Propagation of 50 TW, picosecond pulses through preformed plasma channels

M Borghesi

Department of Pure and Applied Physics, The Queen's University, Belfast, Northern Ireland BT7 1NN, UK

A Schiavi, H Campbell, O Willi

Blackett Laboratory, Imperial College of Science, Technology and Medicine, London SW7 2BZ, UK

M Galimberti, L A Gizzi

IFAM-CNR, 56100 Pisa, Italy

Main contact email address: *m.borghesi@qub.ac.uk*

Introduction

The Fast Ignitor (FI) approach[1] to Inertial Confinement Fusion motivates much of the present interest in ultra-intense 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 ultra-intense 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 even due to 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 provides up to 75 J in 1 ps pulses at a wavelength of 1.054 µm. The propagation of relativistically intense pulses through preformed plasmas was 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.

Experimental arrangement

The plasmas were produced by exploding thin plastic foils (0.1, 0.3 or 0.5 µm thick) with two 1 ns, 0.527 µm laser pulses at a total irradiance of about 5 x 10^{14} W/cm^2 as shown in Figure 1. After a suitable delay (typically of the order of 1 ns) the CPA pulse was focused into the plasma.

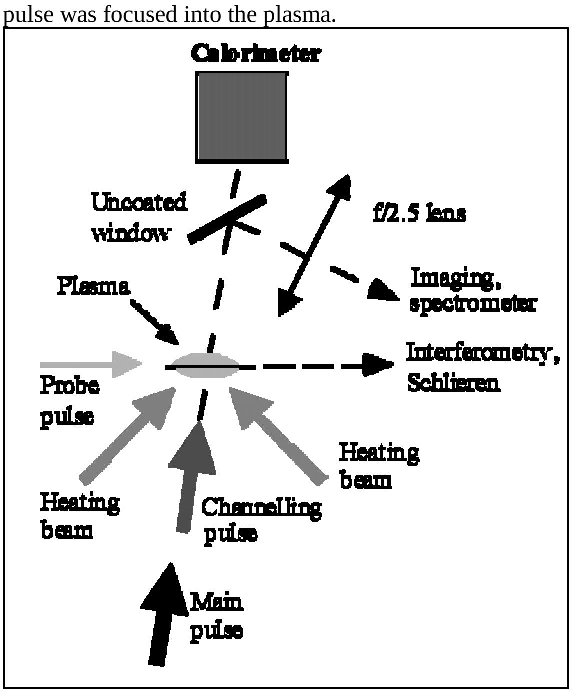

Figure 1. Experimental arrangement.

At this time the peak density of the plasma was below n_c/10 and its longitudinal extension was of the order of 1-2 mm. With f/3.5 focusing optics the CPA vacuum irradiance was up to 5 x 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. Interferometry was performed along this line using a modified Nomarsky interferometer[2]. 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.

Experimental results

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, as seen in Figure 2. The peak densities were estimated using the London and Rosen model[3]. Even when using 0.1 µm targets, which gave a plasma with a 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[4] and previous experiments[5], which have reported anomalously high laser absorption even in very underdense plasmas for relativistically intense laser pulses.

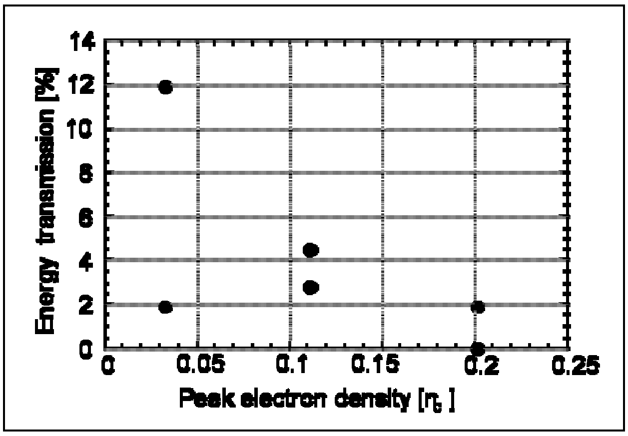

Figure 2. Transmission of CPA pulse energy versus peak density in long-scale, underdense plasmas.

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 seen for example in Figure 3(a), showing an interferogram taken 5 ps after the interaction of a 50 TW pulse with the plasma. The dashed white line indicates the angle of the cone defined by the focusing optics (f/3.5). Some of the filaments appear to diverge at angles larger than the collection angle (about f/3.5) of the calorimeter. The filamentation is even more evident in Figure 3(b), showing the second image of the interaction region in the same interferogram of Figure 3(a). As the fringes on this second image were coarser, the image can be interpreted as a shadowgram of the interaction region. Filaments breaking into other filaments can be seen. It should be noted that such a behaviour was not observed in previous experiments performed at lower laser power (20 TW), in which a single self-focused filament was observed[7,8]. This, together with observations at varying intensities carried out in the present experiment, suggests a transition between two different regimes of interaction (whole beam self-channelling to relativistic filamentation) taking place in the 20-50 TW range.

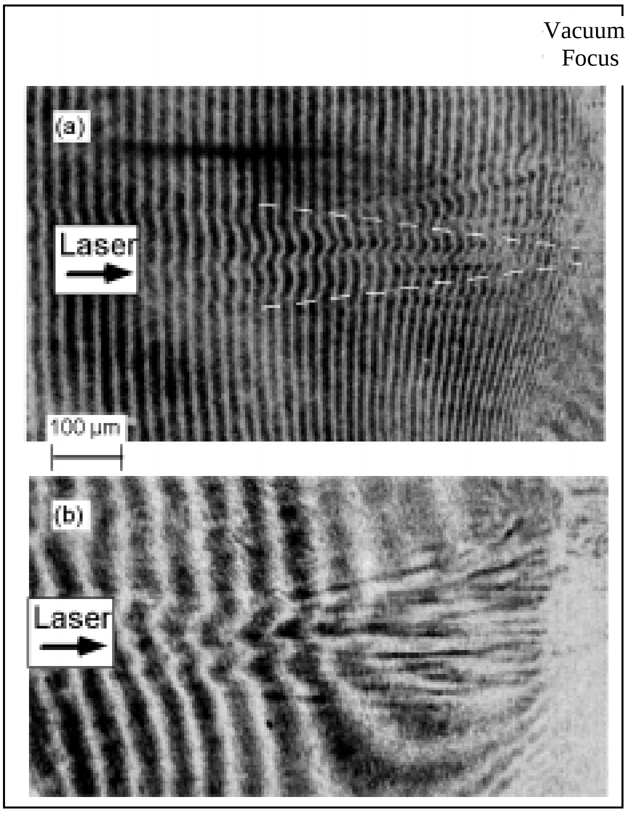

Figure 3. Details of an interferogram taken 5 ps after the propagation of a 50 TW pulse through a laser beam. The two images (a) and (b) (from the same interferogram) both show the interaction region. Laser-break-up and formation of filaments are clearly visible.

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 the 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 a previous experiment[7,8]. The interaction of the 25 TW pulse with the plasma appeared to be less affected by filamentation than in the 50 TW pulse case. An interferogram showing the channel 45 ps after its formation can be seen in Figure 4.

The main CPA pulse was focused into the channel at various stages of the channel expansion, and the CPA main pulse transmittance was measured, for various plasma conditions, as a function of the delay between the main and the channeling pulse.

A clear increase in energy transmission was observed, as visible for example in the graph shown in Figure 5. In the figure the energy transmission is plotted for the case of plasmas produced from 0.1 µm targets.

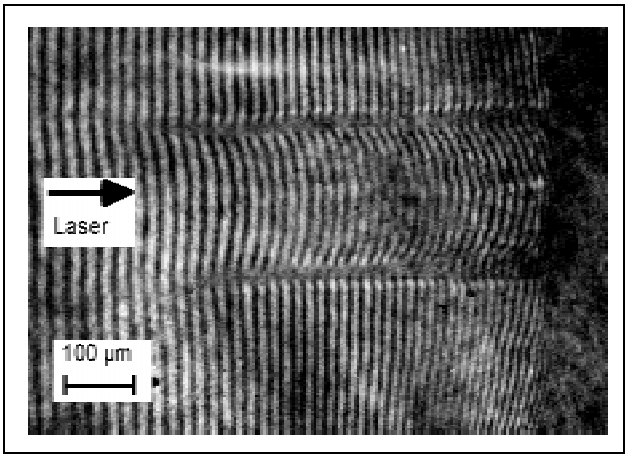

Figure 4. Interferogram of the channel taken 45 ps after its formation.

The energy transmitted through the plasma grows from the few per cent transmittance measured in absence of preformed channel to almost 100 % transmission when the channelling-to-main delay is of the order of 100 ps.

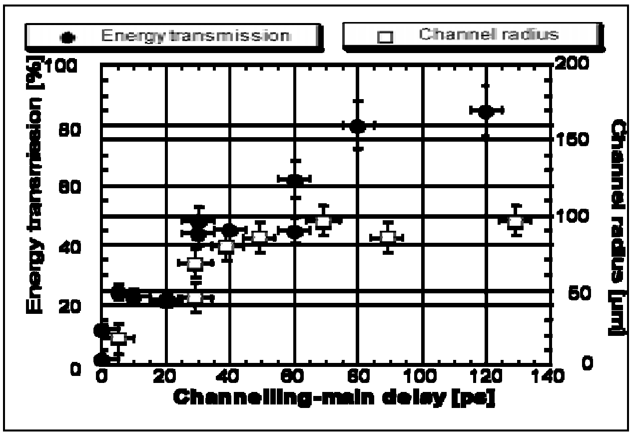

Figure 5. Energy transmission through an underdense plasma (peak density ≈ 0.03 n_c, length ≈ 1-2 mm, obtained from explosion of 0.1 µm targets) in presence of a preformed channel. The transmission is plotted versus the delay between the channel formation and the propagation of the main pulse. The temporal evolution of the channel radius is also plotted.

Although a detailed analysis of the data has still to be done, a number of preliminary considerations can be made. First, one has to take into account the energy distribution in the focal plane of the laser. Typically, only 30-40% of the energy is contained in the small size central spot (10-20 µm diameter), and this determines an intensity exceeding 10^{19} W/cm^2 in this spot. The rest of the energy is distributed throughout lower intensity wings extending around the central spot (a systematic characterization of the focal spot may be required, as previously done [9]). Efficient propagation of the energy contained in the high intensity spot is achieved even after 10-20 ps , with more than half of the energy transmitted through the plasma. The factors leading to increased transmission are substantially two:

1) the fact that the density profile across the channel acts as a positive lens on the main pulse propagating through it, limiting the diffraction of the beam.

2) the fact that the density inside the channel is significantly lower than the background plasma. This leads to decreased absorption and also reduces the effect of relativistic filamentation (as the threshold for relativistic self-focusing $P \propto n_c/n_e$ is increased).

The transmitted energy increase when the channelling-to-main delay is increased may be explained by the fact that, as the channel expands, the low intensity, larger diameter wings of the focal spot are encompassed by the channel walls. The internal dynamics of the channel (e.g. the temporal evolution of the density inside the channel) will also play a role. Detailed modeling and data analysis are required to determine the relative importance of the different factors.

A similar trend for the transmission has been observed through denser plasmas, obtained by exploding 0.3 µm targets. The overall transmission is lower, and this may be due to less efficient channel formation over the whole plasma length as a consequence of the higher density of the plasma. Even in this case the transmission appears to grow with the delay, but a transmission peak is observed at a delay of 40 ps, where conditions for more efficient guiding may have been achieved due to channel density dynamics. Experimental measurements carried out in plasmas obtained from 0.5 µm foils also indicate higher transmission at delays of the order of 30-40 ps. This data set shows a considerable scatter probably due to variation in the plasma conditions. Careful analysis of the interferogram is required in order to discriminate between the various measurements and isolate the data referring to similar plasma conditions.

It is interesting to note that the high transmission observed in the data sets at delays of the order of 20-40 ps seems to correlate with γ-rays measurements performed during the same experiment, which are discussed elsewhere in this Annual Report [11)].

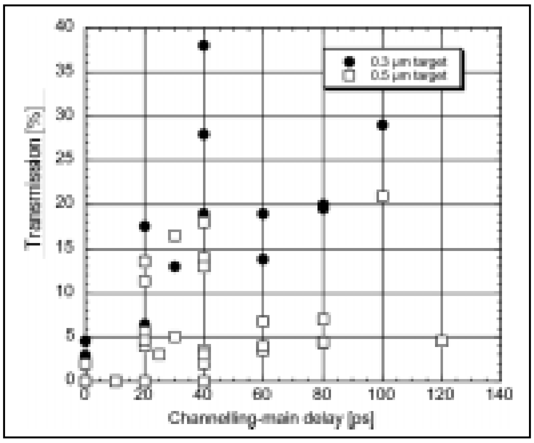

Figure 6. Transmission through plasmas obtained from explosion of 0.3 and 0.5 µm thick CH foils.

Conclusions

The propagation and transmission of relativistically intense picosecond pulses through underdense plasmas have been studied for different plasma conditions. Low transmission was observed even through very underdense plasmas, in correspondence with observation of filamentary laser break-up. The transmission was greatly improved when a channel was preformed ahead of the main laser pulse, using a fraction of the energy of the pulse itself. Under the right conditions up to 90% of the laser energy on target could be propagated through the plasma.

These measurements have obvious relevance to Fast Ignition. In particular, the measurements stress the importance of the presence of a preformed density channel in order to achieve efficient energy propagation through the plasma at ultrahigh intensity. In fact, in absence of a preformed channel the mm-sized coronal plasma surrounding the compressed core of the imploded capsule would be able to absorb most of the energy transported by the pulse.

Acknowledgements

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