The Early Years of Indirect Drive Development for High Energy Density Physics Experiments at AWE.

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Abstract. The importance of laser driven indirect drive for high energy density physics experiments was recognised at AWE in 1971. The two beam 1TW HELEN laser was procured to work in this area and experiments with this system began in 1980. Early experiments in hohlraum coupling and performance scaling with both 1.06 \( \mu \)m and 0.53 \( \mu \)m will be described together with experiments specifically designed to confirm the understanding of radiation wave propagation, hohlraum heating and hohlraum plasma filling. The use of indirect drive for early experiments to study spherical and cylindrical implosions, opacity, EOS, mix and planar radiation hydrodynamics experiments will also be described.

1. Introduction
The potential benefits of using indirect drive laser targets for high energy density physics experiments was recognised at AWE in 1971. Subsequently the ≈1 TW 2 beam 1.06\( \mu \)m HELEN laser was procured for this purpose and an extensive set of experiments was begun in 1980, although some earlier relevant experiments had been conducted on smaller facilities. This talk is principally concerned with describing some of the work carried out between 1980 and 1990, most of which has been previously unpublished.

2. Hohlraum performance scaling
Hohlraum characterisation studies began in 1981. Since then many configurations have been studied on HELEN, initially using 1.06\( \mu \)m light, but mostly using 0.53\( \mu \)m. Two examples dating from the earliest period are shown in figure 1. The principal hohlraum temperature measurement was based on using an array of X-ray diodes, but a comprehensive set of other diagnostics (X-ray imaging, absorption, hard X-ray/fast electrons, X-ray spectroscopy, witness plate shock breakout) was employed. From the beginning we developed analytic models for hohlraum heating based on radiation driven heat loss to the walls and X-ray energy loss through the filling holes. These were similar to those published elsewhere [1, 2]. Good agreement between energy balance and power balance is obtained as long as the energy balance equation is adjusted as follows.

If \( E_X \) is the laser energy converted to X-rays, \( T_w \) is the temperature of the wall surface and \( T_D \) the drive temperature characterising the flux on the wall [1] we have :-

\[
E_X = \int F \cdot A_w \cdot \, dt + \int \sigma T_D^4 A_{ph} \cdot \, dt
\]  

(1)

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where $F$ is the X-ray flux into the walls per unit area and $A_w$, $A_{PH}$ the hohlraum wall and pinhole areas respectively.

\[ 1.06 \mu m \times 10^{-100} J \times 130 \text{ps} \]

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\[ 250 \mu m \times 250 \mu m \]

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**Figure 1.** Schematic of and hohlraum temperature scaling data for (a) single and (b) double stage hohlraums.

Since the flux at the wall boundary is

\[ \sigma T_w^4 = \frac{1}{2} \left[ \sigma T_D^4 + \alpha \sigma T_D^4 \right] \tag{2} \]

where $\alpha$ is the albedo and

\[ F = (1 - \alpha) \sigma T_D^4 \tag{3} \]

it follows that

\[ \sigma T_D^4 = \sigma T_w^4 + F/2 \tag{4} \]

Equation (4) can be used to substitute for $T_D$ in (1).

Solving the diffusion equation for $F$ [1], we currently use, for a wall temperature rising such that

\[ \frac{T(t)}{T_{\text{max}}} = \left( \frac{t}{t_p} \right)^p \tag{5} \]

\[ E_X = \frac{0.34(1 + 4p)^{0.5}}{(3.35p + 0.59)} T_w^{3.35} t_p^{0.59} \left[ A_w + \frac{A_{PH}}{2} \right] + \frac{T_w^4 A_{PH} t_p}{(1 + 4p)} \tag{6} \]

where $E_X$ is in hundreds of J, $T_w$ in hundreds of eV, $t_p$ is the pulse length in ns and the areas are in mm$^2$. In solving for hohlraum performance the biggest uncertainty is usually in the choice of X-ray conversion efficiency. Theory, disc data and simulations act as a guide.

In the 1.06μm target shown in figure 1a there is little laser light absorption at first bounce and the X-ray diagnostic should be measuring something close to $T_D$. We have plotted this parameter in the figure. Two stage hohlraum performance can be predicted by calculating the net flux passing through the gap between the primary and secondary compartments. In the two-stage 0.53μm target shown in
We have compared the measurements with the calculated wall brightness temperatures defined as $T_b = \alpha^{0.25} T_D$. We also show model predictions for primary drive and wall surface temperature. These are in exact agreement with simulations performed using the AWE radiation-hydrodynamics code NYM, a Lagrangian code, typically run with 110 group implicit Monte Carlo (IMC) radiation transport and flux-limited electron thermal conduction [3]. As one might expect the experimental measurement matches $T_b$ in the secondary but records a somewhat higher ‘temperature’ in the primary.

In these early experiments, especially with 1.06$\mu$m light, we found a considerable fraction of the laser energy appeared as energetic electrons. The number and temperature of the hot electrons was deduced using a multi channel filter fluorescer system measuring the hard x-ray bremsstrahlung spectrum. This fraction was associated with the degree of hohlraum filling by plasma ablated from the walls. On the assumption that laser light scattered around the walls of the hohlraum it was possible to estimate the time taken for the hohlraum to fill to $\approx 0.1$ times critical density by hot coronal plasma. Assuming a square laser pulse and an isothermal plasma with convergence the electron density as a function of radius is rather flat at this time offering a fertile plasma for the growth of Raman instability. Filling depends on hohlraum size, geometry, laser energy, pulse length, wavelength, pulse shape and the fraction of wall irradiated. It can be shown:

$$t_{\text{FILL}} = \left( \frac{A^2 t_p}{CE\lambda^2} \right)^{1/2}$$  \hspace{1cm} (7)

where $C$ is a constant depending on the configuration and $E$ is the absorbed laser energy. If the fraction of energy into hot electrons is $\frac{1}{2} \left( t_p - t_{\text{FILL}} \right)$ we find this model agrees qualitatively with experiment (see figure 2). Similar results were obtained at LLNL using a similar model developed by Lindl [2].

![Figure 2](image_url)

Figure 2. Schematic of and data from experiments to explore hot electron production

At shorter wavelength (higher critical densities) smaller targets can be used and filling is usually dominated by cooler X-ray ablated wall material, especially if not all the hohlraum wall is directly irradiated. In this case, because the scale length associated with this process is smaller, filling to $\approx 0.1$ critical density near the hohlraum axis is associated with considerable movement of the critical density surface away from the hohlraum wall. For this situation we have used a different filling criterion viz that the critical surface moves in $\approx 0.15r$, where $r$ is the hohlraum radius. In this case we assume an isothermal expansion at the hohlraum radiation temperature. The temperature and mass of the x-ray
ablated wall material are linked to the laser energy by the hohlraum radiation diffusion models. The density at the front of the radiation wave is assumed to be the mass ablated divided by the isothermal scale length and hence the position of the critical density surface can be calculated.

Combining temperature scaling and filling models we arrived at a set of performance curves for ‘well behaved’ conventional hohlraums as shown in figures 3 and 4. For the examples shown 2-beam cylindrical hohlraums of aspect ratio 1:1.7 (diameter:length) were assumed with about 25% of the cylindrical barrel directly illuminated. Analytic filling and temperature predictions are in good agreement with simulations.

![Figure 3](image)

**Figure 3.** Hohlraum Performance curves for 0.53µm

![Figure 4](image)

**Figure 4.** Hohlraum Performance curves for 0.35µm

Note that the overfilling does not necessarily result in hot electron generation nor does low filling guarantee the avoidance of parametric instabilities in large hohlraums. This will depend on the balance of LPI processes. Too much filling does, however, complicate the design of hohlraums for clean experiments. Since the mid-1980’s hohlraum performance curves, together with view factor analysis, have guided our thinking on what size laser is needed for a given task and they have been a strong driver to move to shorter wavelength.

3. Hohlraum Energetics

![Figure 5](image)

**Figure 5.** Lead foam burn-through experiment

To check our modelling of hohlraum wall loss we performed an experiment in 1983 in which ≈ 100µm thick lead slabs at a density of ≈ 0.1 g/cm³ were directly irradiated by 300ps 1.06µm laser pulses at 10¹⁴-10¹⁵ W/cm². The supersonic energy transport through the lead foam is dominated by radiation. The lead foam layers were mounted in gold washers as shown in figure 5. Each individual foam target was well characterised in terms of thickness, density and uniformity. The foam pore size was 1-2µm. X-ray diode systems were used to measure the front surface emission and to time and measure the X-ray emission from the rear surface at two different angles as shown in figure 5. The rear surface X-ray
diodes were fitted with grazing incidence mirrors so as to only observe X-ray emission at photon energies \(<500\text{eV}\). This was to avoid direct shine through the samples by harder X-rays. Front and rear surface X-ray imaging and box calorimeter measurements were used to constrain the 2D modelling. Good agreement was obtained between simulation and experiment as shown in figure 6. Similar relevant experiments have been performed elsewhere [4].

Figure 6. Results from the Lead foam burn-through experiments.

As a further check on our hohlraum modelling, we irradiated a simple cylindrical hohlraum with thin gold end caps 1.55\(\mu\text{m}\) and 2.43\(\mu\text{m}\) thick. The LEH was in the curved wall of the hohlraum and the acceleration of the cylinder ends was monitored with a streak camera as shown in figure 7. One can think of the experiment as having two unknowns which influence the acceleration, the X-ray drive and the mass of layer ablated. By fitting the motion of both ends we must be calculating both correctly. A number of experiments were performed and agreement was good in each case. An example is shown in figure 8. We have shown the effect of changing the gold opacity by a factor of 2 to indicate the sensitivity to code parameters.

Figure 7. Thin wall acceleration experiment.

Figure 8. Results from thin wall acceleration experiment.

A third set of experiments was aimed at confirming our understanding of coronal laser plasma expansion in confined geometry. This 1984 experiment used low-Z cavities (plastic or glass) in which
the time integrated K-shell emission from aluminium tracers was imaged using KB X-ray microscopy. Many one and two stage hohlraum configurations were studied using both 1.06μm and 0.53μm light. An example is shown in figure 9. The influence of wall blow-in on plasma flow lines is clearly evident, together with some degree of plasma interpenetration before final stagnation.

![Figure 9](image)

**Figure 9.** Coronal expansion in confined geometry. In the simulation result, blue represents emission from the Al wires

4. Early Capsule Implosions

In 1982 we performed a series of experiments to measure neutron yield from the thin-walled (~1μm) DT filled (~10atm) glass microballoons imploded by both direct and indirect drive. The indirect drive configurations employed are shown in figure 10. The neutron diagnostics included a TOF detector, a copper activation system and a sensitive (~10^3 neutrons) capture detector using a gadolinium doped scintillator. Moderated neutrons diffuse until captured by the Gd releasing γ-rays. Other diagnostics included X-ray diodes, X-ray microscopy and a filter fluorescer system to measure hard X-rays/fast electrons, a box calorimeter and an α-particle track etch detector (which only worked for direct drive; no α’s escaped hohlraum targets).

Neutrons were obtained from each configuration. Measured hohlraum temperatures were consistent with simulations. Filter-fluorescer measurements showed up to some tens of percent of the absorbed laser energy went into hot electrons. Since their transport around the target was not well understood and their energy coupling to the capsule was poor we simply subtracted their energy from the laser energy for the simulations although one reason for shooting the various target types was to clarify the role of X-rays, laser light and electrons on the implosions.

![Figure 10](image)

**Figure 10.** Indirect drive implosions: Indirect drive target configurations. Capsule 50-80μm. Primary cavities 0.25mm x 0.25mm, secondaries 0.25mm x 0.125mm. Laser drive 130ps long and λ=1.06μm. The capsules are shown in blue, gold foils in yellow and the plastic barriers as dashed lines.
Calculated and measured neutron yields are shown in table 1. The calculated yields do not take into account loss of the faster DT ions from the compressed fuel due to its low $\rho r$. An analytic estimate implies this is a small effect at the low DT ion temperatures achieved ($\sim 1$-2 keV).

| Experiment | Capsule diam $\mu m$ | Yield (Simulation) | Energy on target |
|------------|----------------------|--------------------|------------------|
| 1a         | 56                   | $4.95 \times 10^5$ | 144J             |
| 1b         | 85                   | $1.49 \times 10^6$ | 179J             |
| 2          | 53                   | $1.69 \times 10^5$ | 151J             |
| 3          | 57                   | $7 \times 10^3$    | 164J             |
| 4          | 53                   | $7 \times 10^4$    | 160J             |
| 5          | 56                   | $1 \times 10^4$    | 182J             |

In one target we captured an X-ray microscopy image of the implosion which showed a much smaller compressed core than for direct drive shots (see figure 11) and good symmetry.

These implosions all operated in the exploding pusher mode. The HELEN laser is too small to pursue low adiabat indirect drive implosions. Subsequent capsule implosion shots on HELEN (from 1983 onwards) concentrated on studying the effects of drive asymmetry or capsule imperfections.

To study implosion dynamics and stability we resorted to cylindrical implosions from 1983. A unique hohlraum geometry was developed to allow symmetrical implosion plus backlighting with only two laser beams (see figure 12). Implosions produced by this system were quite uniform (see figure 13), the cylinders were all of 150 $\mu m$ diameter, 12 $\mu m$ walls with 50 $\mu m$ CH end-caps. Some were empty and some filled with 0.05 g cm$^{-3}$ plastic foam. Some preliminary work was done on the implosion of rippled cylinders in which we observed amplitude growth and jetting in approximate agreement with simulations (see figure 14). (The result shown was obtained with a slightly different hohlraum to that shown in figure 12 with less good drive uniformity). This work was subsequently moved to NOVA in collaboration with LANL [5].

**Figure 11.** X-ray microscope image of IBIS implosion.

**Figure 12.** Annular beam implosion target.
5. High Energy Density Physics Experiments

AWE pioneered the use of indirect drive for the study of opacity, equation-of-state and mix experiments. The techniques we evolved have now become standard.

Point projection absorption spectroscopy to measure the opacity of thin samples mounted within two-stage hohlraums was first used on HELEN in 1983 [6]. Many such experiments have subsequently been performed both at AWE and at other facilities [7,8]. Streaked backlighting was also used as a density diagnostic in these experiments.

![Figure 13. Backlit image of plastic cylinder of inner radius 75 μm and wall thickness 12 μm when r= 36 μm.](image)

![Figure 14. Simulation and data for the implosion of a modulated cylinder](image)

Indirect drive measurements to measure EOS by the impedance match method were commenced in the mid-eighties but it took several years for drive uniformity, preheat and sample quality to be improved to the point where good data could be obtained routinely [9,10].

Point projection spectroscopy was also used as a diagnostic to study mixing in accelerated two-layer targets from 1982. This experiment was also taken to NOVA [11, 12].

A frequent problem for planar radiation hydrodynamics experiments (especially if sidelighting or backlighting is to be employed) is that of keeping the sample flat after it leaves the hohlraum. Considerable effort was expended in the mid-eighties on the study of different mounting configurations to avoid ‘dishing’ and reduce edge effects. For impulses which are not too long one technique which works quite well is the so-called ‘top hat’ configuration shown in figure 15. The ablator covers a wider area than the sample so the shock remains flat as it penetrates the latter with minimal edge effects. When the sample emerges it is flat except for some minor decompression at the edge which can be modelled well by codes. This can be further reduced by the use of a transparent barrel down which the foil is driven. A large number of experiments to study the hydrodynamic
behave the complex multilayer structures have been performed on HELEN and other systems using these ideas.

Figure 15. Schematic (a), data (b) & simulation (c) for the ‘tophat’ design of planar foil experiments.

In general the gross hydrodynamics can be well reproduced as indicated in the example shown in figure 16 of an experiment conducted in 1989. Here the original intention was to provide a gently rising pressure drive at the witness plate for adiabatic compression experiments. In practice we found that expanding material from the ablator collided with the directly driven converter disc to produce a second shock. An optical streak camera looking down the barrel recorded the lighting up of the witness plate, its lateral expansion when its rear surface reached the end of the barrel and faster lateral expansion when the ablating plasma reached this point. Combined hohlraum and hydrodynamic modelling correctly predicted the time sequence of these events (see figure 16).

Figure 16. An example of a multilayer, complex rad-hydro experiment.

6. More recent hohlraum developments
As indicated in section 2 the performance of conservatively designed empty laser-driven gold hohlraums is quite well understood. Similar ideas can be used to estimate the performance of more marginal designs or those filled with gas. It is also possible, in theory, to enhance performance by
carefully selecting either the wall material or using lower density gold walls [13]. In addition, there appears to be a regime, using small targets, where the hohlraum stays open by virtue of the hot laser produced plasma corona holding back the colder X-ray ablated wall. High temperatures can be obtained in a small volume with little generation of SRS or SBS instabilities (as observed experimentally), probably because the density gradient near critical density is very steep [14]. AWE is working in each of these areas.

AWE is currently constructing the Orion laser which will provide >5 TW at 0.35μm in 10 long pulse beams and 2 PW in two short pulse beams (initially at 1.06μm). It is expected that the combination of long and short pulse beams will allow us to use the short pulses to heat matter pre-compressed by the long pulse beams and also to use the short pulses to create harder backlighters with improved spatial and temporal resolution.

Inevitably we have been considering the use of short pulse lasers for indirect drive. Predictions are complicated by uncertain coupling physics of high intensity pulses to high-Z material and applications limited by the low impulse such targets are likely to deliver. One more promising idea we are exploring we are calling ‘boosted hohlraums’. It is well known that short pulse heating of solid targets can briefly produce pressures ~1Gbar. The ‘boosted’ hohlraum idea is to irradiate part of the hohlraum wall with a short pulse, or train of short pulses, so as to produce a high pressure drive after a long pulse has provided a conventional hohlraum ‘foot pulse’ to allow penetration of an assembly by the first shock. The long pulse driven high-Z wall blow off helps to enhance collisional absorption of the short pulse at near critical density and electron thermal conduction and radiation transport rapidly couple the absorbed energy into the denser wall. 2D simulations show it is possible to transmit the short pulse energy through the hohlraum.

There are a number of potential applications. One is shown in figure 17. A 1.12mm x 1.95mm hohlraum is driven by a 2.5kJ, 0.35μm, 500ps long pulse and then a 5ps, 10¹⁸Wcm⁻² short pulse is injected. The back wall of the hohlraum (initially 10μm of gold) is accelerated to ~10⁷ cm s⁻¹ and collides with a copper slab so as to produce a pressure pulse >100Mb remaining approximately constant over 400ps and potentially allowing high pressure impedance match EOS studies. Of course more work needs to be done to properly understand the short pulse coupling physics and to ensure edge effects and preheat can be controlled.

![Figure 17. A possible boosted hohlraum EoS experiment.](image_url)

7. Conclusions
We have been performing indirect drive experiments at AWE for more than 30 years. In general, the gross features of such experiments are well fitted by simulations and analytic models. This means experiments can be used to measure less well understood aspects of radiation hydrodynamics and material properties. The Orion laser will help us to extend the work to higher energy densities and develop experiments for mounting on even larger lasers.
Acknowledgements
This review has described the work of many at AWE. In particular, the major contributions made by John Foster, Norman Daly, Peter Fieldhouse, John Freeman, Steve Davidson, Tim Goldsack, Colin Smith and Steve Rothman should be acknowledged.

The author would like to thank John Morton, Mark Stevenson and Kenny Parker for helping recover and re-analyse old data and assemble this paper.

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