Integrated Design of Robust System for Inertial Fusion Energy

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Executive Summary:

For inertial fusion energy (IFE) to be successful, designs need to work robustly including both target physics and engineering considerations. For a power plant to be reliable and have a high operating capacity factor, the integrated design of the target, driver, target fabrication, target injection system, and chamber all need to work together in way that is robust and repeatable to expected variations. One of the lesson's learned from our experience at NIF is that designs that are sensitive have not performed as expected – even in single shot mode. The lesson's learned from NIF should be folded into creating integrated designs for IFE and for evaluating the tradeoffs between the different parts of the IFE system. To do so, we propose using the NIF 1.3 MJ yield shot/design (N210808) as a starting point of a study of the feasibility of indirect drive designs for IFE. If the hohlraum inefficiency precludes indirect drive, the study would include direct drive or fast ignition versions of this design.

Introduction

The NIF shot N210808, which achieved ignition by the Lawson criteria and target gain of 0.7, is the highest performing, laser-driven ICF shot to date. Getting to this point has taken just over 10 years of experimental work on NIF to get the target physics and design (including diagnostics), the NIF laser, and target fabrication integrated. To achieve these results, we have gone through a process of developing a design (using theory, simulations, and previous data), testing this design and pushing it to its limits, learning what those limits are (using new diagnostics, simulations, analysis), and then using that information to develop a new design. We have gone through this iteration several times over the past 10 years of NIF operations.

The initial design for NIF was a high gain, low adiabat design. While simulations suggested that this design had margin via high yields, the experiments told a different story. The capsule design ended up being very sensitive to engineering features such as the support tent. The hohlraum was susceptible to laser plasma instabilities that backscattered a large amount of energy out of the target. This meant that getting even 10% of the 1d performance was difficult.

The more successful designs, including the "Hybrid E" design [1, 2] used on N210808, are more forgiving of imperfections. Even with this improved robustness, this design seems to be sitting on the ignition cliff – where small changes in the inputs can produce large changes in the fusion yield. For a working power plant, having a robust, repeatable design is a must.

Design study based on NIF Hybrid E shot N210808

Although the ICF target physics is complex, we have found that the essential behavior can often be explained using very simple physical models. Some examples include a model for the capsule approximating it as a set of pistons operating on a single hotspot [3] or the hohlraum asymmetry being dominated by the ingress of the “gold bubble” plasma [4, 5, 6]. By coupling these simple models together, these models can then be used to scope out design space for future designs.

The simplest model is to hydroscale a design. The design can then be studied using more sophisticated tools such as radiation hydrodynamics model. This type of analysis was pursued for the ICF “2020” study. 3d radiation hydrodynamics simulations of the capsule including all known degradations were performed [7] as well as large ensembles of 2d simulations [7a]. However, designs that are hydroscaled from current designs tend to require very large amounts of projected laser energy/power so are not very attractive for power plants that require significant gain in order to keep the recirculating power fraction in the power plant low.

Slightly more complex models can be used to scope out design space by coupling the simple models for the components of the target together. Constraints from the laser such as limits on laser power and energy, for example, can also be included as well. An example of coupling a simple model for hohlraum drive and asymmetry along with a rocket model for the capsule dynamics is shown in reference [8].

We propose using models developed for NIF to scope out integrated designs for inertial fusion energy. To do so, we propose to update our simple models to scope out designs that have the robustness and high gains needed for IFE. These designs will be grounded in current NIF experiments – although getting the performance needed for IFE will likely require significant extrapolation from today’s design. Once promising parts of parameter space are identified, more detailed simulations using our radiation hydrodynamics and laser plasma instability codes can be used to further refine the designs and identify experiments that would be needed to test these concepts.

Given what we have learned from the NIF experiments, we should also re-evaluate the tradeoffs between indirect and direct drive for the integrated system. This will include practicalities such as the complexity in injecting targets into a hot chamber and the ability to track the target in the chamber and point the laser beams to the required accuracy. The inherent inefficiency of the hohlraum for indirect drive should be weighed against the challenges of beam pointing, target survivability in the chamber for direct drive.

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