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Studies of the fast ignition route to inertial confinement fusion at the Rutherford Appleton Laboratory

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Abstract

The Rutherford Appleton Laboratory has been at the forefront of investigations into the physics associated with the fast ignition concept for inertial confinement fusion. This scheme involves complex laser–plasma processes, the theoretical understanding of which relies heavily on particle-in-cell calculations. In this paper, three experiments displaying quantitative agreement with detailed multi-dimensional PIC calculations are reviewed: hole-boring velocity measurements; relativistic self-focusing; and harmonic generation from plasma surfaces. Qualitative agreement of hot electron temperature measurements with PIC simulations are also discussed. The authors believe these results are very encouraging for the fast ignition concept. © 1999 Published by Elsevier Science S.A. All rights reserved.

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1. Introduction

The Central Laser Facility (CLF) at the Rutherford Appleton Laboratory operates two high-power lasers: the Nd glass laser VULCAN and the excimer gas laser TITANIA on which experiments are conducted in association with research groups from the United Kingdom and abroad, particularly the European Community. The VULCAN laser can deliver up to 2.5 kJ (1.2 kJ) of laser energy at 1.053 μm (0.53 μm) in eight beams with pulses of nanosecond duration. The VULCAN CPA system can currently deliver 35-J, 1-ps (35 TW, 10^{19} W cm^{-2}) pulses at 1.053 μm. The laser configuration is very flexible, allowing a wide range of different irradiation geometries. Picosecond pulses can be combined onto target with longer nanosecond pulses in cylindrical, spherical or line foci, as well as in single- and double-sided cluster irradiation geometries.

The experiments conducted at the CLF have covered a wide range of topics in high-power laser science. A significant fraction of this programme is in the area of inertial confinement fusion (ICF) and ICF-related studies. The experiments performed so far have made a significant contribution to the understanding and international development of direct-drive ICF. For instance, measurements of the growth rate of the Rayleigh–Taylor instability have been made using a number of different backlighting sources, such as polychromatic [1] and monochromatic X-rays [2]. bright X-UV sources including X-UV lasers [3,4], and α-particle emission [5]. The laser imprint problem was identified as a significant impediment to direct drive [6] and the strategically important foam-buffered direct-drive scheme promises a new route to solving this problem [7,8].

The fast ignition scheme as originally proposed by Tabak et al. [9] shows a possible route to reducing the energy required to achieve break-even and gain in ICF from the MJ to the 100-kJ level. The scheme consists of three phases. The first is the compression of the thermonuclear fuel mass to a high density (a few hundred g cm^{-3}) whilst keeping the temperature relatively low (a few hundreds of eV). The second stage is the creation of a channel through the plasma atmosphere blown off by the initial compression phase. Here the laser pulse required has intensities of the order of 10^{17}–10^{19} W cm^{-2} with a pulse length of a few tens to a few hundred picoseconds. The laser intensity is sufficient that the light pressure removes plasma from the path of the beam and is sufficient to push the critical density surface to a position much closer to the dense fuel. Through the channel, the igniter beam (10^{19}–10^{20} W cm^{-2} with a pulse length of few picoseconds) propagates and deposits its energy. At these high intensities a large fraction of the igniter beam energy is converted to fast electrons which stop in the dense fuel. Such heating creates a ‘spark’ that propagates a thermonuclear burn wave through the rest of the fuel.

The CPA beam from VULCAN is ideally suited to study the physics of the short-pulse, ultra-high-intensity energy deposition process. The fast ignition scheme involves laser–plasma processes, the theoretical understanding of which rests heavily on particle-in-cell (PIC) simulations. We show below that quantitative agreement with PIC calculations has been demonstrated in three major experiments: hole-boring velocity measurements; relativistic self focusing; and harmonic generation. We will also show that qualitative agreement has been found with hot electron temperature measurements. These results are very encouraging for the fast ignition concept.

2. Experiments

2.1. Hole-boring measurements

The experiment described in this section is fully discussed in the paper by Zepf et al. [10]. The p-polarised laser energy from VULCAN CPA was incident onto optically polished glass slab targets (which were overcoated with CH of 2–4 μm thickness) at an angle of 54° to the target normal. Optical channels, consisting of 25 cm focal length, 5-cm diameter fused silica lenses, were positioned at 80°, 22° and $-20°$ from the target normal. The collimated fourth harmonic radiation was focused onto the entrance slit of three 0.5-m optical spectrometers equipped with 1200 l mm^{-1} gratings.

The dispersed radiation was detected using Oriel Instaspec charge coupled devices (CCDs) or Kodak TMAX film. The direction of motion of the recession of the critical density was shown to be parallel to the target normal.

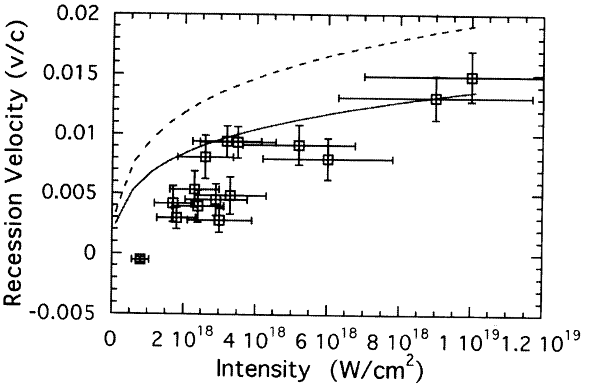


Fig. 1. The recession velocity of the critical density surface as a function of laser intensity on target.

Fig. 1 shows the recession velocity of the critical density surface plotted against incident laser intensity. The spectra change from blue (expanding away from the target) to red shifts as the intensity increased past $I \sim 10^{18}$ W cm^2. Wilks et al. [11] proposed a simple model using mass and momentum conservation which agrees well with PIC simulations for normal incidence irradiation. This model has been modified to include the effects of absorption and angle of incidence, both of which reduce the maximum momentum that can be transferred, thus reducing the observable hole-boring velocities. The recession velocity as a fraction of the speed of light is given by:

$$\frac{v}{c} = \left(\frac{\Delta p}{p_{\text{tot}}} \frac{n_{\text{crit}}}{n_p} \frac{Zm_e}{M} \frac{I\lambda^2}{2.7 \times 10^{18}\ \text{W cm}^{-2}} \right)^{1/2}$$

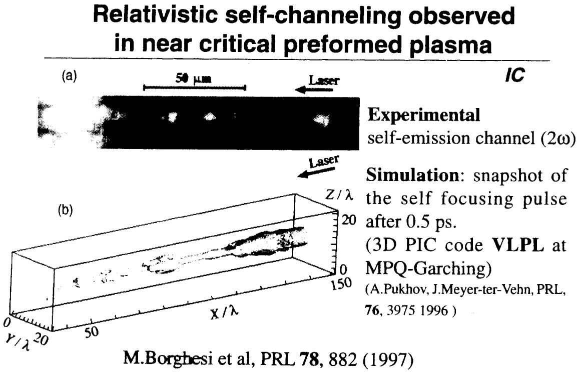
where $p_{\text{tot}} = 2I/c$ and Δp is the transferred momentum (taking into account absorption and angle of incidence). The solid line fit shown in Fig. 1 takes into account the oblique angle of incidence (i.e. $\Delta p/p_{\text{tot}} = [0.5(2 - f_{\text{absorbed}})\cos 54°]$) and the relative fraction of absorbed ($f_{\text{absorbed}} = 0.6$) and reflected photons. The dashed line shows that when the absorption is excluded incidence (i.e. $\Delta p/p_{\text{tot}} = \cos 54° = 0.59$), the theoretical recession velocities are outside of the experimental errors.

2.2. Relativistic self focusing

This experiment is described in detail by Borghesi et al. [12]. Thin CH foils were irradiated by a 400-ps, 527-nm pulse at an intensity below 10^{13} W cm^{-2}. The foils exploded to generate a long scale length plasma. A 1054-nm CPA beam then interacted with the preformed plasma. Both the heating and the interaction pulse were focused onto target using the same $f/4.5$ off-axis parabolic mirror. The intensity of the CPA channel was between 5 and 9×10^{18} W cm^{-2}. Self channelling was observed by both Schlieren photography and by self emission of the plasma. Fig. 2 shows the self emission of the plasma channel showing oscillations in the transverse size of the channel. Also shown are 3-dimensional (3D) PIC simulations from the VLPL (Virtual Laser Plasma Laboratory) code developed for massively parallel processing in Garching [13]. The simulations predict that the channel width pulsates as the pulse defocuses and refocuses with a period of 15–30 λ. There is remarkable agreement between the experimental observations and the 3D PIC simulations.

2.3. High-order harmonic radiation from ultra-intense laser pulse interactions with solids

Recent boosted frame of reference PIC simulations of laser–solid harmonic generation for sub-



Experimental self-emission channel (2ω)

Simulation: snapshot of the self focusing pulse after 0.5 ps. (3D PIC code **VLPL** at MPQ-Garching) (A.Pukhov, J.Meyer-ter-Vehn, PRL, **76**, 3975 1996)

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Fig. 2. Evidence for relativistic self channelling (reproduced with permission of M. Borghesi).

picosecond pulses have been performed [14]. For obliquely incident p-polarised light that is focused onto solid targets, up to 60 harmonics can be generated when $I\lambda^2 \geq 10^{19}$ W cm^{-2} μm^2 with power conversion efficiencies of 10^{-6}. Here, the radiation pressure associated with a intense laser pulse ensures that the plasma density profile remains extremely steep. Both odd and even order harmonics are generated via the relativistic current associated with the electrons being dragged back-and-forth across the vacuum–solid interface.

The laser beam was focused at an angle of 54° to the target normal and the reflected beam was directed into a modified flat-field XUV spectrometer. The harmonic radiation was detected by a slitless flat-field grazing incidence spectrometer. This consisted of a 1200-l mm^{-1} Hitachi concave grating together with a gold-coated grazing incidence cylindrical mirror. The harmonic radiation was observed to be both isotropic and insensitive to the polarisation of the incident laser beam, probably due to rippling of the critical density surface associated with the hole-boring process. Fig. 3 shows the conversion efficiency into harmonic radiation as a function of laser intensity on target, together with the predicted spectra from PIC calculations [15]. There is good agreement for intensities of 5×10^{17} W cm^{-2} and 5×10^{18} W cm^{-2}, whereas the discrepancy at the highest irradiance can be accounted for by pulse shape effects (the PIC simulation uses a trapezoidal rather than sech^2 pulse). These results again validate the PIC calculations for laser–plasma interactions for intensities relevant to fast ignition.

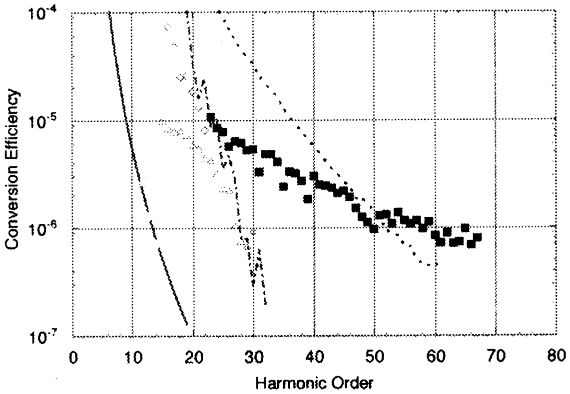

Fig. 3. Conversion efficiencies, both theroetical (*line-type*) and experimental [*symbol*], into harmonic radiation for: 5×10^{17} W cm^{-2} (*solid line*) and [*open squares*]; 5×10^{18} W cm^{-2} (*chain*) and [*open triangles*]; and 1×10^{19} W cm^{-2} (*dotted line*) and [*filled squares*].

2.4. Hot electron temperature measurements

The processes of energy absorption in the presence of very steep density gradients is a topic of lively debate at the present time. At high intensities, a number of collisionless processes become important. These include resonance absorption [16], vacuum heating [17–19], skin-layer heating [20] and, at normal incidence, $\mathbf{v} \times \mathbf{B}$ heating [11,21]. It is important to determine which processes dominate under controlled conditions.

At the highest available intensities at present ($I = 10^{19}$ W cm^{-2}) and an intensity contrast ratio of 1:10^{-8}, Malka and Miquel [22] have shown that the electron temperature is dominated by the ponderomotive potential for those electrons directed along the axis of the laser beam and temperatures of 1 MeV have been measured. In the paper by Beg et al. [23], a series of experiments were reported for laser–plasma interactions with solid targets for intensities up to 10^{19} W cm^{-2} using the VULCAN CPA laser. In this case, the intensity contrast ratio was 1:10^{-6}. It was shown that the maximum ion energy (which is directly related to the hot electron temperature) associated with the fast electron driven plasma expansion scaled as $E_{\max} = 1.2(\pm 0.3) \times 10^{-2} I^{0.313 \pm 0.03}$ keV (where I is in W cm^{-2}). Beg et al. show that this scaling is identical to that reported by Tan et al. for high intensity interactions using nanosecond-duration CO$_2$ lasers ($\lambda = 10.6$ μm) and tens-of-picosecond-duration Nd glass lasers ($\lambda = 1.064$ μm) [24]. The scaling of the maximum ion energy (and therefore the hot electron temperature) with intensity strongly suggests that resonance absorption dominates the interaction process [23]. Resonance absorption is known to be enhanced by hole boring and rippling of the critical density surface [25]. Measurements of the X-ray and γ-ray bremsstrahlung signal reported by Beg et al. support the $T_{\text{hot}} = 100$ $(I/10^{17}$ W cm$^{-2})^{1/3}$ keV scaling. However, two comments are worth making. The first is that Beg et al.'s bremsstrahlung signal has a limited spectral range. Two hot electron temperatures cannot be ruled out from the observed time and spatially integrated spectrum. Secondly, the electrons generated in the channel formed by hole boring should be highly energetic (> 1 MeV) and highly directional (i.e. into the target). The associated bremsstrahlung emission is also likely to be highly directional due to the Lorentz transformation. Beg et al's measurements were taken at ~ 20° from the target surface, and the directional bremsstrahlung emission may not have registered on these detectors.

3. Summary

Some of the most important physical processes of the fast ignition scheme have been investigated with experiments performed at the Rutherford Appleton Laboratory's VULCAN CPA laser. Quantitative agreement with advanced particle-in-cell calculations have been shown in three separate experiments. Qualitative agreement with hot electron temperature measurements have been obtained. We believe these results are very encouraging for the fast ignition concept.

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