Multi-scale modelling for HEDP experiments on Orion

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Abstract. The Orion laser at AWE couples high energy long-pulse lasers with high intensity short-pulses, allowing material to be compressed beyond solid density and heated isochorically. This experimental capability has been demonstrated as a platform for conducting High Energy Density Physics material properties experiments. A clear understanding of the physics in experiments at this scale, combined with a robust, flexible and predictive modelling capability, is an important step towards more complex experimental platforms and ICF schemes which rely on high power lasers to achieve ignition. These experiments present a significant modelling challenge, the system is characterised by hydrodynamic effects over nanoseconds, driven by long-pulse lasers or the pre-pulse of the petawatt beams, and fast electron generation, transport, and heating effects over picoseconds, driven by short-pulse high intensity lasers. We describe the approach taken at AWE; to integrate a number of codes which capture the detailed physics for each spatial and temporal scale. Simulations of the heating of buried aluminium microdot targets are discussed and we consider the role such tools can play in understanding the impact of changes to the laser parameters, such as frequency and pre-pulse, as well as understanding effects which are difficult to observe experimentally.

1. Orion and the need for integrated modelling
Orion is a purpose built laser facility for High Energy Density (HEDP) experiments at the Atomic Weapons Establishment (AWE) in the UK[1][2], consisting of ten long-pulse beams (optimized to ~1 ns pulse duration, each providing 500 J at a wavelength of 351 nm) and two short-pulse beams (each ~500J in 0.5 ps at 1054 nm). Orion also has the option for frequency doubling one of the short-pulse beams to enhance the pulse temporal contrast[3], which we demonstrate here has a significant impact on the coupling of short-pulse energy into the target. One of the primary uses of Orion has been in the study of high-density, high-temperature plasma properties such as opacity and equation of state; the first data shots from the facility studied the material properties of dense plasmas created by a combination of short-pulse laser heating and compression by laser driven shocks[4]. Aluminum samples buried in plastic or diamond foils, compressed to densities ranging from 1 to 10 g/cc were heated to electron temperatures between 500 and 700 eV, and the plasma conditions diagnosed by K-shell emission spectroscopy.

Modelling these experimental campaigns calls for a multi-scale approach. The laser–plasma interaction (LPI) requires a kinetic description of the plasma and a mesh capable of resolving the dispersion of EM waves. The dense material of the bulk target, away from the LPI region, is dominated by collisional physics where the transport of hot particles generated by LPI is governed by their slowing and stopping in the dense material and their need to draw a return current. On longer timescales, the hydrodynamic response of the target to the compression beam (initially) and the pressure generated from isochoric heating (at late times) must be handled with a radiation hydrodynamic model. The approach taken at AWE has been to integrate a number of codes which capture the detailed physics for each spatial...
and temporal scale[5]: the PIC code EPOCH[6] for modelling the short-pulse LPI; the Monte-Carlo hybrid code THOR for modelling fast-particle transport through dense plasma; and the radiation hydrodynamics code CORVUS, which captures long-pulse physics, long timescale hydrodynamic effects and radiation transport.

2. **First and second harmonic irradiation of diamond and plastic**

We consider both diamond and plastic targets, with buried aluminium microdots, of the type used in [4]. These are compressed with 300J of third harmonic (i.e. 351 nm) light from one of Orion’s long-pulse beams and heated with one of the short-pulse beams. The inter-beam timing is such that the shock driven into the target by the long-pulse has not broken out by the time the heating pulse arrives. This timing is somewhat conservative, we do not aim to heat at the point of peak density which occurs as the shock arrives at the material sample as this would not be practical, or reproducible, in experiment. A short-pulse pre-pulse, based on Orion measurements[2], is applied to the front of the target. The density and temperature profiles are mapped to EPOCH where the main short-pulse interaction is modelled.

Considering first 500 J at $1\omega$ in a 27.4 $\mu$m FWHM Gaussian spot with a 700 fs FWHM supergaussian pulse incident on a diamond target.

**Figure 1.** EPOCH generated energy distributions for the interaction of 500J of $1\omega$ (left) and 100J of in $2\omega$ (right) light with the pre-plasma generated by the laser pre-pulse. The distribution is not characterized by a single temperature.

**Figure 2.** Density and temperature history for an aluminium microdot target. Left: a diamond target compressed with a third harmonic long-pulse and heated with 500 J of $1\omega$ light. Right: a plastic target similarly compressed but heated with 100J of $2\omega$ light.

Figure 1 shows the modelled time-integrated energy spectrum of the hot electrons generated by the short-pulse LPI. Simulations also indicate a high divergence (~50% of the hot electrons fall within a half-angle of 49°), it is worth noting that the high divergence of the hot electron source could lead to the generation of an x-ray spot larger than the laser spot or the effective hot electron source. Figure 2a shows the density and temperature history for the aluminium microdot. Shock compression of the sample drives it to densities in excess of 10 g/cc, but the average temperature of the aluminium peaks at just 250 eV.

The use of $2\omega$ short-pulses during the material properties campaigns on Orion, and its predecessor HELEN, has proven very effective at heating buried layer and buried microdot target. The low pre-pulse, a side-effect of the frequency doubling process, generates less pre-plasma accordingly. Combined

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with the higher critical density for green light, this helps to couple the incident beam to the target plasma at a higher density, resulting in a colder fast electron spectrum which is better able to deposit its energy in the target over the spatial scales of interest. The conversion from \(1\omega\) to \(2\omega\) comes at a cost in total energy, with approximately 100 J delivered to target. We consider a 0.2 \(\mu\)m thick aluminium microdot mounted in 10 \(\mu\)m of plastic. CORVUS modelling shows the lower pre-pulse does reduce the level of pre-plasma. Short-pulse LPI modelling in EPOCH shows that the hot electron spectrum is much colder in the \(2\omega\) case (see Figure 1). Figure 2b shows the temperature and density history of the microdot. A peak density in excess of 10 g/cc is achieved, however the average density in the layer when the heating pulse arrives is closer to 5 g/cc. The density of the sample begins to fall as the layer heats and expands, the lower density plastic proving a less effective tamper than the diamond which provides a higher pressure to resist the layer expansion. Adjusting the timing to ensure that the short-pulse heating occurs on the rising edge of the shock could help mitigate this effect, but as discussed above the shock timing is chosen to reflect experimental practicalities. A peak (spatially averaged) temperature of 600 eV is achieved at a density of ~4.5 g/cc. These results are consistent with those seen in experiments [4]

![Figure 3](image_url). Hot electron spectra from EPOCH for interaction of a 500J, \(1\omega\), 700 fs short-pulse beam with pre-plasma conditions modelled in CORVUS. Moving from contrast levels of \(~10^7\) (left) to high contrast \(~10^{10}\) operation using the SPOPA front end (centre) removes the high energy tail of the electron distribution. Adopting pre-plasma conditions equivalent to those experienced with \(2\omega\) operation (a contrast of \(~10^{14}\)) has a relatively small impact on the hot electron spectrum (right).

The poor coupling between the heating beam and the material sample observed (both in experiments and in modelling) in the case of \(1\omega\) light, relative to \(2\omega\), may be due to the high energy tail in the electron distribution. The highest energy electrons are generated from the interaction with the diffuse pre-plasma generated by the laser pre-pulse. Improvements to the Orion front-end can now deliver significantly higher \(1\omega\) contrast – modelling suggests that this has a significant impact on the energy spectrum of hot electrons generated (see Figure 3). However, there may not be much scope for improvement through further increases in contrast. In all the cases discussed here, the improvements to the pre-plasma conditions and the cooling of the electron spectrum do not make a significant impact on the coupling to the material sample. While the effect of changes to the pre-plasma in these cases has brought dramatic changes to tail of the distribution, the bulk remains largely unaffected. Combined with the experimental and modelling results for \(2\omega\), this suggests that planned uplifts in Orion’s \(2\omega\) capabilities may be the best route to further improvements in target heating.

The results summarized in Figure 2 take max, min and spatially averaged values for density and temperature over the material sample at each point in time. From these time histories, it is clear that there are variations over the sample observed in both quantities. These variations appear to be the result of transverse gradients in the plasma conditions of the layer (see Figure 4). Until recently, it has not been possible to observe gradients experimentally, but the recent development of a spatial-imaging spectrometer on Orion has produced results which appear to indicate the presence of spatial temperature gradients in targets with a buried scandium microdot, in the case where the laser focus is smaller than the microdot. While defocused laser spots are often employed, resulting in a spot radius comparable or greater than the microdot, these effects merit further study - in particular it will be important to
understand what impact, if any, the presence of transverse gradients could have on the plasma conditions inferred from both the streaked and time integrated spectroscopy – detailed post-processing of CORVUS simulations with detailed atomic physics codes will be required.

3. Discussion
Since becoming operational, Orion has enabled AWE to conduct an extensive series of HEDP material properties experiments to study plasmas at high temperatures and densities. These campaigns have utilized Orion’s most notable capabilities – its combination of short and long-pulse beamlines, and ability to deliver second harmonic high intensity pulses. These experiments place challenging requirements on modelling – as any campaign attempting to marry such a range of spatial scales, temporal scales, densities and energies would. Here we have outlined AWE’s integrated modelling approach which builds on in-house radiation hydrodynamics capability and collaborative work with the broader community on PIC modelling. The results discussed here are consistent with the early Orion experiments, in particular the observed variation between heating with 1 and 2ω light, which has proven difficult to reproduce in simulations to date. In future advances like the spatial imaging spectrometer, improvements to the fidelity of the diagnostics and the use of a broader range of material samples, which helps to provide a more reliable ‘thermometer’, will facilitate direct comparison between the modelling and experiment. At the same time, short-pulse capability campaigns on Orion will offer a means to study short-pulse LPI in detail to help build confidence in the modelling approach.

Developing and exercising a modelling capability to address these challenges is essential for understanding the physics, for example diagnosing the impact of effects which are difficult to diagnose experimentally, and facilitating the development of more ambitious platforms in future. Orion-scale HEDP modelling and experiments offers an opportunity to: study material properties under extreme conditions; interrogate fast electron properties, and study the impact of changes to laser and plasma conditions; and provide an essential route to building confidence in the multiscale modelling capability required for many alternative ignition schemes.

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