Supplemental heating of conventional Inertial Confinement Fusion

B R Thomas, S J Hughes, W J Garbett, N J Sircombe
AWE Plc, Reading, UK, RG7 4PR
E-mail: stephen.hughes@awe.co.uk

Abstract. We report a new ICF scheme whereby a capsule is imploded to near ignition conditions and subsequently flooded with hot electrons generated from a short-pulse laser-plasma interaction so as to heat the whole assembly by a few hundred eV. The cold dense shell pressure is increased by a larger factor than that of the hot spot at the capsule core, so that further heating and compression of the hot spot occurs. We suggest it may be possible to drive the capsule to ignition by the pressure augmentation supplied by this extra deposition of energy.

1. Introduction

In conventional ICF [1] a shell is accelerated by a rising pressure pulse or series of shocks along a low adiabat. At the end of the implosion, most of the kinetic energy of the inner, unablated part of the shell is converted into compression energy. Because of the nature of the acceleration process in a thin shell, which involves a density and temperature gradient through the layer, the innermost layer is on a higher adiabat than most of the ‘fuel’ and this, plus the initial gas fill of DT in the shell, forms a ‘hot-spot’ inside the cold compressed fuel.

Another approach [2] uses a lower implosion velocity to obtain lower compression in a larger fuel mass, and injects energy from an external source to generate the hot spot. There are more stringent requirements on $\rho r$ and $T_{HS}$ as the fuel is at constant density rather than constant pressure whilst the hot spot is being formed. As a consequence, hot spot formation is accompanied by a shock generated in the spot being sent out into the colder fuel. Extra energy is required in the hot spot to compensate for this work done against the cold fuel.

We propose combining elements of both approaches: an indirect drive, conventional implosion to stagnation at which point external energy is injected to raise the temperature of the whole target. This should have the effect of increasing the pressure in the cold fuel whilst only increasing the pressure of the hot spot by a few percent. The result should be a further compression of the hot spot to a higher $\rho r$ and temperature. The scheme does not offer a route to significantly higher gain and complicates a normal ICF implosion. It should be seen as a way to either remediate lack of pressure at minimum volume or to allow reduction in the implosion velocity to reduce deleterious mix.

2. Heating and energy budget

We consider a target based on a NIF ignition design as in figure 1. Hydrodynamic simulations of the capsule in 1D using the NYM code indicate that dudding the 4th shock to reduce peak velocity...
to 325 kms$^{-1}$, compared with current design mode requirements of 370 kms$^{-1}$. Assuming pressure $P_{stag} \sim v^{2.8}$ this correlates to a 44% shortfall in required pressure.

The final hot-spot radius is about 35 $\mu$m in such an implosion. The main fuel shell has a density of about 1000 gcm$^{-3}$ and a thickness of about 8 $\mu$m so its $\rho r \simeq 0.8 \text{ gcm}^{-2}$. The hot spot $\rho r = 0.3$ so the total fuel $\rho r = 1.1$. Here we consider the total fuel mass at the end of the implosion and assume the ablator (mostly CH) is expanded to low density and only the DT is left.

### 2.1. Heating the cold fuel

The idealised situation at stagnation is an isobaric configuration of a dense shell surrounding hot fuel. Taking $\rho R_{hs} = 0.3$ and $\rho R_{tot} = 1.5 \text{ gcm}^{-2}$ with $\rho_2 = 1000 \text{ gcm}^{-3}$ and $T_1 = 4 \text{ keV}$ gives the configuration as shown in figure 1. We assume that both regions will be heated uniformly, leading to a pressure disparity. Hydrodynamic motion follows, with the main fuel further compressing the hotspot. Final conditions are again isobaric, with the new hotspot dimensions, pressure, densities and temperatures: $\{\rho'_1, \rho'_2, R'_1, R'_2, T'_1, T'_2\}$.

Assuming that mass is conserved separately for hotspot and main fuel regions:

$$
\rho_1 R_1^3 = \rho'_1 R'_1^3,
\rho_2 (R_2^3 - R_1^3) = \rho'_2 (R'_2^3 - R'_1^3).
$$

Pressure balance is $\rho'_1 T'_1 = \rho'_2 T'_2$ and energy balance is:

$$
\left(\frac{3\Delta E}{4\pi}\right) + \rho_1 R_1^3 \epsilon_{DT} T_1 + \rho_2 (R_2^3 - R_1^3) \epsilon_{DT} T_2 =
\rho'_1 R'_1^3 \epsilon_{DT} T'_1 + \rho'_2 (R'_2^3 - R'_1^3) \epsilon_{DT} T'_2.
$$

We make further simplifying assumptions: the hotspot temperature increase is negligible; and the the outer radius does not change significantly. Equation 2 then simplifies to:

$$
(\rho'_1 - \rho_1) r_2^3 = \left(\frac{3\Delta E}{4\pi \epsilon_{DT} T_1}\right),
\frac{\rho'_1}{\rho_1} = 1 + \left(\frac{3\Delta E}{4\pi \epsilon_{DT} T_1 \rho_1 r_2^2}\right),
$$

yielding the pressure enhancement $\rho'_1 / \rho_1$ for a given energy input $\Delta E$. To achieve a $\sim 40\%$ enhancement in $P$ requires $E \sim 5.5 \text{ kJ}$ and a temperature rise of 280 $\text{ eV}$. NYM simulations indicate that artificial heating of the dense fuel layer by this amount generates significant yield, although the heating must be fast to prevent radiative losses cooling the shell.
2.2. Electron penetration and \( T_{\text{hot}} \)

Various formulae for electron range have been proposed. A possible spread of values \[3\] is 0.3 to 0.6 \( T_{\text{hot}} \) gcm\(^{-2}\) where \( T_{\text{hot}} \) is in MeV. To penetrate the fuel from one side with \( \rho r_{\text{tot}} = 1.1 \) gcm\(^{-1}\) we need \( T_{\text{hot}} = 3.67 \) MeV at the lower end of this range and \( T_{\text{hot}} = 1.83 \) MeV at the upper. If \( T_{\text{hot}} \) is given by the common ponderomotive form \[4\] these values translate into irradiances of \( 1.61 \times 10^{20} \) Wcm\(^{-2}\) and \( 4.01 \times 10^{19} \) Wcm\(^{-2}\) respectively for \( \lambda = 1.06 \) \( \mu \)m.

If the laser energy to hot electron coupling efficiency is 0.3 and the hot electron coupling efficiency to the core is \( f_c \) we need \( 8.17/f_c \) kJ per side of laser energy over a cross-sectional area of \( 5.8 \times 10^{-5} \) cm\(^{-2}\). This means a pulse length of \( 0.875/f_c \) ps at the higher irradiance (shorter range) or \( 3.52/f_c \) ps at the lower irradiance (longer range).

Realistically, it appears we may be talking about a total short-pulse energy requirement of \( \sim 50 \) kJ but it should be noted that some allowances have been made for losses in this estimate.

3. Numerical simulation

To reduce the uncertainties in the analytic model we used numerical simulation to determine whether electron heating of the cold fuel by \( \sim 300 \) eV is viable at stagnation time. The density profile from the NYM 1D implosion calculation at stagnation time (figure 2) was used as an initial condition for investigating the electron source and transport physics associated with the short pulse laser.

The scale length of the coronal plasma is very much larger than is practical in a PIC code such as EPOCH, and the resulting electrons would almost certainly be at too high an energy and flood too large a volume. Instead we anticipate that renewed work on channelling (e.g. \[5\]) will provide sufficient control to allow the electron source to be located at a point much closer to the target and with a shorter plasma scale length. With this in mind, EPOCH simulations used a simplified plasma profile with a 20 \( \mu \)m scale length to represent the end of a channel. Figure 3 shows the electron density profile after 0.4 ps of illumination.

![Figure 3. Results from EPOCH simulation of a 20 \( \mu \)m scale-length plasma to generate a source for heating calculations. The white line indicates the probe plane where particles were sampled.](image)

![Figure 4. Pressure change profiles with an EPOCH source. Red lines are for a single heating beam, green for double heating. Continuous lines are in the \( z \)-axis, dashes are in \( r \) to highlight the asymmetry.](image)

To compute the energy deposition and heating, the PIC source was captured at a probe plane (shown in figure 3) and passed explicitly into the hybrid-electron transport code THOR using the approach described in \[6\] together with a radial density profile from the 1D NYM simulations.

Ideally, isotropic heating of the cold fuel by many short-pulse beams would provide a smooth heating profile, however this is probably impractical with indirect drive schemes on current...
facilities. Instead, we consider here the use of one or two electron sources at the equator of the capsule in an indirect drive configuration.

A comparison of the pressure enhancements predicted in THOR calculations is shown in 5 comparing an analytic ponderomotive source (a) with an explicit PIC source (b) and the use of one or two heating beams. In case (a) the heating is significant, and with two beams is well above the 40% enhancement required. With a more realistic PIC source the heating is less pronounced because the electron source diverges more and varies its pitch angle in time.

Pressure change profiles are shown in figure 4. The PIC source is less efficient than the ponderomotive source and there is a marked asymmetry that suggests more work is needed to understand the compatibility of the scheme with indirect drive configurations.

4. Conclusions
This initial study of the supplemental heating scheme suggests that it is practical, but that the major obstacle may be delivering the short pulse energy to the compressed fuel. Although channelling schemes under consideration for fast ignition show some potential this would be the next step in determining the viability of the scheme, and determining if practical electron sources can be generated that will heat with suitable efficiency. Further integrated modelling using THOR inline in a hydrodynamics code is also warranted to demonstrated whether the anisotropic electron heating will lead to significant capsule yield. Alternate capsule designs that are tailored to this late-time heating concept may also be interesting to pursue. It is also worth noting that the scheme could be used a near-ignition directly driven capsule with easier access for the short-pulse heating.

References
[1] Lindl J D, Amendt P, Berger R L, Glendinning S G, Glenzer S H, Haan S W, Kauffman R L, Landen O L and Suter L J 2004 Phys. Plasmas 11 339
[2] Tabak M, Hammer J, Glinsky M E, Krueer W L, Wilks S C, Woodworth J, Campbell E M, Perry M D and Mason R J 1994 Phys. Plasmas 1 1626
[3] Deutsch C, Furukawa H, Mima K, Murakami M and Nishihara K 1996 Phys. Rev. Lett. 77 2483
[4] Wilks S C, Krueer W L, Tabak M and Langdon A B 1992 Phys. Rev. Lett. 69 1387
[5] Mironov V et al 2012 Plasma. Phys. Cont. Fus. 54 095008
[6] Sircombe N J, Hughes S J and Ramsay M G 2013 New. J. Phys. 15 025025

Figure 5. Comparison of one and two beam heating schemes with (a) an analytic ponderomotive source and (b) an EPOCH source. In each panel the left-hand reflection is with a single beam from $-z$ and the right-hand with twin beams from $\pm z$. 