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Performance metrics for Inertial Confinement Fusion implosions: aspects of the technical framework for measuring progress in the National Ignition Campaign

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Abstract

The National Ignition Campaign (NIC) uses non-igniting "THD" capsules to study and optimize the hydrodynamic assembly of the fuel without burn. These capsules are designed to simultaneously reduce DT neutron yield and to maintain hydrodynamic similarity with the DT ignition capsule. We will discuss nominal THD performance and the associated experimental observables. We will show the results of large ensembles of numerical simulations of THD and DT implosions and their simulated diagnostic outputs. These simulations cover a broad range of both nominal and off-nominal implosions. We will focus on the development of an experimental implosion performance metric called the experimental ignition threshold factor (ITFX). We will discuss the relationship between ITFX and other integrated performance metrics, including the ignition threshold factor (ITF), the generalized Lawson criterion (GLC), and the hot spot pressure (HSP). We will then consider the experimental results of the recent NIC THD campaign. We will show that we can observe the key quantities for producing a measured ITFX and for inferring the other performance metrics. We will discuss trends in the experimental data, improvement in ITFX, and briefly the upcoming tuning campaign aimed at taking the next steps in performance improvement on the path to ignition on NIF.

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I. INTRODUCTION

Fusion ignition is a threshold phenomenon [11]. A standard metric of implosion performance for an ignition capsule filled with DT fuel is the neutron yield. As implosionand conditions improve, the neutron yield increases relatively slowly until the onset of ignition is reached. At this performance threshold, the yield increases by orders of magnitude. Once robust conditions are reached, the yield reaches a plateau set by the burn-up fraction of the fuel. A challenge for ICF design has been to develop a performance metric that indicates the quantitative implosion performance – essentially a measurement of distance from the ignition threshold. This problem of judging the proximity of the ignition threshold has been solved in a number of ways. For the purpose of designing DT ignition targets, the Ignition Threshold Factor (ITF) [3] is the standard tool. This technique uses features of the assembling fuel to characterize the robustness of the impending hot spot formation in the presence of heating by alpha particle energy deposition and the resultant feedback on the implosion hydrodynamics. It has proven to be a fundamental tool for determining the quality of ignition capsule designs for the National Ignition Campaign (NIC).

Other complementary metrics judge the robustness of an implosion by quantifying the hydrodynamics of fuel assembly in the absence of feedback by alpha heating. These metrics include the Generalized Lawson Criterion (GLC) [15], the hot spot central pressure (HSP), and the ignition threshold factor (eXperimental), or ITFX [13, 14]. All three of these require estimates or observations of hydrodynamics quantities from non-heating implosions. The GLC, developed from simulations and scaling laws, uses the neutron-averaged conditions of the hot spot and surrounding cold fuel to construct an ordering parameter for the yield in an analogous implosion that can experience thermonuclear heating. Likewise, the HSP and ITFX use hydrodynamics assembly properties, but with an emphasis on inferrence or direct observation in NIC experiments. We will call GLC, HSP, and ITFX collectively the non-heating metrics.

These metrics are all in use by the NIC, an experimental program aimed at achieving ICF ignition on the NIF. The NIC is composed of sequences of tuning experiments [9] to improve basic features ICF implosions: shock timing, hot spot symmetry, implosion velocity, and shell instability or mixing. Basically, the tuning operations aim to improve the input conditions layed out by the ITF. The improvements made during these tuning campaigns are then observed in the implosion of non-heating, layered cryogenic targets with deuterium-poor fuel layers called THD (tritium hydrogen deuterium) targets [4]. The THD targets are constructed with low reactivity fuel so that they produce enough neutron yield to be diagnosed, but not enough to hinder xray diagnostics or to produce alpha heating which disturbs the implosion hydrodynamics. They provide a platform for observing the features of implosions required for constructing the non-heating metrics. Most critically, they allow the NIC to measure improvement as tuning improvements move implosions toward ignition.

We describe in section II the relationship between heating DT implosions and non-heating THD surrogates. In section III, we describe the development of the simulation databases used to define ITFX and to compare the various ICF performance metrics. We then detail the comparision between the four performance metrics described above with an emphasis on ITFX in section IV. We next report in section V on the experimental observation of ITFX, its improvement during the initial cryogenic layered experimental campaigns in the NIC, and its correlation with other experimental measurements. We end in section VI with summary remarks and a brief discussion of future work to be done in the NIC.

II. PLATFORM SURROGACY

Non-heating THD and analogous heating DT implosions are similar for much of their implosion history. This similarity, or surrogacy, is illustrated by the trajectories of the implosions in the $(\rho R, T_{ion})$-plane shown in figure 1. The red trajectory represents the path taken by the DT implosion. Three key phases are of interest. First, the implosion is accelerated to peak kinetic energy and begins giving up that energy by doing compression work on the nascent hot spot. Next, the energy deposition rate by alpha particles dominates losses by conduction leading to a dramatic increase in temperature. The shell stagnates and begins to decompress. The alpha depostion rate still overpowers the loss rate by expansion work, and a propagating burn wave runs back through the fuel, driving the central temperature higher and causing peak neutron production rate. In the third and final phase, the simultaneous losses due to conduction and expansion become larger than the alpha deposition, the implosion loses confinement, and the burn is extinguished.

This trajectory is to be compared with that of a non-heating THD implosion, shown in red in figure 1. The implosion kinematics up to peak velocity are identical in both

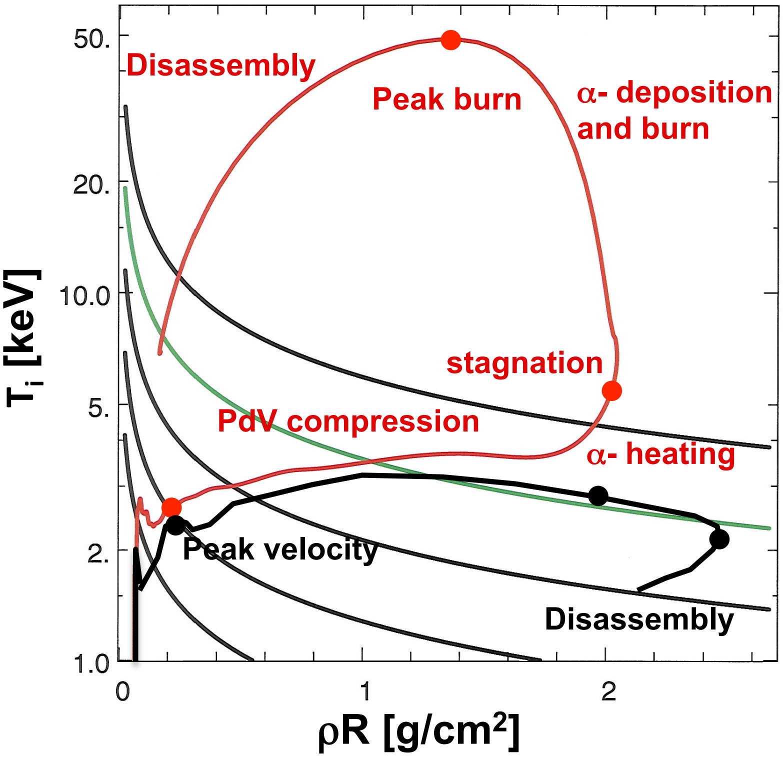

Figure 1: DT and THD trajectories are similar in (ρR, T_{ion})-space until alpha heating in the DT implosion causes the trajectories to diverge. There is also a slight systematic temperature difference due to initial compositional differences in the central gas at $t = 0$.

implosions. During the compression phase, the areal densities are nearly identical. As the THD compresses, no appreciable alpha heating takes place. Consequently, the temperature falls slightly due to conduction losses. The shell then continues to implode, inreasing its areal density. It reaches peak neutron production rate, stagnates, and disassembles, all while continuing to cool. In 2D or 3D, the shell symmetry and stability of interfaces remains similar between the two implosions until very near the time of peak xray production in the THD target. Most of the experimental measurements are made near this xray bang time. Simulations show that THD measurements at this time are strong predictors of DT performance. This will be discussed further below, and more details can be found in [4].

There are slight differences in the implosion due to composition differences between the targets. Notably, there is a systematic shift in ion temperature due to differences in number density in the central gas before implosion. These differences arise from the effects that set the central gas composition. First, the ice layer is composed of a mixture of the six diatomic hydrogen molecules (H_2, HD, HT, D_2, DT, T_2). These molecules undergo hydrogen exchange reactions and come to an equilibrium balance after the long 17 hour cryogenic layering process at a temperature near the mixture triple point (point of last freezing). Each diatomic molecule has its own vapor pressure. The molecular balance combined with the vapor pressure variation among the molecules sets up a central gas head inside the cavity. Finally, the capsule is rapidly cooled by about 1.5 K in the 30 seconds prior to a NIF shot. The heavy species are preferentially plated out. This leaves a thin, tritium rich condensate layer on the interior of the ice cavity, and it leaves the central gas depleted of reactive species. A THD with 2% atomic fraction deuterium in the ice has central gas that is 90 percent hydrogen by atomic fraction and is thus almost completely dudded. Fortunately, composition models suggest that the low density hot spot is formed mainly by material that was initially ice. Thus, the hot spot still produces neutrons that can be used as a diagnostic probe, though the central composition needs to be modeled accurately to better predict the implosion yield.

III. DEFINITION AND DEVELOPMENT OF ITFX

We next describe the definition and development of ITFX. The process begins by simulating ensembles of DT and surrogate THD implosions. First, an input parameter space is chosen. This space may be, for example, a multi-dimensional hypercube whose coordinate axes represent adjustments to the way that radiation flux is delivered to the target as a function of time or space. A design of experiment is constructed by space-filling latin hypercube techniques to vary experiment conditions relative to specifications [7]. Then, pairs of 2D THD and DT simulations are executed at each point in the design of experiment. Finally, NIC diagnostics, especially neutron spectrometers, are simulated using the output from the pairs of implosions. The result is typically hundreds to thousands of simulated THD observations that can be mined in an attempt to order the DT neutron yield performance. During initial development of ITFX, both artificial intelligence techniques (e.g. decision trees) and physics scaling laws were used to find a subset of THD observations that could best represent the DT capsule behavior. The final result is the following definition of an observable performance metric

$$ITFX = \frac{Y}{Y_c}\left(\frac{DSR}{DSR_c}\right)^{2.3}$$

Here, the normalizing constants Y_c and DSR_c are chosen such that $ITFX = 1.0$ when the DT implosion yield, Y_{DT}, is 1 MJ. Restated, the ignition threshold is ITFX = 1.0, and capsules with $ITFX >= 1.0$ are expected to have $Y_{DT} \sim\geq 1.0$ MJ (see figures 2 and 4). The DSR_c value is dependent on capsule scale and design, but is nearly constant across targets used in the NIC and is taken to be $DSR_c = 0.07$. The Y_c value scales with the composition of the THD layer so that $Y_C = 1.8e14\frac{n_D n_T}{0.02*0.74} = 1.2e16 n_D n_T$, where n_D and n_T are the atomic fractions of deuterium and tritium in the fuel. Thus, for NIC Rev5 and related capsule designs,

$$ITFX \simeq \frac{0.02*0.74}{n_D n_T}\left(\frac{Y}{1.8e14}\right)\left(\frac{DSR}{0.07}\right)^{2.3}$$

The correlation between the yield of an implosion capable of heating, Y_{DT}, and the $ITFX$ observed for the analogous non-heating implosion is shown in figure 4. For a given ITFX, there is a distribution of DT yield outcomes. It is notable that at the $ITFX =$ 1.0 threshold, the probability of ignition (yield > 1 MJ) is 50%. Also, the probability of ignition rises sharply as ITFX increases from values just below to values just above 1. This threshold behavior and the predictive nature of ITFX for DT implosion performance has been demonstrated in simulation for both Be and CH ablator materials and for a variety of designs (see figure 2). While the normalization constants y_c and DSR_c vary with design, the functional form of the best fit for DT yield versus ITFX remains unchanged across material and design.

IV. RELATIONSHIP OF ITFX TO ITF AND GLC

Simulation databases suggest that the various ICF performance metrics are well correlated with one another. Each of the three metrics, however, has a clear and distinct purpose. ITF is concerned with the input conditions to the hot spot. The ignition threshold factor is defined as

$$ITF = I_0 S^3\left(\frac{v}{v_0}\right)^8\left(\frac{\alpha}{\alpha_0}\right)^{-4}\left(1-1.2\frac{\Delta R}{R}\right)^{4+\epsilon}\left(\frac{M_{clean}}{M_{DT}}\right)^{\frac{1}{2}}$$

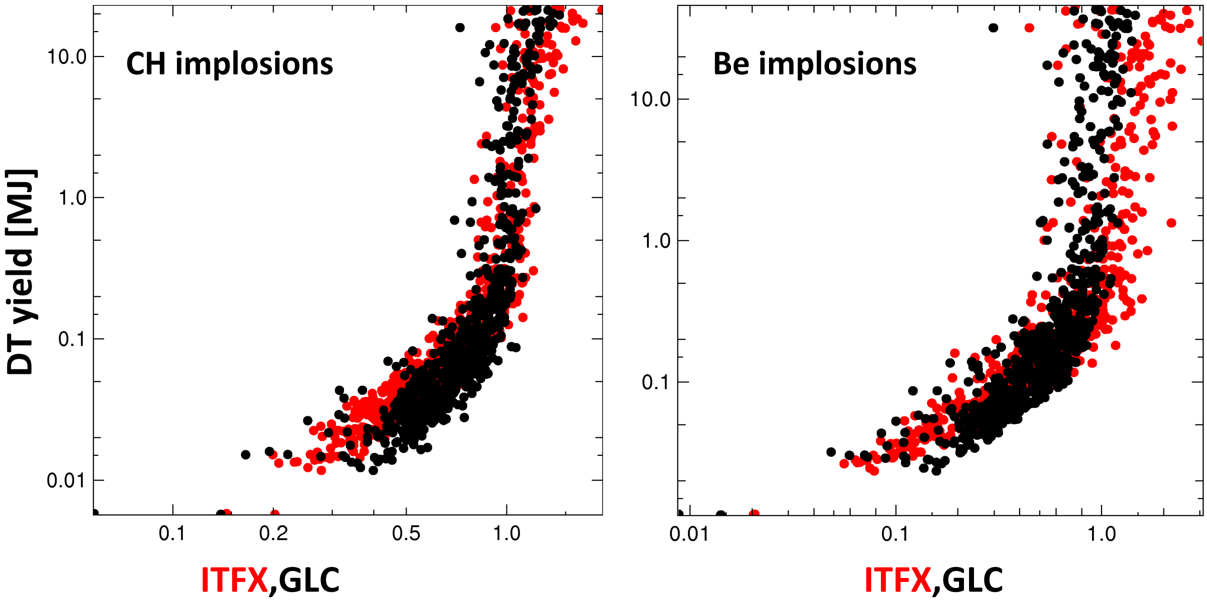

Figure 2: ITFX, plotted in red, is an ordering parameter for DT yield. A clear ignition threshold is present at $ITFX = 1.0$. Similar threshold behavior is observed for GLC, shown in black. The ITFX and GLC are directly related with a multiplicative scaling factor of nearly unity across designs.

Here, I_0 is drive energy and S is a length scale, both for scaling between designs. The remaining terms measure conditions that are critical for setting up a hot spot. These are: peak fuel velocity, v , and its threshold value, v_0; the adiabat at peak velocity, α, and its threshold value, α_0; the Kishony-weighted hot spot perturbation measured at 1D ignition time, ΔR, and the 1D (spherical) hot spot radius at 1D ignition time, R; and the mass of unmixed fuel, M_{clean}, and the initial mass of DT fuel, M_{DT}. The ITF metric uses instantaneous values for the independent variables, and it is defined for DT implosions that are capable of self-heating by alpha deposition. It has served as a primary design tool for evaluating the performance of numerical simulations of ignition designs. It should be noted that it is not an observable quantity. Any experimental inferrence of ITF requires theoretical models to give estimates of the input values based on measurements. The correlation of ITF with DT yield can be seen in figure 3. $ITFX$ is somewhat more predictive than ITF. That is, Y_{DT} has smaller variance at a given $ITFX$ than ITF. In general, $ITFX \sim ITF^{0.5}$.

The GLC, like $ITFX$, provides a performance metric based on non-heating implosions, such as THD implosions, where the hydrodynamics are not influenced by thermonuclear

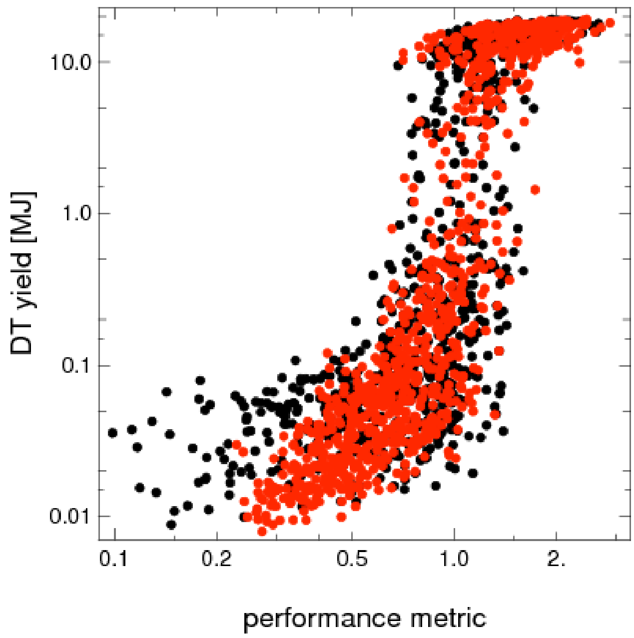

Figure 3: Yields from DT implosions are plotted against performance metrics ITF (black) and $ITFX^2$ (red). ITF is computed from instantaneous features of the DT implosion. ITFX is computed from burn-averaged quantities in analogous THD implosions. The two metrics show similar threshold behavior for DT yields near 1 MJ.

processes [15]. The generalized Lawson criterion is defined as

$$GLC = \left(\frac{\rho R}{\rho R_0}\right)^2 \left(\frac{T_i}{T_{i0}}\right)^{4.5} \frac{Y}{Y_c}$$

Here, ρR is the total (ablator and fuel) neutron-weighted areal density, T_i is the neutron-weighted ion temperature, Y is the neutron yield from the implosion under consideration, and Y_c is the simulated 1D clean yield. The normalizing constants ρR_0 and T_{i0} are chosen such that $GLC = 1.0$ corresponds to $Y_{DT} = 1.0$ MJ. The independent variables for GLC are neutron-averaged, taking it one step closer than ITF to being experimentally observable. However, it depends on knowing the fraction of clean yield obtained for each implosion, thus requiring a simulation for each computation of GLC. Furthermore, ρR is not directly observable, but requires a model to tie it to an experimental observable, like DSR. As mentioned before, $ITFX$ is directly observable, and it can be naively compared to GLC as follows. First, note that the clean yield depends most strongly on the temperature-dependent cross section, and for THD implosions, the DT cross section scales as $< \sigma v >\sim T_i^{4.5}$ in the temperature region of interest. Notionally, the clean yield and the ion temperature cancel

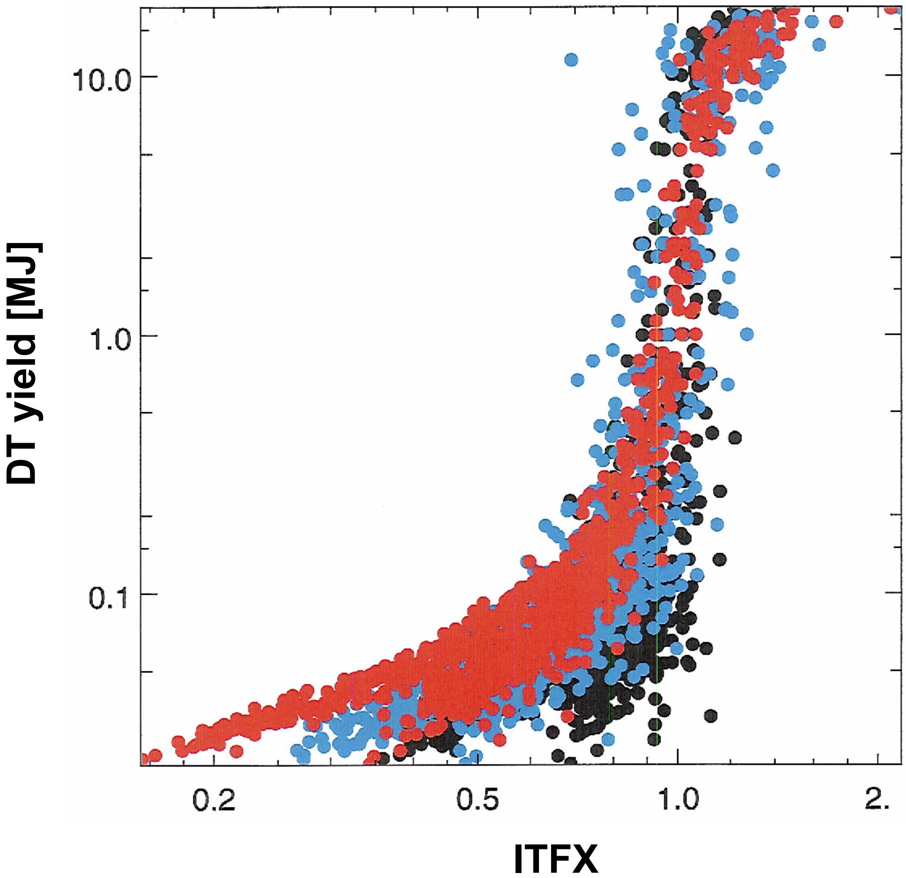

Figure 4: The ITFX metric (red points) is computed for an ensemble of 1000 2D Hydra simulations of THD implosions. The neutron yield is then computed from an ensemble of analogous DT implosions. The ignition threshold can be seen clearly at $ITFX = 1.0$. Though there is residual yield variance at a given ITFX, the metric is quite predictive of DT capsule performance. Also shown are the HSP (black points) and the GLC (blue points) correlations, both of which also predict DT performance.

in gross terms. Furthermore, the areal density is very nearly linear in the down scattered ratio according to $\rho R = 21\, DSR$. Then, one can write $GLC \sim Y * DSR^2 \sim ITFX$. This argument is heuristic and would need correction under detailed numerical or theoretical analysis, but it serves to build intuition about the relationship between GLC and $ITFX$. Figure 4 illustrates the correlation between Y_{DT} and GLC, the quality of which falls between HSP and $ITFX$.

The performance of an implosion may also be characterized by the pressure developed in the hot spot in the absence of alpha deposition. The hot spot pressure (HSP) is defined as the pressure at the center of the hot spot at the time of peak neutron production in a non-heating implosion. Like, GLC or ITFX, HSP serves as an ordering parameter that can locate the ignition cliff or measure the distance from it (figure 4). While the HSP is not directly observable, the NIC computes HSP using the combination of an analytical isobaric model for the implosion near stagnation and a least-squares optimization routine that fits the model to a host of experimental observations. Though less precise than the full isobaric fitting procedure, a closed from statement of the HSP can be defined as

$$HSP = \frac{T_i^{-0.87} Y^{0.5} R^{-1.5} b^{-0.5}}{\sqrt{n_D n_T}}$$

Here, T_i and Y are again the experimentally-measured ion temperature and neutron yield; R is the radius of the hot spot xray image; b is the width of the thermonuclear reaction history. The composition is also accounted for by the number densities of deuterium and tritium, n_D and n_T. While HSP is less predictive than ITFX, it has the benefit of being able to be interpreted directly as a physics quantity. The HSP then serves as an intuitive check that improvement in implosion performance as measured by ITFX is indeed physically plausible.

A summary comparison of the various performance metric definitions and descriptions is presented in I.

V. EXPERIMENTAL OBSERVATIONS OF ITFX AT THE NIF

ITFX has been measured on NIF across a sequence of experimental campaigns totaling 13 cryogenic layered shots. The DSR has been measured by a suite of neutron spectrometers, primarily the MRS ([2, 5]) and nTOF instruments [6]. The yield is reported by the spectrometers, as well as by a collection of activation foils called NADS. The observed values of $ITFX$ have increased across a sequence of three campaigns by nearly a factor of 60 due to technological and tuning advancements (figure 5). In campaign 1 ([10]), the implosion yield was initially badly degraded by frozen condensate on the hohlraum laser entrance hole (LEH) windows. The development of a secondary, thermally-isolated window to prevent this condensation led to a frost-free platform that, together with an increase in laser energy, Comparison of various ICF performance metrics

metric	definition	implosion basis	implosion phase	temporal resolution	metric observability
ITF	$ITF = I_0 S^3 \left(\frac{v}{v_0}\right)^8 \left(\frac{\alpha}{\alpha_0}\right)^{-4} \left(1 - 1.2\frac{\Delta R}{R}\right)^{4+\epsilon} \left(\frac{M_{clean}}{M_{DT}}\right)^{\frac{1}{2}}$	developed for DT implosions	hot spot input conditions	instantaneous	quantities not observable
GLC	$GLC = \rho R^2 T_i^{4.5} \frac{Y}{Y_c}$	developed for no-burn implosions	assembled hot spot conditions	averaged over neutron burn	requires a clean simulation
HSP	$HSP = \frac{T_i^{-0.87} Y^{0.5} R^{-1.5} b^{-0.5}}{\sqrt{n_D n_T}}$	developed for THD implosions	assembled hot spot conditions	averaged over neutron burn	requires a physics model to link observations
ITFX	$ITFX = \frac{Y}{Y_c}\left(\frac{DSR}{DSR_c}\right)^{2.3}$	developed for THD implosions	assembled hot spot conditions	averaged over neutron burn	directly observable

Table I: The definition of each ICF performance metric is presented. Also included are summary features describing the metrics. The implosion basis is a description of the type of implosion or simulation that the metric was based on. Implosion phase describes the period in the implosion evolution when the independent variables in the definitions are observed or defined. The temporal resolution is used to describe whether the metrics ar defined for burn-averaged or instantaneous quantities. The observability column describes the degree to which the metric may be directly computed for experiments.

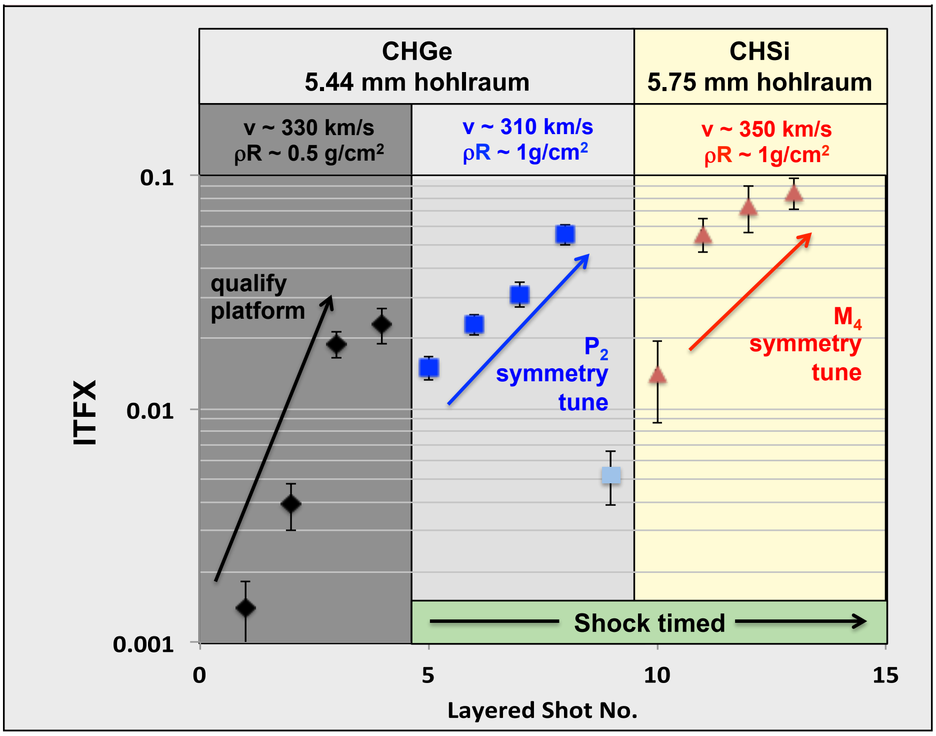

Figure 5: ITFX has been measured on 13 implosions of cryogenic layered targets. As tuning and target design have improved, the implosion performance has increased throughout each campaign of experiments.

provided substantially improved ITFX. The improvement was due mainly to neutron yield increases. This can be seen by examining the campaign trajectories in (DSR, yield)-space, shown in figure 6. The second campaign followed detailed shock timing ([1, 12]). ITFX improvement resulted from a factor of 2 increase in the DSR due to the near-nominal shock timing. However, the timing improvements were initially accompanied by a yield reduction. The yield deficit was recovered by lengthening of the terminal end of the laser pulse in an attempt to prevent late decompression or coasting. In campaign 3, the capsule Ge dopant was replaced with Si which couples more efficiently to the laser drive while still providing an xray preheat shield. The enhanced coupling produced higher implosion velocities and associated yield increases. Azimuthal asymmetries were also reduced. Campaign 3 lead to faster, more axisymmetric implosions and an ITFX of just below 0.1.

In addition to serving as an observable performance metric, ITFX has also been of value as an ordering parameter for exploring other key correlations in the experimental data. In figure 7, the burn-weighted ion temperature is plotted versus ITFX. The blue points represent experiemental data for Ge-doped capsule implosions, the magenta points are Si-doped capsule implosions, and the red are simulations of Ge-doped capsule implosions using the nominal Hydra physics settings (post-shot simulations with emprically-tuned physics parameters can be found in [8]). The data show that, for a given ITFX or implosion performance, the experimental temperatures are high. In the Ge case, the slope is quite steep, which is surprising. High ion temperature is associated with good performance as explicitly stated in the GLC. However, the steep Ge slope suggests that, despite expectations, Ge realizes almost no performance enhancement as the observed hot spot temperature rises. The Si case shows a slope that is nearly as predicted in the code for Ge simulations. (preliminary simulation studies show little difference between Ge and Si for the T_i-ITFX correlation). This suggestst that the Si implosions realize an expected amount of performance improvement as the experimental conditions increase the ion temperature. Nevertheless, it remains to be understood why the ion temperature is so high yet ITFX, the yield term in particular, is so relatively low. This is the outstanding question for the NIC and is the focus of future work.

VI. CONCLUSIONS

Having the ability to quantify the performance of an implosion, specifically its nearness to the ignition threshold, is key to ICF efforts. There exist a variety of performance metrics: ITF, GLC, HSP, and ITFX. All metrics except ITF require non-heating or THD surrogate implosions to compute their values. Large databases of simulated DT and THD implosions show that the various metrics are capable of locating the ignition threshold for NIC target designs, and the metrics are self consistent. Each metric has its particular strength. ITF is essential for designing DT implosions. GLC provides a theoretical scaling basis for the metrics. HSP can be inferred from experiments with the assistance of a model, and it gives a physically interpretable result. Finally, ITFX provides a directly observable measurement that can be used to quantify experimental progress. ITFX has been observed during the NIC. Tuning efforts have resulted in an increase in ITFX by a factor of 60. With ITFX currently at ~ 0.1, NIC requires future tuning operations to increase ITFX by an additional factor of 10 at least. Future tuning campaigns will focus on improvement in the delivery of drive during the fourth pulse, as well as continued improvement of implosion velocity, shape, and shock timing, in a push toward $ITFX$ greater than 1 for THD implosions and ignition for DT implosions.

Acknowledgments

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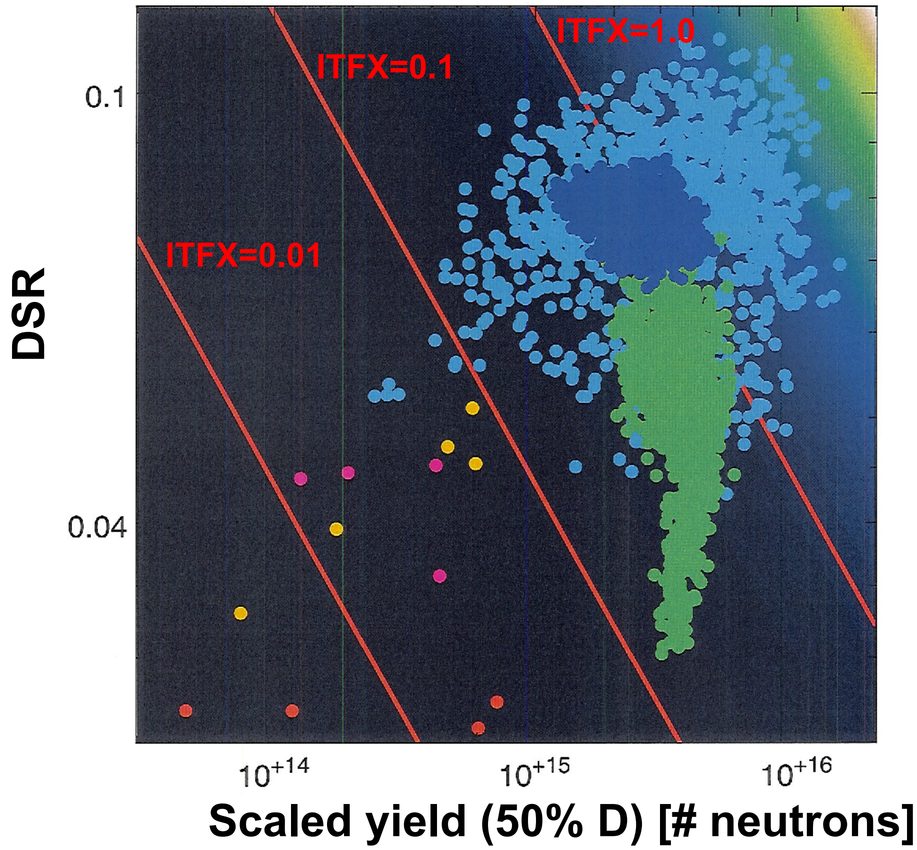

Figure 6: Experimental progress can be tracked in the $ITFX$ space of DSR versus THD yield (scaled to a common deuterium fraction). Campaign 1 points are shown in red and illustrate the substantial increase in yield due frost reduction and laser energy increase. The magenta points of campaign 2 show the increased DSR indicative of improved shock timing. The last orange points of campaign 3 show an increase in both yield and DSR due to improved drive coupling and more nearly axisymmetric implosions. For reference, the dark blue cloud of points straddling the $ITFX = 1$ contour represents the simulated performance of Rev5 implosions with all physics and tolerances set to nominal values. The light blue cloud represents an expanded ensemble with widely varying shock timing. Finally, the green cloud reflects the experimentally observed shock timing, but with wide variation in the way that drive is delivered during the fourth pulse. Each successive tuning campaign is driving the experiments closer to the desired performance region.

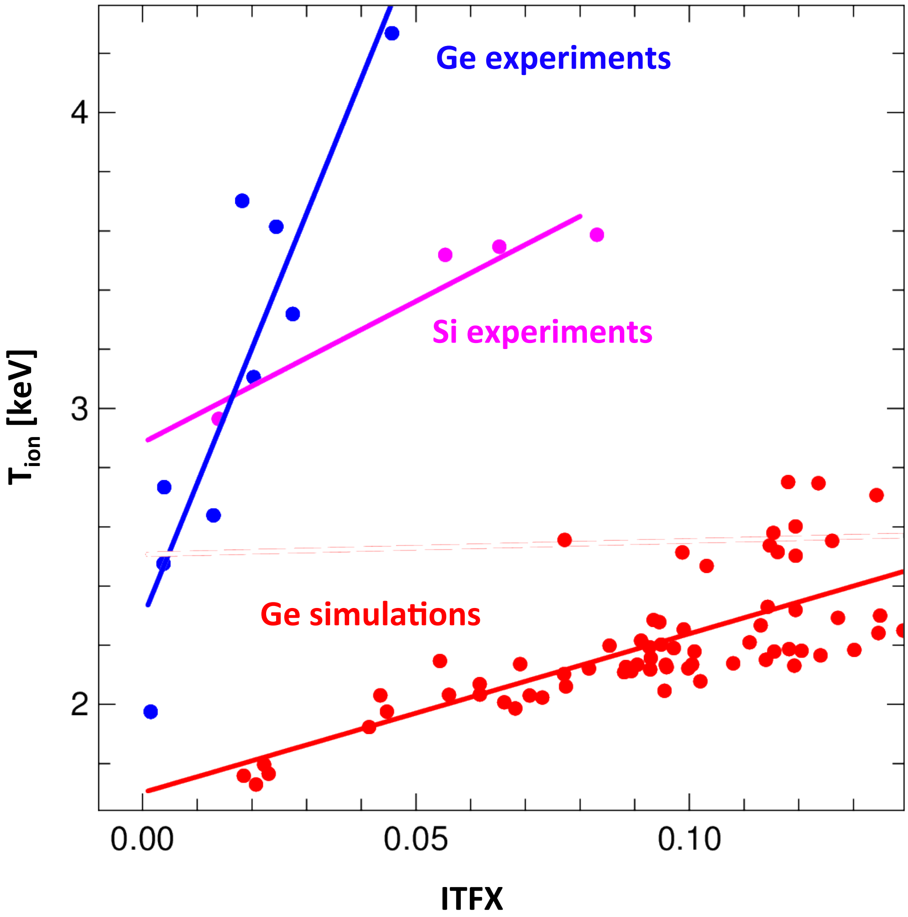

Figure 7: ITFX serves as an ordering parameter for ion temperature in both experiments and simulations. Experiments with Ge dopant show little increase in ITFX as the temperature is increased. Silicon-doped implosion experiments show a sensitivity of ion temperature to ITFX much closer to that of simulations (Ge and Si simulation trends appear very similar). However, the experimentally observed value of the ion temperature remains considerably higher at a given ITFX than for analogous simulations with nominal Rev5 implosions and physics model parameters.