Propagation issues and fast particle source characterization in laser-plasma interactions at intensities exceeding 10^{19} W/cm^2.

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ABSTRACT

A series of experiments recently carried out at the Rutherford Appleton Laboratory investigated various aspects of the laser-plasma interaction in the relativistic intensity regime. The propagation of laser pulses through preformed plasmas was studied at intensities exceeding 10^{19} W/cm^2. The transmission of laser energy through long scale underdense plasmas showed to be inefficient unless a plasma channel is preformed ahead of the main laser pulse. The study of the interaction with overdense plasmas yielded indication of propagation at densities above the critical density, possible due to relativistic effects. The production of fast particles during the interaction with solid density targets was also investigated. The measurements revealed the presence of a small-sized directional source of multi-MeV protons, which was not observed when a plasma was preformed at the back of the solid target. The properties of the source are promising in view of its use in radiographic imaging of dense matter, and preliminary tests were carried out.

Keywords: Laser-plasma interaction, Relativistic plasmas, Laser-produced ions, Proton Radiography.

1. INTRODUCTION

The Fast Ignitor (FI) approach[1] to Inertial Confinement Fusion motivates much of the present interest in ultraintense laser-plasma interaction studies. In fact, as the scheme relies on the energy of an extremely intense laser pulse to start ignition in a compressed capsule, the study of the propagation of ultraintense laser pulses through dense plasmas is of great relevance to the success of this scheme. Nonetheless, this type of studies is of great topical interest also because of the novel and complex physics involved. This paper presents results obtained in an experimental campaign recently carried out at the VULCAN laser facility, Rutherford Appleton Laboratory (UK). In the Chirped Pulse Amplification (CPA) mode the VULCAN laser[2] provides up to 75 J in 1 ps pulses at a wavelength of 1.054 µm. Various aspects of the interaction of relativistically intense pulses with preformed plasmas and solid targets were investigated in the experiments. The analysis and the interpretation of the data are currently in progress. In the following sections, the aims of the experiments, the techniques employed and the main results obtained will be briefly described.

2. PROPAGATION AND GUIDING THROUGH UNDERDENSE PLASMAS

A study of the propagation of ultraintense laser pulses through long scale underdense plasmas was carried out. The plasmas were produced by exploding thin plastic foils (0.1, 0.3 or 0.5 µm thick) with two ns, 0.527 µm laser pulses at a total irradiance of about 5 10^{14} W/cm^2. After a suitable delay (typically of the order of 1 ns) the CPA pulse was focused into the plasma. At this time the peak density of the plasma was below $n_c/10$ and its longitudinal extension was of the order of a mm. With f/3.5

focusing optics the CPA vacuum irradiance was up to 5 10^{19} W/cm^2 (about 50 J on target, with up to 50 % of the energy in a 10-15 µm focal spot). A fraction of the energy of the main CPA pulse was used to provide a prepulse, collinear with the main pulse. The prepulse could be focused into the plasma ahead of the main pulse and used to open a density channel. A further small fraction of the CPA pulse was frequency quadrupled and used as a transverse optical probe. Other diagnostics included calorimetry of the energy transmitted through the plasma, imaging of the transmitted laser spot, forward and back-scatter spectroscopy, γ-ray measurements.

The propagation of the main CPA pulse through the plasma was first studied without a preformed plasma channel. The energy transmission through the plasma in this case was very low. Even when using the 0.1 µm target, which gave a plasma with peak density of a few times $n_c/100$, the energy transmitted was limited to a few per cent of the laser energy incident on target. This is consistent with numerical simulations[3] and previous experiments[4], which have reported anomalously high laser absorption even in very underdense plasmas for relativistically intense laser pulses.

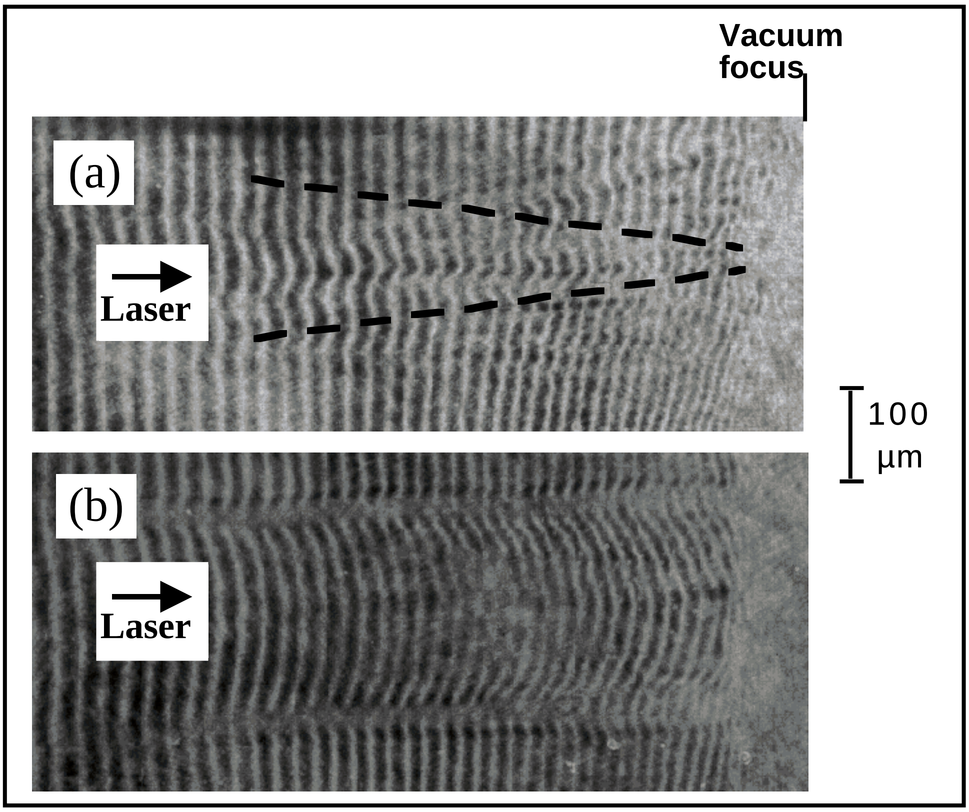

Figure 1. Interferograms taken: (a) 5 ps after the propagation of a 50 TW laser pulse through the underdense plasma (the dashed line shows the cone defined by the focusing optics); (b) 45 ps after the propagation of the channel-forming prepulse.

Reduction in energy transmission may also be related to the onset of relativistic filamentation[5] rather than whole-beam self-focusing[6]. Relativistic filamentation can cause spreading of the beam energy at angles much larger than the focusing angle and has been correlated with more efficient energy transfer into hot electrons. Filamentation and beam spreading was indeed observed in the experiment, as clear for example in fig.1 (a), showing an interferogram taken 5 ps after the interaction of a 50 TW pulse with the plasma.

The effect of the presence of a preformed channel on the propagation of the main pulse was investigated. The channel was formed by focusing into the plasma a prepulse with a prepulse-to-main ratio of 1:2. The intensity of the prepulse was also above

10^{19} W/cm^2, and a rapidly expanding channel was formed via ponderomotive expulsion of the electrons and subsequent Coulomb explosion, as observed in previous experiments[6,7,8]. An interferogram showing the channel 45 ps after its formation can be seen in fig. 1(b). The CPA main pulse transmittance was measured, for various plasma conditions, as a function of the delay between the main and the channeling pulse. Under the right conditions the energy transmission was seen to increase up to 90% of the incident energy. Further details on this experiment can be found in Ref. 9. These measurements have obvious relevance to FI, as in the FI scheme as originally proposed by Tabak *et al*[1], the ignitor pulse propagates toward the compressed core through a density channel previously opened through the plasma by a separate pulse.

3. INTERACTION WITH PREFORMED OVERDENSE PLASMAS

The interaction of the Vulcan CPA pulse with slightly overdense preformed plasmas was also investigated. This is a regime of interaction of particular interest for comparison with computational models, which has not received much experimental attention yet. Relativistic effects, related to the relativistic modification of the mass of the electrons oscillating in the field of an ultraintense laser pulse, may allow propagation of the laser pulse through plasmas with densities higher than critical[10]. This is also of interest to the FI scheme, as this effect, jointly to ponderomotive pushing of the critical density, may contribute to the creation of a channel through the overdense plasma surrounding the compressed core.

The overdense plasmas were preformed via x-ray heating of low density CH foams, with densities in the range 10-30 mg/cc. The x-rays were produced by irradiating two 700A Au foils with 600 ps, 0.527 µm pulses focused at an irradiance of 5 10^{14} W/cm^2. The CPA pulse was focused into the plasma with variable delay after the plasma formation, typically 0.6 to 1 ns after the plasma formation. The density of the foam targets insured that the plasma was overdense for the CPA pulse (between 2 and 6 n_c depending on the target used).The length of the foams varied between 100 and 200 µm.

The x-ray emission from the plasma in the KeV range was imaged with 2 pinhole cameras, with magnification respectively of 10 and 20. The back of the foam was imaged with a f/2.5 lens, and shadowgrams of the target were obtained using the transverse UV ps probe. Although the interpretation of the data is still in progress, the diagnostics seem to provide some indication of propagation through the plasma. Transmission imaging showed that a marginal fraction of the laser energy propagated through the plasma. Filamentary x-ray emission, possibly due to localized CPA-induced plasma heating, was observed to extend throughout the foam along the laser propagation axis. Transverse optical probing revealed localised explosion of the back surface of the target, again likely to have been caused by localized heating.

4. PRODUCTION OF MULTI-MEV PROTONS AND APPLICATIONS

One of the most exciting results recently obtained in this area of research is the observation of very energetic beams of protons (up to 20 MeV), generated during the interaction of ultraintense short pulses with solid targets. The protons originate from hydro-carbon impurities located on the surfaces of the target, so that proton beams are observed even using target which nominally do not contain hydrogen. At present there is debate, which is rapidly evolving, about the mechanism accelerating the protons. A part of our experimental campaign was devoted to the observation of multi-MeV protons emitted by solid targets irradiated by the CPA pulse at 5 10^{19} W/cm^2. The protons were detected by using radiochromic film (RCF) placed at known distance from the back of the target. The influence of a preformed plasma on the efficiency of multi-MeV proton production was investigated. With no preformed plasma on the back of the foil, protons with a cut-off energy greater than 20 MeV were formed with an efficiency of 2.5 % in an exponential energy spectrum of 3 MeV mean energy. When a preformed plasma with a scalelength of a few tens of microns was created on the back of the target the proton beam was not observed. The experimental results are consistent with an electrostatic accelerating mechanism depending on the existence of a very short scalelength at the back of the target.

The measurements indicate a 10 MeV proton source size of the order of 10 µm and a proton beam divergence of the order of 15°. The characteristics of the proton beam make it suitable for point-projection probing and radiographic imaging of dense matter. Some preliminary tests have been carried out in view of this type of applications. Shadows of static objects, such as grids or edges, have been obtained with spatial resolution of the order of 10 µm. Also, plasmas produced by laser irradiation of a secondary Ta target have been transversely probed for the first time with the laser-produced proton beam. Although careful interpretation of the results is required, the proton images collected probing the plasmas showed markedly different features from the proton shadows of the unheated target.

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