Indications of the Rygg Yield Anomaly in Indirect Drive D-^{3}He Implosions

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Abstract

The Rygg effect, an anomalous yield reduction in imploding inertial confinement capsules with D-^{3}He fill, has been demonstrated repeatedly in direct drive experiments. Yield is found to diminish as a function of ^{3}He fraction relative to the yield expected from hydrodynamic scaling[1,2]. OMEGA implosions of DD and D^{3}He-filled capsules in cylindrical and rugby hohlraums[3] provide evidence for the Rygg effect in the indirect drive geometry. In the future, as part of our NLUF research program, we plan to look for the presence of the effect in hohlraum implosions directly.

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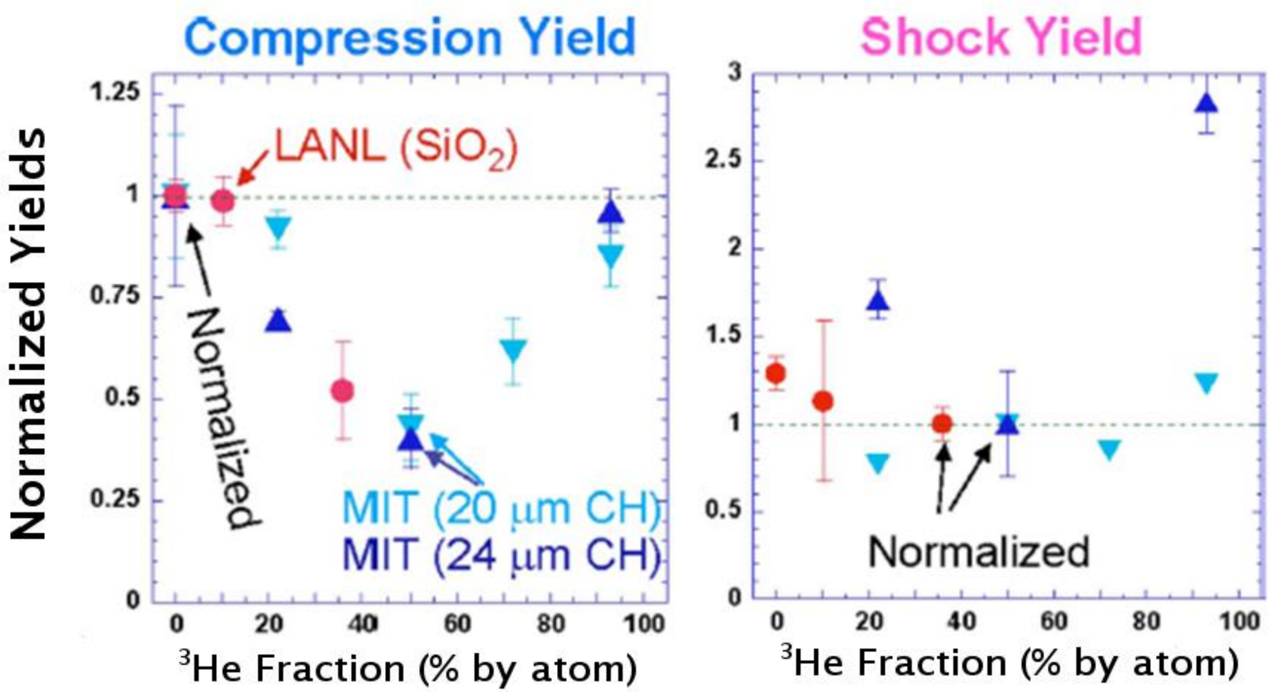
[1] J.R. Rygg, et al. Phys. Plasmas 13 052702 (2006)
[2] H.W. Herrmann, et al. Phys. Plasmas 16, 056312 (2009)
[3] F. Philippe, et al. Phys. Rev. Lett. 104, 035004 (2010)

Anomalous reduction in scaled direct drive yields has been linked to ^{3}He content



D^{3}He fuel (▲,▼): Hydroequivalent, scaled DD-n yields were compared shot-to-shot.

THD+^{3}He fuel (●): DT-n yields were scaled to 1-D simulated yields.

From *H.W. Herrmann, et al. Phys. Plasmas 16, 056312 (2009)*

Atwood Number and EOS can be kept constant for a variety of ‘hydroequivalent’ $\{D, {}^3He\}$ pressures

Atwood number:

$$\frac{\rho_{shell} - \rho}{\rho_{shell} + \rho}$$

Equation of State:

$$p = \left[\frac{\rho(1+Z)}{A}\right]\frac{k_B T}{m_p}$$

For both D and ^{3}He, $\frac{(1+Z)}{A} = 1$:

Fixed ρ ⇒ equivalent Atwood # and EOS
in D^3He mixtures, preserving
hydrodynamic behavior.

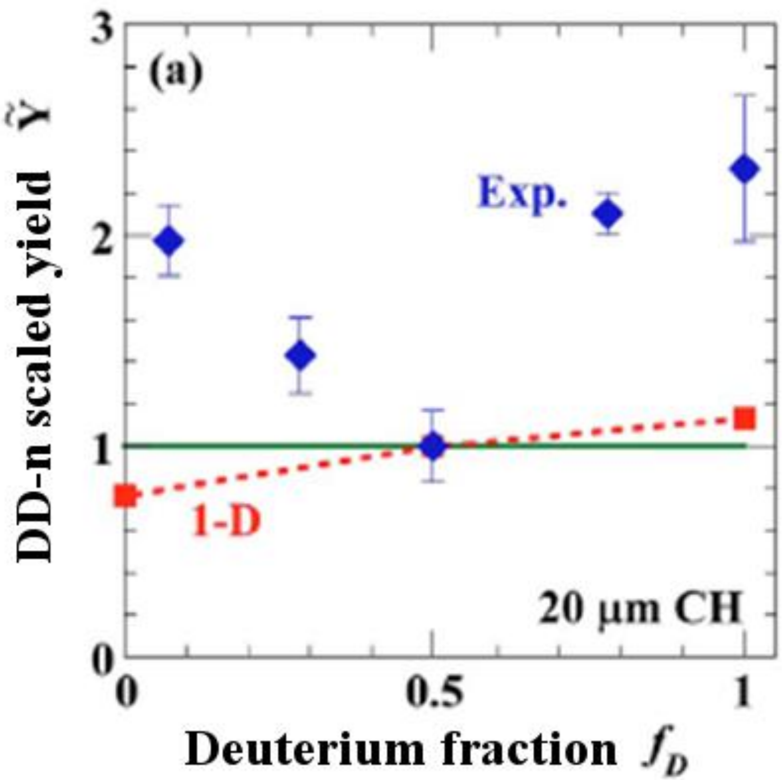
For any fraction of deuterium, a fill pressure may be chosen to set the mass density:

$$P_{D_2} + \tfrac{3}{4} P_{{}^3He} = X_0$$

where X_0 is the hydroequivalent fill pressure for pure D_2

Hydrodynamic scaling for equivalent fuels fails to explain the observed behavior

Hydrodynamics wrongly predicts the scaled yields $\tilde{Y}$ to be **equal** for equivalent fuel mixtures

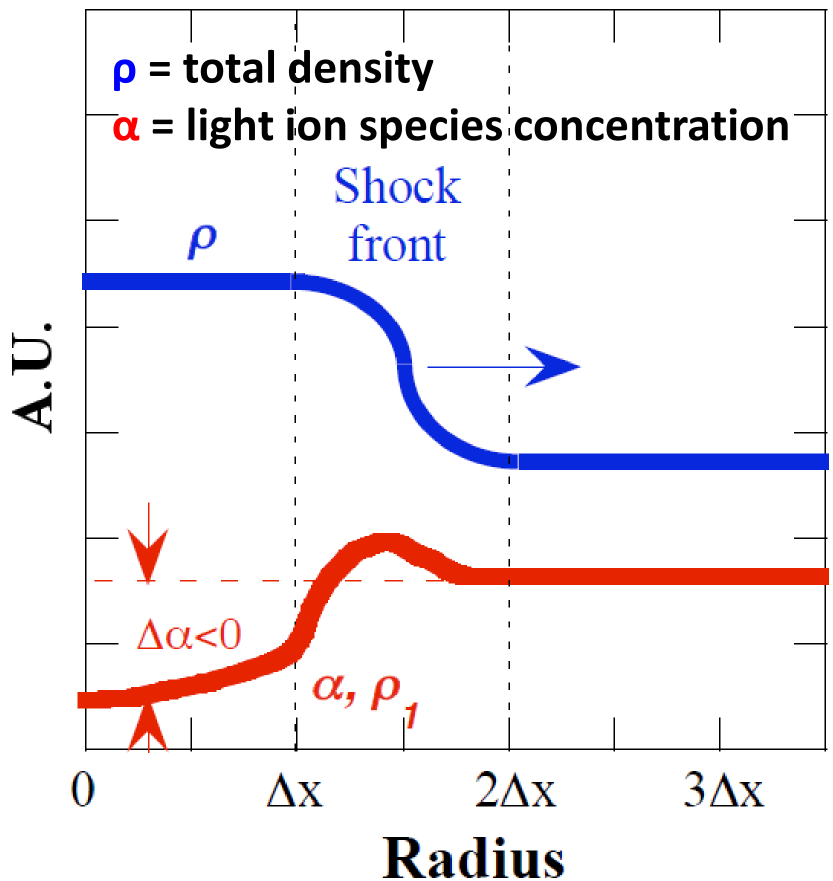


◆ Experiment
— Hydro-scaling
···· Simulation

$$Y_n = \frac{f_D^2}{(1-f_D)^2}\int \frac{\rho^2(\vec{r},t)}{2m_p}\langle\sigma v\rangle_{DD-n}\, d^3\vec{r}\,dt \rightarrow \tilde{Y}_n = \frac{(1-f_D)^2}{f_D^2} Y_n$$

From *J.R. Rygg, et al. Phys. Plasmas 13 052702 (2006)*

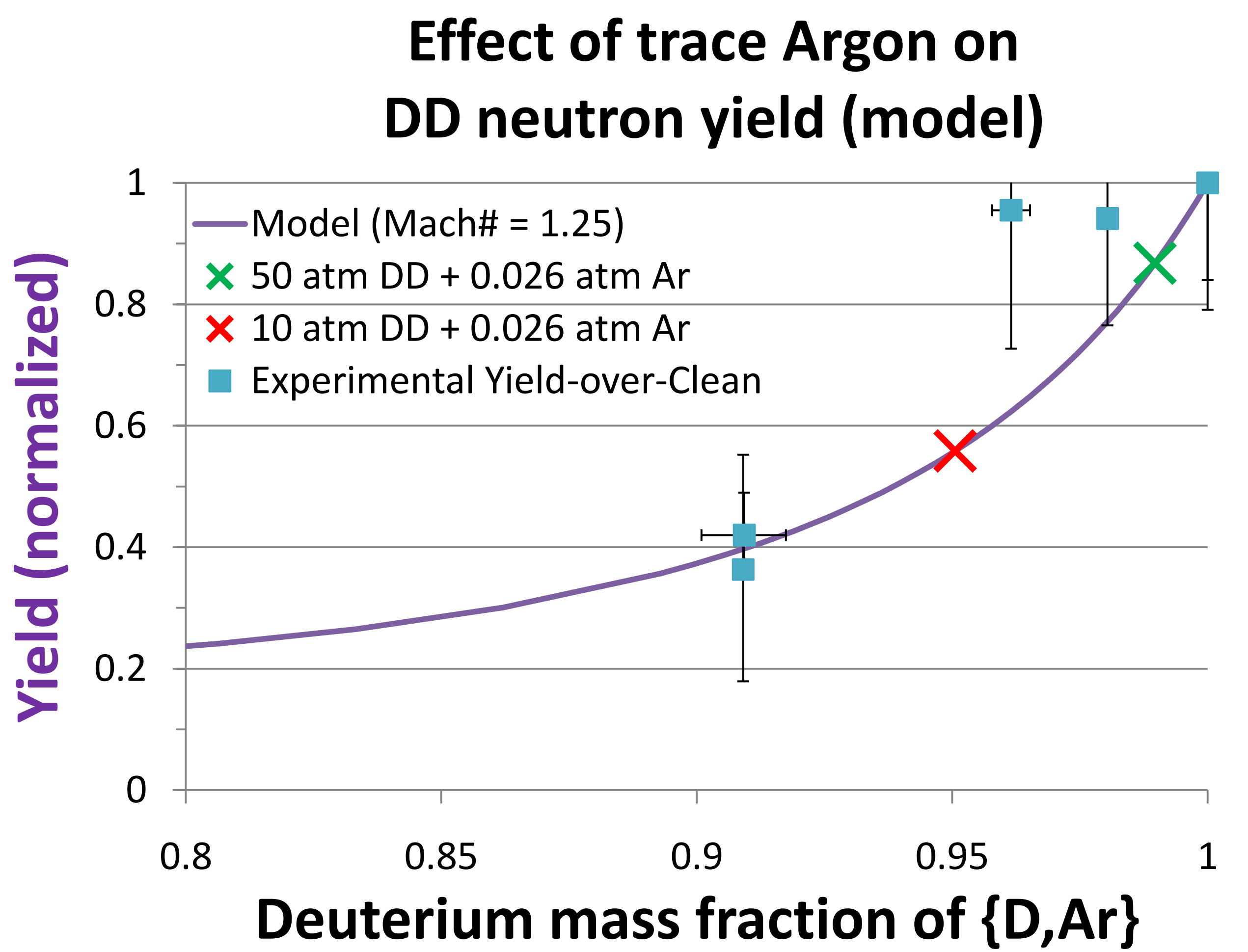
Enhanced barodiffusion due to large electric fields provides a potential mechanism[1]



- "Strong" electric fields across shock fronts increase the diffusion coefficient for the lower-Z ion species
- During the implosion, deuterium diffuses out of the core faster than ^{3}He
- Estimates ~ **30% reduction** in n yield for D^{3}He mixtures with $f_D = 0.5$

[1] *Peter Amendt, O.L. Landen, H.F. Robey, C.K. Li, R.D. Petrasso, unpublished*

Barodiffusive effect accurately describes yield reductions for capsules with trace high-Z impurities



Peter Amendt, et al. unpublished

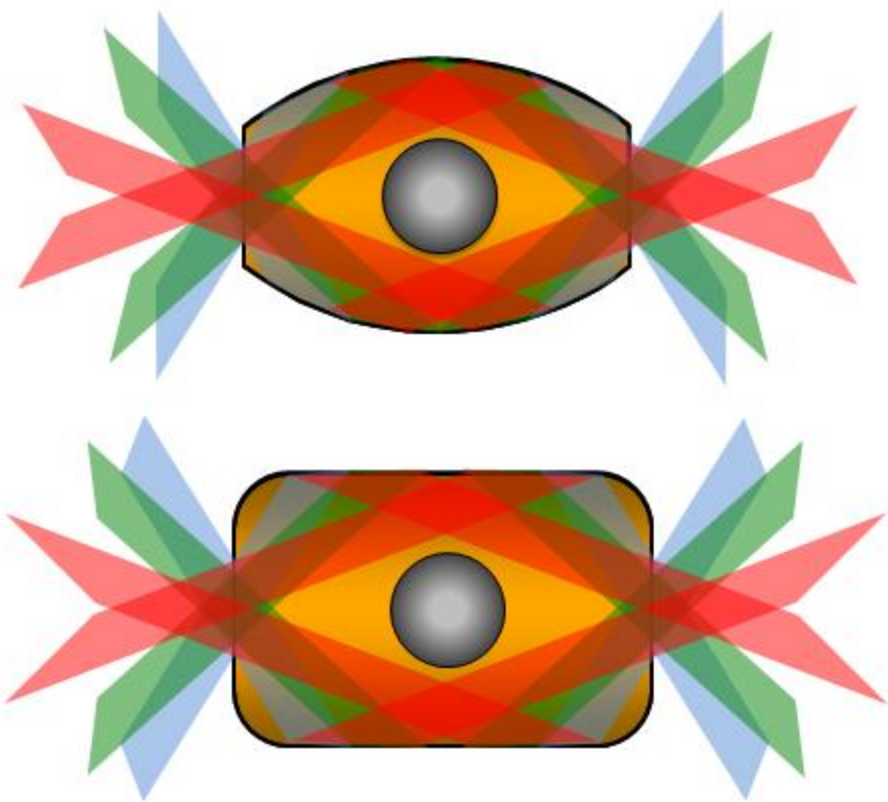
Experimental data from *J.D. Lindl, et al. Phys. Plasmas 11, 339 (2004)*

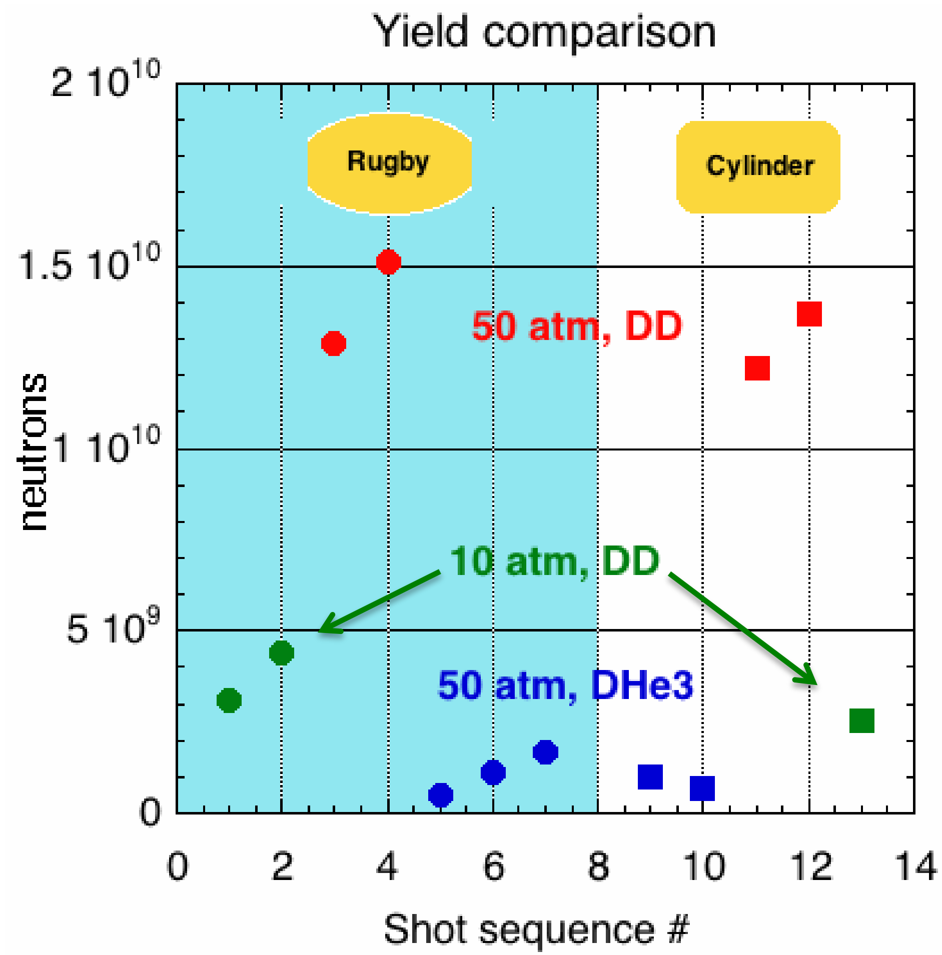
Does the anomaly affect ignition performance?

- The barodiffusion theory predicts that the "strong" effect (due to shocks) is only present when $Z_1 \neq Z_2$
  - ✓ DT yield is directly affected only weakly ($\lesssim$ 1%)
  - ✘ T decay to ^3He will dampen yields

- This mechanism can decrease performance substantially if trace impurities are present

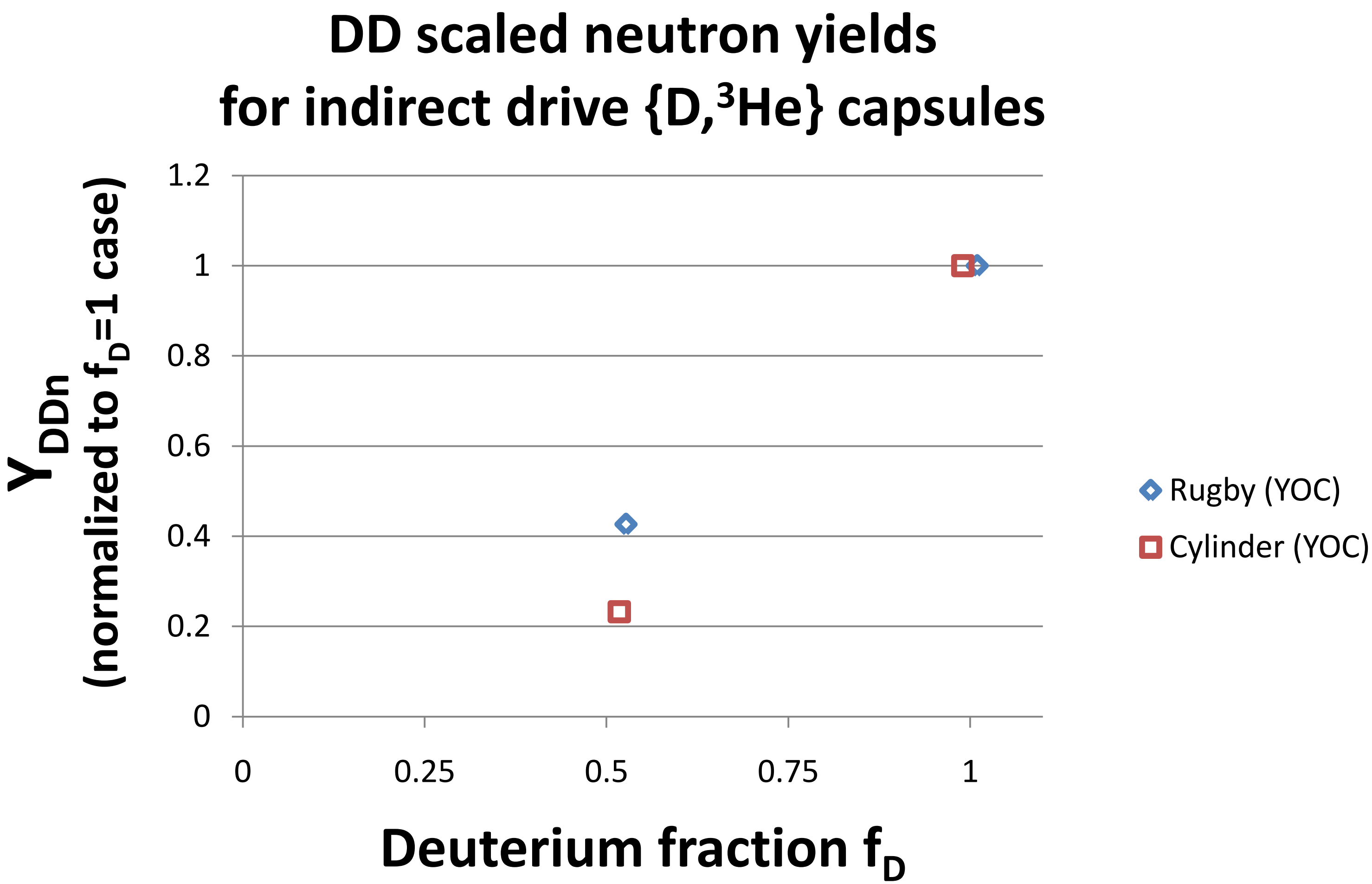
On June 16th, 2009 several rugby and cylindrical hohlraums were shot on OMEGA





From *H.F. Robey, APS 2009, Invited Talk*

Comparison of hohlraum data to simulations shows evidence of reduced yield

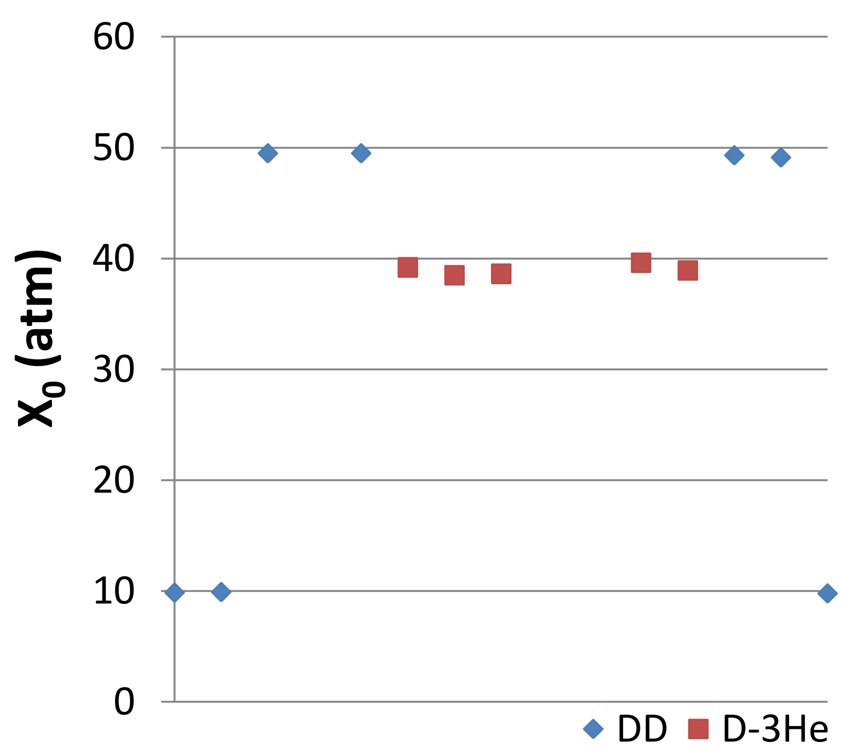


Yield-Over-Clean (YOC) from simulations by H. Robey, LLNL

Analytical comparison is complicated by trace gasses and non-hydroequivalent fuels

- Implosion dynamics make yield scaling more difficult for capsules with non-uniform values of X_0
- All capsules contained trace Ar (0.026 atm) and residual air (0.05 atm)
  - This is known to reduce the DD-n yield by a factor of 2-3, see pg 5.

Hydroequivalent DD Fill Pressure X_0 at shot time



Shot-to-shot comparison of yields is unfeasible for this data due to lack of information

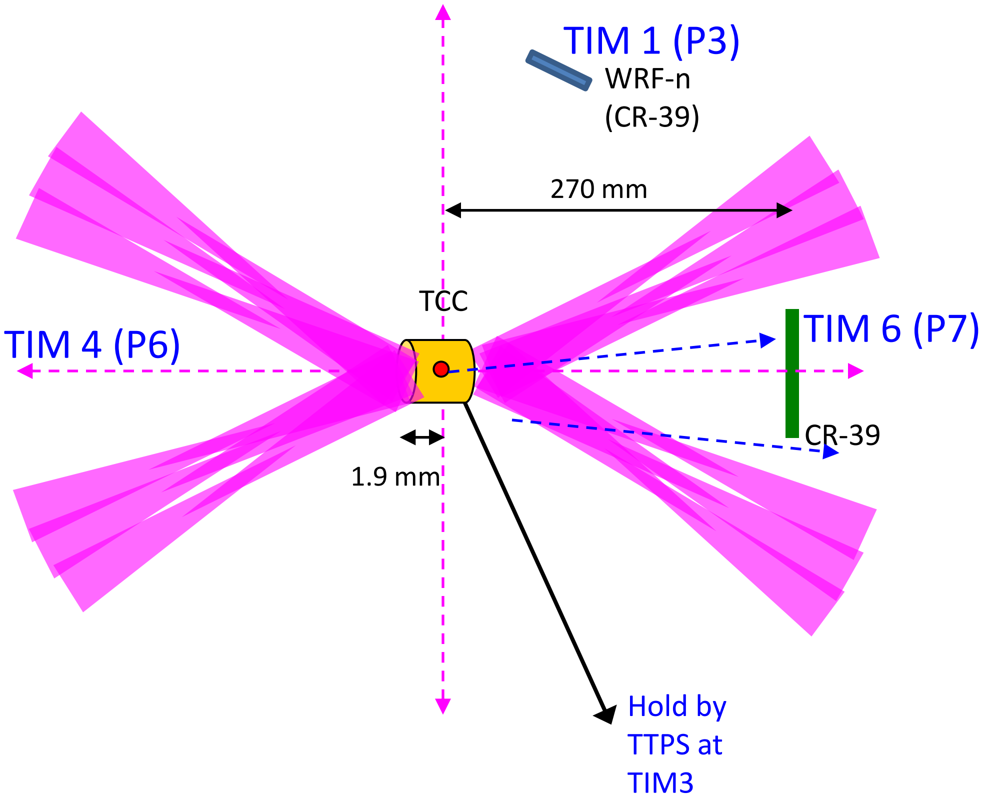
$$Y_n = \int \tfrac{1}{2} n_D^2(\vec{r},t)\langle \sigma v \rangle_{DD-n} d^3\vec{r}\,dt \propto \rho^2 R_b^3 T_i^m t_b \propto \left(\frac{R_b}{R}\right)^3 (CR)^3 T_i^m t_b$$

Where (CR) is the compression ratio; m ≈ 3.5 at these temperatures

- D^3He shot yields were too low for NTD to record the burn duration (t_b)
- Experimental (CR) behavior is unknown above 15 atm
  - has been shown to be ~ constant between 3 and 15 atm, due to fuel-shell mix
  - At 15 atm, $CR_{exp} \approx CR_{1D\text{-}sim}$

From *C.K. Li, et al. Phys. Rev. Lett. 89 (16), 165002 (2002)*

A series of shots is being designed to investigate the Rygg effect in indirect drive implosions



- Sample fill Pressures:

f_D	P_{D2}	$P_{^3He}$	P_{tot}
0.3	12.5 atm	38.9 atm	**51.4 atm**
0.5	20.8	27.8	**48.6**
0.8	29.2	16.7	**45.8**
1	41.67	0	**41.67**

- Fielded Diagnostics:
  - 3nTOF (Y_{DDn})
  - CPS (Y_{D3He})
  - WRF-n (Y_{D3He}, Y_{DDn})
  - PRM (self-emission radiography)

Summary & Future Work

- An anomalous reduction in the yield of capsules filled with mixtures of D and ^3He has been demonstrated in direct drive ICF

- Indirect drive experiments are indicative of the D-^3He anomaly as well

- A series of shots will be planned to look for the Rygg Effect in indirectly driven capsules as part of our NLUF research program.

- We will also investigate the presence of the effect in direct drive exploding pusher capsules

The Rygg Effect
& Hydrodynamic Equivalence

Theory & Possible Explanations

Indirect Drive Experiments