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Deep Dive Topic: Approach to ignition

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Approach to Ignition*

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The current high-foot and related implosions have adequate CR and implosion velocity to ignite, but require improved finesse particularly in, but not limited to, implosion symmetry. This is being pursued.

The challenge of controlling drive symmetry is also motivating lower convergence ratio designs. These require higher velocity implosions and are also being pursued.

In general, three "paths" to ignition present themselves:

1) a path of "finesse" where effects that degrade the implosion with respect to 1D are systematically identified and corrected to the best of our ability, thus obtaining a relatively high-quality implosion at high convergence ratio (CR);
2) a path where we begin with a low CR hot spot with 1D-like behavior and gradually increase CR, repairing departures from 1D as CR is increased; and
3) a path of "energy" where we accept or realize, given enough experiments, that further improvements to the quality will be difficult and therefore we must just put more internal energy into the implosion to pass the ignition boundary.

Effectively, the finesse and CR paths "stretch" the implosion towards the NIF laser while the energy path "stretches" the laser towards the implosion. A combination of all of the above paths will be pursued.

The NAS adopted target gain >1 or ~2 MJ yield as the milestone for unambiguous demonstration of ignition on the NIF.

Definitions used in this paper for the purposes of physics discussion:

- 'Ignition' is the condition in the fusion fuel where the fusion power produced and coupled into the fusing DT is greater than the rate of energy loss from the fusion region due to electron conduction losses, bremsstrahlung radiation losses, and pdV work upon expansion.
- 'Propagation' is the process in which an ignited mass of fusion fuel heats and sometimes additionally compresses an adjacent un-ignited mass of fusion fuel bringing it to ignition conditions. This process happening in succession over-and-over again can lead to very large fusion energy releases from a much smaller investment in energy.

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- 'Gain' is a measure of fusion energy liberated divided by energy input into a specified region. Common gain metrics are[1] G_{fuel}, $G_{capsule}$, and G_{target} (or just G) which are the gains measured in the mass of fusion fuel, capsule, and fusion target (e.g. yield > incident energy). $G_{fuel} > 1$ has already been achieved.[2] $G_{target} \sim 1$ is often stated as the ignition condition, but we do not use that definition here.
- Traditional hot-spot ignition on the NIF requires 'ignition' in a hot-spot (~10-20 micrograms of DT) that then 'propagates' into a surrounding fuel layer (~170 micrograms of DT). 'Ignition' does not guarantee 'propagation.' An ignited hot-spot produces ~100's kJ of yield whereas the energy from the hot-spot propagating into the fuel yields ~10's of MJ potentially. Presently, the highest yield achieved on NIF is ~26 kJ with half this yield coming from alpha-particle self-heating.[3]

We treat ignition, propagation, and gain (fuel, capsule, target) as milestones along the way to target gain. This path allows assessment of progress in a stepwise fashion and helps identify what elements of a given implosion (we plan on multiple paths) may require further improvement in implosion quality as it is pressed to more extreme conditions. This path is more exploratory and conservative than "jumping" straight to high gain (the lesson from NIC).

Program milestones are:

1) Achievement of the 'ignition temperature' (4.3 keV): alpha-particle deposition self-heating is balanced by bremsstrahlung loss. *This has been demonstrated on the NIF*. Losses by electron conduction and hydrodynamic work still prevent ignition.
2) Alpha-heating dominates yield production, the yield is ~2x higher than what is predicted from pdV work alone:[4] burning is confined to the hot-spot. This occurs at hot-spot $\rho R_{hot\text{-}spot}$ ~0.15-0.2 g/cm^2 with T_{ion} > 4.3 keV and *has been demonstrated on the NIF*.
3) Ignition and limited burn propagation: hot-spot $\rho R_{hot\text{-}spot}$ ~0.3 g/cm^3 and total ρR_{total} ~1 g/cm^3. This has not yet been demonstrated on the NIF, limited by insufficient *hot-spot* areal density.
4) Robust burn propagation to high-gain: the confinement time, set largely by ρR_{total}, is long enough so as to allow T_{ion} to ramp up to many times the ignition temperature. The degree to which this is even possible with NIF energies is an open question.

Current efforts towards ignition

Obtaining high $\rho R_{hot\text{-}spot}$ requires as 1D an implosion as is practical and high velocity (which results in high no-alpha *T*). Obtaining propagation and gain requires high ρR_{tot} that is only usefully achievable in as 1D an implosion as is practical with minimal adiabat for maximum compression. High compression increases 1D margin, but high compression can make 2D/3D margin worse since departures from

1D are amplified by CR, hence the strategy of going for more modest implosions first then moving toward more stressing designs.

Since ignition (and therefore propagation and gain) starts with an igniting hot-spot, our strategy starts with making a hot-spot with sufficient $\rho R_{hs} T_{hs}$ by better controlling the imploding shell to pass the ignition boundary. These hot-spot focused implosions serve as integrated implosion 'diagnostics' that identify aspects of the implosions that must be corrected and serve as a test bed for proposed solutions. As more implosion control is demonstrated, the program will shift focus to improving the compression of the implosion shell, thus working towards steadily increasing ρR_{tot}.

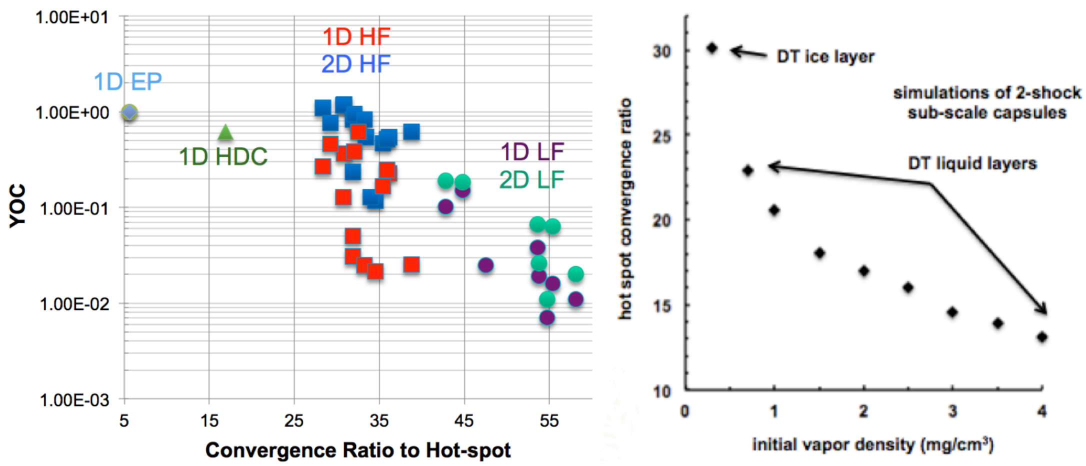

Fig. 1. (Left) YOC from 1D and 2D simulations[11]. are plotted vs. measured hot-spot CR for high-foot (HF) implosions. The 2D HF models generally match DSR, while the 1D models are high in DSR by ~25%. Also shown are the results for low-foot (LF), HDC Symcap, and exploding pusher (EP) implosions. As expected the lower CR implosions are closer to unity than high convergence ones. Generally, the points with YOC < 0.1 have ignited in the simulation. (Right) The expected CR range from wetted foam targets using the HDC ablator and HDC 2-shock pulse-shape.

Efforts along the implosion quality path presently include: 1) Pulse-shape modifications to increase DSR and reduce the hot-electrons[5]; 2) lower LPI and better control of time-dependent implosion shape[6]; 3) thinner tent structures and alternatives to the tent for holding the capsule in the hohlraum[7]; and 4) better controls on capsule finish and exposure to UV light (for CH capsules)[8].

Efforts along the CR path involve the development of a new experimental platform that employs wetted foam layer ICF capsules[9] and the 'Big-foot' design[10] that operates at low CR and very high implosion speed. Reduced CR is an effective way to reduce capsule instability growth and to improve robustness to low-mode x-ray flux asymmetries. For wetted foam targets changing the initial mass in the vapor controls the hot spot CR over a wide range (CR ~14 to 25), extending the range of CR covered by the high-foot experiments (CR ~28 to 38). The 'Big-foot' design operates at CR ~20. We plan to use the wetted foam capsules in a NIF experimental campaign to explore the relationship between hot spot CR and the robustness of hot spot formation. We expect that the predictive capability of hot spot formation is robust for a relatively low CR hot spot (CR ~15), but will become less reliable as hot spot CR is increased to CR >20 as suggested by existing data (Fig. 1).

Efforts along the energy path presently include: 1) design and testing of implosions alternate to indirectly driven hot spot ignition designs, 2) reduction of fuel payload to further increase implosion speeds well above 400 km/s to capitalize on the advantageous scaling of high Mach number, and 3) exploration of techniques to reduce NIF glass damage at high fluence and push the energy/power delivery envelope of the present facility.

Please see classified Appendix (document COPD-2015-0148) for additional discussion on ignition conditions relevant to the NIF ICF Program.

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