Status and Plans of the National Ignition Campaign

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Introduction

A primary goal of the National Ignition Campaign (NIC) is to demonstrate fusion ignition and burn by Inertial Confinement Fusion (ICF)—a goal that has long been recognized as a physics and technology grand challenge. The NIC is rapidly moving forward with new experimental results and code development and developing a large body of knowledge. As such, it is quite difficult to adequately cover all of this information in a single day of presentations. This document provides a summary of and supplements the information presented at the NIC Status Update meeting held on May 31, 2012.

Overall Status and Progress

Progress on NIF capabilities and the NIC experimental campaign in the past year has been considerable and can be summarized as follows:

- Diagnostics, targets, and laser capabilities have reached the levels of performance needed for a systematic optimization of ignition-scale experiments.
- Hohlraum temperatures have been achieved which exceed the 300 eV point design goal with nearly constant laser energy coupling of 84±2% for energies from 1.2-1.7 MJ.
- Hot spot symmetry, which meets ignition specifications, has been achieved using a combination of power balance and wavelength shifts between the inner and outer beams, and an additional wavelength shift between the two cones of inner beams.
- The dependence of implosion velocity on ablated mass has been accurately measured and is consistent with code simulations within the error bars. These measurements have enabled the identification of a mix performance boundary which depends on the velocity and the remaining unablated mass which will be a focus of the go-forward experimental plan.
- The NIC experiments have demonstrated an increase in the fuel areal density (ρr) from ~35% to ~85% of that specified for the point design by implementing systematic improvements to the shock timing, hot spot symmetry, and laser pulse shape.
- The stagnation pressure of the hotspot is within ~40% of point design goals.
- The ITFX of recent experiments has reached ~0.1 for the first time. The improved performance was achieved at a lower implosion velocity and lower laser power than the previous best performing capsule, providing more margin for the path to ignition.

It is important to note that with the fuel ρr currently obtained, an increase in the experimental yield by a factor of about five would achieve alpha dominated burn. Based on our progress, we have identified a set of experiments that have the potential to bridge this gap in yield. This initial set of experiments, planned for the balance of CY2012, includes development of new experimental platforms to broaden the range of data available.

Recent progress in ignition has been achieved by a combination of expanding the physics issues considered in experiments and enhancing facility experimental capability. Experimental platforms have been developed for optimizing key implosion attributes including shock timing in the cryogenic fuel, radiation symmetry at early time in the initial picket of the pulse, symmetry of the imploded capsule at peak compression, and radiography of the imploding shell to enable measuring implosion velocity and mass ablated from the imploding shell. Commissioning of the cryogenic target manipulator, a key piece of facility infrastructure that enables implosions with cryogenic fuel layers, was completed in September 2010. Qualification and integration of key experimental platforms and experimental infrastructure were the primary focus from September 2010-February 2011. Layered experiments using the first precision shock-timed pulses began in June 2011.

Since that time, a wide range of advances in target performance has been made, including:

- Increased implosion velocity by changing the preheat shielding dopant from Ge to Si.
- Obtained improved symmetry by slight modifications to the hohlraum geometry.
- Demonstrated improved drive efficiency by changing the hohlraum material from Au to Au-coated U.
- Demonstrated implosions with improved adiabat using pulses with a modified fourth pulse rise and longer drive.
- Attained higher areal densities using longer pulses at peak power to prevent decompression of the shell during final convergence.

As target performance improved, the effect of mix on implosion performance has been observed, quantified, and is being investigated. In addition, the experimental platforms have become more capable:

- Steady advances in laser performance enabled the longer pulses requiring increased laser energy used in the recent experiments:
  - During the March and April 2012 experiments, the NIF laser routinely delivered pulse energies of 1.45-1.7 MJ with powers over 400 TW. NIF is on track to deliver the full design energy and power of 1.8 MJ and 500 TW in FY2012.
- The number of diagnostics and their performance has continually increased and improved. Approximately 60 diagnostic systems are now in use.
- There have been significant advances in the characterization and precision of targets used for these experiments.

Integration of these capabilities with the experimental platforms has been a key element in the progress toward ignition.

Experimental Ignition Threshold Factor (ITFX)

One metric for expressing progress toward ignition is the Experimental Ignition Threshold Factor (ITFX). The ITFX depends upon the experimentally measured neutron yield and the ratio of down scattered neutrons to unscattered neutrons (dsr) and is proportional to areal density (ρr) of the fuel. ITFX is related to the generalized Lawson criterion and is normalized so that an ITFX of 1 is defined as the condition where the chance of a yield greater than 1 MJ on a given shot is 50%. Progress toward ignition can be graphically represented as shown in Figure 1 where cryo-layered target neutron yield is plotted versus the dsr where the contours drawn represent constant ITFX.

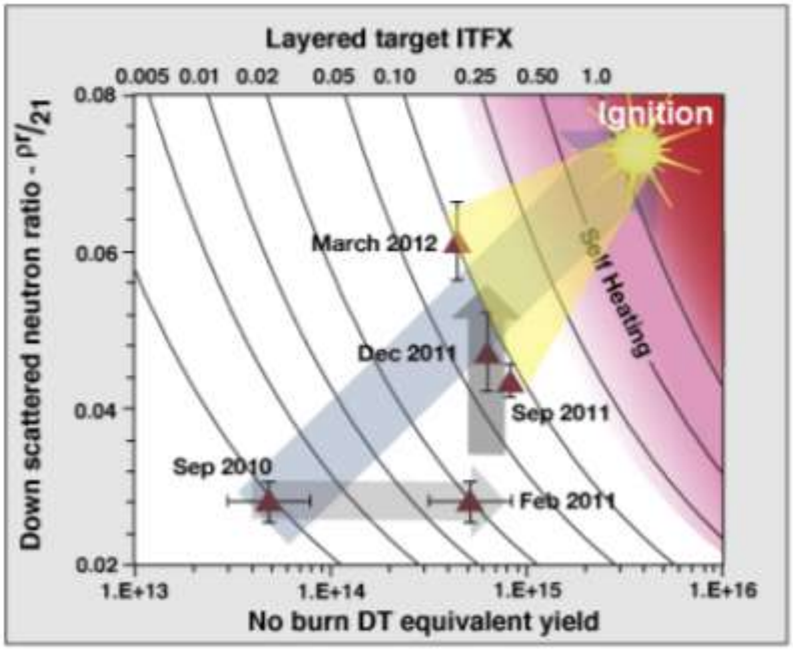

Fig. 1: Fuel ρr is now at about 85% of the ignition point design but we need to increase “no burn” yields ~5X to get into the alpha-dominated self-heated regime.

The yields plotted are those arising from compression during the implosion process and do not include enhancements from alpha deposition that become significant as the implosion quality approaches that required for ignition. This yield is adopted because it provides a metric for the underlying quality of the implosion needed to get into a regime where the alpha particle deposition becomes significant. The ignition regime is above ITFX of 1 while the alpha dominated regime, in which the yield enhancement from alpha particle deposition exceeds the yield from compression alone, occurs for an ITFX of ~0.3—0.5. Progress in ITFX can be summarized by the following:

- Significant improvement in ITFX is shown between the first cryogenic layered implosion in September 2010 and February 2011. This improvement, mostly in the neutron yield, was realized by increasing the laser power and performing initial shock tuning experiments. Target improvements were also realized by preventing frozen condensation on the laser entrance hole windows.
- During 2011, ITFX to was increased to ~0.08. This was achieved with improved shock timing as well as by increasing implosion velocity using Si ablators, increasing laser performance, and improving implosion symmetry.
- In 2012, the slope of the rise of the fourth pulse was decreased producing an implosion with higher compression and lower adiabat. The length of the fourth pulse was extended to better maintain compression of the shell during final convergence producing a higher dsr, or ρr, resulting in an improved ITFX of ~0.1 at significantly lower velocities and decreased drive energy.

ITFX alone does not capture progress in the performance of recent layered implosions. Although ITFX only increased by about 25% from September 2011 to March 2012, the present implosions provide a much better path to ignition.

- Present experiments produce higher compressed fuel densities and higher areal densities, ~85% of the ignition point design.
- The pressure in the hot spot is ~140 Gbars, ~ 40% of the ignition point design.
- These conditions were obtained using peak powers of 320 TW with implosion velocity of ~300 km/s well below the NIF rated performance of 500 TW, substantially increasing the laser performance margin available for ignition.

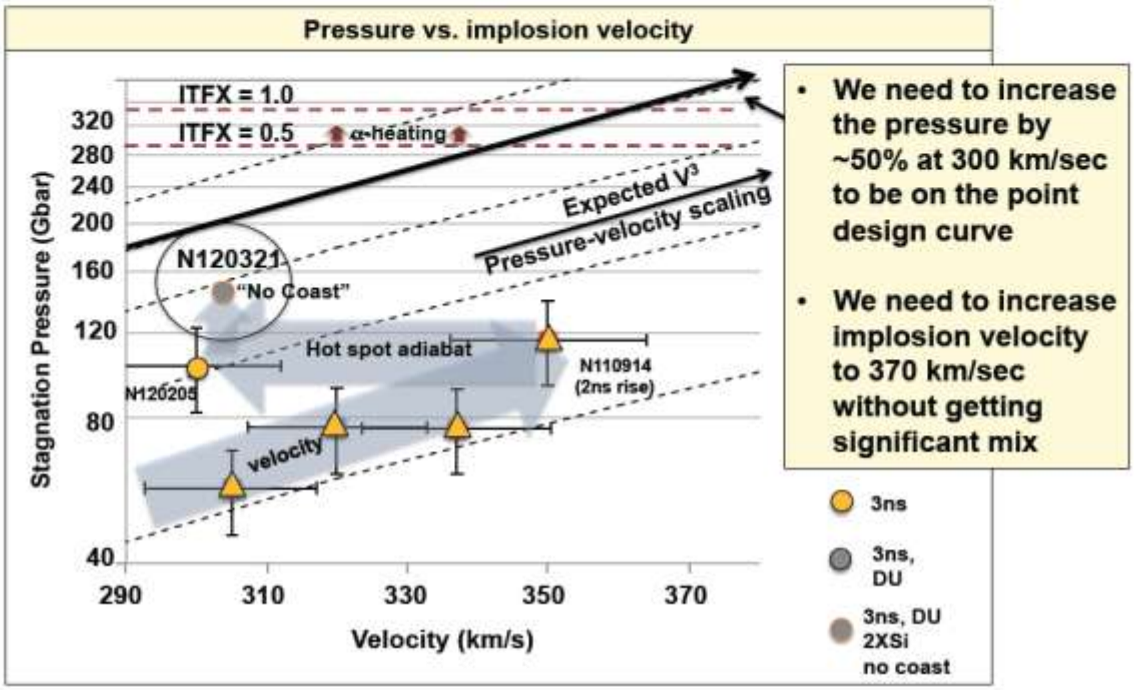

Figure 2: Using "no coast" pulses, with extended duration at peak power to better maintain compression of the shell prior to final stagnation, we have achieved the highest pressure to date (~140 Gbar) at 50-km/sec lower velocity than the previous high pressure in Sept 2011.

In contrast, the best implosions in CY2011 achieved ~65% of the areal density of the point design with an implosion velocity of ~340 km/sec and 420 TW of laser power. Also, these earlier implosions had lower peak hot spot pressures, ~30% of the ignition pressure at ITFX = 1. Since we expect peak velocities to be limited to ~370 km/sec, achieving the improved performance at a substantially lower velocity provides a better path to ignition since ITFX is a strong function of velocity. Figure 2 shows the improvements in peak fuel pressure versus implosion velocity. The challenge is to increase the peak fuel stagnation pressure about 50% at 300 km/sec and then scale present implosions to velocities of ~370 km/s using the increased laser power margin without getting significant mix.

Mix and Cold Fuel Symmetry

Mix of the ablator into the fuel can result from instabilities at the ablation front and at the fuel-ablator interface. Mix becomes more of an issue as the implosion is optimized to produce higher convergence and higher compression. Mix signatures include a reduced yield and ion temperature and high x-ray brightness from the hot core due to the ablator mixing into the compressed fuel. Special targets can use spectroscopic signatures to measure mix. The effect of mix can be seen in Figure 3 where the neutron yield is plotted versus the inferred ablator mass remaining at peak velocity for the recent high areal density implosions. The remaining mass is a measure of the amount of material that instabilities at the ablation front must penetrate to mix ablator into the hot fuel. Target yields are significantly reduced for implosions with less than 0.35- 0.4 mg of remaining mass. This is about 12% of the initial ablator mass. X-ray brightness and spectroscopy measurements also confirm this trend. The red dashed line in Figure 3 is the remaining mass in the ignition point design. The observed “mix cliff” occurs at a remaining mass ~30-40% greater than that used in the point design. Targets designed to maintain the larger remaining mass require thicker ablators and more energy to accelerate the shell to the same velocity.

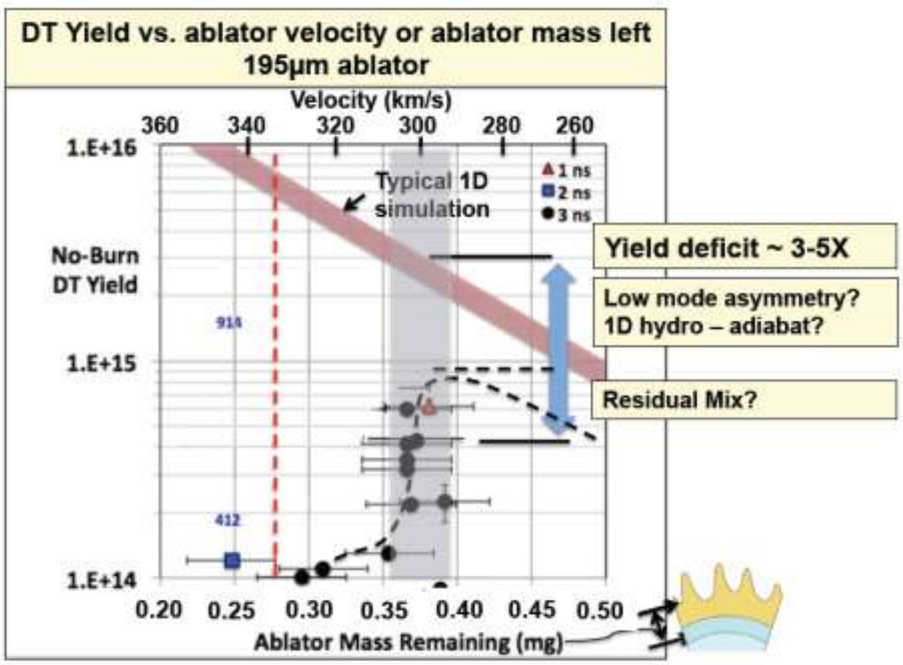

Fig. 3: We find a fairly sharp performance boundary with ~30-40% more ablator mass remaining than that for the point design. Increasing the yield a factor of 3-5 at the current velocity will be a focus of upcoming experiments

There are various possible explanations for the required increase in remaining mass in the current experiments. These include unmeasured sources of perturbation, growth rates which exceed those currently calculated, and long wavelength variations in the fuel thickness that make it easer for the ablator to penetrate through the resulting thin region. Experiments are being developed to test all of these potential issues. Improvements to the target roughness and laser power balance that could reduce the required remaining mass are also being pursued.

In addition to the mix cliff, Figure 3 shows that yields in present experiments are ~3-5x lower than calculated yields. The solid red band shows the predictions of yields from 1D simulations as a function of remaining mass. The simulations are for typical implosions with this ablator thickness and target size and have been adjusted to match the observed shock timing and shell trajectories. Understanding this difference and reducing the magnitude of the difference between experiments and simulations are important for ignition target performance. The simulations show that if the targets were performing at the calculated 1D levels of yield, alpha deposition would be significantly enhancing the yield even at these lower velocities.

A potential source of this yield deficit could be low mode asymmetry of the cold fuel and ablator. Measurements of the isotropy of the neutron yield, the neutron down scatter spectra, and images of the down-scattered neutrons suggest that the cold fuel likely has a higher areal density at the poles of the implosion along the axis of the hohlraum than around the equator. A low mode asymmetry may result in less efficient transfer of the shell kinetic energy to thermal hot spot energy and conversion of the kinetic energy to mass fuel motion instead of thermal energy as well as potentially enhancing mix as indicated above. In addition to minimizing these low mode asymmetries, further optimization of the peak power pulse shape beyond the simple variations in the rise times tested to date may also be required to achieve increased hot spot density and improved yields.

Experimental plan

As mentioned above, with the current fuel ρr, if yields of the experiments are increased by a factor of about 5, we would be at the threshold of alpha dominated burn. The initial set of experiments planned for the balance of CY2012 is summarized below. There will be three principal elements of the experiments requiring development of several new experimental platforms designed to broaden the range of data available:

- Implosion performance using thicker ablators and varying dopant concentrations
- Enhanced radiography of the implosion
- New platforms for improved understanding of target performance

The planned experimental campaign will be exploring the performance of ablator shells that are 10-20% thicker than current targets, driven by laser power and energy of up to 500 TW and 1.8 MJ, respectively. We expect these experiments to allow us to increase the implosion velocity achievable without significant mix. The effect of variations in the ablator Si dopant concentrations and increasing the fuel layer thickness on reducing mix will also be explored. A new platform to measure the growth of perturbations seeded at the ablation front via face-on radiography is also being pursued.

To better quantify and minimize the magnitude of the long spatial scale variation in the fuel ρr, the ignition campaign will be implementing two advanced radiography techniques: 2D radiography of the imploding ablator and Compton radiography of the fuel at peak compression. In conjunction with the development of these techniques, the campaign will implement target fabrication and laser power balance improvements designed to reduce long spatial scale perturbations in the targets, along with optimization of the hohlraum geometry and the symmetry of laser energy delivered to the hohlraum.

To better optimize the 1D pressure history on the capsule to maximize compression, the campaign will implement a new experimental platform with the goal of extending the keyhole pressure measurements to higher shock velocities and another platform to better quantify the x-ray flux arriving at the capsule. In addition, a new 1D radiography technique, Refraction Enhanced Imaging (REI), will be pursued to enable direct imaging of fuel radius versus time and thickness in cryo-layered implosions.

Advances in the Underlying Science and Modeling of ICF

Development of the underlying science of ICF has been a decades long process. By its nature, the scientific challenge of ignition requires the integration of an exceptionally wide range of physical phenomena. ICF computational models incorporate this accumulated knowledge into a system of equations, algorithms, and databases, with calculations carried out on computers where the capabilities have increased more than 3 orders of magnitude in the past decade. The models were developed and tested using a wide range of experiments on Nova and Omega as well as other facilities. However, these experiments were carried out with nearly a factor of 100 less energy than NIF. Accordingly, these models have not been tested over the full range of spatial and temporal scales or conditions of temperature and density required for ignition experiments.

Because of the complexity of the scientific issues involved, and the difficulty of solving the equations describing these phenomena, even with today's computers these computational models necessarily involve approximate solutions of the relevant physics. While recognizing that there will inevitably be areas where the models prove inaccurate, a key challenge in the pursuit of ignition is to identify ways to utilize the models together with experimental data from the campaign, to optimize progress toward ignition.

To achieve this goal, the NIC has been organized around the four high level key attributes of an ICF implosion and the data that would be required to optimize these attributes. These attributes are the implosion velocity, fuel adiabat, hot spot shape, and mix of ablator into the main fuel and hot spot. The expectation has been that in some cases, the models would prove adequate to specify experiments that would achieve the required performance in relatively few iterations. In other cases, we expected that the models might disagree with the data to a sufficient extent that additional experiments, which probed more deeply into the underlying physics, would be necessary. This approach has allowed the NIC team to move quickly through those areas of the physics where the models proved to be adequate for rapid progress while focusing resources on the areas where the data is at greater odds with the models.

Examples of new experimental platforms developed to enable a deeper understanding of certain key processes include the mirrored keyhole target for optimizing the symmetry of each of the 4 shocks generated by the laser pulse, and extensions of the convergent ablator platform to enable measurement of the shell trajectory and shell thickness over almost the entire implosion trajectory. As described above, the NIC is currently developing a variety of new experimental platforms in response to recent findings. This approach helps identify those areas of the underlying physics where improvements would have the largest impact, both in current experiments, and for future applications where a more a priori predictive capability would allow more rapid convergence to the required performance. In advance of experiments conducted so far, it was not possible to know which areas of the physics would prove to be the most challenging.

Although improvement to the models generally occurs over longer time scales than typical elements of the ignition campaign, a number of improvements have been incorporated since the initiation of experiments in 2009. Examples of improvements to the models include:

- The DCA NLTE atomic physics model
- A non-local electron transport model
- An inline model of cross-beam transfer for improved hohlraum modeling,
- Improved equations of state for the CH ablator

The multiple time scales involved in the use, testing, and improvements to the models is depicted schematically in Figure 4. Relying on the physical foundations of ICF developed prior to the start of experiments on the NIF, the models were utilized to develop an ignition point design along with specifications for the NIF laser, targets, diagnostics, and experiments as well as an experimental strategy. Once experiments started, the predictions of the models must be modified in real time to take advantage of the knowledge created by the new data.

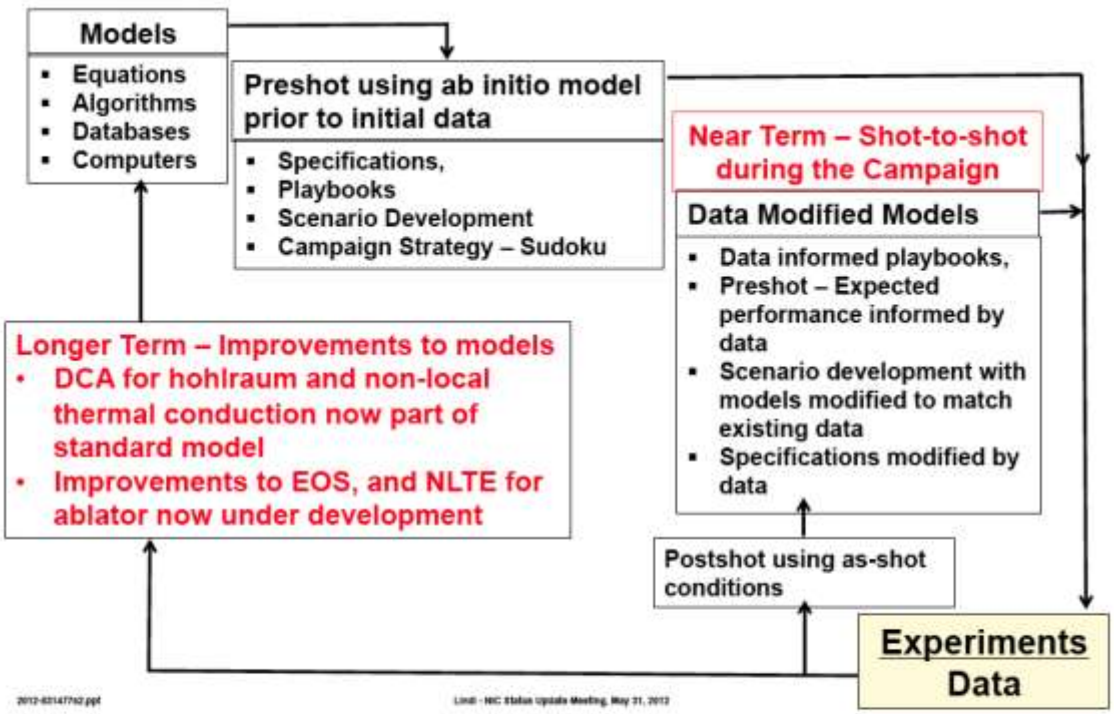

Figure 4: There are multiple time scales for the use and evolutions of numerical models within the NIC. On a time scale that generally takes months to years, the underlying physics in the numerical models is improved in response to new data, improved theories, advances in algorithms, and advances in computational capability. On a shorter time scale, the NIC has adopted an approach to using the models which allows the campaign to incorporate new data in an iterative way as we move through the campaign

While work on the underlying physics of the models proceeds on a longer time scale, in parallel with learning from experiments, the NIC has adopted an approach to using the models that allows the campaign to incorporate new data in an iterative way as we move through the campaign. An example of this approach is shown in Figure 5 in which the radiation drive is modified so that the resulting capsule 1D implosion matches the principal 1D data from the shock velocity experiments and the backlit implosion trajectory data. These two sets of data provide the best information available to constrain the 1D implosion attributes. We then utilize such a 1D calculation to assess the expected impact of 2D and 3D features on the implosion and on the expected performance of cryo-layered implosions.

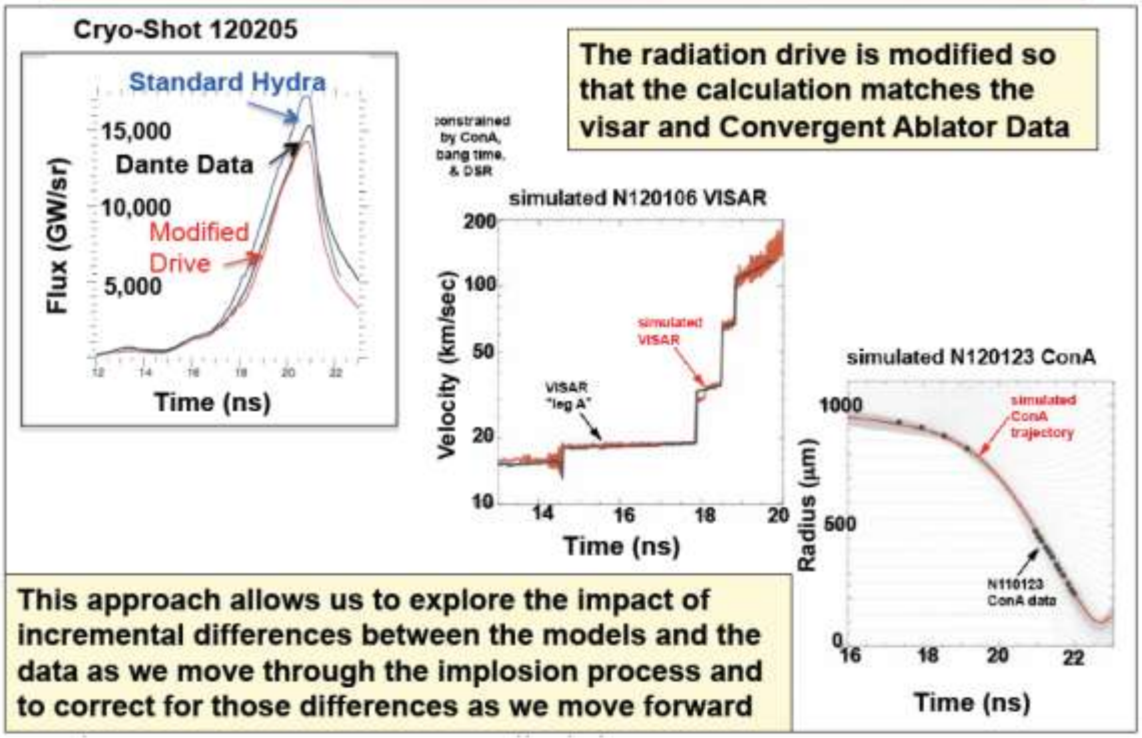

Figure 5: We have developed a standardized approach for generating 1D capsule drives used in calculating cryo-layered capsule performance. While improvements to the underlying physics are being developed on a longer time scale, this approach allows the NIC to utilize existing models of ICF physics while incorporating the impact of differences between the models and data as the campaign progresses through an optimization in performance.

This approach allows the NIC to explore the impact of incremental differences between the models and the data and to correct for those differences as the campaign moves forward. This process is not unique. Differences between measurements and calculations could be due to a variety of uncertainties in the physics models including such issues as the equation of state and opacity of various materials, LTE and NLTE treatments of the dynamics, as well as numerical algorithms and numerical convergence challenges, among others. Adjustment to the drive, as shown in Figure 5, provides a simple way of accounting for differences between measurements and predictions. These adjustments also motivate scenario testing, which can lead to improvements being made in the physics models as well as identifying additional experiments. In this particular example, the experimental data have resulted in improvements to the CH EOS, the NLTE modeling of the ablator and hohlraum, and experiments to measure more directly the X-ray flux seen by the capsule (as opposed to through the LEH), and ablation pressure measurements through the entire pulse. In practice, we do a variety of scenario testing wherever there are substantial differences between experiment and simulation to identify potential sensitivities to uncertainty in the underlying physics.

As described above, the first complete pass at precision optimization of ignition-scale implosions occurred from May 2011 through April 2012. Having carried out a full cycle of experiments through each of the key implosion attributes, we reached the point where it is possible to identify in the go-forward plan the key areas of the underlying physics that could benefit most from further improvement along with experiments and diagnostics to enable those improvements. With this objective in mind, the first formal international workshop on the Science of Ignition on the NIF was held May 23-24, 2012 and a report will be forthcoming. Possible experiments identified at the workshop included, among others:

- Planar experiments to evaluate Richtmyer-Meshkov growth during the early phase of an ignition pulse.
- DT release experiments, in both the Keyhole and planar geometry, as the initial shocks pass through the DT fuel layer into the gas fill.
- Ideas for directly measuring the strength and timing of the stagnation shock utilizing the Keyhole geometry.
- Planar experiments for looking at the physics of alternate ablators which could include High Density Carbon (HDC), Be, and B_4C.
- Hohlraums with different Z gas fill to look at the impacts on laser-plasma interactions (LPI).

As the ideas for these and other experiments mature, they can be incorporated into the ignition campaign and the broader HED campaign on the NIF or on other facilities, as appropriate.

Summary

A primary goal of the National Ignition Campaign (NIC) is to demonstrate fusion ignition and burn by Inertial Confinement Fusion (ICF)—a goal that has long been recognized as a physics and technology grand challenge. The NIC is rapidly moving forward with new experimental results and code development and developing a large body of knowledge. Continuing progress in all aspects of the technology and operational systems, experimental platforms and codes have enabled a robust experimental program to understand the physics of ignition scale implosions and to iteratively improve the performance of the implosions as our knowledge base has grown.

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