

# Implosion configurations for robust ignition using high-density carbon (diamond) ablator for indirect-drive ICF at the National Ignition Facility

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**Abstract.** We present five ignition scale capsule designs using high-density carbon ablators with fuel adiabat ( $\alpha$ ) ranging from 1.5 to 4. All five have 1D yield  $> 1$  MJ. The sensitivities of these capsules to surface roughness and  $P_2$  radiation asymmetries were studied. The most robust configuration with respect to surface roughness depends on the amplitude of the surface spectrum. The most robust configuration with respect to  $P_2$  asymmetry is the  $\alpha = 1.5$  configuration which has the highest 1D margin. We find that  $\alpha = 2$  and 2.5 configurations have the highest overall robustness. Further analysis is needed to study the effects of more complicated 3D behaviors.

## 1. Introduction

The two types of ablators used in most current indirect-drive implosion experiments at the National Ignition Facility (NIF) are plastic (CH) [1 - 4] and high-density carbon (HDC) or diamond [5 - 7]. The HDC ablators are made of micro-crystalline diamond with micron-scale crystal structure having grain size between one and a few microns [8].

The potential advantages of HDC ablator over other ablators, Be or CH, have been described previously [5]. The higher density and consequently thinner ablator allows better energy absorption for a given capsule outside diameter, a shorter pulse that provides hohlraum design flexibility, and less sensitivity to the perturbation seeded by the capsule support tent [Ref. 9].

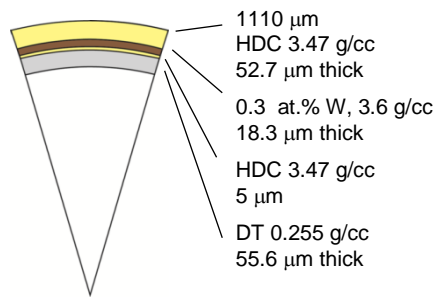
The search for the most robust capsule configuration requires the tradeoff among key implosion parameters: fuel adiabat, implosion velocity, dopant level, hydrodynamic instability, and low-mode radiation asymmetries. Performing this tradeoff to obtain the most robust configuration, which is a fundamental exercise in ICF implosion design and physics, is the goal of this note. A detailed description of this tradeoff and HDC implosion physics will be given in a forthcoming paper [10].

In this note, we present five ignition capsule configurations and their performance with fuel adiabat  $\alpha$  ranging from 1.5 to 4 in Sec. 2. The ignition cliff and robustness with respect to surface roughness are discussed in Sec. 3. The ignition cliff and robustness with respect to low-mode radiation flux asymmetries are discussed in Sec. 4. The selection of the overall most robust implosion configuration, according to the criteria assumed here, is presented in Sec. 5. Section 6 summarizes this work.

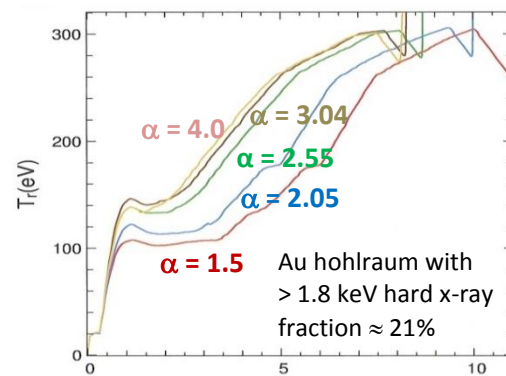
## 2. Capsule configurations and performances

We present five capsule configurations with  $\alpha$  ranging between 1.5 and 4. They have the same outer radius and ablator thickness (see Fig. 1). The fuel layer thickness is 55.6  $\mu\text{m}$  for all except 46  $\mu\text{m}$  for the  $\alpha = 4.0$  configuration. The radiation temperature  $T_r$  of the drive pulses are shown in Fig. 2. Note





**Figure 1.** HDC capsule configuration with  $\alpha = 2.05$ .



**Figure 2.** Channel Tr vs time for the  $\alpha = 1.52$ , 2.05, 2.55, 3.04, and 4.0 configurations.

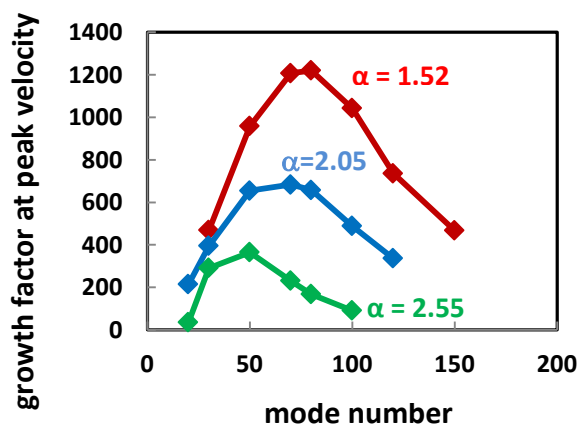
by the foot of the Tr profile of the  $\alpha = 1.52$  configuration, is close to the minimum required

for HDC ablators. Experiments using the Omega laser showed that the velocity ripples of the first shock become unacceptably large if it is below 6 Mbar [11]. Shocks do not merge inside the fuel layer for all, except the  $\alpha = 4$  configuration in which the first two shocks merge inside the fuel layer.

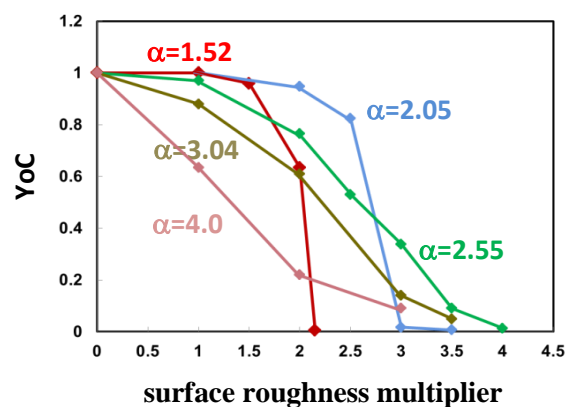
The capsule performance parameters, computed using the radiation-hydrodynamics code HYDRA [12], are listed in Table 1. A doped layer with 0.3 at.% W, is used to control the Atwood number at the ablator-fuel interface. The amount of dopant is close to the highest level currently accessible to the fabrication technology, and appears to be suitable for these designs. The dopant layer thickness is determined by the requirement that the simulated clean fuel fraction (fraction of initial fuel mass contaminated by 5% or less by mass of ablator material, from 2D simulations) at peak velocity ( $v_{\text{peak}}$ ) is between 80 and 85%. Ablation front Rayleigh-Taylor instability (RTI) growth decreases as  $\alpha$  increases (as indicated by the single-mode growth factors shown in Fig. 3) and this reduces the feedthrough that enhances the mix at the ablator-fuel interface. Also, the in-flight fuel density is lower with higher  $\alpha$ . The required dopant layer thickness therefore decreases with increasing  $\alpha$ .

Table 1. 1D capsule performance

Fuel adiabat $\alpha$	doped layer thickness ( $\mu\text{m}$ )	absorbed energy (kJ)	1D yield yield (MJ)	no-burn stagnation pressure	$v_{\text{peak}}$ (km/s)	fuel $\rho$ (g/cm <sup>3</sup> )	Atwood number	percent ablator mass remaining	convergence ratio
1.52	25.5	209	20.5	515	382	1.41	0.074	7.7	34.6
2.05	18.3	215	17.8	441	400	1.29	0.087	5.5	32.7
2.55	15.1	216	13.6	376	417	1.14	0.11	4.3	31.1
3.04	14.0	216	10.4	341	424	1.08	0.134	3.6	29.4
4.0	15.5	214	1.7	259	429	0.8	0.06	4.2	26.0



**Figure 3.** Ablation front growth factor at peak velocity vs mode number for  $\alpha = 1.52$ , 2.05, 2.55 configurations.



**Figure 4.** Yield cliff with respect to surface roughness.

Increasing  $\alpha$  reduces the fuel compressibility which lowers the convergence ratio (initial outer radius to hotspot radius at ignition); consequently the no-burn stagnation pressure drops. This is the main disadvantage of high- $\alpha$  implosions. However, two factors partially offset this disadvantage: (i) thinner dopant layer improves ablation efficiency; (ii) lower RTI growth allows higher- $\alpha$  implosions to have less ablator remaining at while maintaining the same clean-fuel fraction. These two factors results in higher  $v_{\text{peak}}$ , as shown in Table 1. This is why 1D yield  $> 10$  MJ is possible in these simulations for high  $\alpha = 2.5$  and 3 implosions. Doped layer thickness does not decrease further when  $\alpha = 4$  because of the thinner fuel layer. To maintain the same clean fuel fraction at  $v_{\text{peak}}$  for a thinner fuel layer, dopant layer thickness cannot be decreased further.

### 3. The ignition cliff and robustness with respect to surface roughness

The ignition cliffs for the five configurations with respect to surface roughness are shown in Fig. 4. The nominal ablator surface roughness used here is based on Atomic Force Microscope (AFM) spectra obtained prior to mid-2015. The indicated multiplier was put on the roughness of all surfaces.

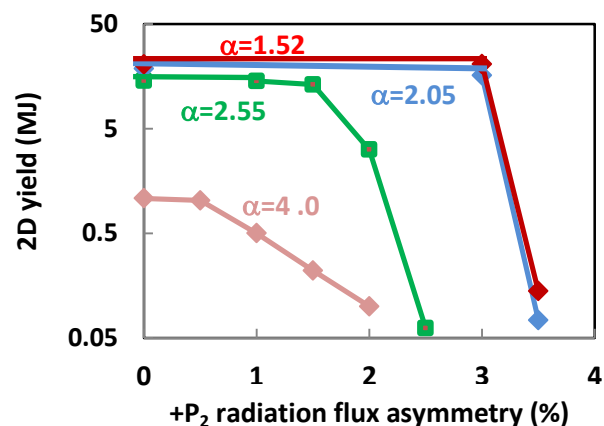
The  $\alpha = 2.5$  design allows the largest surface roughness. At lower adiabat, the implosions fail at low surface roughness multiplier because larger ablation-front RTI. As  $\alpha$  increase beyond 2.5, higher  $\alpha$  reduces 1D margin and the ignition cliff becomes susceptible to perturbation growth at the hotspot boundary during deceleration phase RTI. Consequently, ignition becomes less robust for  $\alpha > 2.5$ .

Substantial improvement on HDC surface roughness has been achieved for ablators fabricated after mid-2015. Simulations with smoother outer surface roughness show the ignition cliff of the  $\alpha = 1.5$  configuration becomes more robust and approaches that of the  $\alpha = 2$ . Therefore, improvement on the outer surface roughness improves the robustness more on low- $\alpha$  than on high- $\alpha$  implosions. The simulations shown in Fig. 4 do not explicitly include the effects of the capsule fill tube or support tent.

### 4. The ignition cliff and robustness with respect to $P_2$ radiation flux asymmetry

We found that with surface roughness, yield degradation is more susceptible to  $+P_2$  than to  $-P_2$  radiation flux asymmetry. To be conservative,  $+P_2$  is therefore being used in our study.

The yield cliffs for  $P_2$  asymmetry is shown in Fig. 5. Prior to the shocks merge near the inner fuel layer,  $P_2 = 0$  and then in 0.5 ns, rises to a constant value thereafter. The performance becomes less robust as  $\alpha$  increases. Even though the high- $\alpha$  implosions have lower convergence ratio, their low 1D margin makes them more susceptible to low-mode asymmetries. Therefore, this study leads us to the conclusion that the advantage of high 1D margin overrides the disadvantage of high convergence. The effect of the capsule support tents is not included in this analysis.



**Figure 5.** Yield cliffs for  $P_2$  flux asymmetry for  $\alpha = 1.52, 2.05, 2.55$ , and  $4.0$  configurations.

### 5. The most robust overall implosion configuration and relation to CH implosion experiments

Combining the results from these two sensitivity studies allows us to select the overall most robust implosion configuration for an ignition experiment. The logic for this selection is:

(a) For rougher outer surface spectrum

- Since the difference between the ignition cliff for  $+P_2$  for  $\alpha = 1.5$  and  $2.0$  configuration is not large but  $\alpha = 1.5$  has the worst surface roughness sensitivity, is more susceptible to the tent, and is more difficult to obtain good radiation symmetry for its longer pulse, this eliminates  $\alpha = 1.5$  from the selection for the most overall robust configuration.
- The ignition cliff for  $+P_2$  falls off rapidly for  $\alpha > 2.5$  and therefore configurations with for  $\alpha > 2.5$  can be eliminated from the selection.
- $\alpha = 2.5$  is slightly more robust than  $\alpha = 2.0$  in terms of surface roughness but worse than  $\alpha = 2.0$  for

+P<sub>2</sub> robustness. Therefore, the choice between  $\alpha = 2.0$  and 2.5 depends on the following factors: the importance of tent perturbation and the quality of radiation symmetry provided by the hohlraum.

(b) For smoother outer surface spectrum

The robustness of the  $\alpha = 1.5$  becomes close to that of the  $\alpha = 2.0$  in terms of surface roughness if tent perturbation is not dominant (e.g., using alternate support strategy, or if the tent-seeded perturbation is acceptable for HDC capsules). If the hohlraum can accommodate the longer pulse length of the  $\alpha = 1.5$ , then this design could be the most robust as it has the largest tolerance to P<sub>2</sub> asymmetries.

While the above description provides the first attempt to select the most overall robust configuration for ignition, some factors have not been included. For a detailed search of the most robust configuration, other factors to consider would include: P<sub>4</sub> radiation asymmetries, the effect of the tent, 3D phenomena, and the time-dependent radiation asymmetries for specific hohlraum designs.

The “high-foot” CH implosion campaign during the last two years shows higher  $\alpha$  ( $\sim 2.3$ ), implosions perform better than low- $\alpha$  ( $\sim 1.5$ ) implosions [4] since higher  $\alpha$  has RTI growth substantially lower than the low-foot. Because of this, high-foot is less sensitive to perturbations caused by the tent, which is the major factor in causing yield degradations in low-foot. The major sources of yield degradation for high-foot then becomes low-mode flux asymmetry as demonstrated by detailed 3D simulations by Clark [13]. This suggests the value of going to higher adiabat for stability. Furthermore, high-foot CH implosions typically have higher  $v_{\text{peak}}$  than low-foot, i.e.,  $\sim 355$  vs  $\sim 320$  km/s and would make the high-foot even more robust than the low-foot implosions. In contrast, the ignition HDC capsules studied here have  $v_{\text{peak}} > 380$  km/s and therefore the relative sensitivity to low modes are further reduced. Taking into account all these differences between CH experiments and our calculations, the CH experimental results are consistent with what we have presented here.

## 6. Conclusions

We have optimized the design of five DT-layered capsules with  $\alpha$  between 1.5 and 4. By applying the appropriate amount of dopant so that the clean-fuel fraction at  $v_{\text{peak}}$  is between 80 and 85%, we are able to demonstrate that high- $\alpha$ , i.e., 2 to 3, implosions can achieve high yield. The most robust configuration with respect to surface roughness depends on the amplitude of the surface spectrum. For robustness with respect to P<sub>2</sub> flux asymmetry, the configuration with the lowest  $\alpha$  is the most robust and the advantage of 1D margin overrides the advantage of low convergence. Combining the consideration of surface roughness and P<sub>2</sub> asymmetry,  $\alpha$  between 2 and 2.5 appears to be the most robust overall configuration for ignition and high yield even taking into the consideration of the tent. Although the  $\alpha = 4$  configuration has low convergence ratio, it has less overall robustness, unless the corresponding hohlraum design can provide considerably better symmetry.

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