Study of laser-matter interaction in an intensity regime relevant for shock ignition

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Shock ignition (SI) is a novel approach to Inertial Confinement Fusion (ICF) [1], based on the separation of the compression and ignition phases. The first implies “normal” compression of a thermonuclear DT pellet with ns laser beams at I ≈ 10^{14} W/cm^2. The second phase relies on delivery of a very strong shock (P ≈ several 100 Mbar), created by a laser at intensities I ≈ 10^{15}- 10^{16}W/cm^2, which heats the central part of the compressed fuel and creates the conditions for ignition. The SI regime is largely unexplored due to the well-known fact that laser-plasma interactions at intensities above 10^{14}W/cm^2 are characterized by extreme non-linearity. Strong parametric instabilities (SBS, SRS, TPD) may arise with the unwanted effect of reflecting incident laser light (reducing absorption) and generating fast electrons, which may preheat the ICF targets . To study the SI regime, we recently performed an experiment using two beams from the Prague Asterix Laser System. The first beam at low intensity was used to create an extended preformed plasma, and the second to create a strong shock (see Fig. 1 a). Goals of the experiment were to:

1) study the coupling of the high-intensity laser beam to the payload through an extended plasma corona, and whether it is really possible, under such conditions, to create a strong shock.

2) study the effect of laser-plasma instabilities at I ≈ 10^{16} W/cm^2, their development, the amount of light which is reflected.
3) study the generation of hot electrons and their impact on laser-payload coupling.

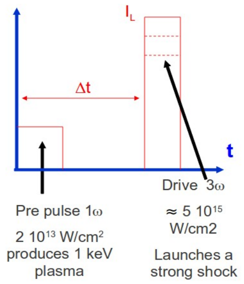

Fig. 1a: Laser profile in the experiment

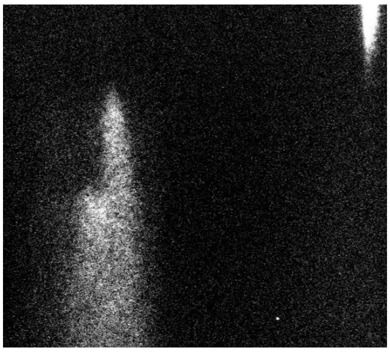

Fig. 1b: Shock breakout

1.Experimental set-up: The first phase of the experiment was dedicated to the creation of the extended plasma and its characterization with: i) X-ray deflectometry, using the PALS X-ray laser to get density profiles [5], ii) X-ray pin-hole cameras. Phase 2 addressed the characterization of shock and laser-plasma interaction using: i) EEPHC (energy encoded X-ray pin-hole camera) to measure plasma extension and characterize its emission [6], ii) Shock chronometry (measuring the self emission from the target rear side with a streak camera), iii) Optical imaging, spectroscopy, and calorimetry of radiation reflected within the cone of the focusing lens (f/2), to evaluate the amount of back reflected light from parametric instabilities.

The PALS system is an Iodine Laser delivering a pulse at λ =1.3 μm, τ = 300 ps. The auxiliary beam creating an extended plasma was operating at the fundamental with E = 30 J and focused with intensity I ≤ 2 10^{13}W/cm^2 to an extended spot (diameter Φ ≈ 900 μm, nearly flat top), in order to create an approximately 1D expanding plasma. The main beam was used in Phase 1, linearly focused, to create the XRL beam for diagnostics [14]. In Phase 2, it was converted to 3ω (getting λ =438 nm and E ≤ 250 J) and focused with a lens of diameter 30 cm and focal length f = 60 cm to a spot Φ =100 μm to an intensity I = 10^{16}W/cm^{2}and create a strong shock. In the experiment, we used targets with a 25-µm plastic (CH) layer (containing Cl to allow for X-ray spectroscopy) on the laser side, and a 25 µm Al layer on the rear. The low-Z material on the front layer mimi cked the typical ICF target. On some targets we used an additional 10 µm Al step on the back and an intermediate Cu layer (1 µm thick) between plastics and Al. These respectively allowed for shock chronometry (Al being a standard material for this kind of measurements [4]) and for hot electrons characterization by using the EEPHC.

2. Experimental results: The 2D density profiles of the plasma obtained using XRL deflectometry [5], gives 2D density profiles 0.3ns and 0.9 ns after the arrival driving pulse. We see that the plasma with n e > 10^{20} cm^{-3} extends over 200 µm (perpendicularly to target surface) and over 800 µm radially. These numbers are also confirmed by X-ray PHC images. The density profile along the axis of the focal spot is reproduced very well by 1D hydro simulations performed with the code MULTI [16]. The main pulse was fired in the preformed plasma with delays Δt = 0, 150, 300 and 500 ps. Fig. 1 (b) shows a streak camera image of a shock breakout on a stepped target. 2D simulations of shock propagation performed with the hydro code DUED [xx] showed that we got a shock pressure ≈ 90 MBar on front side at the beginning of the interaction, decreasing to less than 10 MBar at shock breakout. Results from the EEPHC allowed to confirm the focalization of the main l aser beam to 100 µm. Spectra obtained with CH/Cu/Al showed clear K-α lines from Cu (or Ti and Cu), confirming the presence of hot electrons, whose energy has been estimated ≈ 50 keV from the required penetration depth in CH.

Finally, the analysis of the backscattered light showed a little amount of reflection (< 5%) and a substantial stability of SRS spectra vs. pulse delay Δt (see Fig. 4). SRS spectra are characterized by Landau cut-off at short wavelengths (λ ≈ 670 nm) while at long wavelengths it extends up to λ ≈ 720 nm (value at 0.5 of the maximum). No sign of SRS generation at ≈ n c/4 is present. This is probably the signature of strong delocalized absorption in the extended plasma corona.

3. discussion and conclusions : Using the classical ablative scaling of shock pressure vs. laser intensity, the shock pressure P ≈ 90 MBar corresponds to a laser intensity on target I ≈ 2 ×10^{15} W/cm^2 , instead of the measured value I ≈ 10^{16} W/cm^2. This is probably the signature of strong inhibited thermal transport. Simulations done with the code CHIC [xx] show the generation of very strong magnetic fields (up to 5 MG) due to the $\nabla n \times \nabla T$ mechanism. These imply a large Hall parameter $\omega\tau$ (up to 10), where $\omega = eB/mc$ is the electron cyclotron frequency and τ the collision time. Therefore the motion of electrons is largely magnetized and the transport of heat inside the target may be inhibited. In conclusion, our experiment shows that we can couple a laser beam to a payload and generate a rather strong shock (100 MBar in our case) even in presence of an extended plasma corona. However it seems that at the high intensities required for SI, the usual diffusion approximation of thermal transport does no longer hold. We do need a more detailed description of transport including magnetic fields and/or the effects recently predicted by Bell et al. [19].

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