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Capsule Performance Optimization in the National Ignition Campaign*

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Abstract. A capsule performance optimization campaign will be conducted at the National Ignition Facility [1] to substantially increase the probability of ignition. The campaign will experimentally correct for residual uncertainties in the implosion and hohlraum physics used in our radiation-hydrodynamic computational models before proceeding to cryogenic-layered implosions and ignition attempts. The required tuning techniques using a variety of ignition capsule surrogates have been demonstrated at the Omega facility under scaled hohlraum and capsule conditions relevant to the ignition design and shown to meet the required sensitivity and accuracy. In addition, a roll-up of all expected random and systematic uncertainties in setting the key ignition laser and target parameters due to residual measurement, calibration, cross-coupling, surrogacy, and scale-up errors has been derived that meets the required budget.

1. Introduction

The overall goal of the capsule performance optimization campaign is to empirically correct for residual uncertainties in the implosion and hohlraum physics used in our radiation-hydrodynamic computational models [2,3] before proceeding to cryogenic-layered implosions [4] and ignition attempts. This will be accomplished using a variety of surrogate targets that will set key laser, hohlraum and capsule parameters to maximize ignition capsule implosion velocity, while minimizing fuel entropy (or adiabat), core shape asymmetry and ablator-fuel mix. This is followed by intentionally-dudded tritium-rich but deuterium-poor cryo-layered implosions to check the efficacy of the tuning through shared observables such as core symmetry and bangtime, and from implosion performance. Finally, if the chosen ignition design called for larger scale, the tuning would be checked at this scale, before proceeding to tests of alpha-heating and ignition.

Extensive computational multivariable sensitivity studies have shown that, the probability of ignition is well correlated [5] to the four key implosion parameters of 1D peak fuel implosion velocity v, 1D burn-averaged imploded fuel adiabat α, rms asymmetry $\Delta R_{hotspot}/R_{hotspot}$ at the hotspot-main fuel interface, and fraction $\Delta R_{mix}/\Delta R_{fuel}$ of fuel mixed with ablator. The product of power laws of these four parameters, for small excursions, can be used to define an Ignition Threshold Factor (ITF) given by the following equation:

$$\mathrm{ITF} = \frac{E_{fuel}}{3.2kJ}\left(\frac{v}{380km/\sec}\right)^{5.9}\left(\frac{\alpha}{1.46}\right)^{-3.9}\left(1-\frac{\Delta R_{hotspot}}{R_{hotspot}}\right)^{3.5}\left(1-\frac{0.5\Delta R_{mix}}{\Delta R_{fuel}}\right)$$

The constants 380 km/s and 1.46 in the denominators are specific to the particular 285 eV 1.2 MJ Be design [6] considered here that culminates in 3.2 kJ of stored capsule fuel energy. An ITF of 1 equates to 50% probability of ignition. Tuning is expected to increase the mean ITF from ≈0.2 to ≈1.5, with ITF widths of ≈0.2 and ≈0.5 as set by the target physics models uncertainties, and by the quadrature sum of expected residual shot-to-shot variability in laser and target parameters and residual errors in tuning, respectively.

Implosion Performance Offsets			Laser or Target Offsets			Tuning Accuracy	
Parameter	Initial	Final	Parameter	Initial	Final	Observable	Value
DT Fuel Adiabat	+10%	+3%	1st 2ns Inner Cone Energy Fraction	±25%	±10%	Reemit P2 flux asymmetry	±15%
Implosion Core Asymmetry	50% rms	15% rms	1st 2ns Inner Cone Energy Fraction	±25%	±10%	Reemit P2 flux asymmetry	±15%
DT Fuel Adiabat	+10%	+3%	1st 2ns Laser Power	±20%	±10%	1st Shock velocity	±5%
DT Fuel Adiabat	+10%	+3%	Trough Laser Power	±20%	±10%	1st Shock velocity	±5%
DT Fuel Adiabat	+10%	+3%	2nd Shock Laser Power	±10%	±4%	2nd Shock velocity	±2%
DT Fuel Adiabat	+10%	+3%	3rd Shock Laser Power	±10%	±4%	3rd Shock velocity	±2%
DT Fuel Adiabat	+10%	+3%	2nd Shock Launch Time	±200ps	±50ps	2nd Shock overtake point	±6 μm
DT Fuel Adiabat	+10%	+3%	3rd Shock Launch Time	±200ps	±50ps	3rd Shock overtake point	±6 μm
DT Fuel Adiabat	+10%	+3%	4th Shock Launch time	±200 ps	±100 ps	4th Shock breakout time	±100 ps
DT Fuel Adiabat	+10%	+3%	4th Rise Duration	±200ps	±100ps	4th rise Tr slope to peak power	±5%
Ablator Mass Remaining	±80%	±25%	Initial Ablator Thickness	±30 μm	±10 μm	StreakCap Mass Remaining	±13%
Peak Implosion Velocity	±10%	±2%	Peak Laser Power	±20%	±4%	Velocity at r = 300 μm	±2%
Implosion Core Asymmetry	50% rms	16% rms	Peak Inner Cone Energy Fraction	±20%	±5%	Symcap P2 core asymmetry	±7.5 %
Implosion Core Asymmetry	50% rms	16% rms	Hohlraum Length	±400 μm	±200 μm	Symcap P4 core asymmetry	±7,5 %
Ablator-fuel Mix	±40%	±15%	Mid-Z Ablator Dopant Fraction	±0.3%	±.0.1%	2-5 keV x-rays in hohlraum	±10%
Peak Implosion Velocity	±10%	±2%	Peak Laser Power	±20%	±4%	Symcap Bangtime	±50 ps

Table I. Expected initial and residual post-tune 1σ offset from optimum ignition implosion performance, associated initial and post-tune 1σ offsets in optimal laser and target parameters, and required accuracy for tuning associated observables.

The expected initial and final uncertainties in the four implosion parameters are given in the second and third columns in Table I. The initial uncertainties have been estimated based on a combination of level of confidence in extrapolating radiation hydrodynamics models fitting Nova, Omega and Z facility hohlraum energetics, x-ray driven planar hydrodynamics and gas-filled hohlraum implosions data and residual differences between EOS, opacity and conductivity models for the hohlraum, ablator and DT fuel plasmas. These uncertainties translate to uncertainties in capsule ablation rate affecting implosion velocities, to uncertainties in hohlraum x-ray conversion efficiency, albedo and radiation hydrodynamics affecting drive symmetry, and to uncertainties in hard x-ray preheat levels, ablator compressibility and dopant opacity affecting fuel adiabats through shock transit times, and affecting level of ablator-fuel mix through the ablator-fuel interface Atwood number.

The tuning campaign is based on the principal that these physics uncertainties can be empirically corrected for by adjusting key laser and target parameters around their nominal values, thereby increasing the ITF by increasing implosion velocity, and lowering fuel adiabat, asymmetry and mix. 16 principal adjustable parameters have been identified, schematically shown in Figure 1 and listed in the fourth column in Table I alongside the implosion parameter they affect. For the laser, they are the power levels for the 5 phases in the laser pulse, the launch time for the second, third and fourth steps, the end-point in the 4^{th} rise of laser power (when the pulse first reaches peak power), and the power balance between inner and outer cones during the first and last phase. For the target, there are 3 parameters; the hohlraum length, capsule ablator thickness for fixed inside diameter, and capsule ablator mid-Z dopant fraction. The fifth and sixth columns show the expected initial and final 1σ uncertainties in setting these parameters that are consistent with the uncertainties quoted for the four implosion parameters

2. Tuning Techniques

Extensive sets of shots were completed at the Nova and Omega facility to demonstrate and downselect between proposed tuning techniques. The mainline tuning targets chosen are the high Z re-emission spheres [7] setting the foot cone power balance from the observed foot drive symmetry, liquid D_2-filled "keyhole" targets setting the laser power profile up to peak power from the observed shock speeds and overtake distances and times [8], x-ray imaged imploded capsules setting the peak cone power balance and hohlraum length from observed core symmetry [9] and streaked x-ray backlit imploding capsules [10] setting the initial ablator thickness and peak laser power from the radiographically-inferred ablator mass remaining [11] and implosion velocity. In addition, the soft x-ray power diagnostic "Dante" will be used to set the 4^{th} rise launch time from the 4^{th} rise slope and to set the ablator dopant fraction from the measured hard (> 1.8 keV) x-ray preheat levels. The last two columns of Table I list the observables and their required tuning accuracy.

3. Tuning Strategy and Accuracy

The goals of the capsule tuning campaign are to specify the optimum adjustable parameter value and its uncertainty, and to assess that shot-to-shot variability is as expected. A cluster of N shots at a nominal laser and target setting would be taken to assess the 1σ shot-to-shot variability in the observable (to $\sigma/\sqrt{[2(N-1)]}$ accuracy) and compare to expectations. For the latter, the random measurement error bars must be and are expected from scaling from current technique demonstrations to be less than the data scatter. The second step is to correct the data for known preshot shot-to-shot target variations and postshot shot-to-shot laser variations, using calculated slope sensitivities to reduce the scatter in the data to just target and laser diagnostic metrology errors and errors in measuring the observable. In general, the mean of this corrected data will be offset from the optimum value of the observable we are aiming for, precorrected for any known surrogacy offset. The third step is to gather another set of M data points, where in general M < N since data scatter has already been established, for another value of the adjustable parameter that would bracket the optimum setting. The optimum value of the adjustable parameter is then found by linear interpolation between the two datasets with a statistical accuracy = $\sigma/\sqrt{(M+N)}$/mean slope. Finally, one will have to add in quadrature systematic errors due to uncertainty in surrogacy, physics of the technique and calibrations. The various contributions to the tuning accuracy for each of the adjustable laser and target parameters is shown in Figure 1 in terms of their variance normalized to the tuning budget [12] listed in the sixth column in Table I. Many of these terms are themselves rss sums of various contributors [13]. Fig. 1 shows that we expect to meet the tuning accuracy budget for all parameters.

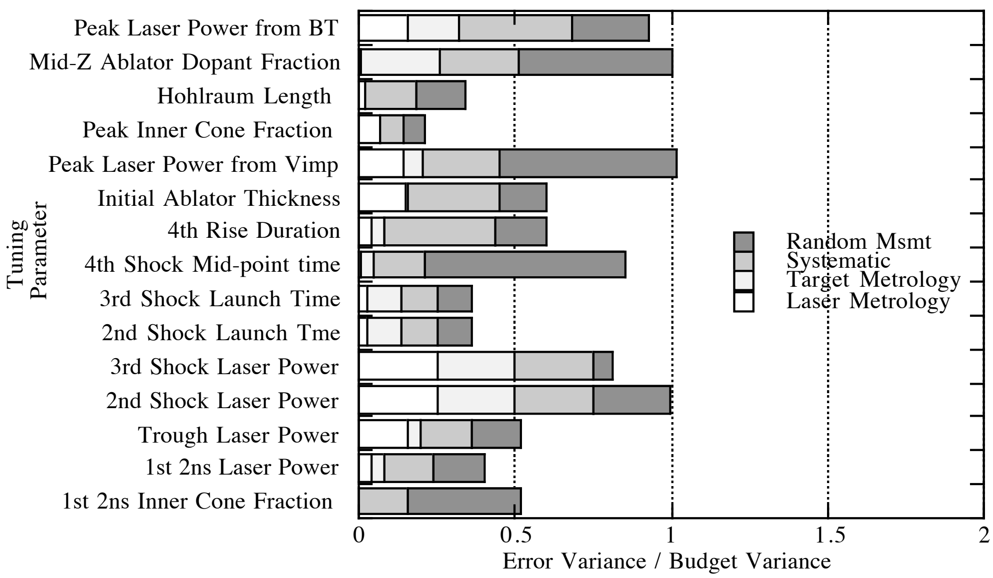

Figure 1. Residual expected variances after tuning normalized to budget for each of the laser and target adjustable parameters.

4. Summary

A capsule performance optimization campaign will experimentally correct for residual uncertainties in the implosion and hohlraum physics used in our radiation-hydrodynamic computational models before proceeding to cryogenic-layered implosions and ignition attempts. The required tuning techniques have been shown experimentally and computationally to meet the required sensitivity and accuracy. The tuning campaign plans include checks of repeatability, iterations to overcome residual cross-couplings and contingency shots. Finally, a set of additional in-flight capsule measurements to isolate capsule implosion physics issues if needed have also been conceptualized.

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