AN EXPERIMENTAL STUDY OF LASER-PLASMA COUPLING IN A SHOCK-IGNITION RELEVANT REGIME

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Shock-ignition is an attractive possible solution in the inertial fusion scenario for ignition and burn of a pre-compressed pellet [1]. Models predict that sufficient shock pressure may be achieved at values of $I > 10^{15}$ W/cm^2. This approach is being foreseen for future Inertial Fusion Energy schemes like the High Power Laser Energy Research Facility (HiPER)[2]. However, in a realistic scenario, the shock-driving laser beam has to propagate in a long scale-length coronal plasma before reaching the critical density region. The use of shorter wavelength laser light is therefore mandatory so that energy coupling at a higher electron density is enhanced. The shorter wavelength also helps to mitigate the growth of non-linear processes, including laser-driven instabilities that, at such laser intensities, are well known to be very effective.

Stimulated Raman scattering (SRS), Stimulated Brillouin scattering (SBS) and Two Plasmon decay (TPD) are the most important processes that can lead to unwanted or uncontrolled effects in the laser-plasma coupling. In the case of SRS and TPD the collision-less damping of electron plasma waves generated in these processes yields a significant population of hot electrons that can lead to a pre-heating of the dense plasma region. In general, the modification of the energy distribution function of the electrons can also modify the thermal transport and, consequently, affect the efficiency of shock production as already observed in earlier experiments at somewhat similar intensities [3]. SRS is also responsible, along with SBS, for the scattering of incident radiation that can reduce the effective laser intensity at the critical density.

This scenario is being explored world-wide using advanced modeling tools and performing dedicated experiments. Some preliminary tests carried out in compression experiments at the OMEGA laser facility have already shown that indeed a properly timed shock can enhance neutron production [4]. However, a reliable description of laser-plasma interaction and shock formation at the required intensity is still lacking. In view of this, simple planar geometry experiments of laser interaction with a preformed plasma are crucial for the validation of this approach. In a recently published paper [5] this approach was used and the generation of a strong shock was found to be in a good agreement with 2D numerical hydrodynamic simulations. However, in that study, kα signal was found to be always below the detection level, indicative of a lack of significant fast electron generation. This was probably due to the relatively low intensity used in the experiment, not exceeding 1E15 W/cm^2. As pointed out in the same publication, this conclusion leaves an important open question on the possibility to further increase the laser intensity to the values required for shock ignition.

We studied the same scenario in a series of dedicated experiments at the Prague Asterix Laser System (PALS) using higher nominal laser intensities, well above 1E15 W/cm^2 and up to 1E16 W/cm^2. In contrast with Baton et al., our measurements show a considerable production of hot-electrons as demonstrated by the presence of kα fluorescence line emission. Therefore, we are able to access a regime of interaction where non-linear effects show up very clearly and shock production can be investigated in a realistic shock-ignition regime. In the following a focus will be given on the optical and X-ray measurements which allow us to identify the interaction regime activated in our experiments.

In our experiment a 300 ps, 70 J beam at 1.3 μm is focused on a solid target at a relatively low intensity (≈4E13 W/cm^2) in a 800 μm diameter spot, to create an extended preformed plasma. A second beam at 0.438 nm wavelength is tight focused to create a strong shock as shown in Figure 1. Main targets for shock velocity measurements consist of a thin multilayer of 25 μm CH + 5 μm Cu + 20 μm Al, also with a 20 μm step at the rear surface Alternative targets for laser-plasma interaction measurements only consist of a Cu substrate with a CH coating of 25 μm. The latter targets provide the same preformed plasma conditions as the multilayer targets and are also used for fast electron measurements based upon Cu Kα yield measurements. We carried out a detailed characterization of the preformed plasma conditions using X-ray laser deflectometry [6] and high resolution X-ray spectroscopy for density and electron temperature measurements. The interaction of the main pulse with the preformed plasma was studied using a collection of diagnostics including X-ray spectroscopy in the keV range using single-hit CCD detector and calorimetry and spectroscopy in the 400-800 nm spectral range.

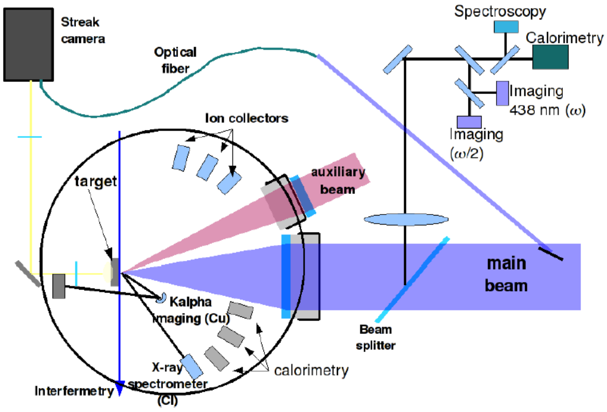

Figure 1. Schematic experimental set up of the experiment to study shock generation in a planar geometry in a regime relevant to shock-ignition.

Our preliminary results on optical spectroscopy of scattered radiation from the shock-driving beam show systematically low levels of backscattering. Measurements of hard X-ray emission and Kα spectroscopy show evidence of production of hot electrons. Moreover, our shock velocity measurements are consistent with shock pressures which are below the values expected for the nominal focused intensities.

More in details, at the current stage of analysis, the results on the backscattering diagnostics on the multilayer (thin) targets show that the backscattered energy in the detected spectral range (400-800nm) and collected by the focusing lens is below 3%. A similar result was obtained in the previous experiment when the backscattered energy was found to be below 4%. These values are significantly lower than those obtained by Baton et al., and this difference is another evidence of a change in the interaction conditions at higher laser intensities. Moreover, our calorimetry measurements show no significant dependence of backscattered energy with respect to the delay between main and auxiliary beam.

From the point of view of the relative contribution of SRS and SBS to the whole backscattered energy, the component at 438 nm, around the fundamental wavelength and including reflection from the critical surface and SBS, is always dominant over the SRS component. The SRS component varies roughly between 0.3% and 12% of the whole back-scattered energy. Again, no clear dependence of the relative weight of these spectral components with respect to the delay between the two beams was observed in our experiment.

A special attention deserves the detailed spectral distribution of the SRS component. A typical spectrum obtained with a thin layered target, with a delay of 350 ps and an energy of the main beam on target of 159 J is shown in **Figure 2**. The overall SRS emission is centered at around 650 nm, with a stronger component around 670 nm and a width of approximately 20 nm. The shorter wavelength limit of the overall emission is located at 600 nm. For a temperature of 800 eV, as obtained from independent, simultaneous X-ray spectroscopy, the peak at 650 nm corresponds to a plasma density of ~0.09 n_C, where n_C is the critical density for the main laser wavelength of 438 nm.

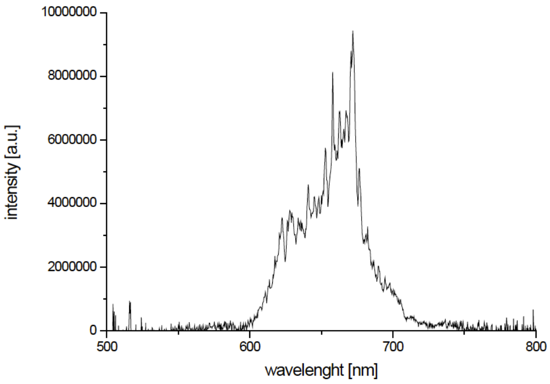

Figure 2. A typical SRS spectrum obtained from irradiation of thin multilayer target consisting of 25 µm CH + 5 µm Cu + 20 µm Al target, with a delay of 350 ps between the plasma preforming beam and the main beam with the energy of 158 J at 438 nm.

Interestingly, this low density suggests that a strong interaction occurs in the very low density region, possibly leading to a modification (e.g. depletion) of the intensity of the laser pulse propagating up to the critical density. This may consequently reflect in a change of the ablation pressure and of the intensity of the shock. Indeed, as discussed elsewhere in this conference [7], shock velocity measurements suggest a shock pressure significantly lower than that expected from hydrodynamic simulations for the nominal laser intensity.

The SRS spectra also show a low intensity wing at higher wavelengths (beyond 700 nm) for short delays, typically below 350ps, and a wing at lower wavelengths for longer delays. In particular, the spectrum at 1200 ps delay shows a second component centered at around 540 nm, corresponding to a plasma density of ~0.02 n_C. This is consistent with the fact that at shorter delays, interaction will occur with a shorter scale-length plasma, and therefore, easier access to higher electron densities. In contrast, at larger delays and consequently longer scale-length plasmas, interaction with even lower densities than that of the main component can occur.

Finally, concerning the fast electron population, we measured the X-ray spectrum using both crystal spectroscopy and cooled CCD detector in single-hit mode. The crystal spectrometer will be discussed in a separate paper in this conference [7]. As for the single-hit data, while the analysis is not completed yet, as anticipated above, we can we can already confirm that a strong kα line is visible in our spectra. As shown in the plot of Figure 3, the Kα fluorescence emission around 8 keV originating from the Cu target substrate hit by fast electrons propagating through the 20 μm plastic layer is clearly visible.

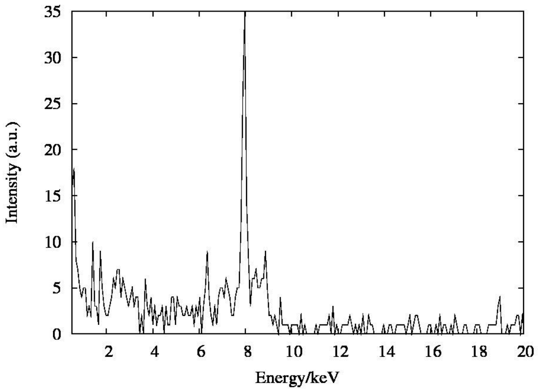

Figure 3. X-ray spectrum obtained using the single-hit spectrometer showing the Kα emission from irradiation of a multilayer "step" target consisting of 25 μm CH(Cl) + 5 μm Cu + 10 μm Al + 10 μm Al step used simultaneously for shock velocity measurements. The delay between the plasma preforming pulse and the shock driving (main) pulse was 350 ps.

These data are being analyzed to obtain the absolute Kα yield and to recover the absolute fast electron energy conversion. At this stage we can say that the Kα flux measured with our single-hit detector was unexpectedly high and required more attenuation than initially planned and we are looking into the accuracy of the measurements. At this stage we can anticipate that the conversion efficiency into fast electrons is expected to be in the range of a few percent.

In view of the above, we can conclude that our planar target experiments carried out at realistic laser intensities for the shock ignition regime show a different scenario than that obtained in similar experiments at relatively lower intensities, suggesting a quite different interaction regime, with a substantial further reduction of back-scattered energy and a much more efficient production of fast electrons.

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