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Optimism is not a strategy: A white paper on how to give IFE a fighting chance to be real

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With NIF shot N210808, we now have an existence proof of ignition (i.e. Lawson-like criteria exceeded and capsule gain well exceeding unity) in the laboratory and it has generated renewed interest in IFE. However, it is important to recognize that ignition on the NIF has been much more difficult than what was originally envisioned. Moreover, the design for the target that actually obtained burning plasma (Kritcher, Young, Robey, et al., Nature Phys. 2022; Zylstra, Hurricane, Callahan, et al., Nature, **601**, 542, 2022) and ignition conditions is much different than the high gain design originally planned in the National Ignition Campaign (NIC; e.g. Lindl, Phys. Plasmas, **2**, 3933, 1995; Lindl, Amendt, Berger, et al., Phys. Plasmas, **11**, 339, 2004). In order to avoid squandering time and resources, the IFE community must learn the lessons of what happened on the NIF over the past decade.

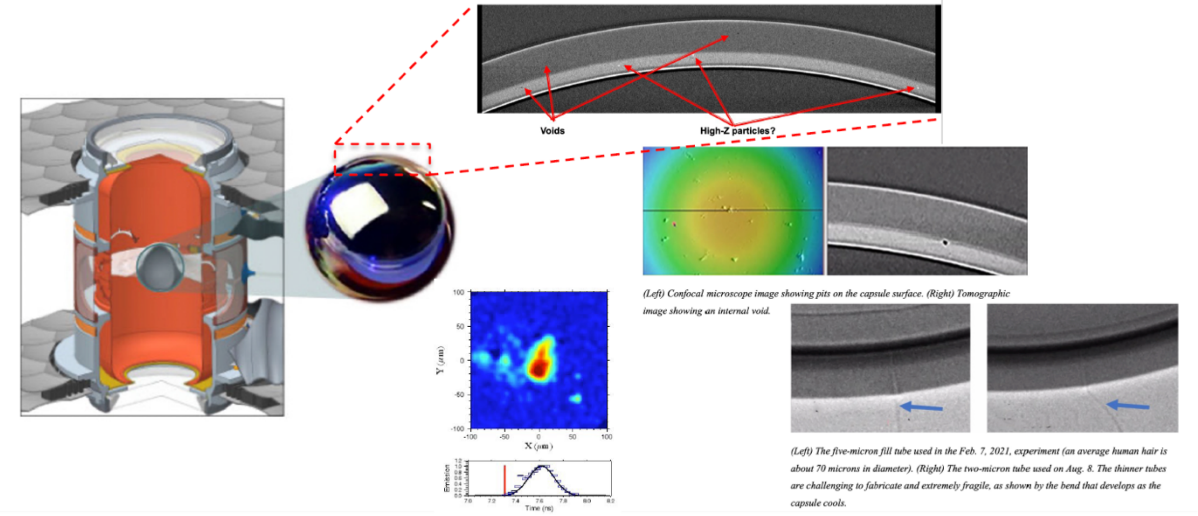
A common belief before the NIC was that a high gain (low adiabat) ignition design was synonymous with high margin against failure, but this belief was demonstrated to be incorrect by NIC and subsequent experiments. Despite decades of design effort and work on the scientific underpinnings, instead of obtaining the 1-10's of MJ of fusion energy expected (Haan, et al., Phys. Plasmas, **18**, 2011), the actual level of performance in the NIC was more than 1000 times less than hedged expectations (Lindl, et al., Phys. Plasmas, **21**, 2014). To be fair, all but the least stressing ICF designs tested on NIF, after NIC, performed below simulation projections, albeit after observed degradations were added to high resolution detailed simulations, the simulations are essentially consistent with experiment (e.g. Clark, et al, Phys. Plasmas, **23**, 056302, 2016).

Fundamentally, the same design features that make an ICF design high gain, a necessary feature for useful IFE, make it more sensitive to engineering aspects of the target and laser system (assuming laser drive) that we have less than perfect control over and more sensitive to physics where our understanding is incomplete. Namely, key lessons learned listed in the paragraphs below.

Symmetry Control: Indirect drive symmetry control was much more difficult than expected. We have learned to imperfectly manage asymmetry and often asymmetry (usually mode-1) appears anomalously (i.e. of unknown origin, even after post-shot investigation) or due to known causes such as capsule non-uniformity from fabrication (Casey, et al. PRL, **126**, 025002, 2021). Symmetry of the shell (fuel+remaining ablator) areal density (Hurricane, et al., Phys. Plasmas, **27**, 062704, 2020 and 2022), which minimizes residual kinetic energy (RKE; see Kritcher, et al., Phys. Plasmas, **21**, 2014), is the driving physics, so asymmetry means wasted energy. The hohlraum physics of symmetry control has so far favored shorter laser pulses, lower hohlraum helium gas fills (for LPI control), and larger case-to-capsule ratios (which is unfavorable for energy coupling to the capsule).

Stability Control: Indirect drive stability control has so far required a significantly higher design adiabat than desired (Dittrich, et al, PRL, **112**, 2014). Like asymmetry, we've learned to manage instability, yet mixing is still present and performance limiting on almost every implosion, even some the highest performing ones. Even when x-ray emission implies a relatively clean hot spot, spectroscopy often implies cold mixing of ablator into the cold DT fuel. Adiabat shaped designs (e.g. Peterson, Berzak Hopkins, et al., PRE, **91**, 031101 2015; Clark, et al., Phys. Plasmas, **21**, 112705, 2014; Milovich, et al., Phys. Plasmas, **22**, 122702, 2015), which had the promise of low fuel adiabat compression, yet high adiabat like stability have so far performed like high adiabat implosions in spite of having a higher total fuel areal density (Smalyuk, Phys. Plasmas, **23**, 2016), implying a performance disconnect between the shell of the implosion and the hot spot for adiabat shaped implosions.

Compression: Predictive capability and experiment diverge at lower adiabat, higher gain indicating an incomplete understanding of compression. In general, NIF ICF experiments appear stiffer than expected (Landen, et al., Phys. Plasmas, **28**, 042705, 2021). Leading hypothesis are ultra small-scale hydro-instability impacting the fuel-ablator interface region of the implosion, the statistical mechanics derived equations of state (EOS) models getting shock compression/rarefactions wrong, and x-ray preheat (levels and/or non-uniformity not modeled correctly).



(Left) Confocal microscope image showing pits on the capsule surface. (Right) Tomographic image showing an internal void.

(Left) The five-micron fill tube used in the Feb. 7, 2021, experiment (an average human hair is about 70 microns in diameter). (Right) The two-micron tube used on Aug. 8. The thinner tubes are challenging to fabricate and extremely fragile, as shown by the bend that develops as the capsule cools.

Figure 1: Not for lack of trying to resolve fabrication issues, even after years of development many capsule defects are presently impacting HDC ablators. Figure from T. Braun, et al., Diamond (HDC) capsules at LLNL (LLNL-PRES-825972). HDC ablators are not unique is this respect as all ablator materials exhibit implosion performance impacting defects of various types.

Target quality: Even high adiabat ICF implosions have been more sensitive to target quality than expected and many more damaging flaws are present in targets, in particular capsules, than expected. For crystalline materials, pits in the surface of capsules (albeit largely resolved at this time), voids in the interior of the shell, high-Z particles in the interior of shell, and high-Z particles on the surface of the capsule are continual challenges (see Fig. 1) even after years of effort on these problems. For plastic capsules, an unanticipated surface roughness increasing sensitivity to UV light was discovered (e.g. see Haan, et al., Fusion Sci. and Tech, **73**, 83-88, 2018).

Interior to the capsules the cryogenic DT fuel layer is prepared by a team of experts. Even with several days to a week preparation time of the cryogenic DT layer on NIF, only roughly 30% of DT layers are inside the quality spec set for high yield experiments.

Laser Delivery: Even high adiabat ICF implosions have been more sensitive to variability in laser delivery than expected. Variations in the rise to peak power, the cross-timing between beams, the power delivery in the peak, and the symmetry of the laser delivery (MacGowan, et al., HEDP, **40**, 100944, 2021) have negatively impacted implosion behavior. Higher laser energy has been more practically useful for increasing implosion performance than high laser peak power, albeit mode-2 symmetry control is more challenging with longer duration laser pulses (Callahan, PoP, **25**, 056305, 2018).

Strategy: Obtaining fusion performance increases in steps over time, and being willing to investigate problems experimentally, has been much more successful in terms of tangible ICF performance increases than the more optimistic short-term approaches that swing for the fences while downplaying potential problems. This is because the problems of obtaining ultra-high energy density are common to all concepts.

The above lessons provide guidance for an intensive physics and engineering R&D program that could be leveraged to increase the probability of IFE success. Given the lessons learned above, let's now translate the above lessons into implications for IFE.

The flexibility to test different targets and approaches is a great advantage of ICF over magnetic fusion energy (MFE), so any new IFE focused facility should not be built around a single point design, but instead allow for a range of target designs because some exploration of different designs will almost certainly be needed.

It needs to be remembered that ICF implosions require dramatically more finesse and precision engineering control of the target and laser with limited energy. So, higher delivered laser energies greatly reduce the likelihood of ICF implosion failure and opens a larger target design parameter space, especially in target scale size, as we seek high gain for IFE. Increased energy to an implosion compensates, to a degree, for less-than-ideal target quality and less than perfect pulse shape delivery. Any proposed new IFE facility should have extra margin in energy.

Even after years of skilled engineering R&D effort, the present indirect drive targets for NIF are costly, complicated, fragile, and have many performance limiting defects. So, a major target fabrication R&D effort will be needed for IFE to reduce target cost, reduce target complexity (this goes hand-in-hand with target design), while dramatically increasing robustness, and decreasing the presence of defects. Engineering features like the fill-tube and tent that presently hold the capsule in the hohlraum in IDD targets could not possibly survive the projectile-like target delivery systems imagined for IFE, yet we know the gossamer thin tent membrane that holds the capsule in the hohlraum has been found to generate perforations in the implosion, and alternate tents have proven to be so fragile that only 3 alternate tent targets (all of the same type) have survived transport to target chamber center for experiment (e.g. Ralph, et al., Phys. Plasmas, **27**, 2020) even after years of attempts.

These realities beg the question of how an IDD target that is minimally damaging for the physics of the implosion can be made to work with any type of IFE projectile target delivery system? Foams filling the volume between the capsule and hohlraum has been proposed as a tent membrane work-around, but foam density needed was evaluated to be incompatible with known LPI and hydro-coupling issues, but perhaps all ideas have not yet been fully explored.

Wetted foams *inside* capsules are the primary proposal for bypassing the complexities of forming a cryogenic DT layer for an IFE system, yet we know that the presence of foam, and the large fill-tube aperture needed to make the foam, will increase x-ray losses as compared to a standard DT layer. For IFE it is worth examining additional ideas on making a DT layer-like configuration without foams (e.g. form a DT layer from liquid dynamically using acoustic cavitation physics; capsule spin to generate centrifugal forces, etc.).

While a stunning engineering achievement, the NIF laser system has ongoing laser pulse quality delivery issues that impact ICF performance. The bottom line for an IFE is that any new IFE focused facility will need specs on laser delivery that are tighter than those presently on the NIF.

More research is needed on what is presently limiting high compression implosions from functioning as expected. High compression and high gain go hand-in-hand, so it's a necessity for useful IFE to understand the limits of DT compression in an ICF implosion.

Exploring target design ideas to further mitigate hydro instability, while being consistent with target engineering and laser pulse-shape delivery realities is essential for limiting x-ray energy losses and maximizing potential compression in an ICF implosion.

Having an existence proof of ignition (LLNL-JRNL-830617-DRAFT) in the laboratory is extremely exciting and it should motivate further work to see if we can make IFE a reality, but let’s not gloss over how difficult it has been to get here and how many physics and practical problems remain to be solved. Only by facing reality and acknowledging all the challenges can we identify and solve the issues that stand in the way of practical fusion energy.

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