Divergence control with two laser pulses – results of first experiment

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Introduction

The first results of an experimental campaign are reported in which it is intended to demonstrate whether it is possible for the fast electron beam (produced at irradiances in excess of 10^{19} Wcm^{-2}µm^{2}) to be artificially collimated even when the beam enters the target with a large divergence angle. The artificial collimation occurs because of a pre-generated magnetic field that is produced by a laser pulse of 10^{18} Wcm^{-2}µm^{2} that precedes the main pulse.

Background

Atzeni[1] showed that for ignition of preformed DT plasma with compressed core density of 400 gcm^{-3}, at least 11 kJ must be deposited in the hot-spot region with a radius of up to 15 µm (0.6 g cm^{-2}) and a length of up to 30 mm (1.2 g cm^{-2}) in a time less than the inertial confinement time (16 ps). The electron energy required to give a stopping distance of 1.2 g cm^{-2} in 400 g cm^{-3} DT is 1.4 MeV (that varies weakly with density). Matching this energy to the ponderomotive potential gives an $I\lambda^2$ of 1.5×10^{19} Wcm^{-2} µm^{2}. This is lower than the values that can be achieved by the current generation of high-intensity lasers such as Vulcan PW, but on the other hand these machines provide pulse durations much smaller than that required by fast ignition (≤1 ps).

For these reasons, we carried out an experimental campaign on the Vulcan PW laser using pulse durations of 5 - 10 ps, giving values of both $I\lambda^2$ and pulse duration comparable to those that would be required for an ignition laser, which are two key parameters in determining the physics of laser-plasma interactions. The spot radius and pulse energy were, however, much lower than those required for an ignition laser. Obtaining all of the required laser parameters simultaneously is clearly only possible with a laser far larger than any that currently exists.

We measured the divergence of the electrons accelerated into the target, which is a crucial parameter in determining the coupling of the electrons to the hotspot in fast ignition[2]. The divergence was found to be 29° (±7°) and 32° (±18°) by X-ray K_α imaging and optical shadowgraphy, respectively at 1.5×10^{19} Wcm^{-2} and 35° (±13°) at 4×10^{19} Wcm^{-2}. An intensity dependence to the beam divergence has been revealed for the first time when these divergence measurements were compared with other measurements reported in the literature.

Both the experiment and theory indicate that for realistic fast ignition beam energies (i.e. ≤100 kJ), the irradiance on target is limited to $I\lambda^2$ of 5×10^{19} W cm^{-2} µm^{2}, unless further measures are taken to control the beam divergence pattern. The HiPER beam operating at $2\omega_0$ delivering 70 kJ in 16 ps to a focal spot of 40 µm gives an irradiance on target of 9×10^{19} Wcm^{-2} µm^{-2}. This makes the achievement of ignition appear to be at risk - control of the fast beam divergence appears to be necessary to the success of the project. This is also important to other areas of research relevant to the HiPER such as X-ray back-lighters and high-temperature material properties.

Two-dimensional (2D) particle-in-cell simulations using the OSIRIS framework confirmed that the divergence effect is independent of focal spot radius. The divergence is primarily governed by the small scale break up of the critical surface due to a Rayleigh Taylor-like rippling instability but is clearly affected by the laser wavelength as well. These results have recently been published in Physical Review Letters [3].

Divergence control

The leading approach to control the beam divergence pattern is the vacuum gap method proposed by Campbell *et al.* [4] The idea has a great deal of merit as collimation and guiding of MeV electrons has been observed in cone-wire plasmas [5], although at distances >200 μm from the cone-tip. We have shown that the energy is transported close to the wire surface, by comparison of interferometric measurements of the expansion of the wire with hydrodynamic and hybrid particle-in-cell simulations [6]. This approach demands additional target engineering of the cone, and one must ensure that the vacuum gaps in the cone itself are not filled by plasma.

A new approach has been proposed that does not suffer from these problems (see reference [7] for further details). We have used the recently developed LEDA code to numerically demonstrate artificially induced collimation in 2D Cartesian geometry. LEDA is a novel 2D hybrid-Vlasov-Fokker-Planck code that treats the fast electrons via an algorithm similar to the KALOS code of Bell and Kingham [8], whilst the background plasma is treated in the fashion of Davies' hybrid code [9].

Experiment

A full suite of well-tested plasma diagnostics were used for this investigation. These included Cu K_α imaging; time-resolved optical imaging of the thermal radiation from the rear surface of the foil; transverse optical probe; X-ray pinhole imaging; X-ray spectrometers (HOPG and conically curved KAP); single hit CCD spectrometer etc.

Energy (J)	Pulse Length (ps)	Pulse Separation (ps)	Pulse 1 Intensity (W/cm^2)	Pulse 2 Intensity (W/cm^2)
300	5	X	X	5E19
300	5	7.5	2E18	5E19
300	5	15	2E18	5E19
50	0.5	X	X	8E19
50	0.5	1.5	3E18	8E19

Table 1. Shot energy, pulse length, pulse separation and the intensities of the two pulses. The X's denote where only a single pulse was used for reference.

The titanium targets were shot at normal incidence and were varied in thicknesses from 10 to 140 μm. Table 1 summarises the parameter space investigated during the experiment.

In this report, we will concentrate on unexpected features observed using rear surface temperature diagnostic HISAC [10]. The temporal evolution of the rear surface thermal radiation was imaged in 2D in the spectral region between ω_0 to $2\omega_0$. $2\omega_0$ coherent transition radiation was removed by the use of dichoric filters. Optical fibres were used to convert the 2D thermal image from the target rear surface into a 1D image which was then streaked in time. The resulting image was 4 dimensional (2 space, 1 time and 1 intensity). By deconvolving this image and assuming a Planckian radiation spectrum, the 2D temporal evolution of the rear surface temperature was obtained. Absolute calibration of the device using the X-ray diagnostics has yet to be performed for this experiment – that analysis is still underway. A preliminary estimate of rear surface temperatures has been made by comparing the results with those obtained from previous experiments performed on the same facility in a similar parameter regime [10].

Results

The results for the two pulse duration (0.5 ps and 5 ps) regimes investigated are summarised in figures 1 and 2. Both show similar characteristic features; single pulse interactions used for normalisation purposes show a double temperature gradient for both pulse durations used, as observed in previous experiments [10]. On the other hand, the double pulse results for both pulse durations have significantly reduced rear surface temperature for thin targets (areal electron density ~10^{25} m^{-2}) and in both cases the double gradient is not present.

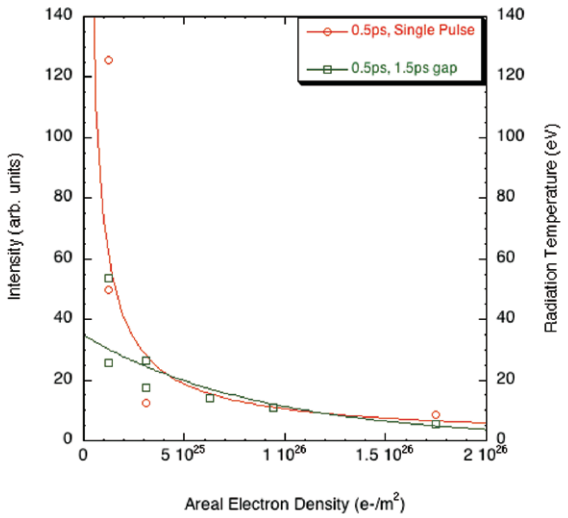

Figure 1. 50 J, 0.5 ps pulse length, rear surface optical emission results. Variation in peak rear surface radiation intensity and estimated radiation temperature with areal electron density.

In the event that collimation had occurred a clear increase in rear surface temperature would have been expected for the double pulse results, particularly for the thicker targets (whose electron areal density > 5×10^{25} electrons m^{-2}). As this increase was not observed, it confirms that beam collimation did not occur. This result is further supported by the 2D K-α data (shown in figure 3); there is no clear reduction in the K-α spot size with the introduction of the double laser pulse, as would be expected if collimation was occurring.

Discussion

The lack of a double gradient in simulations of previous experiments was explained by the generation of an azimuthal magnetic field inside the solid density plasma that prevented refluxing fast electrons from the rear surface returning to the focal region. This resulted in a reduced temperature and was attributed to single pass heating that resulted from the electron motion in the magnetised plasma [10].

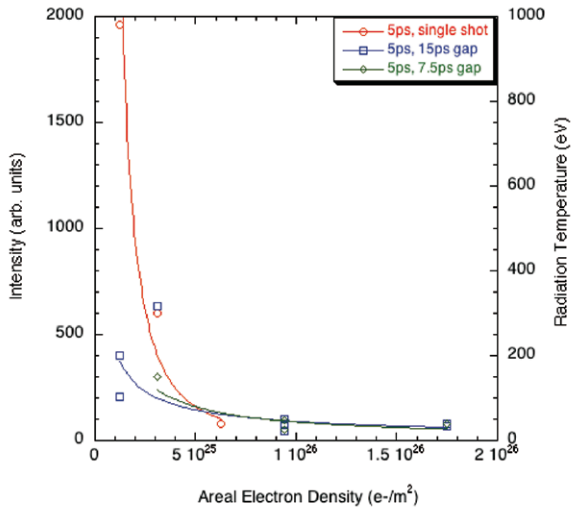

Figure 2. 300 J, 5 ps pulse length rear surface optical emission results. Variation in peak rear surface radiation intensity and estimated radiation temperature with areal electron density.

The same observation in this experiment might be thought to be at odds with the apparent lack of collimation. This is not necessarily true. The lack of collimation implies that the azimuthal magnetic field is insufficient to collimate beam, but it does not imply that there is no magnetic field there at all. Competing hypotheses have to be excluded as well before one can be satisfied with this explanation. This is currently being studied with hybrid codes.

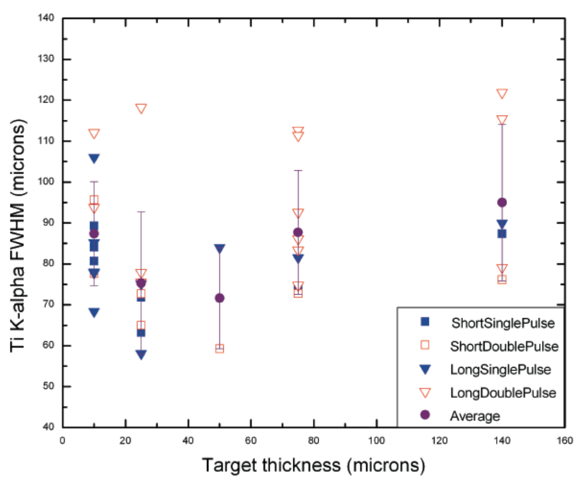

Figure 3. 2D Ti K-α results. Variation in FWHM spot size with target thickness. No clear reduction in spot size was observed with the introduction of the double laser pulse.

The failure of two-pulse collimation in this experiment clearly needs to be fully explained. Much of this explanation probably lies in the fact that the original study by Robinson and co-workers [7] did not consider a number of factors that are always present in experiments. This includes the hydrodynamic effect of the laser pre-pulse, the details of the specific target material used (Ti in this case), and a realistic fast electron energy distribution. Studies are already underway to look at the role of these.

Summary

The first experiment to examine the double pulse collimation concept has revealed evidence for single-pass heating for Ti foils of ≤25 μm thickness irradiated by the double pulse. This may be evidence for magnetic field generation in the dense plasma that prevents refluxing of the fast electrons from the rear surface. There was no evidence for collimation of the main pulse for these conditions. Detailed modelling of the experiment using hybrid codes is now underway to examine the transport physics in detail, particularly the role of the laser pre-pulse, target material and fast electron energy distribution.

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