GA–A23803

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APRIL 2002

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GA–A23803

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This is a preprint of a paper to be presented at the 2nd International Conference on Inertial Fusion Science and Applications, September 9–14, 2001, Kyoto, Japan, and to be published in *Fusion Technology*.

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Work supported by
General Atomics IR&D Funds

GA PROJECT 40009
APRIL 2002

Optimizing the structure of fast ignition targets

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Fast ignition targets are ignited on the outside surface so they have no need for a low density, high temperature center required by central hot spot ignition. On the contrary, such a center will lower the burn efficiency by forcing the nuclear burn to follow a longer path around the outside rather than straight across the core. Yet that center is difficult to avoid. Even if the central space begins as a vacuum, the initial shock wave from compression will release some gas into the central space when it reflects off the interior surface. We present some estimates of the size of the problem, and simple estimates of the effect of mixing and shell breakup on mitigating it.

1. Introduction

Fast ignition (FI) is a variation of inertial confinement fusion in which the compression and ignition steps are separated [1]. The compression step (which may equally well utilize a laser, z-pinch, or heavy ion beam driver) assembles the fuel as a compact mass of uniform density, ρ~200 g/cc in typical designs. The ignition step (which requires a short-pulse laser) heats a small volume near the surface of the assembled fuel to ~10 keV, and initiates a nuclear burn which sweeps across the mass. Surface ignition, although it loses 10%–20% of its energy compared to a central hot spot (CHS) [2], is very efficient because the high density if the "spark" (typically 200 g/cc for FI versus 50 g/cc for central hot spot), allows one to burn lower density fuel [3]. The energy required for ignition was calculated using a model in which a uniformly dense lamp of fuel was an assumed starting point.

A basic problem with this scenario is that it is rather difficult to compress a target as a uniformly dense, cold mass. The fuel is assembled from a shell that is accelerated inward by a driver. During startup, the shock of acceleration travels through the shell and reflects off the inner wall. On reflection, some of the inner wall is vaporized into the inner cavity, adding to whatever was in there to start (the density begins at ~0.3 mg/cm^3 for typical CHS targets, ~10^{-4} of the total fuel, but much more, a few percent of the total, is mixed into the hot spot by the end [3]). This gas is adiabatically heated by the collapsing shell, so:

$$P \propto V^{-\gamma} \text{ , and} \tag{1}$$

$$T \propto V^{1-\gamma} \text{ ,} \tag{2}$$

where $\gamma \sim 1.66$.

Its pressure increases until the compression stops at isobaric equilibrium. At this point, a typical target designed for central hot spot (CHS) ignition will have a hot core with ρ_{hot}~50 g/cm^3, and r_{hot}~60 µm comprising ~ 1% of the mass of the target. The surrounding shell has density, ρ_{cold}~500 g/cm^3, and wall, th_{cold}~20 µm. The core $\rho_{hot} r_{hot}$~0.3 g/cm^2 is sufficient to contain the fusion α particles, and self heat itself thermally to the 30–40 keV range, where about 5% of the atoms fuse. The resulting alphas heat up an adjacent shell with thickness th = $0.3/\rho_{cold}$~6 µm. Under these conditions, sufficient energy is deposited in that adjacent shell to heat it to ignition and continue the burn [3]. If that outer density is much lower, the α particles travel farther and heat up more material to a lower temperature; in that case shell will not be heated sufficiently and the burn will fizzle out.

Such a low density central core would pose a problem in a surface ignited shell. The fusion burn could not propagate across a low density center; it would instead have to travel along the surface. Since the fuel is disassembling from the surface in, this route would ultimately give lower yield.

We consider two ways to mitigate this problem: 1) mixing cold fuel in with the hot gas, and 2) breaking up the shell. We use very simple arguments to indicate directions; proper modeling will be needed to quantify the effects we describe. The next section describes the parameters for a typical central hot spot target and considers how much density must be increased to allow burn across the low density center. In the succeeding sections we consider how either mix or breakup might accomplish that.

2. Fast ignition parameters

The parameters quoted above are for a target optimized for central hot spot ignition. The initial gas density was adjusted to make a sufficiently large hot spot, and then the shell had to be made dense enough (ρ_{cold}~500 g/cm^3) that it could be ignited from the gas. We want to consider a shell with minimal initial gas compressed to a value typical of fast ignition targets (ρ_{FI}~200 g/cm^3). Table I shows the consequences of these assumptions using a very simple model in which the gas starts at 1/2 eV inside a shell collapsing at a specified speed and heats according to Eqs. (1) and (2). The shell is assumed to collapse along a nearly Fermi degenerate isentrope, with α= 1.5. The compression velocity and gas fraction were adjusted to give final shell density 500 g/cm^3, and gas density 50 g/cm^3. The radius and wall were adjusted so that for the first case ρR~3 g/cm^2 in the absence of a gas core. In all the cases considered here, the energy in the shell was several orders of magnitude larger than that in the gas, so the pressure in the shell was calculated from the energy put into it by the driver, and the gas was assumed to be compressed to that pressure. The initial gas density was adjusted to give a hot spot ρR~0.3 g/cm^3.

Table I. Shell parameters.

		(a) Central hot spot shell	(b) Low density CHS	(c) FI shell - low density, sized for rR~3	(d) FI shell with added cold mass	(e) FI shell unstable at mode 200
Radius	µm	1400	1400	2000	2000	3400
Wall thickness	µm	450	450	900	900	170
Compression veloc	cm/s	$2.38\text{x}10^7$	1.76×10^7	1.76×10^7	1.76×10^7	2.35×10^7
Gas density	mg/cm^3	10	10	1	1	1
Gas fraction		0.04	0.04	0.015	0.015	0.06
Final pressure	g/cms^2	1.5×10^{15}	6×10^{14}	6×10^{14}	6×10^{14}	1×10^{15}
Shell density	g/cm^3	500	200	200	200	480
Increase mass ratio					8	
Hot spot radius	µm	54	65	110	38	120
Hot spot density	g/cm^3	50	30	12	150	21
Hot spot temp	eV	150	100	260	33	363
ρR for hot spot	g/cm^2	0.29	0.2	0.14	0.57	0.24
Assembled fuel radius	µm	82	110	150	160	140
ρR for assembled fuel	g/cm^2	2.9	1.7	3.0	3.2	2.9

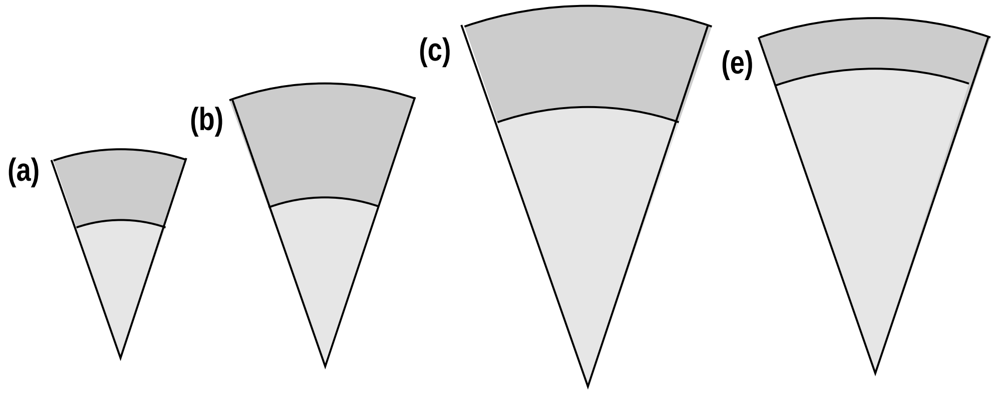

Fig. 1. Cross-sections of the assembled cores that have hot spots, as described in Table I.

To get the high gain advantage of surface ignition, one reduces the drive sufficiently compared to the CHS shell to give a 200 g/cm^3 shell [column (b) above], and then add mass and minimize the interior gas to maintain ρR~3 g/cm^2 [column (c) above]. The interior gas of (c) is still a barrier to a surface ignited burn; the shell is barely thick enough to contain the ignition volume ($d_{ignition}$=30 µm~th_{wall}=40 µm) and the low density hot spot has a long α-particle range (~250 µm), so the heated mass is too large relative to the burning mass in the radial direction. The ratio of those masses has to be less than the product of the α particle energy and burn fraction, over the specific heat, (E_α~ 3.6 MeV, f_B~5%, and E_{ignite} ~60 keV, respectively [3]):

$$E_\alpha f_B/E_{ignition} \sim 3 \geq m_{cold}/m_{hot} \sim 3 + 3\rho_{hot}/\rho_{cold} + (\rho_{hot}/\rho_{cold})^2 \quad (3)$$

From a 200 g/cm^3 starting point, the burn will not propagate into regions of much lower density. The next two sections consider what is needed to allow propagation.

3. Mixing cold fuel

Fast ignition targets do not require the symmetry of central hot spot targets. Conceptual target designs exploit this in adding reentrant cones for a protected ignition path [4–6]. At the least, the presence of those cones will cause mixing. One could take advantage of them to add a controlled mixing by freezing DT to the sides or the tip of the cone. To explore this effect, we consider the case that there is a mass, m_{mix}, of DT ice suspended in the center of a shell with mass = $m_{initial}$. Assume m_{mix} mixes into the "gas" when ρ_{gas} ~0.2 g/cm^3. The temperature is reduced by $m_{initial}/m_{total}$ and the volume increases by the sum of the masses. Then the mixed mass is further adiabatically compressed to isobaric equilibrium. The final hot spot volume and density are changed by

$$V_{final2}/V_{final1} = (m_{mix}/m_{initial})^{(1/\gamma-1)} \quad (4)$$

$$\rho_{final2}/\rho_{final1} = (m_{mix}/m_{initial})^{(2-1/\gamma)} \quad (5)$$

so by our simple formula, increasing the mass 6 times gives increases the core density to ~150 g/cm^3. That requires an DT ice sphere ~300 µm radius in the center of the shell which initially has 1100 µm inside radius. That is feasible, perhaps.

4. Shell breakup

The previous section invoked mixing, but otherwise kept spherical symmetry. One could simply have the shell break up. That is easy to do. Thin shell, high gain targets are quite sensitive to surface perturbations. Gardner *et al*. [7,8] found that the perturbations caused by the foam structure in a high gain target could cause breakup on compression. Is this useful?

The latter paper found that the modes most effective in breaking up the shell ("most dangerous" in their words, but we are taking a different view of their value) are several times the effective thickness of the shell; the shell compresses ~4× in flight. So take the dominant breakup length to be ~shell thickness/2.

Plugging the values for their optimized shell into our model, one finds very high densities – it is overdriven for our purposes. The parameters in the table have been adjusted to give densities adequate for fast ignition. This example might not be RT unstable – we will assume it is for the purposes of this discussion. This shell is sensitive to break up in modes about $4\pi r/th \sim 200$. If that proceeded to completion, the shell would consist of $\sim 10^4$ cold chunks $\rho \sim 480$ g/cm^3, r~6 µm embedded in much lower density hot DT. The ρR of each chunk is ~0.16 g/cm^2, so somewhat less than an α-particle range. As a result, they would not notice the fluctuations. The ignition dynamics would be roughly that of a shell with average density ~200 g/cm^2. Notice though that in order to do this, the shell had to be driven just as hard as a standard CHS target. The mixed target is effectively on a much higher adiabat and the compression energy is correspondingly large. The gain from this target might be more like a CHS than a FI target.

5. Summary

We have qualitatively shown that a target designed for central hot spot ignition is not ideal for a fast ignition target. The inevitable low density center forces the burn to traverse the outside of the assembled target rather than propagate through the center. This will reduce burn efficiency.

We have indicated several ways of removing that hot spot. One could either mix cold DT into the gas near the end of the compression, or simply break up the shell so that the density fluctuations are on a sufficiently fine scale (less than an α particle range) that the burn processes ignore them.

Targets have already been designed which are unstable at the high modes (≥200) required. They were optimized for central hot spot ignition, with the required high temperature hot spot and high density shell – perhaps they can be reoptimized for fast ignition purposes without losing their instability, and retaining the hoped for high gain.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48, and with the additional corporate support of General Atomics.

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