Preliminary results from recent experiments and future roadmap to Shock Ignition of Fusion Targets

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Abstract. Shock ignition (SI) is a new approach to Inertial Confinement Fusion (ICF) based on decoupling the compression and ignition phase. The last one relies on launching a strong shock through a high intensity laser spike ($\leq 10^{16}$ W/cm$^2$) at the end of compression. In this paper, first we described an experiment performed using the PALS iodine laser to study laser-target coupling and laser-plasma interaction in an intensity regime relevant for SI. A first beam with wavelength $\lambda = 1.33 \mu m$ and low intensity was used to create an extended preformed plasma, and a second one with $\lambda = 0.44 \mu m$ to create a strong shock. Several diagnostics characterized the preformed plasma and the interaction of the main pulse. Pressure up to 90 Mbar was inferred. In the last paper of the paper, we discuss the relevant steps, which can be followed in order to approach the demonstration of SI on laser facilities like LMJ.

1. Introduction

Shock ignition (SI) [1-5] is a novel approach to Inertial Confinement Fusion (ICF) [6-8], based on the separation of the compression and ignition phases The first phase implies compression of a thermonuclear DT pellet by ns laser beams at I < $10^{13}$ W/cm$^2$. The second relies on a laser pulse...
with intensities $I \approx 10^{15} - 10^{16}$ W/cm$^2$, driving a very strong shock ($P \approx$ several 100 Mbar), by, which generates the hot spot required for ignition. SI has potentials for high gain and could also allow achieving ignition using relatively small laser energy for compression (a few hundred kJ).

Several experiments have shown that compression to a regime of interest for ICF is possible [9-12]. Ignition by the standard approach of creating a central hot spot by hydrodynamic cumulation at the end of the implosion [1] is the objective of the current National Ignition Campaign [12] at the National Ignition Facility, NIF [13]. It requires, *inter-alia*, the achievement of high implosion velocity (about 360 km/s for the NIF baseline target). Separation of compression and ignition allows lower implosion velocity [1], thus reducing risks associated to hydrodynamic instabilities. Such a separation is also common to fast ignition [14,15]. However, SI has the advantage that it is compatible with present-day “NIF like” laser technology [1]. Also, it does not rely on such an extreme physics as fast ignition (i.e. generation of an intense beam of relativistic electrons, its propagation in dense matter and deposition of energy in the compressed core). Preliminary SI experiments in spherical geometry [16,17] are encouraging and demonstration experiments are possible within the next decade on NIF or LMJ [18].

The physics related to SI is also largely unexplored. Laser-plasma interactions at intensities above $10^{14}$ W/cm$^2$ are characterized by non-linearity. Strong parametric instabilities (SBS: Stimulated Brillouin Scattering, SRS: Stimulated Raman Scattering, TPD: Two-Plasmon Decay) may arise with the unwanted effect of reflecting a substantial amount of incident laser light and generating fast electrons. These may preheat the fuel of ICF targets, making compression more difficult. Also, laser beam filamentation may produce strong inhomogeneities, which alter the uniformity of target compression and enhance parametric instabilities. We notice that the generation of fast electrons, provided they are not too energetic, may not be dangerous in SI, since they may not be able to penetrate the large areal density $<\rho_r>$ achieved at late stages of compression.

While, of course, SI “demonstration” experiments need spherical geometry, many related issues can be addressed using planar targets. Indeed, 1D planar geometry offers the advantage of a simpler scheme and easier access of diagnostics. In this context, some results have been reported in [19], for intensities $\leq 10^{15}$ W/cm$^2$.

In this paper, first we report results of an experiment in the intensity range up $10^{16}$ W/cm$^2$, the upper limit that is considered for SI. The experiment was performed using two beams of the Prague Asterix Laser System, PALS [20]. The goals of the experiment were to study: 1) the coupling of the high-intensity beam to the payload through an extended plasma corona, and the generation of a strong shock, 2) the effect of laser-plasma instabilities at $I \approx 10^{16}$ W/cm$^2$, and the amount of light which is reflected, and 3) the generation of hot electrons and their impact on laser-payload coupling.

In the last paper of the paper, we discuss the relevant steps, which can be followed in order to approach the demonstration of SI on laser facilities like LMJ.

### 2. Experiment at PALS

The PALS Iodine Laser delivers pulses at the fundamental wavelength $\lambda = 1.3 \mu$m, with duration $\tau = 300$ ps [20]. In the experiment we used two pulses, namely an auxiliary one delivering about 30 J, and the main one delivering up to 300 J, with time delay of 0 - 1.2 ns with respect to the auxiliary beam (see later). This pulse is preceded (by about 8 ns) by a small prepulse due to leakage in the mode-locker, with relative power about $10^{-5}$. The auxiliary beam was used to create an extended plasma. It was operating at the fundamental frequency and focused to an extended spot (diameter $\approx 900 \mu$m, nearly flat top, intensity $I \approx 10^{13}$ W/cm$^2$) so to create an approximately 1D expanding plasma. The beam was smoothed using a random phase plate (RPP) to produce a uniform irradiation. The fundamental wavelength was used in order to generate a plasma with relatively high temperature at the critical surface, despite the low intensity, thereby allowing better approaching the conditions of the plasma corona in SI. The main beam was used in the first phase of the experiment, to create the XRL beam for diagnostics [21]. In the second
phase, it was converted to 3w (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 of diameter about 100 µm and intensity I = 10^{16} W/cm^2 to create a strong shock.

In most of the shots we used a target with a 25-µm plastic layer (parylene-C; C₆H₇Cl, with Cl to allow for X-ray spectroscopy) on the laser side, and 25 µm Al on the rear. The low-Z material on the front mimicked the typical ICF ablator material. However, in some targets we used an additional 10 µm Al step on the back and an intermediate Cu layer (5 µm thick) between plastics and Al. These respectively allowed for shock chronometry (Al being a standard material for this kind of measurements [22]) and for hot electrons characterization. To the same goal, we used targets with two layers Ti (20 µm) / Cu (20 µm). Also, we used targets with different plastic thickness in front of the Cu layer: these allowed estimating the average energy of hot electrons by looking at the signal reduction vs. overcoat thickness. Finally, thicker targets were used for crater measurements.

Several diagnostics were used. In phase 1, the extended plasma was characterized by X-ray deflectometry, using the PALS X-ray laser to get density profiles [16,17]. In phase 2, addressing intense interaction and shock generation, we used: i) X-ray CCD working in a single-hit mode to measure plasma extension and characterize its emission [18, 19], ii) ion collectors for cross-checking of plasma temperature [20,21], iii) shock chronometry (measuring the self emission from target rear side with a streak camera) [22], iv) optical spectroscopy, and calorimetry of the radiation reflected within the cone of the focusing lens (f/2), to evaluate the onset and amount of back reflected light from parametric instabilities, v) a set of mini-calorimeters to measure the light scattered outside the lens cone, and vi) Kα imaging to evaluate hot electron generation [23].

In addition, optical interferometry was used in both phases [24] because, unlike X-ray deflectometry, it did not require using the main beam, even if of course the accessible electron density was smaller. Finally post-mortem analysis of the crater size in thick targets was used as a diagnostic of the total deposited energy. X-ray pin-hole cameras, were used in both phases to obtain the transversal size of preformed plasma. Finally, X-ray spectroscopy was also used in both phases to obtain plasma temperature [25]. The X-ray spectra were measured using a spherically-bent mica crystal spectrometer, which was aligned to provide a spatial resolution along the laser axis. In the 4th order, it covered the wavelengths 4.17 ÷ 4.52 Å, to image the chlorine Heα and Lyα lines. The Heγ ÷ Heη and Lyβ lines were observed in the 5th order.

The copper Kα emission was measured using a spherically-bent quartz (211) crystal, which was set up as a monochromator in imaging mode (Bragg angle θ = 88.7°) to provide a quasi-monochromatic distribution of Kα intensity, 2D-spatially resolved along the target surface. Another X-ray keV spectrometer used a flat ADP (ammonium di-hydrogen phosphate) crystal with 2d ≈ 10.659 Å placed at ≈ 20 cm from the source and with a Bragg angle ≈ 19°. It recorded X-ray spectra with an observed range from 2600 to 3600 eV. We detected X-ray lines from Li-, He- and H-like Cl ions, however the spectral resolution was poor due to large source size (≈ 1mm implying a spectral resolution ΔE ≈ 40 eV) [26]. The 3 diagnostics used the Kodak AA400 film to detect the signal.

2D plasma density profiles were obtained with XRL deflectometry, a technique based on the deformation of Talbot pattern of 2D grating caused by gradients of index of refraction (plasma electron density), assuming cylindrical symmetry and using Abel transform. The diagnostics is described in [27]. A Ne-like zinc X-ray laser was used, emitting at 21.2 nm, operated in single pass providing 150-ps pulses of 200 µJ. A Mo-Si multilayered spherical mirror with f = 250 mm was used to image the plasma on back-illuminated X-ray CCD with magnification M = 8.2. Fig. 1 shows the obtained 2D density profiles 0.3 ns and 0.9 ns after the arrival driving pulse.
The plasma with $n_e > 10^{20}$ cm$^{-3}$ extends over 200 µm perpendicularly to target surface and over 800 µm radially (comparable to the spot size $\approx 1$ mm), in agreement with X-ray PHC images. The density along the axis of the focal spot is characterized by an exponentially decreasing profile. The low-density portion of such a profile superimposes to the one obtained by optical interferometry and it is well reproduced by 1D hydro simulations performed with the code MULTI [28]. The coronal plasma temperature predicted by such simulations is $\approx 500$ eV and $\approx 200$ eV in the overcritical region. X-ray keV spectra analyzed with the help of the codes RATION [29] and SPECT3D-A [30], yielded similar temperatures.

The main pulse was fired in the preformed plasma with delays $\Delta t = 0, \ldots, 1200$ ps. We also made shots without the creation beam (main only). Fig. 2 (a) shows a streak camera image of a shock breakout on a stepped target, while (b) shows a simulation of shock propagation (we performed 2D simulations with the hydro codes DUED [31, 32] and MULTI-2D [33]). Shock
pressure is rapidly decreasing partly due to 2D effects (the total target thickness being comparable to the focal spot radius) but mainly, due to the short duration of the laser pulse (a relaxation wave is generated on the front side at the end of the pulse and rapidly catches up with the shock front). Data analysis and simulations indicate that the peak shock pressure is \( \approx 90 \text{ MBar} \) on front side during pulse interaction, and decreases to less than 10 MBar at shock breakout.

Results from the X-ray pin-hole camera allowed confirming the focalization of the main laser beam to 100 \( \mu \text{m} \). Also, by measuring the energy deposited in each pixel, we could obtain emission spectra and get monochromatic images. Spectra obtained with CH/Cu/Al (and Ti/Cu) showed clear K-a lines from Cu (or Ti and Cu), confirming the presence of hot electrons. The penetration depth in CH was estimated by comparing results with different plastic thickness as \( \approx 27 \mu \text{m} \). By using the online database ESTAR of NIST (with the table of Mylar which as a similar density to the plastic used in our experiment), this corresponds to an average hot electron energy \( \approx 50 \text{ keV} \), in agreement with predictions from scaling laws [34] and available data [35]. Data obtained from Ti/Cu targets are also compatible with this result. The K\( \alpha \) imager showed images with size \( \approx 200 \mu \text{m} \), larger than the focal spot but compatible with the hot electron range (taking into account that at such low energies, hot electron propagation is practically isotropic). By measuring the total flux of Ka photons (with the CCD and the K\( \alpha \) imager) we could estimate the total number of hot electrons, finding a conversion efficiency from laser to hot electrons of the order of 1\%, in agreement with what estimated in [36].

Finally, the analysis of the backscattered light showed a little amount of reflection within the focusing lens cone (\(< 5\% \) in all cases) and mainly dominated by SBS. The scattered light outside the lens cone was of the same order of that within the lens cone, bringing the total reflectivity to \( \leq 10\% \). We also observed a substantial stability of SRS spectra vs. pulse delay \( \Delta t \) (see Fig.3). SRS spectra are characterized by a Landau cut-off at short wavelengths (\( \lambda \approx 670 \text{ nm} \)), while at long wavelengths extend up to \( \lambda \approx 720 \text{ nm} \) (value at 0.5 of the maximum). No sign of SRS generation at \( \approx n_e/4 \) is present. This is probably the signature of strong delocalized absorption in the extended plasma corona. Alternatively, such low density could be the sign of cavitation taking place in the plasma, as shown in [37].

![Figure 3. Backreflected Raman spectra at different prepulse delays](image-url)
Our experimental results show that during interaction we can obtain shock pressure $P \approx 90$ Mbar. This is indeed the highest pressure measured so far in this kind of experiment.

3. Preliminary Roadmap to Shock Ignition

Shock Ignition has been selected as the main approach to demonstration of ignition via ICF by the HiPER Project [38]. The goals of the HiPER Project are to study the follow up to NIF ignition and prepare the way to future Fusion reactors. The preparatory phase of the project covers the period 2009-2013 and it is mainly funded by the EU, UK, France, and the Czech Republic. The work includes both scientific and “more technical” issues like: i) Study of high-energy high-repetition laser drivers, ii) Study of target mass production, injection, tracking and positioning at high repetition frequency, iii) Studies on chamber design, material resistance, material activation at high radiation fluxes, iv) Study of advanced ignition concepts.

Shock Ignition has been selected as the main route to IFE being promising and, unlike fast ignition, compatible with present day’s laser technology, allowing demonstration on LMJ within the next decade.

The Laser Megajoule (LMJ) in France is a Nd:glass facility, becoming operational in 2015, which will finally deliver 2 MJ of laser energy in $\approx 10$ ns using 160 beams (see Fig. 4). It has been constructed in the framework of the French Programme for the Stewardship of Nuclear Stockpiles but thanks to the agreement between region Aquitaine and CEA, $\geq 20\%$ of shots will be allocated for civilian academic research oriented towards fusion for energy.

![Figure 4. In-principle scheme of LMJ laser](image)

In order to realize the demonstration of feasibility of shock ignition on LMJ, one must first be able to compress a target using the Polar Direct drive options. Indeed LMJ, like NIF, has been constructed to work with indirect drive, which means that the beams are not uniformly distributed over the whole surface of the spherical targets, but they come in two poles (corresponding to the entrance holes of the laser holraith). In order to perform uniform direct drive, one must repoint the laser beams in order to cover the whole target surface. After that, the energy of the beam must be balanced: the beams, which have been repointed, will be incident at some angle on the target surface, thereby having a larger focal spot and a lower intensity. Therefore the energy of the beams, which have not been repointed, needs to be lowered in order to get uniform laser intensity everywhere. When this is done, it turns out that about only 0.5 MJ of the initially available 2MJ can be used. Luckily, such energy would still be sufficient for performing a direct-drive implosion.
The next step would then be performing shock ignition demonstration experiments. This requires dedicating a part of the beams of LMJ to drive the final laser spike. For instance a 40 quads pattern could split the quads, defocus and repoint the beams with 80 beams used for compression (PDD) and the generation of the spike, and 80 beams for spike only.

Before getting on the demonstration of PDD and shock ignition on LMJ, several issues can and need to be investigated on intermediate facilities. These include physical issues (Capability of generating 300 Mbar shocks, Absorption at oblique incidence, Impact of parametric instabilities on laser absorption and hot electron generation, impact of hot electrons ion shock formation, smoothing, timing and dynamics of shock collision, shock isotropization and smoothing by electron conduction). The physical results from all such points should also be used to validate code platforms in order to get predictive capability.

Finally, also some laser issues need to be investigate, for instance LMJ beams are focused on target using gratings (unlike NIF). In principle, by putting some programmed chirp on the laser beam, this should allow to do a dynamic pointing of the laser beams in order to follow the laser implosion in “real time”.

In Europe there is a possibility to use a whole Laser “Rainbow” to study such topics, moving from the less big lasers (LULI, Vulcan, PALS, Phelix) to larger ones (Orion, LIL) and finally the LMJ/PETAL laser facility. This offers a unique opportunity for European Science and for ICF studies.

Conclusions
Shock ignition appears to be a promising approach to demonstration of nuclear fusion ignition by laser direct drive. In order to contribute to investigate the physical unknowns of shock ignition we have performed an experiment at PALS. Our experiment has shown that we can couple a laser beam to a payload and generate a rather strong shock (90 MBar) even in presence of an extended plasma corona. This is indeed the highest pressure measured so far in this kind of experiments, showing a clear progress in approaching a shock ignition relevant regime.

Unlike in experiments performed in spherical geometry [13,14], we measured little back-reflection due to parametric instabilities. Although this sounds as good news for SI, nevertheless one should be cautious, since the growth rate and saturation of parametric instabilities critically depends on plasma conditions, which in our experiment are quite different from a real SI experiment in spherical geometry, especially concerning plasma extension and plasma temperature. Clearly a more detailed analysis is required here. Our results also point out to the need of improving the modelization of energy transport in SI experiments, for instance taking fully into account the effect of parametric instabilities, filamentation, hot electrons generation, magnetic fields, etc.

The final part of the paper was devoted to briefly explain the steps (physical roadmap), which are needed in order to progress from present physical experiment, to the future demonstration of Polar Direct Drive and Shock Ignition on the LMJ/PETAL laser facility.

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