Modelling the interaction of CPA lasers with solid targets

R G Evans

AWE plc, Aldermaston, Reading, RG7 4PR, UK

Main contact email address: *roger.evans@awe.co.uk*

Introduction

The interaction of an intense laser with a solid target is a difficult problem to model in its entirety since there are disparate length and time scales for different parts of the process. The electromagnetic interaction with the plasma interactions is predominantly around the critical density, $n_e = 10^{21}$ cm^{-3} for a 1µm glass laser with a laser period of 3fsec. The intense laser light accelerates electrons to energies of some MeV with ranges of more than 100µm in solid and collision times around 1psec. At the same time there is an induced return current of relatively cold electrons with mean free paths and Debye lengths less than 10^{-2} µm.

Bell$^{1)}$ and others have shown that over a large part of the parameter range of interest the dynamics of the laser generated hot electrons are controlled by the collisional return current with its associated electric and magnetic fields. The magnetic fields generated according to $\partial\mathbf{B}/\partial t = \mathrm{curl}\mathbf{E}$ acts to focus the hot electrons into a moderately parallel beam so that they retain their initial density for a few focal spot diameters.

Density of Beam and Return Currents

If the normalised intensity of the laser is $a_0 = eE/(m_e\omega c)$ then the laser accelerates electrons from a region around the relativistically corrected critical density $n_c{\sim}a_0m_e\omega^2/4\pi e^2$ to energies of about the ponderomotive potential of the focused laser $\Phi{\sim}a_0m_ec^2$.

The maximum power flux that can be carried away from the interaction region in relativistic electrons is $n_e\Phi c = E^2c/4\pi$ which is identical to the power flux in the laser beam in vacuum. Thus to a good approximation 50% absorption of laser energy requires 50% of the electrons at the corrected critical density with the remaining 50% forming a return current also moving at a velocity of c!

In the solid material at 3 x 10^{23} cm^{-3} the return current drift energy will range from 1eV for a_0=1 to 1keV for a_0=30 (10^{21}Wcm^{-2}). If the return current drift velocity exceeds the ion acoustic velocity $c_s^2 = ZT_e/Am_p$ then there is likely to be current driven ion turbulence which will increase the resistivity above the Spitzer value. For moderate Z materials Z/A ~ 1/2 so the energy of electrons drifting at the ion acoustic velocity is $m_ec_s^2/2 \sim T_e/7200$ and most regions of interest in the solid will be susceptible to current driven turbulence. The ion plasma period in the solid is typically a few fsec so there is ample time for the turbulence to grow.

Understanding the resistivity of the solid material is further complicated by the fact that at temperatures below 100eV the effects of strongly coupled plasmas will be reflected in $\ln\Lambda \sim 1$ and further corrections to Spitzer resistivity are required.

Previous Models

Most of the existing work eg $^{1,2,3)}$ on the heating of solid density material assumes that the generation of the energetic electrons is a separate process and the models begin with a mandated source of electrons with spatial and momentum distributions given by explicit PIC models or by experiment.

The beam electrons are treated as a distinct species moving in self-consistent **E** and **B** fields and weakly scattered by the background material. The background plasma is treated as a thermal fluid with an equation of state and resistivity independent of the beam electrons. **E** and **B** are obtained either from an assumption that $\mathbf{j}_{\mathrm{cold}} = -\mathbf{j}_{\mathrm{hot}}$ or from implicit methods that make fewer assumptions but are difficult to test against known solutions.

Recently Campbell and others$^{4)}$ have extended the implicit PIC method to include the interaction of the laser with the plasma electrons so that the generation of the relativistic electron beam is obtained self-consistently in the simulation. This note explores the applicability of this method and makes an initial comparison of implicit and explicit PIC models at the rather coarse resolutions needed for these models.

Simulations

The work of Campbell attempts to simulate a very complex situation where the initial conditions are the result of a pellet implosion and not well characterised. It is difficult to judge the sensitivity of their conclusions to the assumptions in the model and to the uncertainty of the initial configuration. The simulations described here are deliberately simple, a planar homogeneous target where the only uncertainty in experimental work is the level of laser pre-pulse.

The simulation is shown schematically in Figure 1.

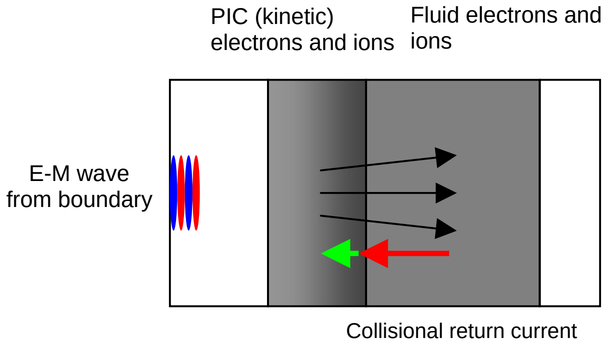

Figure 1. Schematic of simulation showing vacuum region, PIC electrons and fluid electrons.

The simulation uses the LSP simulation model$^{5)}$ set up to use implicit differencing for the PIC species, to transform PIC electrons to fluid electron when their energy drops to ten times the background temperature, and to promote fluid electrons to PIC electrons when their drift velocity becomes more than three times the thermal velocity. PIC electrons are also split (fission) to maintain large enough numbers per cell for good statistics.

The PIC region extends for 10µm as a linear ramp rising to 30 times the critical density, the fluid layer has a short linear ramp up to solid density where it stays constant. The laser is incident from the left boundary into a vacuum that serves as a matching region before striking the plasma.

These simulations are expensive in computing effort because of the need to adequately resolve the laser wavelength. In a purely underdense plasma 12 points per wavelength would be the minimum for confidence but with substantially over-dense PIC plasma we have used 20 points per wavelength for initial calculations and would need to show later by means of higher resolution simulations whether this is adequate. The present simulations require around 24 hours on 32 nodes of an IBM SP to run to 500fsec of simulation time.

Figures 2 and 3 show the number density of PIC electrons and the temperature of the fluid electrons in a simulation with peak irradiance of 1.5 x 10^{20}Wcm^{-2}. Simulations from 10^{19}Wcm^{-2} to 10^{21}Wcm^{-2} show a clear increase in thickness of the heated layer and micron scale filamentation of the heating which is more pronounced at higher irradiances.

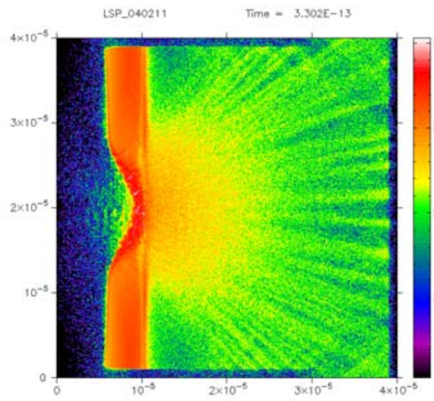

Figure 2. Number density of PIC electrons at the peak of the laser pulse at 300fsec. Dimensions in m.

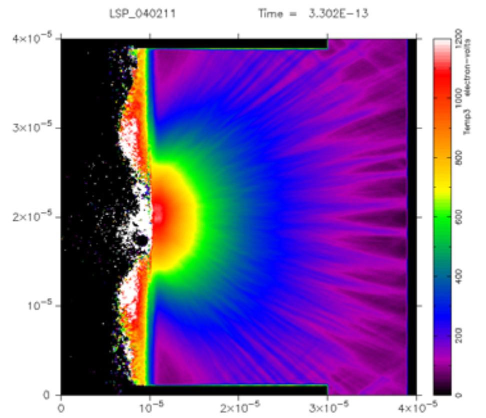

Figure 3. Temperature of the fluid electrons at the peak of the laser pulse at 300fsec.

There are numerical stability issues that remain to be resolved which prevent all of these simulations continuing beyond the end of the laser pulse to a point where the plasma might be considered to have thermalised. There is also a very clear numerical issue at the higher irradiances after the time when the laser 'hole-boring' has penetrated the PIC layer and 'fluid' electrons are being accelerated by the laser. An extreme example of this is shown in Figure 4.

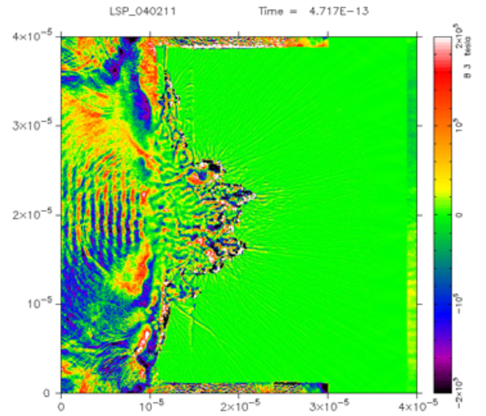

Figure 4. The B_z component of magnetic field after the laser has penetrated through the PIC layer.

All the LSP laser simulations we have carried out to date have used 20 cells per laser wavelength. Comparisons between implicit LSP and explicit OSIRIS in the 'PIC' region of the mesh with as far as possible identical simulation parameters show extremely good agreement at low densities but poor agreement for these high density high irradiance simulations. An example of the disagreement is the energy distribution of the accelerated electrons as shown in Figure 5. The disagreement also shows in the rate of 'hole boring' observed in LSP and OSIRIS at nominally the same irradiance.

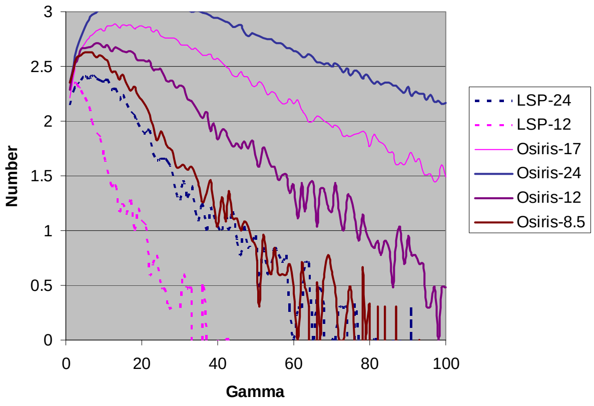

Figure 5. Energy distributions of the accelerated electrons in runs of LSP and OSIRIS at different values of laser intensity a_0 as indicated in the key.

Preliminary work shows that the discrepancy between implicit LSP and explicit OSIRIS is not removed by carrying out simulations at higher resolution. There may be an issue with boundary conditions in LSP associated with the laser input but this needs further clarification.

References

1. A R Bell, J R Davies, S Guerin, and H Ruhl,
   Plasma Physics and Controlled Fusion 39, 653 (1997)
2. L Gremillet, G Bonnaud and F Amiranoff,
   Physics of Plasmas 9, 941 (2002)
3. R G Evans *et al.*,
   Applied Phys Lett 86, 191505 (2005)
4. R B Campbell, R Kodama, T A Mehlorn, K A Tanaka, D R Welch,
   Phys Rev Lett 94, 055001 (2005)
5. D R Welch, D V Rose, B V Oliver, and R E Clark,
   Nucl. Instrum. Methods Phys. Res. A 464, 134 (2001)