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Development of a polar direct drive platform for mix and burn experiments on the National Ignition Facility

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Abstract. Capsules driven with polar drive [1, 2] on the National Ignition Facility [3] are being used [4] to study mix in convergent geometry. In preparation for experiments that will utilize deuterated plastic shells with a pure tritium fill, hydrogen-filled capsules with copper-doped deuterated layers have been imploded on NIF to provide spectroscopic and nuclear measurements of capsule performance. Experiments have shown that the mix region, when composed of shell material doped with about 1% copper (by atom), reaches temperatures of about 2 keV, while undoped mixed regions reach about 3 keV. Based on the yield from these implosions, we estimate the thickness of CD that mixed into the gas as between about 0.25 and 0.43 µm of the inner capsule surface, corresponding to about 5 to 9 µg of material. Using 5 atm of tritium as the fill gas should result in over $10^{13}$ DT neutrons being produced, which is sufficient for neutron imaging [5].

1. Effects of mix on burn
Mix of plastic into the DT fuel of an ICF capsule adds non-burning material, diluting the fuel and reducing burn. At a sub-grid scale, the mix can be described as a distribution in concentrations of the DT within a region of mixed DT and plastic.

Turbulent mixing in ICF capsules must be described using models that attempt to capture the important physics in a computationally efficient manner, allowing large-scale simulations of imploding capsules. One such model is the BHR model [6] and its revisions [7, 8]. Results from this model have been used in burn models that use a probability distribution function [9] (PDF) to describe concentration variations at the sub-grid level to determine the effect on burn [10].

In order to measure the mix of materials at an interface and determine its effect, we are performing experiments leading to implosions of capsules with doped-deuterated inner layers and a tritium gas fill [4]. As this layer mixes into the gas, the x ray self-emission will be imaged.
using a multi-monochromatic imager (MMI) currently under development [11] to determine the amount and extent of mix [12] of the deuterated layer into the tritium gas. This mix will be compared to the source region for DT neutrons [5] which can only come from the region where the deuterium from the deuterated layer mixes with the tritium gas [13]. X-ray and neutron images of sufficient quality require 1 J/sr in the Ly-β and He-β x-ray lines of the dopant material and a DT neutron yield exceeding $10^{13}$ [5], respectively.

2. Defining the measure of mix

To illustrate the PDF model in a simplified way, assume a mixture of deuterium and tritium, initially separated. DT neutron yield increases with increasing mix of the two species. This can be calculated, noting that the yield from a volume element is dependent on the average of the product of the densities of deuterium and tritium, rather than the product of their averages.

\[ Y_{DT} = \langle n_D n_T \rangle \langle \sigma v \rangle_{DT} V \tau \]  \hspace{1cm} (1)

where, in general,

\[ \langle n_D n_T \rangle \leq \langle n_D \rangle \langle n_T \rangle . \]  \hspace{1cm} (2)

Defining the concentrations of D and T at any point as $c = n_D/n_i$ and $1 - c = n_T/n_i$, where $n_i$ is the ion density, and letting $\bar{c} = \bar{c} + \tilde{c}$, the spatially averaged concentration and the spatially varying concentration within a computational volume, one can show:

\[ \langle n_D n_T \rangle = \langle n_D \rangle \langle n_T \rangle \theta \]  \hspace{1cm} (3)

where

\[ \theta = 1 - \frac{\left( \bar{c} \right)^2}{\bar{c}(1-\bar{c})} \]  \hspace{1cm} (4)

so that

\[ Y_{DT} = \theta \langle n_D \rangle \langle n_T \rangle \langle \sigma v \rangle_{DT} V \tau . \]  \hspace{1cm} (5)

\[ \theta \] is referred to as “mixedness” and ranges from 0 to 1; $1 - \theta$ is the “degree of segregation” [14]. This parameter can be directly related to quantities produced by the BHR turbulence model [15].

The goal of these experiments is to image the x-ray emission due to mix [11, 12] of doped deuterated plastic shell material into the tritium fill gas in an ICF capsule and image the DT neutrons [5] produced. Results will be compared to determine the mixedness ($\theta$) and how it compares to simulations utilizing the BHR2 turbulent mix model and the PDF burn model.

3. Copper-doped deuterated shell implosions

Two implosions were performed using capsules (figure 1) in which the inner 3 $\mu$m were deuterated and which contained a 1-$\mu$m copper-doped layer either at the inner surface or buried under 1 $\mu$m of undoped deuterated plastic. The capsules were filled with 5 atm of hydrogen. These implosions were performed using polar direct drive [1, 2]. Laser pointing that produces the necessary symmetry has been simulated [16] and symmetric implosions have been obtained. Total laser energy of 355 kJ on the capsules in a 2.15 ns square pulse was used. Power in the polar beams was reduced to 80% of the equatorial beams to improve the drive symmetry.

X-ray spectroscopy (figure 2) using the SuperSnout [17] spectrometer shows a number of x-ray lines from the surface doped layer, while none are apparent from the buried layer. This indicates that less than 1 $\mu$m of shell material mixed into the gas. The $\beta$ lines of copper were too weak for imaging with the planned MMI but the line ratios indicate that the temperature in the mix region is about 2 keV. Detailed modeling suggests that changing from copper to a lower
atomic number dopant such as titanium or iron should produce sufficient x rays for imaging. Reduction of the concentration may be necessary to minimize the effect of the dopant on the implosion.

Neutron yield measurements from these implosions allow an estimate of the DT neutron yield that would have been produced had the capsules been filled with 5 atm of tritium gas instead of the hydrogen that was used for these experiments. If we assume that the yield comes from a layer of deuterated plastic of thickness $\Delta_o$ that uniformly mixes into the shell, then then the number of deuterium atoms that mix into the fuel is given by

$$N_d = 4\pi R_{io}^2 \Delta_0 n_{CD}$$

(6)

where $n_{CD}$ is the number density of CD in the unimploded capsule. From this, the DD neutron yield can be estimated:

$$Y_{DD} = \frac{1}{2} n_D^2 \langle \sigma v \rangle_{DD} V_f \tau$$

$$= \frac{1}{2} \left( \frac{N_D}{V_f} \right)^2 \langle \sigma v \rangle_{DD} V_f \tau$$

$$= 6\pi C^3 R_{io} \Delta_0^2 n_{CD}^2 \langle \sigma v \rangle_{DD} \tau$$

(7)

where the convergence ratio is defined as $C = R_{io}/R_{if}$.

The mix depth needed to explain a given neutron yield in this model is given by

$$\Delta_0 = \sqrt{\frac{Y_{DD}}{6\pi C^3 R_{io} n_{CD}^2 \langle \sigma v \rangle_{DD} \tau}}.$$ 

(8)

We can then estimate the DT yield resulting if the hydrogen fill is replaced by tritium at initial number density $n_{tio}$ using equation 5:

$$Y_{DT} = \theta \langle n_D \rangle \langle n_T \rangle \langle \sigma v \rangle_{DT} V_f \tau$$

$$= \theta N_D \langle n_T \rangle \langle \sigma v \rangle_{DT} \tau$$

$$= \theta 4\pi R_{io}^2 \Delta_0 n_{CD} n_{tio} C^3 \langle \sigma v \rangle_{DT} \tau$$

(9)

Results from these equations are shown in table 1 assuming a convergence of 7, complete mixing of the deuterium in to the tritium, and that the burn time $\tau$ can be approximated by the measured x-ray emission width.
Table 1. Measurements used in determining the amount of deuterated plastic which contributes to the neutron yield in the deuterated shell implosions, and the estimated DT yield if the capsuled had been filled with tritium gas.

| Capsule Surface doped layer | Buried doped layer |
|-----------------------------|-------------------|
| $T_i$ | 2.00 | 3.03 |
| $\langle \sigma v \rangle_{DD}$ | $3.00 \times 10^{-21}$ | $1.59 \times 10^{-20}$ |
| $\tau$ | 343 | 398 |
| $Y_{DD}$ | $1.28 \times 10^9$ | $7.38 \times 10^9$ |
| $\Delta_{max}$ | 0.26 | 0.25 |

Estimated $Y_{DT}$

| $\langle \sigma v \rangle_{DT}$ | $2.71 \times 10^{-19}$ | $1.81 \times 10^{-18}$ |
| $Y_{DT}$ | $1.85 \times 10^{12}$ | $1.39 \times 10^{13}$ |

4. Summary

Data from these implosion experiments contribute to the design for a mix and burn platform on the National Ignition Facility. X-ray spectroscopic data has been used to determine the range of elements that would be suitable as a tracer for imaging the mix of a deuterated plastic layer into the fuel gas. Neutron data suggests that with a tritium fill, a sufficient neutron yield would be produced to allow neutron imaging.

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