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Integrated modelling framework for short pulse high energy density physics experiments

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Abstract. Modelling experimental campaigns on the Orion laser at AWE, and developing a viable point-design for fast ignition (FI), calls for a multi-scale approach; a complete description of the problem would require an extensive range of physics which cannot realistically be included in a single code. For modelling the laser-plasma interaction (LPI) we need a fine mesh which can capture the dispersion of electromagnetic waves, and a kinetic model for each plasma species. In the dense material of the bulk target, away from the LPI region, collisional physics dominates. The transport of hot particles generated by the action of the laser is dependent on their slowing and stopping in the dense material and their need to draw a return current. These effects will heat the target, which in turn influences transport. On longer timescales, the hydrodynamic response of the target will begin to play a role as the pressure generated from isochoric heating begins to take effect. Recent effort at AWE [1] has focussed on the development of an integrated code suite based on: the particle in cell code EPOCH, to model LPI; the Monte-Carlo electron transport code THOR, to model the onward transport of hot electrons; and the radiation hydrodynamics code CORVUS, to model the hydrodynamic response of the target. We outline the methodology adopted, elucidate on the advantages of a robustly integrated code suite compared to a single code approach, demonstrate the integrated code suite's application to modelling the heating of buried layers on Orion, and assess the potential of such experiments for the validation of modelling capability in advance of more ambitious HEDP experiments, as a step towards a predictive modelling capability for FI.

1. Integrated Modelling

The use of short pulse lasers to heat materials to high temperatures in order to study their properties has been a key part of the laser programme at AWE for some time – both on the HELEN laser [2, 3] and, more recently, the more energetic Orion laser [4, 5]. The compression of material by long pulses prior to heating offers an opportunity to study a broad range of temperatures and densities in the laboratory. A complete description of an Orion experiment requires an extensive range of physics, including: accurate treatment of Maxwell's equations and kinetic effects where the laser is absorbed; collisional effects for the onward transport of the fast particles generated, including return current effects; and hydrodynamic response in the dense target, using an appropriate equation of state (EOS).

We have tools available to model these key aspects: EPOCH – a massively parallel, relativistic electromagnetic particle in cell (PIC) code for modelling laser-plasma interaction; THOR – a Monte-Carlo fast electron transport code for modelling hot electron energy deposition in dense plasmas; CORVUS – an ALE radiation hydrodynamics code, with an extensive suite of physics packages available, for modelling hydrodynamic compression, laser pre-pulse, and target evolution following the short pulse energy deposition.

Since combining all of the required physics in one code is not practical, or tractable with existing (and anticipated) HPC, we link our kinetic, transport and hydro-codes together (see figure 1) to provide an integrated modelling capability. Our aim is to prepare a robust tool for high energy density physics (HEDP) research that will allow as much of the relevant physics to be modelled as possible.

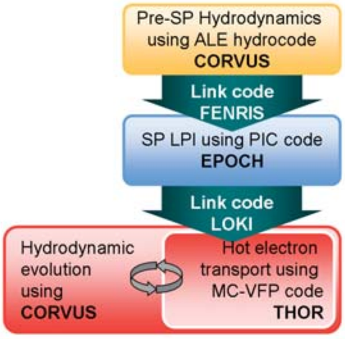


Figure 1. Integrated modelling framework. Hydrodynamic effects prior to the arrival of the short pulse are modelled in hydro-code CORVUS, which is linked to the PIC code EPOCH using the link code FENRIS. Hot electrons from EPOCH are fed back into CORVUS via the MC-VFP code THOR, using the link code LOKI, and their onward transport is captured by sub-cycling THOR within CORVUS

We use our modelling suite to study the heating of aluminium microdots buried 4 microns from the front of 10 micron diamond foils. Initially we consider only the action of the short pulse, before demonstrating the capability to model both compression and heating. The challenge of modelling the combination of both long and short pulse LPI, with fast electron transport through dense material and long time-scale hydrodynamic motion, has much in common with that of fast ignition (FI). Experiments on systems such as Orion offer an opportunity to refine and test modelling capabilities required for developing FI point designs in the future.

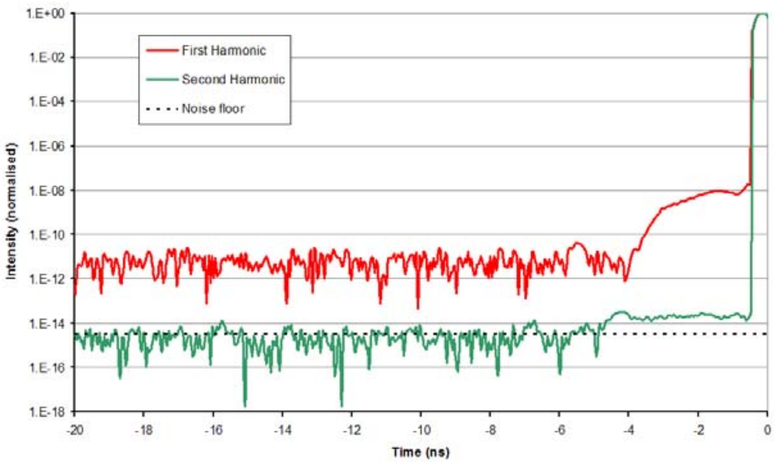


Figure 2. Measured pre-pulse from the first and second harmonic short-pulse beams on Orion.

2. The Orion Pre-pulse

Each of Orion's two petawatt beamlines can deliver a peak intensity of ~10^{21}Wcm^{-2} and in excess of 500J in the first harmonic ("red" light). One beamline can be converted to deliver in excess of 100J in the second harmonic ("green" light), using a sub aperture 3mm thick KDP crystal. Measurements taken using a two-photodiode pre-pulse monitor (see figure 2) indicate a 3-4 ns pedestal [6] due to parametric fluorescence in the OPA. Results indicate a contrast of approximately 10^8 in the first harmonic and 10^{14} for the second harmonic. The laser package in CORVUS was configured to deliver the recorded red pre-pulse to target, see figure 3. CORVUS density and temperature profiles are then mapped onto EPOCH's Eulerian mesh using the link code FENRIS.

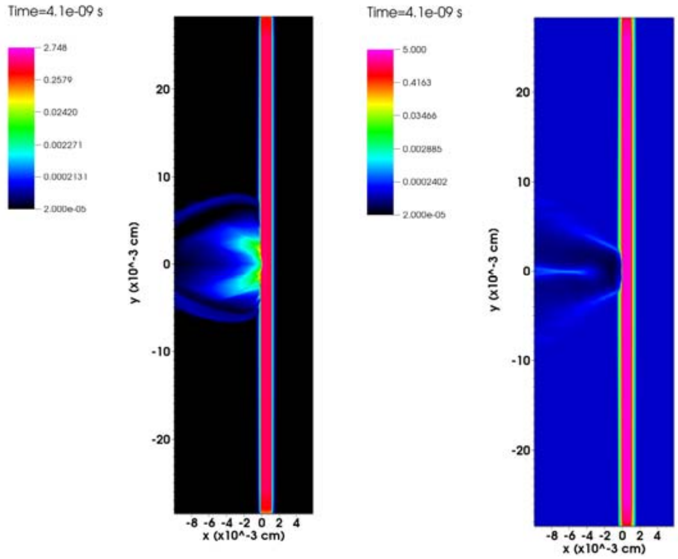


Figure 3. Density profiles for plastic (left) and diamond (right) foils, with buried Al microdots, following the pre-pulse.

3. Laser plasma interaction modelling

EPOCH was used to model the interaction of the main pulse with the plasma profile generated from the pre-pulse modelling performed in CORVUS. A 500J, red, 0.5ps (full width half maximum) pulse was focussed to a 10μm spot and angled at 20° to target normal. The hot electron spectra generated are captured by a particle probe placed at solid density, behind the laser interaction region. The link code LOKI generates a time-resolved source distribution function in (*y*, *E*,) from the probe data which is passed to the transport code THOR.

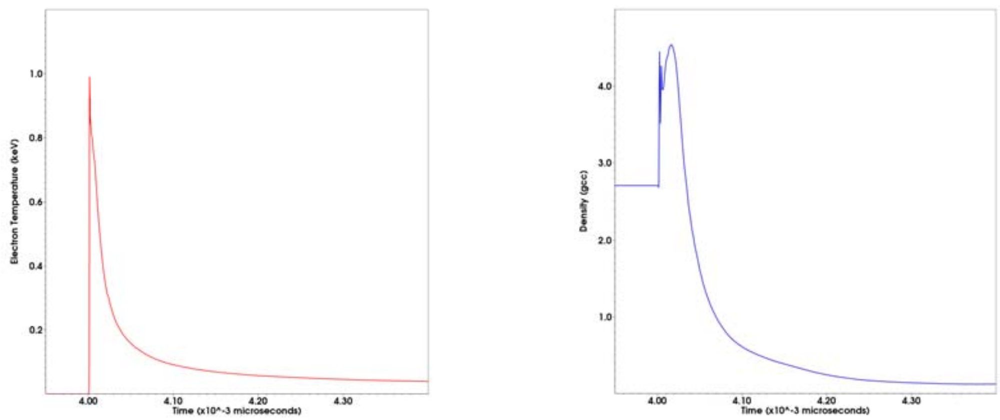


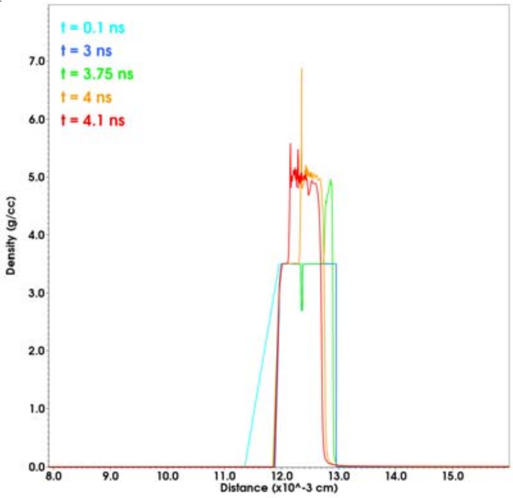
Figure 4. Temperature (left) and density (right) histories for a single cell at the centre of the aluminium sample.

4. Transport modelling

CORVUS modelling, using THOR for hot electron transport, shows the Al sample reaching a temperature close to 1 keV at a density in excess of 4 g/cc (see figure 4). There is little bulk hydrodynamic motion during the heating phase. However, capturing the long timescale evolution of the target as the heated material expands necessitates the integration of a robust fast electron transport model within a hydrodynamic framework.

5. Long pulse compression

The rear surface of the diamond buried-microdot target was illuminated by 500J of third harmonic ("blue" light) long-pulse energy over ~1ns. Ablation drives a shock into the target which compresses the Al (see figure 5), achieving a peak density of ~7g/cc, falling to ~5.5 g/cc by the time the shock reaches the front of the target. Using THOR, sub-cycling within CORVUS, with an EPOCH generated source distribution to model the effect of short pulse heating, starting at 4ns, close to peak density, temperatures of ~800eV at densities ~7g/cc can be achieved, with higher densities likely with further optimisation.



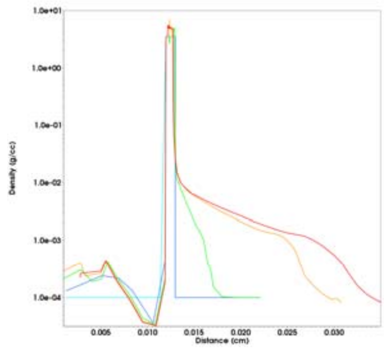


Figure 5. Linear (left) and log (above) density line-outs through the target at various times showing the generation of a pre-plasma at the front, a long scale length plasma at the rear, and a shock travelling through the target which compresses the sample.

6. Discussion

We have shown how an integrated modelling framework can be employed to simulate short and long pulse irradiated targets with an application to HEDP experiments. The use of explicit PIC sources in a hybrid code captures the distribution in energy and divergence angle, as well as the spatial and temporal evolution of the hot electron population, which is difficult to capture with a parameterized analytic form.

Coupling transport and hydrodynamic algorithms also confirmed that, over the timeframe of the short-pulse interaction, an isochoric approximation is often sufficient, as little hydrodynamic motion takes place. This means that a considerable quantity of modelling can be carried out using just THOR, drawing on the same set of EPOCH simulations for the hot electron source. This provides a flexible tool for designing and interpreting experiments which can be refined with further PIC simulations and augmented with bulk hydrodynamic motion as required. The isochoric approximation is less appropriate if pulses get longer and more energetic, as would be the case for many FI concepts and for HEDP experiments which utilize long-pulse beamlines, it is here that the integration of THOR into CORVUS comes to the fore.

The capability outlined here can already be applied to help design and interpret experiments; the efficacy of this approach will improve over time as HEDP campaigns progress. Continuing development of both the constituent codes and a refinement of the links between them, underwritten with new experimental data from facilities such as Orion will ensure that these nascent capabilities develop into a practical, predictive modelling tool which can help the design and interpretation of ever more ambitious HEDP experiments in the coming years.

References

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