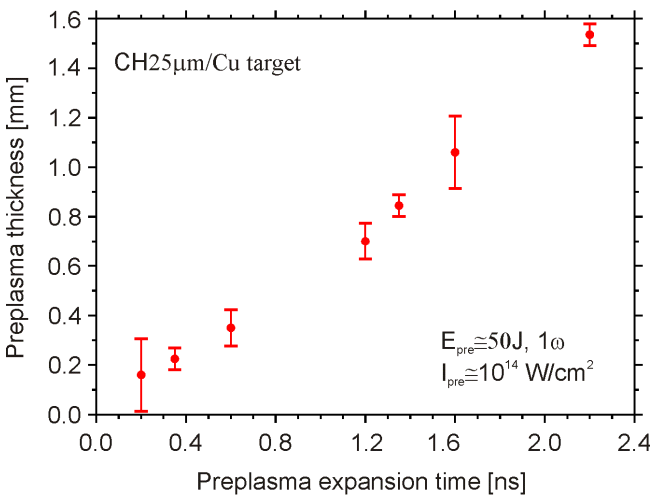

Fig.1. The thickness of preplasma at $n_e \approx 10^{19}$cm^{-3} as a function of the preplasma expansion time.

the preplasma expansion time t [11]. The preplasma thickness almost linearly increases with t and at $t \equiv \Delta t$ = 1.2 ns, which corresponds to a maximum delay between the auxiliary beam and the main beam, L_{pre} ≈ 0.7 mm, which is a value of the same order of magnitude as that expected at real SI experiments. However, the temperature of the preplasma measured by the X-ray spectrometer at the target surface was found to be ~ 175 eV , and the temperature of the plasma produced by the main laser beam for the main beam energy E_m ~ 100 – 200 J was found to be ~ (750 ± 100) eV, which are values significantly lower than those predicted for the actual SI experiments.

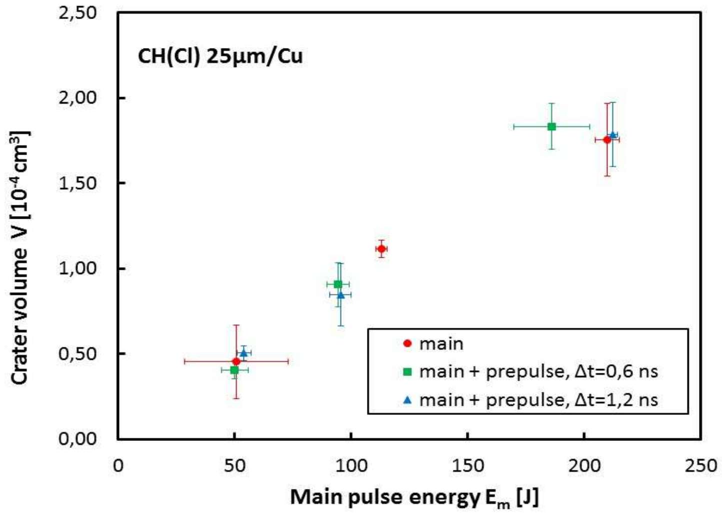

Fig. 2. The volume of craters produced in the Cu massive target by the shock wave, induced in the 25µm CH(Cl) layer by the main pulse or by the main pulse with the prepulse, as a function of the main pulse energy. E_{pre} = 52 ± 3 J or 0.

Fig.2 presents the volume of craters produced in the Cu massive target by the shock, as a function of the main beam energy, for the case of absence and presence (Δt = 0.6 ns or 1.2 ns) of the preplasma on the CH(Cl) layer surface. The crater volume almost linearly increases with E_m and it does not depend (within the experimental error) on the preplasma thickness. Similar behavior we observed for the crater depth.

Typical energy spectra of fast ions (protons) emitted from the ablated CH(Cl) plasma at the angle of 30^0 from the target normal and measured by SiC detector are presented in Fig.3.

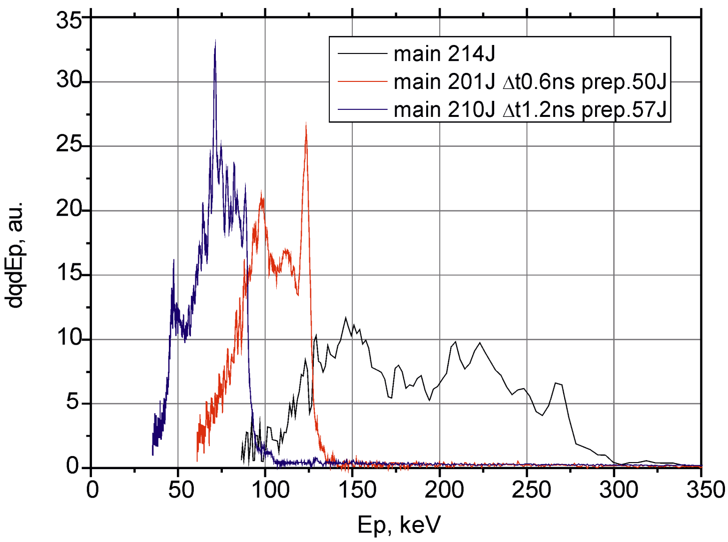

Fig. 3. Energy spectra of fast ions (protons) emitted from plasma produced by the main pulse and by the main pulse with the prepulse with Δt = 0.6 ns and 1.2 ns.

As the fast ions are driven by hot electrons, these spectra proved the existence of hot electrons in the plasma. The highest ion energies are achieved in the absence of the preplasma (at the smallest plasma density gradient scale length) which suggests that in this case the resonance absorption plays a significant role in the hot electron production, contrary to the case of large plasma gradient scale length where TPD or/and SRS are expected to play a dominant role. The total charge of fast ions is small – below 1% of the total charge of thermal (slow) ions. For $E_m \approx 200$ J the mean energy of fast ion reaches values in the range ~ 70 – 200 keV, which suggests the hot electron temperature ~ tens keV. This is in a rough agreement with results of K_α measurements from which the mean energy of hot electrons ~ 50 keV and the laser-to-hot electrons energy conversion efficiency below 1% were inferred.

To asses the pressure of the shock produced in the CH(Cl) layer by the 3ω laser beam, the laser-target interaction and crater formation by the shock in the thick Cu layer was simulated using the two-dimensional PALE code. Based on the consistency (within 15%) of the crater volumes obtained from measurements and simulations, it was found that for the 3ω beam energy of 200 J ($I_{3\omega} \approx 9 \times 10^{15}$ W/cm^2) the shock pressure at the rear side of the 25-μm plastic layer reaches 102 Mbar for the case when there is no preplasma, while in the case when the 3ω beam follows the auxiliary (1ω, 60J) beam with a delay $\Delta t = 0.6$ ns it is found to be82 Mbar.

Conclusions

In conclusion, it has been found that the total energy and pressure of the shock produced in the plastic target by a short-wavelength ($\lambda < 0.5$ μm) sub-ns laser beam very weakly depend on the preplasma thickness, and that at the main beam intensity ≈ 10^{16} W/cm^2 the pressure at the rear side of the 25-μm target reaches about 100 Mbar. Both in the presence and the absence of the preplasma on the target surface, the energy conversion from the beam to hot electrons is small (<1%) and the mean energy of hot electrons is below 100 keV.

This work was supported in part by the Access to Research Infrastructure activity in the 7^{th} Framework Program of the EU Contract No. 284464, Laserlab Europe III, and by the National Centre for Science (NCN), Poland under Grant No 2012/04/M/ST2/00452.

References

1. R. Betti et al., Phys. Rev. Lett. **98**, 155001 (2007).
2. V. A. Shcherbakov, Sov. J. Plasma Phys. **9**, 240 (1983).
3. X. Ribeyre et al., Plasma Phys. Control Fusion **51**, 015013 (2009).
4. A. J. Schmitt at al., Phys. Plasmas **7**, 042701 (2010).
5. M. Lafon et al., Phys. Plasmas **20**, 022708 (2013).
6. W. Kruer, The Physics of Laser Plasma Interaction, New York, Adisson -Wesley 1988.
7. O. Klimo et al., Plasma Phys. Control. Fusion **52**, 055013 (2010).
8. R. Betti et al., J. Phys.: Conf. Ser. **112**, 022024 (2008).
9. L. J. Perkins et al., Phys. Rev. Lett. **103**, 045004 (2009).
10. S. Gus'kov et al., Phys. Rev. Lett. **109**, 255004 (2012).
11. See also T. Pisarczyk et al., poster P5.210 at this conference.