Prepulse measurements from laser cluster interaction experiments on the Vulcan Petawatt laser

J Lazarus, P M Nilson, R A Smith

The Blackett Laboratory, Imperial College London, Prince Consort Road, London, SW7 2BW, UK

A S Moore, E L Clark, R T Eagleton, R D Edwards, E T Gumbrell

AWE plc, Aldermaston, Reading RG7 4PR, UK

R J Clarke

Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX, UK

Main contact email address: *james.lazarus@imperial.ac.uk*

Introduction

Since the development of techniques, such as mode-locking and chirped pulse amplification (CPA)[1], laser technology has advanced towards ever-decreasing pulse durations, with modern TW systems capable of achieving $\Delta t \sim 30$fs. The reduction in energy required to access the high intensity regime ($>10^{16}$Wcm^{-2}) has followed on from this and small (university scale) multi terawatt lasers have been developed as a result. In addition to high intensity, short pulses, CPA lasers often exhibit other common temporal characteristics.

The un-seeded amplification of light spontaneously emitted in laser amplifiers can occur over the gain duration (~90µs for Nd:YAG-pumped Ti:Sapphire lasers and ~250µs for flash lamp-pumped systems). In this way amplified spontaneous emission (ASE) can give rise to a substantial 'pedestal' of light before the arrival of the main pulse. The extent of this prepulse can be reduced by using an appropriately-timed Pockel's cell/polariser combination to select the main pulse. However, due to the contrast limit of the optical elements used, a 'slicer' will only reduce the level of ASE by a factor of $\sim 10^3$. Moreover, the ~1ns rise time of Pockel's cells does not reduce ASE prepulse at all on shorter timescales. Critically, prepulses can also arise due to spectral clipping or imperfect recompression[2] of the amplified stretched pulse or through "cavity bleeding" from regenerative amplifiers which can create discrete short pulses over a broad range of times. Despite these problems, with careful laser design contrast ratios, $C(t) = I(t_0)/I(t)$ where $I(t_0)$ is the peak intensity, of 10^6 can be achieved.

For modern table-top systems operating in the moderately high intensity regime, $C \sim 10^6$ is sufficient for many experiments since at best focus the prepulse intensity will only reach 10^{10}–10^{11}Wcm^{-2}, the limit of the breakdown threshold for solid dielectric surfaces. However, for relativistic laser-plasma interaction experiments, where larger, *ultra*-intense ($I(t_0)\tau 10^{20}$Wcm^{-2}) laser systems are required, the same contrast ratio would produce a prepulse of $I\tau 10^{13}$Wcm^{-2}. Although this only corresponds to a ponderomotive potential of ~few eV, over these relatively long timescales multi-photon effects can be strong enough to cause target pre-ionisation, long scale-length plasma formation and thus significantly alter the physics of the main interaction from an otherwise 'clean' experiment. Here we report on the first attempts to characterise the prepulse produced by the Vulcan petawatt laser[3] by studying the laser interaction with atomic clusters.

Atomic cluster absorption

Atomic clusters exhibit very efficient absorption of high intensity laser light[4] and have consequently been a subject of recent research into high energy density plasma physics[5]. Figure 1 shows a plot of energy absorbed by ~10nm Xe clusters vs. peak intensity for 1ps pulses and from it one can see three distinct regions. $I \sim 5\times10^{12}$Wcm^{-2} sees the onset of absorption and a rapid growth until $I \sim 10^{14}$Wcm^{-2}, where it saturates and eventually tails off after $I \sim 5\times10^{16}$Wcm^{-2}. Similar results were found with Ar, but with absorption starting at $I \sim 5\times10^{13}$Wcm^{-2}. The first, low intensity region is the subject of this report and is attributed to low-probability, multiphoton ionisation, which releases a small number of electrons, seeding an avalanche ionisation of the clusters under the laser potential and hence collisional absorption.

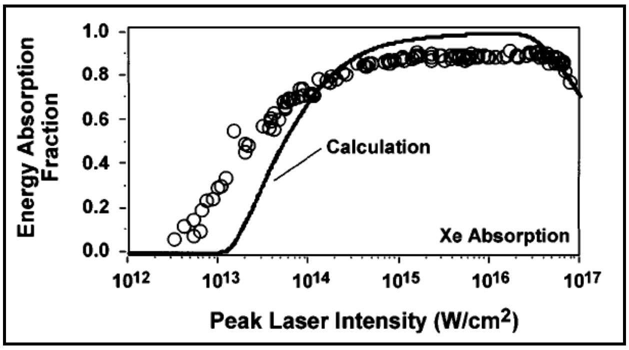

Figure 1. Reproduced, with permission, from ref.[4]. A moderate-high intensity frequency-doubled Nd:glass laser ($E \sim 0.5$J, $\Delta t \sim 1$ps) was focussed at f/12 into Xe clusters. Calorimetry showed the sudden onset of laser absorption at $I \sim 5\times10^{12}$Wcm^{-2}.

It is possible to exploit the efficient absorption of high intensity light by atomic clusters in order to couple a large amount of energy into the medium using relatively moderate laser intensities ($I \sim 10^{17}$Wcm^{-2}). The resultant energy deposition creates a shock which can evolve over a ns timescale into a blastwave, and this has been a topic of recent research[5]. During a recent effort to extend this field into the *ultra*-high intensity regime by Imperial College and AWE[6] investigations into the levels of prepulse on the Vulcan petawatt system were carried out.

Optical probing experiments

The Nd:glass Vulcan Petawatt laser ($E \sim 400$J, $\Delta t \sim 400$fs)[3] was focussed into a 45º expanding plume of atomic clusters (produced by a modified series 99 solenoidal valve[7,8]) using an f/3.1 off-axis parabola, giving a peak intensity of $\sim 10^{21}$Wcm^{-2}. Using a delayed frequency-doubled optical probe it was possible to record a shadowgraph of the plasma formed over a range of timescales. By setting the delay such that the probe pulse arrived *prior* to the main heating pulse and then varying the heating pulse energy, an estimate of prepulse intensity can be obtained.

At a time, t, the intensity on target can be assumed to be greater than the threshold value for cluster absorption (5×10^{12}Wcm^{-2} for Xe clusters, 5×10^{13}Wcm^{-2} for Ar) if plasma is visible in the shadowgram. This value can then be scaled according to the laser energy in order to obtain an upper estimate for the contrast, C(t).

Shadowgram results

Figure 2 shows a selection of shadowgrams of ~20nm Xe and Ar clusters, irradiated at I~10^{21}Wcm^{-2} and I~10^{20}–10^{21}Wcm^{-2} respectively, taken before t_0 (the peak of the pulse). Using the reasoning explained above estimates of I(t_0-700ps)τ5×10^{12}Wcm^{-2}, I(t_0-500ps)τ5×10^{13}Wcm^{-2} and I(t_0-400ps)τ5×10^{13}Wcm^{-2} can be obtained.

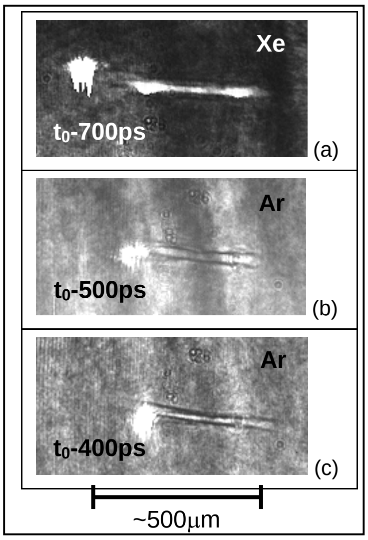

Figure 2. Shadowgrams taken of laser cluster interactions prior to the peak of the heating pulse. Images (a) and (b) are 400J shots and image (c) is an 80J shot. The laser is incident from the left and an approximate spatial scale is shown.

By renormalising these values to the laser energy, one arrives at contrast levels of C(t_0-700ps)~10^8, C(t_0-500ps)~5×10^7 and C(t_0-400ps)~5×10^6, as summarised in Figure 3. This is in reasonable agreement with previous measurements[9)], where an estimate of 10^5<C(t)<10^7 over a timescale from ~100ps to ~10ns was obtained (also shown in Figure. 3) by analysing the preplasma produced in petawatt-solid target experiments.

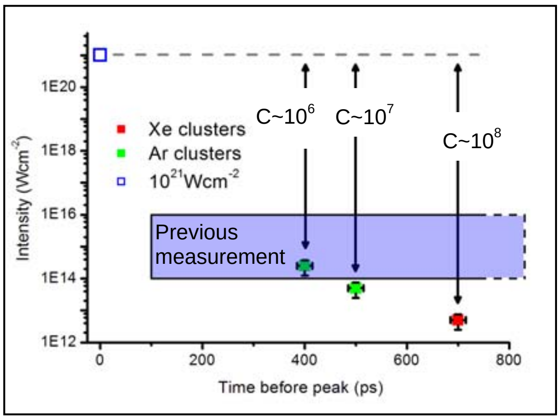

Figure 3. Time scan of scaled petawatt prepulse levels from t_0-700ps to t_0-400ps. Contrast ratios, assuming I(t_0)=10^{21}Wcm^{-2} (point included), are also given, along with the result of ref.[9)].

The levels of prepulse on the timescales of this investigation are slightly lower than those indicated by Patel *et al.*[9)]. Although our measurements constitute a minimum estimate of the prepulse, the upper bound, suggested in ref. [9)], of 10^{16}Wcm^{-2} is likely to be an overestimate, since our results show that negligible plasma expansion (and hence only very marginal laser energy deposition) is seen to have taken place over this timescale. However, Figure 3 also shows an increase in the inferred minimum prepulse intensity over time and this is supported by the disappearance of preplasma formed in D_2 clusters seen in an 80J shadowgram (not shown here) at t= t_0-400ps when the probe time was moved to t_0-500ps (also not shown). It is possible, therefore, that the level of prepulse between t_0-400ps and t_0 may well be slightly higher than at earlier times. In order to conserve the energy of a ~10^{16}Wcm^{-2} prepulse acting over 9.9ns (as suggested in ref. [9)]) when the time window is reduced to 400ps, the intensity must be raised by an order of magnitude to I~10^{17}Wcm^{-2}. It should be stressed, however, that C(t)~10^4 is only an estimate of the *minimum* contrast level for the timescale t_0-400ps<t<t_0 and in practice, one would expect much higher contrast from the Vulcan Petawatt laser system.

Conclusion

We have shown that a focussed prepulse intensity of at least 10^{12}–10^{13}Wcm^{-2} currently exists up to 700ps before the arrival of the main pulse on the Vulcan Petawatt laser. This appears to grow with time and may extend to 10^{16}Wcm^{-2} and higher on shorter timescales. These levels could be verified by 3rd order autocorrelation of the unfocussed main beam.

There are several techniques for laser contrast enhancement which might be possible to implement on the Vulcan Petawatt system. These include frequency doubling, where the main, high-intensity pulse is preferentially converted over prepulse into second harmonic light, and the use of plasma mirrors[2)]. The former solution, although more established technologically, is limited by optic size considerations. Plasma mirroring, therefore, appears to be the preferred method, although at ultra-high intensities it is an inherently low repetition rate solution.

Acknowledgements

The authors gratefully acknowledge the support of the operational staff at the Central Laser Facility. This work was funded by the UK MoD. Two of the authors (J. L. & P. M. N.) are funded by AWE CASE studentships.

References

1. D Strickland and G. Mourou,
Opt. Comm. 56 (1985).

2. I Watts *et al.*,
Phys. Rev. E 66 1 (2002).

3. C N Danson *et al.*,
Nucl. Fusion 44 S239 (2004).

4. T Ditmire *et al.*,
Phys. Rev. Letters 78 3121 (1997).

5. A S Moore *et al.*,
Phys. Plasmas 12 052707 (2005).

6. A S Moore *et al.*,
CLF Annual Report 2004/2005, p34.

7. R A Smith *et al.*,
Rev. Sci. Instrum. 69 11 (1998).

8. J Lazarus *et al.*,
CLF Annual Report 2004/2005, p40.

9. P K Patel *et al.*,
CLF Annual Report 2003/2004, p34.