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Design Considerations for a Cone in a Fast Ignition Capsule

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Design Considerations for a Cone in a Fast Ignition Capsule

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Abstract. An alternative to inertial fusion with central ignition is "fast ignition", in which one laser compresses the DT fuel adiabatically and a second laser with a short, very intense pulse heats the compressed core with super-thermal electrons[1]. One approach to fast ignition entails the introduction of the second laser beam via a hollow cone that pierces the side of the capsule. Critical considerations for the design of the cone in such an experiment include:

- Perturbation of the implosion by the cone
- Minimization of the column density of material between the critical density surface for the ignitor beam and the converged high density region
- Positioning, alignment, and shape of the cone to minimize deleterious hydrodynamic effects
- Effect of radiation gradients around the cone on the symmetry of the implosion.

This study entails the 2D and 3D simulations of a fast-ignitor experiment having a cryogenic deuterium-tritium capsule imploded within a high-Z hohlraum heated by about 650kJ of 3ω laser beams on the NIF.

1. Introduction

Inasmuch as the relativistic electrons generated by the high-intensity, short-pulse ignitor beam will probably have a broad angular distribution[2], absorption at the critical density surface of a capsule will result in few of the electrons traversing the compressed DT core and, consequently, only a small fraction of the ignitor beam energy absorbed in the compressed core. Using a hollow reentrant cone to provide an unobstructed path to the compressed core might be a solution for this problem, but introduces a number of its own difficulties: (1) asymmetry of implosion, (2) cone metal impurity mixing with the DT fuel, (3) metal spray from shocking the inner surface of the cone and subsequently occluding the ignitor beam, (4) the tip of the cone being crushed and/or penetrated by the high pressures generated in the compressed DT core. This study seeks a design which successfully addresses these problems.

Our method is to use a single capsule design[3] and to conduct 2D HYDRA[4] simulations to find an optimal cone design for that capsule. The capsule design has Be and Be/Cu ablator layers and DT ice. It is driven by x-radiation with a peak equivalent radiation temperature of 210eV. The time of peak ρR in the compressed DT fuel is about 32.5ns. Calculations reported here have used a time and frequency dependent x-radiation source generated by 1D radiation-hydrodynamic hohlraum calculations. After

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completing this 2D study, 3D HYDRA calculations that model the radiation fluxes in the cylindrical hohlraum with the cone protruding from the hohlraum wall at the center plane and with NIF laser illumination of about 650kJ will be conducted.

Several design parameters have been investigated:

- inner and outer angles of the conical surfaces with respect to the axis of the cone
- thickness of the nose of the cone on axis
- distance of the nose of the cone from the center of the capsule
- distance from the center of the capsule to the intersection of the projection of the outer conical surface with the axis of the cone
- coefficient of the P1 asymmetry in the x-ray flux incident upon the ablation surface.

Key results from the simulations are summarized by several quantities as noted in Figure 1:

- peak ρR in the DT, evaluated perpendicular to the axis
- X, distance from the critical density surface to the 100g/cc contour in the compressed core at the time of peak ρR
- ρX, the column density along the distance X
- location of the shock front on the inner surface of the cone near the tip at the time of the ignitor beam

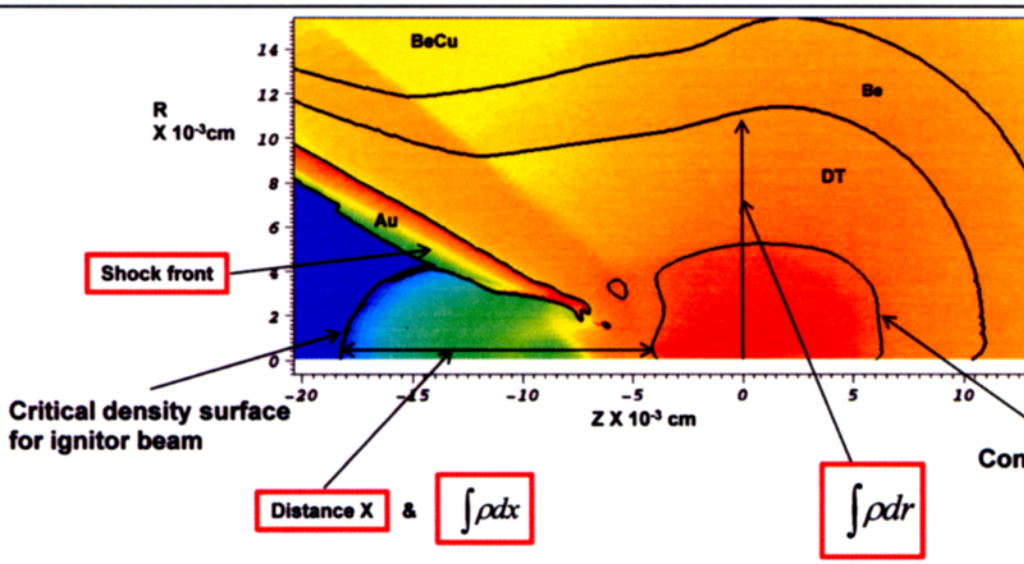

Figure 1. This picture shows the region boundaries and a pseudocolor plot of log ρ. Four key figures of merit that result from a 2D HYDRA simulation, taken at 32.5ns, roughly the time of peak ρR are shown in red boxes.

As illustrated in Figure 1, the pressure generated in assembling the DT core is so great, typically exceeding 50Gbars, that the DT punches through the tip of the cone. According to these calculations, then, the ignitor beam would be incident on the DT jet, with only a thin wisp of cone metal (gold in these simulations) remaining.

Since the fusion efficiency of the DT is proportional to $\rho R/(\rho R + 6\text{g/cm}^2)$, it is clearly advantageous to maximize ρR. Because the energetic electrons generated by the ignitor beam have such a broad angular distribution, the distance X should be less than or comparable to the size of the compressed core; its 100g/cc contour typically has a radius of about 60μm. To reduce energy loss of these electrons in traversing the remaining metal of the cone tip and the low density DT jet, the column density over X should be small, well less than 1g/cm^2. If a shock breaks out of the inside surface of the cone near the tip before the illumination of the ignitor beam, the path of the laser beam may well be occluded.

2. HYDRA calculations

These HYDRA calculations were conducted with 6 user blocks and 40 domains on 40 processors. The angular zoning in the capsule was about 1°. The finest zone on the inner surface of the DT ice was 225nm, as determined by a convergence study. The finest zone in the Be ablation region was 75nm. The finest zone on the outer surface of the cone was 175nm. These calculations employed flux-limited x-radiation diffusion approximation for radiation transport.

These calculations display extreme shear between the motions of the imploding DT and capsule shells and the relatively immobile cone surface. Several Arbitrary Lagrange Eulerian (ALE) options were exercised in order to maintain fairly regular zoning. One technique was to permit the nodes to "relax" as various criteria were satisfied and, additionally, to schedule more extensive remapping at specified intervals. A second technique was to map the zoning from the unperturbed side of the implosion onto the side with the cone perturbation during much of the implosion. Thereafter, techniques similar to the first ALE methods were employed. Aggressive ALE methods, used to reduce mesh distortion, had the deleterious effect of coarsening the zoning on the outer surface of the cone and so artificially reducing any ablation of the cone resulting from short wavelength Au M- and L-band radiation (2-5keV and 8-12keV, respectively) penetrating through the ablators shells.

As shown in Figure 2, the implosion along the cone lags the implosion elsewhere in the capsule. This effect does not stem from the influence of viscosity. Near the cone a lower ablation pressure is achieved since a shock is launched into the cone, thus relieving some of the ablation pressure. Moreover, outside of the capsule the cone is strongly ablated sending a large plume of ablated gold that subsequently shadows the capsule near the cone.

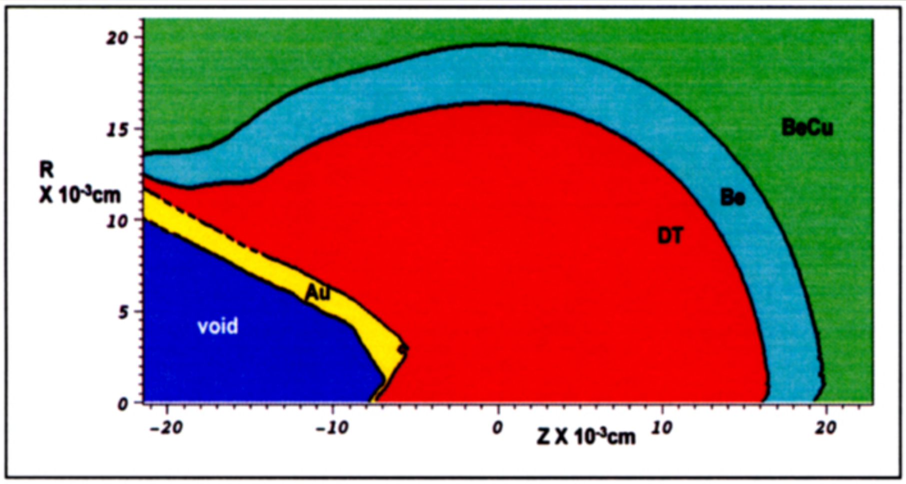

Figure 2.
This illustration, taken at 32ns, shows material boundaries. The implosion is clearly lagging on the side with the cone.

The implosion along the cone lags so much that, by the time of peak ρR (see Figure 1), some of the DT has been trapped next to the cone. This implies that gold ablated from the surface of the cone would not be entrained and carried down to contaminate the compressed core. The coarsening of the mesh by ALE relaxation might have resulted in underestimating the ablation of the gold and might have caused this entrainment to be neglected. Test 1D calculations with finer zoning in the gold and with the gold zoning kept Lagrangian strongly suggest that toward the end of the implosion and near the tip of the cone short wavelength M- and L-band photons originating in the areas of laser absorption will generate ablated plumes of gold extending as much as a few tens of microns. Test 1D calculations indicate that much of that ablation can be adequately suppressed with low-Z coatings (eg., Be, CH, or diamond).

Another consequence of the implosion lagging along the cone is that the shock from the unperturbed side strikes the nose of the cone before the arrival of shock from the side with the cone. Consequently, we have explored calculations with a first-order Legendre perturbation (P1) to advance the implosion on the cone side. In order to perform calculations using flux-limited diffusion, we inhibited transverse (not radial) diffusion outside of the ablation surface. To represent adequately the ablation of the cone at radii greater than that of the ablation surface, we permitted transverse diffusion closer to the cone. This suppression factor varied smoothly by eighteen orders of magnitude from angles near the cone to those angles on the side without the cone. Because the implosion had a relatively low Mach number (~3) as the implosion "launched" off the tip of the cone, it tended to fan out rather than proceeding directly ahead as it would with a much higher Mach number. This factor tended to make the implosion near the tip of the cone cylindrical and to exacerbate tip penetration by the DT jet.

3. Conclusions

These simulations attained peak ρR of 1.3 to 1.9g/cm^2, distances X of 100 to 140μm, column densities along X of 0.15 to 0.30g/cm^2, and shock breakout times preceding the time of peak ρR by 100 to 500ps. As the ρR reaches its peak, it tends to plateau so that illuminating with an ignitor beam earlier would not greatly decrease the burn efficiency. This expedient would decrease X and retard the timing of the shock break-out time until after the ignitor beam. Thickening the cone near the tip by larger values of projection of the outer conical surface past the center would also shift the shock break-out times later. We are continuing this tuning and are making progress in ensuring cone tip survival.

While the column density between the critical density surface and the compressed core is small enough to be negligible. The distance X is larger than needed to ensure the absorption of much of the energy of the electrons, and we are continuing the tuning to shorten this distance. Some recent papers[5] suggest than self-generated magnetic fields might constrain the angular divergence of the electrons though it is unclear whether this effect is present in the parameter regime of interest.

We are also conducting HYDRA calculations with implicit Monte Carlo transport of x-radiation photons in order to compute more accurately the variation of the ablation pressure with polar angle.

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