Recent developments in ignition target designs for the National Ignition Facility

L Suter, S Haan, J Lindl, T Dittrich, B. A. Hammel, D Hinkel, O Jones, S Pollaine, J Rothenberg, Lawrence Livermore National Laboratory, Livermore, California 94551
E-mail: suter1@llnl.gov

Work on design of ignition targets for the National Igntiion Facility (NIF) has progressed in three areas. First, hohlraums have been re-optimized taking advantage of improvements in efficiency in several areas: use of high albedo material mixtures in the hohlraum wall; optimizing the laser entrance hole; optimizing the case-to-capsule ratio; and taking advantage of increased efficiency of longer pulses. These changes, in combination, allow for the possibility of quite high yields (~100MJ), gains (>40) and significantly more margin for ignition on NIF. Second, work has continued on specifications for target fabrication. Third, detailed design and analysis has been done on targets for the commissioning phase of NIF, when only 96 beams are available. We find excellent hydrodynamic similarity is possible with sub-scale cryogenic targets. These targets can be used to test all of the physics of full-scale ignition targets in detail except, perhaps, for ignition itself.

Work has progressed both on full scale ignition targets and possible 96-beam targets for experiments during the commissioning phase of the National Ignition Facility (NIF) [1]. The full-scale work includes exploration of the possibility of high yield. The sub-scale work has examined the hydrodynamic equivalence of lower energy capsules, and their performance relative to the ignition cliff. Several key findings have resulted from these studies:

1) With full NIF and improvements in hohlraums and laser efficiency, capsules absorbing ≥300kJ of energy at 300eV and ~600kJ at 250eV are plausible. This would correspond to yields ~50 to 150MJ from targets optimized for thermonuclear output.

2) Cryogenic targets at 0.6 scale, driven with 96-beams (half NIF) at half performance per beam, as is expected during the commisioning phase, for a total output of ~450 kJ, would not ignite but would allow detailed verification of all of the physics of full ignition target designs, except for actual ignition (α-deposition).

3) Cryogenic targets at 0.9 scale, driven with 96-beams at full performance per beam (~900 kJ), that utilize potential hohlraum-to-capsule coupling improvements, appear to be on the threshold of ignition, making ignition conceivable, but suspect. If all of the proposed improvements in coupling can be obtained, and if all other issues work out favorably, ignition is plausible. However, the combined downsides (laser performance, target fabrication, scattering losses, etc.) make ignition unlikely. An aggressive program on the Omega laser at the University of Rochester in the next few years will increase our knowledge of the yield achievable with a 96-beam NIF.

Possible hohlraum coupling improvements:

Our original ignition "point designs"[2,3] (circa 1992) for the National Ignition Facility (NIF) were made energetically conservative to provide margin for uncertainties in laser absorption, x-ray conversion efficiency and hohlraum-capsule coupling. Since that time, an extensive experimental effort, first on Nova and, more recently, on the Omega laser, has significantly reduced the uncertainties in coupling[4,5]. Ongoing experiments studying stimulated Brillouin and Raman backscattering (also known as Laser Plasma Interactions or LPI) in ignition hohlraum "plasma emulators" provide reason to think that the total backscattered losses from these two processes may be $\leq$ 5%. Complementing this work are experiments studying the radiation drive and symmetry in laser heated hohlraums. Analysis of these experiments shows that x-ray production and capsule coupling is very close to our modeling.

Given close agreement between experiment and theory/modeling, we can credibly explore target enhancements that couple more of NIF's energy to an ignition capsule[6]. These include using optimized mixtures of materials to reduce x-ray wall losses[7,8] (these mixtures are known as “cocktails”), slightly smaller laser entrance holes to reduce hole x-ray losses, and laser operation strategies which increase the amount of energy we can extract from NIF. We find that by simultaneous combining a number small improvements the overall hohlraum coupling efficiency (capsule absorbed energy/laser energy) can be increased by 1.5 to 2X at 300eV and 2 to 2.5X at 250eV[6]. See, for example, table 1.

Table 1- Hohlraum efficiency can be significantly increased by a combination of many relatively small improvements

Hohlraum	efficiency (%)
300eV, 150kJ, 3ns	11
250eV, 600kJ, 7.5ns	14.5
Reduce LEH only	16.2
Cocktails only	17.7
Both cocktails & reduced LEH	20.3
CE rises from ~80% to ~90%	22.9
Reduce case:capsule ratio by 10%	25.3

High yield:

In addition to increased hohlraum coupling efficiency we have found that there are operational strategies which may allow us to extract more energy from 192 beam NIF than had been previously assumed. For example, using a technique known as “ultra-fast pickets” [9] we can envision average conversion efficiency of 1μm light into 1/3μm light of ~70%, as measured on the target. Consequently, it is not unreasonable to think that full NIF might be able to drive a target with as much as ~2.5MJ of light at the lower powers required with improved hohlraum coupling efficiency and, perhaps, 250eV. An analysis which includes improvements to both hohlraum coupling and laser extraction indicates that capsules absorbing ≥300kJ of energy at 300eV and ~600kJ at 250eV are plausible. This would correspond to yields ~50 to 150MJ from targets optimized for thermonuclear output and energy gains of 25 to more than 40.

"Sub-scale" target design

Detailed analysis has been done on two possible 96 beam experiments: (i) a cryogenic target that only requires 50% performance from the 96 beams; (ii) a cryogenic target at 0.9 scale that assumes 100% performance from 96 beams. In both cases we use cocktail hohlraums, but assume "standard" laser entrance holes and laser performance.

For both cases, an important issue is the symmetry achievable with 96 beams. Both the intrinsic asymmetry and asymmetry due to power balance and pointing errors are larger. Achieving acceptable intrinsic asymmetry requires repointing the beams slightly off axis, since the 96 beam configuration has only a 4-fold azimuthal symmetry for the inner beams rather than the 8-fold symmetry of full NIF. Even with this change, the asymmetry would still be at best marginal except for the improvement that results from the higher albedo of the cocktail wall material. This reduces the asymmetry by nearly a factor of two, bringing it below 1% for 96 beams. Similarly, the power balance and pointing asymmetry would be worse by a factor of $2^{1/2}$, simply because of statistics. This increase can be recovered, according to our current modeling, by using the high-albedo cocktail wall. Hohlraum modeling with a 3D viewfactor code indicates that the resulting net asymmetry, with 96 beams with a cocktail wall, is acceptable for implosions with convergence ratios similar to those needed for ignition with full NIF. Results from 3D hohlraum calculations and albedo tests with candidate cocktail wall materials will be required to verify these initial conclusions.

Integrated simulations have been done to verify the hohlraum energetics and 2D asymmetry. These indicate that 96 beams at 50% performance can drive a capsule that is scaled from our usual point design by a factor of 0.6, using 350 kJ and 140 TW of 3w light absorbed in the hohlraum. For the full-laser performance 96 beam target, a scale 0.9 capsule can be driven by 900 kJ and 250 TW of absorbed 3w light.

The hyrdrodynamics of the implosion and hot-spot formation scales very well over the relatively small scale factors being applied here. In fact, the Rayleigh-Taylor hydrodynamics is replicated extremely well at 0.6 scale. The instability growth can be regulated by varying the concentration of Ge dopant (other materials such as Br could also be used). Figure 1 shows the growth of instability, seeded by a multi-mode perturbation, for a full scale ignition target and for two 0.6 scale targets (which do not ignite) which bracket the growth on the full scale capsule. The spectral nature of the perturbation growth is also reproduced, as are all details of where and how the growth is driven.

Hot-spot formation is also very well replicated. Both at 0.6 scale and at full scale, the hot-spot is formed as material that was initially gas heats late in the implosion and, via conduction, heats surrounding material that was originally solid. Eventually (at ignition time at full scale, or peak burn at 0.6 scale), the hot-spot in both cases is comprised of about 90% material that was originally solid..

At scale 0.9, the cryogenic targets can ignite, according to current modeling. To do so would require the calculated, but still to be tested improvement in hohlraum-to-capsule coupling efficiency obtained with the use of cocktail hohlraum walls. It would require surface roughnesses similar to the very best that has ever been achieved, on both the ice and the ablator. It would also require that all of the hohlraum physics and laser-plasma instability losses be in agreement with the low scattering obtained on Nova surrogate experiments with a high level of beam smoothing. It is also important to emphasize that these designs leave very little margin for less than ideal laser performance. Taken together, these uncertainties make it impossible to predict the outcome of an attempted ignition implosion at 0.9 scale. Achieving greater confidence in the proposed improvements in capsule coupling is crucial in reducing this uncertainty. Experimental studies on the Omega laser over the next few years will address this issue.

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.

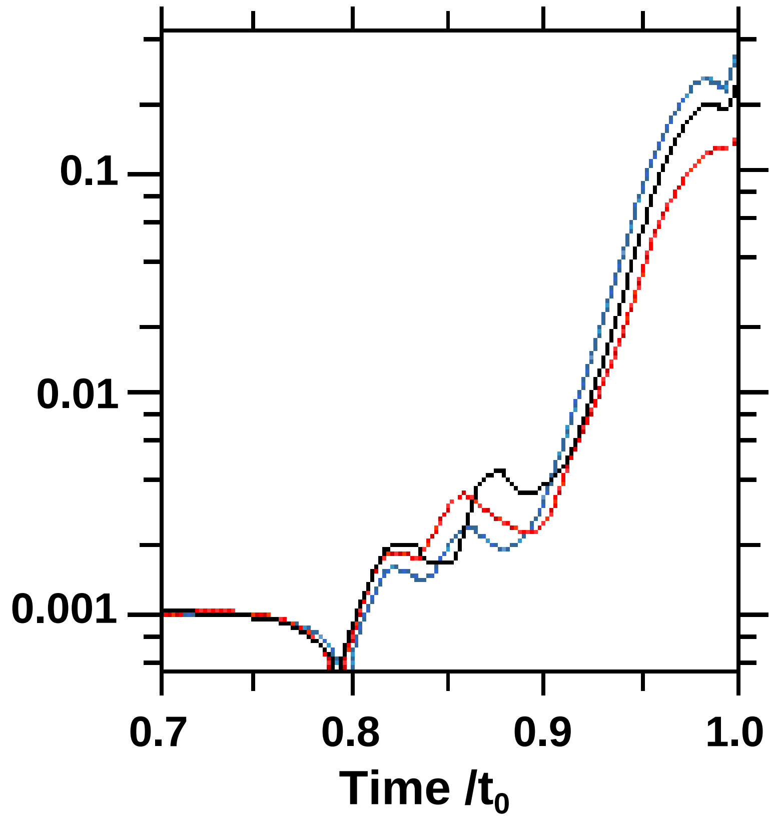

Figure 1. Perturbation growth vs. time for three implosions. The perturbation growth is measured as the rms deviation in the column density (ρr), normalized to the total ρr. The central curve is for a full scale polyimide ignition target, with the time normalized to ignition time. The upper and lower curves are for 0.6 scale targets, made of polyimide doped with 0.25% Ge (upper curve) and 0.5% Ge (lower curve). These curves are plotted with the time normalized to their time of peak burn,which is very close to 0.6 times the ignition time of the full-scale capsule. The 0.6 scale capsules can be used to mimic the instability growth in the full-scale capsule.

1- J. A. Paisner, E. M. Campbell and W. J. Hogan, Fusion Technology, 26, 755 (1994)
2- S. W. Haan, S. M. Pollaine, J. D. Lindl, et. al., Phys. Plasmas 2, 2480 (1995)
3- W. J. Krauser, N. M. Hoffman, D. C. Wilson, et. al., Phys Plasmas, 3, 2084 (1996).
4- L. J. Suter, E. Dattolo, S. Glenzer, et. al.. "Understanding and Modeling of Ignition Hohlraum X-ray Coupling Efficiency", Lawrence Livermore National Laboratory UCRL-LR-105821-98-4, p 171 (1998))
5- - B. J. MacGowan, R. L. Berger, S. I. Glenzer, et. al., Laser Beam Smoothing and Backscatter Saturation Processes in Plasmas Relevant to National Ignition Facility Hohlraums, Proceedings of the 17th IAEA Fusion Energy Conference, Yokohama, Japan (October, 1998), International Atomic Energy Agency, Vienna (1998).
6- L. Suter, J. Rothenberg, D. Munro, B. Van Wonterghem and S. Haan, Phys. of Plasmas, 7, 2092 (May, 2000)
7- H. Nishimura, T. Endo, H. Shiraga, Y. Kato and S. Nakai, Appl. Phys. Let., 62, 1134, (1993).
8- T. J. Orzechowski, M. D. Rosen, H. N. Kornblum, et. al., Phys. Rev. Lett. 77, 3544 (1996).
9- J. Rothenberg, "Ultra-fast pickets", private communication (LLNL, 1999).