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Producing shock-ignition-like pressures by indirect drive

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The shock ignition scheme is an alternative Inertial Confinement Fusion ignition scheme that offers higher gains and a robustness to hydrodynamic instabilities. A desirable aspect of shock ignition is that the required intensities are achievable on existing facilities. Conventional approaches to shock ignition have only considered the use of direct laser drive. This is in part due to concerns that achieving the rapid rise in drive pressure needed in the final pressure spike may not be feasible using the indirect drive approach. The primary advantage of being able to utilise a hohlraum drive for a shock ignition experiment is that experiments could be carried out at existing, or soon to be completed, Mega-Joule scale facilities. Furthermore, this could be done without the need for any major modification to the facility architecture, such as would be required for direct drive experiments. One and two-dimensional radiation hydrodynamic simulations have been performed using the codes HYADES and h2d. The simulations investigated the level of x-ray fluxes that could produce shock ignition scale pressures as well as the laser powers that would be required to generate those pressures in a NIF scale-1 hohlraum. The second aspect of this work was to investigate the x-ray flux rise times that would be necessary to create a large enough shock ignition spike pressure (200-300 Mbar). It was found that pressures of 230 Mbar could be achieved through indirect drive using a laser source with a peak power of 400 TW. In addition, the rate of pressure increase in the final pressure spike is similar to the expected requirements for directly-driven shock ignition.

INTRODUCTION

In conventional Inertial Confinement Fusion (ICF), a series of shock-waves of gradually increasing strength are sent through the fuel, compressing it to a high density on a relatively low isentrope, and accelerating it to a high implosion velocity ($>350\,\mathrm{km\,s^{-1}}$). These shock-waves then coalesce and converge toward the centre of the capsule where the densities are lower. Ignition is triggered by the formation of a central hotspot driven by a combination of the high velocity dense shell doing work on the central region as it decelerates, and shock heating. The high implosion velocities and convergence ratios required by such conventional central hotspot (CHS) ignition schemes are susceptible to hydrodynamic instabilities that can prevent ignition. The shock ignition scheme separates the compression and ignition into two phases. The first phase is a compression similar to the conventional CHS scheme but with the use of a lower implosion velocity. Ignition is then triggered by a final much stronger shock that raises the fuel to ignition conditions. The use of lower implosion velocities and convergence ratios makes shock ignition more robust to hydrodynamic instabilities [1].

The shock ignition scheme uses the collision of a spherically imploding and exploding shock-wave to create a high-pressure, high-density region in the compressing shell. In both CHS and shock ignition, when the fuel begins to stagnate, a divergent shock-wave is created at the r=0 point which propagates outwards through the dense fuel. In shock ignition, the igniter shock is launched at a late stage in the implosion so as to collide with this divergent shock. The igniter shock is timed such that this shock-wave collision will occur near the inner edge of the imploding dense fuel, amplifying the pressure of the igniter shock and enabling the fuel to be raised to ignition conditions. Direct drive shock ignition pulses contain less energy than standard compression pulses, but may sometimes produce even higher yields. A detailed review of the state of shock ignition research is given by reference 1.

Previous work in the area of shock ignition has only considered the use of laser-driven direct drive. Currently, there are no spherical direct drive facilities that are close to the scale necessary for carrying out ignition scale experiments. The two existing ICF ignition scale facilities, the National Ignition Facility (NIF) and Laser Mega-Joule (LMJ) are both set up for indirect drive experiments. There are three potential approaches to conducting ignition-scale shock ignition experiments. The first would be to modify NIF or LMJ to a spherical direct drive geometry or build a new, dedicated facility. This would come at great financial cost and no such facility is currently planned. The second option would be to carry out shock ignition experiments at NIF or LMJ in a polar direct drive configuration. There have been proposals put forward to make these modifications [2][3]. Whilst these modifications are achievable, there are concerns that the potential for reduced drive uniformity will make it difficult to achieve a sufficiently symmetric implosion. The National Ignition Campaign highlighted low-mode asymmetry as a key barrier to ignition [4]. The final option, investigated here, would be to develop an indirect drive shock ignition scheme that could be tested using the current NIF and final LMJ set-ups. The primary motivation of the study described in this manuscript is to investigate whether ignition-scale shock ignition experiments can be carried out using existing indirect drive facilities. In this case the shock ignition scheme could be tested in the relatively near future, without the need to construct a new facility or modify an existing one. Furthermore, ignition designs based upon conventional high implosion velocity approaches have not yet been able to achieve ignition at the NIF, so it is interesting to consider other routes that could be explored. It is also noted that, whilst an indirect drive shock ignition scheme may offer the potential for some interesting experiments in the near term, it does not seem an ideal route from the standpoint of Inertial Fusion Energy (IFE). The 5-7 times enhanced laser to capsule coupling in direct drive makes it a more preferable driver in terms of energy efficiency. This is especially prevalent at the higher shock ignition intensities, where the hohlraum coupling efficiency is notably worse.

There are a number of apparent difficulties with an indirectly driven shock ignition scheme. There is a latency in the rise of the hohlraum temperature relative to the laser pulse. Reference 5 mentions that the heat capacity of the hohlraum can cause an appreciable time lag in the rise of the x-ray flux, but does not give a detailed qualification of this statement. This time lag may make it problematic to produce the sharp rise in the x-ray flux required to drive the igniter shock. This difficulty can be mitigated by increasing the laser power. However, the required laser intensities may then be above the threshold for the production of unacceptable levels of pre-heating electrons through parametric instabilities [6], or they may exceed those permitted by the performance characteristics of the laser. The combination of these issues makes it challenging to create a steep rise in the x-ray flux in a hohlraum which is already at a relatively high temperature.

This paper presents a study of the laser parameters required to generate the steep x-ray flux rises needed for shock ignition. A numerical study has been carried out using the one- and two-dimensional radiation hydrodynamics codes HYADES and h2d to investigate the requirements in terms of x-ray and laser driver intensities [7]. First an x-ray flux profile is developed that is able to produce a pressure profile matching that expected to be required for direct drive shock ignition using HYADES. Then a series of h2d simulations are carried out to estimate the corresponding laser powers that would be required to produce the same levels of x-ray flux. Finally, the temporal profile of the ignition spike is modified to achieve the necessary ignition shock pressure.

PRESSURE SCALING

This study used the laser profile from reference 8 as an example shock ignition drive profile; it is shown in figure 1. The power profile can be separated into two components: the compression pulse and the igniter pulse. The compression pulse consists of a low adiabat 4 ns foot at 0.5 TW. From 4-7.5 ns there is a Kidder-like [9, 10] rise

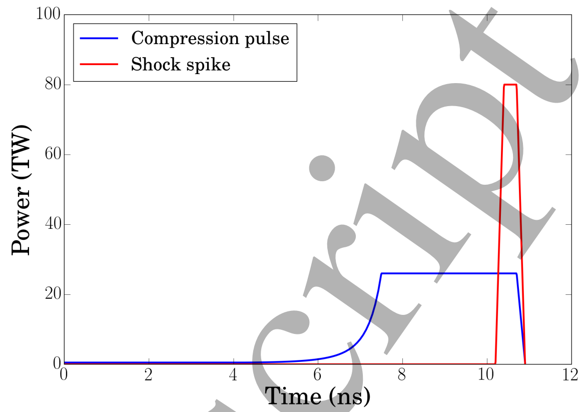


FIG. 1: The Ribeyre direct drive power deposition profile from reference 8 used to run shock ignition simulations

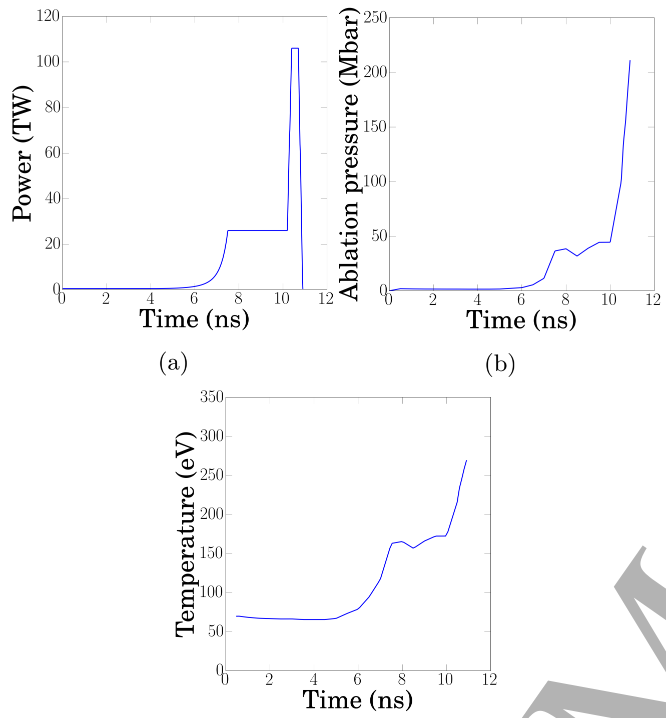
up to 26 TW. The igniter spike rise begins at 10.2 ns and at 10.4 ns peaks at a power of 80 TW which lasts until 10.7 ns before dropping. This power profile has successfully ignited a DT capsule in 1D radiation hydrodynamics simulations [8].

The ablation pressure profile produced by the Ribeyre shock ignition profile is found using the 1D radiation hydrodynamics code HYADES. The simulations in this work were run with electron transport handled by a flux-limited diffusion approximation with a flux limiter value of 0.06, SESAME equation of state, an average atom LTE ionization model and multi-group radiation diffusion. A 0.351 µm laser drives a spherical capsule with the power profile shown in figure 2a. The capsule used in that study was the HiPER baseline target design [11] of 833 µm DT gas with a 211 µm solid DT outer layer. The ablation pressure profile can be seen in figure 2b.

Scaling laws can be used to estimate the x-ray fluxes that will produce the calculated ablation pressures. In the present study a beryllium ablator is used as the coupling of x-rays to DT is insufficient to allow the use of a pure DT design with indirect drive. In the steady state ablation deflagration regime, the scaling law for ablation pressure with a thermal x-ray drive on a Be surface is

$$P_a = 6.6 T_r^{7/2}, \tag{1}$$

where P_a is the ablation pressure in Mbar and T_r is the radiation temperature in hundreds of eV. The x-ray profile produced from this scaling is shown in figure 2c. This scaling was confirmed through further 1D simulations run in spherical geometry in which a thermal x-ray drive ablated a 1044 µm radius beryllium target. Adding a layer of Be to an igniting all-DT design will clearly change the implosion dynamics and therefore, not produce ignition with the same driver profile. However the objective of this study was not to produce a complete indirectly driven shock-ignition target design, but to investigate some aspects of the practicality of producing shock-ignition-like pressure profiles using indirect drive. The detailed requirements for an indirectly driven shock ignited fuel capsule are not explored here. The pressure profiles from both the



(a) (b) (c)

FIG. 2: Figures showing a shock ignition laser power-profile (a), the ablation pressure it produced in a spherical simulation (b) and the x-ray radiation temperature profile scaled from the pressure (c)

laser and x-ray simulations can be seen in figure 3. The x-ray profile in figure 2c is able to replicate the ablation pressure profile produced by the Ribeyre power profile.

LASER TO X-RAY CONVERSION

A study of the conversion of laser energy to x-rays was carried out to find a laser power-profile capable of reproducing the soft x-ray drive profile shown in figure 2c. This was done using h2d simulations. The hohlraum design used was NIF-like Au hohlraum, thickness of 10 µm, 8.2 mm long and 5.1 mm diameter with a 2.6 mm diameter opening for laser entry. The dimensions of this hohlraum are of similar scale to those used in the National Ignition Campaign [4]. The laser source was 0.35 µm in wavelength. Radiative transport was handled using a multi-group diffusion model. The x-ray flux was

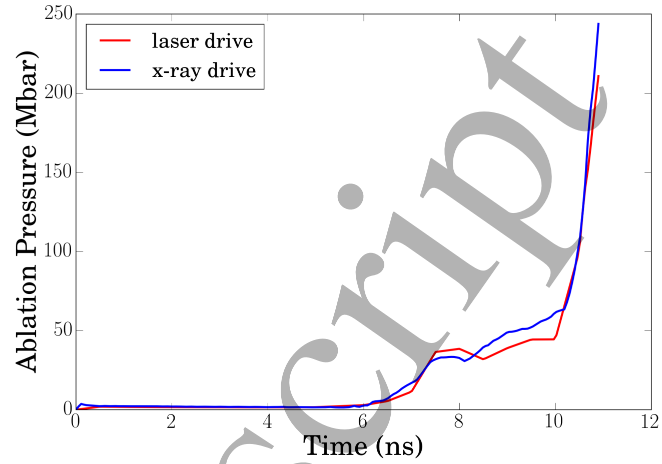


FIG. 3: The ablation pressure profiles produced from laser drive on a DT capsule (red) and x-ray drive on a Be surface (blue).

measured at a radial distance of 1044 µm (typical ICF capsule size) from the centre of the hohlraum. Figure 4 shows the laser profile that produced the required x-ray profile.

The laser pulse has a 2.5 TW foot, between 4 ns and

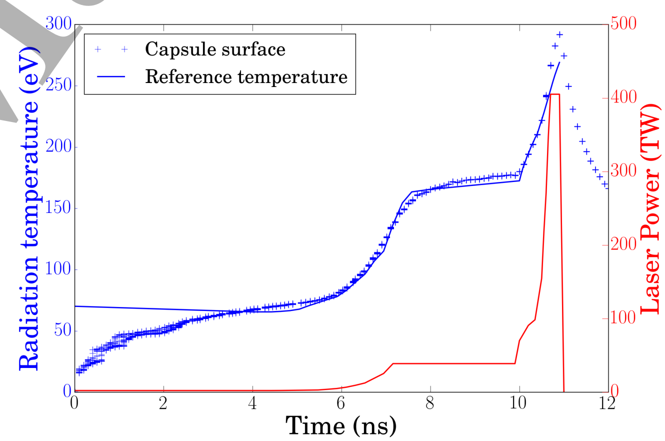


FIG. 4: Figure of the x-ray flux profile produced by a laser driving a hohlraum. The blue line shows the reference profile (solid line) in figure 2c and the x-ray flux (crosses) produced in the hohlraum at the capsule surface.

7.12 ns it rises to 39 TW. The spike rise begins at 9.9 ns and peaks at 400 TW at 10.7 ns until 10.9 ns decaying to zero at 11.0 ns. This gives a total drive energy of 290 kJ. This laser drive profile bares some similarities to the high-foot, high-adiabat profiles designed for use on the NIF [12]. The high-foot NIF profiles have not managed to achieve rises from 200 eV to 300 eV faster than 3 ns[13]. The laser spike profile proposed in this study has 3 key differences that result in a faster rise in radiation temperature. Firstly, an overall steeper rise in the laser power means more time is spent at higher powers, heating the hohlraum faster. Secondly, the plateau region before the ignition spike is longer. This has two beneficial effects: Firstly, it allows the hohlraum to reach a higher temperature before the spike time, reducing the size of the required temperature jump. Secondly, as the laser to x-ray conversion efficiency increases with time, the longer time-scale of this plateau region means the coupling is better at the beginning of the spike. Finally, the addition of an early rise 300 ps before the main spike arrives results in a faster initial rise in radiation temperature which produces a consistently rapid rise in radiation temperature.

The laser drive profile proposed produces an x-ray drive that matches well in the Kidder rise region and in the ignition spike region. Crucially, the rise in x-ray flux occurs at an acceptable rate. This ignition spike in x-ray flux was achieved with a laser power of 400 TW. These laser powers are within the limits of NIF's current operating parameters.

The scaling of the conversion from absorbed drive power to radiation temperature has been compared to the time dependent scaling law for gold proposed in reference 14. The scaling is expressed by the equations

$$S_r(t, \mathbf{r}) = 14.1[E_a(t, \mathbf{r})]^{0.510}[S_a(t, \mathbf{r})]^{0.748} \tag{2}$$

$$\frac{\partial E_a(t, \mathbf{r})}{\partial t} = S_a(t, \mathbf{r}) \tag{3}$$

where $S_r(t, \mathbf{r})$ is the emitted flux and $S_a(t, \mathbf{r})$ is the absorbed drive flux. The scaling law was intended to model sudden rises in drive power. The deposited laser energy in the simulation has been scaled to x-ray flux using equations 2 and 3. This has been plotted against the radiation temperature at the hohlraum wall in the simulation in figure 5. The scaling law shows good match with the simulation results. Further to this, the scaling of these simulations matches well with the scaling laws derived from experimental data (figure 56 in reference 15). Along with the scaling, similarly fast rise times have been observed in vacuum-fill hohlraums [16].

It is noted here that the simulations have only considered an empty hohlraum. In this case the effects of plasma fill and wall expansion are being neglected. Typically, experiments on the NIF use a low density gas-fill to combat the hohlraum wall expansion. The presence of low density gas-fill along with ablated plasma filling the hohlraum in later stages will reduce the coupling. It is hard to estimate the extent of these effects without a more in depth study in which an exact drive profile and capsule design is arrived at but it is likely that, in an experimental scenario, higher laser powers than the ones presented here would be required.

The igniter shock in these simulations was launched with a pressure of 240 Mbar. An igniter shock pressure in the range of 200−300 Mbar is typical for shock ignition schemes [1]. Further simulations were carried out with the same procedure as before but for higher laser powers. They showed that the production of a 330 Mbar shock could be achieved through indirect drive with a 600 TW laser power.

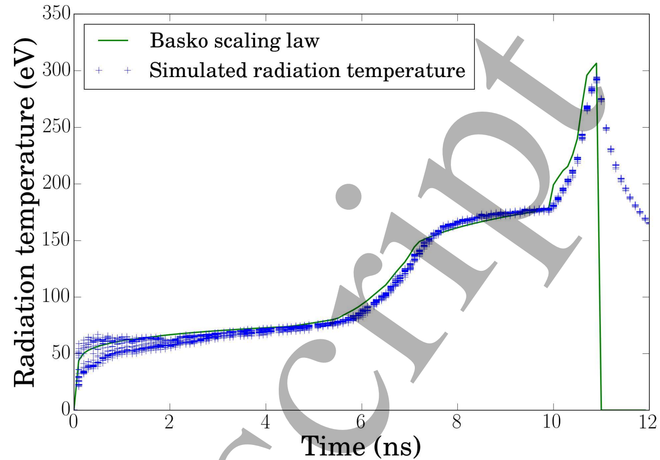


FIG. 5: Figure of the radiation temperature at the hohlraum wall compared against the radiation temperature predicted by the scaling law from reference 14.

FEASIBILITY OF ACHIEVING SHOCK IGNITION PRESSURES

The scaling of x-ray flux to ablation pressure in this work has been compared to experimental results and analytical models. From the one-dimensional radiation hydrodynamics simulations performed (figure 3) the ablation pressure has been plotted against the radiation temperature that produced it. The scaling laws in figure 6 are taken from references 15 and 17. The simulated results match well with the $6.6T_r^{3.5}$ law which is derived from a steady-state ablation case. This approximation is true in the deflagration regime which, for Be, is valid up to a radiation temperatures of approximately ∼400 eV (using $0.12T_r^{5/2} < 4$ from reference 17). The simulated results are matched well with experimental data in the range of 40-150 Mbar (figure 7 from reference 18). The lower ablation pressures from the Lindl scaling law is a result of the assumption of an accelerated thin shell [17]. However, as the target shell is thicker and the acceleration is slower in this case, it is not clear that the pressure reduction will be as large. The previous concerns with indirect drive shock ignition were that the laser powers required to produce the sharp rise in x-ray flux would be unrealistically high. This study has shown that such a rapid rise in the x-ray flux at high temperatures may

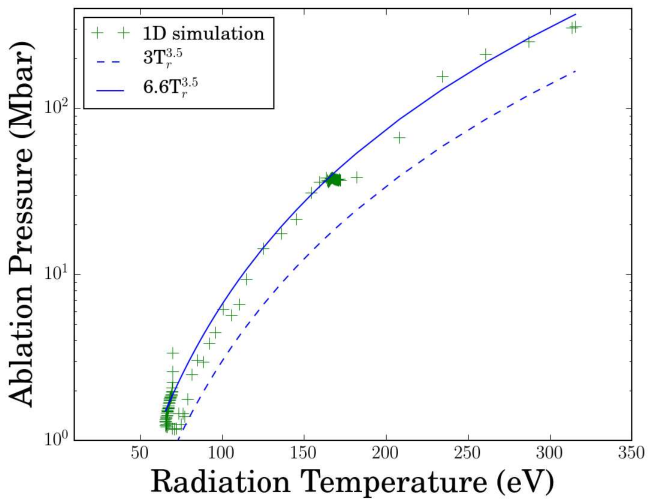


FIG. 6: The scaling of radiation temperature to ablation pressure in the h2d simulations. The scalings from Atzeni [17] (solid) and Lindl (dotted) [15] have been plotted against the simulation results

not be beyond the capabilities of NIF. However, at these intensities, the effects of suprathermal electron preheat must be considered.

For a NIF-like best focus of $0.004\,\mathrm{cm}^2$ [15] the of the proposed igniter pulse will be in the range of $5-8\times10^{15}\mathrm{W\,cm}^{-2}$. This is above the threshold for the stimulated Raman scattering (SRS) [19] and two plasmon decay (TPD) [20] parametric instabilities. The SRS and TPD laser-plasma instabilities occur in the ablated plasma in the hohlraum and produce hot electrons that can go on to heat the DT fuel, raising its entropy and making it more difficult to compress.

Previous work on electron preheat in indirect drive has found that the more stringent restrictions on preheat levels are on the initial compression [6]. In shock ignition, the laser power will be lower in the initial stages than in conventional central hotspot ignition. It is therefore, only the shock spike that raises preheat concerns. The work on suprathermal electron preheat on NIF capsules has been concerned with >170 keV electrons, based on the National Ignition Campaign capsule design [21]. For a 400 TW pulse these measurements have been made on NIF with the FFLEX diagnostic [6, 22]. For the drive pulses currently employed on NIF the levels of these suprathermal electrons are within allowable limits. If indirect drive shock ignition needed laser powers above 400 TW, it could be pushing the limits of allowable suprathermal electron preheat in conventional indirect drive. However, much as with direct drive shock-ignition, it is possible that the fact that the intensity only becomes high late in time may substantially mitigate the problem. It has been suggested that for directly driven shock ignition targets that suprathermal electrons may in fact support the formation of the igniter shock [8, 23, 24], and this may also be the case in an indirect drive shock ignition scenario.

CONCLUSION

The work presented here develops a laser power-profile for hohlraum heating that, in simulations, can produce a soft x-ray drive that appears suitable for shock ignition experiments. It has been shown that an igniter shock pressure of 240 Mbar can be produced with a laser pulse that peaks at 400 TW. However, it is likely that, given the anticipated reduction in coupling at higher powers, a more powerful (>400 TW) laser pulse will be required to produce the necessary jump in x-ray drive for the igniter spike. In this case, the intensities may be pushing the limits of allowable preheat due to suprathermal electron production and the damage threshold limitations of the laser system. The production of suprathermal electrons through laser plasma instabilities will remove energy from the beam before it reaches the hohlraum wall ultimately reducing the efficiency of the coupling. However, at the late timing of the igniter spike the capsule will already be significantly compressed and may be more tolerant to the production of suprathermal electrons. Further work is required to design a complete capsule implosion so that the full extent of late-stage reduction in hohlraum coupling can be assessed. This study has not considered such effects but has achieved shock-ignition relevant pressures in 2D radiation hydrodynamics simulations using indirect drive in vacuum hohlraums.

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