PREDICTION OF IGNITION IMPLOSION PERFORMANCE USING MEASUREMENTS OF LOW-DEUTERIUM SURROGATES

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Abstract. The National Ignition Campaign (NIC) will use non-igniting “THD” capsules with cryogenic ice layers to study and optimize the hydrodynamic assembly of the fuel without burn. These capsules are characterized by the ratios of T:H:D. The species ratios are set with two goals in mind: (1) control T:D in order to adjust the nuclear energy production and (2) preserve the average atomic number of the fuel at 2.5 to maintain hydrodynamic similarity with the DT ignition capsule.

We have developed an experimentally observable ignition threshold factor (ITFX) that uses measurements from THD experiments to predict the performance of DT ignition implosions. It was developed and tested on multiple large databases of 2D radhydro simulations. Each of the thousands of simulations includes twin DT and THD simulations with a variety of physical failure mechanisms – drive asymmetry, capsule roughness, continuum mixing, fabrication errors, among others.

The results of our numerical database and the ITFX metric have allowed us to develop an experimental estimate of the probability of DT ignition based on THD experiments. The analysis accounts for both diagnostic precision and the effects of a finite number of shots. The NIC expects to field a combination of diagnostics and experimental attempts that result in a 15 to 20 percent uncertainty in the experimentally inferred probability of ignition.

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1. Introduction

NIF implosion performance can be characterized by a theoretical metric called ITF. ITF is a measure of the probability of ignition and is a function of both 1D and 2D/3D quantities. The probability of ignition is a relatively steep function of ITF, rising rapidly around ITF=1 where the probability is 50 percent. At the nominal value of ITF, 2, associated with the point design the probability of ignition is high. However, when the NIC begins in September, the ITF will be less than 1 because of physics uncertainties that need to be corrected for, empirically, during the ensuing "tuning" campaigns. [1]

We will then field low-deuterium “THD” targets with dudded cryogenic fuel layers. The THD capsules are designed to be hydrodynamic analogues of DT implosions by specifying the T:H:D ratios to be about 74:24:2. Their low deuterium content leaves them unaffected by thermonuclear energy production, yet their radiation and hydrodynamic transport mirror that of DT implosions up to the point where DT implosions become perturbed by alpha production and deposition.

Below we describe a database of simulations that we have used to elucidate the relationship between THD and DT implosions. We develop an experimental version of ITF called ITFX. This metric allows us to diagnose directly the performance of a THD experimental implosion to predict the performance of the analogous DT implosion.

2. The relationship between THD and DT implosions via ITFX

To further investigate the relationship between THD and DT implosions, we have developed a numerical database of simulated implosions. The implosions are located in parameter space according to NIC estimates for target and laser variability (see [2]). We account for variation of many 1D parameters (capsule thickness, peak laser power, etc.) and 2D parameters (capsule surface roughness, radiation asymmetry, continuum mixing, etc.). Our database is composed of 1000 sample points in the parameter space, each point constructed from 4 simulations: a 1D clean DT implosion, a 2D DT implosion, a 1D clean THD implosion, and a 2D THD implosion. For each quadruplet, we model not only the radiation hydrodynamics, but also the output from a variety of x-ray cameras, neutron spectrometers, and other diagnostics. This simulated diagnostic data forms the key link between the experimental observables produced by THD implosions and the related DT implosion performance.

The THD and DT implosions show identical peak mass-averaged fuel velocity and identical integrated entropy, two key theoretical implosion metrics. The simulated diagnostic data show even more striking trends. Presently, we have considered the simulated nTOF neutron spectrometry data most closely. We find that two features from the THD neutron spectrum are particularly predictive. These are the number of primary DT neutrons (or yield), defined as those neutrons detected with energies between 12 and 17 MeV, and the down scattered fraction, defined as the number of neutrons between 10 and 12 MeV divided by the primary yield. From basic physics
reasoning, the downscattered fraction (dsf) is expected to be proportional to the rhoR of the cold, stagnated fuel. The yield (y), is generally proportional to the rhoR of the hotspot as well as its temperature. Using decision tree and regression analysis, we find that implosions cluster tightly in the space (y,dsf^2) (see figure 2). Here the colored clusters represent implosions filtered by 2D behavior. The red represent asymmetric, highly mixed implosions, whereas the blue are nearly spherical and lightly mixed. This clustering suggests that dsf and y not only encode the 1D implosion behavior implied by our physics intuition, but 2D shape and mix characteristics as well.

Regression analysis shows that the yield of the analogous DT implosion is strongly correlated with an experimental THD metric, \( ITFX \ y*dsf^2 \) (see figure 2(a)). The general shape of the dependence of DT yield on ITFX reveals the expected threshold behavior typical of ignition phenomena. We have normalized the metric so that ITFX of 1.0 represents marginal implosions. Implosions with ITFX of 1.2 or higher are likely to ignite; implosions with ITFX substantially less than 1 are expected to give very low fusion yields. This ITFX measurement is found to be a power law of the standard theoretical ITF metric ([3]). Further comparison with a threshold metric developed by Betti and co-workers (c.f., [4]), ITF3D, also reveals linear dependence. The detailed physics of the tight correspondence of the ITF, ITFX, and ITF3D continues to be investigated in order to clarify the fundamental physics basis for the strong predictive nature of ITFX.

For a given ITFX, there is a nearly Gaussian probability distribution of associated DT yields. The probability density of DT yield given ITFX is shown in figure 2(a), where the color map represents likelihood. This can be turned directly into a conditional probability function that gives the probability that DT yield will be greater than 1 MJ, that is the probability that the DT capsule will ignite, for a given ITFX value. We call this conditional probability function F.

In addition to F, one needs the probability distribution for ITFX itself to predict the expected probability of ignition. This can be obtained experimentally by measuring the dsf and y for a number of THD shots. The resulting distribution for ITFX values will possess inherent variability from two sources: (1) experimental measurement
uncertainties in dsf and y and (2) uncertainty from finite n-shot sampling of the true underlying ITFX distribution. These two sources of variability combine to set up the precision with which one can know ITFX.

The probability distribution for ignition can be found as

$$POI = \int F(ITFX) P(ITFX) dITFX$$

where $POI$ is probability of ignition and $P$ represents the probability distribution for ITFX. The standard deviation of this distribution is explicitly dependent on the ITFX width, and thus is also dependent on the number of THD shots and the measurement precision. We show in figure 2(b) the uncertainty in probability of ignition versus both number of shots and measurement error.

3. Conclusions

We have produced a large numerical database of radiation hydrodynamics simulations that elucidate the relationship between low yield THD and DT implosions. Analysis of simulated diagnostics signatures shows that key features of the experimental neutron spectrum can be used to predict DT performance and can be used to give the expected probability of ignition based on a set of THD experimental measurements. The uncertainty in this inferred probability is set by both diagnostic precision and the number of shots taken. The NIC expects to operate the THD campaign with enough THD shots to give an uncertainty in ignition probability of 15 to 20 percent.

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